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Shales and Other Argillaceous Strata in the United States

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Preface

This report was originally prepared for the U.S. department of Energy (DOE) as part of the United States government effort to identify a site suitable for building a repository for disposal of high-level radioactive wastes. The authors, contracted through the Office of Nuclear Waste Isolation (ONWI) at Battelle Memorial Institute, made a study of all the thick shales and argillaceous strata in the conterminous United States to characterize their general suitability to serve as host rocks for disposal of such waste material. Subsequently, DOE had the report released by Oak Ridge National Laboratory (ORNL) in its current form, as part of the ORNL program to investigate rock formations other than salt for disposal of radioactive wastes.

Although this report is now dated, there is continued interest in finding a suitable site for disposal of high-level radioactive wastes, and there may still be interest in examining the potential for disposal of these wastes in thick shales or argillaceous strata. The original report had a limited distribution, and an electronic copy has not been available; because of this, and because a number of Oklahoma shale units are described, the Oklahoma Geological Survey is making the document available online as an Open-File Report.

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OAK RIDGE NATIONAL LABORATORY

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SHALES AND OTHER ARGILLACEOUS STRATA IN THE UNITED STATES

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FOREWORD

In 1976 the National Waste Terminal Storage (NWTS) Program was established by the U.S. Energy Research and Development Administration (ERDA), the agency that has now become the U.S. Department of Energy (DOE). The NWTS Program is directed toward development of technology for the permanent disposal of high-level radioactive waste in an environmentally safe manner. Emphasis has been placed on disposal of the wastes deep underground in repositories constructed in geologically stable rocks. Several rock types are being considered by the DOE as host rocks for disposal of wastes; these rocks include basalt, crystalline rock (granitic), volcanic tuff, salt, and various other sedimentary rocks, such as shales and argillaceous strata.

In 1979, the DOE, through the Office of Nuclear Waste Isolation (ONWI) at Battelle Memorial Institute, contracted with Serge Gonzales and Kenneth S. Johnson to prepare a report on the geologic and hydrologic characterization of shales and other argillaceous strata in the conterminous United States. This report was to serve as a data base for further assessment of such rocks as possible candidates for hosting a repository. The report was first produced by ONWI in preliminary draft form in 1982. In 1984, the DOE requested that Oak Ridge National Laboratory (ORNL) issue this second, revised draft of the report for review, as part of ORNL's program to investigate sedimentary rocks other than salt for waste disposal purposes. With one exception, revisions made in preparing the second draft have not incorporated geologic data and reports issued since the first draft was prepared, and, thus, the effective date for information upon which this revised draft is based is early 1982. Because of new geologic data, developed by ORNL staff, on the Conasauga Group of rocks, the description of this group has been updated to include publications since 1982.

This report presents detailed geologic and hydrologic data that describe shales and other argillaceous rocks; data are from the open literature. These data are intended to be used in the future to aid in assessment of various strata and their potential for repository siting.

No observations, conclusions, or recommendations are made by the authors of this report relative to the suitability of various argillaceous rocks for waste disposal. There are, however, other published reports that contain technical data and evaluative statements regarding the suitability of various argillaceous rocks for repository siting. Where appropriate, the authors of this report have referenced this previously published literature and have summarized the technical data.

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TABLE OF CONTENTS

TABLE OF CONTENTS

(Continued)

TABLE OF CONTENTS

(Continued)

TABLE OF CONTENTS

(Continued)

TABLE OF CONTENTS

(Continued)

Page

TABLE OF CONTENTS

(Continued)

LIST OF FIGURES

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

LIST OF FIGURES
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Page

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(Continued)

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(Continued)

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LIST OF FIGURES
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LIST OF FIGURES
(Continued)

Page

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

LIST OF TABLES

1. INTRODUCTION

1.1 BACKGROUND

Even though rock salt was suggested in the 1950s as a potential host rock for a high level radioactive waste repository, interest has continued in other rock types as well. The different rock media that have been proposed from time to time for regional and site-specific investigations toward this objective include basalt, granite, volcanic tuff, serpentinite, certain "dry" limestones, and shales and clays. The greatest level of initial interest in argillaceous, or clay-rich, strata has been shown by several European nations (Italy, Belgium, United Kingdom) that either lacked salt deposits or some of whose nuclear facilities were sited above thick deposits of clay. Examples of this latter circumstance are to be found at Mol, Belgium, and Trisaia, Italy.

Desirable attributes such as low permeability, plasticity toward self-sealing of fractures and other openings, and high ion-exchange capacity were cited as positive reasons for more fully investigating deposits of shale and other argillaceous strata. Concerns entailed the finding of thick homogeneous units that lacked any interbedded strata such as siltstones, sandstones, and carbonates; the effect of thermal loading (from waste in canisters) on the clay minerals, with an attendant release of water, alteration of the pore-fluid chemistry, and possible desiccation and weakening of rock-mechanical properties.

Although various investigations had been carried out on argillaceous rock units in the United States prior to the late 1970s (see subsequent discussion), two events, one foreign and one domestic, have helped to stimulate greater interest in such clay-rich media more recently. When the Swedish Kärnbränslesakerhet (KBS) program championed the multibarrier concept within the total philosophy of a repository design, one of the essential components was the use of a buffering material as an overpack around the waste canisters. Bentonite, a clay mineral having high ion-exchange capacity, has been one of the leading candidate materials in this regard.

The domestic event of note was the issuance of recommendations by the Interagency Review Group, whose final report in 1979 strongly urged that the United States pursue the concept of regional repositories and more vigorously investigate nonsalt lithologies. In addition to rock types that are present in the immediate area of several domestic nuclear facilities (Hanford Reservation, Washington - basalt; Nevada Test Site, Nevada - volcanic tuff, granite, and argillite; Los Alamos Laboratory, New Mexico - volcanic tuff), the two rock types proposed for study to increase the level of knowledge about their potential were granites (and related "crystalline" igneous rocks) and argillaceous strata.

Each of these efforts was to be initiated by a regional-level, nationwide assessment of these rocks within the conterminous United States, and the recommendation of more promising regions that could be studied in more specific detail. These studies were approved and coordinated by the Battelle Office of Nuclear Waste Isolation. A draft report on crystalline intrusives (granites) was issued (Murrie and Gates, 1979), and was reissued in revised form. The current report represents the culmination of the effort to summarize data on shales, clays, and argillites.

As previously noted, several earlier studies have been of assistance in this endeavor and represent both literature and field investigations as well as in situ thermal experiments (Figure 1-1). These studies were directed toward the New Albany and Maquoketa Shales in Indiana (Droste and Vitilian, 1976), the Porters Creek and Yazoo Clays and certain other shales and clays in the eastern Gulf Coast - Black Warrior Basin area (Mellen, 1976), and several Triassic shale-bearing basins along the Atlantic Coastal Plain - Piedmont trend (Weaver, 1976). Work on all these projects was supported and directed by the now defunct Office of Water Isolation (OWI) of the Union Carbide Corporation (UCC). All of these projects focused on investigating certain regional properties of individual stratigraphic names of localized deposits (Triassic Basins). A more recent, followup study on the eastern United States Triassic Basins

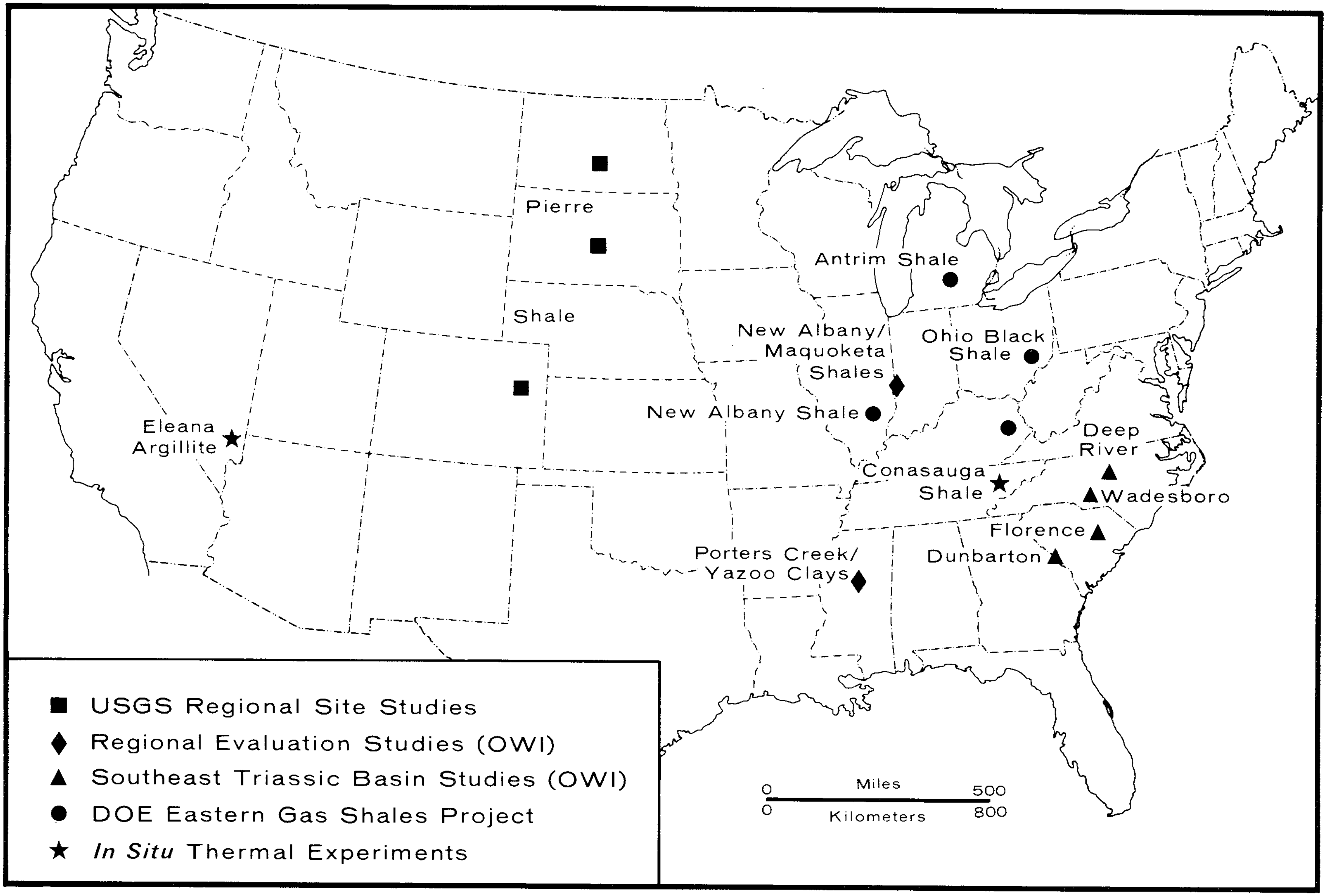

FIGURE 1-1. MAP OF UNITED STATES SHOWING LOCATIONS OF PREVIOUS FIELD AND SUBSURFACE STUDIES AND IN SITU THERMAL EXPERIMENTS CONDUCTED ON ARGILLACEOUS STRATA

was completed (Dames and Moore, 1980) and issued through the Savannah River Laboratory.

For many years the U.S. Geological Survey (USGS) has conducted a wide spectrum of basic geologic, geochemical, and mineralogic studies of the Upper Cretaceous Pierre Shale in the Northern Great Plains.

Because of their unusual potential for the production of unconventional natural gas, the Devonian-Mississippian shales in the Appalachian, Michigan, and Illinois Basins have been studied in great detail since the late 1970s, although the overriding focus has been on ultimate resource recovery. The massive amount of geologic data acquired under the Eastern Gas Shales Project, however, has furthered efforts in studying these shales, especially the low-hydrocarbon-potential zones, for their application in the waste-disposal program. A recent report by Lomenick et al. (1980) summarizes these interpretative studies.

Lastly, both the Conasauga Shale in east Tennessee and the Eleana Argillite at the Nevada Test Site were examined via in situ thermal experiments by researchers at Sandia Laboratories. Results of the test methods and the analytical results were presented by Krumhansl (1979a, b) and Lappin and Olsson (1979).

Although the level of knowledge and accumulated data on rock salt are extensive, and applied geotechnical programs on the Permian salts in the Palo Duro Basin of Texas and on the diapiric salt in selected domes along the Gulf Coast are far more advanced than any corresponding effort on granites or argillaceous rocks, the efforts briefly reviewed here are evidence of more effort being directed at nonsalt lithologies. Recent government policy decisions would appear to increase the effort on crystalline rocks and suspend work on shales and clays, at least temporarily.

1.2 GEOLOGIC PROPERTIES OF SHALE

Shales and other argillaceous strata have been proposed as potential host rocks for radioactive-waste disposal because of their geologic properties. Such rocks generally display plasticity, very low permeability, good adsorptive characteristics, and low solubility. In addition, thick deposits of fairly homogeneous shale are present in many structurally undeformed regions of the United States at depths that are considered favorable for geologic isolation of waste.

Geologic properties that represent potential disadvantages to geologic disposal of waste in shale include: possible dewatering of hydrous clay minerals owing to thermal loading; possible presence of organic matter, oil, and/or natural gas; and possible difficulty in mining of plastic shales with retention of the structural integrity of underground excavations.

Among the principal works that summarize properties of shales and similar rocks are those by Grim (1968), Pettijohn (1975), Weaver (1977), Blatt et al. (1980), and Potter et al. (1980). Studies that have focused on the general potential use of shales and other argillaceous strata for radioactive waste disposal include those by Merewether et al. (1973), Johnson (1975), Walsh and Bathke (1976), Weaver (1976a, 1976b, 1979), Witherspoon (1977), Dames and Moore (1978), Apps et al. (1978), Connolly and Woodward (1980), and Isherwood et al. (1981). A number of other reports that discuss the potential use of selected shales in specific regions of the United States are referred to in later discussions of each of the geologic provinces.

1.2.1 Terminology

Shale is the common name given to a large group of sediments or sedimentary rocks that are characterized by a predominance of clay minerals or clay-sized (less than 4 μm or 0.004 mm, in diameter) mineral grains. As an alternative, the adjective "argillaceous" is often used (as in "argillaceous strata") to describe a rock unit containing mostly clay-sized particles or clay minerals. Other, more specific terms have also been used to describe certain fine-grained sedimentary rocks based on variations in their textures and/or sedimentary structures.

The following definitions are quoted from the Glossary of Geology published by the American Geological Institute (Bates and Jackson, 1980).

1.2.1.1 Shale

"A fine-grained, indurated, detrital sedimentary rock formed by the consolidation (as by compression or cementation) of clay, silt, or mud, and characterized by finely stratified (laminae 0.1-0.4 μm thick) structure and/or fissility that is approximately parallel to the bedding (along which the rock breaks readily into thin layers) and that is commonly most conspicuous on weathered surfaces, and by a composition with an appreciable content of clay minerals or derivatives from clay minerals and with a high content of detrital quartz; a thinly laminated claystone, siltstone, or mudstone.....Shale is generally soft but sufficiently indurated so that it will not fall apart on wetting; it is less firm than argillite and slate, commonly has a splintery fracture, and is easily scratched. Its color may be red, brown, black, gray, green, or blue. The term 'shale' is regarded sometimes as a structural term with the significance of thin bedding or fissility and without implying any particular composition; it has been loosely applied to massive or blocky indurated silts and clays that are not laminated, to fine-grained and thinly laminated sandstones, and to slates...."

1.2.1.2 Mudstone

"(a) An indurated mud having the texture and composition, but lacking the fine lamination or fissility, of shale; a blocky or massive, fine-grained sedimentary rock in which the proportions of clay and silt are approximately the same; a nonfissile mud shale....(b) A general term that includes clay, silt, claystone, siltstone, shale, and argillite, and that should be used only when the amounts of clay and silt are not known or specified...."

1.2.1.3 Claystone

"An indurated clay having the texture and composition, but lacking the fine lamination or fissility, of shale; a massive mudstone in which the clay predominates over the silt; a nonfissile clay shale...."

1.2.1.4 Siltstone

"An indurated or somewhat indurated silt having the texture and composition, but lacking the fine lamination or fissility, of shale; a massive mudstone in which the silt predominates over clay; a nonfissile silt shale. Pettijohn regards siltstone as a rock whose composition is intermediate between those of sandstone and shale and of which at least two-thirds is material of silt size...."

1.2.1.5 Argillite

Argillites by definition have progressed only through diagenetic or very low-grade metamorphism (as defined by Winkler, 1974), and thus are only associated with sequences that have undergone less than greenschist-facies metamorphism. Argillite is defined as "a rock derived either from claystone, siltstone, or shale, that has undergone a somewhat higher degree of induration than is mudstone or shale...and that lacks the cleavage distinctive of slate" (Bates and Jackson, 1980). Argillites are thus intermediate between shale and slate, and the term is more descriptive of the physical appearance of a rock and makes no reference to the mineralogy or grade of diagenesis.

1.2.2 Mineralogy

The mineralogy of shales typically is complex because the rocks consist of a mixture of the products of abrasion (mainly silt), end-products of weathering (residual clays), and other chemical and biochemical components, and the varieties of shales are mainly dependent on the relative importance of each of these contributing sources (Pettijohn, 1975). The kinds and abundances of mechanically derived silts in a given shale depend upon the lithology, relief, and climate of the source area from which the silt-sized sediment was derived. If silt is absent or rare, then the shale is enriched in clay minerals, and under appropriate conditions it may be enriched in chemical precipitates such as calcite or silica or in organic matter.

The fine grain size of particles in shales makes identification of mineral constituents difficult. Only the larger grains (more than 0.01 mm) can be identified with any certainty under the microscope. The finer-grained fraction is normally examined on the x-ray diffractometer so that its constituents can be identified and their proportions approximated. Shaw and Weaver (1965) established that the average mineral composition of 400 shale samples is as follows: clay minerals, 60 percent; quartz, 30 percent; feldspar, 4 percent; carbonates, 4 percent; organic matter, 1 percent; iron oxides, less than 0.5 percent; and other minerals, less than 2 percent.

1.2.2.1 Clay Minerals

Clay minerals are hydrated silicates of aluminum with some replacements by iron and magnesium. They have a sheet structure, somewhat like that of mica minerals, with tightly bound silica tetrahedra or alumina octahedra occurring in layers that are more loosely bound together by ionic attraction. Comprehensive discussion of the clay minerals can be found in reports by Weaver (1959), Grim (1968), and Weaver and Pollard (1973). The principal clay minerals in shales are kaolinite, illite, montmorillonite, chlorite, and mixed-layer clays.

Kaolinite has a simple two-layer structure consisting of one layer of silica tetrahedra and one layer of alumina octahedra. This lattice does not expand with varying water content, and it has little capacity for ionic exchange and adsorption. The clay also generally lacks plasticity.

Illite has a three-layer structure wherein an alumina octahedral layer is sandwiched between two silica tetrahedral layers. These layers are held together tightly by potassium ions, and thus little expansion of the lattice is possible. Illite has moderate ionic exchange and adsorption properties, and it has variable plasticity.

Montmorillonite (the name given to a group of clay minerals and to the chief member of that group) also has a three-layer structure consisting of an alumina octahedral layer between two silica tetrahedral layers. These three layers are held together loosely by water molecules and various cations, and because of this weak bonding the lattice can expand considerably to accept additional water molecules. Montmorillonite minerals exhibit large variations in plasticity and ion exchange and adsorption properties.

Chlorite also has a three-layer structure, but the groups of three-layer segments are separated by a brucite layer consisting of magnesium hydroxide. Chlorite is typically rich in iron and magnesium. The mineral has moderate ionic exchange and adsorption properties and variable plasticity.

Mixed-layer clays are the result of ordered or random stacking of the above-mentioned basic clay-mineral units, one upon the other. Illite-montmorillonite, one of the important mixed-layer clays present in shales, has ion exchange, adsorption, and plasticity properties that are intermediate between those of illite and montmorillonite.

1.2.2.2 Nonclay Minerals

Quartz is normally the dominant nonclay mineral in shales, with feldspar, calcite, and dolomite often making up much smaller amounts. Quartz and feldspar are mostly detrital mineral grains in shales, and they may be present in both the silt- and clay-sized fractions of the rock.

Nondetrital minerals - mainly the carbonates, iron oxides, and some of the quartz - are products of chemical or biochemical processes that acted upon the muds as they were being deposited or upon the sediment during later stages of diagenesis. Nondetrital minerals range from clay-sized grains to silt- and even sand-sized particles. These minerals tend to be mobilized (that is, they may be dissolved and redeposited), and they may greatly alter the properties of a shale by filling pore space, increasing the strength or competence of the rock, and/or reducing its plasticity and ion-exchange capacity.

1.2.3 Diagenesis

Shales are subject to many profound chemical, mineralogical, and physical changes after initial deposition; the processes that bring about these changes are referred to as diagenetic. The changes can be complex, and the resultant rock may have properties vastly different from those of the original soft sediment or mud; water is expelled by compaction, mineral grains are reoriented, the size and shape of grains change, new minerals form, the composition of pore fluids is modified, and pores may be filled with silica or other mineral cement. If the rock is later subjected to high temperatures and pressures (as would be encountered during deep burial or pronounced deformation), additional drastic changes may occur and impart a new set of chemical, mineralogical, and physical properties.

1.2.3.1 Compaction

The porosity of freshly deposited mud is as much as 50 to 80 percent, whereas the porosity of partly lithified shale is 30 to 35 percent and that of hard shale under several thousand meters of overburden in only about 10 percent (Pettijohn, 1975). This decrease in porosity accompanies the conversion of mud to shale and is largely the result of compaction owing to pressure imposed from overlying layers of sediment. Muds are generally compacted to about one-third to one-sixth of their original thickness as they are transformed to shale. During the compaction process, many of the original pore fluids are expelled from the sediment. Also, the platelike clay-mineral grains tend to become flattened and reoriented parallel to bedding planes, thus enhancing the fissility and layering that is common in shales. This process also is important in creating the very low permeability that is typical of shales.

1.2.3.2 Mineralogical Changes

Chemical and mineralogical changes are believed to begin almost as soon as the original mud is deposited, but the stronger evidence of mineral alteration is seen after the sediment is buried (Pettijohn, 1975). Montmorillonite and kaolinite tend to disappear with increasing depth of burial, and they are replaced by illite and chlorite minerals. The changes that occur with depth of burial, and the associated increase in pressure and temperature, were reported by Weaver and Beck (1971).

Other changes appear to be related to the aging of clay minerals. In general, older Paleozoic shales are largely illitic, whereas Mesozoic and Cenozoic shales are more likely to be montmorillonitic. Kaolinite is also less abundant in the older sediments than in the younger ones. Weaver (1967), however, suggested that these changes may be due to differing atmospheric and biospheric conditions in the geologic past, and not due to aging or alteration alone.

1.2.3.3 Change in Pore Fluids

The composition of pore fluids in muds during the early stages of burial is basically the same as that of the depositional environment: seawater in marine muds, and fresh water or lake brine in terrestrial muds. As time passes and the mud is subjected to compaction, heating, pressure, and other diagenetic changes, the pore fluids interact with the surrounding mud and other fluids. Changes in the Eh and pH of the fluid are accompanied by changes in the concentrations of ions in the fluids, and these ions are exchanged with the clay minerals making up the shale. Thus the characteristics of the pore fluid of each shale are dependent upon the original fluid composition, the mineral components of the shale, and the complex sequence of events that have acted on the shale since its deposition.

1.2.3.4 Cementation

Owing to chemical and mineralogical changes in a shale during burial, some shales contain abundant free silica or other constituents that are deposited as a cement. These cements - mainly quartz, calcite, and dolomite - partially to almost totally fill the pore spaces in the rock.

Thus the cements help to bind the mineral grains together, thereby reducing the porosity, permeability, and plasticity, and at the same time increasing the strength and density of the rock.

1.3 REGIONAL GEOLOGIC CHARACTERISTICS IMPORTANT FOR WASTE DISPOSAL

Thick deposits of shale and other argillaceous strata have existed below the earth's surface for hundreds of millions of years without undergoing apparent significant changes. Substantial parts of these deposits have remained free of circulating ground water since their initial period of compaction and partial expulsion of pore fluids. By studying individual shales, along with the hydrology, geologic structure, and general geologic framework of nearby rock units, it is possible to interpret the geologic processes that affected the region in the past and also to forecast, in general, the future impact of such processes on a repository site for long periods of geologic time.

General characteristics of the geologic environment are relevant to the use of salt deposits for waste storage were discussed in a recent report by the International Atomic Energy Agency (1977). Johnson and Gonzales (1978) later summarized the regional geologic characteristics important for disposal of radioactive wastes in salt deposits, and much of that discussion is repeated here because it also generally applies to storage of wastes in shales. The importance of these characteristics is discussed in the following paragraphs, and the specific characteristics for each of the major shale units in the United States are discussed in subsequent sections of this report using these characteristics as a framework.

1.3.1 Structure and Geologic Framework

The regional geology and geologic history of a thick shale unit must be known in order to understand the processes that have acted on a potential repository site in the past and that will affect containment of waste in the future. Regions that have been tectonically stable over the past tens of millions to hundreds of millions of years are likely to remain stable during the next several hundred thousand years. Areas of anticipated rapid uplift or strong deformation are less desirable for waste storage, because radionuclides in such a setting might escape as a result of such uplift and accompanying denudation or through disruption and distortion of the host rock. Some of the more important structural elements that should be studied for each deposit include the following.

1.3.1.1 Dip or Inclination of Strata

In thick shale deposits, the preferred dip of strata is generally less than a few degrees, as this would enable design of nearly horizontal underground workings in the same rock layers over fairly large areas. Steep dips or tight folds with frequent reversals in dip also indicate that the rocks were subjected to deformation or tectonic stresses that may still be operating and that may have produced complex geologic structures.

1.3.1.2 Faults and Joints

Faults and joints generally are not desirable in rocks that may be used for containment of waste. The self-healing plastic behavior of most shales at moderate depths would most probably cause closing of the fractures in the repository bed itself, but fractures in adjacent, more brittle rocks might become pathways for circulating ground water. Faults and joints may also cause physical discontinuities in the shale that could adversely affect mining operations. A region with few faults or joints might be suitable for waste storage if these structural features can be located and then avoided or circumvented in the excavations for waste emplacement.

1.3.1.3 Nature and Extent of Adjacent Strata

Primary reliance for geologic containment of radioactive waste in shale rests on the properties of the shale itself, but additional protection may be gained by other strata located above and below the host rock. Additional thick beds of shale, salt, or other plastic-behaving rocks with low permeability would help protect the repository unit from circulating ground water, and would tend to deform without fracturing, if there were subsequent disturbance of the repository area. The least desirable adjacent strata would be those containing large quantities of circulating water that might enter the repository and eventually leave it contaminated with radionuclides.

1.3.2 Shale Deposits as Repository Host Rocks

The geometry, character, thickness, depth, and stability of the host rock for a radioactive-waste repository is critical to long-term containment of radionuclides. Shales and other argillaceous strata have persisted tens of millions to hundreds of millions years in almost all geologic provinces, and they have remained in much the same form they acquired following diagenetic changes that occurred fairly soon after deposition.

1.3.2.1 Depth of Storage Zone

A repository should be deep enough below the present land surface to ensure that its contained waste will not be exposed to the biosphere through erosion or denudation during its hazardous period. To negate the slow removal of the land surface through erosion, which generally is proceeding at an average rate of 2.5 to 7.5 m per 100,000 years in the continental United States (Ritter, 1967), and to avoid the shallow circulation of fresh ground water that might come in contact with the upper parts of a repository host rock, the waste should probably be stored at least 300 m beneath the present land surface. The rate of plastic flow of clays and shales resulting from overburden pressure increases markedly with depth, and therefore it is prudent to restrict mechanical mining operations in shale to depths of no more than 1,500 m, and preferably less than 900 m. Thus, the most feasible depth range for a repository in shale probably extends from 300 to 900 m. In this report, shales in that depth range are commonly referred to as being at "moderate" depth; those at lesser depths are commonly referred to as "shallow"; and those at greater depths are "deep."

1.3.2.2 Thickness and Extent

In general, a shale unit must be of such a vertical and lateral extent so as to ensure an adequate impermeable barrier and to ensure that any fractures emanating from the repository will be sealed and will not jeopardize containment. The host rock must also be extensive enough to provide for adequate heat dissipation. A thickness of at least 75 m of shale is preferred, although a lesser thickness may be suitable under certain circumstances.

1.3.2.3 Homogeneity

In general, a high degree of homogeneity or consistency is desirable in shale deposits being considered for emplacement of radioactive wastes. Layers or irregular masses of some nonshale rocks can adversely affect mining operation when they are encountered during repository excavation. Heat dissipation also may be adversely affected if large quantities of certain impurities occur near the disposal zone.

1.3.3 Seismic Activity

Areas of low seismicity are favored for waste-storage facilities. Violent earthquakes could damage surface facilities and entrances to the repository and could lead to temporary disruption of operation. The major seismic risk to long-term containment would be an earthquake-induced fault that might extend through the disposal zone in the future. Although the plastic behavior of shale would be likely to cause healing of fractures, ground water might circulate more freely along such a fault in adjacent rocks. A map showing earthquakes reported in the United States through 1970 is shown in Figure 1-2, and other maps depicting the potential risk from seismic activity in various parts of the country are shown in Figures 1-3a and 1-3b.

1.3.4 Hydrology

Special attention must be paid to the hydrology of a prospective waste-storage area because of the extreme importance of keeping circulating water away from a repository. A comprehensive geohydrologic study of the entire region or basin should identify recharge and discharge sites and should establish spatial relationships, interconnections, and fluid characteristics of all aquifers above and below a prospective host rock.

1.3.4.1 Surface Water

The mere presence of surface streams, lakes, and ponds above an otherwise suitable repository site should not necessarily rule out its use. But it must be determined that this water would not interfere with the short-term operation of a disposal facility or compromise the long-term containment of any emplaced wastes. Prospective sites lying beneath flood plains or other areas prone to flooding may be especially difficult to develop, because extreme conditions could lead to the flow of water into underground excavations through open shafts or boreholes unless special design features are implemented. Surface streams may undergo marked changes in their flow regimes over long periods of time, and thus such future behavior as the rate of incision and shifting of the streambed must be predicted to guard against breaching of the repository by erosional processes.

1.3.4.2 Ground Water

The repository must be free of circulating ground water, which represents the main threat to containment of radioactive waste placed in

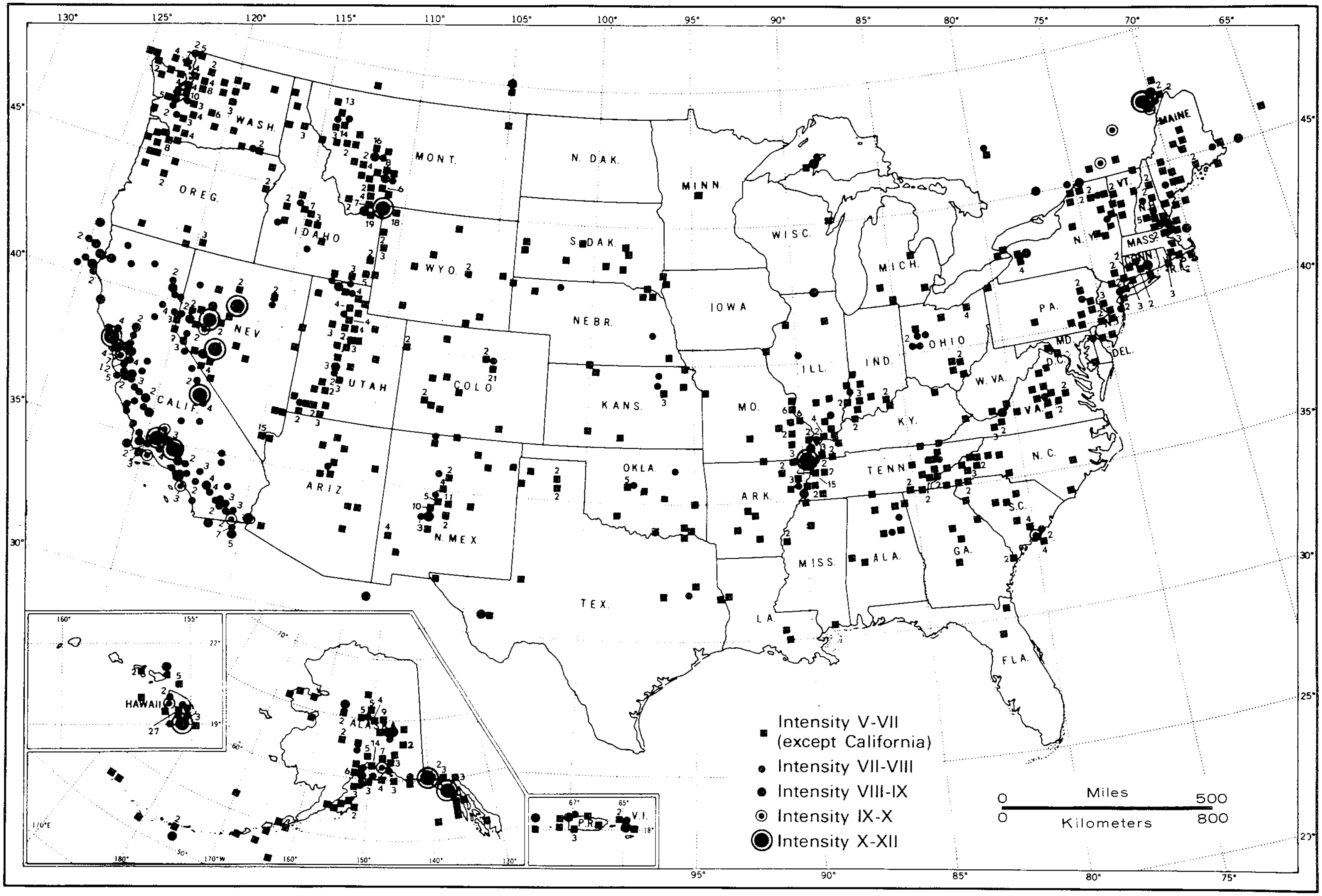

FIGURE 1-2. MAP OF UNITED STATES SHOWING LOCATIONS AND INTENSITY OF HISTORICALLY RECORDED EARTHQUAKES THROUGH 1970 (MODIFIED FROM COFFMAN AND VON HAKE, 1973)

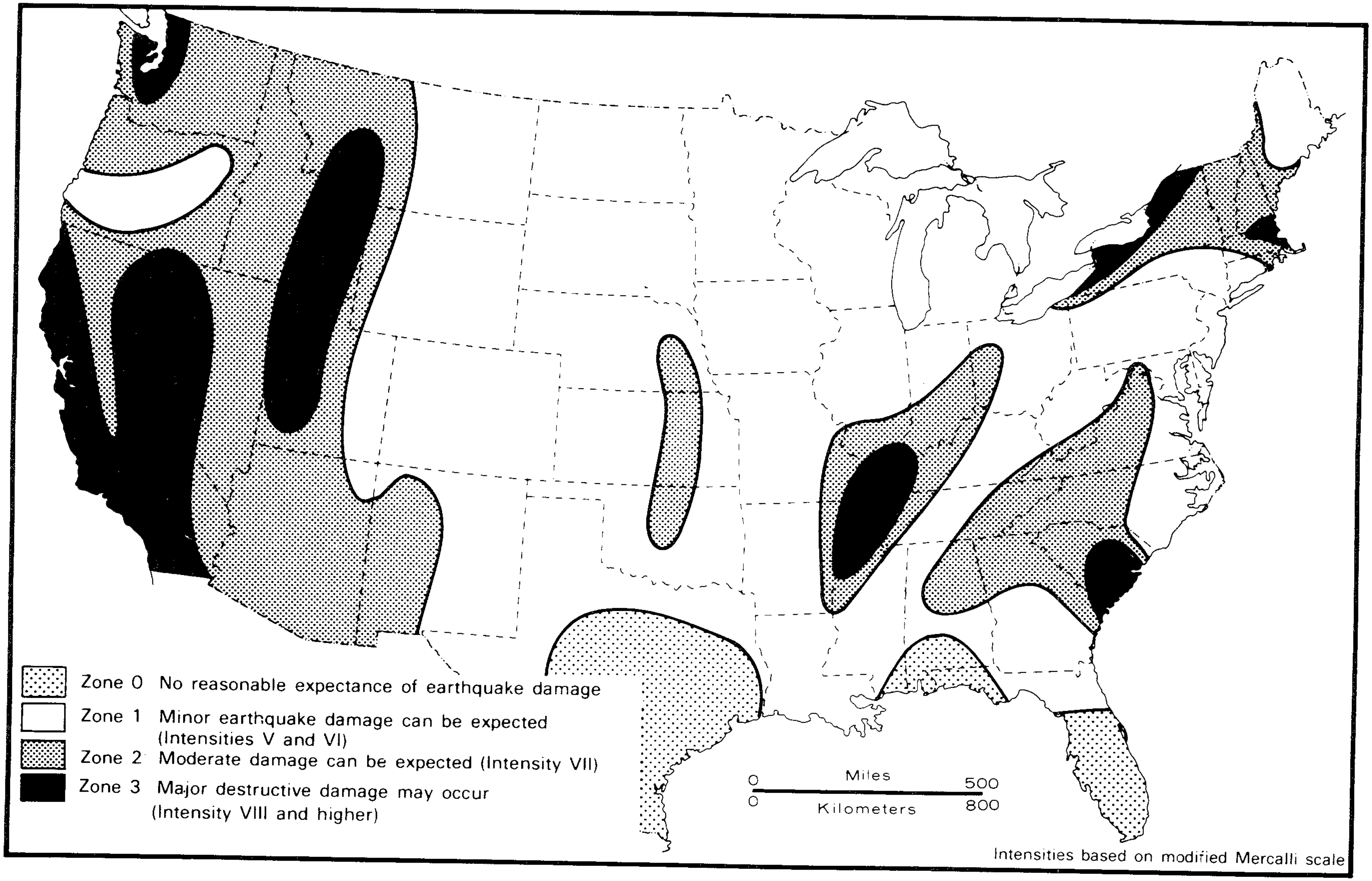

FIGURE 1-3a. MAP OF UNITED STATES SHOWING SEISMIC HAZARD BASED UPON SEISMIC-RISK ZONATION (a) AND PROBABILITY OF GROUND SHAKING (b) (MODIFIED FROM ALGERMISSEN, 1969; ALGERMISSEN AND PERKINS, 1976)

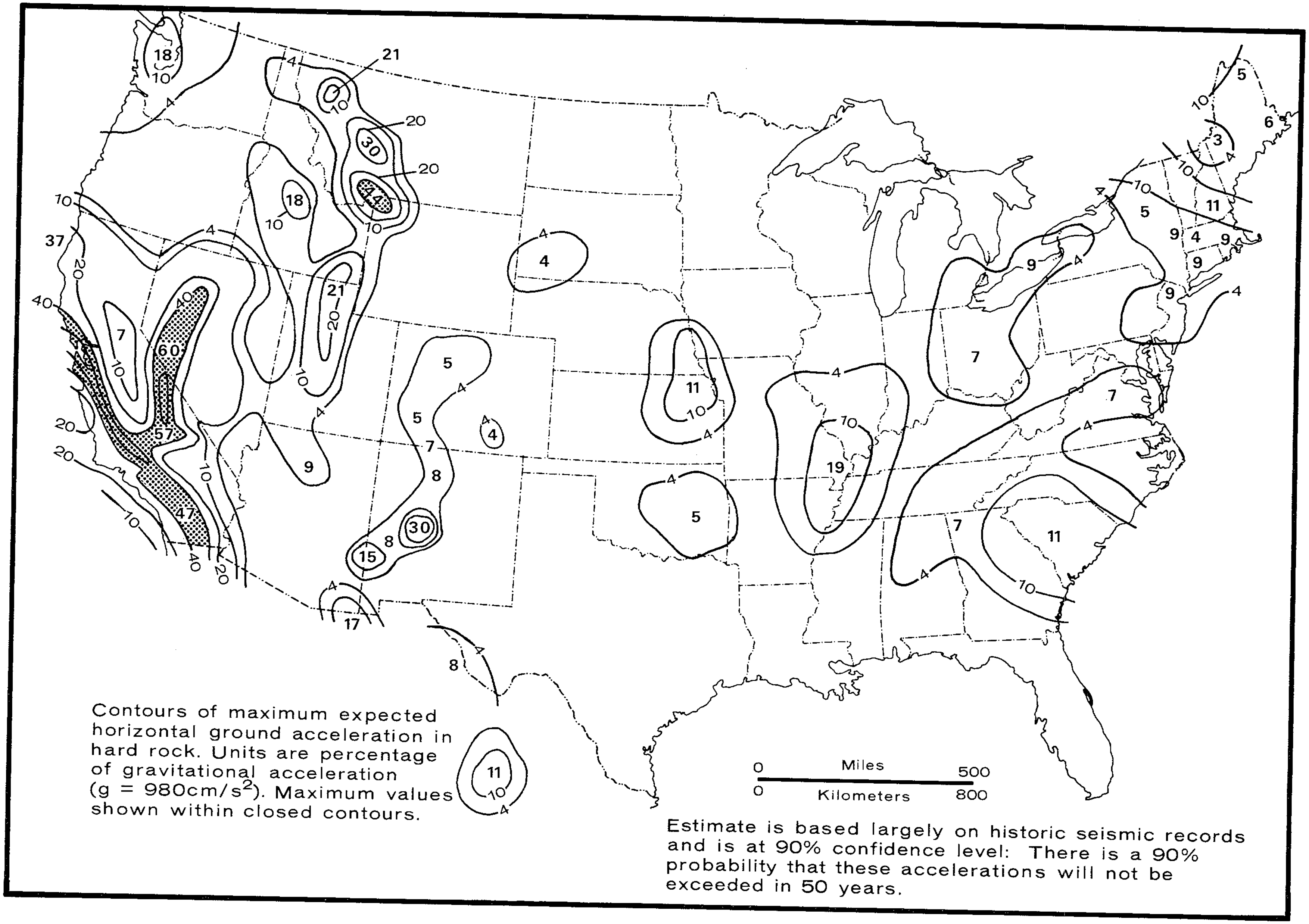

FIGURE 1-3b. MAP OF UNITED STATES SHOWING SEISMIC HAZARD BASED UPON SEISMIC-RISK ZONATION (a) AND PROBABILITY OF GROUND SHAKING (b) (MODIFIED FROM ALGERMISSEN AND PERKINS, 1976)

deep geologic formations. Thus, the nature and characteristics of water-bearing strata near a potential disposal zone are critical elements in establishing its suitability. Investigations need to ascertain the nature and occurrence of ground-water flow, and also the direction, velocity, and volume of the flow. In many areas, ground water is an important resource for municipalities, industry, and agriculture, and special care must be taken to protect these water resources.

1.3.5 Mineral Resources

Important mineral deposits, such as oil, natural gas, coal, salt, or mineral-laden brines, may be present in the subsurface at or near a potential disposal site. These and other resources can occur in formations that overlie or underlie a prospective shale host rock, or at some locations they may be interbedded with the shale, and it is necessary to weigh the need for a particular waste-repository site against the present or potential need for extracting mineral resources at that site. In general, a region would be viewed more favorably as a repository site if it had little or no potential for the discovery of scarce or valuable mineral resources. Another aspect of mineral-resource investigations is the need to identify all preexisting boreholes, mine shafts, solution cavities, and other man-made excavations in the vicinity of a proposed repository. All such artificial openings that penetrate the repository zone represent potential migration paths for ground water, and it is essential that they all be plugged and sealed effectively.

2. PRINCIPAL SHALES IN THE UNITED STATES

2.1 DEPOSITION OF SHALES

Shales and other argillaceous strata occur in sedimentary units of both marine and continental origin. Accumulation of muds and other sediments that produced these rocks required an abundant source of clay-sized particles that generally were produced by (1) chemical weathering of a landmass, and (2) substantial elimination of the coarser grains by selective sorting (winnowing) or turbulent abrasion during transportation.

The most extensive shale units were deposited in oceans or shallow seas, especially in those marine areas within or bordering a continental landmass of low relief. In such a setting, be it a geosyncline or interior cratonic basin, coarser-grained detrital sediments introduced by streams were deposited close to the shore, whereas the finer-grained silt- and clay-sized particles and colloidal material were carried farther from the shore by gentle currents and were deposited in the deeper, more central part of the basin. Persistence of these basins, and continuation of somewhat constant and favorable conditions over long periods of time (several hundred thousand to several million years), has led to accumulation of most of the thick and widespread shales that are of primary interest for disposal of radioactive waste.

Muds also accumulated in estuaries, lagoons, tidal flats, deltas, and other areas where marine waters lacked turbulence, and if the conditions remained fairly constant for a long period of time, or if an excessive load of fine-grained sediment was deposited, a thick sequence of shale could have formed.

Shales and other argillaceous strata were also formed in a number of continental environments, such as alluvial flood plains and lakes. Although the flood plains of large rivers have accumulated many deposits of mud during flood stages, the shales derived from these muds typically are thin, are of limited lateral extent, and are interbedded with sandstones and other coarser-grained strata. On the other hand, some of the ancient freshwater and saline lakes occupied long-lasting depressions or basins that received thick and extensive accumulations of muds, somewhat similar to those deposited in marine geosynclines or cratonic basins.

2.2 DISTRIBUTION OF PRINCIPAL SHALES

Shales and other argillaceous strata are among the most common and widespread rock types in the United States, and thick deposits of shale occur in almost every state in the nation. Thick shales that warrant full-length discussion in this report are present in 41 of the 48 conterminous states (Figure 2-1). Unlike salt deposits, which tend to be primarily confined to specific geologic basins, several of the shale units of interest are thick and at moderate depth both in geologic basins and in the extensive interbasin and platform regions (Figure 2-2).

Geologic conditions favoring deposition of thick shale units were repeated many times in various sedimentary basins and interbasin regions of the United States. As a result, thick shale deposits cover a wide range of geologic time and range in age from Precambrian through Tertiary.

Principal shale units in the Eastern Interior of the United States include the Late Ordovician shales of Ohio, Pennsylvania, and New York, and the Devonian-Mississippian shales of the Appalachian, Illinois, and Michigan Basins. These widespread units are locally at least 1,000 m thick and contain illite and chlorite as dominant clay minerals.

Triassic fault-block basins of the Eastern Margin contain thick sequences of continental sediments, and several of the basins have thick shale units.

The most significant argillaceous unit in the Gulf Coast region is the Paleocene-age Porters Creek Clay, which is 150 to more than 300 m thick and contains montmorillonitic clay. Other units of Paleocene and Eocene age are also important.

Shales of the Great Plains include a number of important Paleozoic units in the Midcontinent region and several Cretaceous units in the northern part of the Great Plains. Midcontinent shales include the

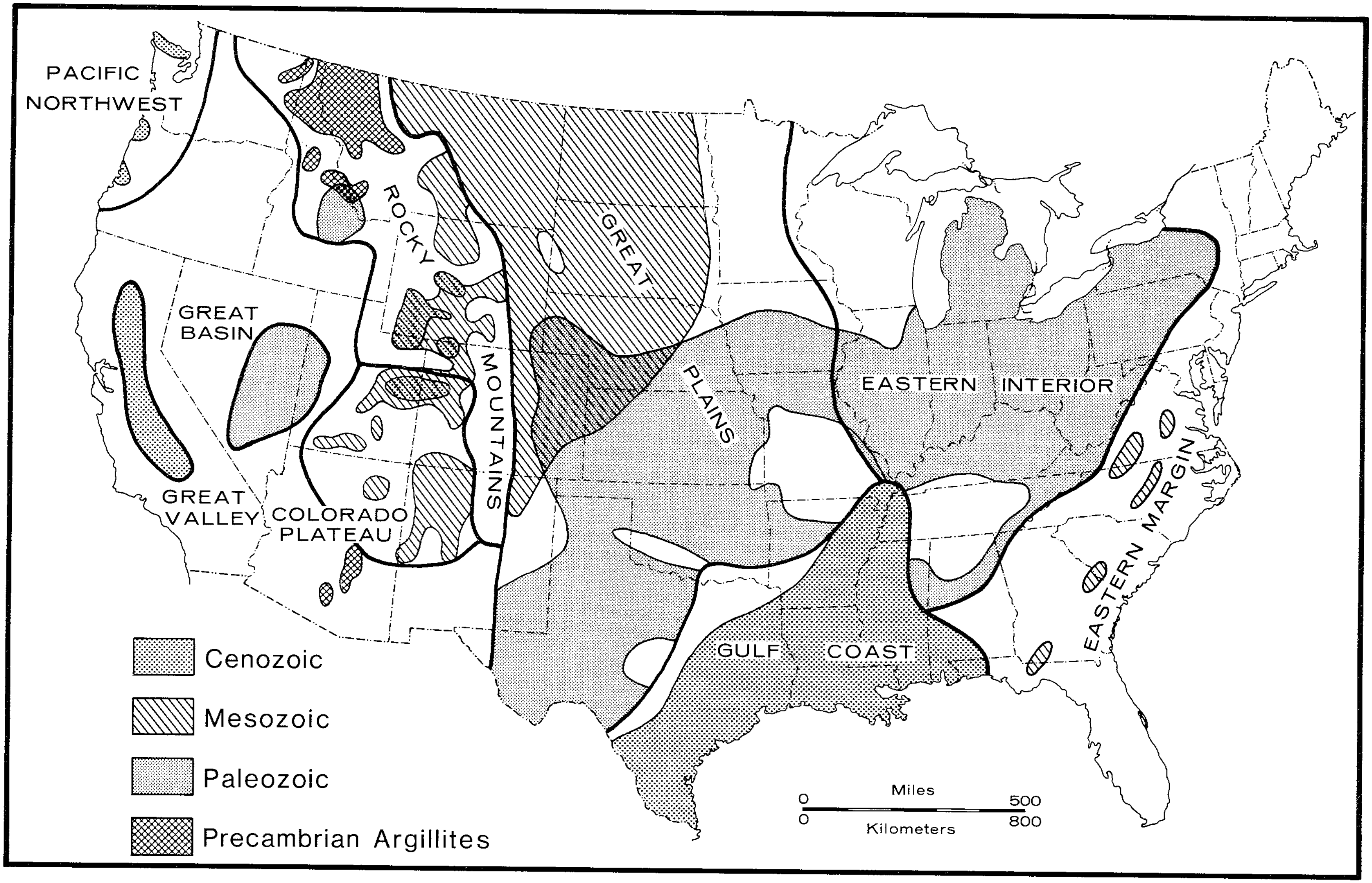

FIGURE 2-1. MAP OF UNITED STATES SHOWING DISTRIBUTION OF PRINCIPAL SHALES BY GENERAL GEOLOGIC AGE, AND REGIONS UNDER WHICH EACH SHALE UNIT IS DISCUSSED IN THIS REPORT

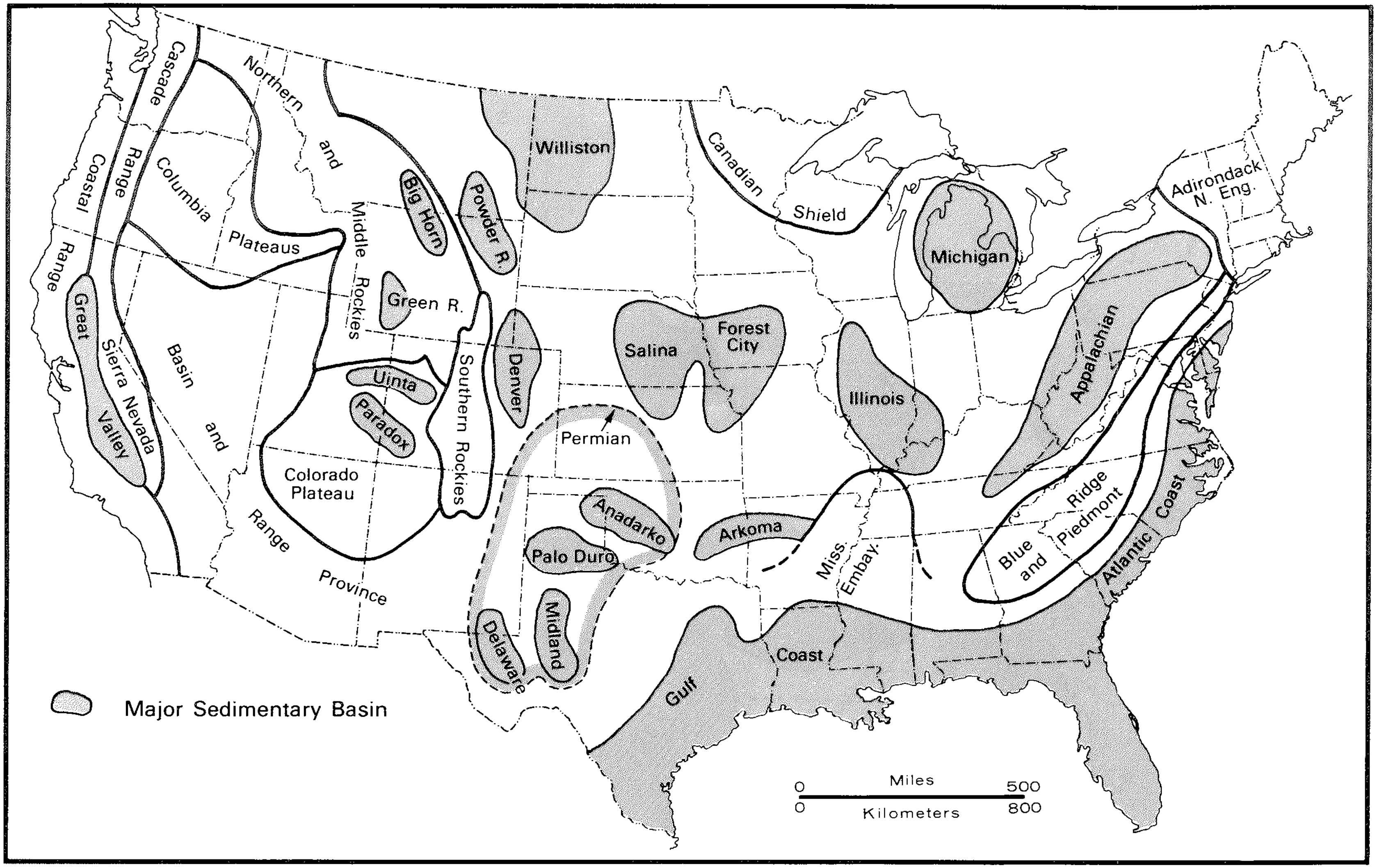

FIGURE 2-2. MAP OF UNITED STATES SHOWING LOCATIONS AND EXTENT OF PRINCIPAL AND SELECTED SMALLER SEDIMENTARY BASINS

Devonian-Mississippian black shales, as well as thick sequences of shale interbedded with other strata of Late Mississippian, Pennsylvanian, and Permian age. Many of these shales are 75 to 150 m thick, but locally they are more than 1,000 m thick. Illite and chlorite are the major clay minerals.

The northern Great Plains is underlain by the Pierre Shale and other thick shales of Cretaceous age. The Pierre typically is 100 to 750 m thick and locally is as thick as 1,800 m; it lies at moderate depth throughout most areas in the region. The principal clay mineral is montmorillonite.

Basins and platforms within the Rocky Mountain region contain several thick shales of Cretaceous and Tertiary age, and these units are generally undeformed in the nonmountainous areas. Several thick units of Devonian-Mississippian-Pennsylvanian age are also present in structurally complex areas of Idaho.

The Colorado Plateau contains thick Cretaceous and Tertiary shales in several basins. The Mancos Shale is as thick as 1,800 m in the region, and the Green River Formation contains oil shale units as thick as 400 m.

The Eleana Formation and other units of Devonian and Mississippian age crop out in block-faulted areas of the Great Basin of Nevada and Utah. This area is structurally very complex.

Thick clays and shales of Cretaceous and Tertiary age underlie the Great Valley of California. Individual units are as thick as 1,500 m.

Several thick Tertiary shales are present in small and structurally complex coastal areas of the Pacific Northwest. This area is characterized by ongoing seismic and volcanic activity.

Precambrian argillites and associated rocks are present in outcrops in the northern part of the Rocky Mountains and in central Arizona. Although these units are thick in outcrops, there are few data that allow a reasonable assessment of their character and distribution in the subsurface.

3. EASTERN INTERIOR

3.1 STRUCTURE AND GEOLOGIC FRAMEWORK

Westward from the central, tectonically disturbed core of the Appalachian Mountains trend (orogen), there extends a geologic province referred to in this report as the Eastern Interior region. Developed there on a regional level are two other structural-sedimentary basins whose stratigraphic sequences are dominated by Paleozoic rocks that dip gently inward toward the basin centers from the flanks of a series of broad, regional uplifts that separate the basins. Stratigraphic units from one basin also commonly extend across these broad structures, where the dips are similarly very gentle. With the exception of a few narrow fault zones, some isolated folds, and several localized astrobleme features (impact structures), this province is mainly characterized by essentially horizontal sedimentary sequences resting on a stable Precambrian basement complex.

The Eastern Interior region includes, too, the relatively underformed Paleozoic strata of the Appalachian Basin, which extends from northern Alabama and Mississippi (including the more localized Black Warrior Basin) northeastward to east-central New York (Figure 2-2). Westward, the Cincinnati Arch system - which consists, from south to north, of the Nashville and Jessamine Domes, and the Findlay and Algonquin Arches - separates the Appalachian Basin from the two other major basins, the Illinois and Michigan. The latter is bounded by the Canadian Shield to the north and northeast and by the Wisconsin Dome and Wisconsin Arch to the west and northwest, and is separated from the Illinois Basin to the southwest by the northwest-oriented Kankakee Arch (Ells, 1967). The Illinois Basin is flanked by the Ozark Dome and Mississippi Arch along the west and by the Pascola Arch on the south (Bond et al., 1971). Other tectonic elements farther to the south are buried beneath the Cretaceous-Tertiary overlap sequence that makes up the Mississippi Embayment; the southernmost part of the Illinois Basin is also buried by these clastic sediments.

Regionally widespread strata or stratigraphic equivalents of units found in the Illinois and Michigan Basins extend westward into the adjacent eastern Midcontinent region of the Great Plains province. In this part of the central stable craton, horizontal strata overlying the basement are even more prominent because discrete basins and uplifts have not yet developed. Exceptions include the Forest City and Salina Basins of Missouri, Iowa, Kansas, and Nebraska; separating these two basins is the Nemaha Uplift.

The Appalachian Basin portion of the Appalachian trend and the Illinois and Michigan Basins of the Eastern Interior region are basins in both the structural and depositional sense; all were principally active as centers of largely marine sedimentation during the Paleozoic Era. Non-Paleozoic strata include thick Precambrian clastic sequences in the deep, central part of the Michigan Basin and the southeasternmost part of the Appalachian Basin; a small sequence of Jurassic strata is also known from the Michigan Basin.

The Michigan Basin, covering an area of nearly 300,000 km^2, extends throughout all of the Southern Peninsula of Michigan as well as parts of several adjacent states and Ontario. Elevations range from nearly 200 m near the Great Lakes to some 400 m near the basin interior. From a geomorphic standpoint, terrain in the basin involves maturely dissected and glaciated cuestas and intervening lowlands. A veneer of glacial till and glacial lake sediments, which can reach up to 275 m in thickness, covers much of the bedrock, although these unconsolidated Pleistocene deposits tend to be more widespread in the lowland areas.

The Howell Anticline, a northwest-trending structure in the southeastern part of the Michigan Basin, is the most noteworthy tectonic feature that affects the otherwise gently dipping strata. The general inclination of strata elsewhere throughout the basin is less than 0.5 degrees. The Howell structure is one of several subparallel, plunging folds that constitute a larger feature called the Washtenaw Anticlinorium (Ells, 1969). A prominent fault is present along the western flank of the Howell Anticline and is believed to extend upward from the basement in displacing Ordovician and younger strata (Ells, 1969). Other than this one sharp flexure, faulting in the Michigan Basin is small scale and is revealed only by small anomalous changes in dips and outcrop patterns.

The sedimentary sequence that overlies the Precambrian basement attains its greatest thickness of more than 5,000 m near the center of the basin, or beneath Gladwin and Clare Counties (Ells, 1967). Strata representing every Paleozoic system except the Permian are present; a minor volume of Jurassic rocks is also preserved. Although Pleistocene glacial deposits are widespread overlying bedrock, at many places these unconsolidated sediments are thin to absent.

Significant publications on the geology and stratigraphy within the Michigan Basin, and the Devonian-Mississippian shales in particular include those by Cohee et al. (1951), DeWitt (1960, 1970), Fisher (1969), Ells (1971, 1978, 1979), and Lilienthal (1978).

Because of the basin's growth history and greater subsidence in the central part, strata thicken from the rim toward the interior of the basin. The Cambrian and Ordovician strata are represented by a thick sequence composed chiefly of sandstones and carbonates. Overlying these strata are nearly 2,000 m of Silurian and Devonian units that are dominated by carbonates, salt, and anhydrite. Included here are the evaporite-bearing Salina and Detroit River Groups. Other notable formations are the Bass Islands Dolomite, Dundee Limestone, and Traverse Group. Above this carbonate-rich sequence the remainder of the stratigraphic column is dominated by clastic strata. Included within the lower part is a thick interval of Devonian-Mississippian argillaceous units. The Antrim, Ellsworth, Bedford, Sunbury, and Coldwater Shales have a combined maximum thickness of nearly 500 m, and have been previously studied by DeWitt (1960) and Merewether et al. (1973) relative to radioactive-waste disposal.

Overlying this largely shale sequence is a series of alternating shales, sandstones, siltstones, and limestones that represent strata formed during the remainder of the Carboniferous and the Jurassic times. These strata above the Coldwater Shale attain a maximum thickness of

400 m. Directly above the Coldwater Shale lies the Marshall Sandstone, which is a major freshwater aquifer in the basin.

The unconsolidated glacial deposits are the result of four separate advance-retreat sequences during the Pleistocene Epoch. The average aggregate thickness of glacial till (ground and other moraine) and associated lacustrine sediments is 70 m, although areas in the north-central part of the basin are covered by more than 275 m (Akers, 1938). There are many areas where the shale units are at moderate depth in the subsurface and this glacial veneer is insignificant to absent.

In summary, the Michigan Basin has been characterized by pronounced tectonic stability since this region ceased being a depositional center. There has been no major deformation involving the strata in the basin; faulting and folding from all evaluations appear to be of little significance except near the Howell structure. Paleodissolution of deep salt beds has created a recognizable disturbance to certain overlying rock units, as evidenced by the formation of the so-called Mackinac Breccia. However, this collapse-related feature appears confined to the northernmost part of the Southern Peninsula (Landes, 1959). Since the last glacial ice retreat, some isostatic rebound has also been recorded throughout parts of the basin, but this phenomenon is not of concern from a tectonic standpoint.

The Illinois Basin is an elongated feature that trends roughly north-west-southeast for some 500 km and is nearly 305 km wide at its broadest point. The basin embraces all of southern Illinois as well as parts of the adjacent states of Indiana, Kentucky, and Missouri. Land elevations vary slightly from some 100 m near the Mississippi Embayment on the south to more than 200 m in some upland areas. Most of the Illinois Basin was glaciated during the Pleistocene Epoch; however, the resulting topography is developed on young till plains that lack a typically morainic (hummocky) character. That portion of the basin in southern Indiana and western Kentucky was not glaciated and consists of low, maturely dissected plateaus and intervening lowland valley areas filled with silty-sand alluvium.

Several structural features developed within the Illinois Basin are of sufficient magnitude and extent that they influence the regional geology. The most significant is the Shawaneetown-Rough Creek fault zone that extends east-west across southern Illinois and northwestern Kentucky. Bounded by a high-angle reverse fault whose southern block has been uplifted, this fault system extends westward into the New Madrid seismic zone, is intersected by a crossing set of northeast-trending faults (the Wabash Valley system), and is associated with the very complex pattern of faulting characteristic of the Illinois-Kentucky fluorspar district (Bristol and Buschbach, 1971). Because displacements are more pronounced in the Precambrian basement, and this fault system aligns with several other regional structural features, the suggestion has been made that this zone is a manifestation of major Precambrian deformation, possibly involved in continental-scale rifting (Heyl, 1972; King, 1977). Other fault systems in close association with the Shawaneetown-Rough Creek zone in southern Illinois are the Rend Lake (Keys and Nelson, 1980), Cottage Grove, and Ste. Genevieve (Krausse et al., 1979).

Some of these zones of faulting in the southern part of the Illinois Basin occur in proximity to, and may be genetically associated with, the New Madrid zone, the most significant belt of seismic activity within the continental interior. To the north and northeast is another, but less severe, structural trend, the La Salle Anticline. The deformation here does not involve major faulting; rather, the La Salle trend consists of a series of roughly enecheloned anticlinal folds that extend northwestward nearly to the southern limits of the Kankakee Arch (Krausse et al., 1979). Viewed as a single structural element, the La Salle Anticline is strongly asymmetrical in that westward dips are much steeper than those in the opposite direction (Bristol and Buschbach, 1971).

Despite the existence of these two tectonic systems, there are considerable areas within the northwestern part of the Illinois section of the basin and eastward across Indiana where significant geologic structures are absent.

A thick sequence of Paleozoic strata, which dip gently toward the center of the basin (southern Illinois) at rates approximating 0.5°, has been preserved, such that thicknesses range from 1,000 to 3,000 m around the margins to nearly 4,300 m in the deepest part (Buschbach, 1971). All Paleozoic systems except the Permian are represented. North of the Ohio River the bedrock is covered by a veneer of Pleistocene glacial materials that locally reaches 140 m in thickness. Throughout the southern part of the basin, Cretaceous and Tertiary clastic sediments of the Mississippi Embayment overlie bedrock. Articles by Atherton (1971), Bond et al. (1971), and Buschbach (1971) discuss the stratigraphy and geologic history of the bedrock within the Illinois Basin.

The underlying Precambrian basement consists mainly of granitic to rhyolitic rock types. Pre-Knox clastic and carbonate units, which are up to 1,000 m thick in the northern half of the basin, overlie this igneous complex. Upper Cambrian to Middle Ordovician strata are 2,500 m thick in the southern basin (Buschbach, 1971). Well-known stratigraphic units in this interval include the Knox Megagroup, St. Peter Sandstone, and Ottawa Megagroup.

The Upper Ordovician Maquoketa Group is composed of silty to calcareous, argillaceous units that collectively extend across the entire basin. Although this shale-rich interval here does not exceed 100 m, it thickens eastward across Indiana and reaches some 200 m along the west side of the Cincinnati Arch. A southward-thickening wedge of carbonates, assigned to the Hunton Megagroup of Silurian through Middle Devonian age, succeeds the Maquoketa and attains some 550 m of thickness across southern Illinois and western Kentucky.

Overlying the Hunton Megagroup is an extensive sequence of Upper Devonian-Lower Mississippian argillaceous strata. Extending westward from the Cincinnati Arch and across all of the Illinois Basin, this sequence is called the New Albany Shale (Group in Illinois, Formation in Indiana and Kentucky). Equivalent strata to the southeast as far east as the southern Appalachian Basin are referred to as the Chattanooga Shale. Within the Illinois Basin the New Albany Shale ranges in thickness from 30 to 125 m. This wedge of fine-grained units thins in a westward direction, an aspect attributed to increasing (east to west) distance from an eastern sediment source (Atherton, 1971). Above the New Albany Shale, clastic units of the

Borden Formation occur in the eastern part of the basin, while carbonates and shales, assigned to the Burlington, Keokuk, and Warsaw Formations, are present in the western part. Overlying these laterally variable units is a sequence composed of the Salem, St. Louis, and Ste. Genevieve Limestones; these carbonates extend throughout the basin and are subsequently overlain by an Upper Mississippian (Chesterian) sequence of cyclic limestone/clastic units. The entire Mississippian interval reaches a maximum aggregate thickness of 900 m.

The Illinois basin underwent regional tilting and erosion prior to the formation of Pennsylvanian strata (Atherton, 1971). The latter lie with unconformable relationship upon Mississippian rocks and consist of a series of cyclic units whose lithologies include shales, sandstones, limestones, coal seams, and underclays. Even though subsequent erosion has reduced the extent and thickness of these cyclothemic deposits, those strata which remain range from 200 to 600 m in thickness. They locally reach 1,000 m in western Kentucky.

Extensive post-Pennsylvania erosion destroyed a sizable thickness of strata; as much as 1,500 m in southern Illinois is believed to have been removed. In addition to erosion, gentle warping in several areas within the basin also took place, uplift of the Cincinnati Arch was reactivated to the east, faulting occurred within the Shawaneetown-Rough Creek zone, and the folding along the La Salle Anticline developed (Atherton, 1971).

Although most of the Illinois Basin experienced erosion throughout the Mesozoic and Tertiary times, a region to the south was subsiding during the Cretaceous and Tertiary periods and gave rise to the so-called Mississippi Embayment. A thick sequence of semiconsolidated sands, silts, and clays represents the record of this younger sedimentation. Within the basin proper, the Cretaceous and Tertiary units (mainly represented by the Midway and Wilcox Groups) form a thin overlap above the beveled Paleozoic bedrock.

Pleistocene glacial deposits are extensive throughout the basin and extend in places as far south as the Ohio River. Multiple glaciation and ice retreats left behind frontal and ground moraines, glaciofluvial sands and gravels, and loess. The thickness of these unconsolidated Quaternary deposits generally ranges from 10 to 60 m within the basin, although a northwest-trending belt in the northeastern to north-central part of the basin shows thicknesses up to 140 m (Willman et al., 1975). There are, however, numerous areas in the basin where the glacial mantle is only a few meters thick.

Although the Appalachian Mountain chain or Appalachian orogen extends some 1,600 km northeastward from northern Alabama to the Maritime Provinces of Canada, the Appalachian Basin per se parallels this trend only from northern Mississippi and Alabama to east-central New York (see Figure 3-2). The western boundary of this foreland basin is the Cincinnati Arch system, while the eastern margin is delineated by the area where the sedimentary units of the fold belt (the Valley and Ridge portion of the basin) are against the "crystalline" Appalachians, namely the Blue Ridge and Piedmont provinces. In the southeastern part (Alabama to Virginia), however, this eastern boundary is defined by a series of regional thrust faults that have displaced Precambrian and Lower Paleozoic rocks westward upon younger Paleozoic strata.

As thus defined, the Appalachian Basin, including the folded and faulted Valley and Ridge region along its eastern margin, covers all of West Virginia as well as large areas of New York, Pennsylvania, Ohio, Kentucky, Tennessee, Virginia, Alabama, and Mississippi (assuming that the Black Warrior Basin is grouped with this Appalachian system). The land area thereby included totals 540,000 km^2. From a geomorphic standpoint, the Appalachian Basin spans several physiographic provinces: Valley and Ridge, Appalachian Plateaus (Allegheny in the north and Cumberland in the south), Interior Low Plateaus, and Central Lowlands. The Valley and Ridge Province consists of alternating, parallel ridges and valleys, all of which are aligned toward the northeast and which arose from the differential erosion of folded, fractured (jointed), and faulted strata.

Most of the basin is confined to the Appalachian Plateaus, where a maturely dissected upland developed on nearly horizontal bedrock has resulted in moderate elevations of generally less than 1,000 m. Gently dipping Paleozoic strata, slightly deformed locally or toward the more intensely folded Valley and Ridge, constitute the bedrock. Located essentially along the axis of the Cincinnati Arch system and south of the southern extent of Pleistocene glaciation, the Interior Low Plateaus are characterized by gently rolling topography and elevations of generally less than a few hundred meters. North of this province are the Central Lowlands, which consist of a glaciated plain that slopes southwestward from higher elevations near the Allegheny Plateau toward the Mississippi River. Essentially flat-lying Paleozoic bedrock underlies both these lowland provinces, and only localized zones of faulting and some minor folding have structurally disturbed these strata.

Multiple glaciation during the Pleistocene exerted a significant influence on the topographic expression and surficial geology of both the Central Lowlands and the more northerly parts of the Appalachian (the Allegheny) Plateau. Modification of surface drainage, formation of buried valleys, and deposition of unconsolidated sediments also have had a profound effect on the regional ground-water systems in those provinces.

Sedimentary strata currently preserved within the basin attain a maximum thickness of some 12,000 m in east-central Pennsylvania. There is evidence, however, that the probable maximum total thickness for the basin may have reached 19,000 m in the past but that post-Permian erosion removed as much as one-quarter of the original rock record (Colton, 1970). Other areas containing a very thick sedimentary sequence are in eastern West Virginia, western Virginia, and north-central Alabama. The aggregate thicknesses of the strata in the more distal parts of the basin generally range from 1,000 to 3,000 m. Strata from the Precambrian to the Lower Permian are present.

Although the geological literature on the Appalachian system is voluminous, representative discussions that comprehensively consider the more regional aspects of the sedimentary sequences and tectonic history, especially of the Appalachian Basin portion, include those by Woodward (1958), Roth (1968), Zen et al. (1968), Colton (1970), Fisher et al. (1970), Rodgers (1970), Harris and Milici (1977), and Hatcher (1978a, 1978b).

Precambrian metasedimentary and volcaniclastic units, estimated to be as much as 10,000 m thick, are confined to a relatively small region in eastern Tennessee and northern Georgia. These strata are discussed in more detail elsewhere in this report.

Paleozoic strata in the basin form a prism-like mass of sandstones, shales, limestones, dolostones, and evaporites that basically thicken toward the east and southeast. On a volumetric basis, the most noteworthy sequences are (1) Lower Cambrian clastics, (2) Cambrian-Ordovician carbonates, (3) Upper Ordovician clastics, (4) Silurian-Devonian carbonates, and (5) Devonian clastics (Colton, 1970).

The Lower Cambrian sequence is dominated by medium- to coarse-grained marine clastics whose development is more pronounced in the southern half of the basin, where some 3,000 m of strata remain. Above this sandstone-dominated interval is one of the most extensive marine carbonate (principally dolostone) sequences known; these Upper Cambrian to Middle ordovician limestones and dolostones cover the entire length of the basin, and, even though thinner, they also extend westward over the crest of the Cincinnati Arch. Although these carbonates are only 200 m thick in the most northerly part of the basin, they reach some 2,500 m in thickness in both east-central Pennsylvania and east Tennessee. Such widely studied stratigraphic units as the Knox, Beekmantown, Trenton, and Black River Groups occur in this sequence. The overlying Upper Ordovician clastic sequence is the result of renewed tectonics toward the east in the more central Appalachian orogen. More than 2,000 m of these strata are present in eastern Pennsylvania. Continental to deltaic red beds, formed under subaerial conditions because sedimentation rates exceeded basin downwarping, are preserved in this clastic wedge which is represented farther to the west by marine limestones and mudstones of the Cincinnatian Series.

Marine limestones, together with some evaporites (salt), dominate the Middle Silurian to Middle Devonian carbonate sequence. Some stratigraphic intervals of note here are the Onondaga Limestone and the Helderberg and Salina Groups. Although this sequence is essentially missing in the southern part of the basin, nearly 1,000 m is preserved in central Pennsylvania and New York. The overlying Middle Devonian to Upper Mississippian clastic sequence is most closely associated with the well-known Catskill Delta. This wedge of clastics contains marine units at its base in the east that have been succeeded both vertically and in a progressively westward direction by nonmarine deltaic to continental deposits. The result is that the sequence is thickest in the east; it is dominated by fine-grained clastics (shales and siltstones) within its lower part but contains more coarse-grained units in the younger intervals. East-to-west facies changes are numerous. Black, dark-brown, and dark-gray shales are abundant in this sequence, but individual stratigraphic units are progressively younger in a westward direction. In parts of eastern Pennsylvania, western Virginia-Maryland, and eastern West Virginia, this shale-rich sequence is more than 3,000 m thick. Several of the shale units also are regionally extensive beyond the limits of the basin and, while thinner, do occur well to the west within the shallow shelf succession. Above this clastic sequence, whose shales are of interest in this report, is a regionally extensive interval of Mississippian limestones. Stratigraphic units such as the Salem, St. Louis, and Ste. Genevieve Limestones obtain a maximum thickness of 1,800 m in eastern Kentucky but are also well developed throughout the central part of the basin and extend westward all the way into the Illinois Basin.

The overlying Pennsylvanian and Permian strata are mainly clastic units, many of which are deltaic to fluvial-continental in origin. Principal lithologies are sandstones, siltstones, and shales; numerous extensive Pennsylvanian coal seams and their underclays also are present. The maximum thickness of Pennsylvanian strata is 3,000 m in north-central Alabama; farther to the north a thinner succession some 1,200 m thick is present in West Virginia and Pennsylvania. The Permian System, represented by about 100 m of clastic strata called the Dunkard Group, is found only within a small area where Ohio, Pennsylvania, and West Virginia converge.

The structural geology within the Appalachian Basin shows a marked contrast between the Valley and Ridge portion and areas to the west of that deformed belt. In the former region, numerous parallel folds with extensive jointing are present. Most folds are asymmetrical to overturned, with steeper dips developed on the northwestern limbs (King, 1977). Within the southeastern part of the fold belt, numerous bedding-plane thrust faults, in which upward ramping and thin-skinned decollement detachments involving incompetent glide zones, become the dominant structural style in addition to strongly asymmetrical folds broken by these thrusts (Harris and Milici, 1977; King, 1977; Odum and Hatcher, 1980). The Pine Mountain, Pulaski, and Saltville faults are examples of thrust faults whose low angles and regional extent toward the southeast clearly indicate that many of these features are not restricted to the ruptured limbs of folds.

Although extensively deformed and injection-gouged shales are known to have acted as the major glide zones, decollement thrusting in Virginia and West Virginia has been interpreted to involve Silurian salt (Gwinn, 1964, 1967). In a similar manner, folds that affect younger strata in the north-central part of the Allegheny Plateau are believed to involve decollements related to salts in the Salina Group (Frey, 1973).

To the west of the folded and/or faulted Valley and Ridge province, comparable folds and smaller thrust faults affect the strata in the eastern foreland portion of the basin. Progressing to the west, these structures tend to become less common, the folds are broad and widely spaced, faulting is generally not present, and regional dips are gentle (less than 1°).This pattern extends westward across the broad Cincinnati Arch system into the Illinois Basin. An exception to this is the cross-basin zone of faulting called the Kentucky River fault zone, which can be recognized at the surface in eastern Kentucky, based on displacements in Ordovician strata there, and which may extend westward to join the Shawaneetown-Rough Creek fault system developed along the southern margin of the Illinois Basin. Heyl (1972) and King (1977) both have speculated that these fault zones are part of a larger, long-persistent series of ruptures that affect the Precambrian basement and represent rifting on a continental scale. Based on more recent drilling and geophysical data, Harris (1978) postulated that the Kentucky River zone is part of a more extensive fault system called the Rome Trough that extends from east-central Kentucky northeastward through West Virginia and into Pennsylvania. As viewed by Harris (1978), the Rome

Trough is basically a graben-like structure that formed initially in the Precambrian and was reactivated periodically throughout the Paleozoic to such a degree that it influenced sedimentation patterns. Additional work by Ammerman and Keller (1979) revealed that the tectonics of this feature are complex, that several episodes of rifting are involved, and that a full understanding of this buried feature is not yet at hand. An additional speculation about the Rome Trough is that it marks the point at which the structural style of the Central Appalachian Fold Belt (Valley and Ridge) changes from one of parallel folds to one of thrust-faulted folds (Shumaker, 1976).

Outside of the extensive thrust faulting in the southeastern part of the fold belt and the Kentucky River-Rome Trough fault system, faulting is relatively uncommon throughout the remainder of the basin. Minor exceptions include several so-called cryptoexplosive features such as the Wells Creek, Flynn Creek, and Howell disturbances, where highly localized centers of brecciation and concentric faulting have been described (Odum and Hatcher, 1980). The prevailing interpretation is that these small centers of intense deformation represent meteorite impact features (French, 1968).

Planar fractures or joints are common in many of the rock units exposed at the surface throughout the Appalachian Basin. Evidence has also clearly shown that the improved production of natural gas from Devonian black shales in the subsurface is related to natural fracture systems (Nuckols, 1978). There is no direct correlation between these subsurface fractures and surface joints. Four mechanisms are responsible for the joints and fractures in the Appalachian Basin, as summarized by Shumaker (1978): (1) regional folding and thrust faulting, (2) reactivation of basement structures, (3) topographic unloading, and (4) post-depositional processes. With regard to some of the subsurface fractures, some measure of stratigraphic restriction appears evident so that only certain shale zones are affected. For these intervals, Shumaker (1978) proposed abnormally high pressured gas trapped in the shales as the cause. Fractures are very prevalent in the Valley and Ridge province. Elsewhere in the basin, many joints appear to be limited to near-surface bedrock and do not apparently affect deeper strata. Subsurface fractures also exist without clear indication at the surface. Therefore, any shale interval would require detailed study to determine whether joint/fracture systems visible at the surface extend into the deeper subsurface, or whether any fractures confined to the subsurface have developed.

3.2 REGIONAL SEISMICITY

Although neither the Appalachian nor the Illinois Basin directly contains any seismically active areas, both lie adjacent to areas where historical seismicity has produced ground shaking felt within each basin. In the case of the Appalachian Basin, this involves proximity along its southern part to the Charleston, South Carolina, seismic zone; for the Illinois Basin, its location relative to the New Madrid zone to the south and southwest is involved (see Figures 1-2 and 1-3a).

Even though some seismic events have occurred within the Appalachian Mountains so that their distribution parallels the prominent northeasterly trend, as well as being within linear zones of mild seismicity perpendicular to that trend, the seismicity of the Appalachian Basin itself is low. There have been relatively few events in that portion of the entire Appalachian orogen, and those recorded have all been less than Modified Mercalli Intensity (MMI) V. Seismic hazard, as forecast in terms of ground-shaking probability, shows a very low value (4 percent) for most of the basin (see Figure 1-3b). Only a slightly greater frequency of moderate-sized seismic events from northeastern Ohio to western New York has increased the assigned value to a maximum of 7 percent. Thus, despite the possible external influence from the Charleston zone southeast of the basin and the Ohio-New York trend, the seismic risk or hazard in most of the Appalachian basin remains low.

Because of its proximity to the New Madrid zone, where earthquakes above MMI V are fairly common and where several large-scale events have been recorded, the southern part of the Illinois Basin has been assigned to a slightly greater (10 to 19 percent of horizontal ground acceleration) category of seismic hazard (see Figure 1-3b). Seismic events greater than

MMI V are also more common in the southern part of the basin (Docekal, 1970). The Rough Creek-Shawneetown fault zone along the southern basin margin is part of the general seismotectonic setting. The northern half of the basin, however, lacks any significant seismic activity and lies more distant from the New Madrid zone and its associated zones of faulting.

Seismic activity within the Michigan Basin and adjacent areas in this country and Canada is quite low. Except for two small areas, one in northwestern Michigan and the other near northwestern Ohio, earthquakes above MMI V are sparse (Bricker, 1977). As a result, the entire Michigan Basin lies within a region assigned a very low seismic hazard (see Figure 1-3a).

3.3 REGIONAL HYDROLOGY

3.3.1 Surface Water

Surface drainage from the Illinois Basin of the Interior Lowlands flows into the Mississippi River network and eventually to the Gulf of Mexico, whereas the drainage from the Michigan Basin enters the Great Lakes, whose ultimate drainage course is the St. Lawrence River into the Atlantic Ocean. Drainage from the northern Appalachian Basin is either eastward into the Atlantic Ocean, northward to the Great Lakes, or eventually southward to the Gulf of Mexico via the Ohio-Mississippi River system. In the central and southern parts of the Appalachian Basin, drainage is toward the Gulf of Mexico, either directly by south-flowing streams or through tributary connection of the Ohio-Mississippi system.

Most of the surface drainage from the Michigan Basin enters either Lake Michigan or Lake Huron; a lesser volume flows into Lake Erie. Principal rivers flowing into Lake Michigan include, from north to south, the Manistee, Muskegon, Grand, Kalamazoo, and St. Joseph; those emptying into Lake Huron are the Thunder Bay, Au Sable, and Saginaw. In the southeast part of the basin, drainage is directed into Lake Erie by the Detroit, Raisen, and Maumee rivers, even though the latter receives much of its drainage from northwestern Ohio. Numerous lakes in Michigan's Lower Peninsula retain a modest volume of the annual inventory of water.

Average annual precipitation over the Michigan Basin is 78 cm, of which nearly two-thirds is lost to the atmosphere as evaporation and transpiration (Weist, 1978). The remaining 29 cm is available as runoff, which contributes to both streamflow and ground-water recharge. Conversely, there is an appreciable contribution from the ground-water system to streamflow (Waller and Allen, 1975). Lakes Michigan and Huron collectively receive an annual average runoff of 2,660 m^3/s (Weist, 1978), although appreciable drainage enters them from outside the Michigan Basin.

Surface water is utilized extensively by industry and municipalities within the Michigan Basin. Although the Great Lakes are the principal sources, streams and lakes inland from the large lakes also are widely used as sources, streams and lakes inland from the large lakes also are widely used as sources of fresh water. Even though the volumes of available ground water are sizable, Murray and Reeves (1972) estimated that the Great Lakes region, which includes the Michigan basin, obtains 95 percent of its freshwater demand from surface sources. This is in spite of appreciable pollution from industrial effluents, especially in the southern half of the basin.

The Illinois Basin, through major rivers that have their headwaters outside the basin but flow through it, contributes all of its drainage to the Mississippi River. From northwest to southeast, these principal streams are the Mississippi, Illinois, Kaskaskia, Wabash, White, Ohio, Green, Cumberland, and Tennessee Rivers.

Precipitation across the Illinois Basin ranges from about 80 cm along the northwestern and northern margins to more than 120 cm in the area where the Mississippi Embayment abuts the basin along its southern margin (Bloyd, 1975). Losses to the atmosphere over the same geographic extent are 68 to 80 cm, respectively (Bloyd, 1975).

In this region, there is a very close correlation between the shallow ground-water system and surface drainage. This relationship is embodied by the recharge of ground-water aquifers, such as buried glacial valleys and glacial sediments (outwash) or alluvium in modern stream valleys, as well as by appreciable ground-water discharge to numerous lakes and perennial streams whose low-flow periods are sustained by ground water.

Compared to the use of surface water, ground water is an underutilized resource in the Illinois Basin, although sizable volumes are removed, especially from the shallow glacial and alluvial aquifers for municipal purposes (Bloyd, 1974, 1975). Thus, surface water remains the principal source to meet industrial, rural, and municipal demand.

Part of the drainage from the northeasternmost part of the Appalachian Basin (including the Valley and Ridge) is eastward to the Atlantic Ocean by means of the Mohawk, Hudson, Delaware, Susquehanna, Potomac, and James Rivers. Part of the remaining westward-flowing drainage enters the Great Lakes (Erie and Ontario) by means of such larger streams as the Black, Oswego, Genessee, Niagara, and Cuyahoga Rivers and numerous small tributaries. The drainage that does not flow to either the Atlantic Ocean or the Great Lakes moves in a similar path to the drainage from the central and south-central parts of the basin by entering the Ohio River for eventual discharge into the Mississippi River and final flow to the Gulf of Mexico. Principal rivers that receive this drainage, from north to south, include the Allegheny, Monongahela, Muskingum, Little Kanawha, Kanawha, Guyandotte, Big Sandy, Kentucky, Green, Cumberland, and Tennessee (Bloyd, 1974).

Although most of the drainage from the southern part of the Appalachian Basin is handled by the Cumberland and Tennessee Rivers, a small amount from the southernmost parts of the Cumberland Plateau and Valley and Ridge provinces enters the drainage areas of the Alabama and Tombigbee Rivers. These streams eventually merge and flow into Mobile Bay on the Gulf Coast.

As might be expected, considering the great north-south length of the Appalachian Basin, annual precipitation varies widely. In the New York-Pennsylvania-Ohio area, a value of 100 cm is average; throughout the central and southern parts, the range is 100 to 140 cm. In east Tennessee, however, values between 150 and 200 cm are recorded over a small region (Cederstrom et al., 1979).

Although precipitation accounts for much of the runoff drainage, discharge from ground-water aquifers into streams is a very important component. The degree of contribution is of course controlled by the physical nature of the bedrock present and whether or not that bedrock is overlain by unconsolidated sediments. The latter include glacial outwash and till, colluvium, and alluvium in the northern part and alluvium, colluvium, and porous saprolite in the central and southern parts. Sinnott and Cushing (1978) showed that certain bedrock units can account for ground-water discharges that range from 25 to 90 percent of streamflow.

As is the case in the Illinois and Michigan Basins, the principal sources of fresh water are surface streams, impoundments, and lakes. Murray and Reeves (1972), however, estimated that only approximately 10 percent of the water demand in 1970 was met by ground water, although the region surveyed extended beyond the Appalachian Basin per se. This extensive use of surface water, especially in the more industrialized-urbanized northern part, is made despite the fact that industrial pollution has severely impaired the water quality of many streams. Additional pollution of stream waters has occurred as a result of acid drainage from improperly designed and operated coal mines (surface and underground). Future water demands, especially in certain localized areas, may thus dictate a greater dependence upon ground-water supplies.

3.3.2 Ground Water

Although surface water is the primary source for fresh water in all three basins, appreciable ground water, in unconsolidated sediment and bedrock aquifers, is present in each region. In all three basins the ratio of natural recharge to the ground-water system versus withdrawal via wells also is most favorable. The two main limitations to reliance upon ground water are that certain areas lack either permeable, unconsolidated deposits and/or bedrock, and that the depth to the saline water in the bedrock is fairly shallow.

Within the Michigan Basin, thick, sandy glacial deposits are easily recharged and thus are capable of furnishing appreciable ground water with good long-term yields (Waller and Allen, 1975). Large areas in north-central and southern Michigan contain wells in glacial drift capable of sustained yields approximating 2,000 l/min. The quality of this water is good, as total dissolved solids (TDS) are generally less than 500 mg/l, even though most of the TDS are those ions that make water hard (Piper, 1972). Other areas, such as northeasternmost Michigan and a linear north-south trend from Saginaw Bay to near Detroit, recover very low yields from wells in glacial material (Waller and Allen, 1975). This is because the clay content is high, as is the case with till and fine-grained lacustrine sediments, or because the glacial veneer is thin. Yields from these areas are generally less than 40 l/min.

Bedrock aquifers within the Michigan Basin (Southern Peninsula only) include Silurian-Devonian limestones along a narrow band in the northeast, the Mississippian Marshall Sandstone, and the Pennsylvania Saginaw Formation (mostly sandstone) over a large area within the south to east-central part of the basin. Well yields from these more productive aquifers range from 190 to more than 2,000 l/min (Waller and Allen, 1975). In these two important aquifers, the depth to the base of fresh water (less than 1,000 m/l TDS) is approximately 100 to 150 m (Feth et al., 1965).

Elsewhere in the Michigan Basin, the base of fresh water may be as deep as 270 m, but this occurs where glacial drift provides an adequate supply of fresh water. Even though much of the formation fluid below these relatively shallow depths is too saline for domestic potable application, considerable brine is purposefully recovered in Michigan as a source of contained mineral resources. Another application for the deeper salaquifers is their use as injection zones for the disposal of industrial wastes (Warner and Orcutt, 1973). Some 21 such wells are active in Michigan (Weist, 1978), although the greatest concentration is near Midland in the east-central part of the state.

Shales, including those of the Devonian-Mississippian interval, are poor sources of water. In addition to very low yields of generally less than 35 l/min, the fluids are high in dissolved solids. Where natural gas has been produced from the Antrim Shale, associated formation fluids are brines (Ells, 1978).

Even though there is considerable good quality ground water in the glacial outwash, alluvial-valley fills, and sand-filled buried valleys of the Illinois Basin, there is even a larger volume contained within the bedrock aquifers beneath these unconsolidated sediments (Bloyd, 1975). Despite the large volumes of water available from bedrock aquifers, considerably more use is made of shallow ground water from unconsolidated deposits.

Most of the more favorable glacial-outwash and alluvial aquifers are found in narrow bands along present-day drainage courses or in sinuous buried glacial valleys that were filled with sorted sand and gravel as the result of several episodes of ice advances and retreats. Deposits in buried valleys may range up to 60 m in thickness, but most of the outwash and alluvial-fill aquifers are less than 20 m thick. The yield from wells drilled into these deposits ranges from 100 to 2,000 l/min, although some alluvial and terrace deposits near major streams exceed 2,000 l/min (Bloyd, 1974, 1975). Between these high-yield sandy deposits are areas in which till (ground and frontal moraine material) is the principal glacial sediment; here, well yields between 40 and 100 l/min are common.

Much of the shallow (buried by glacial drift) or exposed bedrock in the Illinois Basin is either Mississippian or Pennsylvanian, although Silurian and Devonian units are also exposed (or lie at shallow depths beneath glacial drift) along the northern and eastern boundaries. Ground-water aquifers are mainly found in carbonates or sandstones of these ages; exceptions are the Ordovician St. Peter Sandstone, which is an important aquifer in the northernmost part of the basin, and the Cambrian Ironton-Galesville Sandstone, which is widely used for large-volume supplies.

Well yields from 100 to 400 l/min constitute a representative range; however, yields may be less than 100 l/min in some cases. In less common circumstances, short-term yields as high as 2,000 l/min have been reported from some bedrock aquifers. Pennsylvanian sandstones are widely used but tend to be highly variable in their yields and more likely to serve domestic/agricultural demand. Mississippian limestones (e.g., St. Louis, Salem), especially where secondary solution porosity has developed, and sandstones (e.g., Aux Vases) are also used extensively, tending to be more dependable regionally in terms of yields and commonly serving as sources for industrial and municipal supplies (Brueckmann and Bergstrom, 1968). The Chouteau and other Lower Mississippian strata, including the New Albany Shale, are usually impermeable and are not considered as good ground-water sources.

Devonian limestones and some Silurian dolomites with solution porosity also yield fresh ground water locally. Other than the St. Peter and Ironton-Galesville Sandstones, the remainder of the Lower Paleozoic sequence is not an important source of ground water. Deeper aquifers, where they contain saline water, are utilized as injection zones for industrial-waste-disposal wells (Warner and Orcutt, 1973). Units such as the St. Peter, Ironton-Galesville, and Mt. Simon Sandstones are the principal salaquifers used for disposal within the Illinois Basin.

The southern and eastern parts of the Illinois Basin are characterized by karst topography, and hence surface drainage is more closely connected to the ground-water system as a result of dissolution of limestones there. Disappearing streams, caves, sinkholes, and very porous zones within the bedrock are typical (Thornbury, 1965). The northwest-southeast trend in south-central Indiana involves Mississippian limestones and is the more extensive.

Within the Appalachian Basin, ground water occurs in areas covered with a veneer of glacial materials and alluvium and in areas that lack such a surficial mantle. Ground-water aquifers thus include bedrock units of several ages, glacial drift, and alluvium along stream valleys. Some ground water also occurs in colluvium or regolith from the weathering of bedrock and porous saprolite, although generally only small well yields are possible. Where these weathering-residue deposits are thick, such as the above-mentioned Mississippian carbonates or the Fort Payne Chert in the Cumberland Plateau part of the basin, water yields can be appreciable.

In the northern part of the basin, most ground water is derived from coarse-grained deposits, or sand and gravel, of glacial origin. Buried, glacially scoured valleys filled with outwash are especially productive, and commonly display well yields up to 4,000 l/min (Bloyd, 1974). Where clay-rich glacial till is present, well yields are much less, and little ground water is recovered. Sand and gravel deposits along modern-day stream valleys and in alluvial terraces also are important sources of fresh ground water.

In those areas that lack glacial drift, most ground water is derived from shallow bedrock aquifers. Yields generally range from 200 to 1,200 l/min, although utilization is much less than the available volume (Sinnott and Cushing, 1978). Excluding the productive units in the deformed Valley and Ridge province, some important bedrock aquifers in the Appalachian Basin include (1) sandstones within the Pennsylvanian Allegheny and Pottsville Formations; (2) the Mississippian Berea Sandstone; (3) selected zones within the Mississippian Tuscumbia, Warsaw, and St. Louis Limestones; and (4) several Silurian and Devonian carbonate units in areas where they are near the surface. Locally in the southern part of the basin (Nashville Dome region), the Cambrian-Ordovician Knox Dolomite is a reliable source of fresh ground water, even though well yields rarely exceed 200 l/min and are generally much lower (Zurawski, 1978).

The Devonian-Mississippian shale sequence, except where the associated Berea Sandstone is water-bearing, does not constitute a source of usable ground water. In fact, at the depths where the shale sequence is encountered, formation fluids are commonly saline. Also, salaquifers stratigraphically below the shale sequence represent major sources of commercially used brines; for example, deep brine recovery is extensively practiced in the Upper Ohio River Valley.

Within the Appalachian Basin, several industrial disposal wells are used to inject liquid wastes into deep bedrock aquifers containing saline water. These systems are small in number and are of relatively localized extent.

3.4 SHALES AND ARGILLACEOUS STRATA

3.4.1 Introduction

Within the Eastern Interior region, the following discussion is centered chiefly on three shale-bearing sequences of Paleozoic age that are relatively widespread and thick. These sequences are the (1) Upper Ordovician Maquoketa Group (also called Formation); (2) Upper Ordovician Cincinnatian Series and eastward equivalents; and (3) Middle-Upper Devonian to Lower Mississippian clastic (shale-rich) sequence. Other units, the Precambrian Ocoee Supergroup, the Cambrian Conasauga Group, and the Mississippian Floyd Shale, are briefly discussed.

In the case of the Maquoketa, strata within this interval extend eastward from the Midcontinent region of the Great Plains province through the Illinois Basin and its flanks to a point along the western limb of the Cincinnati Arch. Because of stratigraphic-correlation difficulties, the partially equivalent Cincinnatian Series is treated as a separate entity. These latter strata are exposed along the crest of the Cincinnati Arch and extend eastward where they increase in thickness, change their lithologic expression, and are referred to by alternative, yet correlative, stratigraphic names. This eastward phase extends into the norther part of the Appalachian Basin.

The Devonian-Mississippian clastic, shale-rich sequence is best developed within the Illinois, Michigan, and northern-to-central Appalachian Basins, although thinner extensions of several stratigraphic units named throughout this three-basin region extend over the intervening structural uplifts. Within the Illinois Basin, one principal stratigraphic unit, the New Albany Shale, applies to the Upper Devonian-Lower Mississippian interval even through its stratigraphic rank is viewed differently by the Illinois and Indiana geological surveys. Within the Michigan Basin, several discrete shale formational names (Antrim, Ellsworth, Bedford, and Sunbury) are recognized but are collectively correlative with the New Albany Shale to the south. Because of its genetic and spatial relationships, the Lower Mississippian

Coldwater Shale is described together with those other shale formations, even though it is younger.

A larger number of stratigraphic units that are either nearly all shale or that contain several shale zones are recognized within the Appalachian Basin. One explanation for this circumstance is that the more complex depositional conditions that existed in that basin produced a greater number of recognizable phases (magnafacies) and therefore a more extensive stratigraphic nomenclature. Also, shale-rich intervals were formed earlier in geologic time here; hence, black to dark-gray marine shales date from the Middle Devonian time in the eastern part of this basin, whereas the oldest shales in the other two basins date from the late Devonian time.

Because of these regional differences, and for other considerations, the shale intervals of Middle to Late Devonian and Early Mississippian ages in these basins are discussed separately on a basin-by-basin approach.

3.4.2 Maquoketa Group

3.4.2.1 Stratigraphy

The term "Maquoketa" has been used by various authors and state geologic surveys to define an Upper Ordovician stratigraphic sequence that chiefly underlies Indiana, Illinois, and western Kentucky and also extends westward into parts of Missouri, Wisconsin, Minnesota, and Iowa. This report follows the terminology adopted by the Illinois State Geological Survey (Willman et al., 1975) in which the Maquoketa is treated as a group even though elsewhere the term carries formation status. As a group, the Maquoketa is subdivided, in ascending order, into the Scales Shale, Fort Atkinson Limestone, Brainard Shale, and Neda Formation (Figure 3-1). The Scales Shale has been subdivided further into two members, the Elgin and Clermont Shales.

The term "Maquoketa" was first used by White (1870) to describe strata exposed along the little Maquoketa River in Dubuque County, Iowa. This exposure is part of the outcrop belt that extends from southeastern

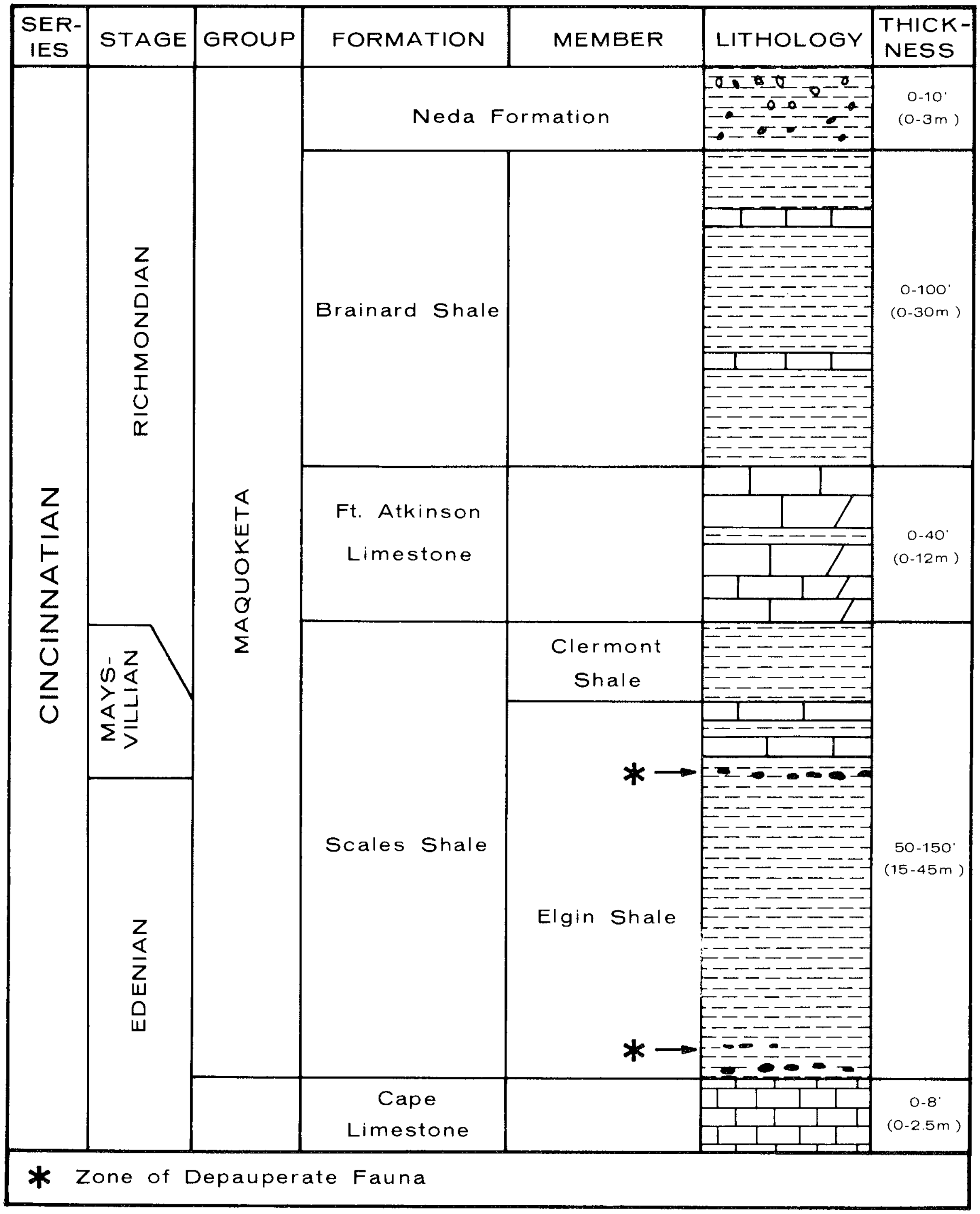

FIGURE 3-1. COLUMNAR SECTION OF CINCINNATIAN SERIES IN ILLINOIS (MODIFIED FROM WILLMAN ET AL., 1975)

Minnesota through northeastern Iowa and southwestern Wisconsin into northwestern Illinois (Figure 3-2). Although the Maquoketa Group underlies a considerable part of a five-state area as far eastward as Indiana, strata assigned to it are exposed in only two very narrow belts, one of which trends north-south in southeastern Wisconsin and northeastern Illinois, and a second in eastern Missouri and northwestern Illinois. In the latter area, the Scales Shale consists of two members, the Thebes Sandstone and the Orchard Creek Shale. The Fort Atkinson Limestone, Brainard Shale, and Neda Formation are, however, missing in this area.

The Maquoketa Group has been recognized in the subsurface eastward across Illinois and into western and central Indiana. Not clear, however, is how the formations of this group correlate or intertongue with those of the type section for the Cincinnatian Series in the Ohio Valley region. This situation exists because of the provinciality of the Ohio Valley fossil assemblage. The Indiana Geological Survey, however, has extended the stratigraphic terminology of the Maquoketa Group to the eastern border of the state (Gray, 1972), thus abandoning the classical Eden, Maysville, and Richmond names that were originally defined in southeastern Indiana and southwestern Ohio. There nevertheless is considerable question about the validity of this extension because of the faunal and lithologic differences between these two Upper Ordovician stratigraphic sections.

Recent work by Fluegeman (1979) indicates that a more widespread unit of the Brainard Shale can be traced in the subsurface across Indiana to an outcrop area as far east as Decatur County. This unit, called the New Point Tongue, lies above the Whitewater Formation, thus indicating that a portion of the Maquoketa Group is younger than the Richmond Group. Sweet et al. (1959) and Webers (1961), using conodonts as a means of determining time-correlative units, conversely suggest that most of the Maquoketa Group is older than Richmond age. Time-stratigraphic correlations thus are uncertain, and additional research is needed before such correlations can be made with certainty.

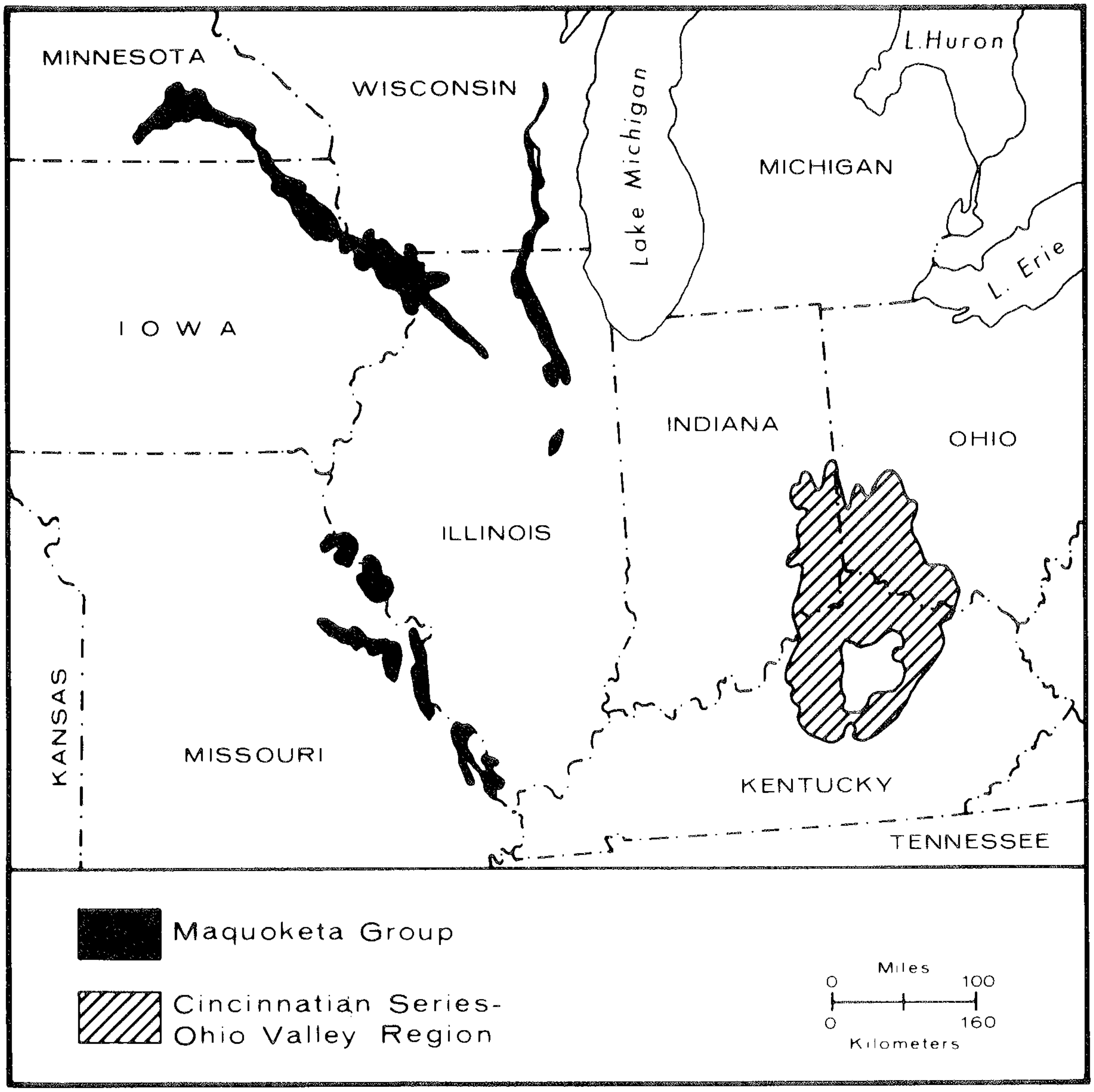

FIGURE 3-2. MAP SHOWING DISTRIBUTION OF OUTCROP AREAS OF UPPER ORDOVICIAN SHALE-RICH STRATA THROUGHOUT THE MIDWEST (MODIFIED FROM BAYER, 1965)

3.4.2.2 Geologic Setting

In the western extension of the Maquoketa Group beyond the Illinois Basin proper, the sequence typically is thin and/or composed largely of carbonate strata. In Iowa, the Maquoketa Group is distinctly rich in carbonate material in the subsurface to the west, where it reaches a maximum thickness of approximately 90 m throughout a band that extends from the southwestern to the northeastern corner of the state. On the outcrop in northeastern Iowa, the Scales and Brainard Shales are represented by 118 m of greenish-gray calcareous shale interbedded with limestone and dolostone. The high content of carbonate, particularly in the Elgin Shale Member, led Parker (1970) to refer to it as a limestone despite its designation by the Iowa Geological Survey as a shale. The Elgin Shale Member contains two well-known zones called the "depauperate beds" because of the distinctly dwarfed or stunted faunal assemblage preserved within these units.

The Fort Atkinson Limestone in Iowa is predominantly a limestone-dolostone unit, reaching a maximum thickness of 45 m in the south-central part of the state. The Neda Formation is an oolitic iron-bearing unit that may be as thick as 18 m near its type locality in eastern Wisconsin. This zone was mined as a source of iron beginning in the late 1800s, but, because the ore contained an appreciable amount of phosphorus, a constituent that makes steel brittle, the mines closed in the early 1900s (Paull and Paull, 1977). In Iowa, the Neda Formation ranges from 1 to 6 m thick and is composed of red to maroon shales that locally contain hematitic to limonitic oolites.

Few data are available concerning the entire Maquoketa Group in Minnesota, Wisconsin, and Missouri. In Minnesota, erosion has removed all but the lower member (Elgin Shale) of the Scales Shale. In Wisconsin, the Maquoketa Group is exposed in the southwestern corner and along a narrow band down the eastern edge of the state. Taylor (1964) states that here the sequence is represented by approximately 39 m of olive-gray to dark-yellow-orange shale. To the east, outcrops of the Maquoketa Group were reported by Sivon (1979) to include the Fort Atkinson Limestone and

Brainard Shale. Exposures in Missouri consist of approximately 36 m of olive-gray shale with thin interbeds of argillaceous limestone that make up the Scales Shale.

The character and thickness of the Cincinnatian Series and Maquoketa Group in Illinois are well documented by William et al. (1975). As illustrated in Figure 3-3, the Maquoketa Group is thinnest along the western and northern boundaries of the state, where typically it is 60 m thick; however, in places it has been eroded. The unit thickens and the amount of clastic sediments increases in an eastward direction. At the eastern edge of the state, the group reaches a thickness of approximately 90 m.

The Scales Shale, in contrast to its high content of carbonate in Iowa, consists of 25 m of dark-gray to brown shale with minor beds of dolostone, limestone, siltstone, and sandstone in Illinois. The overlying Fort Atkinson Limestone is recognized widely across Illinois as a thin (average thickness, 8 m) carbonate zone whose lithologic character changes within short distances.

In Illinois, the Brainard Shale averages 26 m in thickness where it has not been deeply eroded along the overlying sub-Silurian unconformity. Although the Brainard Shale is mainly a green to greenish-gray shale, it locally contains thin beds of siltstone, limestone, and dolostone. The Neda Formation is generally less than 3 m thick in most of the subsurface throughout Illinois. As elsewhere, this unit is largely a maroon to red shale that contains iron-rich oolites. Distribution of the Neda Formation is limited to sites the underlying Brainard Shale is relatively thick.

Although the Scales, Fort Atkinson, and Brainard divisions of the Maquoketa Group can be recognized in the western half of Indiana, precise time-stratigraphic relationships between these formations and those of the Cincinnatian Series of the Ohio River Valley are not clear, as mentioned in Section 3.4.1. Gray (1972), however, correlated the Maquoketa Group across Indiana and showed (Figure 3-4) that the Maquoketa thickens to the east and reaches a maximum thickness of approximately 285 m at the Ohio state line. The percentage of carbonate in the section also increases toward the east.

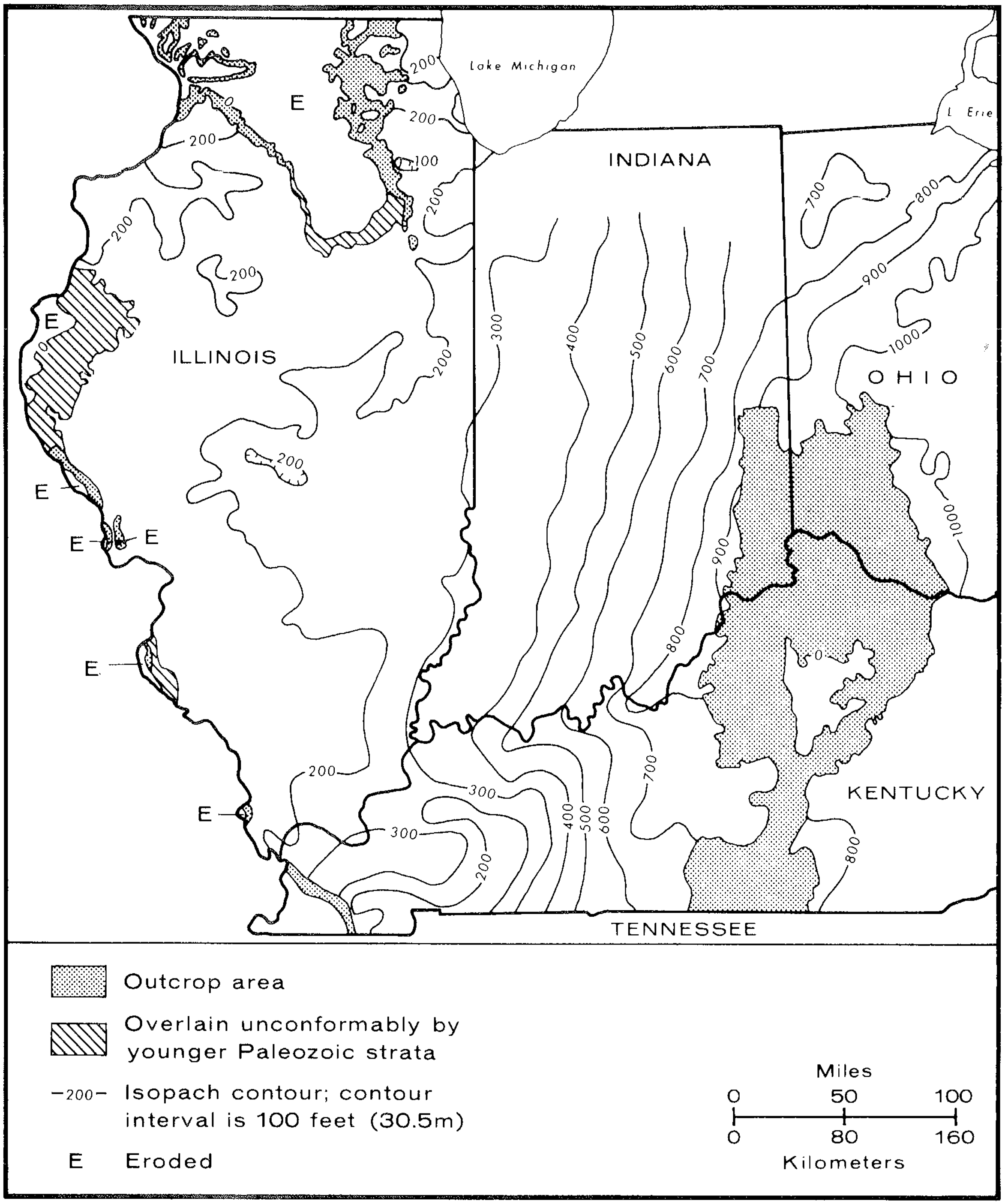

FIGURE 3-3. MAP SHOWING THICKNESS OF MAQUOKETA GROUP IN ILLINOIS BASIN (MODIFIED FROM BOND ET AL., 1971; WILLMAN ET AL., 1975)

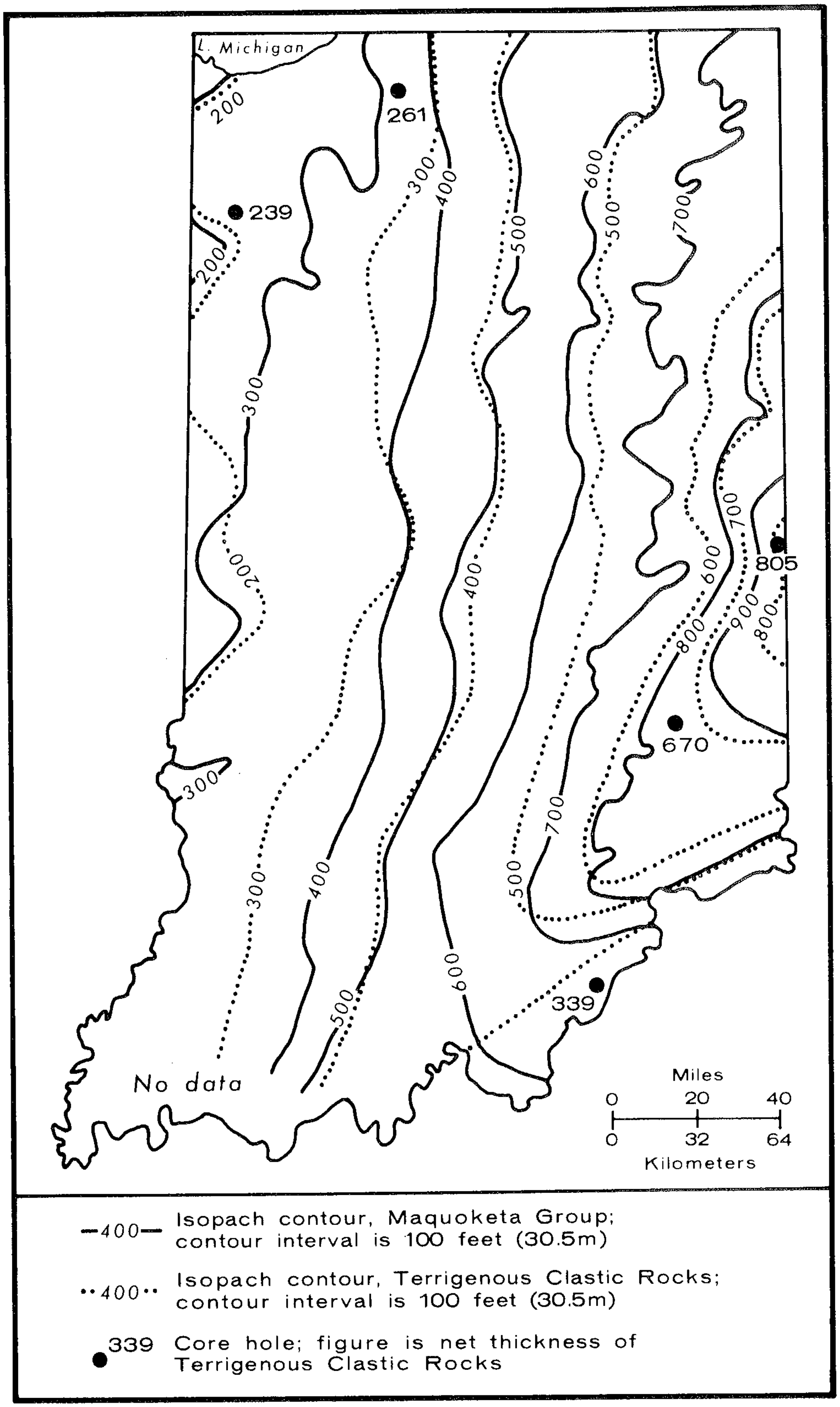

FIGURE 3-4. MAP SHOWING THICKNESS OF ENTIRE MAQUOKETA GROUP IN INDIANA, AND APPROXIMATE NET THICKNESS OF TERRIGENOUS CLASTIC ROCKS (MODIFIED FROM GRAY, 1972)

Throughout north-central Illinois and Indiana and as far east as the Ohio state line, the top of the Maquoketa Group is shallower than 200 m. In southwestern Indiana and southeastern Illinois, however, the top of the sequence, reflecting the influence of the Illinois Basin, lies below 1,000 m and is nearly 2,000 m deep toward the center of the basin. Toward the northeast, or from eastern Illinois into south-central Indiana, the depth to the top of the Maquoketa Group generally ranges from 400 to 900 m. Farther to the northeast, in the northeastern corner of Indiana, where the influence of the Michigan Basin is felt, the Maquoketa is 150 to 200 m thick and lies at depths of 400 to 650 m. Thus, throughout a large region embracing parts of Illinois and Indiana, the Maquoketa Group lies at moderate depths within the subsurface.

Droste and Vitaliano (1976) conducted a study of the shale formations within the Illinois Basin. In southcentral Indiana, the Maquoketa sequence is typically 75 to 150 m thick and 100 to 900 m deep, lies outside the principal areas of petroleum exploration, and consists predominantly of shale (Figure 3-5).

Most parts of the Illinois Basin are structurally simple, with complex faulting and pronounced seismic activity being largely confined to the southernmost part of the basin. Regional dips throughout most areas where the Maquoketa Group is thick, shale-rich, and at moderate depth are gentle, averaging less than 1 degree. One notable, localized exception involves the cryptoexplosive (astrobleme) feature at Kentland Dome, Indiana, where strata, including the Maquoketa, are steeply inclined around the centrally disturbed core of this structure.

3.4.2.3 Mineralogy and Rock Properties

Limited data are available concerning the clay mineralogy of shales within the Maquoketa Group. Droste and Vitaliano (1976) reported that a core from a borehole in south-central Indiana contained shale and fine-grained siltstone that were thin to massively bedded and extremely impermeable. Quartz is the dominant mineral in this sequence, making up 70 percent or more of the bulk mineralogy in the noncalcareous samples.

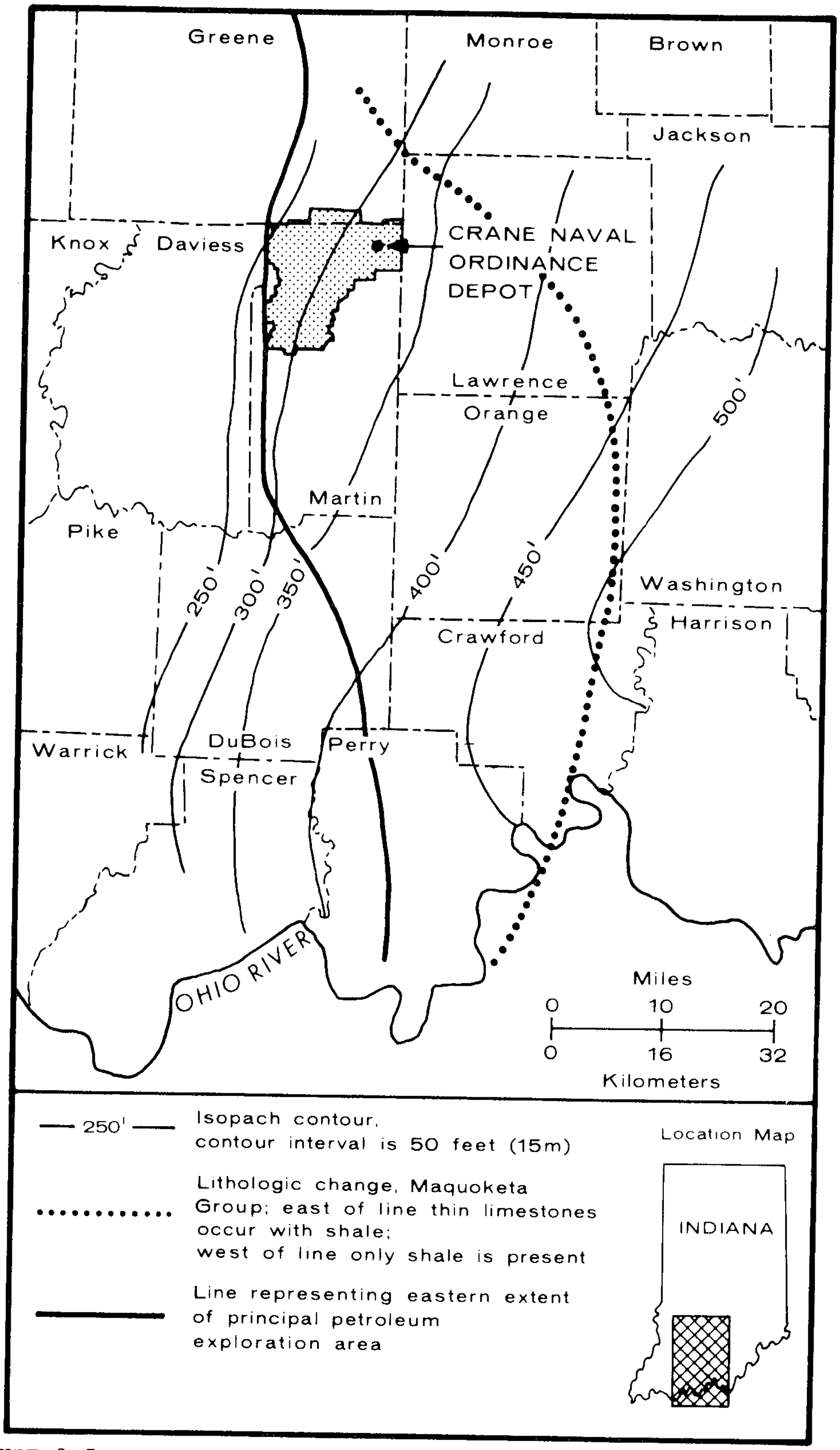

FIGURE 3-5. MAP SHOWING THICKNESS-LITHOLOGIC DATA AND REGIONAL MINERAL-RESOURCE ACTIVITIES FOR THE MAQUOKETA GROUP IN SOUTH-CENTRAL INDIANA (MODIFIED FROM DROSTE AND VITALIANO, 1976)

Insoluble residues from the calcareous shale and argillaceous limestone range from 50 to 90 percent by weight and consist of quartz, clay minerals, small amounts of pyrite, and organic matter of unknown composition. The purest limestone contains 20 percent insolubles (Droste and Vitaliano, 1976).

Illite is the dominant clay mineral, although chlorite may reach 20 percent of the total clay-mineral assemblage in certain samples. Fluegeman (1979) reports, however, that chlorite is absent in the so-called New Point Tongue. This finding is in marked contrast to the findings of Scotford (1965), who reported that chlorite was always present in rocks of the Cincinnatian Series collected in southwestern Ohio and southeastern Indiana. This absence of chlorite has been cited as evidence that the New Point Tongue may represent an eastward extension of the Brainard Shale.

Numerous subsurface storage caverns have been developed within the Maquoketa Group (Table 3-1). Compressive strengths range from 11 to 115 MPa; this wide range reflects the difference between shales, limestones, and dolostones in the excavated rock sequences. A representative average figure reported for rocks at the Will County, Illinois, site was 26 MPa. Whether this value represents an in situ or a laboratory measurement was not specified (Cobbs Engineering, 1975).

Most caverns have not experienced operating difficulties, although small amounts of water entered some excavations during the construction of the facilities at Huntington County, Indiana, and Johnson County, Iowa. Air slacking and eventual failure of a site in Kankakee County, Illinois, is attributed to early construction practices that were not as advanced and successful as those in current use.

3.4.2.4 Hydrology

The Maquoketa Group is a highly impermeable unit even in the relatively carbonate-rich section of eastern Iowa. Parker (1970) states that the Maquoketa Group there serves as an effective aquitard by limiting the downward movement of poor-quality water into an important, deeper

TABLE 3-1. SUBSURFACE STORAGE CAVERNS DEVELOPED WITHIN MAQUOKETA GROUP (MODIFIED FROM COBBS ENGINEERING, 1975)

Location	Date of Operation (Number of Caverns)	Stratigraphic Units (Penetrated Thickness)	Lithology
Iowa City, Johnson Co., Iowa	1963 (1)	Brainard (20 m) Fort Atkinson (1.8 m)	Shale and dolostone Dolostone
Iowa City, Johnson Co., Iowa	1967 (1)	Brainard (51 m) Fort Atkinson (34 m) Elgin (16 m)	Dolomitic shale Shale, some dolostone Dolostone and shale
Des Moines, Polk Co., Iowa	1970 (1)	Undifferentiated (60 m)	Shale and dolostone
Kankakee, Kankakee Co., Illinois	1953 (1)	No data available (Cavern failed in 1971 due to poor design)	Shale
Monee, Will Co., Illinois	1972 (2)	Neda (1.8 m) Brainard (29 m) Fort Atkinson (6 m) Scales	Shale Shale; minor dolostone Dolomitic shale; dolostone Dolomitic shale
Lemont, Will Co., Illinois	1967 (3)	Undifferentiated (65 m)	Shale and dolostone
Aurora, DuPage Co., Illinois	1953 (1)	No data available (Cavern purposely abandoned due to design defect)	No data
Huntington, Huntington Co., Indiana	1966 (1)	Undifferentiated (57 m) (Questionable Maquoketa)	Dolostone and dolomitic shale
Griffith, Lake Co., Indiana	1970 (1)	Brainard (2 m) Fort Atkinson (17 m) Scales (33 m)	Shale and dolostone Shale and dolostone Shale; minor dolostone

sandstone aquifer of Cambrian age. In the western quarter of the state, however, the absence of shale in the Maquoketa section underlying permits and exchange of water with a high content of dissolved solids into this Cambrian sandstone, thereby causing water-quality deterioration.

Walton (1960) estimated the average hydraulic conductivity of the Maquoketa Group in northern Illinois to be 2.29 x 10^{-9}cm/s. Here, the Maquoketa Group also acts as an effective aquitard to limit the movement of water into or out of valuable carbonate and sandstone aquifers of Cambrian and Early Ordovician age.

3.4.2.5 Mineral Resources

Limestone is the only resource directly recovered from the Maquoketa Group, and then only from surface quarries where the Fort Atkinson Limestone is exposed in eastern Iowa. The Maquoketa Group, however, has been penetrated in the Illinois Basin by numerous petroleum-exploration wells. Well density is particularly high in northeastern Indiana, where the well-known Lima-Indiana (Trenton) gas field is located. As noted in the previous section, good-quality ground water is recovered in parts of Iowa and Illinois from aquifers beneath the Maquoketa Group. Thus, those areas where water wells penetrate the sequence will also require investigation relative to well density.

Recovery of mineral resources from rock units other than the Maquoketa sequence includes strip and underground mining of Pennsylvania coals that are much shallower than the Maquoketa, and underground mining of shallower Mississippian gypsum in the Shoals district of Indiana. The surface mining of crushed stone, clays, sand and gravel, and other mineral resources occurs on a local basis.

3.4.3 <u>Cincinnatian Series</u>

3.4.3.1 Stratigraphy

The highly fossiliferous shales and thin limestones of the Upper Ordovician Cincinnatian Series crop out throughout a three-state region covering southwestern Ohio, southeastern Indiana, and north-central Kentucky and where these strata have been exposed by erosion along the crest of the Cincinnati Arch (Figure 3-6). Study of this sequence of rocks begin in the late 1800s and has provided some of the most widely known literature concerning stratigraphy and paleontology in North America.

The Cincinnatian Series is divisible, in ascending order, into the Eden, Maysville, and Richmond Groups, and consists of a nearly horizontal sequence of alternating, thin-bedded, fossiliferous limestones and gray-blue shales (Figure 3-7). Within the outcrop area, the limestone units are not continuous but rather pinch out in lateral distances ranging from a few to several hundred meters. The percentage of limestone is also markedly greater in the upper two groups than in the lowermost Eden Group. For example, the clastic ratio, expressed as the percentage of shale in vertical intervals approximately 1 m thick, is as high as 84 percent in the upper part of the Eden Group and the lower part of the Maysville Group (Hay, 1975). By contrast, this ratio falls to values as low as 20 percent in the uppermost Richmond Group.

Development of the stratigraphic classification for Upper Ordovician strata along the Cincinnati Arch was documented by Weiss and Norman (1960). Early workers defined stratigraphic boundaries largely, if not entirely, upon biostratigraphic rather than lithostratigraphic characteristics. A clear understanding of the term "formation" has become clouded here, owing to this tendency and the lithologic uniformity typical of the entire sequence. Figure 3-9 presents a widely used classification that is based almost entirely upon such biostratigraphic criteria.

According to this scheme, the Eden Group (named after Eden Park, Cincinnati) contains but one "formation," the Latonia, while the overlying Maysville Group (named after Maysville, Kentucky) is divided into two "formations," the Fairview and the McMillan. The Richmond Group (named after Richmond, Indiana) is the youngest division of the Cincinnati Series and is divided into five "formations."

More recent efforts have, however, attempted to redefine this classic stratigraphic sequence in accordance with the rules established by the

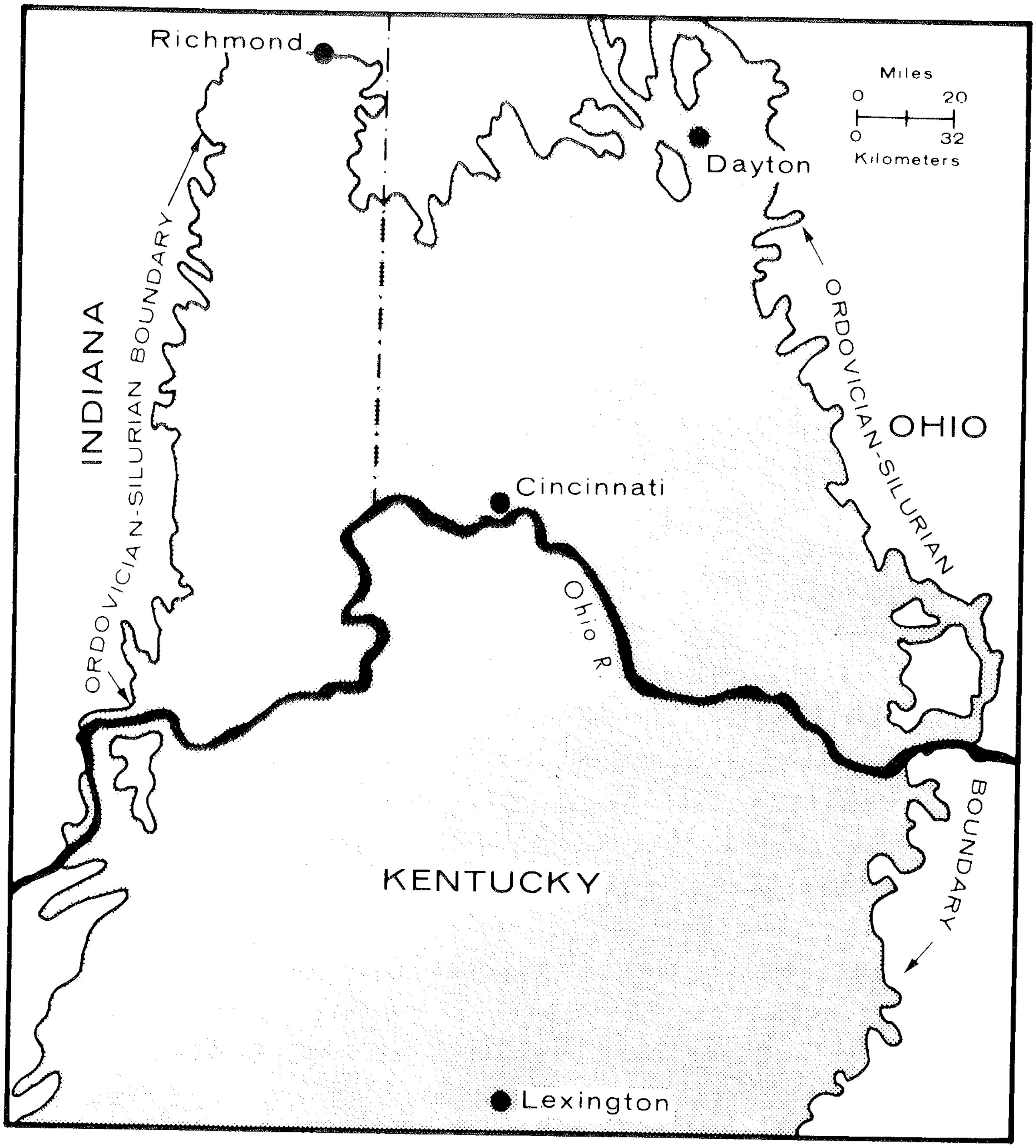

FIGURE 3-6. MAP SHOWING EDGE OF OUTCROP BELT OF UPPER ORDOVICIAN STRATA WITHIN SOUTHWESTERN OHIO, SOUTHEASTERN INDIANA, AND NORTH-CENTRAL KENTUCKY

Series	Group	Formation	Member
CINCINNATIAN	RICHMOND	Elkhorn	Elkhorn
		Whitewater	Upper Whitewater
			Lower Whitewater
		Liberty.	Liberty
		Waynesville	Clarksville
			Blanchester
			Ft. Ancient
		Arnheim	Oregonia
			Sunset
	MAYSVILLE	McMillan	Mt. Auburn
			Corryville
			Bellevue
		Fairview	Fairmont
			Mt. Hope
	EDEN	Latonia	McMicken
			Southgate
			Economy
			Fulton

FIGURE 3-7. CHART SHOWING BIOSTRATIGRAPHIC CLASSIFICATION OF UPPER ORDOVICIAN CINCINNATIAN SERIES WHERE THESE STRATA ARE EXPOSED ALONG CINCINNATI ARCH

American Commission on Stratigraphic Nomenclature (1970). Sweet and Bergstrom (1971) summarized these studies, and their results are shown in Figure 3-8. Despite the great deal of effort expended to reclassify these rocks on lithostratigraphic criteria, there still exists a need to integrate these attempts into a more unified nomenclature.

3.4.3.2 Geologic Setting

Within the general Cincinnati Arch region of outcrop, the Eden Group is composed largely of gray-blue shale, but it also contains a few lenses of thin argillaceous limestone. The total thickness of the Eden interval is approximately 75 m. In similar manner, the Maysville Group consists predominantly of gray-blue shale, even though thin argillaceous limestones increase in number within the upper part. The Maysville Group collectively is 60 m thick. Approximately 97 m of strata is assigned to the Richmond Group, which contains the greatest percentage of limestone units.

Distinct facies changes occur from west to east and north to south within these Upper Ordovician rocks. The thin, discontinuous limestone units found in the Maysville and Richmond Groups of southeastern Indiana and southwestern Ohio are missing from a more shale-rich section in central and eastern Ohio. In northwestern Pennsylvania, these rock units grade into a coarser clastic sequence represented by the Utica, Reedsville, and Queenston Shales and the Oswego Sandstone (Figure 3-9).

A marked difference in depositional environment also existed between north-central Kentucky and southwestern Ohio and southeastern Indiana. To the south there was a carbonate platform characterized by relatively high-energy, shallow-water conditions. Because of water turbulence, only the coarsest carbonate material was collected, as represented by the Lexington Limestone. Northward, however, the water deepened, and in this quieter environment the finer-grained clastic sediments that now constitute the strata in the Eden Group accumulated (Ansley and Fowler, 1969). This difference in water depth and the resulting influence upon sediment deposition became less important in the latter half of

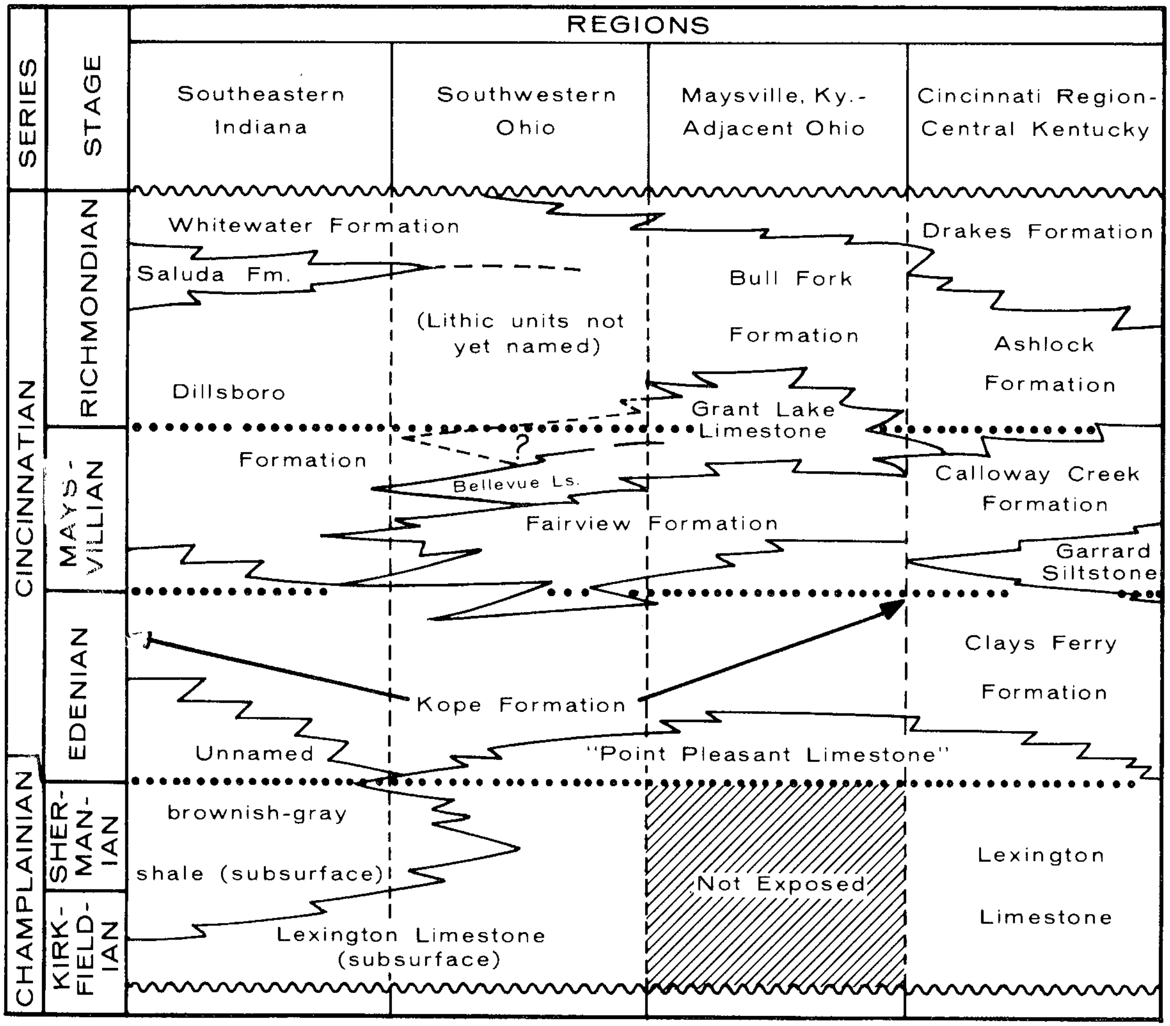

FIGURE 3-8. CHART SHOWING FORMATIONS OF CINCINNATIAN SERIES BASED UPON LITHOSTRATIGRAPHIC CRITERIA (MODIFIED FROM SWEET AND BERGSTRÖM, 1971)

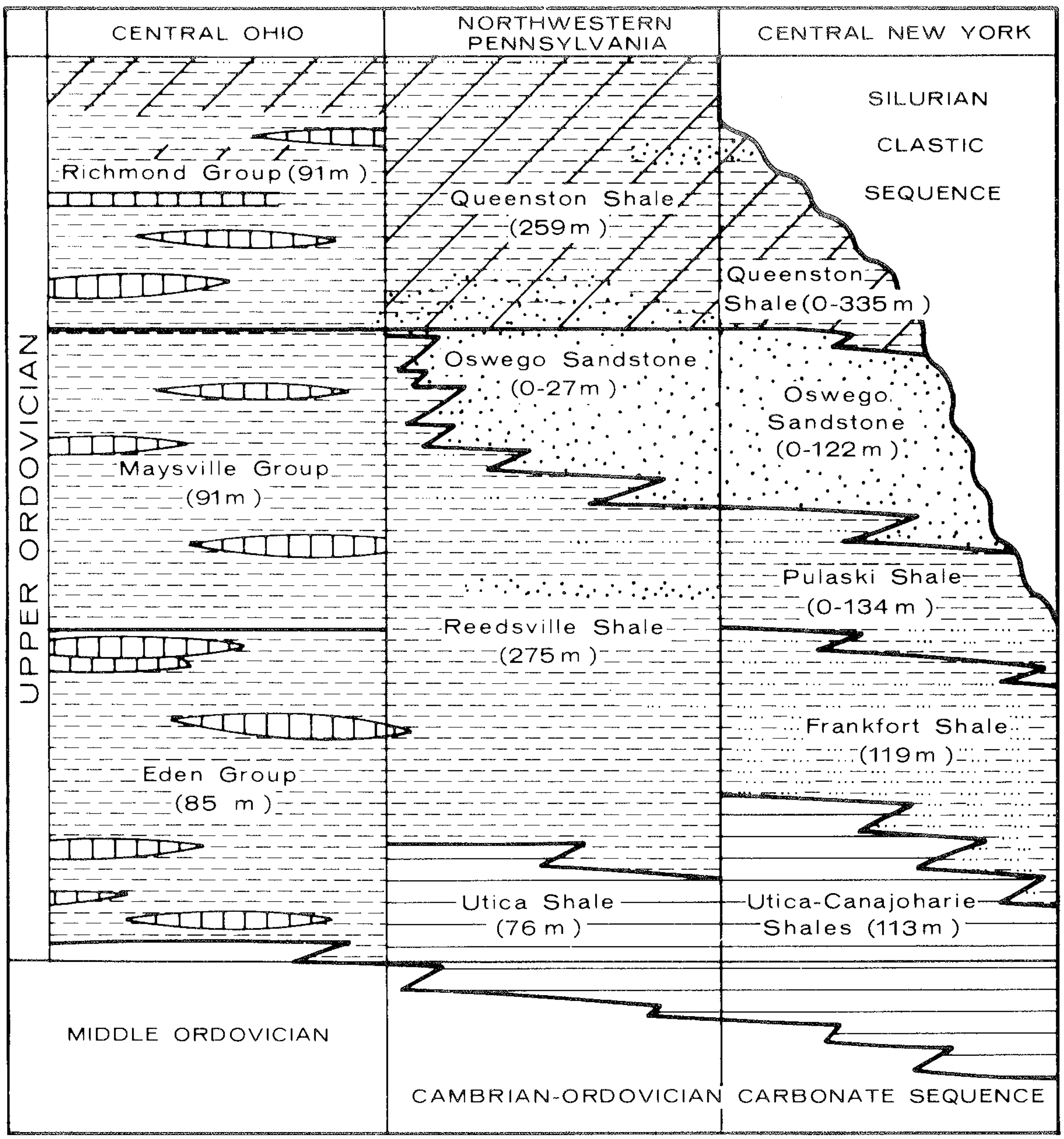

FIGURE 3-9. SCHEMATIC DIAGRAM SHOWING GENERALIZED STRATIGRAPHIC RELATIONSHIPS WITHIN UPPER ORDOVICIAN SEQUENCE IN OHIO, PENNSYLVANIA, AND NEW YORK (MODIFIED FROM COLTON, 1970)

Cincinnatian time. Strata of the Maysville and Richmond Groups thus document a progressive shallowing of the seas. Indeed, certain individual units in the upper part of the Richmond Group contain desiccation structures indicative of tidal-flat sedimentation (Martin, 1975).

The total thickness of the Eden, Maysville, and Richmond Groups ranges from about 60 m in the western part of Indiana (Gray, 1972) to nearly 600 m at the Ohio-Pennsylvania state line (Colton, 1961). In western and central Ohio, these groups vary in aggregate thickness from approximately 240 to 300 m (Johnson, 1975). As shown in Figure 3-10, the depth to the top of the Upper Ordovician shale sequence ranges from the land surface along the outcrop belt in western Ohio to more than 1,500 m in easternmost Ohio. Consequently, there is an appreciable extent of shale-rich section that is reasonably thick and within moderate depths below the land surface.

Rocks of the Cincinnatian Series exposed along the axis of the Cincinnati Arch in southwestern Ohio, southeastern Indiana, and northern Kentucky are covered by younger strata in all of central and western Indiana and most of Illinois. Strata of similar age crop out once more in northeastern Iowa, southeastern Minnesota, and along narrow belts in Missouri, Illinois, and Wisconsin. These Upper Ordovician rocks have been assigned to the Maquoketa Group and have their type sections in Iowa and Wisconsin. The Maquoketa Group is more fully described in Section 3.4.2.1, where the problems inherent in correlating the rocks in the Cincinnati area with those to the west are discussed.

3.4.3.3 Mineralogy and Rock Properties

The petrology of the shales of the Cincinnatian Series was studied by Scotford (1965). This quantitative and semiquantitative mineralogical, chemical, and textural investigation involved the collection and analysis of samples from outcrops in Ohio, Indiana, and Kentucky. Additional samples were taken from a 115-m core recovered by Texas Eastern Co. from a locality south of Middletown in Butler County, Ohio. A total of 41 samples from the Fulton Member of the Latonia Formation, 42 samples from the Clarksville Member of the Waynesville Formation, 32 samples from a

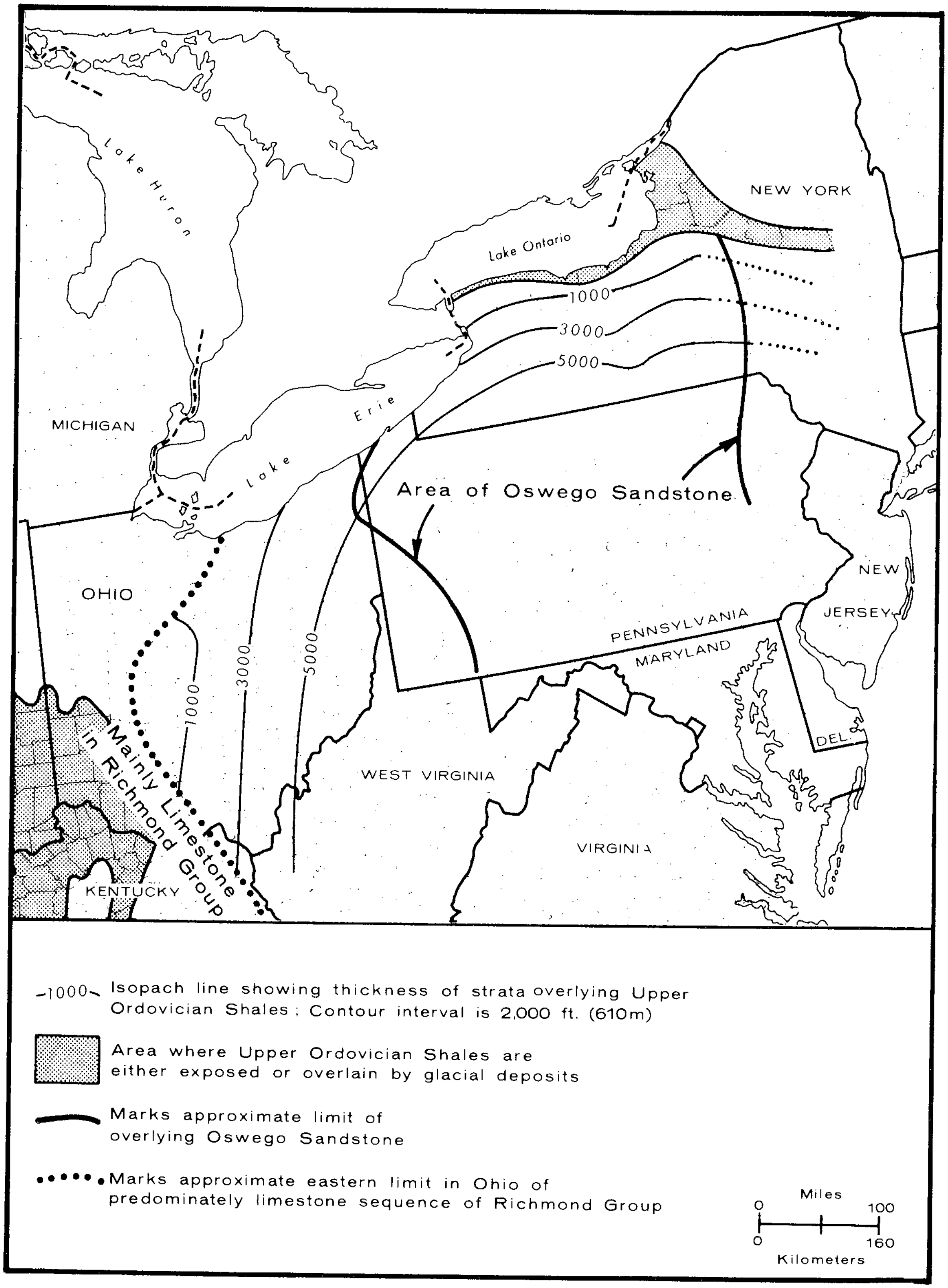

FIGURE 3-10. MAP OF DEPTH TO TOP OF UPPER ORDOVICIAN (CINCINNATIAN SERIES AND EQUIVALENTS) SHALES IN OHIO AND NEW YORK, AND PARTS OF ADJACENT STATES (MODIFIED FROM COLTON, 1961; MILLER, 1975). THICKNESS OF SHALE SEQUENCE RANGES FROM ABOUT 300 M NEAR THE OUTCROP TO NEARLY 600 M NEAR 1,500-METER-DEPTH ISOPACH LINE

shale at the very top of the Richmond Group were analyzed. As shown in Figure 3-7, the Fulton Member lies at the base of the Eden Group, the Clarksville Member near the middle of the Cincinnatian Series, and the youngest shale sampled just beneath overlying Silurian strata. The mean size distribution for all these shales is 38 percent clay, 59 percent silt, and 3 percent sand. The mean mineral composition consists of 47 percent illite, 24 percent quartz, 9 percent dolomite, 7+ percent chlorite, 6 percent calcite, 4+ percent mixed-layer illite, and 2 percent mixed-layer chlorite. Trace amounts of kaolinite, feldspar, and pyrite also were detected.

In general, there is lack of systematic variation in the shale parameters both vertically and horizontally within the study area. This indicates that depositional conditions across the area were relatively uniform. One exception is illustrated by the progressive increase in the weight percent of calcite and dolomite, as well as by an increase in the sand fraction in the upper part of the sequence. These trends are interpreted as being caused by a shallowing of the water with time and the growing importance of both biogenic and chemically precipitated carbonates.

Cobbs Engineering (1975) reports that three hydrocarbon-storage caverns were excavated in the Upper Ordovician shale sequence in western Ohio. These facilities, in Butler, Allen, and Lucas Counties, have been developed at depths from 117 to 174 m. The average compressive strength for the shale and limestone as these three sites ranged from 20 to 32 MPa. Information is lacking, however, as to whether these values were determined in situ. Minor spalling of the roof material occurred during construction of these caverns and appears to have been caused by air slaking of the shales. Roof bolts and light channel bands on closely spaced centers solved the problem. All three facilities have operated successfully since 1959, 1969, and 1970, respectively, without evidence of structural failure or ground-water inflow.

3.4.3.4 Hydrology

Shales within the Cincinnatian Series of Ohio exhibit very low values of hydraulic conductivity. Although no data could be found in the literature about specific determinations of hydraulic conductivity, many water wells drilled into the sequence are either "dry" or yield less than 40 l/min. The small volumes of water obtained from these rocks typically contain high concentrations of total dissolved solids. This shale sequence thus acts as an effective aquitard to the downward movement of infiltrating water. The ground water that is available in the area of outcrop in southwestern Ohio is largely dependent upon the thickness and character of the veneer of glacial drift and outwash that blankets the bedrock. The relatively impermeable nature of these rocks is further indicated by the lack of reported seepage into the aforementioned hydrocarbon storage caverns.

3.4.3.5 Mineral Resources

Although small amounts of oil and gas have been encountered during drilling into the Cincinnatian Series, no deposits of commercial value have ever been found. Most petroleum production in Ohio is derived from younger rocks in the eastern and east-central parts of the state. Wells drilled to test the potential of the underlying Trenton Limestone and Lower Ordovician and Cambrian carbonates also have been drilled mainly in the north-central part of Ohio. A relatively small number of wells have been drilled to these deeper carbonate units because of their low exploration potential. There are no other known mineral commodities of economic value presently being produced from the shales within the Cincinnatian Series.

Younger rocks have been mined underground at a number of places in Ohio. Coal mines are common in the Pennsylvanian rocks of eastern Ohio, salt is mined from Silurian strata in Cuyahoga and Lake Counties, and brine-well systems have operated in several counties of northeastern and southeastern Ohio.

3.4.4 Devonian-Mississippian Shales

3.4.4.1 Introduction

A thick and extensive sequence of shales and associated siltstones and sandstones of Middle-Late Devonian to Early Mississippian age is present in the Appalachian, Michigan, and Illinois Basins; thinner extensions of the sequence are developed over some of the intervening broad structural uplifts (Figure 3-11). Much current interest has been focused on certain of the black to dark brown shales found within these sequences, especially within the Appalachian Basin, because they represent an unconventional natural-gas resource. In fact, appreciable current production of natural gas is derived from such units in the Appalachian Basin. Since 1976, an extensive research and development program known as the Eastern Gas Shales Project (EGSP) has been coordinated by the U.S. Department of Energy's Morgantown, West Virginia, Energy Technology Center in assessing the magnitude of the gas resource, characterizing the shales and the factors that control gas accumulation, and developing improved exploration and production techniques. The volumes of proceedings from technical symposia held annually from 1977 to 1979 contain appreciable literature on the results of this program.

Previous interest in some of these shales relative to their potential for the disposal of radioactive waste is expressed in publications by DeWitt (1960) and Merewether et al. (1973). A more recent, comprehensive study of these deposits by Lomenick et al. (1983) is also available, and much of the subsequent discussion is based on this study.

Until recently, a complete understanding of these shales and the strata closely associated with them was hindered because (1) the geology of the sequence is different for each basin, despite many similarities and correlative units; (2) facies changes are numerous within each basin, and thus the overall stratigraphy throughout a three-basin region is complex; (3) stratigraphic terminology has been variable and subject to numerous revisions, a situation made more complicated by the sizable number of geological organizations attempting to deal with the differences; and

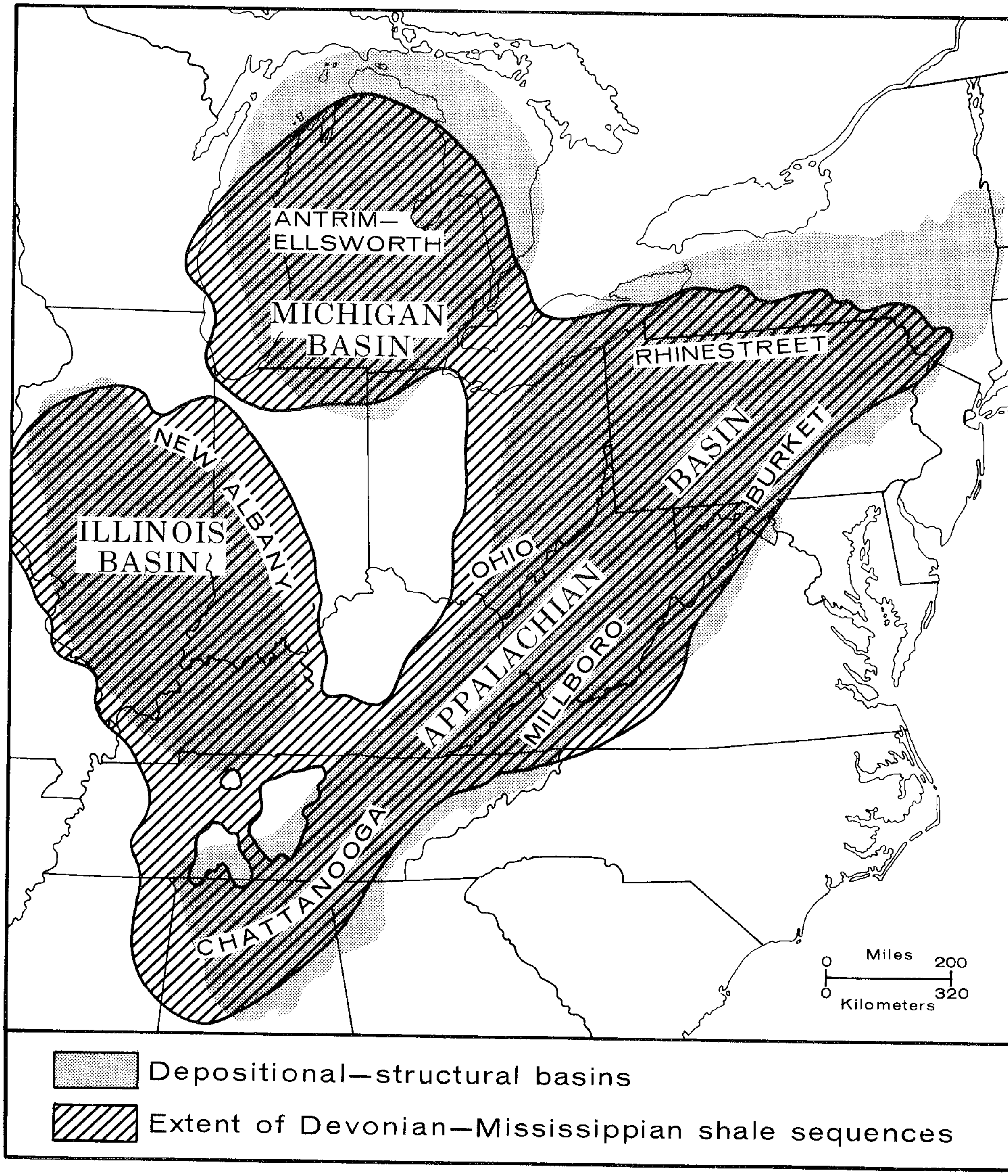

FIGURE 3-11. MAP SHOWING LOCATION OF APPALACHIAN, ILLINOIS, AND MICHIGAN BASINS; PRESENT EXTENT OF DEVONIAN-MISSISSIPPIAN SHALE SEQUENCE; AND REGIONAL POSITION OF SEVERAL WELL-KNOWN SHALE FORMATION NAMES (MODIFIED IN PART FROM PROVO ET AL., 1978)

(4) appreciable stratigraphic terminology has been based on surface outcrop data and has proved difficult to apply within the subsurface, especially in light of the many facies changes. The extensive stratigraphic nomenclature is partially summarized in Figure 3-12.

The ensuing discussion begins with the New Albany Shale of the Illinois Basin and is followed by treatments of the several shale-bearing intervals within the Michigan and Appalachian Basins, respectively.

3.4.4.2 New Albany Shale

3.4.4.2.1 Stratigraphy. Upper Devonian-Lower Mississippian shales in the Illinois Basin are collectively called the New Albany Shale (Figures 3-12 and 3-13) and conformably overlie Middle Devonian limestones (Hunton Megagroup). This unit, named for exposures near New Albany, Floyd County, Indiana, in 1874 (Campbell, 1946), consists of interbedded brown, black, and gray shales and ranges in thickness from 15 to 140 m within the basin. Equivalent strata extend westward across much of Missouri and Iowa (Collinson, 1968; Collinson et al., 1968) and are described in the section dealing with the Great Plains.

Recent standardized stratigraphic nomenclature for this sequence throughout the subsurface of the Illinois Basin has facilitated division of the New Albany Shale, in ascending order, into the Blocher Shale, Sylamore Sandstone, Selmier Shale, Sweetland Creek Shale, Grassy Creek Shale, Saverton Shale, Louisiana Limestone, Horton Creek Formation, and Hannibal Shale (Figures 3-13 and 3-14). In Illinois, subdivisions of the New Albany Shale represent formations because it is considered a group there. In Indiana and Kentucky, however, the sequence is treated as a formation, thereby making the various subdivision members. There also remain some problems regarding exact correlations within the basin owing to facies changes and the difficulty of correlating units identified at the outcrop with those found within the subsurface in the deeper parts of the basin (Figure 3-14).

The Blocher Shale (named for the town of Blocher, Scott County, Indiana) is brownish-black, calcareous, dolomitic, and rich in

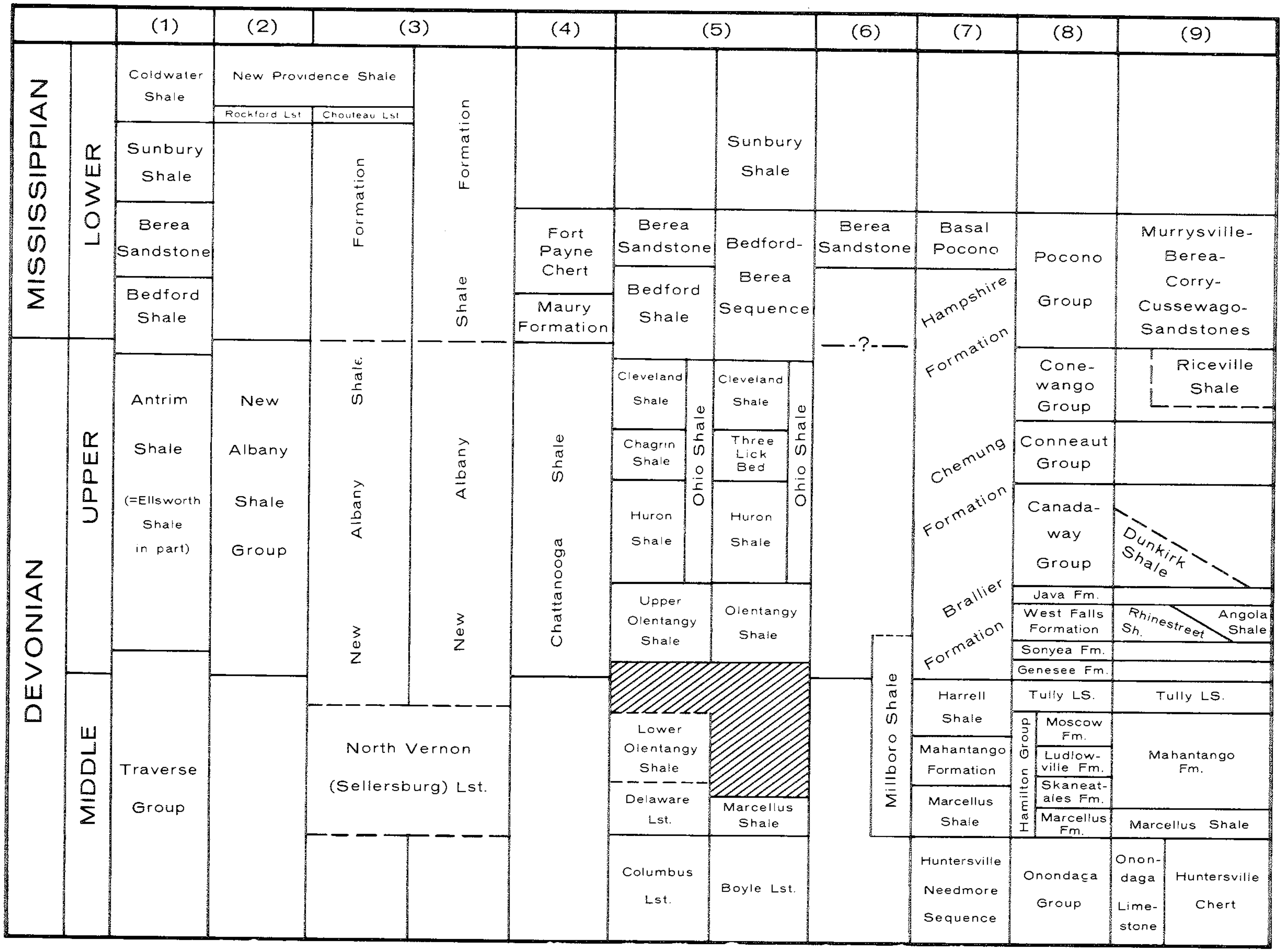

FIGURE 3-12. CHART SHOWING GENERALIZED STRATIGRAPHIC RELATIONSHIPS OF MIDDLE-UPPER DEVONIAN AND LOWER MISSISSIPPIAN SHALE-BEARING SEQUENCES IN APPALACHIAN, ILLINOIS, AND MICHIGAN BASINS (MODIFIED FROM PATCHEN, 1977; ELLS, 1979; HARPER AND PIOTROWSKI, 1979; BLACKBURN, 1980; CLUFF ET AL., 1981; MICHIGAN BASIN; 2-3, ILLINOIS BASIN, WEST TO EAST; 4-5, SOUTHERN APPALACHIAN BASIN; 6-9, CENTRAL-NORTHERN APPALACHIAN BASIN)

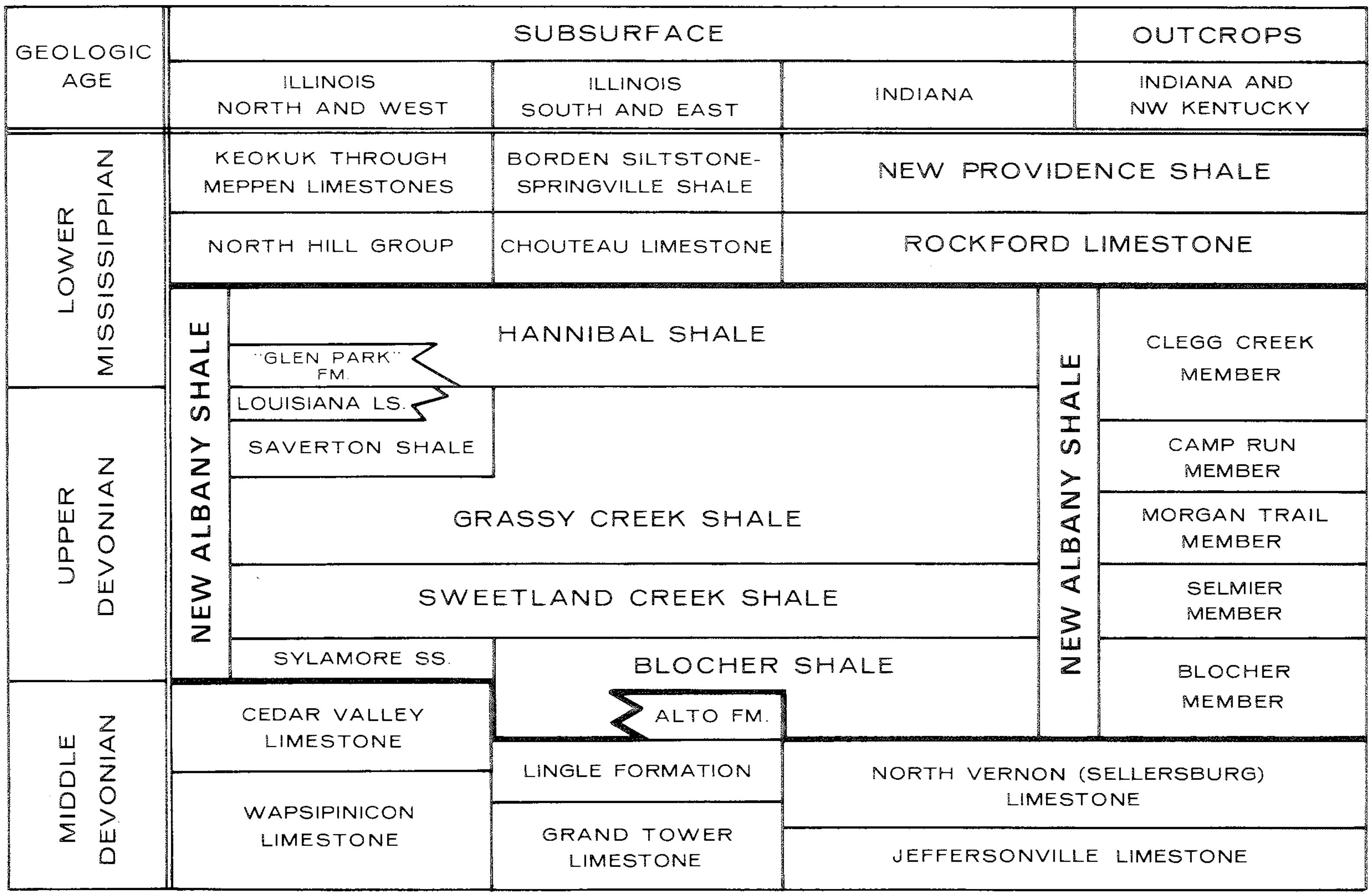

FIGURE 3-13. CHART SHOWING CORRELATIVE RELATIONSHIPS BETWEEN NEW ALBANY SHALE AND ADJACENT UNITS FROM EAST TO WEST SIDES OF ILLINOIS BASIN (MODIFIED FROM WILLMAN ET AL., 1975; BASSETT AND HASENMUELLER, 1977; REINBOLD, 1978; CLUFF ET AL., 1981)

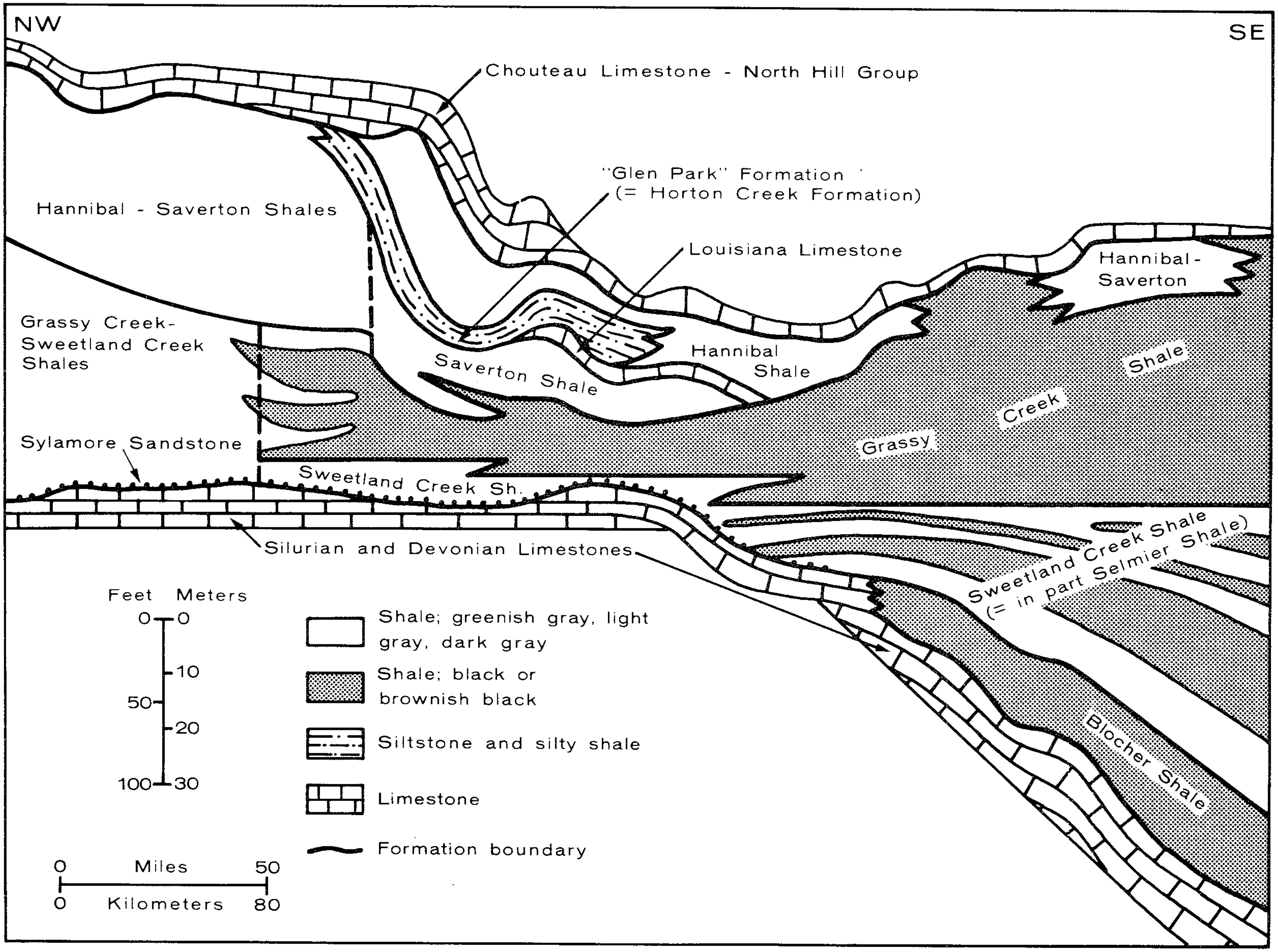

FIGURE 3-14. GENERALIZED NORTHWEST-SOUTHEAST CROSS SECTION THROUGH THE ILLINOIS PORTION OF THE ILLINOIS BASIN, SHOWING STRATIGRAPHIC RELATIONSHIPS BETWEEN SUBDIVISIONS OF NEW ALBANY SHALE AND ADJACENT STRATA (MODIFIED FROM REINBOLD, 1978; CLUFF ET AL., 1981)

carbonaceous matter and pyrite. Present in southeastern Illinois and eastward across Indiana and Kentucky, the Blocher Shale typically ranges from 10 to 20 m thick throughout most of the basin. The unit's high carbonate content is responsible for high resistivity readings on electric logs, while a relatively low natural radioactivity accounts for the low gamma-ray response (Figure 3-15). Westward across the basin, a brown argillaceous limestone occurs at the base of this unit and laterally grades into the underlying Lingle Limestone.

The Sylamore Sandstone is named for Sylamore Creek in Arkansas and serves as the basal unit of the New Albany Shale throughout central and western Illinois, where the Blocher interval is represented by the Lingle Formation. Developed only as a thin (less than 2 m) layer of well-rounded quartz sand, the Sylamore Sandstone is nearly impossible to identify in the subsurface except in cores. This thin unit is commonly phosphatic, and while it clearly marks an unconformable surface, it is generally not mapped as a separate stratigraphic division.

The Selmier Shale was originally named by Lineback (1968) as a unit at the outcrop in eastern Indiana (Figure 3-13). Recent work by Cluff et al. (1981) has modified the original stratigraphic definition and extended the unit into the subsurface toward the west. The Selmier Shale consists of dolomitic and green-gray shale to the east but becomes progressively blacker toward the center of the basin. Despite this stratigraphic change, the vertical extent of the Selmier Shale in the subsurface remains an arbitrary choice. Until a final resolution is made, the Selmier Shale is considered by this report as largely equivalent to the Sweetland Creek or included within the Sweetland Creek-Grassy Creek interval where the three units cannot be separated in the subsurface.

The Sweetland Creek Shale is named after Sweetland Creek in Muscatine County, Iowa, and consists of mainly gray to greenish-gray shales but also contains some dark-gray to black beds, especially in southeastern Illinois and Indiana, where these more carbonaceous intervals tend to dominate. Although dark shale samples cannot easily be separated lithologically from the underlying and overlying shales in the southeastern part of the basin, this unit can be clearly identified on well logs, where lower resistivity

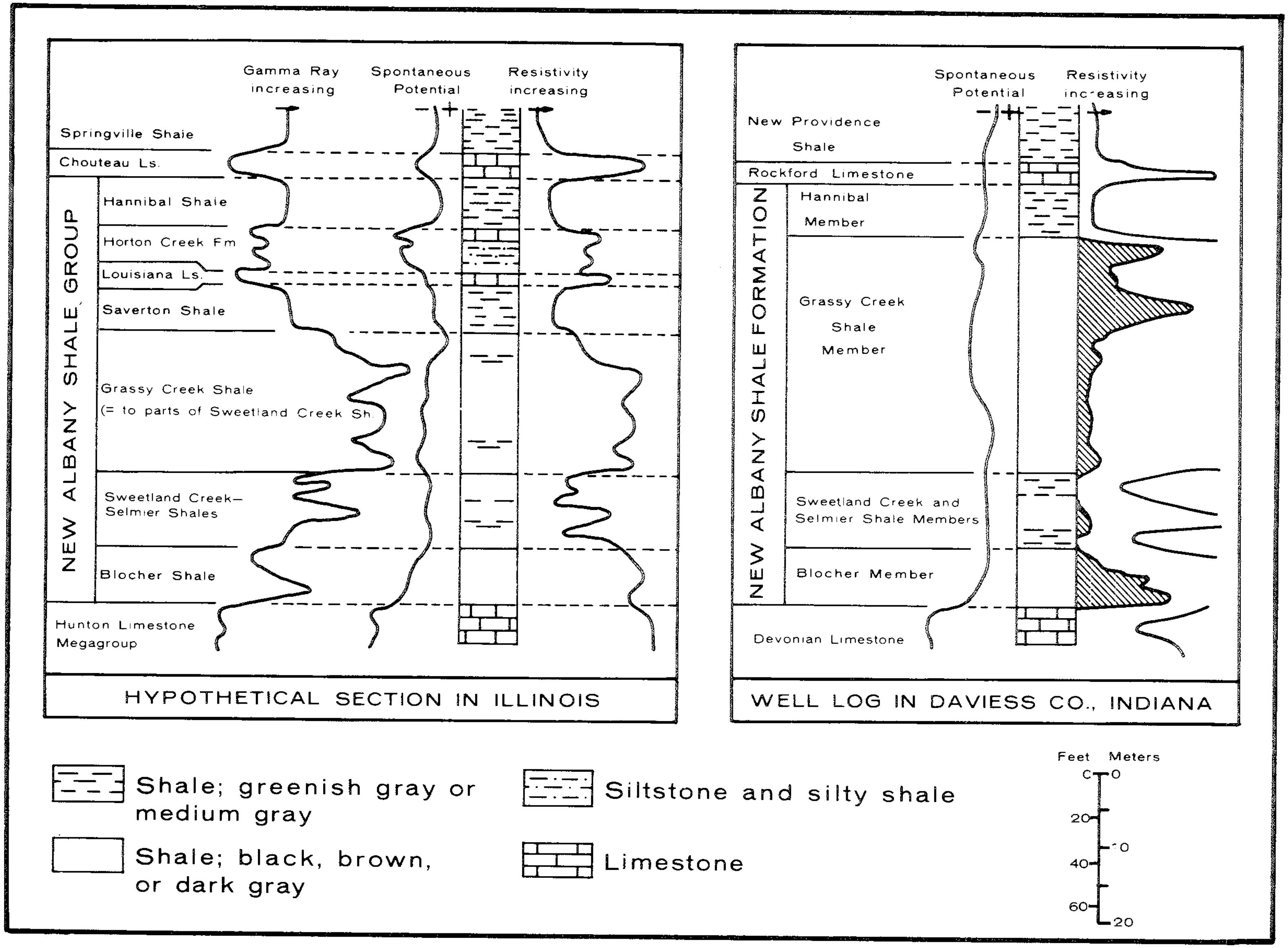

FIGURE 3-15. DIAGRAM SHOWING BOREHOLE-LOG RESPONSES OF STRATIGRAPHIC DIVISIONS OF NEW ALBANY SHALE GROUP IN ILLINOIS AND NEW ALBANY SHALE FORMATION IN INDIANA (MODIFIED FROM BASSETT AND HASENMUELELR, 1977; REINBOLD, 1978; CLUFF ET AL., 1981)

and gamma-ray values than those of the overlying Grassy Creek Shale are evident (Figure 3-15). The Sweetland Creek Shale reaches a maximum thickness of 60 m in southeastern Illinois along the Kentucky state line.

As a stratigraphic unit that extends throughout the basin, the Grassy Creek Shale (named after a small stream in eastern Missouri) is a brownish-black to black, pyritic, noncalcareous shale rich in organic matter. The unit is typically up to 30 m thick over much of the basin but exceeds 45 m locally in southeastern Illinois. On well logs, the shale can usually be recognized because of high resistivity and gamma-ray values (Figure 3-15). Toward the northwest, the unit contains considerable interbedded greenish-gray shale that exhibits lower such responses on well logs. In this area, this unit is distinguished from the underlying Sweetland Creek Shale with difficulty. Where recognizable as a separate unit, the Grassy Creek Shale is equivalent to the Morgan Trail, Camp Run, and lower Clegg Creek Members, which crop out to the east (Figure 3-13).

The Saverton Shale consists of bluish to greenish-gray, silty shale that is identified principally in western Illinois, where it is as thick as 37 m. This unit was named for the town of the same name in Ralls County, Missouri. Thin arenaceous and calcareous beds are present; ultimately, the shaly units grade upward into calcareous siltstone. In eastern and southern Illinois, the Saverton and Hannibal Shales are indistinguishable and are mapped as a combined sequence because neither the intervening Louisiana Limestone nor the Horton Creek ("Glen Park") Formation is present.

The Louisiana Limestone (named from exposures near the town in Pike County, Missouri) is light-gray to buff lithographic limestone interstratified with thin shale partings and minor dolostone. Restricted to a narrow east-west belt less than 30 km wide in west-central Illinois, this lenticular deposit does not exceed 12 m throughout its extent except for a very small area in eastern Missouri, where 21 m of thickness is developed (Cluff et al., 1981). Where this interval is absent in Illinois, the underlying Saverton Shale, or the Grassy Creek Shale, is directly overlain by the Hannibal Shale. Also, in west-central Illinois, the lower part of the Hannibal Shale grades laterally into various lithologies that are collectively termed the Horton Creek ("Glen Park") Formation. This restricted interval is typically less than 10 m thick.

The Horton Creek Formation includes the various lithologies previously called the "Glen Park" Formation and was originally defined by Conkin and Conkin (1973) as a member of the Hannibal Shale. This largely carbonate interval is confined to west-central Illinois and locally becomes very shaly and silty so as to be indistinguishable from the overlying and underlying shales. Where the Louisiana Limestone is absent and the Horton Creek is shale-dominated, the Horton Creek is included in the combined Saverton-Hannibal interval.

The type section for the Hannibal Shale is along the Mississippi River near Hannibal, Missouri. The unit is mainly greenish-gray to gray and contains some argillaceous siltstone and silty shale. Minor black shale, especially in Illinois, occurs near the top, but generally the Hannibal is low in organic matter. The Hannibal Shale attains a maximum thickness of 34 m in Illinois but thins slightly in an eastward direction, where differentiation of it from the underlying Saverton or Grassy Creek Shale in the deeper basin and into Indiana is difficult. The Hannibal Shale responds with low to moderate resistivity and gamma-ray readings on geophysical well logs. This unit is conformably overlain by several largely carbonate sequences that carry different stratigraphic names (Chouteau, McCraney Limestones; North Hill Group) depending on the geographic location within the basin.

3.4.4.2.2 Geologic Setting. The New Albany Shale is a widespread unit throughout the Illinois Basin, even though erosion has removed some of the updip parts of the sequence around the edge of the basin. Although the unit thickens toward the axial center of the basin, its greatest thickness of 140 m occurs near the Ohio River in southeastern Illinois and adjacent Kentucky where the top of the shale may be as much as 1,300 m below the surface (Figure 3-16). In much of the remaining central part of the basin, the shale is more than 900 m deep, while its thickness does not exceed 100 m. Into southwestern Illinois, the sequence thins to as little as 15 m.

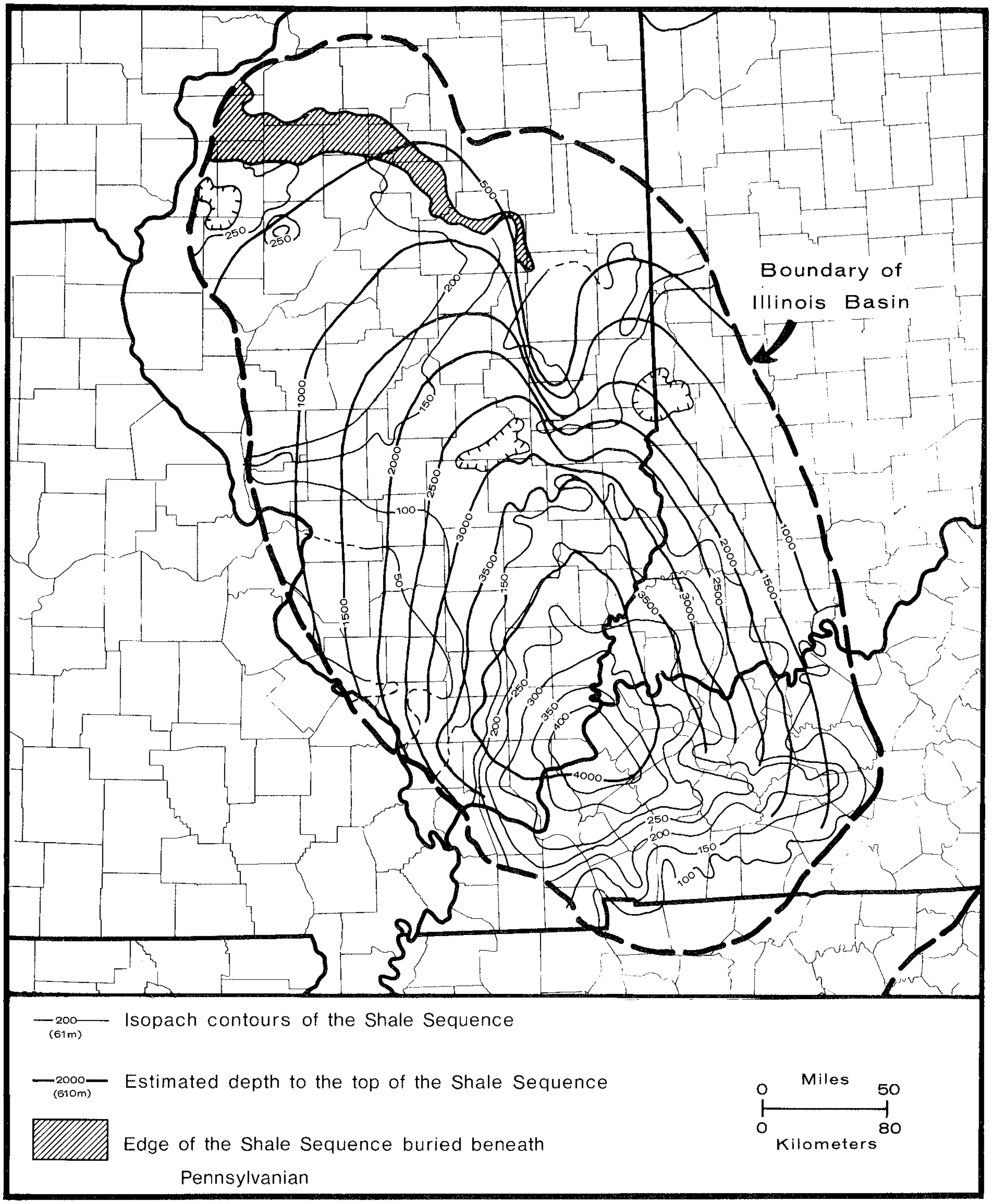

FIGURE 3-16. MAP OF ILLINOIS BASIN, SHOWING THICKNESS OF AND DEPTH TO DEVONIAN-MISSISSIPPIAN NEW ALBANY SHALE (MODIFIED FROM LOMENICK ET AL., 1983). THICKNESS DATA (NARROW CONTOUR LINES) AND DEPTH DATA (WIDE CONTOUR LINES) ARE GIVEN IN FEET. DIAGONAL LINES IN NORTH SHOW AREA WHERE ERODED EDGE OF NEW ALBANY SHALE IS BURIED BENEATH PENNSYLVANIAN STRATA

There is, however, an additional area to the northwest in west-central Illinois and adjacent Iowa, where the New Albany Shale becomes thicker; Bergstrom et al. (1980) designated this secondary area as the "western depocenter." Previous workers have described it as the Petersburg Basin. In this area, the New Albany Shale ranges from 30 to 90 m in thickness and consists mainly of the light- to dark-gray shale intervals that are not especially rich in organic matter (Figure 3-14). Also in this area the top of the shale sequence lies generally within 300 to 600 m of the surface. Where the shale is as thick as 60 m, it may be as deep as 450 m. The northeast-trending belt containing these conditions extends across a nine-county area in northwest-central Illinois.

In the Indiana portion of the basin, the New Albany Shale rarely exceeds 50 m in thickness, even though it lies at moderate depth throughout an extensive area. Between 60 and 75 m of shale is, however, present at depths between 750 and 900 m in a south- to southeast-trending belt that extends through six counties in southwestern Indiana and passes into adjacent Kentucky.

3.4.4.2.3 Mineralogy and Rock Properties. Mineralogical investigations of the black-shale units in the New Albany Shale from Indiana indicate that quartz is the dominant mineral but that illite (2M polymorph) and chlorite, in a weight ratio of approximately 2:1, are also abundant (Patton, 1977). Other minerals identified are pyrite, marcasite, mixed-layer clays, kaolinite, dolomite, calcite, and feldspar. The iron sulfide minerals represent the dominant species among the accessory minerals. In fact, pyrite and marcasite make up certain thin beds or laminae; they also occur as small disseminated grains, irregular nodules, and intergranular cement (Patton, 1977). The greenish-gray shale units are similar mineralogically, except that their content of mixed-layer clay minerals is greater.

Harvey et al. (1977), however, report that samples taken from cores recovered in Sangamon County, Illinois, and Christian County, Kentucky, are richer in illite than in quartz. Other minerals identified in this petrologic study include calcite, dolomite, pyrite, chlorite, and feldspar. No kaolinite was reported from these core samples.

X-ray diffraction studies of shale samples from the cores recovered from EGSP boreholes in Sullivan County, Indiana, Effingham County, Illinois, and Christian County, Kentucky, also revealed that illite is the dominant mineral, although quartz also is abundant (Kalyoncu et al., 1979a, 1979b, 1979c). Pyrite and calcite also were found in all samples; nahcolite, shortite, siderite, kaolinite, feldspar, and gypsum also were identified, but none of these minerals occurred in all the samples.

Some rock-property data also have been reported from New Albany Shale intervals, as determined from five EGSP coreholes in the Illinois Basin (Clark and Sullivan Counties, Indiana; Effingham County, Illinois; Christian County, Kentucky). The average (as taken over a vertical interval of core) bulk density ranges from 2.36 to 2.53 g/cm^2, with a median value of 2.47 g/cm^2. Porosity also was measured and varied from a low value of 0.95 percent by volume to a high value of 4.64 percent; the median value for intervals tested was 2.67 percent (Kalyoncu et al., 1979a, 19679b, 1979c).

No subsurface storage caverns have been constructed within the New Albany Shale; neither are there any rock mechanical data available for this shale sequence in the published literature. Based on results obtained on comparable Devonian shales (Chagrin Shale) from Ohio in the Appalachian Basin (Dames and Moore, 1978), uniaxial compressive strength for these shales is not likely to exceed 13.8 MPa.

3.4.4.2.4 Hydrology. As noted in the previous section, porosity in unfractured shale units of the New Albany Shale is low, averaging less than 3 percent by volume. Although no values were reported, permeability (expressed as hydraulic conductivity) is also low, inasmuch as a sample from the Sullivan County, Indiana, core measured below the detectable limits of the testing procedure. Conversely, natural gas has been commercially produced for several decades from fractured shale intervals in several fields in Indiana (Bassett et al., 1978) and Kentucky. Salt water also has been produced with this gas. It is clear, therefore, that fluids can move effectively through these shales where natural fracturing has formed secondary porosity and permeability.

Some ground-water aquifers within the overlying Mississippian sequence furnish potable supplies for primarily local use. Lower Mississippian strata directly overlying the New Albany Shale are characterized, however, by low permeability and therefore do not represent valuable ground-water sources. Bedrock units older than the New Albany Shale locally yield ground water of acceptable quality, except that these cases are confined to areas where these units lie at shallow depths, namely around the perimeter of the Illinois Basin or along the uplifted La Salle Anticline within the basin.

None of the shale intervals in the New Albany Shale serves as an aquifer capable of yielding fresh ground water. Undoubtedly there are other localities where naturally fractured gas-bearing zones ultimately may be discovered; even there, the associated formation fluids are expected to be exclusively saline.

3.4.4.2.5 Mineral Resources. The New Albany Shale is, of course, one of the principal stratigraphic sequences being currently investigated for its natural-gas potential under the federal government's EGSP. Historical evidence supporting this current interest includes the following: deeper petroleum boreholes commonly report gas shows across this interval in each of the states embraced by the Illinois Basin; and some 10 fields in Harrison County, Indiana, in the extreme south-central part of the state have been commercially productive from fractured shale intervals in the past (Bassett et al., 1978). Although these fields were small, were developed with few wells per field, and flowed at low daily production rates, they were characterized by productive histories of more than five decades in many cases. Most of these fields have been depleted and do not produce gas at present; one field (Laconia) has been converted into a gas-storage facility.

Work by Bassett et al. (1978) showed that the gas fields developed within the New Albany Shale were productive primarily from zones in the upper part (Grassy Creek Shale) and directly above the base (Blocher Shale). Studies under the EGSP have shown that the New Albany Shale is generally less thermally mature than correlative black shales in the

Appalachian Basin, yields lower volumes of natural gas on outgassing tests, and has a lower overall resource potential than the shales of the Appalachian and Michigan Basins.

Those shale zones believed to be the most promising for natural gas are characterized by black coloration and higher natural radioactivity, as indicated by higher responses on gamma-ray logs. A 45-county area in southeastern Illinois, northwestern Kentucky, and southwestern Indiana, or where such black shales having higher radioactivity are thickest, seems to offer the most promise from a gas-resource standpoint (U.S. Department of Energy, 1981).

Elsewhere within the basin, the gas-resource potential of the Devonian-Mississippian shale sequence now appears to be less promising. Where the New Albany Shale contains appreciable gray to gray-green (low-radioactivity) shale intervals, such as in the Petersburg Basin of northwestern Illinois, the prospect of natural-gas development is probably the lowest.

Other than as a potential gas resource, the New Albany Shale is not likely to have commercial mineral resource application. Although uraniferous, especially in the black shale zones, the grade is considerably below the cutoff applied to uranium recovery from currently commercial deposits. Bergstrom et al. (1980), in analyzing samples from two coreholes, reported average uranium concentrations of 0.0019 and 0.0011 percent. No shale deposits are actively mined for ceramic, brick, aggregate, or cement applications. The New Albany Shale is exposed, however, in various surface quarries where associated carbonate bedrock is being recovered. These shallower mining operations are localized and do not interfere with subsurface applications.

Petroleum, however, is produced from strata both above and below the New Albany Shale. Most of this production is from younger (Carboniferous) sandstones and limestones and is more concentrated in the southeastern half of the basin. Boreholes have obviously been drilled through the shale sequence to test as well as to produce oil from deeper zones; most of these areas lie in the central part of the basin (Bond et al., 1971). There are other areas, such as the northwestern part of the basin, where the density of deeper boreholes is decidedly less. Detailed studies would, however, be required to establish the exact locations of all petroleum boreholes.

Other mineral resources that are recovered by means of subsurface mines within the Illinois Basin include coal of Pennsylvanian age in southern Illinois (Hamilton County), gypsum from Mississippian strata in south-central Indiana (Martin County), and fluorspar from Mississippian carbonates in southeastern Illinois (Hardin County) and adjacent Kentucky (Crittenden County). In all cases, the mining activity occurs at shallow depths, generally within the depth range of 30 to 300 m. The fluorspar district lies in a structurally disturbed part of the basin, where faults and extensive fracturing occur.

More regionally extensive is the surface mining of coal throughout this major coal-producing basin. Large tracts of land in Illinois, Indiana, and Kentucky are currently under mine development or leased for future mining.

Other mineral resources, such as crushed stone, clays, sand and gravel, and cement raw materials, are recovered throughout the basin, but from fairly localized surface quarries. Nine subsurface storage caverns have been developed at seven sites within the Illinois Basin (Cobbs Engineering, 1975). All are within bedrock of either Mississippian or Pennsylvanian age, or units younger (shallower) than the New Albany Shale. These mined caverns range in depth from 70 to 140 m below the land surface and are relatively localized.

3.4.4.3 Michigan Basin Shales

3.4.4.3.1 Stratigraphy. The thick sequence of Upper Devonian-Lower Mississippian clastic strata in the Michigan Basin is dominated by shales and includes, in ascending order, the following clay-rich stratigraphic units: Antrim Shale, Ellsworth Shale (equivalent to the Antrim and post-Antrim Shales), Bedford Shale, Sunbury Shale, and Coldwater Shale (Figure 3-17). Also included within the Lower Mississippian portion is a well-known petroleum-producing unit, the Berea Sandstone. This entire sequence lies directly on Upper Devonian carbonates. With the principal exception of the Coldwater Shale of somewhat younger Mississippian age, all the shale formations are partly or wholly equivalent to the New Albany Shale Group from the Illinois Basin and to several black shales within the Appalachian Basin.

Even though the Coldwater Shale is a separate and younger stratigraphic unit, it is considered here as part of this shale sequence of predominantly Devonian age. Inasmuch as the depositional conditions that produced complex facies relationships in these Devonian units persisted into Coldwater time and these shales share other features in common, they are discussed collectively here. As such, this shale-rich clastic sequence ranges in thickness from 150 to 500 m, depending on the geographic position within the basin.

The Antrim Shale, named originally for exposures in Antrim County, Michigan, is typically carbonaceous, brittle, and thin bedded. Coloration ranges from dark gray through brown to black, although some lighter gray units occur in the lower part. Abundant pyrite-marcasite, organic matter, and fetid-bituminous-calcareous concretions attest to the strongly euxenic depositional environment during Antrim time.

Varying from 35 to 175 m in thickness, the Antrim Shale displays a characteristically high natural radioactivity, as shown in its responses on gamma-ray logs (Figure 3-17). This property has led to the confident identification of this unit within the subsurface and separation of it from the less radioactive underlying carbonates (Traverse Group) and overlying (Bedford or Ellsworth) shales (Lilienthal, 1978; Ells, 1979).

Overlying the Antrim Shale, and partially equivalent to it within the western part of the basin, is the Ellsworth Shale. The green, gray, and green-gray shales of this formation correlate with the Bedford-Sunbury interval, which overlies the Antrim Shale in the eastern half of the basin. Toward the west and southwest, the Ellsworth Shale becomes more silty and includes discrete layers of siltstone, limestone, and dolostone.

Based upon responses to gamma-ray logging, the conventional practice is to place the basal contact of the Ellsworth Shale below the lowest, less radioactive shale where it is underlain by the more radioactive,

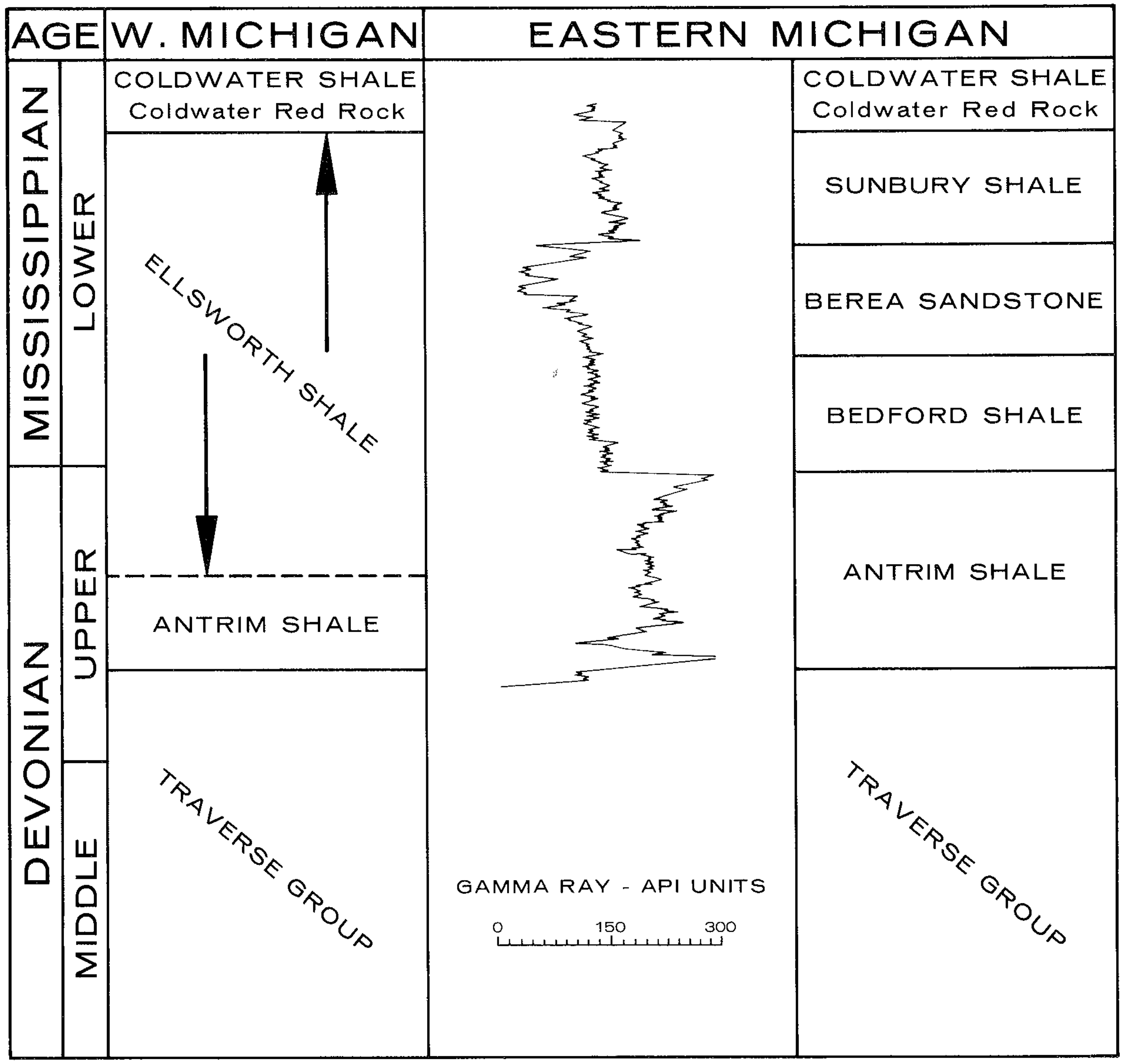

FIGURE 3-17. CHART SHOWING STRATIGRAPHIC RELATIONSHIP WITHIN DEVONIAN-MISSISSIPPIAN SHALE SEQUENCE BETWEEN EASTERN AND WESTERN PARTS OF MICHIGAN BASIN. ALSO SHOWN IS GAMMA-RAY BOREHOLE-LOG RESPONSE FOR SHALE SEQUENCE IN SANILAC COUNTY IN EASTERN MICHIGAN (MODIFIED FROM ELLS, 1979)

dark-brown to black units of the Antrim Shale (Figure 3-18). Exact stratigraphic relationships between the Antrim and Ellsworth Shales have been interpreted differently by various workers (Tarbell, 1941; Lilienthal, 1978; Ells, 1979). Most agree, however, with Cohee et al. (1951) that the transition between the two units occurs along a north-south line that passes through the center of the basin.

The top of the Ellsworth Shale also can be positioned with certainty throughout most of its extent because the overlying Coldwater Shale is generally marked by a distinctive basal red carbonate unit informally called the "Coldwater red rock." Thus defined, the Ellsworth Shale, so named from exposures in a quarry near Ellsworth in Antrim County, Michigan, ranges in thickness from 75 to 200 m throughout its subsurface extent.

To the east of the Antrim-Ellsworth transition zone, three formations--the Bedford Shale, Berea Sandstone, and Sunbury Shale--lie between the Antrim and Coldwater Shales. The total maximum thickness of this interval is approximately 125 m; this development occurs along the eastern margin of Michigan.

The Bedford Shale, named for outcrops near Bedford in Cuyahoga County of northern Ohio, consists generally of silty gray shale but also contains some zones of black shale as well as thin sandstone layers. Because the Bedford interval has a more pronounced gamma-ray response than the overlying Berea Sandstone, but a decidedly lower reading than the underlying Antrim Shale (Figure 3-17), this unit can be separated rather readily in the subsurface. Westward, the Bedford Shale becomes thinner as it merges into the Ellsworth Shale (Cohee et al., 1951).

Gradationally above the Bedford Shale is the Berea Sandstone, which was named from exposures near Berea in Cuyahoga County, Ohio. Although the Berea Sandstone contains some gray shale, it is composed principally of light-gray, fine-grained sandstones. In contrast to its lower contact, the Berea's contact with the overlying Sunbury Shale is sharp and easily recognized because of the contrasting lithologies and highly different signatures on gamma-ray logs. The Berea Sandstone, in a westward direction, becomes dolomitic, thins, and also grades laterally into the

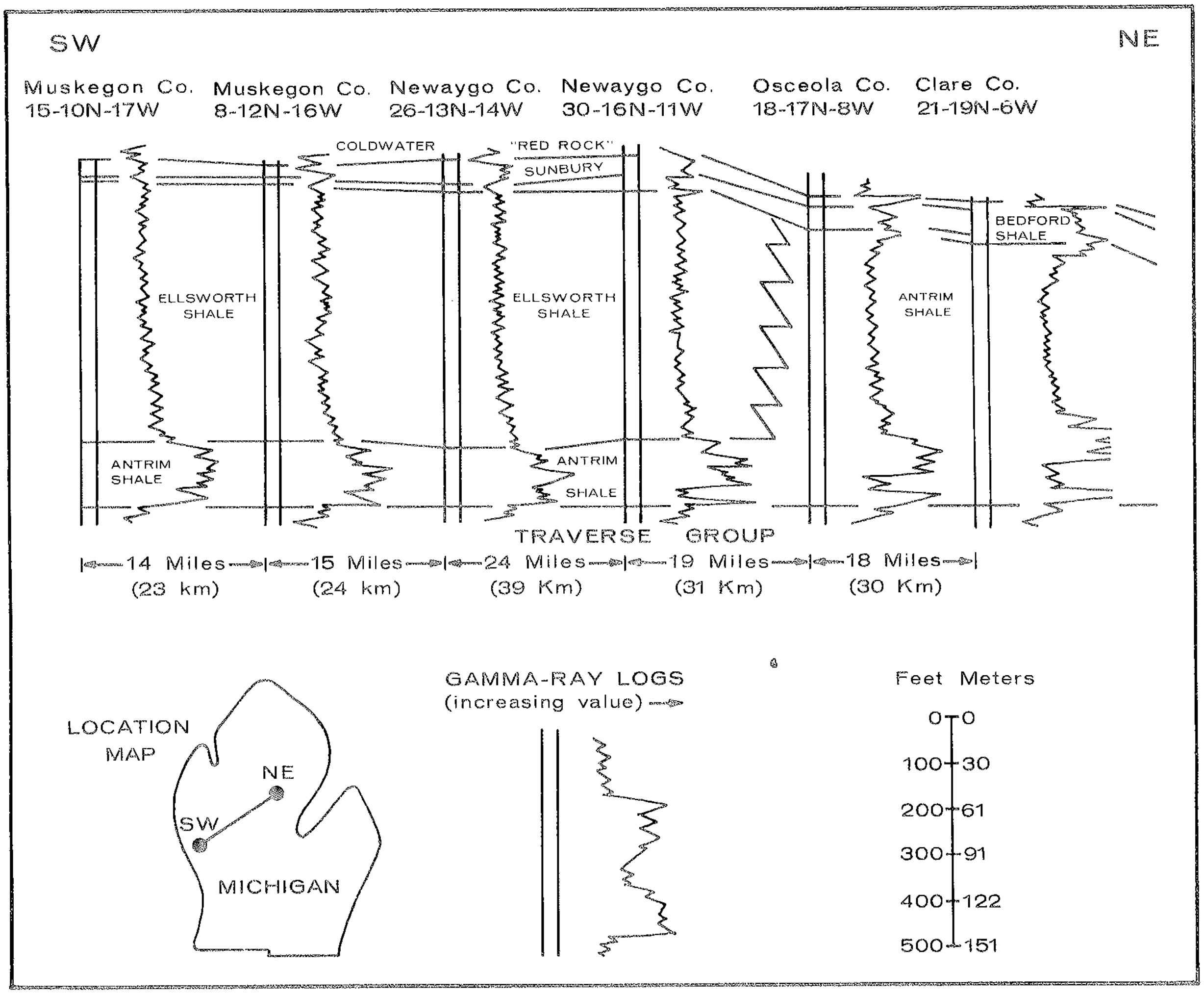

FIGURE 3-18. SOUTHWEST-NORTHEAST STRATIGRAPHIC CROSS SECTION, BASED UPON BOREHOLE LOGS, SHOWING RELATIONSHIPS BETWEEN DEVONIAN-MISSISSIPPIAN SHALE SEQUENCE AND ADJACENT STRATA WITHIN CENTRAL PART OF MICHIGAN BASIN (MODIFIED FROM ELLS, 1979)

Ellsworth Shale. Several important petroleum fields in eastern Michigan produce from this zone (Lilienthal, 1978). The Bedford-Berea sequence, although predominantly red in color owing to deposition under deltaic conditions, is also well known across northern Ohio and eastward into the northern Appalachian Basin (Pepper et al., 1954).

Lithology most similar to that typical of the Antrim Shale characterizes the Sunbury Shale. This black, bituminous shale formation was named for a small town in Delaware County, Ohio. Although gamma-ray logs show higher values measured across this unit, the overall response is not quite as pronounced as for the Antrim Shale. The Sunbury-Coldwater contact is distinct even where the Sunbury-equivalent interval is represented by the upper Ellsworth Shale owing to the persistent extent of the "Coldwater red rock."

As the youngest argillaceous formation in the Upper Devonian-Lower Mississippian sequence, the Coldwater Shale (named from exposures along the Coldwater River Valley in Michigan) consists mainly of nonblack shales interbedded with several thin carbonate and sandstone layers. Many of these nonshale lithologies are lenticular and discontinuous, yet they account for an appreciable part of the formation in eastern and northeastern Michigan (Figure 3-19). Despite this relationship, there are large areas in central to western Michigan where nearly all of the 150 m of thickness is dominated by shale.

3.4.4.3.2 Geologic Setting. Figure 3-20 shows the depth and thickness relationships expressed by the Coldwater Shale in the Michigan Basin. Within a sizable area throughout the central to western parts, the Coldwater Shale ranges in thickness from 150 to 300 m, and throughout this same area the top of the formation lies from 300 to 550 m below the land surface. Throughout this large region, the Coldwater Shale is primarily shale and thus lacks the silty to sandy zones typical of this formation farther east (Figure 3-19).

Below the Coldwater Shale in this western area, another 150 m of shale within the Ellsworth-Antrim interval is found. Thus, in this part of the basin, a combined thickness of nearly 450 m of shale is present.

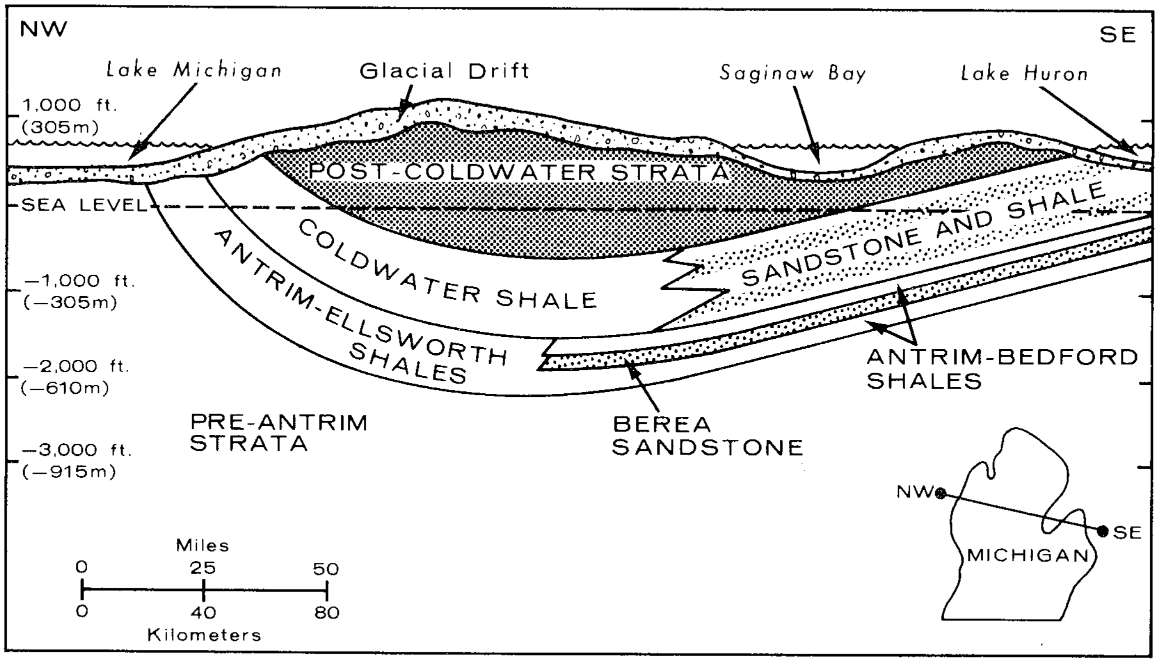

FIGURE 3-19. GENERALIZED NORTHWEST-SOUTHEAST CROSS SECTION SHOWING STRATIGRAPHIC AND LITHOLOGIC RELATIONSHIPS BETWEEN COLDWATER AND ANTRIM-ELLSWORTH SHALE SEQUENCES IN NORTH-CENTRAL PART OF MICHIGAN BASIN (MODIFIED FROM LOMENICK ET AL., 1983)

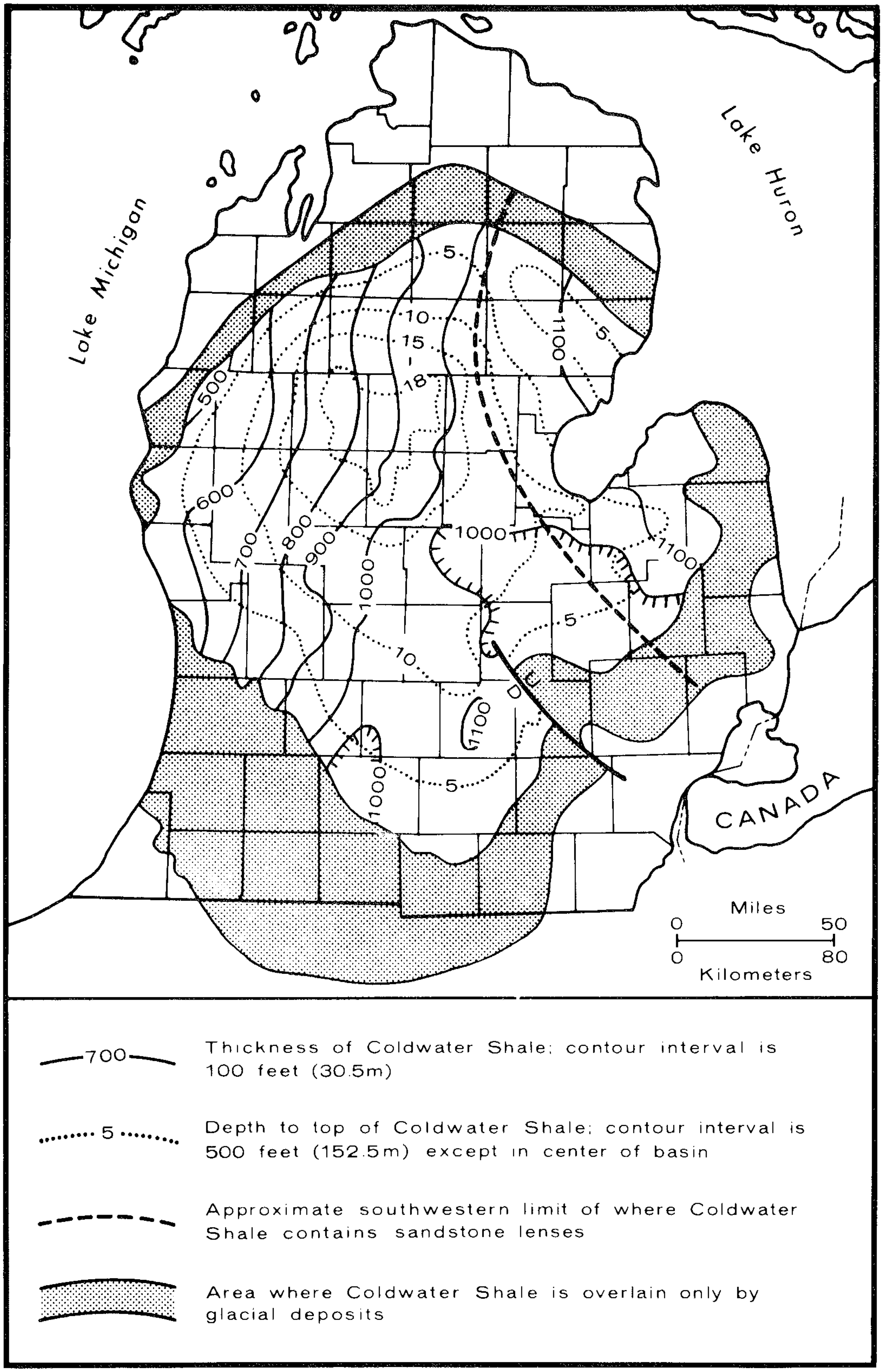

FIGURE 3-20. MAP OF MICHIGAN BASIN SHOWING THICKNESS OF AND DEPTH TO MISSISSIPPIAN COLDWATER SHALE (MODIFIED FROM COHEE ET AL., 1951; MEREWETHER ET AL., 1973)

Furthermore, the green-gray units of the Ellsworth portion of the interval are more significant than the thinner, basal black shales of the Antrim portion.

Although the Ellsworth-Antrim interval underlies most of the Michigan Basin, includes subcrops beneath glacial drift around the basin perimeter, and is shallower than 300 m around the edges of the basin, there is a considerable area where this interval is deeper than 300 m (Figure 3-21), regardless of the character of the younger Coldwater Shale. In the eastern half of the basin, or where the Berea Sandstone is well developed, and where the Bedford Shale contains interbeds of siltstone and sandstone, the total thickness of shale as a distinct lithology decreases to somewhat less than 150 m. Also, the Antrim and Bedford Shales in this area both contain black shales in which interest is high for their possible gas-resource potential. Despite these factors, Lomenick et al. (1983) showed that the Bedford-Antrim interval in the counties near Saginaw Bay ranges up to 140 m in thickness at depths that range between 300 to 675 m. Despite the abundance of black shale zones, this interval is relatively thick at moderate depth.

3.4.4.3.3 Mineralogy and Rock Properties. Samples of the Antrim Shale from several coreholes in eastern Michigan (Sanilac County) have been mineralogically analyzed by x-ray diffraction (Hockingset al., 1979). The principal minerals identified are quartz (50 to 60 percent), illite (20 to 35 percent), and kaolinite (5 to 15 percent). Calcite and/or dolomite were shown to range from 15 percent upward, depending on the number of carbonate interbeds within the shale section analyzed. Pyrite is the most abundant accessory mineral. The Antrim Shale appears unusual among black shales in having a significant content of kaolinite but yet no chlorite. The overlying Bedford Shale contains an even higher percentage of kaolinite in the several samples tested. Comparable mineralogical data for the other shale formations are presently not available in the geologic literature.

Physical property determinations on these same corehole samples (Young, 1978) reveal bulk densities of 2.2 to 2.8 g/cm^3, porosities

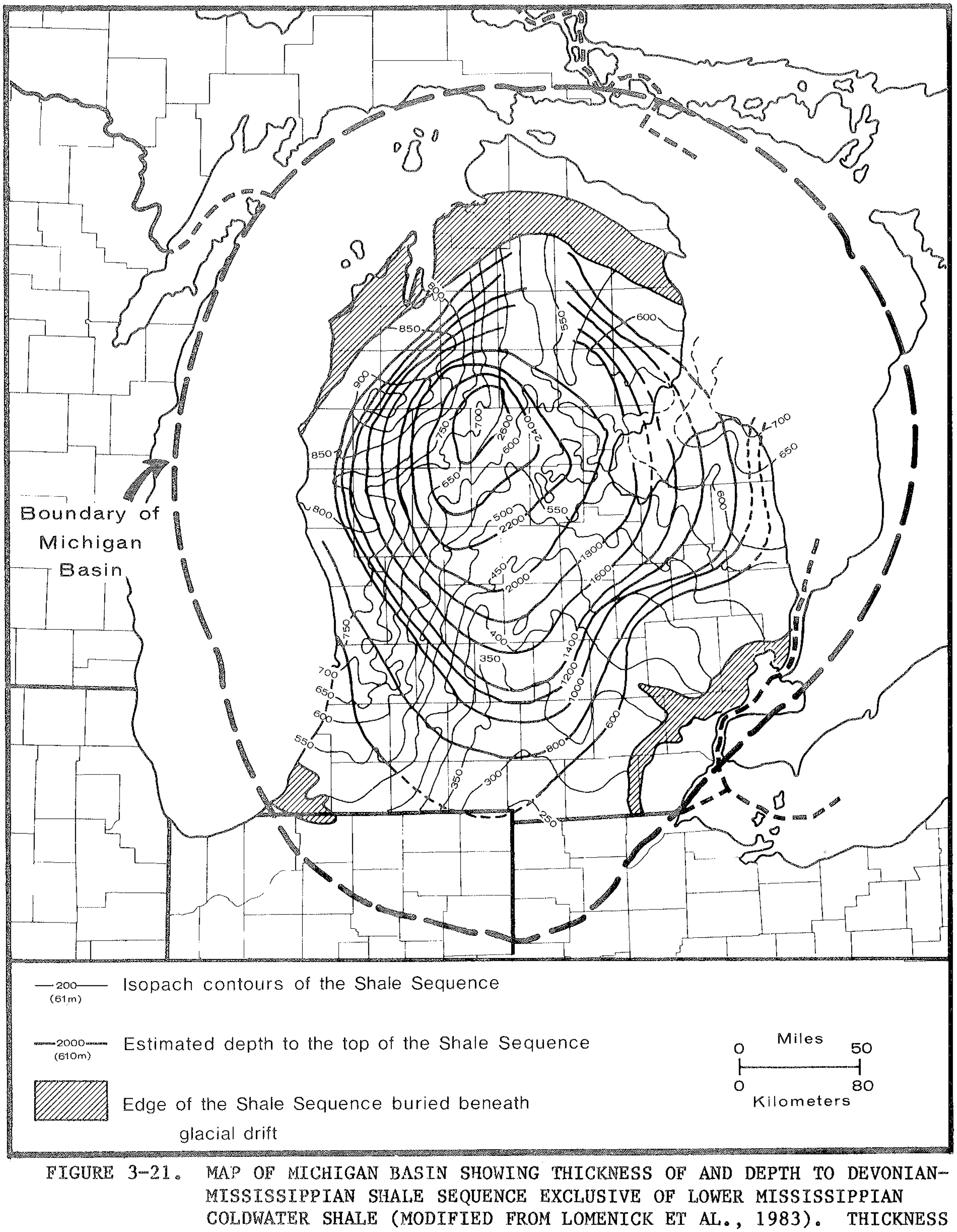

FIGURE 3-21. MAP OF MICHIGAN BASIN SHOWING THICKNESS OF AND DEPTH TO DEVONIAN-MISSISSIPPIAN SHALE SEQUENCE EXCLUSIVE OF LOWER MISSISSIPPIAN COLDWATER SHALE (MODIFIED FROM LOMENICK ET AL., 1983). THICKNESS DATA (NARROW CONTOUR LINES) AND DEPTH DATA (WIDE CONTOUR LINES) ARE GIVEN IN FEET. DIAGONAL LINES IN NORTH AND SOUTH SHOW AREAS WHERE ERODED EDGE OF SHALE UNIT IS BURIED BENEATH GLACIAL DRIFT

ranging from 3 to 10 percent, and permeabilities as low as 0.001 millidarcys but ranging upward to 2.0 millidarcys. The average values of permeability were generally much less than this maximum. Furthermore, permeability measured perpendicular to the stratification in these shales was much less than that measured in a parallel direction.

Various rock mechanical tests were performed on the Antrim Shale by Kim (1978). The principal outcome of this work was to demonstrate that certain standard rock mechanical properties varied according to the organic matter content of the test samples. Rock-strength tests also indicated a pronounced weakness along the stratification.

3.4.4.3.4 Hydrology. Although sandy glacial drift is the principal source of potable ground water throughout the Michigan Basin, several bedrock aquifers are also important sources (Waller and Allen, 1975; Weist, 1978). The most noteworthy of these, with reference to this study, is the Mississippian Marshall Sandstone, which supplies appreciable ground water in the southern to southeastern parts of the basin. The Marshall Sandstone and the more sandstone-rich parts of the Coldwater Shale in the eastern to northeastern parts of the basin are closely associated. Where productive of ground-water supplies, the Marshall Sandstone contains fresh water as deep as 120 m (U.S. Geological Survey, 1968a).

All the bedrock aquifers of importance within the basin contain saline waters at depths that range from as little as 60 m to as much as nearly 300 m. Because the highly saline brines recovered commercially from Middle Devonian strata are so abundant, renewed commercial interest in the future in the deeper saline waters in the Marshall Sandstone is doubtful.

The shale formations may yield small volumes (35 l/min) of water locally, but the quality is generally poor and the extent of such development is limited. The Berea Sandstone, where productive of hydrocarbons, also yields saline water, but this water must be disposed of by reinjection. For all practical purposes, the Upper Devonian-Lower Mississippian shale sequence does not supply any significant amount of usable ground water. There are areas, however, where a thick shale sequence at moderate depths coincides with where the Marshall aquifer supplies large quantities of ground water. Although deep-well disposal of brines and industrial effluents is practiced in Michigan, the facilities involved are localized and/or inject into shallower horizons.

3.4.4.3.5 Mineral Resources. Commercial production of petroleum from units within the Upper Devonian-Lower Mississippian section has taken place since 1925 (Ells, 1978). Despite an active level of exploration drilling in the Michigan Basin for several decades, there are large expanses where the shale sequence is thick and at moderate depth, and where the number of boreholes is low. The Antrim Shale has yielded natural gas from fractured intervals (artificially stimulated also) at five fields in north-central and northwestern Michigan, while the Ellsworth Shale has yielded both natural gas (eleven fields) and crude oil (six fields) in western Michigan. Production from the Ellsworth Shale is from reservoirs of dolostone and sandy, oolitic limestone that are concentrated within the upper 30 m of the formation (Ells, 1978). No production has been recorded from any shale zone within the Ellsworth Shale.

The largest volume of petroleum from the shale sequence is derived from the Berea Sandstone in eastern Michigan, where seven gas fields and nine oil fields have been established (Ells, 1978). These fields, of course, produce gas/oil from a conventionally porous and permeable reservoir.

Noncommercial amounts of gaseous hydrocarbons are also known to exist in shallow glacial drift where the gas has migrated from the underlying subcrop of either the Antrim or Ellsworth Shale. Minor shows also have been reported from scattered localities in the Coldwater Shale (Lilienthal, 1978). The Antrim Shale, furthermore, is a principal target for unconventional-gas development under the extensive applied research program of the U.S. Department of Energy. Interest in the Antrim Shale is centered on eastern to northeastern Michigan, and specifically on the in situ conversion of that unit's kerogen into gas (Matthews et al., 1978). Here, the dark-brown to black Antrim Shale is rich in organic matter and represents the most favorable lithology for this approach. Elsewhere in the basin, or where the Antrim-Ellsworth-Coldwater Shales are primarily gray to green, the organic matter (kerogen) content is much lower, as is the gas-resource potential.

Although the Antrim Shale is uraniferous, its average content of uranium is only 0.002 percent (Swanson, 1960), which is not especially high compared to other black shales. Unlike the Chattanooga Shale in the southern Appalachian Basin, the Antrim Shale would not be considered a low-grade, potential uranium resource. Both the Antrim and Ellsworth Shales are actively mined in surface quarries for raw materials for the cement and brick industries (Sorenson, 1970).

Mineral resources that are derived from rock units above or below the shale sequence include oil and gas, rock salt, gypsum, natural brines, and coal. These deposits are summarized by Johnson and Gonzales (1978) and Gere (1979). Outside of the oil and gas already discussed, all the conventional petroleum comes from deeper strata, especially several zones within the Silurian-Devonian interval. Likewise, all the salt mined is from either the Silurian Salina Group or the Devonian Detroit River Group; the latter sequence of strata is also the principal source of natural brines.

Pennsylvanian coal is found within the Saginaw Formation in the central part of the basin. At present, there is no commercial production, and in the event of future development, mining activities would probably be localized and confined to site-specific underground operations. Likewise, gypsum currently recovered from the Mississippian Michigan Formation lies at near-surface depths and is produced principally from mines in only adjacent Kent and Iosco Counties.

3.4.4.4 Appalachian Basin Shales

3.4.4.4.1 Stratigraphy. For purposes of this report, the base of the Devonian-Mississippian shale-rich clastic sequence in the Appalachian Basin is placed at the top of the Middle Devonian Onondaga Limestone or equivalent carbonate unit. The top of the sequence is drawn arbitrarily at the base of the oldest coarse-grained clastic unit of Mississippian age. Within the thick northeastern sequence of that unit is the Pocono Formation (or Group); to the northwest, either the Berea, Cussewago, or Corry Sandstone serves as the upper limit, while elsewhere in the basin the Price Sandstone or equivalent unit forms the bounding formation. In progressing northwestward toward the Michigan Basin, stratigraphic conditions dictate a slight modification. Above the Berea Sandstone along this trend the Sunbury Shale is present, and within the Michigan Basin both the Sunbury and Coldwater Shales occur in that position. Thus, west of the main part of the northern Appalachian Basin, the Berea Sandstone is included within the clastic sequence. Within the Michigan Basin, the Marshall Sandstone, a well-known aquifer, represents the capping unit.

Thus defined, the Devonian-Mississippian shale/clastic sequence is a wedge-shaped mass in a rough east-west sense, is moderately thick throughout the basin except where it thins to only a few meters in the southern basin (Figure 3-22), and is much better developed in the north-central and northern parts of the basin. The maximum thickness for the interval is projected to be greater than 3,300 m in eastern Pennsylvania. By contrast, the sequence, where shale-dominated as in Ohio, ranges from 140 m on the west (central Ohio) to more than 1,100 m in the east adjacent to Pennsylvania (Hoover, 1960). As previously noted, part of the sequence here is Middle Devonian in age; collectively, the Middle-Upper Devonian shales constitute a more important component than do the Lower Mississippian units.

Strata within the clastic interval consist of black (carbonaceous) shales, nonblack shales and mudstones, siltstones, and sandstones. Although some rock units are calcareous, and carbonate concretions are developed in several shale intervals, very few significant limestones or dolostones are present. To the east within the Middle Devonian section, several carbonate units are widely developed; the Tully Limestone is the most noteworthy. Above that point, carbonate units are minor compared to the other lithologies. Some coarse-grained sandstones, including red beds along the eastern margin at several intervals and within the Berea Sandstone, are also present.

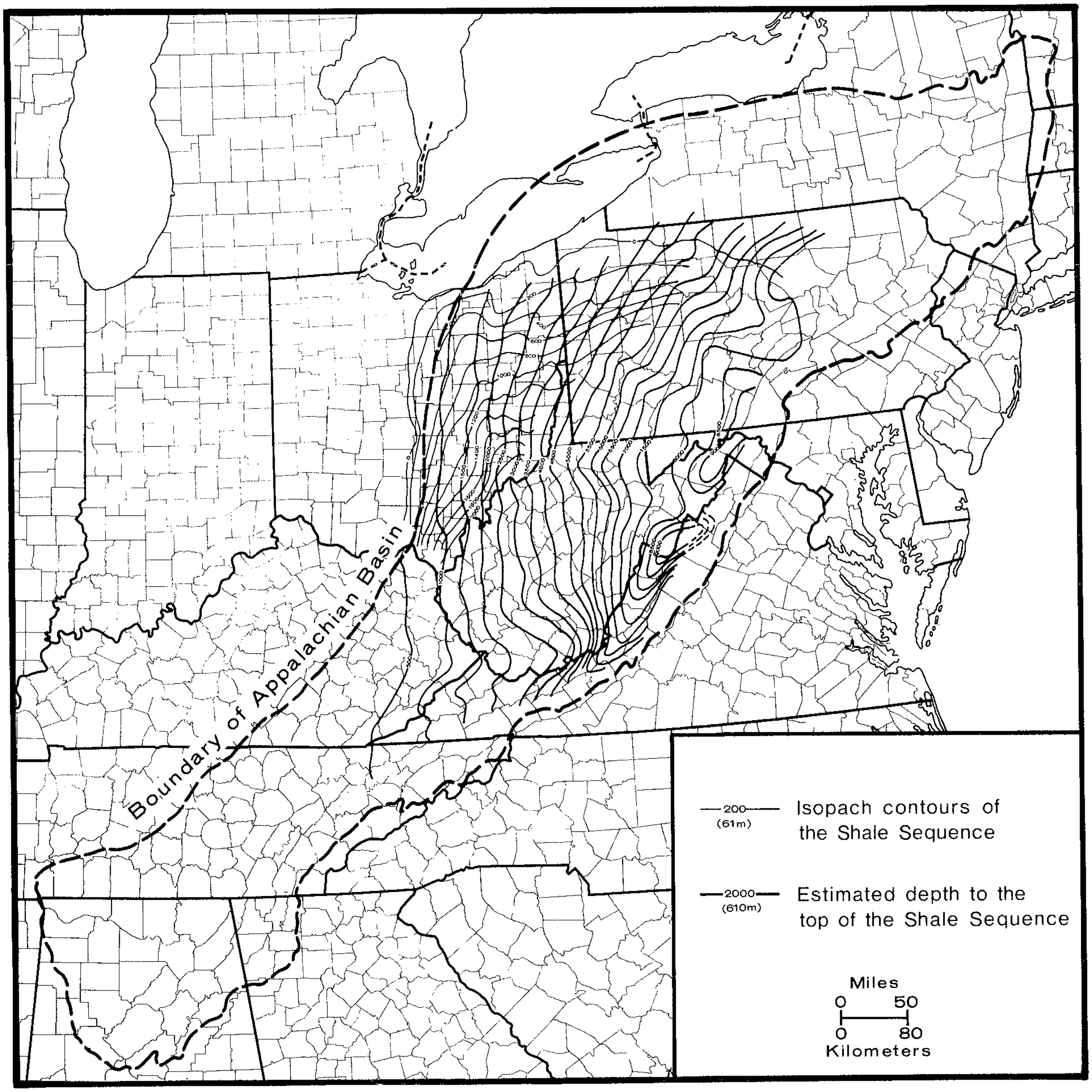

FIGURE 3-22. MAP OF APPALACHIAN BASIN SHOWING THICKNESS OF AND DEPTH TO DEVONIAN-MISSISSIPPIAN SHALE SEQUENCE (MODIFIED FROM LOMENICK ET AL., 1983). THICKNESS DATA (NARROW CONTOUR LINES) AND DEPTH DATA (WIDE CONTOUR LINES) ARE GIVEN IN FEET

Following the approach of Klepser and Hyder (1983) and Lomenick et al. (1983), only certain of the shale-rich intervals in the Appalachian Basin are discussed as opposed to the entire stratigraphic sequence. It would be a prohibitively lengthy undertaking to do otherwise, as there are so many stratigraphic terms and facies changes to consider. In addition to depth and thickness considerations, the following parameters were applied to distinguish among shale units; (1) avoidance of units with a known history of natural gas; (2) avoidance of black or dark-brown shales whose hydrocarbon generation potential is greater; and (3) recognition of the absence or minimal presence of interbedded nonshale lithologies that could act as avenues for fluid movement. In one sense, no identified shale-bearing stratigraphic units in the Devonian-Mississippian sequence of the Appalachian Basin can fully meet these criteria. The units discussed here, however, more closely approximate these conditions, but all will require further study. Well-known shale formations, such as the Marcellus, Moscow, Middlesex, Cleveland, Rhinestreet, and Chattanooga, are either thin or above or below the moderate depth range where thickness exceeds 75 m. These formations furthermore commonly contain interbedded nonshale rock types, or consist mainly of black shale known to be productive of and/or highly prospective for natural gas.

Lomenick et al. (1983) presented detailed information on nine shale formations or larger stratigraphic intervals rich in shale. From oldest to youngest, these units are the (1) Hamilton Group, (2) Millboro Shale, (3) Lower Olentangy Shale, (4) Genessee Group, (5) Sonyea Group, (6) West Falla Group, (7) Upper Olentangy Shale, (8) Huron Shale, and (9) Chagrin Shale. The following data and conclusions are summarized from Lomenick et al. (1983).

3.4.4.4.2 Geologic Setting. The four sequences identified as groups (Hamilton, Genessee, Sonyea, West Falls) contain one or more shale units each. They are all thickest within central New York, but thicknesses vary east and west of that area. Each group also exhibits some degree of vertical and lateral lithologic variation. More detailed data on thicknesses and depths of the shale-rich intervals need to be acquired.

Some general comments, however, are possible. The Hamilton Group generally lies below 900 m where it or a single formation within it contains more than 75 m of shale. Both the Genessee and Sonyea Groups are thick below about 700 m; moreover, it is not clear whether a single shale-rich interval exceeds 75 m where the units occur at moderate depth. The Cashaqua Shale (named from exposures along the creek of the same name in Livingston County, New York), however, may be as thick as 150 m within west-central New York (Sutton, 1960). The West Falls Group contains the Rhinestreet Shale and is generally shallow where its shale zones are collectively thick.

Although the Millboro Shale is up to 450 m along its eastern extent, it is involved in the fold belt of the Central Appalachians throughout Pennsylvania, Maryland, West Virginia, and Virginia. Westward, the unit thins and becomes deeply buried. In West Virginia and western Pennsylvania, the shale may exceed 900 m in depth. In this area production of natural gas from the Ohio Shale is moreover significant.

The Lower Olentangy Shale is generally thin (less than 50 m) where it is at moderate depth. Where stratigraphic equivalents are thick in western Pennsylvania, the sequence is deeply buried. Also showing pronounced thickness changes over its extent is the Chagrin Shale, which, though up to 350 m thick in northeastern Ohio, is shallow throughout its trend from northern to east-central Ohio. The Upper Olentangy Shale and equivalent strata (Figure 3-23) are more than 200 m thick throughout a sizable region in eastern Ohio and west-central Pennsylvania. These shale-rich strata occur at moderate depth for part of this trend. There is also less black shale in this overall interval, silty interbeds are absent, and several dark-gray shale intervals are present (Figure 2-24) above a basal black shale rich in organic carbon and with a high gamma-ray-log response (Majchszak, 1978; Schwiettering, 1979). Eastward into Pennsylvania this interval becomes deeply buried. In southeastern Ohio, the Upper Olentangy interval is present in an area where shale gas from the overlying Ohio Shale is widely recovered from several currently productive fields.

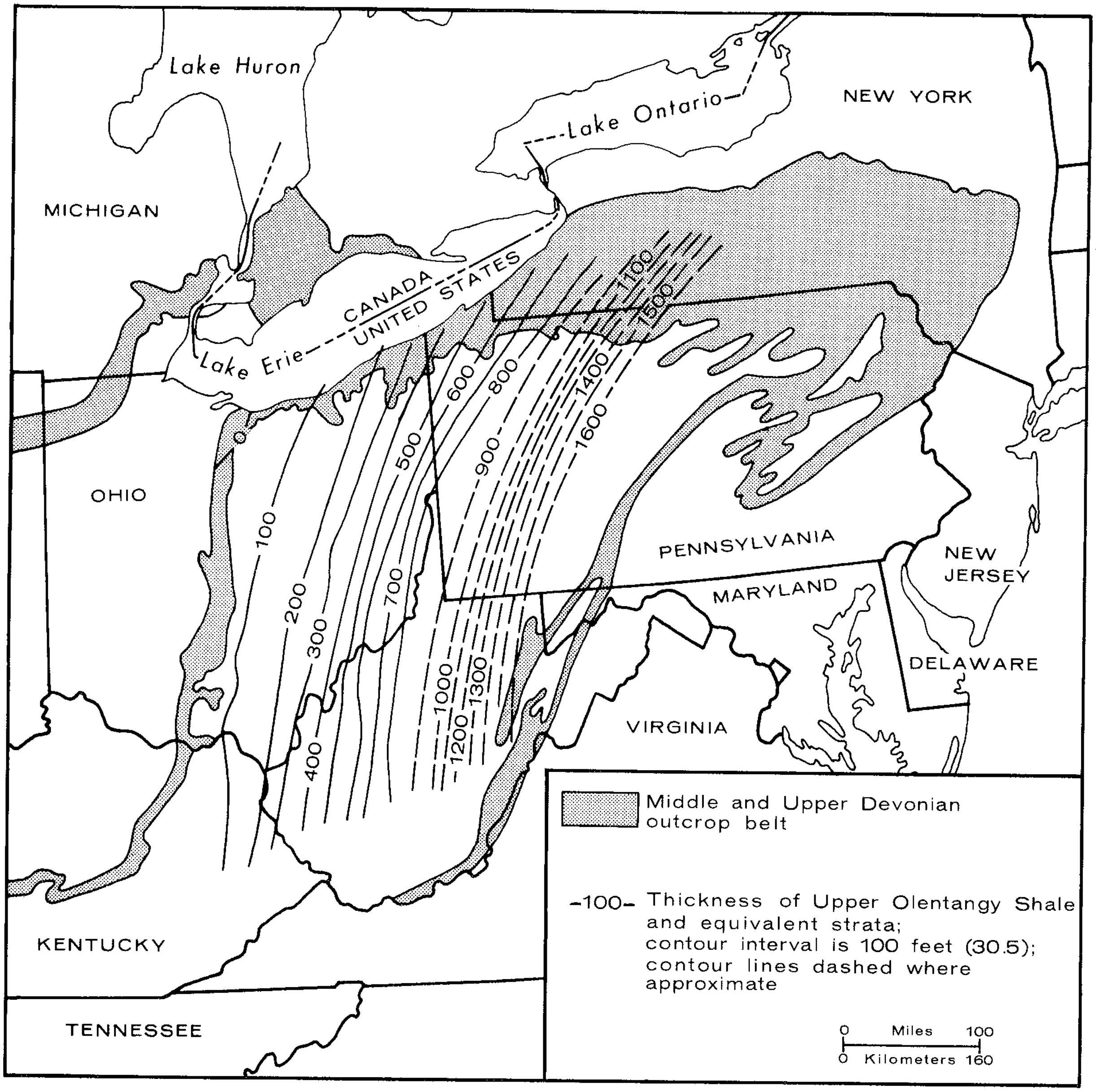

FIGURE 3-23. ISOPACH MAP OF UPPER OLENTANGY SHALE AND EQUIVALENT STRATA IN NORTHERN APPALACHIAN BASIN (MODIFIED FROM SCHWIETERING, 1979)

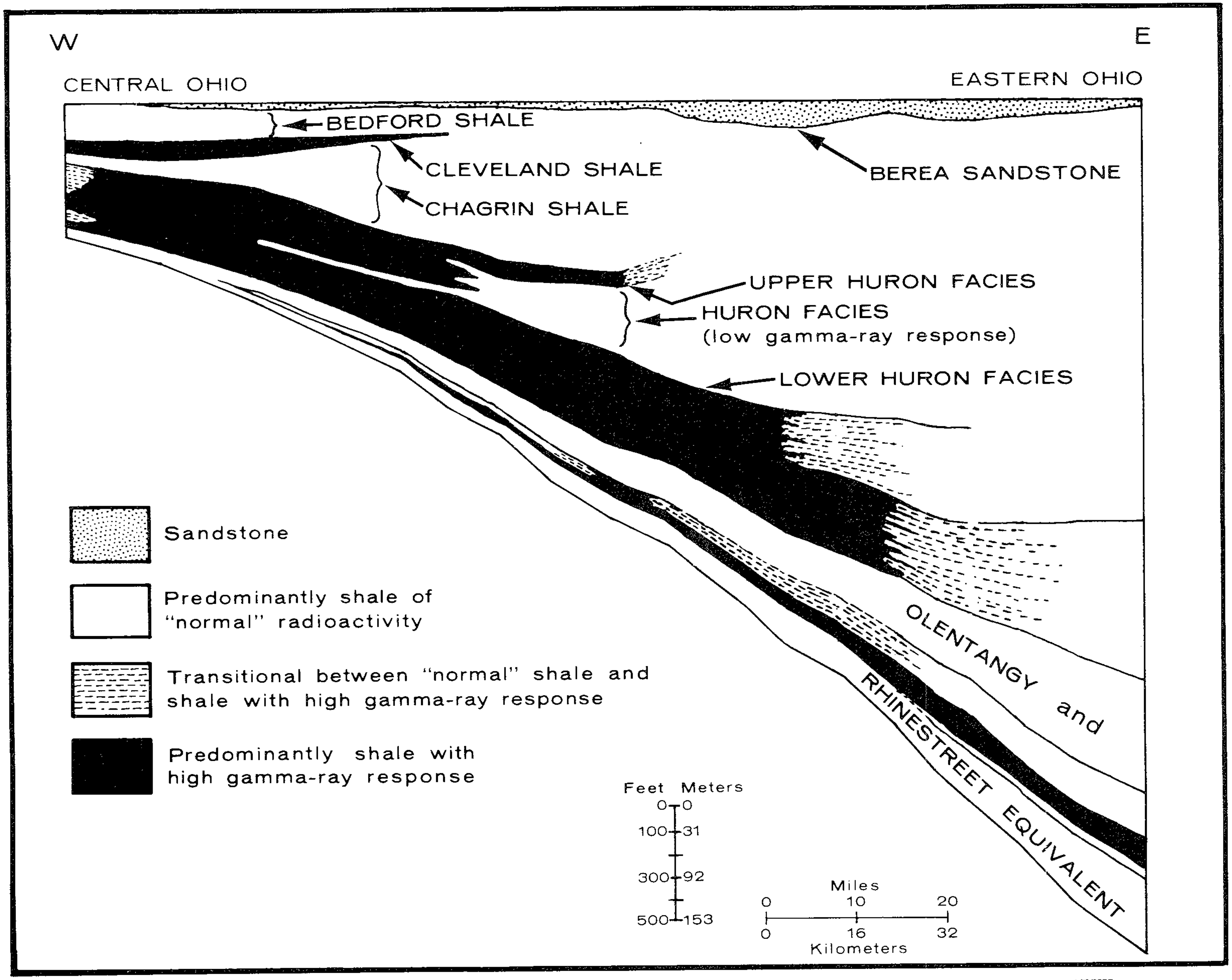

FIGURE 3-24. WEST-EAST STRATIGRAPHIC CROSS SECTION SHOWING RELATIONSHIP BETWEEN SHALES WITH HIGH GAMMA-RAY RESPONSES ("RADIOACTIVE" FACIES) AND OTHER LITHOLOGIES OF UPPER DEVONIAN-LOWER MISSISSIPPIAN IN EASTERN OHIO (MODIFIED FROM MAJCHSZAK, 1978)

The Huron Shale, which forms the basal unit of the Ohio Shale, averages only about 125 m of development in central Ohio. Eastward and southeastward it eventually thickens, but it becomes deeply buried in the southwest Pennsylvania-West Virginia area. As shown in Figure 3-24, the Huron Shale is divisible basically into two different "facies," one of which is black, gas productive, and more responsive on gamma-ray logs owing to a higher natural radioactive background, and a second which is dark gray to gray, less prone to contain gas, and lower in its radioactivity. Majchszak (1978), as well as other researchers such as Martin and Nuckols (1976), Piotrowski et al. (1978), and Van Tyne and Peterson (1978), utilized the characteristic gamma-ray responses to establish an improved correlation framework for several black shale sequences throughout the northern basin. Of interest is the less radioactive zone between the lower and upper facies (Figure 3-24). It is represented by gray shales that are at moderate depth along a trend in eastern Ohio and western Pennsylvania. Some of this interval, however, may be deep, as the depth to the top varies between 600 and 1,000 m. The Huron Shale is also a significant gas-producing zone in southeastern Ohio, adjacent West Virginia, and eastern Kentucky.

Additional data acquired under the EGSP program may provide further definition of the depth, thickness, gas content, and other physical parameters of the Upper Olentangy and Huron Shales, as well as about individual shale intervals within the other seven stratigraphic units.

3.4.4.4.3 Mineralogy and Rock Properties. Data on these aspects are moderately limited, but those available and reported here have been drawn exclusively from various publications released through the EGSP program. Among the principal sources for these data is a series of oriented cores taken at various localities throughout the basin and from several stratigraphic intervals.

Mineralogical investigations using a standard array of analytical methods have shown that (1) the clay-sized fraction is dominant; (2) illite is the most prevalent clay-mineral species, ranging up to 80 percent of the clay fraction in some samples; (3) kaolinite is a minor constituent except for one core in southwestern West Virginia; (4) other clay-mineral species are chlorite and mixed-layer varieties; (5) quartz and pyrite are present in all samples and the latter may be abundant in several intervals; and (6) carbonates such as calcite and siderite are present but reveal no regular pattern of distribution, an aspect typical of other low-abundance mineral forms.

Bulk density determined on several representative core samples shows an average value of 2.65 g/cm^3 with very little variance. Average primary porosity is slightly more than 3 percent by volume, but this value does not reflect those zones that have extensive natural fractures developed within them.

Rock mechanical data on Devonian-Mississippian shales from the Appalachian Basin are limited; the one set of analyzed values was derived from very shallow samples obtained at a depth of less than 30 m below the surface from the Chagrin Shale at a locality near Cleveland, Ohio (Dames and Moore, 1978). Intact rock properties show a uniaxial compressive strength of 13.8 MPa and a tensile strength of 0.34 MPa. Other data are reported relative to elastic moduli and triaxial testing, but because of the presence of clay seams in the samples and the very shallow depth, the values can be considered only as highly generalized compared to test data from deeper, more compact rock.

3.4.4.4.4 Hydrology. Although specific data are not especially abundant, it can be observed that below the Berea Sandstone and its coarse-grained equivalents that cap the shale-rich section, very little ground water is available except at greater depths below the shale sequence. At these depths, the formation fluids are saline, and in some areas, such as the upper Ohio River Valley, the deeper brines are purposefully recovered.

Natural fractures are also known to exist within the shale sequence and to be responsible for higher yields of natural gas. This evidence clearly indicates that fluids are capable of movement through certain zones, provided secondary openings are present. However, nothing could be found in the literature about the nature or chemistry of formation fluids (water) recovered along with the gas. It is estimated that while the fluid volumes are probably small, the composition is saline or mineralized.

Near-surface fractures are probably responsible for the small volumes of ground water recovered from shales in West Virginia, as reported by Sinnott and Cushing (1978). The quality of this water is stated to be poor because of high iron content and a high level of hardness.

3.4.4.4.5 Mineral Resources. The only significant mineral resource obtained from the shale-clastic sequence within the Appalachian Basin is natural gas, and the wells are confined to the Devonian portion. The principal production has been from fields in eastern Kentucky, southwestern West Virginia. and eastern Ohio. Smaller fields also have been productive in northeastern Pennsylvania, southcentral to southwestern New York, and western Virginia. Production at low, yet long-term, sustained rates is typical of many shale gas wells; the earliest recovery begin in the early 1800s, and many wells have produced for more than 50 years. Ray (1977) estimated that one-seventh of all the gas-producing wells in this basin are completed in Devonian shales.

The largest concentration of shale gas production is from the Eastern Kentucky or Big Sandy Field. Some 60 percent of this field's more than 84 billion m^3 of gas has come from shale, of which the Upper Devonian Ohio Shale (or Brown Shale) is the most significant producing interval. Within the latter, the lowermost, or D zone, which is equivalent to the Huron Shale, is the single most productive zone (Negus-deWys, 1979).

A number of recent publications have inventoried the extent of shale gas production, the location of historically and currently producing fields, and the producing shale zones. By state, these include (1) Ohio, Janssens and DeWitt (1976); (2) Pennsylvania, Piotrowski et al. (1978); West Virginia, Martin and Nuckols (1976) and Patchen (1977); and (4) New York, Van Tyne, and Peterson (1978).

The natural-gas potential of Devonian shales appears related to organic carbon content, type of organic matter, and degree of thermal maturation (Nance et al., 1979). Another factor that enhances production from any given shale zone is the presence of natural fracture systems.

There is good evidence that the major production in Kentucky and West Virginia is related to fractures induced by movements along basement faults of the Rome Trough (Nuckols, 1978). There is also a correlation between black to dark-brown shales that display high gamma-ray responses and higher natural-gas production.

Studies from the EGSP program have shown that algal-amorphous organic matter having a lower content of herbaceous (plant) matter is more likely to produce gas, that the shales in the Appalachian Basin are more thermally mature than those in the other basins, that a level of catagenesis in the thermal-maturity sequence has been reached, and that thermal-maturity increases with both depth and position within the basin relative to major structural elements (Nance et al., 1979). Considerable interest has been directed to ascertain where natural fracture systems occur in these shales and why they develop, and at improving artificial-stimulation techniques to enhance production where natural fractures are not sufficiently present. Any shale must, therefore, be carefully assessed with regard to its natural-gas potential.

Shales in this basin also are mined locally at the surface. The Chattanooga Shale contains low amounts of uranium, known for years to be characteristic of the unit (Conant and Swanson, 1961). Many factors argue strongly against the ultimate recovery of uranium from this or other similar low-grade shales. There also has been some interest in the oil potential of these shales relative to their treatment by a special (Hytort) process (Engineering and Mining Journal, 1981).

Other mineral resources within the Appalachian Basin in these shales are the widespread deposits of conventional oil and gas, bituminous coal, and, to a lesser degree, salt (including brine) and gypsum. Conventional petroleum is produced from sandstone and carbonate reservoirs that range in age from Cambrian through Pennsylvanian; every state within the central and northern parts of the basin has sizable established production, while Alabama, Tennessee, and Mississippi to the south have some production from strata of similar age. Several spatially associated Devonian and Mississippian units, such as the Oriskany, Maxon, and Berea Sandstones, and the Onondaga Limestone and "Big Lime," are well-known producing zones. Numerous boreholes have penetrated the shale sequence either in search of natural gas within these rocks or for deeper oil and gas in Silurian and Ordovician strata; there is presently no inventory of borehole penetrations in areas of higher well density.

Although coal is mined by both surface and subsurface methods, the coal is stratigraphically shallower than the shale units discussed herein. The potential impacts of leased acreage, subsidence from underground coal mining, methane formed in coal seams as it relates to any penetration through the coal-bearing interval, and disruptions to the hydrologic system caused by mining on subsurface development are unknown and would need to be studied.

Salt is recovered from deeper units of the Silurian Salina Group in south-central New York and northern Ohio; likewise, gypsum is mined from rocks of similar age in western New York and northwestern Ohio. Salt and other minerals also are extracted from brines recovered from Mississippian salaquifers in the general vicinity of Charleston, West Virginia. This production involves units closely aligned to the shale sequence.

In Ohio, Devonian limestones are recovered by means of subsurface mines; one of these, the Barberton Mine was studied by Byerly (1975). Black shales of the shale sequence overlie the minable limestone at this localized facility.

Other mineral resources that are recovered from bedrock units within the Appalachian Basin include dimension stone, zinc ore, barite, phosphate, and glass sand. Deposits of these resources are generally surface-mined; the exception is zinc ore in central and eastern Tennessee.

3.4.5 Other Units

3.4.5.1 Ocoee Supergroup

Connolly and Woodward (1980) presented data on several Precambrian supracrustal sequences that contain thick argillaceous strata. The Ocoee sequence, which contains Z-age rocks, is within the Southwestern Appalachian Foreland, or specifically in the western part of the Blue

Ridge province of Tennessee, Georgia, and Alabama. Although the total thickness can only be estimated, at least 7,600 m of strata is believed to be present in this region. The principal clastic sedimentary lithologies are graywackes and interbedded units of dark-colored argillite. The latter vary appreciably in thickness from unit to unit but are generally rich in sulfide accessory minerals. This thick sequence, which has been subdivided (in ascending order) into the Walden Creek, Snowbird, and Great Smoky Groups, is largely of allochthonous origin in that its current position has been dictated by major thrust faulting (Rodgers, 1970). Recent deep seismic reflection work (Oliver, 1980) has added evidence to the interpretations of Hatcher (1978a) that large-scale faulting displaced this block farther westward than previously suspected.

Hadley (1970) showed that virtually all portions of the Ocoee Supergroup have been metamorphosed from lower greenschist to upper amphibolite facies. The only relatively unmetamorphosed strata are localized in extent and occur in small outcrops near Knoxville, Tennessee, or at the extreme northern end of the sequence's extent. Even here, the exposed argillites display multiple folding, indicative of several stages of deformation.

3.4.5.2 Conasauga Shale

The Conasauga Group is a complexly interfingered sequence of Middle to Upper Cambrian clastic and carbonate strata that crop out throughout the Valley and Ridge province from southwestern Virginia to northwestern Georgia and northern Alabama. The group also extends into Kentucky but is confined to the subsurface northwest of the Cumberland escarpment in Tennessee. Throughout its extent, the Conasauga Group is in conformable contact with the underlying clastics of the Lower to Middle Cambrian Rome Formation and the overlying carbonates of the Cambro-Ordovician Knox Group.

The Conasauga Group exhibits complex lithofacies transitions within its outcrop area, becoming more carbonate-rich in an west-to-east direction. Rodgers (1953) divided the Conasauga Group into three phases within east Tennessee. In his northwestern phase, the Conasauga Group is represented by the lowermost Conasauga Shale and the uppermost Maynardville Limestone formations. The Conasauga Shale consists of thin-bedded shales, mudstones, and siltstones. Carbonate lenses and stringers are locally abundant within the middle section. The Maynardville Limestone is a laminated and ribbon-bedded, partially dolomitized carbonate that contains abundant oolites (Rodgers, 1953). The central phase occurs throughout the middle of the Valley and Ridge province in Tennessee and Virginia. Within this phase, six formations are recognized, from oldest to youngest, the are: Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale, and Maynardville Limestone. Shales and mudstones comprise 40 to 60 percent of the Conasauga Group here; remaining strata are carbonates and siltstones. The shales are gray to maroon and maroon-brown, and vary from massive to laminated. Calcareous siltstone and calcarenite stringers are abundant. The formations within the central phase exhibit complex stratigraphic and lithologic relationships that are summarized by Markello and Read (1981, 1982). The southeastern phase occurs eastward of two regional thrust faults, the Pulaski and Great Smoky faults. Within this phase the Conasauga Group is divisible into three formations, which are, from oldest to youngest, Honaker Dolomite, Nolichucky Shale, and Maynardville Limestone. Only the Nolichucky Shale contains clastic units. Eastward into Tennessee and northeastward into Virginia, the Nolichucky Shale thins to extinction at the eastern extent of the Conasauga Group; the remaining carbonates form the laterally equivalent Elbrook Dolomite.

Maximum thickness for each of the shale formations within the Conasauga Group is: Pumpkin Valley Shale-200 m; Rogersville Shale-120 m; Nolichucky Shale-300 m. These maxima do not, however, occur at the same locality. The Conasauga Shale of the northwestern phase commonly exceeds 300 m in thickness. In numerous areas throughout the Valley and Ridge province, formations of the Conasauga Group are exposed, typically in valley lowlands. Depth information relative to the subsurface extent of these formations is limited. Subsurface evidence near Oak Ridge, Tennessee (deLaguna et al., 1968; Haase, in press; Haase et al., in press) suggests that the top of the Pumpkin Valley Shale is no more than 500 m below the land surface within narrow strips along the hanging walls of major thrust fault slices. In eastern Kentucky, the top of the Conasauga Shale is at a minimum depth of 1100 m (Thomas, 1960).

Little is known in detail about the hydrology of the Conasauga Group. Few data from the Oak Ridge vicinity (deLaguna et al., 1968; Weeren, 1976) suggest that the Pumpkin Valley Shale and the Rogersville Shale exhibit low permeabilities within the subsurface. Sledz and Huff (1981), however, document moderate to high permeabilities and a complex hydrologic behavior for the Pumpkin Valley Shale, Rutledge Limestone, and Rogersville Shale under near-surface conditions. They also illustrate the importance of structural fabric in controlling water movement within these strata.

Oak Ridge National Laboratory has disposed of low-level radioactive liquid wastes by injecting cement grouts containing these wastes into hydraulically-induced fractures within the Pumpkin Valley Shale at depths of 215 to 320 m (deLaguna et al., 1968; Weeren, 1976). This procedure has been used for 20 years and studies thus far indicate that the host shale provides satisfactory isolation (Weeren, 1976).

Short-term, near-surface heater experiments have also been conducted on the Oak Ridge Reservation (Figure 1-1) (Krumhansl, 1979a and b). These experiments, performed in the Rogersville Shale, showed modest thermal-induced expansion of the shale. Heat transport was dominated by conduction, while through-flowing water transported insignificant amounts of heat. A general decrease in permeability was noted over the eight month duration of the tests.

3.4.5.3 Floyd Shale

Originally named from exposures of clastic strata in northwestern Georgia, the Floyd Shale is part of an Upper Mississippian shale-limestone-sandstone sequence that is present in the southwestern Appalachian belt. In particular, the Floyd Shale is recognized throughout the Valley and Ridge province in northwestern Georgia, northeastward into southern Tennessee, and southwestward into northern Alabama. In these areas the unit is involved in complex structures and grades into the Bangor Limestone, Hartselle Sandstone, and other formations (Thomas, 1979). Westward across northern Alabama, the Floyd Shale crosses the East Warrior Platform and dips gently into the Black Warrior Basin in west-central Alabama and northeastern Mississippi. Depending on its exact location, the Floyd Shale overlies either the Tuscumbia Limestone or the Fort Payne Chert, grades into and is eventually overlain by the Parkwood Formation, and thickens (Thomas, 1979). In addition, the lithologic expression of the unit becomes more argillaceous except for the basal part, which contains several limestone beds locally.

Along the Alabama-Mississippi line, the thickness of the Floyd Shale approximates 70 m of shale-rich interval. In the only part of Mississippi where Carboniferous strata are exposed at the surface - Tishomingo County in the far northeast - the stratigraphic terminology applied recognizes several formations composed of sandstone, sandy shales, shale, and limestone (Bicker, 1979). Although Welch (1959) identified the Floyd Shale as a mappable unit in this same general area of Mississippi, Bicker (1979) did not retain that earlier usage. Therefore, the Floyd Shale appears to be restricted to the subsurface of the Black Warrior Basin for purposes of this report. Its occurrence throughout some of that extent is at moderate depth.

Mellen (1976), in briefly describing this unit, pointed out that the same stratigraphic interval in which the Floyd Shale occurs has produced natural gas within the Black Warrior Basin. Although Mellen (1976) discounted the possibility that any uniformly thick Mississippian (this would include the Floyd) or Pennsylvanian shales occur here within the moderate depth range, a more detailed investigation might reveal different circumstances. A more detailed investigation using a larger amount of subsurface data will be needed to establish the actual regional characteristics of this unit.

3.5 REGIONAL SUMMARY

The Eastern Interior region is an extensive area characterized by nearly horizontal to gently dipping Paleozoic bedrock, broad regional structures, and a long history of tectonic stability. The Appalachian, Illinois, and Michigan Basins, which are both structural and depositional in nature, are the principal tectonic features; they are separated by intervening broad uplifts such as the Cincinnati Arch system. With the exception of the eastern margin of the Appalachian Basin - i.e., the Valley and Ridge province and the Kentucky River-Rough Creek-Shawneetown fault zone, which extends westward from the east-central Appalachian Basin through the southern margin of the Illinois Basin - significant zones of structural deformation are rare.

Seismic activity within the region has been minimal. The Michigan Basin has had very little seismicity inside its boundaries or adjacent to it. Although parts of the Appalachian Basin, such as the trend through northern Ohio and west-central New York, have a slightly higher level of earthquake frequency, overall seismicity is essentially low here as well. The Charleston, South Carolina, seismic center, although lying outside the basin proper, might extend its felt area into the southern part if any recurring event of sufficient magnitude were to be generated. Only the New Madrid zone, south and southwest of the Illinois Basin, represents an area of historically significant seismicity lying close to this region.

Within the Eastern Interior region, Paleozoic strata are thickest inside the three basins but also extend across the intervening regional uplifts. Although numerous shales occur throughout the region and throughout the overall stratigraphic column, many are thin or deep. Those shales that can be found over large expanses within the accepted depth and thickness ranges include (1) the Upper Ordovician Maquoketa Group, especially along the eastern margin of the Illinois Basin; (2) the Upper Ordovician Cincinnatian Series and equivalent shales eastward into eastern Ohio and western Pennsylvania; (3) the Upper Devonian - Lower Mississippian New Albany Shale or Group in the northwestern part of the Illinois Basin; (4) the Upper Devonian - Lower Mississippian

Antrim-Ellsworth shale sequence in the western half of the Michigan Basin; (5) the Lower Mississippian Coldwater Shale in the Michigan Basin, especially to the west, where the Marshall Sandstone aquifer is not present; and (6) the Upper Devonian - Lower Mississippian upper Olentangy and Huron Shales, and possibly the Middle Devonian Sonyea Group (Cashaqua Shale), all of which occur in the north-central to northern parts of the Appalachian Basin.

The production and potential production of natural resources - most particularly petroleum, coal, natural gas from shales, and ground water - are significant in the Eastern Interior region. The region has been extensively drilled, oil and gas are produced stratigraphically above and below these shales (and in some cases within shale-bearing intervals), and future petroleum exploration is expected to add to the number of existing boreholes. For any given shale unit, however, there are regions where the level of petroleum exploration has been lower and commercial successes have been fewer than elsewhere. Even in these cases, determining the density of boreholes that penetrated the shale in question, locating old boreholes, and conducting a detailed assessment of the undiscovered hydrocarbon resources are studies that would need to be undertaken.

All coal is mined at depths shallower than any of the deep extensive shale formations; however, large tracts of land leased for future coal mining coincide with areas where the shale units are present. Land availability, as well as assessment of the coal resource value, are resource-related questions that are presently unanswered.

Ground water, although not as widely used by several orders of magnitude in comparison with surface water, is nonetheless a valuable resource at present and can be expected to become even more valuable in the future. Even though bedrock aquifers are not generally the most widely used sources of potable ground water, important exceptions exist. The most notable is the Lower Mississippian Marshall Sandstone in the Michigan Basin. This aquifer lies in close contact to the Coldwater and other shales, especially in the eastern the western half of the basin. The relative role of certain carbonate aquifers in the eastern Illinois Basin and salaquifers in the Mississippian sequence of the Appalachian

Basin are other examples where aquifers may prove important to use of a given shale.

In the Devonian-Mississippian shale sequence and, to a lesser degree, in the other shales, the black shales with a high carbon content are closely associated with the generation of hydrocarbons. Residual methane - or, in the case of the eastern gas shales, commercial amounts of natural gas - may occur. The dark-gray, gray, and gray-blue or green shale zones, which generally are much lower in their content of organic matter, are not closely associated with hydrocarbon production.

Recovery of other mineral resources tends to be localized at surface mines or in a few well-delineated mining districts. Other applications of subsurface space, such as disposal wells and LPG-storage caverns, are relatively few.

Unlike the Devonian-Mississippian sequence, the two Upper Ordovician sequences have a potential for occurrence or discovery of commercial petroleum in associated strata that is somewhat less. Also, these Upper Ordovician units have a highly successful history of construction and operation of LPG storage caverns; this experience clearly shows the low permeability and homogeneous nature of the shales involved in these units.

4. EASTERN MARGIN

4.1 STRUCTURE AND GEOLOGIC FRAMEWORK

As used in this report, the Eastern Margin embraces two major geologic-physiographic divisions, the eastern Appalachian Mountains and the Atlantic Coastal Plain (Figure 2-1). Thus included are the geologic terranes lying east and northeast of the Appalachian Basin, which has been discussed as part of the Eastern Interior province (Chapter 3). Specific belts of the Appalachian mountains (orogen) included are thus the Blue Ridge subregion to the south and the Piedmont, which extends from Alabama to New York. Also included is the northern counterpart of the Piedmont, the New England subregion, as well as the Adirondack Mountains of eastern New York and the adjacent Taconic zone along easternmost New York and western Vermont.

Although the Atlantic Coastal Plain technically contains small extensions into the New York-New England region, its principal extent is from New Jersey southwestward to a transition area in eastern Alabama and western Florida, where its sedimentary units merge laterally into equivalent Cretaceous and Cenozoic strata of the Gulf Coast. The boundary between the Atlantic Coastal Plain and the crystalline Piedmont subregion is more pronounced, as shown by the definitive topographic feature known as the Fall Line.

Superimposed across the Piedmont and Atlantic Coastal Plain, within the subsurface in the latter case, are several isolated, fault-bounded basins that contain thick sequences of Triassic and Jurassic continental strata. These so-called Triassic or Newark basins are elongate, northeast-trending features that collectively extend from northwestern Florida into the Canadian Maritime Provinces. Most, however, are concentrated within the Piedmont subregion from North Carolina to Connecticut (Figure 4-1).

For the purposes of this report, several of these geologic provinces or subregions will not be discussed because they lack any argillaceous units that fall within the range of characteristics cited in chapter one of this report.

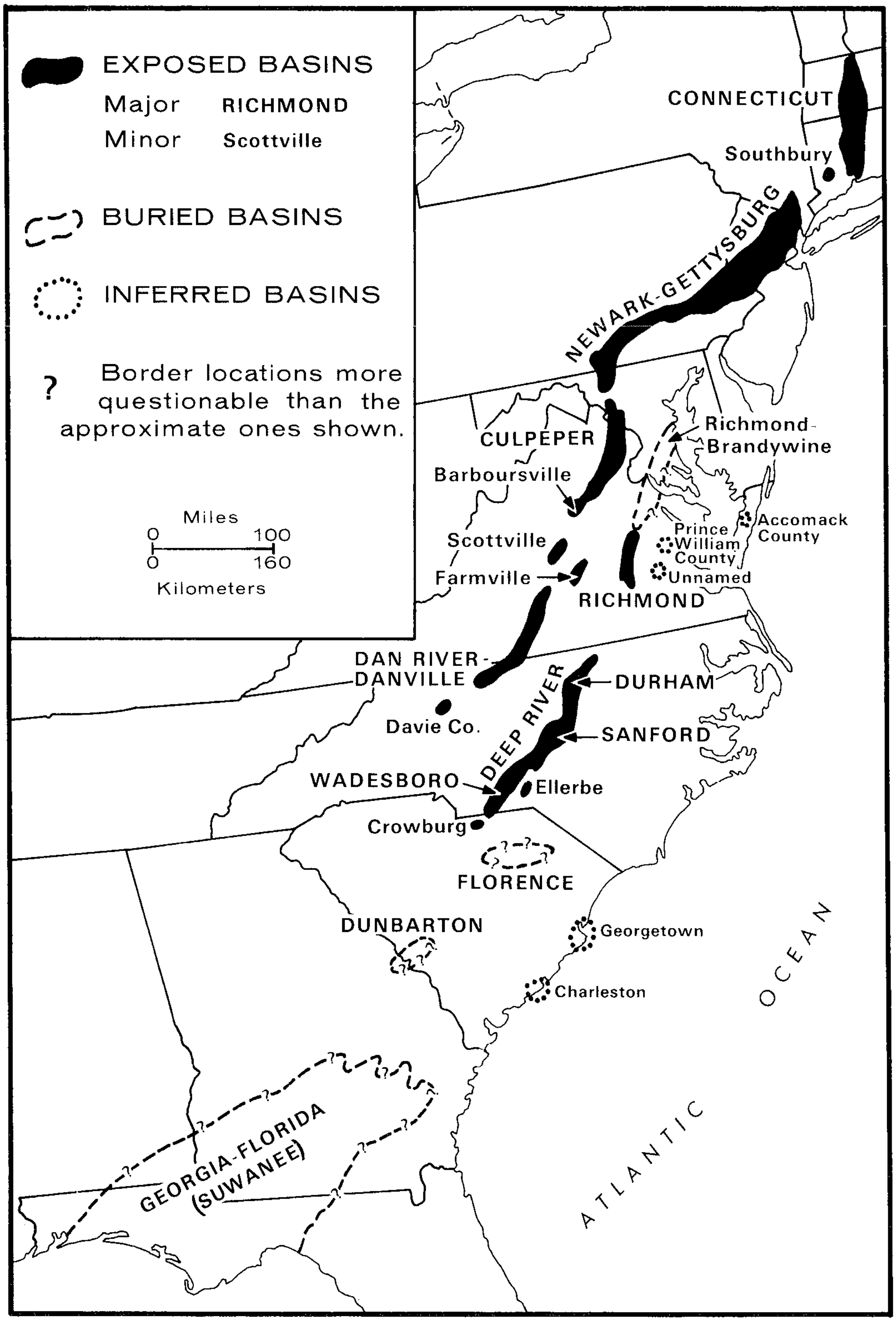

FIGURE 4-1. MAP OF EASTERN MARGIN SHOWING LOCATIONS AND NAMES OF KNOWN EXPOSED AND BURIED TRIASSIC (NEWARK) BASINS AS WELL AS SEVERAL INFERRED BASINS WITHIN SUBSURFACE (MODIFIED FROM RODGERS, 1970; MARINE AND SIPLE, 1974)

Therefore, no further discussion is made of the: (1) metasedimentary-metavolcanic sequence of the Blue Ridge (brief mention of the Ocoee Supergroup is made under the discussion of Other Units in the preceding chapter on the Eastern Interior (Section 3.4.5); (2) igneous-metavolcanic-metamorphic complexes in the Piedmont, New England, and Adirondack Mountains subregions (brief mention of the Carolina Slate belt in the southern Piedmont is made within Section 4.4.3); and (3) the complexly folded, sheared, and thrust-faulted rocks of the Taconic zone. Attention rather is directed at the sedimentary sequences within several Newark basins and beneath the Atlantic Coastal Plain. Also, rather than describe the varied and complicated geology that exists throughout the Eastern margin, especially when several important subdivisions do not contain extensive clay-rich units, the treatment of geologic framework centers primarily upon the Triassic basins and secondarily upon the Coastal Plain, which is discussed mainly in Section 4.4.

The available literature dealing with the regional aspects of the Triassic basins is extensive; only selected references are cited here, which include those by Bain (1973), Dames and Moore (1980), Krynine (1950), Klein (1962, 1969), Sanders (1963), Glaeser (1966), Van Houten (1969, 1977), Randazzo et al. (1970), Cornet et al. (1973), and Weaver (1976).

The Newark basins are elongate structural troughs (and topographic lowlands where subaerially exposed) that parallel the regional tectonic grain from the southeastern United States into the offshore Gulf of Maine and continental shelf of Nova Scotia (Van Houten, 1977). They contain thick sequences of nonmarine clastic sedimentary units with associated basaltic lava flows and diabase dikes. The original sediments from which the present-day fanglomerates, conglomerates, arkosic sandstones, siltstones, and shales arose were deposited under alluvial, fluvial, and lacustrine conditions. Black shales and coal seams, as found for example in the Deep River (Sanford) Basin in North Carolina, were formed, however, in stagnant swampy areas within the central low parts of certain basins.

A significant exception to these thick, largely red-colored continental sequences is afforded by the Canadian basins, where well-developed deposits of rock salt (some as diapiric masses) and associated marine carbonates are present (Jansa and Wade, 1975). Van Houten (1977) argued that the lithologic and sedimentologic contrasts between the U.S. basins to the south and their Canadian counterparts to the north were the result of climatic differences combined with the timing of North Atlantic rifting and the spread of Liassic-age marine waters only into the more northern basins.

As noted, most eastern U.S. basins are exposed at the land surface and flanked by more resistant crystalline rocks of the Piedmont subregion. These exposed basins extend from northern South Carolina (Crowburg Basin) to central Connecticut (Hartford Basin) (Figure 4-1). Other known basins are overlain at depth by Cretaceous and Tertiary strata of the Atlantic Coastal Plain; the best understood of these subsurface basins is the Dunbarton Basin, which lies astride the Georgia-South Carolina state line southeast of Augusta. Several, presumably smaller and more localized, basins also have been inferred from limited borehole penetrations and/or geophysical interpretations.

Most of the exposed basins are characterized by steeply dipping border faults (normal type) on one or both sides; these structures not only were instrumental in the initiation of the oldest and coarsest sediment deposits, but also created the depositional basins themselves. One exception may be the Deep River (Sanford) Basin in North Carolina, which appears to have formed from symmetrical subsidence of the crust; any border faulting was along only the southeastern margin and subsequent to actual basin formation (Reinemund, 1955). Several basins furthermore show evidence that the border faulting and uplift of the adjacent sediment-source areas were intermittent, as seen by the repeated occurrence of fanglomerates within the stratigraphic sequence (Faust, 1975). In those basins where no border fault is evident along one side, the suggestion is strong that the fault is buried at depth by basin-fill strata that simply overlapped the basin's margin. There is also some suggestion that certain border faults are actually broad zones of faulting and that these zones "step down" toward the center of the basin (Dames and Moore, 1980). This in part refutes the long-accepted view that the sedimentary section was always thickest next to the principal border fault.

Although much evidence supports the genetic relationships between border faulting, the origin of the basin troughs, and the associated basin-fill sedimentation in the sense that these basins have always been isolated from each other, an alternate concept, called the broad-terrane hypothesis, was readvocated by Sanders (1963). Under this hypothesis, all the Newark basins were originally connected, and similar sedimentation conditions existed over their regional extent. Thus, the present-day separation or isolation was caused by postdepositional faulting, arching, and erosion. Even though long-term erosion has removed much of the original sedimentary record in these basins and possibly obscured some relationships with the adjacent bedrock, the basin-controlled concept, which holds that these separated basins were created as individual, fault-induced subsidence centers, is generally more widely held than the broad-terrane hypothesis.

Strata within the basins generally dip toward the major border fault(s) at moderate to locally steep angles. Local reversals in dip occur in the vicinity of nonborder faults and major dike intrusions. Both longitudinal faults, or those that run essentially parallel to the basin margins, and cross faults, which are oriented basically perpendicularly to the basin axes, are present and are believed to postdate sedimentation. Some more prominent cross faults have in essence divided larger basins into several subbasins.

Igneous rocks associated with the continental sedimentary sequences include diabase (dolerite) in the form of sills and dikes, basalt flows such as the well-known Watchung flows in the Newark-Gettysburg Basin of northern New Jersey, and minor tuffaceous-pyroclastic deposits within the Culpeper Basin of northern Virginia (Toewe, 1966). Igneous activity appears confined to those basins extending from Virginia northward. Evidence assembled from several investigations points strongly to the fact that many of these shallow intrusives and lava flows are Early Jurassic in age (Van Houten, 1977). Vertical dikes that fill some cross faults clearly appear to be Jurassic (Bain, 1973).

Of the some 15 exposed basins, all but one are flanked by Precambrian to Lower Paleozoic igneous and metamorphic (crystalline) rocks. Only with the Maryland part of the Newark-Gettysburg Basin is there a contrast in that some of the bordering bedrock was uplifted by regional arching and border faulting and eroded to provide detritus that was swept into the subsiding basins by the local drainage systems to become incorporated as the sedimentary filling. As a general result, the coarsest zones of fanglomerate occur adjacent to the major border fault(s). Various conglomeratic and coarse-grained sandstones do, however, extend across much of several basins. The lithologies formed throughout these basins are very similar except for the occurrence of coal seams, which are restricted to three basins (Sanford, Dan River, and Richmond). Sorting of sediment grains tends to be poor as a general rule, and even though erosion-sedimentation is typically thought to have been rapid, much clay and silt-size material is present in the rock sequence (Weaver, 1976). These basin-fill stratigraphic sequences display abrupt lateral and vertical changes in coloration, grain size, thickness, composition, and sedimentary features such as stratification. Key marker beds that could facilitate precise correlation within specific basins are few. Reliable correlation of individual mapping units (formations) from one basin to another is difficult to essentially impossible; thus, formation names used in one basin have relatively little relevance to those used in other basins, unless the latter are nearby.

Parts of the exposed Newark-Gettysburg, Richmond, and Deep River (Sanford) Basins have been overlapped from the east by various semiconsolidated sedimentary units of the Atlantic Coastal Plain. Obviously, less is known about the buried basins that underlie areas within the coastal plain, because there is a general lack of definitive borehole data. An exception is the Dunbarton Basin, where extensive drilling, coring, and hydrologic testing have been conducted by the Savannah River Laboratory in both the Triassic strata and the adjacent crystalline rocks (uplifted along a border fault along the northwestern margin) (Marine and Siple, 1974). Other than some geophysical interpretations and very limited borehole information, little is definitively known about the border faults, adjacent bedrock, sediment fill, and ground-water systems in the other buried basins. Even less is known about the so-called inferred or hypothesized basins.

Because of the lack of systematic deep boreholes, few detailed geophysical surveys, and an absence of fully exposed stratigraphic sections, the exact thickness of these Triassic-Jurassic strata can only be estimated. In some cases the exact thickness for an individual formation can be determined, but generally this is possible for only one or a few areas within a given basin and not over the entire basin. Thicknesses up to several thousand meters appear to be present in the larger basins (Ackermann et al., 1976).

The age of the strata in these basins historically has been considered to be solely Triassic (Rodgers, 1970). Current thinking is that the age ranges from Late Triassic through Early Jurassic (Van Houten, 1977). Cornet et al. (1973) showed, based on palynological and other supporting evidence, that the northern U.S. basins tend to contain more Jurassic strata than the southern basins, in which sedimentation is also believed to have commenced earlier in the Triassic. Much of the sequences within the Nova Scotia basins also appears to be Jurassic (Jansa and Wade, 1975). Although it is a southern basin, the Culpeper Basin in northern Virginia also contains Jurassic strata. Conversely, the Deep River (Sanford) Basin appears to contain only Triassic rock units (Van Houten, 1977).

Summaries of the general geologic history of the development of these Newark basins were given by Bain (1973) and Van Houten (1977). In Van Houten's study, more emphasis was placed on the role of plate tectonics in the genesis of these structural-sedimentary troughs; Van Houten also outlined the numerous similarities and several contrasts between the basins in eastern North America and northwestern Africa (Morocco). Differences in latitudinal position relative to the influence of marine waters, climate, onset and cessation of continental sedimentation, and relative timing of nonborder faulting and igneous activity account for the variations observed between the basins from south to north on both continents.

4.2 REGIONAL SEISMICITY

With the exception of a few areas, such as along the St. Lawrence Lowland, the Cape Ann area in eastern Massachusetts, and a region near Charleston, South Carolina, the frequency of earthquakes within the Eastern Margin region is relatively low (see Figure 1-2). Unlike the seismotectonic conditions that prevail in the far western United States, there is no direct evidence from this eastern region linking earthquakes with movement along faults identifiable at the land surface. Furthermore, there are no known major (regional) faults in this eastern region with evidence of large-scale displacement younger than Triassic age. Data presented by York and Oliver (1976) do, however, suggest that some Cretaceous and Cenozoic faults may have had seismic magnitudes of up to 6 on the Richter scale associated with them. These investigators further suggested that these younger episodes of faulting, especially in the southeastern United States, are found only in areas that have experienced some level of historic seismicity.

The origin of the very large intensity (Modified Mercalli Intensity value of X; Bollinger, 1977) earthquake at Charleston, South Carolina, in 1886 and the recurrence of several hundred smaller events since then still is not known. Recent studies under the supervision of the U.S. Geological Survey have advanced the state of knowledge considerably (Rankin, 1977); nevertheless, several hypotheses about the cause of this seismicity can be found in the literature.

In an earlier study of the seismicity of the eastern United States, Fox (1970) reported that (1) present-day seismotectonics were mainly related to tectonic features active during the Paleozoic and Mesozoic Eras; (2) most seismic events occur in areas with known faulting, although the best estimate on the age of the faulting is simply post-Paleozoic; (3) seismicity and any related faulting appear associated with reactivated faults, as opposed to the creation of new faults; and (4) most of the earthquakes known to occur along the Appalachian orogen within the southeastern states are found in the Blue Ridge and Valley and Ridge provinces.

A subsequent investigation (Hadley and Devine, 1974) plotted the number and distribution of seismic events with Modified Mercalli intensities (MMIs) greater than III relative to regional tectonic features. From this, a generalized seismic-frequency contour map was constructed and an estimation of the anticipated level of seismic activity determined. With regard to the regions that include the Triassic basins and the Atlantic Coastal Plain, one area of level 5 activity was shown to be centered around Charleston, South Carolina. This area is characterized by having one or more epicenters of intensity IX or higher and is bounded by a seismic-frequency contour of more than 32. A broad east-west zone of level 3 also was identified throughout central Virginia in which the seismic frequency was estimated to be greater than 32 but in which no epicenters of intensity greater than VI had ever been recorded.

According to York and Oliver (1976), one main seismic trend in the eastern United States is along the Appalachian fold belt (central orogen), suggesting an association between seismicity and the regional tectonic features along that trend. To the west, a parallel seismic belt can be observed to extend from the northern part of the Mississippi Embayment (New Madrid seismic center) northeastward through the St. Lawrence Lowland. In this trend (parts of which are discussed elsewhere in this report) the relationship between seismicity and tectonic control is not apparent. In addition to these regional trends, several cross trends transverse to this northeast alignment can be observed. They include belts in the northeastern United States-eastern Canada, as well as somewhat more minor trends across the Mississippi Embayment and in Virginia. Of interest to the discussion here are those trends that extend across the Piedmont and Atlantic Coastal Plain provinces and thereby involve areas included within the Eastern Margin region.

Three such transverse belts of higher seismic activity previously were recognized by Bollinger (1973); from north to south, they were named by Bollinger the Northern Virginia-Maryland, Central Virginia, and South

Carolina-Georgia seismic zones. The most noteworthy center of seismicity within the Eastern Margin, the area around Charleston, South Carolina, lies at the eastern landward extent of the latter zone. Two zones of occurrences of post-Cretaceous faulting were further reported by York and Oliver (1976) from the eastern part of the Central Virginia cross trend.

One question with regard to partially understanding the seismotectonics within the Eastern Margin is the degree to which, if any, the faulting associated with the Triassic (Newark) basins is also related to Cretaceous-Cenozoic faulting (fault reactivation) and/or contemporary seismicity. Although many of the limited data bearing upon this point are far from conclusive, some evidence suggests that certain Triassic basins may be associated with more recent faulting and seismicity.

Faults within the Deep River (Sanford) Basin in North Carolina show offsets in both igneous dikes (Late Triassic to Early Jurassic) and overlying surficial deposits of possible Pliocene (?) age (Reinemund, 1955). As cited from the older literature by York and Oliver (1976), gravels of Quaternary age also have been displaced along the eastern side of the Newark-Gettysburg Basin in central New Jersey, where these younger sediments overlap this Triassic basin. Page et al. (1968) also suggested that a zone of minor seismic activity along the New Jersey-New York state line may be associated with the Ramapo fault, which borders the Newark Basin in that area. Faulting at Quantico, Virginia has offset Cretaceous sediments (York and Oliver, 1976) and is on strike with the Stafford (Virginia) fault system, which Mixon and Newell (1977) showed clearly to have involved Cretaceous-Tertiary movement. Both these sites are aligned with an aeromagnetic lineament that lies on strike to the northeast of the Farmville Basin (Figure 4-1) and are associated with several structures apparently related to the buried Brandywine, Maryland, Triassic basin, which is along strike with the Richmond Basin (Mixon and Newell, 1977).

Although Hadley and Devine (1974) contended that most of the seismic events in the Central Virginia seismic zone of Bollinger (1973) appear to have originated within crystalline rocks and not within the Triassic basin (Richmond) or along its border faults, there exists a crude alignment of several epicenters parallel to this basin's border faults. Some 13 events with MMIs III through VI have been reported within the immediate vicinity of the Richmond Basin through 1972 (Hadley and Devine, 1974). The fact that three Triassic fault basins (Richmond, Scottsville, and Farmville) lie within the Central Virginia seismic zone may bear upon the higher level of seismicity there or may be fortuitous.

Hadley and Devine (1974), in analyzing one MMI VII event near the head of Delaware Bay and a grouping of lower-intensity events east of the pronounced east-west offset in the regional alignment of the Newark-Gettysburg Basin, were inclined to feel, however, that the data suggested, but did not strongly indicate, movement along the border faults there.

Although the interpretation of some data, and geophysical data in particular, has given rise to inconsistent results within the U.S. Geological Survey's investigation of the Charleston, South Carolina seismic center, both Long and Champion (1977) and Talwani (1977) postulated the existence of a faulted Triassic (?) basin in the subsurface on the basis of gravity and velocity modeling supported by other geophysical data, respectively. Talwani (1977) especially felt that border faults on the southern side of the buried graben are directly involved with the observed seismicity. Drilling in this area also has recovered basaltic rock whose geochemical affinities suggest a Triassic-Jurassic origin and add support to the belief that a buried Triassic (Newark) basin underlies the Charleston-Summerville area (Rankin, 1977).

Even though one plausible explanation for the Charleston, South Carolina, seismicity entails a Triassic basin and its border faults, both Kane (1977) and McKeown (1978) advanced the hypothesis that there is a causative relationship between mafic and ultramafic (now serpentinized) igneous intrusives and seismicity in the central and eastern United States. Each investigator includes the Charleston center as an example of this phenomenon and cites gravity and magnetic data to indicate the presence of a mafic body within the subsurface basement there. Under Kane's explanation, serpentinization of the mafic body and concentration of stress along the margins of the altered igneous body are involved. If correct, this explanation would invalidate the role of the inferred Triassic basin's border faults in both the past and ongoing seismicity near Charleston.

Further evidence that border faults may not be involved in the Charleston area seismicity may lie in the focal-plane solution for the largest modern event (recorded in 1974), as detected by the U.S. Geological Survey seismograph network (Tarr and Carver, 1978). Tarr and Carver's work indicated dip-slip motion along a nearly vertical fault whose strike is northwest, or exactly opposite to the northeast orientation of the inferred border faults as postulated by Long and Champion (1977).

From the above, it is obvious that the regional seismotectonics within the Eastern Margin region currently are not understood with clarity. Furthermore, while there is some evidence to suggest a seismotectonic involvement of certain Triassic basins and their major border faults, this relationship is not conclusive either. And lastly, several different interpretations, each of which retains validity, have been proposed to explain the seismicity near Charleston, South Carolina. Additional data gathering and interpretation are undoubtedly needed before the cause of that seismic activity can be firmly determined. The same holds true for several Triassic basins whose more localized seismicity relative to border faults must also be more fully studied.

4.3 REGIONAL HYDROLOGY

4.3.1 Surface Water

Drainage from the central and eastern Appalachian province, from New England, from the Triassic lowland basins, and from most of the Atlantic Coastal Plain is eastward into the Atlantic Ocean by means of drainage systems whose principal streams have their headwaters within the higher elevations of the Appalachian Mountains or the several ranges along the western border of the New England region. One exception to this pattern is in western and south-central Georgia, where streams such as the

Chattahoochee, Flint, Apalachicola, Alapaha, and Suwannee Rivers flow from the Piedmont-Blue Ridge and (or) Coastal Plain provinces into the Gulf of Mexico.

From north to south, the principal rivers that directly drain either the Triassic (Newark) basins, the central Piedmont, or the Atlantic Coastal Plain are the Connecticut, Delaware, Susquehanna, Potomac, Rappahannock, James, Roanoke, Neuse, Cape Fear, Yadkin, PeeDee, Broad, Santee, Edisto, Savannah, Ogeechee, Ocmulgee, Altamaha, Satilla, Flint, and Chattahoochee. Within Florida, especially the northern and north-central parts, the Peninsular Arch influences whether drainage is toward the Atlantic Ocean via the St. Marys and St. Johns Rivers or into the Gulf of Mexico via the Suwannee, Withlacoochee, Hillsborough, and several smaller rivers. Because of the appreciable amount of karst topography within north-central and central Florida, much of the precipitation that fails on the land surface there is diverted directly into the ground-water system.

Annual precipitation throughout the Eastern Margin region varies from an average of 102 cm in the northern half of the region to an average of 132 cm in the southern half. Areas within eastern North Carolina, the western part of the southern Piedmont and the adjacent Blue Ridge, and far southern Florida average several more centimeters of precipitation per year.

Precipitation provides both direct and indirect sources of recharge throughout the region. Within the Atlantic Coastal Plain, for example, recharge may be directly into various shallow sand aquifer systems or into the updip parts of the several deeper artesian aquifers. The latter may also be indirectly recharged by percolated water that first enters overlying unconsolidated sediments (commonly containing aquifers themselves) and then infiltrates into the subcrop areas of the gently dipping, deeper aquifers.

Within the Piedmont province, infiltration moves water into the near-surface zone of weathering and the more deeply developed zone of intensely weathered bedrock known as saprolite. Wells of small to moderate volume tap this shallower source of ground water; deeper ground water, which has been recharged indirectly from the overlying soils, regolith, any overlying unconsolidated sediments, and the zone of saprolite, occurs principally in fracture systems within the igneous-metasedimentary-metavolcanic bedrock and generally yields higher volumes to wells. Some shallow ground water is also found in alluvial sand and gravel deposits along stream valleys; recharge of these more localized sources of ground water is from both precipitation and infiltration from the streams flowing in the valley-flat areas. Where relatively unweathered crystalline bedrock is exposed at the land surface, some infiltration along fractures and joints takes place, although the presence of zones of gouge and/or faulting or sharp contrasts in rock types, especially involving intrusive bodies, tends to increase the amount of recharge.

Recharge from surface waters into the bedrock of the Triassic basins may also be direct or indirect. In those basins where overlapping unconsolidated sediments of the Atlantic Coastal Plain occur, or in those parts of basins where alluvial valley fill, glacial sediments, or zones of pronounced weathering are present, water that initially entered these near-surface materials can percolate further downward into the sedimentary bedrock. Direct recharge into the more porous fanglomerates, conglomerates, and sandstones within these basins also takes place as well as direct recharge to deeper intervals along fracture and joint systems, border and cross faults, and in areas adjacent to dike intrusives.

For those basins that lie totally buried by overlying sediments of the Atlantic Coastal Plain, recharge is from the porous-permeable units within the shallow stratigraphic sequence or along fault zones along the margins of those basins whose principal extent is overlain by clay aquicludes within the basal coastal-plain sequence.

4.3.2 Ground Water

Within the Eastern Margin region, the occurrence of ground water shows marked contrasts between Piedmont crystalline terranes, the poorly consolidated sediments of the Atlantic Coastal Plain, and the sedimentary strata that fill several Triassic (Newark) basins. In the first case, ground water is limited largely to shallow depths, being found principally in weathered residuum (includes saprolite), fractures and joints that do not extend to appreciable depths, and along zones of faulting or igneous intrusion. Well yields range from small to moderate and commonly are adequate for modest domestic, industrial, and municipal use. Most of the demand for water supplies throughout the Piedmont province, however, is met by surface-water sources, especially streams and man-made reservoirs along streams. Although the specific rock types within the Carolina Slate belt are different from the more widespread igneous and metamorphic assemblages typical of the Piedmont as a whole, ground-water conditions there do not vary appreciably from this regional situation.

Abundant ground water occurs within numerous aquifers along the entire extent of the Atlantic Coastal Plain. Shallow sources include unconsolidated sand and gravel deposits of Pleistocene to Holocene age, deeper sands of Tertiary and Cretaceous age, and widespread (especially throughout the southeastern states) carbonate aquifers of Tertiary age. Many aquifers display excellent porosity, hydraulic conductivities, and transmissivities and are capable of very high yields. These aquifer systems all dip gradually toward the coastline from recharge areas farther west, are confined (artesian), and are heavily pumped in many areas from New Jersey to Florida. Fresh water occurs within several of the deeper artesian systems to depths greater than 1,000 m.

In several of the more widely utilized aquifers, excess pumpage also has created pronounced regional cones of depression. Where these aquifers possess saline-water legs below their fresh water, these high levels of withdrawal have led to saltwater encroachment. Areas along the eastern coastline in Florida, Georgia, South Carolina, and New Jersey particularly have experienced lowered water quality as a result. More discussion of the ground-water conditions within the Piedmont and Atlantic Coastal Plain is found in a subsequent section of this chapter.

The occurrence of ground water relative to depth, rates and directions of movement, and availability within the Triassic basins is much less understood. Few deep wells have been drilled in these basins, and relatively few hydraulic tests have been performed to evaluate the aquifers involved.

In the general sense, ground water is found within these Triassic basins in the intergranular porosity of the coarser-grained lithologies such as fanglomerates, conglomerates, and sandstones, and in secondary porosity represented by joints and fracture systems developed within several rock types, zones of weathering, and fault zones. Because of the significant number of faults that either border or cut across these basins, the numerous dike intrusions, the presence of impervious basalt flows, and the pronounced lateral and vertical lithologic variation typical of the sedimentary strata, flow patterns within the subsurface are undoubtedly complex and not well understood.

Bain (1973) expressed the view that an apparent difference exists in the water-yielding characteristics of basins north and south of the Culpeper Basin in Virginia. To the north, sustained yields are fair to moderate, and productive wells are commonly developed within the consolidated strata of these basins. Those basins to the south display much lower hydraulic conductivities, and productive wells generally provide only modest yields. According to Bain (1973), this generalized regional contrast is due to the fact that the strata within these southern basins contain more fine-grained (clay) material and display a very poor level of sorting. The causes for these apparent gross lithologic differences could entail different sediment sources, different depositional conditions, or both.

Aquifer testing of wells drilled into the buried Dunbarton Basin in South Carolina tends to substantiate this view (Marine and Siple, 1974). Laboratory analysis of cores from these wells showed low conductivities in the range of 10^{-5} to 10^{-8} m/d, whereas long-term field tests gave values around 10^{-7} m/d. Effective porosity was as low as 0.5 percent in cores, many of which were recovered from a dense mudstone. Weaver (1976) concluded that these poor hydraulic characteristics are directly related to the high content of clay minerals present in all samples tested, while Marine and Siple (1974) favor poor sorting as the main cause. Some slight increase in the water-bearing properties of deeper Triassic strata directly overlying the surrounding crystalline bedrock also was noted (Marine and Siple, 1974).

Two additional points of interest with respect to the ground-water system within the Dunbarton Basin is a dissolved-solids content of 11,000 mg/l (Marine and Siple, 1974) and hydraulic heads that indicate that some parts of the basin are actually geopressured (Marine, 1974). The water from the Triassic strata is therefore much different chemically from ground water in either the surrounding or deeper crystalline bedrock, or the overlying, water-bearing strata of Cretaceous age. Slightly fresher water was found in wells drilled nearer the basin margins; this might suggest some leakage-recharge along fault zones. The observable differences in water chemistry may also indicate the long-term segregation of the ground water found in these Triassic rocks. Satisfactory explanations for the high hydraulic heads include tectonic compression, osmotic phenomena, and climatic variations, but the exact extent of the geopressured zone and any regional implications are not known (Marine, 1974).

Dames and Moore (1980) reported that the fracture-joint systems that account for the porosity to contain and yield water to wells in the more northerly basins generally do not extend below 180 m. However, they summarized information on several deep (262 to 306 m) wells drilled within the Virginia portion of the Culpeper Basin, and these data suggest that effective ground-water flow exists to those depths. Inasmuch as the wells--one near Manassas, Virginia, and the others near Dulles International Airport--penetrated a sequence of sandstone and shale, respectively, the suggestion is strong that the yields of up to 2280 l/s may have involved deep fractures. Bain (1973) also reported that a third well near the airport reached a depth of 314 m and yielded up to 3780 l/s.

Data on ground-water characteristics and well production from the Newark-Gettysburg Basin in Pennsylvania and Maryland were presented by Bain (1973) and Nutter (1975). Water of generally good quality is produced from the carbonate conglomerate facies of two stratigraphic units (Gettysburg Shale and New Oxford Formation), but joints, fractures, and solution-expanding bedding planes also appear to be involved. Yields from

6 to 360 l/s are typical, while the reported hydraulic conductivities range from values near zero to 8.5 x 10^{-5} m/d. Wells drilled in lowland areas bordering various streams also appear more productive, which suggests possible joint control of both the stream courses and the deeper aquifers within the Triassic bedrock (Nutter, 1975).

The Brunswick Shale, which is a principal stratigraphic unit within the New Jersey portion of the Newark-Gettysburg Basin, is another example of a fine-grained rock unit that serves as an important local aquifer because of the presence of abundant fractures and joints (Jumikis and Jumikis, 1975). Wells up to 60 m in depth are productive throughout much of this unit's extent, although no uniform pattern of ground-water production is apparent. Because the strata dip gently within the basin, and surface exposures are commonly the sites of springs and seepage, expansion along bedding surfaces apparently is also involved in the development of the subsurface secondary porosity.

As discussed by Dames and Moore (1980), some ground water is recovered from wells in the other major, more southern Triassic basins (Danville, Dan River, Durham, Sanford, and Wadesboro). Yields range from less than 30 to more than 450 l/s; controls on the relative production of water include the primary-porosity of the aquifer lithology, the presence and number of secondary joint-fracture openings, topographic position (wells in valley areas generally yield more water), and depth. For the most part, yields are low but are adequate in volume and quality for domestic and localized consumption. Wells tend to be drilled only to depths of a few tens of meters. Essentially no information, outside of that already discussed under the Dunbarton Basin, exists on the occurrence and nature of deep ground water in these more southern basins or on the paths of ground-water circulation (where active) within any basin.

Low values for porosity and hydraulic conductivity are typical for many of these Triassic strata as a whole (Weaver, 1976; Bain, 1973; Bledsoe and Marine, 1980). There is, however, a general lack of data about deeper (more than 300 m) ground water, basin-wide circulation paths, and hydrologic systems in general. The clear association of faults, fractures, and igneous intrusives to the occurrence of shallower ground water, and the highly irregular distribution of useful well and hydraulic-testing data are noted. At the present time, the existing knowledge about ground water in all these basins is very incomplete.

4.4 SHALES AND ARGILLACEOUS UNITS

4.4.1 Introduction

Because the Triassic (Newark) basins represent the only geologic subdivision within the Eastern Margin region that contain argillaceous strata of significant thickness and extent, this section is devoted solely to considering these basins. Other strata are, however, present within both the Piedmont and Atlantic Coastal Plain provinces and are discussed more briefly under "Other Units" (Section 4.4.3).

4.4.2 Triassic Basin Shales

Sedimentary-rock sequences within the Triassic basins contain some thick intervals of shale and mudstone, while many of the other lithologies contain poorly sorted sediments and/or abundant fine-grained material (silt and clay). Thus, as already noted, hydrologic properties, even though poorly to slightly known in some basins, generally reflect low values of porosity and hydraulic conductivity. Many basins are therefore poor in their ability to provide ground water to wells, and in most cases no fresh ground water is recovered from depths greater than 300 m. Several basins and large parts of others lie within regions of low seismicity; exceptions may include certain basins in south-central Virginia and those near the South Carolina-Georgia seismic zone.

Although the exact thickness of the sedimentary fill is not known for many of these basins because of nearly total lack of deep boreholes, geophysical and other evidence suggests that several thousand meters of sedimentary strata may remain in the larger basins. For example, Ackermann et al., (1976), using electrical-resistivity measurements, interpreted that up to 2,300 m of strata is present in the Durham-Wadesboro Basin of North Carolina. Basing his thickness figures on outcrop data and projections of identified stratigraphic units, Lee (1977) estimated that strata within the Culpeper Basin range in thickness from 640 to 3,000 m within the Maryland portion of the basin and reach a maximum thickness of more than 10,000 m in parts of Virginia. These values are comparable to that of 4,200 m given by Krynine (1950) for Connecticut (Hartford) Basin, and the range of 5,000 to 9,000 m presented by Sanders (1963) for the more northern basins.

Specific studies that have addressed geologic aspects of the Triassic Basins include those by Bain (1973), Weaver (1976), Dames and Moore (1980), and Bledsoe and Marine (1980). Also, Marine and Siple (1974) and Marine (1974) specifically evaluated the buried Dunbarton Basin on the basis of various geophysical surveys, borehole data, and hydraulic well tests.

The investigation by Weaver (1976) was limited, moreover, to those basins in the south of North Carolina. The principal output of this study was a review of the available data, especially those on clay mineralogy, covering the several basins from North Carolina to northern Florida.

Inasmuch as Bain (1973) was primarily interested in the nature and availability of data on these basins, the Dames and Moore (1980) study, conducted for the Savannah River Laboratory, represents the principal study of all the basins south of Pennsylvania. Bledsoe and Marine (1980) summarized the information on those basins.

As shown in Figure 4-1, Triassic basins can be divided into the following categories: (1) exposed basins, or those having appreciable outcrop areas within the borders of the basin, those borders being delineated on the basis of known border faults or inferred contacts; (2) buried basins, or those that totally lack any surface exposures and lie beneath several hundred meters of sediments making up the Atlantic Coastal Plain; and (3) inferred or hypothesized basins, or those whose existence is postulated on the basis of extremely few drill-hole data and/or geophysical interpretations. Also indicated in Figure 4-1 is a division among the exposed basins wherein some are classified as major and others as minor. This basically parallels the subdivision adopted in the Dames and Moore (1980) study, in which 388 km^2 served as the separation.

This report makes no effort to consider these inferred basins inasmuch as little or no data are available for any of them, and their exact extents and sizes are unknown. Several minor, exposed basins (Barboursville, Crowburg, Davie County, Ellerbee, Farmville, and Scottsville) are also not discussed because of their limited extents and/or the lack of pertinent data.

The exact dimensions of the Richmond-Brandywine and Georgia-Florida Basins are poorly known (Dames and Moore, 1980). The Richmond-Brandywine Basin is associated with several geologic structures with which some seismicity and/or fault reactivation may be involved, and it is adjacent to the heavily populated Washington-Baltimore metropolitan regions. The Georgia-Florida Basin is, for much of its subsurface extent, very deep; also, too little is known about the lithologies present, and the overlying Coastal Plain sediments are involved in a major aquifer system.

Relatively little is known about the Florence Basin other than it is shallow (between 183 and 213 m deep) and contains supposedly Triassic sandstone and diabase, as reported from two water wells (Dames and Moore, 1980). Seismic data suggest a northeast-trending length of 64 km and a width of 21 km, although there is no borehole confirmation to support this interpretation. The overlying Cretaceous Tuscaloosa Formation contains several zones of sand and gravel that constitute productive ground-water aquifers.

The Dunbarton Basin represents the most widely studied example among the buried basins (Marine and Siple, 1974; Marine, 1974). It is the only buried basin to have been investigated by both indirect means (geophysical surveys) and direct observations (cores, logs, well tests). The upper contact of the Triassic sequence lies beneath some 305 m of overlying Coastal Plain strata, which include the Cretaceous Tuscaloosa Formation at the base. The Tuscaloosa Formation contains two specific aquifers throughout this area as well as a basal aquiclude believed to be composed largely of saprolitic clay (Christl, 1964). Some difference of opinion exists, however, with regard to interpretation of stratigraphic-sedimentologic relationships in these overlying strata (Marine and Siple, 1974).

In addition to the presence of overlying ground-water aquifers, hydraulic heads determined from two wells drilled into the Triassic sequence reveal a geopressured situation (Marine, 1974). Weaver (1976) indicated that such a situation could cause possible upward movement of groundwater into the shallower aquifers. Hydrologic and core data reveal that the Triassic strata possess low values of porosity and hydraulic conductivity, contain abundant clay minerals (one interval is a mudstone), and consist of poorly sorted sediment grains. As noted already, the Dunbarton Basin lies less than 160 km from the central part of the Charleston, South Carolina, seismic center. The Georgia-South Carolina seismic zone of Bollinger (1973) also passes northwestward through this area.

The aquifers in the overlying Tuscaloosa Formation aquifers, the geopressured zone (or zones) within the Triassic sequence, and the nearness of a major center of seismic activity are aspects that must be evaluated in more detail in the Dunbarton Basin.

Dames and Moore (1980) noted a number of general characteristics for the following major exposed basins: (1) Newark-Gettysburg, (2) Culpeper, (3) Richmond, and (4) Sanford. These characteristics include: the fact that ground water is recovered from the Triassic sequence; the possible association with or influence by seismicity; possible fault reactivation; occurrence of large amounts of coarse-grained, and hence porous, rock types; and other mineral-resource conflicts involving coal deposits and increased future demand for ground water. The Dames and Moore Report (1980) addressed characteristics of the Connecticut (Hartford) Basin. The Meriden Formation in the Hartford Basin consists of several thick shale units (Krynine, 1950; Sanders, 1963); the sedimentary fill is highly variable in its lithologic expression, both across the basin and in a north-south direction. Coarse-grained units (arkoses and fanglomerates) are also present, and ground water is obtained from some of these units. Information on the depth and thickness of the shale intervals is scarce, but where these shales are believed to be sufficiently thick, they appear to be deeply buried in the central part of the basin (Krynine, 1950).

Dames and Moore (1980) noted that four exposed basins, arranged here in order of increasing areal extent, have common characteristics: Dan River, Danville, Wadesboro, and Durham. Each basin contains intervals of shales, claystones, and/or clay-rich siltstone; interbedded with these are the expected coarser-grained rocks such as conglomerates and sandstones, which contain a considerable amount of clay and display a fairly poor degree of sorting. Although the values are largely estimates, the thicknesses of the basin-filling strata are as follows: Wadesboro, 600 to 1,150 m; Dan River, 1,525 m; Durham, 3,050 m; and Danville, 4,570 m (Bledsoe and Marine, 1980).

In the strict sense, none of these basins contains an individual, thick (75 m) shale-mudstone-claystone unit of persistent lateral extent. Probably that condition is most closely approximated by intervals within the Pekin and/or Cumnock Formations from the Durham and Wadesboro Basins (Reinemund, 1955; Randazzo et al., 1970) and possibly the Cow Branch and Stoneville Formations within the Danville and Dan River Basins (Meyertons, 1963; Thayer, 1970).

Because of a lack of outcrop and borehole control from which to precisely establish subsurface correlations, and because of the pronounced vertical and lateral changes in lithologic character, the exact extent of any argillaceous units cannot be determined with certainty in any of these four basins. As an indication of this situation, Figure 4-2 shows some of the stratigraphic complexity within the central part of the Dan River Basin, where numerous diabase dikes occur. As observed by Dames and Moore (1980), the stratigraphic terminology (and hence understanding) applied to the Dan River Basin differs from that of the closely adjacent Danville Basin, which is along strike to the south. There also is a significant difference in interpretation with regard to stratigraphic units and lithofacies within the Durham Basin when newer investigations are compared with those of the established literature.

Additional details on the structure, geohydrology, mineral resources, and seismic setting, as best known based upon limited data for these basins, also were inventoried by Dames and Moore (1980). Even though no discrete shales or mudstones can be identified without the benefit of considerable new borehole data, some further commentary can be made on these basins. The Dan River Basin, as the smallest in surface area, is similar to the Danville Basin in being much more elongate than the two North Carolina basins and having a maximum width of less than 10 km. Faults and associated diabase dikes actually have cut the Dan River and Danville Basins into numerous subbasin areas. Furthermore, the strata dip at an average angle of 30 degrees. Although the development of ground-water resources has been minimal in both, virtually nothing is known about the ground-water regime at the depths anticipated for repositories.

The Durham and Wadesboro Basins cover appreciably larger areas but are characterized by the common occurrence of faulting, dike intrusions, and other structural complications. Strata in both basins dip from 15 to 20°, although some areas of flatter inclination are known. Some ground water has been produced, but again essentially no data exist to facilitate an understanding of the entire hydrologic regime within either basin, particularly the deeper ground-water flow systems. Shales rich in organic matter occur within the Cumnock Formation. Extensive investigations would be required merely to ascertain more about the regional characteristics of the basins.

In summary, the Triassic basins are essentially difficult to characterize because data on subsurface conditions are either few or lead to inconclusive results. If argillaceous strata in any of these basins are to be studied further, a significant amount of original geotechnical information will first have to be acquired in order to better assess the regional characteristics.

4.4.3 Other Units

4.4.3.1 Carolina Slate Belt

Extending from Georgia through the Carolinas and into southern Virginia, the Carolina Slate belt is one of several northeast-trending zones within the southern Piedmont (Figure 4-3). As originally defined by King (1955), these belts were recognized on the basis of similarities in rock types, geologic structure, and landform expression. Even though the

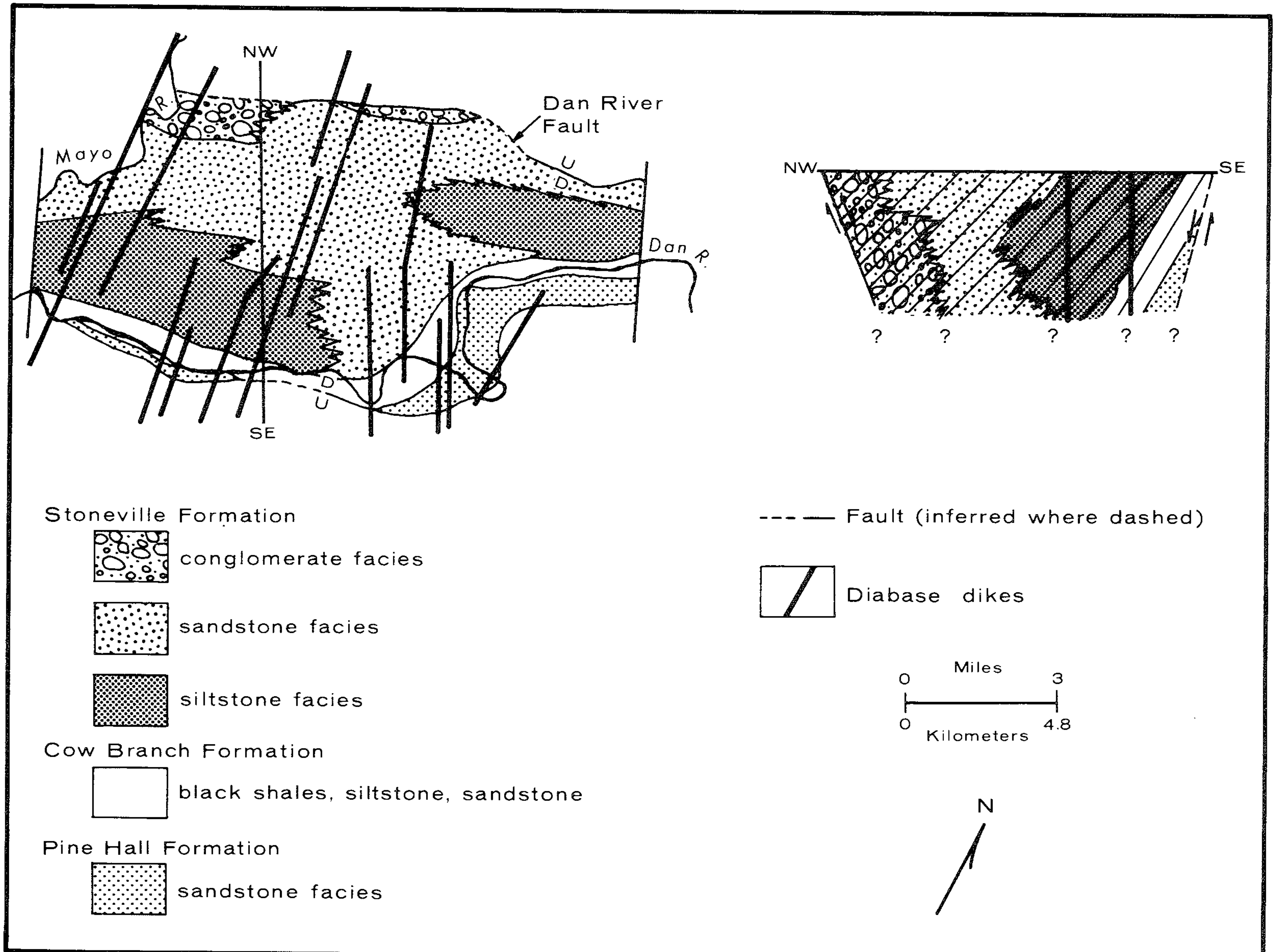

FIGURE 4-2. GEOLOGIC MAP AND CROSS SECTION OF DAN RIVER BASIN, IN NORTH-CENTRAL NORTH CAROLINA, ILLUSTRATING GEOLOGIC COMPLEXITY AND HIGHLY VARIABLE LITHOLOGY (MODIFIED FROM THAYER, 1970)

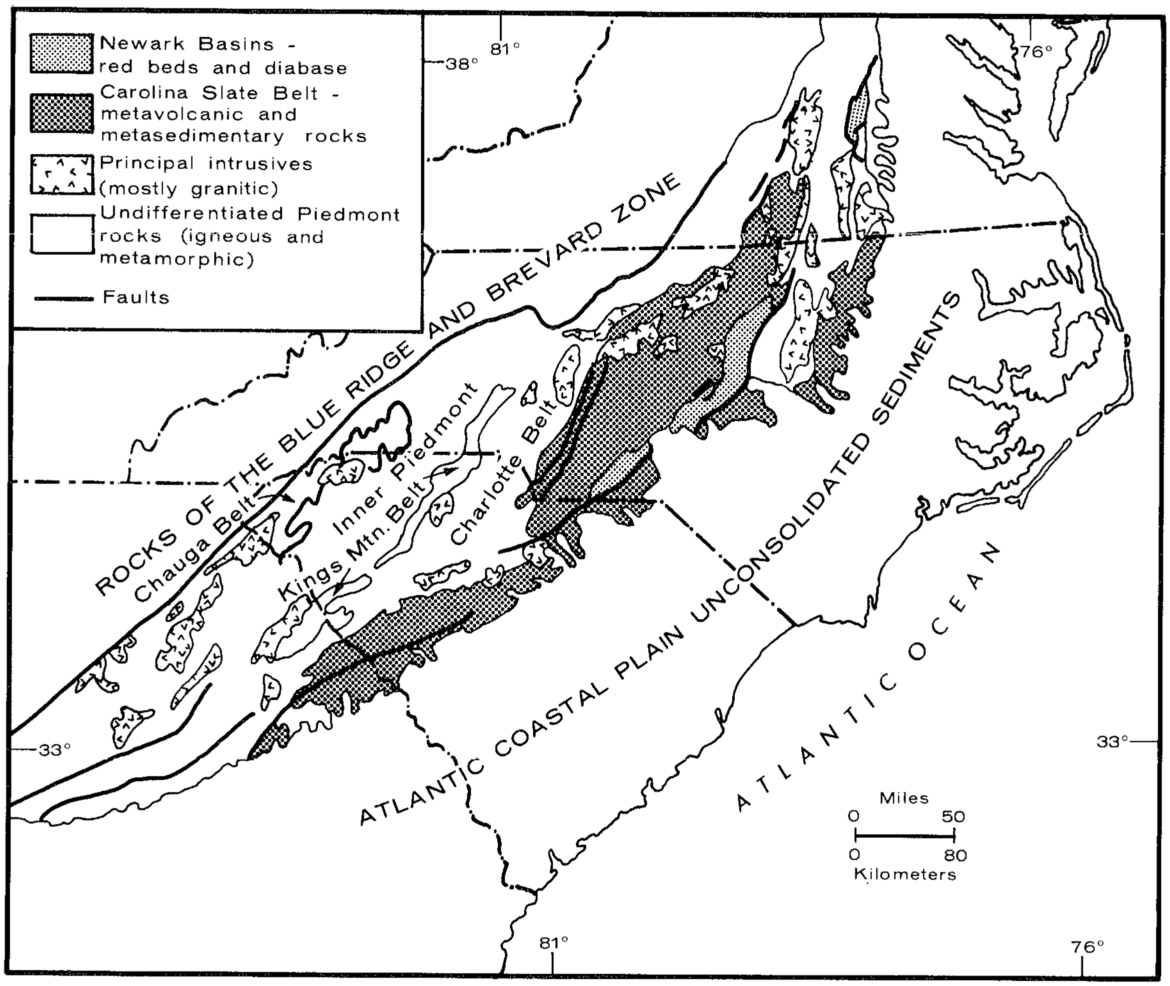

FIGURE 4-3. MAP SHOWING GENERALIZED REGIONAL GEOLOGY OF SOUTHEASTERN STATES, WITH EMPHASIS UPON SUBDIVISIONS OF APPALACHIAN PIEDMONT SUBPROVINCE (MODIFIED FROM RODGERS, 1970; HATCHER, 1978b; BELL ET AL., 1980)

regional geology in the southern Piedmont is much better understood than it was in the 1950s, utilization of these regional belt terms retains its validity (Bell et al., 1980).

The Carolina Slate belt consists of an assemblage of mafic and felsic volcanic rocks and very low grade metasedimentary lithologies that range in age from late Precambrian to early Paleozoic (Cambrian-Ordovician). This assemblage has been intruded (Figure 4-3) by a series of older (510 to 705 million years) gabbroic to granite plutons and younger (300 million years) granitic intrusives (Hatcher, 1978b).

The name "slate belt" is actually a misnomer, inasmuch as true slate as a rock type is not widely present; rather, rocks originally termed slate are fine-grained metavolcanic and metasedimentary units that have progressed to the greenschist grade of metamorphism and generally lack slaty cleavage. Alternate names for this belt are the Virgilina Volcanic Group in Virginia and the Little River Series in Georgia (Sundelius, 1970).

West of the Carolina Slate belt are higher-grade metamorphic rocks of the Charlotte belt; this contact may be either metamorphic or structural in nature (Hatcher, 1978b). Eastward, slate-belt rocks extend beneath overlapping sediments of the Atlantic Coastal Plain. In addition to various igneous intrusives, several Triassic-Jurassic fault-block basins are interspersed throughout the extent of the Slate belt (Figure 4-1).

Stromquist and Sundelius (1969) recognized a stratigraphic sequence for the lower Paleozoic section within south-central North Carolina that demonstrates the significance of volcanic and volcanic-clastic rocks typical of this eugeosynclinal environment (interpretations about the specific original depositional setting of the Slate belt were reviewed by Bell et al., 1980). The stratigraphic succession contains two principal divisions, the Uwharrie Formation (mainly Upper Precambrian to Cambrian volcanics) and the younger Albermarle Group, which is divisible, from oldest to youngest, into the Tillery, Cid, and Millingport Formations. Within these three formations are considerable thicknesses of fine-grained rocks of possible interest to this report.

These fine-grained rocks are generally well bedded and finely laminated and consist mainly of quartz, feldspar, muscovite, and chlorite (Sundelius, 1970). In previous literature descriptions, rocks of this type have been termed slate, volcanic slate, shale, mudstone, argillite, and siltstone. Representative of this general assemblage of fine-grained rock units are the Tillery Formation, the Mudstone Member of the Cid Formation, and the Floyd Church Member of the Millingport Formation.

Three major rock types, expressed in current lithologic terminology, are recognized (Sundelius, 1970): (1) blocky to massive-bedded, gray mudstone; (2) olive-gray to brown siltstone; and (3) very well laminated (varved) argillite in which graded bedding (silt at the base with clay sizes concentrated at the top of each unit) is evident. Geochemical and mineralogic evidence reveals that all these lithologies also contain appreciable volcanic (rhyodacitic in composition) ash (Sundelius, 1970).

Various tuffs, volcanic flows, volcanic tuff-breccias, and pyroclastic sandstones are interbedded with these mudstone-siltstone-argillite units. The total thickness of this complex probably exceeds 10,000 m in south-central North Carolina (Bell et al., 1980). Lateral and vertical variation in lithologic expression, poor sorting of sediment sizes, and abrupt facies changes within the identified stratigraphic units are typical.

Throughout the belt, furthermore, there are regional differences in the degree of metamorphism and the nature of the geologic structure. Some rocks have developed phyllitic to schistose foliation, especially those closer to the Charlotte belt and the Deep River-Wadesboro Triassic-Jurassic basin. In spite of this higher level of textural development, none of the Carolina Slate belt rocks contains mineralogies reflective of metamorphic grade beyond lower greenschist level (Sundelius, 1970). Contact-metamorphic effects in the vicinity of various intrusive bodies are, of course, more pronounced locally. Most of the belt in central North Carolina is folded into broad, northeast-aligned folds that plunge gently to the southwest (Bell et al., 1980). Elsewhere, folds are asymmetrical to overturned and tightly compressed and exhibit steep dips along the limbs (Sundelius, 1970).

Interest in the Carolina Slate belt, as indicated by a renewed level of detailed mapping and commercial exploration efforts, is directed toward the occurrence there of base-metal sulfide mineral deposits, some of which have also produced gold and silver in the past (Bell et al., 1980).

Although current corehole exploration is under way, borehole data from moderate depths are scarce.

Despite this general lack of detailed subsurface data, and the possibility of metallic ore mineralization and lithologic variations within this volcanic-volcaniclastic sequence, there may be large areas where the mudstones and argillites described previously deserve additional attention. A sizable amount of additional mapping and other geologic investigations would be needed before even a regional assessment about the potential of these fine-grained rocks could be achieved.

4.4.3.2 Atlantic Coastal Plain Clays

As a major geologic-geomorphic province within the eastern United States, the Atlantic Coastal Plain has received considerable attention in the geological literature. Important references that discuss the geologic history, structural geology (including the nature of the underlying basement), and stratigraphy of this province in greater detail than is given here include those by LeGrand (1961; 1962), Murray (1961), Richards (1967), Maher (1971), Brown and Reid (1976), and Brown et al. (1972; 1978). The prolific ground-water resources of the province are described from a regional perspective in articles by LeGrand (1964), Parker et al. (1964), Stringfield (1966), Sinott and Cushing (1978), and Cederstrom et al. (1979).

The Atlantic Coastal Plain lies east of its contact (Fall Line) with the Appalachian Piedmont subprovince (New England subprovince along Cape Cod) and is underlain by a seaward-thickening and dipping sequence of poorly consolidated to semiconsolidated sediments that range in age from Early Cretaceous (possibly Jurassic in some areas; Jurassic and possibly Triassic sediments are involved in the sequence at greater depth beneath the continental shelf) to Holocene. These sedimentary deposits consist of gravels, sands, clays, marls, and shell beds and thicken from a feather edge (exclusive of several erosional remnants) along the Fall Line to more than 3,000 m in easternmost North Carolina and the Delaware-southern New Jersey area (Figure 4-4).

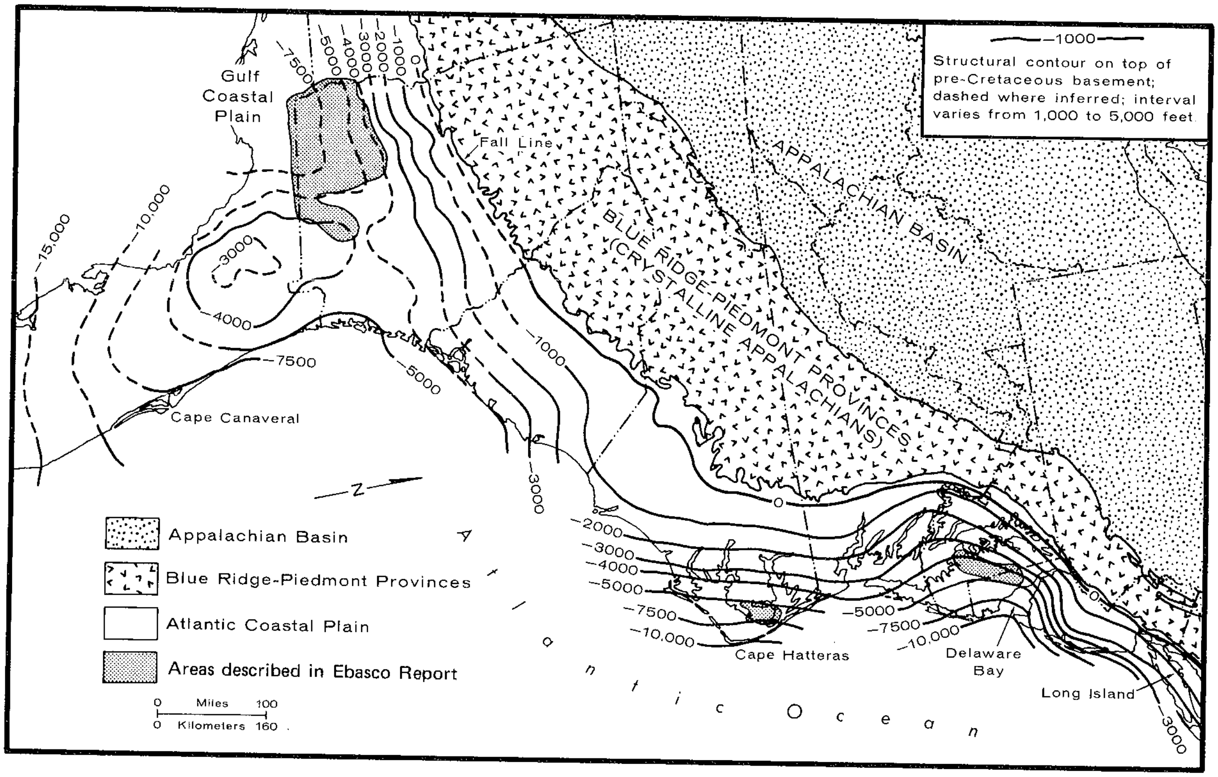

FIGURE 4-4. STRUCTURE-CONTOUR MAP OF BASEMENT BENEATH ATLANTIC COASTAL PLAIN FROM NEW YORK TO FLORIDA. ALSO SHOWN ARE POSITIONS OF FALL LINE, ADJACENT GEOLOGIC PROVINCES, AND LOCATION OF AREAS AS STUDIED BY EBASCO SERVICES, INC. (MODIFIED FROM MAHER, 1971; EBASCO SERVICES, INC., 1980)

The resulting stratigraphic sequence rests directly upon what has been termed "basement"; however, the underlying basement rocks now are clearly known to vary, depending upon geographic location. Crystalline igneous and metamorphic rocks, as buried extensions of the Piedmont (ranging in age from Precambrian to as young as Permian), probably represent the most widely distributed units. Also constituting basement in different areas are continental sedimentary and igneous rocks associated with the Triassic-Jurassic (Newark) fault basins, metamorphic rocks of probable Paleozoic age, and unmetamorphosed Lower Paleozoic sedimentary strata.

The oldest exposed stratigraphic units are found to the west along the Fall Line area and belong to the Upper Cretaceous; most exposures (mainly along major streams) throughout the Coastal Plain contain Tertiary strata. Lower Cretaceous strata are entirely confined to the subsurface. Along the coastline and adjacent areas, unconsolidated sand and gravels as terrace, shoreline, and associated deposits of Pleistocene and Holocene age constitute the principal surficial material. Therefore, progressively younger units are exposed in a seaward direction within bands that roughly parallel the regional trend of the province. Throughout, the regional dip is gently to the east and southeast, but some local areas of reversal and higher rates are known.

Common characteristics of this sedimentary wedge, as noted by LeGrand (1961), include: (1) changes in lithologic expression in a downdip direction, generally from coarse-grained clastics to fine-grained clastics to carbonates; (2) thickening of individual stratigraphic units in a downdip direction; (3) the unconsolidated nature of most formations, except for some sand and clay units at great depth; and (4) a general decrease in porosity and permeability with depth. The exhaustive study by Brown et al. (1972), based upon appreciable data from boreholes and surface exposures, divided the sedimentary sequence into several chronostratigraphic units in an effort to quantify relationships between permeability and the various lithologies present. Earlier investigations (Murray, 1961; Richards, 1967; Maher, 1971) had followed the more conventional lithostratigraphic terminology employed by numerous other workers. Despite the departure from this established nomenclature, the regional correlations and detailed lithologic descriptions by Brown et al. (1972) probably represent the most comprehensive regional study of the Atlantic Coastal Plain sedimentary sequence to date.

There is relatively little observable geologic structure within the sedimentary strata proper. Large, broad regional features developed within the basement (and possibly reactivated through time) have exerted controls on the thickness, extent, and lithofacies patterns of the Cretaceous-Tertiary strata. Noteworthy among these broad basement features that represent thicknesses in the sedimentary sequence are embayments such as the Salisbury, Albermarle, and Southeast Georgia; positive features such as the Cape Fear and Peninsular Arches and Yamacraw Ridge constitute intervening "thins" in the sequence. No regional faults have been conclusively recognized in the Atlantic Coastal Plain. Small-displacement faults, generally near the Fall Line, have been observed in exposures and construction excavations (Mixon and Newell, 1977); lineaments noted from aerial photographs and satellite imagery have not been identified to date as faults, based on ground checking.

Ground water is a major resource for municipal, industrial, and agricultural use throughout nearly all areas in the Coastal Plain. Water-table (unconfined) aquifers in the highly permeable, shallow sand-gravel deposits yield up to 7,500 l/min in many areas (Sinott and Cushing, 1978). These shallow deposits are furthermore significant because they typically provide recharge to the updip subcrops of deeper, confined aquifers (Parker et al., 1964). From north to south, and throughout the sedimentary sequence, numerous sand and carbonate artesian aquifers are present. Possibly the most significant is the so-called Tertiary limestone aquifer (also called the Principal Artesian or Floridian aquifer), which extends throughout much of the southeastern part of the Coastal Plain and is one of the nation's largest and most heavily utilized sources of potable ground water (Stringfield, 1966).

Actually, many of these Coastal Plain artesian aquifers are systems in which more than one (in some cases, several) individual aquifer interval is involved (Cederstrom et al., 1979). Fresh water to depths of more than 600 m is known in central Florida, while other areas to the north obtain fresh water from depths as great as 300 m. In addition to the shallow Holocene-Pleistocene sand aquifers, fresh water is obtained from throughout the Tertiary sequence as well as from Upper Cretaceous units in certain areas.

Against this regional background, Ebasco Services, Inc. (1980) presented detailed data for four areas that have fine-grained intervals present below the level of fresh water, contain less than 25 percent limestone, and do not lie above any limestone-rich formations. These four areas are outlined in Figure 4-4 and include one area each in eastern Maryland, eastern North Carolina, southwestern Georgia and south-central Georgia. In the cases of southwestern Georgia and North Carolina, more than one subsurface interval of clay-rich strata was identified within each area. Bledsoe and Marine (1980) also reviewed the information on these areas, and the following is summarized from their report.

Of the four areas, those with zones (Table 4-1) designated Unit G (North Carolina; southwestern Georgia), Unit H (southwestern Georgia), and lower Paleozoic (no unit assigned) in south-central Georgia all are deeper than 900 m. Unit E underlying southwestern Georgia (Table 4-1) occurs toward the upper limit of the moderate depth range, but is closely associated with the Principal Artesian aquifer. Bledsoe and Marine (1980) also cited the potential for quick-sanding conditions in the overlying strata in the Unit E area.

Bledsoe and Marine (1980), also list several geotechnical characteristics about the area in eastern Maryland. The strata there show a significant degree of lithologic variation, and lie adjacent to shallow aquifers that are important sources of fresh water.

The remaining area involves Unit B (Upper Cretaceous Black Creek Formation) in eastern North Carolina (Table 4-1). Within that area, the interval consists largely of micaceous clay and shale laying at depths from 458 to 625 m below the land surface. The thickness of the clay-rich zone ranges from 65 to 93 m. Knowledge of this interval is based upon only two boreholes, separated by nearly 25 km. The general location is adjacent to Pamlico Sound and thus is in an area that possesses very low surface elevations and that periodically is subjected to hurricane-force storms with attendant tidal flooding. As in the case of the southwestern Georgia area, the engineering-geologic response of the unconsolidated,

TABLE 4-1. CLAY-RICH AREAS AND HOST ZONES, ATLANTIC COASTAL PLAIN (FROM EBASCO SERVICES, INC., 1980)

State/Location	Chronostratigraphic Terminology (after Brown and others, 1972	Age	Litho-stratigraphic Nomenclature
Eastern Shore, Maryland	Unit F	Lower Cretaceous	Potomac (Patapsco Fm.)
Pamlico Sound Area, Eastern North Carolina	Unit B	Upper Cretaceous	Black Creek Fm.
	Unit G	Lower Cretaceous	Undifferentiated Lower Cretaceous
Twenty-County Area, Southwestern Georgia	Unit E	Upper Cretaceous	Tuscaloosa-Atkinson Fms.
	Unit G	Lower Cretaceous	
	Unit H	Lower Cretaceous (Upper Jurassic?)	Undifferentiated Lower Cretaceous
Echols-Clinch Counties, South-Central Georgia	Not Applicable	Lower Paleozoic (Devonian)	Unnamed Unit

water-saturated sediments at shallower depths indicates lack of structural integrity.

Merewether et al. (1973) cited a thickness of up to 152 m for the Hawthorne Formation. The apparent source for this value is an earlier paper by Stringfield (1936); however, more recent literature indicates that the Hawthorn Formation not only displays a highly irregular thickness distribution but also is considerably thinner. The erratic thickness of this unit evidently stems from both its depositional genesis (deltaic to prodeltaic) and the presence of erosional unconformitites at its base (= top of the underlying Tampa Limestone) and at its top (Puri, 1953). Erosional removal of an appreciable part of the original upper Hawthorn is indicated throughout its widespread outcrop area, which extends from north-central and western Florida across Georgia in a northeasterly direction into adjacent South Carolina (Cooke, 1943, 1945).

Cooke (1943) estimated that the Hawthorn does not exceed 100 m in thickness anywhere throughout its extent and is thickest along the border between southwestern Georgia and northwestern Florida. Espenshade and Spencer (1963), from borehole data in the phosphate district of northern peninsular Florida, indicated that the Hawthorn Formation ranges in thickness from only 7 to 88 m but is only 30 m thick near its type locality in Alachua County, Florida. Within the Meigs-Attapulgus-Quincy district of southwestern Georgia and northwestern Florida, where fuller's earth and attapulgite clays are mined, the Hawthorn Formation is thin, or only about 30 m thick (Patterson, 1974). In the adjacent Southwest Georgia Embayment (also called Gulf Trough), the unit is nearly 85 m thick, but much of that increase is a basal sandy carbonate interval that in fact may be part of the underlying Tampa Limestone.

In addition to its extensive outcrop belt, the Hawthorn Formation appears confined to the shallow subsurface at depths of only a few hundred meters across northern Florida and adjacent Georgia. In southern Florida, the top of the unit reaches a maximum depth of 200 m (Parker and Cooke, 1944).

The Hawthorn Formation is lithologically variable and contains beds of phosphatic limestone and dolomite, phosphorite, quartz sands, and marls in addition to its clay-rich intervals. The noncarbonate, nonphosphatic units appear better developed west of the northern Florida peninsula (Espenshade and Spencer, 1963). The principal clay mineral is smectite (= montmorillonite), while attapulgite or palygorskite, a unique clay having amphibole-like characteristics including a fibrous to rod-like habit, is also abundant (Patterson, 1974). Some kaolinite is also present. Most of the industrial-clay deposits (fuller's earth and attapulgite) mined in the Meigs-Attapulgus-Quincy district are stratigraphically confined to the Hawthorn Formation, even though most of the lithologic expression is sand facies in which the clays occur as lenses. North of Lake City, Florida, the Hawthorn Formation also is commercially mind for phosphate.

Throughout the southern part of peninsular Florida, the Hawthorn Formation is overlain by the Tamiami Formation and is a freshwater aquifer (Cederstrom et al., 1979). Elsewhere throughout northern Florida and Georgia, the unit as a whole is a poor source of water, but sand lenses are productive locally. LeGrand (1962) also showed that such sands beneath several counties along coastal Georgia represent a valuable ground-water resource. Of greater significance is the fact that the Hawthorn Formation lies directly above either the Tampa or Ocala Limestone, both of which are integral portions of the Principal Artesian aquifer (Stringfield, 1966; Cederstrom et al., 1979).

The Hawthorn Formation is thin in many localities and contains a variable suite of lithologies that further reduces the net thickness of clay zones present. It also lies adjacent to the upper part of the region's major ground-water aquifer. This formation does not appear to exhibit the regional characteristics established for this report.

4.5 REGIONAL SUMMARY

Within the Eastern Margin region, only the Triassic (Newark) basins and possibly the Carolina Slate belt within the south-central Piedmont province represent large areas that contain argillaceous strata. Although the Atlantic Coastal Plain is an extensive area within this region and contains a large volume of Mesozoic and Cenozoic sediments, argillaceous units that are at least 75 m thick, are at a moderate depth, and that lack a close proximal association with important ground-water aquifers, do not appear to be present. The only possible exception may be a Cretaceous sequence in eastern North Carolina.

Most of the known Triassic basins are characterized by limited areal extent, significant local ground-water utilization, faulting, dike intrusions, highly inclined strata, pronounced lithologic variation, possible fault reactivation, and undetermined seismic conditions. Only the Durham and Wadesboro Basins in North Carolina appear to depart from this picture, but because of the general paucity of critical data needed to evaluate their geologic and hydrologic characteristics fully, definitive statements about these basins are not possible. Two other basins, the Dan River in Virginia and the nearby Danville in North Carolina, appear to contain several clay-rich zones within the stratigraphic intervals present. Some of the characteristics cited above pertain, however, to these basins.

Argillites and associated fine-grained units within the volcaniclastic sequence that marks much of the Carolina Slate belt appear to be thick and of reasonable lateral extent. They are characterized further by a low degree of metamorphism. There are numerous igneous intrusions and structural deformation. Economic mineralization is also possible. A general lack of meaningful subsurface data on the clay-rich units in this deformed belt constitutes a significant limitation to any in-depth evaluation.

Short of the widespread and commonly prolific aquifers beneath the Atlantic Coastal Plain, knowledge about the ground-water hydrology in both the Triassic basins and the Carolina Slate belt is extremely minimal. For all practical purposes, the nature of the ground-water systems below 300 m remains unknown, and considerable study will be needed before an adequate understanding is attained. With few exceptions, deep boreholes that could provide data about the sequences penetrated, stratigraphic relationships, structure, and ground water are lacking for the basins and the Carolina Slate belt. Appreciable future drilling, coring, well-bore logging, and hydraulic testing will be needed to answer even regional-level questions.

Because of the significant data gaps, especially pertaining to subsurface conditions at moderate depths, clear statements about whether thick and laterally extensive argillaceous units actually exist in any of these settings cannot be made at the present time.

5. GULF COAST

5.1 STRUCTURE AND GEOLOGIC FRAMEWORK

The Gulf Coastal Plain is a major physiographic province that extends from the Texas-Mexico border on the southwest to the Florida Panhandle in the east (Figure 5-1) and contains several thick Cenozoic clays. The northern limit of this region is marked by the updip limit of Tertiary strata, which make up a gulfward-thickening wedge of clastic sediments. Along the central Texas coast and in the Alabama-Florida area, this contact is within a few hundred kilometers of the Gulf of Mexico. The deposits extend much farther inland near the Rio Grande River, in east Texas, and along the Mississippi River. The latter area, known as the Mississippi Embayment, extends 350 km north into southern Illinois.

The Gulf of Mexico Basin (geosyncline) began to develop during Triassic time, when grabens, which formed beneath shallow, restricted seas, became the evaporating basins in which thick salt deposits accumulated during the Jurassic (Martin, 1978). Subsidence continued into the Cretaceous Period, when large volumes of detrital sediment were introduced from the rising continental areas via fluvial systems in the vicinity of the modern Rio Grande and Mississippi Rivers.

Since the end of the Cretaceous Period, the history of the Gulf Coast Basin has been characterized by varying sedimentation rates and fluctuating sea levels. The rate of sediment accumulation has generally exceeded the rate of subsidence, resulting in a long-term gulfward migration of the shoreline as the geosyncline filled.

During the Tertiary Period, depocenters migrated coastward and eastward from positions approximately 160 km inland from the present south Texas coast during the Eocene Epoch, to coastal Louisiana during the Miocene Epoch, and lastly to a position approximately 160 km off the Louisiana coast by Pleistocene-Holocene times (Martin, 1978).

As the geosynclinal axis migrated southeastward, the inland limits of sedimentation moved progressively gulfward. Thus, the oldest Tertiary sediments (Midway Group) occur at the updip limit of the Tertiary outcrop

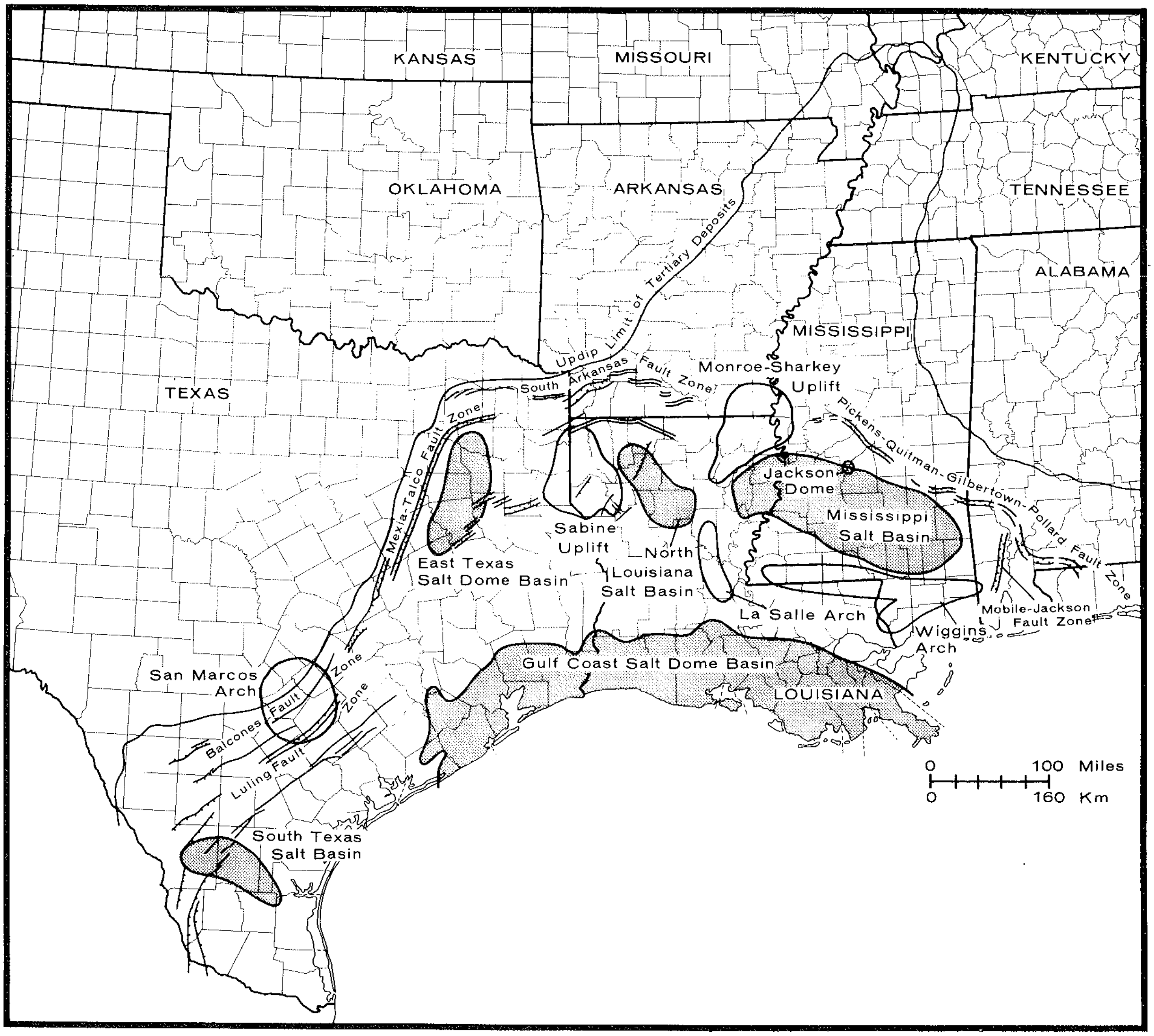

FIGURE 5-1. MAP OF GULF COAST REGION, SHOWING EXTENT OF TERTIARY DEPOSITS AND PRINCIPAL TECTONIC AND STRUCTURAL FEATURES (MODIFIED FROM AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, 1972; MARTIN, 1978)

belt, as shown in Figure 5-1. Because the geosyncline has continued to subside even to the present, younger sediments crop out gulfward and are tilted less than the older, deeper deposits. In general, formations thicken and become finer grained downdip, or nearer the center of active subsidence and more distant from the source of clastics.

Cenozoic deposits thicken from a few hundred meters near outcrop areas to more than 9,000 m off coastal Louisiana and more than 13,500 m along the southeast Texas coast. This same sequence, however, is only about 1,500 m thick along the Mississippi, Georgia, and Florida coasts (Williamson, 1959). A thinner and more limited wedge of Quaternary deposits overlies the Cenozoic in coastal Texas and Louisiana.

The resulting sedimentary sequence is complicated by numerous deltaic influxes that produced complex, wedge-shaped deposits of clay, silt, sand, and gravel in which abrupt lateral facies changes are common. Some units, such as marine clays, are relatively uniform and can be traced several hundred kilometers without significant variation.

Martin (1978), in describing the Cenozoic sedimentary wedge using the magnafacies approach of Caster (1934), noted that the deposits generally grade gulfward from continental deposits and deltaic sandstones to sequences of alternating sands and shales and lastly to deep-water marine shales, submarine fans, and turbidite sands formed on the continental slope.

The two principal structural features of the northern part of the Gulf Coast Basin are several salt-dome basins and the structurally high areas that separate them and the regional fault systems associated with the inner margin of the Tertiary embayment (Figure 5-1). The five salt-dome basins formed in areas of thick Jurassic salt accumulation as well as thick Cenozoic sedimentation, whereas the structural highs between these basins are considered to have had little or no salt accumulation (Murray, 1961). Salt domes are present in each basin and increase in number eastward from only six in the South Texas Basin to 77 in the largest interior basin (Mississippi Basin), whereas more than 135 onshore domes are known from the Gulf Coast Basin along the Texas and Louisiana coasts (Jirik and Weaver, 1976).

Salt domes formed from the upward flow of once-bedded salt in response to the overlying weight of the rapidly accumulating Cenozoic sediments. Rising from a "mother salt bed" (Louann Salt) at a depth of 9,000 m, the mobile salt uplifted and pierced the thick, overlying sediments and caused complex structures and stratigraphic relationships, many of which became hydrocarbon traps.

A fault system peripheral to the basin follows the outline of the Tertiary embayment through Texas and into Arkansas, where it turns eastward and terminates west of the Monroe-Sharkey Uplift. This same system begins anew in central Mississippi, where it turns southeastward to once more parallel the embayment border as far as western Florida. Martin (1978) divided this fault system into three components: (1) Triassic-Early Jurassic grabens along the inner margin of the Tertiary embayment, (2) Late Jurassic to Miocene grabens developed at the updip edge of the Louann Salt, and (3) Late Cretaceous, down-to-the-coast normal faults associated with the San Marcos Arch. Of these, the graben network that consists of the Balcones-Mexia-Talco, South Arkansas, and Pickens-Gilbertown-Pollard fault zones is the most prominent fault trend that affects Cenozoic deposits.

Although not shown in Figure 5-1, a complex and dense network of down-to-the-coast normal faults also disrupts Tertiary strata along the coastal margin of Texas and Louisiana. These fault trends are typically mappable for distances up to tens of kilometers and characteristically dip steeply near the surface and become less vertical with depth. Displacement also decreases with depth. Together with salt-related structures, these faults form numerous Gulf Coast petroleum traps.

5.2 REGIONAL SEISMICITY

The Gulf Coast is an area of low seismicity relative to the remainder of the continental United States. As shown in Figure 1-3a in the Introduction, most of coastal Texas and the coastal areas of Mississippi, Alabama, and Florida lie within Zone 0, where no damage is expected from earthquakes. All of Louisiana and most of Mississippi and Arkansas are in

Zone 1, where only minor damage may be expected. The northern part of the Mississippi Embayment is, conversely, one of the most seismically active areas in the eastern United States. Seismic-risk Zones 2 (moderate damage) and 3 (heavy damage) have been designated in this area.

Two of the most violent earthquakes ever recorded in this country occurred in the New Madrid, Missouri, area during 1811 and 1812 (von Hake, 1974b; Geotimes, 1979). These earthquakes were felt along the entire Atlantic seaboard north of Florida and as far south as New Orleans. A recently discovered fault zone in the basement of northeastern Arkansas has been postulated as the focus of the New Madrid earthquakes (Geotimes, 1979). This fault zone exhibits as much as 900 m of displacement and may still be active. Within the region, Mississippi and Louisiana have each recorded fewer than five earth quakes of MMI V, while the coastal plain of Texas has experienced fewer than 10 such earthquakes. The Tennessee-Missouri-Arkansas section (von Hake, 1974a, 1977a) of the Mississippi Embayment, however, has been subjected to numerous earthquakes (see Figure 1-2).

In an assessment of seismic risk within the interior part of the Gulf Coast, exclusive of the northern part of the Mississippi Embayment, Bechtel National, Inc. (1980) suggests that "very small sources" may be associated with known seismic activity and that adjustments along large regional fault systems are not indicated from historical seismic experience. This report also found that the seismic events tend to be somewhat random in location and indicative of "modest offsets during ... single earthquakes" and concluded that the interior Gulf region is tectonically inactive in that the stress release is aseismic.

5.3 REGIONAL HYDROLOGY

5.3.1 Surface Water

The major drainage systems of the Coastal Plain remain those established during the Cenozoic Era, namely, the Rio Grande-Neches in south Texas and the Mississippi River. Because the region is so large, climatic conditions are highly variable. Precipitation ranges from a minimum of slightly more than 50 cm per year in south Texas to more than 150 cm annually in southeastern Louisiana. Evaporation generally exceeds precipitation in Texas, but in the remaining coastal plain states, the reverse holds. Runoff increases from approximately 3 cm or less in southwestern Texas to 38 to 50 cm in the Mississippi Embayment and to as much as 75 cm in the Alabama-Georgia coastal area (McGuinness et al., 1963).

The largest surface-drainage system is the Mississippi River, which accepts approximately 60 percent of the runoff from the continental United States and produces a mean annual flow of 20,100 m^3/s. Principal streams west of the Mississippi River from east to west include the Atchafalaya, Sabine, Neches, Trinity, Brazos, and Colorado. East of the Mississippi, the primary streams are the Pearl, Alabama, and Chattahoochee Rivers.

5.3.2 Ground Water

Ground-water resources of the Gulf Coastal Plain are prolific and are described in numerous reports, the most comprehensive of which include (1) McGuinness et al. (1963); (2) a series of papers on the principal Cenozoic aquifers of the upper Gulf Coast by Payne (1968); (3) studies of the aquifers in the Mississippi Embayment by Cushing et al. (1964), Boswell et al. (1968), and Cushing et al. (1970); and (4) a series of U.S. Geological Survey Professional Papers that summarize the nation's ground-water resources (Baker and Wall, 1976; Terry et al. 1979).

The Gulf Coast province contains a series of layered, unconsolidated and semiconsolidated sand and gravel aquifers separated by clay layers that, in some cases, are regionally extensive. The oldest deposits that contain fresh water are Cretaceous sands and limestones, which occur at the inland edge of the Tertiary embayment. The youngest aquifers are surficial alluvial deposits along stream valleys. Cenozoic aquifer systems are highly variable with respect to volume and water quality.

Freshwater resources are, however, generally available from various Cenozoic aquifers throughout the region.

There are two types of aquifer systems: (1) confined artesian sands, silts, and gravels; and (2) shallow, water-table, alluvial aquifers in stream valleys and outcrop areas. The geohydrologic system can be described simply in terms of receiving recharge from precipitation in relatively high inland outcrop areas with a resultant gravity-induced flow of water downdip. Near-surface deposits may operate as water-table aquifers, but most of the ground water is stored in deeper artesian aquifers. Because of the complexity of the stratigraphic framework, a particular aquifer need not crop out at the surface in order to receive recharge. Many aquifers are recharged at depth from adjacent water-bearing sediments, either by direct contact or by slow seepage through confining, low-permeability clay layers.

Discharge of ground water occurs by lateral and vertical flow into stream valleys and discharge in the coastal areas (McGuinness et al., 1963; Payne, 1968). Jones (1969) reported that the deltaic sand sequences along the Louisiana coast are "closed gulfward" by confining marine clays that prevent discharge of ground water to the sea. Thus, as water is squeezed out of the subsiding and compacting sediment wedge, the only avenue for escape is landward. Jones concluded, therefore, that the coastline is an important zone of ground-water discharge from both inland and offshore areas.

Gulf Coast aquifers were either deposited in brackish to saline waters or were inundated and recharged with saline water during numerous sea-level rises. Decline in sea level since the Early Pleistocene has resulted in the gulfward (downdip) displacement of the saline water by fresh meteoric water recharged from upland areas. The depth to the base of fresh water is highly variable and depends upon factors such as effectiveness of fault barriers, volume of available recharge, and variations in aquifer permeability. The deepest occurrence of fresh water throughout the region approaches 1,500 m in northeast Texas. In southwest Mississippi and adjacent areas of Louisiana, fresh water is found as deep as 900 m, while throughout most of the Mississippi Embayment depths between 150 and 300 m are common. Along most coastal areas, fresh water is limited to the upper 50 m or less.

Ground water is an important resource in the Gulf Coast in that it is of consistent quality and temperature for municipal and industrial users. Among the principal population centers that rely upon ground water as their primary water supply are Houston, Baton Rouge, and Memphis. Pumpage has been sufficient in many local areas to cause declining water levels and to alter patterns of natural ground-water flow. In some areas, such as Houston and Baton Rouge, subsidence is occurring as the result of ground-water withdrawal, and declines in aquifer pressure have resulted (Holdahl and Morrison, 1974).

5.4 SHALES AND ARGILLACEOUS UNITS

5.4.1 Introduction

The argillaceous formations discussed here have been principally identified by reviewing published cross sections (based on mechanical logs) of the Cenozoic sequence. The following publications have been used in identifying those clays that are at least 75 m thick and lie within a depth range of 305 to 915 m: Cushing et al. (1964), Cushing et al. (1970), Shows et al. (1966), Hosman et al. (1968), Payne (1968), Taylor et al. (1968), Taylor and Thomson (1972), Newcome et al. (1972), Newcome (1975, 1976), Bebout et al. (1976), Bettandorff and Leake (1976), Boswell (1976a, 1976b), Jones et al. (1976), Spiers (1977a, 1977b), Spiers and Dalsin (1979), Baker (1979), and Brahana and Dalsin (1977).

Johnson (1975) and Mellen (1976) studied the Porters Creek Clay (Paleocene) as the Cenozoic clay in the region, while Mellen (1976) also studied the Yazoo Clay (Eocene). This study expands the data base for these units westward into Arkansas, Louisiana, and Texas.

Of the remaining Cenozoic clays, two units, the Cane River and Cook Mountain Formations within the Claiborne Group (Eocene), fall within the range of thickness and depth characteristics given in Chapter One. Both are widespread and, although arenaceous and thin in some outcrop areas, they increase in clay content and thickness with depth. Figure 5-2 summarizes the stratigraphic relations of the Gulf Coast Cenozoic.

5.4.2 Porters Creek Clay

5.4.2.1 Stratigraphy

The Porters Creek Clay is the thickest and most extensive of the Cenozoic clays within the Gulf Coast, and is the thickest subdivision of the Paleocene Midway Group. The name Porters Creek Clay was given to outcrops along Porters Creek near Millington, in Hardeman County, Tennessee, in 1864, by Safford, who described the unit as "dark, laminated, micaceous and in some places slightly arenaceous clay." A more current description of the Porters Creek Clay in Mississippi is that provided by Conant (1965):

> "The exposed Porters Creek Clay ranges in thickness from about 200 feet at the north end of Mississippi to about 500 feet where the outcrop belt passes into Alabama. It is a nearly black clay that, except for the upper part, is chiefly massive and has only indistinct lamination. Locally, parts of the formation, especially the massive ones, may be bentonitic ... but the formation as a whole does not have the characteristics of a sediment derived primarily from volcanic ash.
>
> "A three-fold division of the formation has been widely noted in Mississippi.... The lower unit ... has been described in the southern part of the State as a black massive clay containing foraminiferal shells and small lenses of sandy glauconitic, calcareous material in which are small molluscan and foraminiferal fossils.... In the northern part of the State the lower unit is very similar to the middle unit but differs from it in being somewhat glauconitic, harder, more noticeably bentonitic, and in having a green cast and a somewhat waxy appearance.
>
> "The middle unit is the typical near-black massive clay in which are inconspicuous thin and irregular laminae of very fine silt. "The

EAST TEXAS

SERIES	GROUP	FORMATION	THICK-NESS*
HOLOCENE		Alluvium	31m
PLEISTO-CENE		Willis Terrace	
PLIOCENE		Goliad	
MIOCENE		Fleming	442m
		Catahoula	122m
EOCENE	JACKSON	Whitsette• Manning Welborn Cadell-Moodys Branch	305m
	CLAIBORNE	Yegua	1,068m
		Cook Mountain•	
		Sparta	
		Cane River•: Weches QueenCity Reklaw	
		Carrizo	
	WILCOX	Sabinetown Rockdale Seguin	1,068m
PALEO-CENE	MIDWAY	Wills Point• Kincaid•	427m

*maximum

NORTH LOUISIANA

SERIES	GROUP	FORMATION	THICK-NESS*
HOLOCENE			107m
PLEISTO-CENE			31m
PLIOCENE		Citronelle	122m
MIOCENE		Pascagoula Hattiesburg Catahoula	488m
OLIGO-CENE	VICKSBURG		92m
EOCENE	JACKSON	Danville Land• Yazoo Clay• Moodys Branch	305m
	CLAIBORNE	Cockfield Cook Mountain• Sparta Cane River• Carrizo	458m
	WILCOX	Sabinetown Rockdale Seguin	1,098m
PALEO-CENE	MIDWAY	Porters Creek• Kincaid• Clayton	153m

MISSISSIPPI AND ALABAMA

SERIES	GROUP	FORMATION	THICK-NESS*
HOLOCENE			
PLEISTO-CENE			92m
PLIOCENE		Citronelle	122m
MIOCENE		Pascagoula Hattiesburg Catahoula	1,007m
OLIGO-CENE		Chickasawhay	122m
	VICKSBURG		
		Forest Hill Red Bluff	
EOCENE	JACKSON	Yazoo Clay• Moodys Branch	153m
	CLAIBORNE	Cockfield Cook Mountain• Kosciusko Zilpha• Winona Tallahatta Neshoba	763m
	WILCOX	Hatchetigbee Tuscahoma Nanafalia	1,220m
PALEO-CENE	MIDWAY	Naheola Porters Creek• Clayton	305m

FIGURE 5-2. CORRELATION CHART OF CENOZOIC STRATIGRAPHIC SECTION WITHIN GULF COAST, ARGILLACEOUS UNITS OF INTEREST ARE INDICATED

upper unit ... is much more variable but consists chiefly of alternate layers of the more typical massive black clay of the formation and dark finely sandy, micaceous clay. Unlike the two lower units, this one has a distinctly laminated or stratified appearance. Concretions of siderite, usually weathered to limonite, are common along some layers. Cross-bedded, micaceous, fine-grained sand that is present locally ranges in thickness from a few inches to as much as 50 feet and increases in abundance upward."

In the central part of the Gulf Coast region, the Midway Group consists of the basal Clayton Formation, a marl and clay unit that overlies the Cretaceous strata; the Porters Creek Clay; the Matthews Landing "marl", which is a glauconitic marine sequence having informal stratigraphic status; and the Naheola, a largely nonmarine sand, silt, and clay unit indistinguishable from the overlying Wilcox sands in the subsurface (Rainwater, 1964). Figure 5-3 shows the relationships of these stratigraphic units from eastern Alabama to central Texas.

Eastward into Georgia, the Porters Creek Clay thins, and the Midway Group is represented only by the Clayton Marl. Westward into Texas, the Porters Creek Clay is equivalent to the Wills Point Formation and in part to the Solomon Creek Clay, which has been considered both as part of the overlying Wilcox-age Seguin Formation and a member of the Wills Point. Here, the Kincaid Formation forms the basal part of the Midway Group and may also be equivalent in part to the lower portion of the Porters Creek Clay.

Penrose (1890) assigned the term Wills Creek Clays to outcrops near the town of the same name in Van Zandt County, Texas, and applied this designation to all clays between the Cretaceous and the overlying Wilcox Group. The term subsequently has been limited to clays below the Wilcox Group and above the Kincaid Formation (Sellards et al., 1932).

5.4.2.2 Geologic Setting

Throughout the Gulf Coast, the Porters Creek Clay and its equivalents are characterized as dark, organic, "firm" clays or shales. The unit

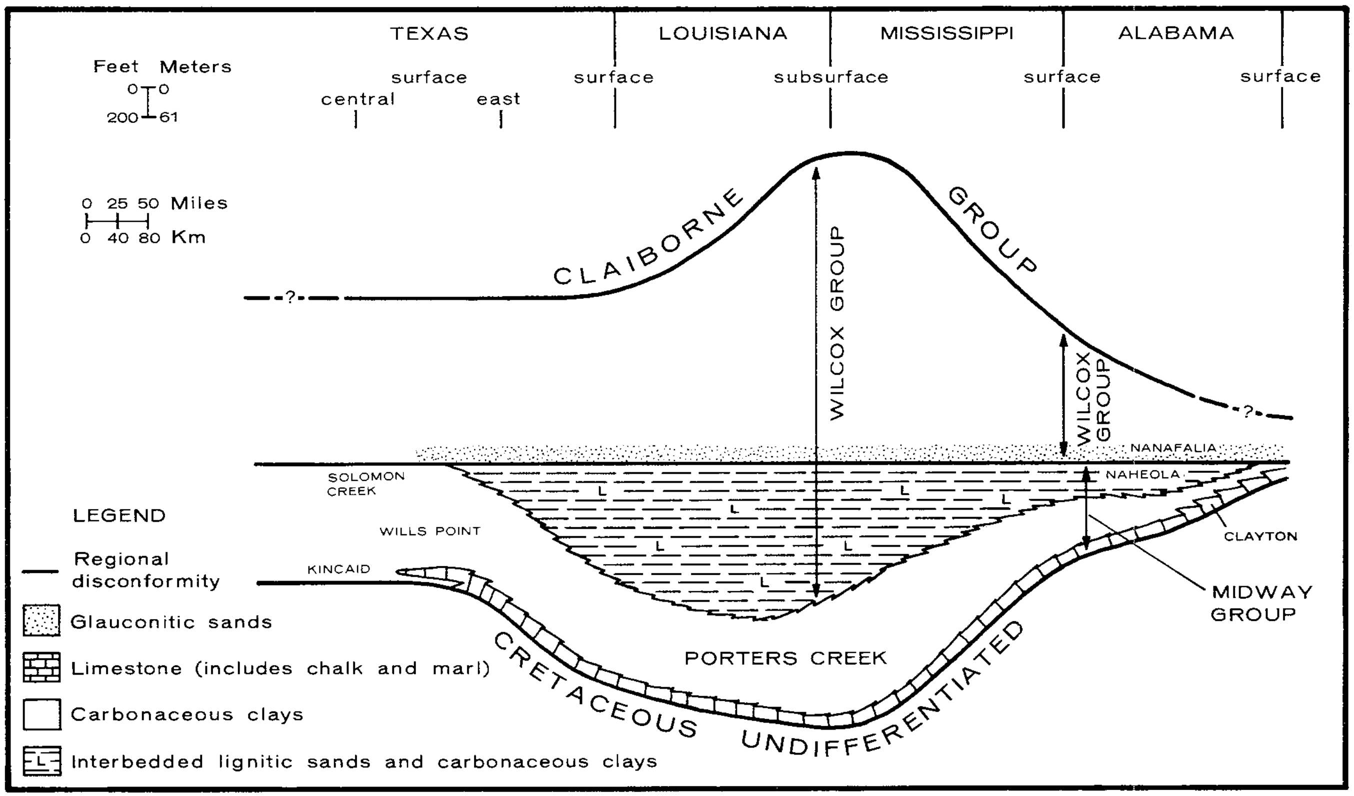

FIGURE 5-3. DIAGRAM OF GENERALIZED STRATIGRAPHIC RELATIONSHIPS BETWEEN PORTERS CREEK CLAY AND OTHER FORMATIONS IN THE MIDWAY AND WILCOX GROUPS OF THE GULF COAST (MODIFIED FROM MURRAY, 1961)

displays a distinctive pattern of low resistivity and low spontaneous potential on electric logs (Figure 5-4). This has led to the confident mapping of this unit from Florida to the Rio Grande River as the "Midway shale" (Murray, 1961).

The Porters Creek Clay dips principally gulfward but locally is inclined into the axial portion of the Mississippi Embayment. The narrowest subsurface extent of this unit within a moderate depth range throughout the Texas coastal plain occurs where the rate of dip is at a maximum.

The Mississippi-Arkansas region of the Mississippi Embayment contains the least complicated occurrence of the Porters Creek Clay. All the salt-dome basins and regional fault systems lie south of this area, and no oil or gas production has been established there. The northeastern part of the embayment, as it extends into northeastern Arkansas, western Kentucky and Tennessee, and southern Illinois, is conversely the most seismically active.

A unique structural anomaly has been produced in surface exposures of the Porters Creek Clay in west Tennessee. Clastic dikes were reported in the basal part of the unit in Madison County by Nyman (1965), and in Hardeman, Chester, and Henry Counties by Russell and Parks (1975). Vertical dikes of sand that extend an undetermined distance into the Porters Creek Clay from the underlying beds have been mapped in road cuts. These dikes range from 2 cm to 6 m in width and represent zones of potential ground-water migration within a unit of otherwise low permeability. Nyman (1965) postulated that saturated sand was forced into vertical fractures during movement of the Porters Creek Clay, possibly during settlement of the unit following deposition.

Mellen (1976) reported a significant and equally unique structural anomaly involving the Porters Creek Clay in Montgomery County, Mississippi. Here, complex faulting and reversals in dip affect the Porters Creek Clay and are developed over an area up to 16 km in diameter. This feature is called Kilmichael Dome and is believed to be an astrobleme or cryptoexplosive structure.

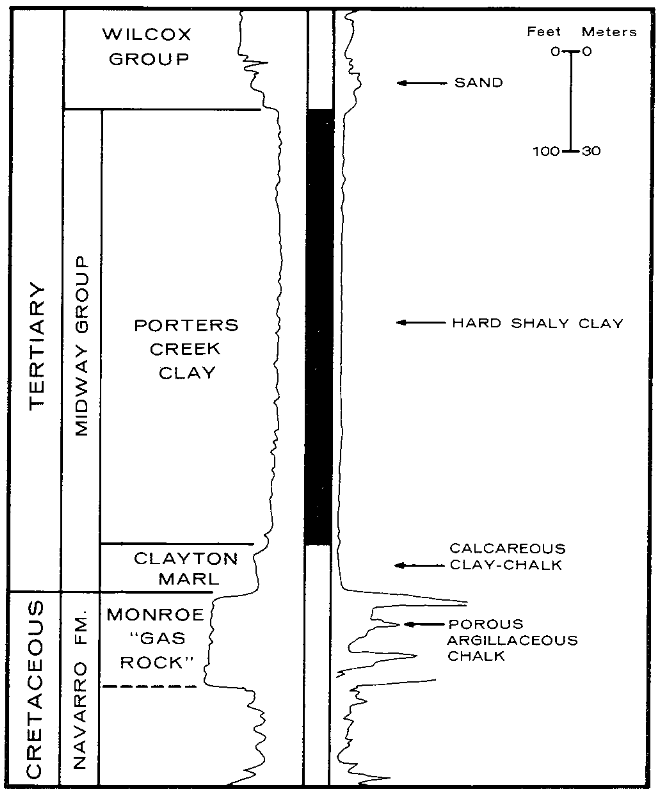

FIGURE 5-4. DIAGRAM SHOWING CHARACTERISTIC ELECTRIC-LOG RESPONSE OF PORTERS CREEK CLAY AS DOMINANT UNIT WITHIN MIDWAY GROUP OF GULF COAST (MODIFIED FROM WANG, 1952)

The Porters Creek Clay is draped over the Sabine and Monroe-Sharkey structural highs in north Louisiana. Structural warping and faulting, generally located off the flanks of these uplifts and in the adjacent North Louisiana Salt Dome Basin, displace Tertiary and Cretaceous strata and create prolific oil and gas traps. In northwestern Louisiana, the Porters Creek Clay has been displaced within the salt-dome basin by faulting associated with the Rodessa and Hosston fault systems. Salt domes of the Mississippi Basin have uplifted and pierced the Porters Creek Clay, whereas the Pickens-Quitman-Gilbertown-Pollard fault system intersects the formation downdip near a depth of 900 m. These faults, together with the Mobile-Jackson fault system, displace the formation in southern Alabama and northwestern Florida.

The outcrop pattern of the Midway Group is shown in Figure 5-5, which also indicates the subsurface interval in which the Porters Creek Clay lies between 305 and 915 m below the land surface. The formation is thicker than 150 m in most of the area with the exception of the northeastern corner of Louisiana and the western and northern parts of the Mississippi Embayment. The thickest expression of this argillaceous formation occurs along the axis of the Mississippi Embayment in central Mississippi, where the unit exceeds 300 m in thickness.

In Texas, the most widespread extent of the Porters Creek Clay (represented by its stratigraphic equivalent, the Wills Point Formation) within the appropriate depth interval occurs within the East Texas Embayment. Salt dome structures and faulting in and around the East Texas Basin and the Sabine Up lift are, however, sites of extensive petroleum production. To the southwest, the Wills Creek Clay, although at favorable depths, is affected by the Mexia-Talco and Balcones fault zones. Numerous oil and gas fields also have been discovered here.

Despite the general abundance of structural complexities throughout the southern region in which the Porters Creek Clay (or equivalents) lies at moderate depth, large areas measured in hundreds of square kilometers exist in Texas, Louisiana, Mississippi, and Florida where the clay is a continuous unit with minor structural variations and limited borehole penetrations.

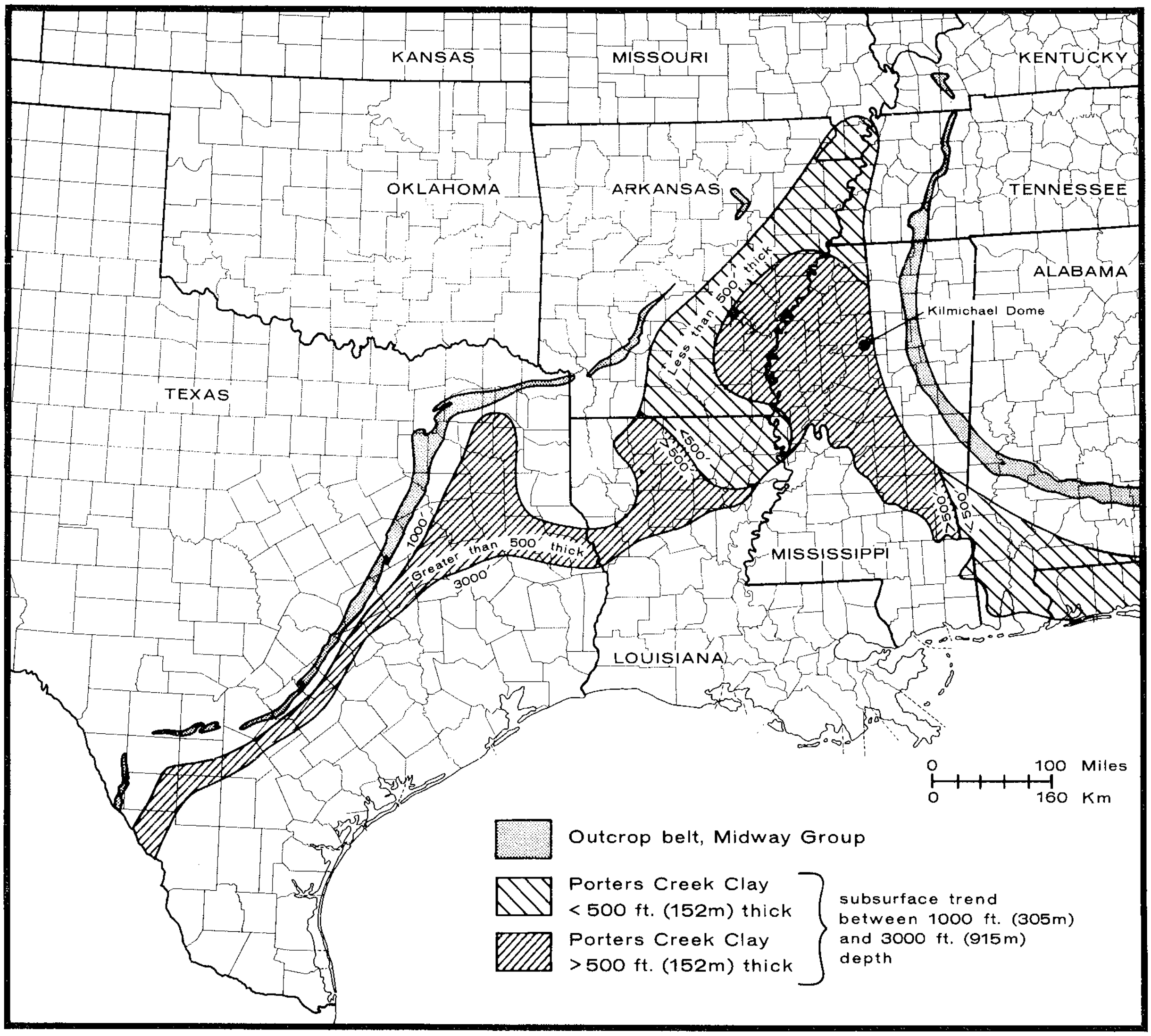

FIGURE 5-5. MAP SHOWING OUTCROP BELT OF MIDWAY GROUP, AND DISTRIBUTION AND THICKNESS OF PORTERS CREEK CLAY WITHIN THE MODERATE DEPTH RANGE

5.4.2.3 Mineralogy and Rock Properties

Bennett (1976) studied the physical, chemical, and mineralogical properties of the Porters Creek Clay from samples collected at surface exposures in the northern Mississippi Embayment. He reported that the nonclay portion was largely detrital quartz but that secondary goethite and other crystal growths were common. Analyses of the clay composition from four locations are presented in Table 5-1; these data show that smectite is the dominant clay-mineral group in almost all samples but that illite and kaolinite are also important constituents.

Sims (1972) also studied the Porters Creek Clay, except that his samples came from western Kentucky, where the formation is relatively high in sand content. Analyses showed from 5 to 50 percent silica in the form of quartz. Silica as cristobalite was also present in most samples and ranged from 2 to 35 percent. In order of relative abundance, clay minerals present include montmorillonite, kaolinite, mixed-layer types, illite, and chlorite. Evidence for a volcanic origin for this part of the formation is based upon the occurrence of glass shards in the unit here and the presence of volcanoclastic material in "equivalent" rocks of Mississippi (Sims, 1972).

The following physical characteristics were determined for the Porters Creek Clay from Caddo Parish, Louisiana, in a foundation analysis (Boutwell, personal communication, 1980): strength = 0.19 MPa; density = 1,954 kg/m^3; plasticity index = 40.

5.4.2.4 Hydrology

The Porters Creek Clay is a relatively impervious clay that separates the freshwater sands of the Paleocene Wilcox and younger Tertiary aquifers from deeper Cretaceous sands and limestones that are typically freshwater reservoirs within only a few tens of kilometers from their outcrop areas. The Porters Creek Clay thus marks the base of fresh and slightly brackish ground water in a large part of the area between outcrop and the 3,000-ft-(915-m) depth contour shown in Figure 5-5. Inasmuch as fresh

TABLE 5-1. CLAY MINERALOGY OF 31 SAMPLES OF PORTERS CREEK CLAY FROM ILLINOIS, MISSOURI, AND TENNESSEE (MODIFIED FROM BENNETT, 1976)

	Clay Minerals (in weight percent)					
Samples	**Smectite**	**Mixed-Layer**	**Illite**	**Kaolinite**	**Kaolinite-Chlorite**	**Chlorite**
Olmstead, Illinois						
Top 0675-7	79	4	6	11		
0675-6	36		36	28		
0675-5	65	1	15	19		
0675-4	84		12	4		
0675-3	67		14	19		
0675-2	63	3	16	18		
0675-1	67		18	15		
012276-2	59	5	28	8		
Base 012276-1	51	6	32	11		
Paris, Tennessee						
Top P12376-3	47	5	14	34		
P12376-2	64	3	9	24		
P12376-1	73	1	5	21		
P775-3	42		15	43		
P775-2T	41		18	41		
P775-2B	32		33	35		
P775-1T	38		17	48		
Base P775-1B	38		21	41		
Bloomfield, Missouri						
Top B775-9	37	21	28		14	
B775-8	69		14		17	
B775-7	61		26		13	
B775-6	48	7	30		15	
B775-5	52	7	28	12-1		1-11
B775-4	83	2	6		9	
B775-3	56	8	24		12	
B775-2	75		13		12	
Base B775-1	75		15		10	
Oran, Missouri						
Top R12476-2	66	8	18	8		
R12476-1	51	8	28	13		
R775-3	80	2	10	8		
R775-2	70	5	14	11		
Base R775-1	71	4	15	10		

water commonly extends to a depth less than 600 m throughout the Gulf Coast, the top of the Porters Creek Clay is separated from freshwater aquifers by several hundred meters of more saline aquifers over a sizable segment of the subsurface area of interest.

No analyses of the hydraulic conductivity of the Porters Creek Clay have been reported. Based on descriptions of typical outcrops, a value as low as 1 x 10-8 cm/s would seem reasonable. Higher values might be expected where the unit contains silt, and even higher values where sand lenses or jointing and faulting are present.

Sands in the overlying Wilcox Group serve as potentially useful aquifers for freshwater supplies in extreme northeast Arkansas, as well as in Mississippi along a band extending some 115-km downdip from the outcrop of the Midway Group. The principal withdrawal area for the lower Wilcox aquifer is the Memphis, Tennessee, area (Hosman et al., 1968). The potentiometric surface in this aquifer indicates that the ground water flows westward toward the center of the Mississippi Embayment and that a significant decline in water levels has developed at Memphis.

In Texas, the Midway Group is overlain by freshwater resources in the Carrizo-Wilcox, Sparta, and Queen City sands, which extend from east Texas to the Rio Grande Valley. These aquifers, where freshwater-bearing, are shallower than 300 m.

Any subsurface utilization of the Porters Creek Clay would require penetration of productive or potentially productive aquifers within the Mississippi Embayment. Important aquifers that overlie the Midway Group within the embayment include Quaternary alluvium in the Mississippi River Valley, the Cockfield Formation, the Sparta Sand, and the Wilcox Group. The greatest vertical separation between the Midway Group and overlying freshwater resources is found in northeasternmost Louisiana, where the top of the Porters Creek Clay is almost 900 m deep and the base of fresh water is as shallow as 90 m (Winslow et al., 1968).

5.4.2.5 Mineral Resources

The Porters Creek Clay is recovered from numerous outcrops as a source of clay for pottery and bricks. The unit is also mined for bentonite in Mississippi and is a source of material suitable for lightweight aggregate in western Alabama (Clarke and Tyrrell, 1976). Mineral development from the unit has been limited to these clay mines, with the exception of a unique oil reservoir that produces from sands within the Wills Point Formation in Wilson and Gonzales Counties, Texas. Production there is found in faulted, offshore-bar sands that lie along strike at depths less than 825 m (Hopf, 1965).

Bauxite occurs at the Midway-Wilcox contact in Alabama, Arkansas, and Mississippi, although mining of this resource has been limited to outcrops in only the former two states (Gordon et al., 1958; Conant, 1965). The Porters Creek Clay also forms the "cap" for the Monroe Gas Field in northern Louisiana and lies above numerous other pre-Tertiary oil and gas reservoirs.

5.4.3 Cane River Formation

5.4.3.1 Stratigraphy

The Cane River Formation was originally named and described by Spooner (1926) for exposures along the Cane River at Nachitoches, Louisiana. In Bienville and Bossier Parishes, the unit was described as varying from glauconitic sands to sands. Spooner also reported that well cuttings revealed that the Cane River Formation consists "chiefly of glauconitic clays with subordinate beds of sand."

In western Louisiana, Andersen (1960) described the Cane River as "a basal glauconitic fossiliferous sand similar to the lithology of the Weches Formation in east Texas and an upper silty clay unit probably equivalent to the Therril clay of Texas." In an exposure along the Sabine River, Andersen (1960) further described the unit as follows:

"approximately 25 feet of highly glauconitic, argillaceous silts and sands with lime ledges." He noted that in southern Sabine Parish, where the formation dips below 300 m in the subsurface, the unit is approximately 75 m thick and is principally a clay.

The Cane River Formation is the oldest marine glauconitic-clay unit in the Eocene Claiborne Group. Murray (1961) defined the typical Claiborne sequence from Mississippi to Texas as containing the following formations (from oldest to youngest): Reklaw, Queen City, Tallahatta-Neshoba, Weches, Cane River, Winona, Zilpha, Sparta, Cook Mountain, and Cockfield or Yegua.

Claiborne time represented a period of cylic sedimentation in the Gulf Coast region (Dixon, 1965). Both the Cane River and Cook Mountain Formations resulted from major marine transgressions and are the only gulfwide argillaceous units within the Claiborne Group. The Cockfield, Sparta, Winona, and Tallahatta Formations are predominantly arenaceous facies developed during sediment influx and marine regressions. The Cane River Formation furthermore is considered equivalent to and continuous with the Weches Formation of Texas and in part the Zilpha Clay in Mississippi (Figure 5-6). To the east of Mississippi, equivalent units become calcareous and are not considered here.

5.4.3.2 Geologic Setting

Like many other strata of the Gulf Coast Cenozoic series, the Cane River Formation dips toward the axis of the Mississippi Embayment as well as principally gulfward. Areas where the unit exceeds 75 m in thickness occur in a northeast-trending band across central and northeastern Louisiana (Figure 5-7). Much of this trend, however, produces oil and gas and lies within the western end of the Mississippi Salt Dome Basin. The most extensive thick subsurface belt of the Cane River Formation occurs at the common corner of Louisiana, Arkansas, and Mississippi on the Monroe-Sharkey Uplift.

The Cane River Formation varies in thickness from only a few meters to nearly 600 m in outcrops throughout the central Gulf region. The unit

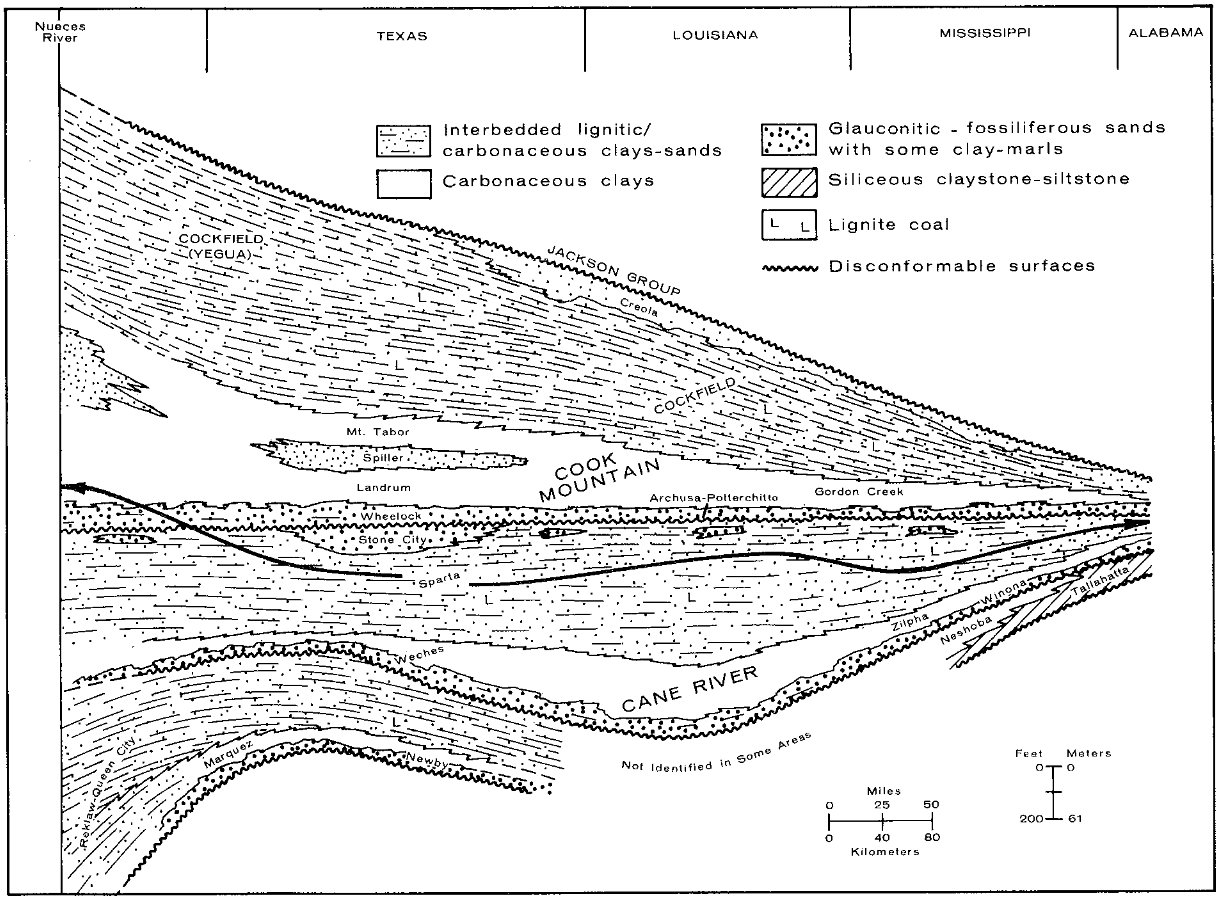

FIGURE 5-6. DIAGRAM OF GENERALIZED STRATIGRAPHIC RELATIONSHIPS BETWEEN CANE RIVER AND COOK MOUNTAIN FORMATIONS AND OTHER CLAIBORNE GROUP UNITS OF GULF COAST (MODIFIED FROM MURRAY, 1961)

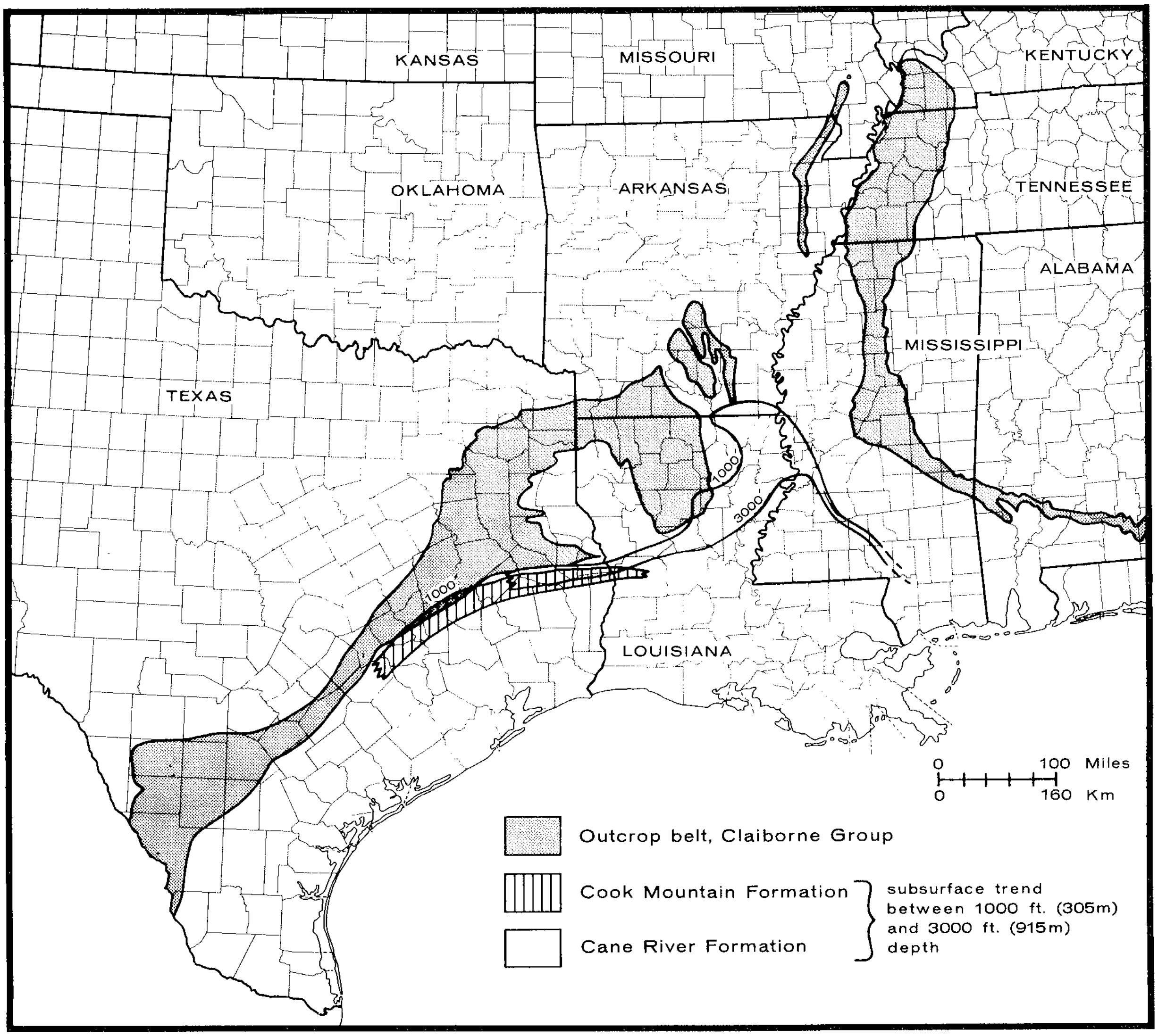

FIGURE 5-7. MAP SHOWING OUTCROP BELT OF CLAIBORNE GROUP, AND DISTRIBUTION OF CANE RIVER AND COOK MOUNTAIN FORMATIONS WITHIN THE MODERATE DEPTH RANGE

thickens downdip to 120 m in east Texas within the appropriate depth interval but appears from electric logs to contain considerable silt and thus exhibits higher permeability. In the Louisiana-Mississippi area of the Mississippi Embayment, the Cane Formation is approximately 90 to 120 m thick and is predominantly a marine clay (Hosman et al., 1968). In updip areas of Arkansas, northwestern Louisiana, and northeastern Texas, the middle portion of the formation becomes sufficiently sandy to constitute an aquifer or to merge with adjacent aquifers such as the Queen City Sand. Of significance is the fact that only the updip portion of the formation contains such porous beds and that the subsurface interval of interest here appears to be a rather consistent marine clay.

From central Louisiana into Texas along the southern flank of the Sabine Uplift, the subsurface portion of the Cane River Formation lying at moderate depth is only 16 to 24 km wide. This region, moreover, is virtually devoid of oil and gas production and lacks any significant faults. The typical electric-log response for the Cane River Formation and other units of the Claiborne Group is illustrated in Figure 5-8.

5.4.3.3 Mineralogy and Rock Properties

The Cane River Formation is characterized as a glauconitic clay with sparse sand beds. Beyond this general description, information on the mineralogical and physical nature of the formation is very limited. The following analyses were provided from files of the Louisiana State Geological Survey on clay samples analyzed for their ceramic properties (Dixon, personal communication, 1980):

Sample no. LGS-874, Natchitoches Parish, Louisiana:

X-ray analysis:	88 %	montmorillonite, mixed-layer montmorillonite-illite
	12 %	kaolinite (no chlorite or illite)
Grain-size analysis:	4.8 %	coarse and medium sand
	7.2 %	sand
	19.2 %	silt (calculated)
	68.8 %	clay

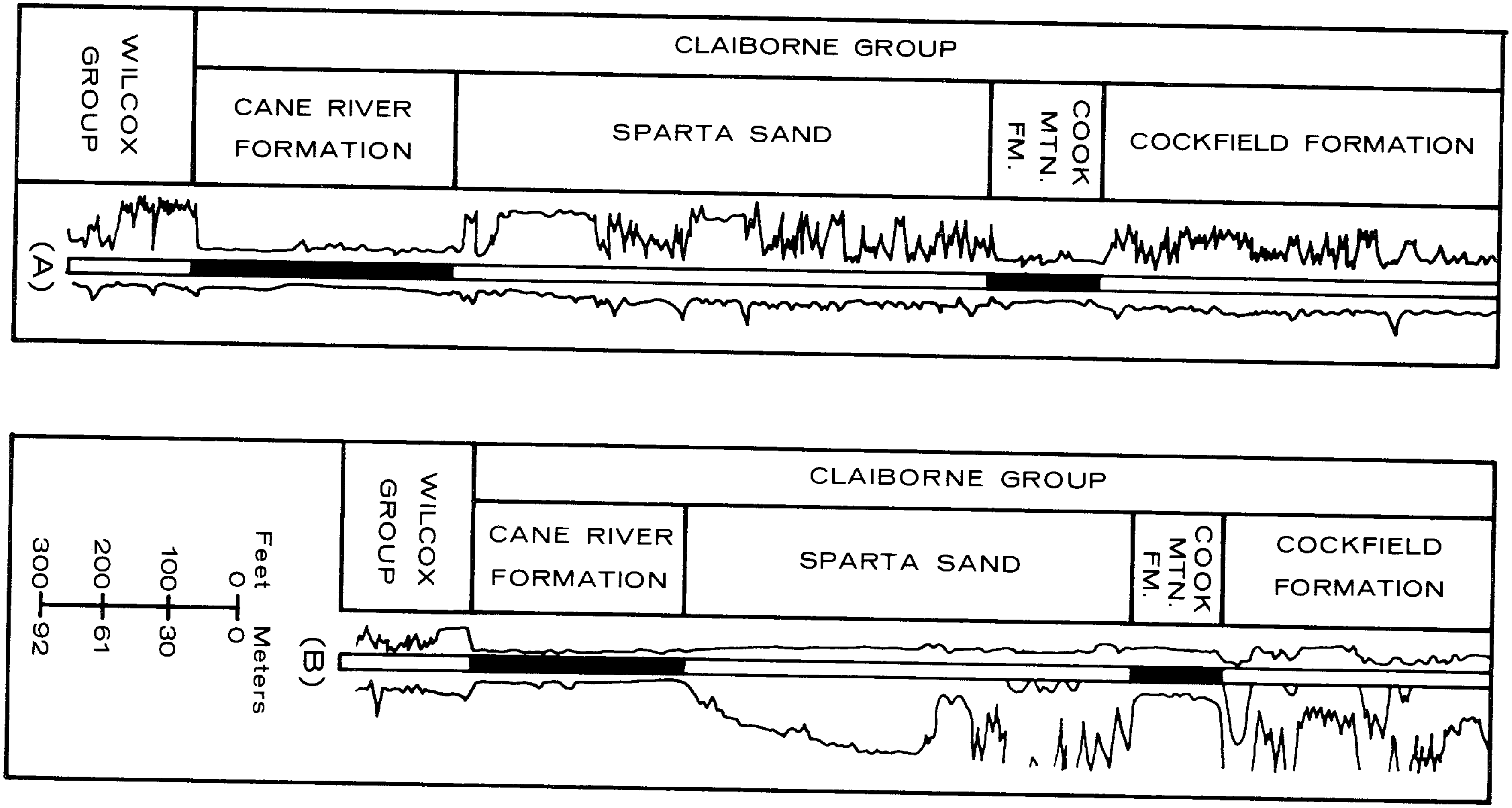

FIGURE 5-8. DIAGRAM SHOWING ELECTRIC-LOG RESPONSES FOR CANE RIVER AND COOK MOUNTAIN FORMATIONS IN COMPARISON TO OTHER CLAIBORNE GROUP UNITS (MODIFIED FROM ROLLO, 1960)

Sample no. LGS-863, Bienville Parish, Louisiana:

X-ray analysis:	71 %	montmorillonite
	17 %	illite
	12 %	kaolinite
Grain-size analysis:	1.04%	coarse and medium sand (glauconite)
	11.53%	fine sand (glauconite)
	22.23%	silt (calculated)
	65.20%	clay

No analyses of the physical properties of the Cane River Formation were found.

5.4.3.4 Hydrology

In the subsurface, the Cane River Formation is a marine clay of low permeability. Hydraulic characteristics, however, are available only for the updip arenaceous facies of the unit where significant aquifers are developed. In the northern Mississippi Embayment, sands developed in the upper part of the formation constitute a part of the Memphis aquifer, which is an important water-supply source in the northern Mississippi Embayment and is the principal aquifer for the city of Memphis, Tennessee (Hosman et al., 1968). In Mississippi, the Cane River is continuous with the Meridian Sand of the Tallahatta Formation, which is an aquifer in the northern part of that state. In northwestern Louisiana, east Texas, and western Arkansas, the typical argillaceous facies becomes sandy and merges with the Queen City Sand (Hosman et al., 1968).

Utilization of sands in the Cane River Formation for water supplies has generally been limited to domestic wells, but some large-volume systems have been developed in northern Louisiana and Texas, where these sands merge with the underlying Carrizo Sand to form thick, permeable aquifers. Further information concerning ground-water conditions in aquifers within the sandy phase of the formation and units surrounding the Cane River Formation within the Mississippi Embayment is presented by Hosman et al. (1968).

5.4.3.5 Mineral Resources

The Cane River Formation does not rank with other Gulf Coast argillaceous units, such as the Porters Creek and Yazoo Clays, as an economically important resource for clay products, owing to its arenaceous composition in areas where it lies at the surface. The unit, however, has been the source of brick clay for one processor in Bienville Parish, Louisiana (Dixon and Tyrrell, 1972). The most significant economic use of the formation involves development of important freshwater supplies in updip areas. Ground-water pumpage from this unit is limited to the far updip areas, and does not affect the downdip marine-clay facies (Figure 5-8).

5.4.4 Cook Mountain Formation

5.4.4.1 Stratigraphy

The name Cook Mountain Formation was originally suggested by Kennedy (1892) for exposures at Cook Mountain, in Houston County, Texas. Kennedy's descriptions of the greensands, glauconitic sandstones, and clays that occur at that locality actually apply to a unit now known as the Weches Formation, which is a stratigraphic equivalent of the older Cane River Formation. Deussen (1924) clarified this issue by applying the name Cook Mountain Formation to those marine units lying directly below the Vicksburg-age Yegua (Cockfield) Formation.

Ellisor (1929) and Wendlandt and Knebel (1929) applied the name Crockett Formation to certain exposures of bentonitic clay in Houston County, Texas, to the Cook Mountain equivalent in eastern Texas. Sellards et al. (1932) describe the Crockett (= Cook Mountain Formation) in east Texas as consisting of "about 90 percent fine sediments, clay shale and sandy shale, 9 percent medium-grained sediments, sands and glauconite and 1 percent rock, limestone and ferruginous concretions. In south Texas it contains a larger proportion of sands and sandy clay. The glauconite is distributed uniformly through the sands and sandy clays and does not occur in thick, pure beds as in the Weches.... The clays are bluish gray to black, weathering to buff and yellow colors."

5.4.4.2 Geologic Setting

The Cook Mountain Formation, like the deeper Cane River Formation, is a marine argillaceous unit of Claiborne age whose eastward-thinning and lithologic expression throughout the central Gulf Coast region can be seen in Figure 5-6.

Farther westward in Texas, the equivalent Crockett Formation can be distinguished from other Claiborne units by its predominance of clay, relative lack of arenaceous zones (lentils), thickly bedded zones of glauconite, and a large content of fossils (Sellards et al., 1932). A well drilled in Angelina County of east-central Texas penetrated 139 m of the Crockett Formation, which was described by Wendlandt and Knebel (1929) as being sticky to hard shale.

Cross sections along the Texas coast reveal that the Cook Mountain Formation is from 120 to 150 m thick within the depth range selected for this report. The formation, however, only meets the thickness and depth ranges adopted in Chapter One along the northern half of the Texas coast (Figure 5-7). In the remaining regions of the Texas coast, the Cook Mountain Formation is excessively arenaceous. To the east in Louisiana and Mississippi, the unit thins appreciably.

5.4.4.3 Mineralogy and Rock Properties

A number of analyses of the Cook Mountain Formation in Louisiana indicate that the clay fraction of the unit is largely mixed-layer clays with chlorite and montmorillonite dominant (Dixon, 1967). In east Texas, the formation is a bentonitic clay composed entirely of montmorillonite (Fisher, 1965). The most common nonclay components in this bentonitic phase are quartz and feldspars with traces of mica, tourmaline, and zircon and other heavy minerals. No rock mechanical data about the Cook Mountain Formation are available in the published literature.

5.4.4.4 Hydrology

The Cook Mountain Formation is not an aquifer but rather serves as a major confining unit in Texas and Louisiana, where it separates the Sparta Sand from the overlying Yegua Formation (Terry et al., 1979). Along the Texas northern coast where the Cook Mountain Formation is at moderate depth, the formation lies at the boundary between two major aquifer systems. These are the Carrizo-Wilcox inland and the Gulf Coast aquifers (= Catahoula and younger sands) gulfward (Baker and Wall, 1976). In the central Texas coast, the unit is also coincident with the productive area of the Sparta Sand. Subsurface utilization of this formation would thus require penetration of a fresh-water aquifer in most areas.

5.4.4.5 Mineral Resources

The Cook Mountain Formation is a potential clay resource, mainly for nonceramic uses, throughout its outcrop belt in Texas and Louisiana. No commercial subsurface utilization of the argillaceous part of this unit has occurred to date.

5.4.5 Yazoo Clay

5.4.5.1 Stratigraphy

The youngest Cenozoic argillaceous unit described in this report is the Yazoo Clay. As originally applied by Lowe (1915), the name, Yazoo Clay, referred to clays in the upper part of the Eocene Jackson Group as exposed in a bluff along the Yazoo River at Yazoo City, Mississippi. The outcrop was described as "dark-colored lignitic clay strata toward the base, with thin lignite beds at some points near Yazoo City. The bulk of the exposure, however, consists of drab or yellowish calcareous clays, showing heavy bedding and distinct jointing."

In Yazoo County, Mississippi, Mellen (1940) described the formation as consisting of two distinct units, a lower zone composed of 106 m of silty, calcareous, fossiliferous, plastic montmorillonitic clay, and an upper zone that contains "relatively pure beds of massive, gummy, noncalcareous montmorillonitic clay, beds of interlaminated silt and silty clay, a thin bentonite, and lentils of limestone and marl." This upper unit is 45 m thick.

Murray (1961) mapped the Yazoo Clay as four distinct zones within the Jackson Group of Mississippi and Alabama (Figure 5-9). From oldest to youngest, these divisions are the North Creek Clay, Cocoa Sand, Pachuta Marl, and Shubuta Clay. Murray also distinguished three regionally distinct facies in the Jackson Stage of the Gulf Coast: (1) Ocala for the predominantly calcareous phase east of Mississippi, (2) Yazoo for the dominantly arenaceous-argillaceous deposits in the central Gulf, and (3) Fayette Group for the increasingly argillaceous-arenaceous deposits in central and south Texas.

5.4.5.2 Geologic Setting

Based upon electric logs, the Yazoo Clay is not readily divisible into the units mapped at the surface in Louisiana and Mississippi; therefore, it is treated as a single formation in the subsurface mapping throughout much of the Gulf Coast. In this report, the Yazoo Clay is considered the low-resistivity clay zone that occurs above the Moodys Branch Marl of early Jackson age (a consistent marker throughout the region) and below the more arenaceous sediments of the Vicksburg Group. In some areas, such as in Texas and north Louisiana where the Whitsett Formation occurs, the Vicksburg Group is not separable from the Yazoo Clay (Rollo, 1960). In such cases, the two intervals are included in a single mappable unit (Figure 5-10). In central Louisiana (Evangeline and St. Landry Parishes) the Yazoo Group is considered transitional from the Moodys Branch below and the Vicksburg sediments above (Varvaro, 1957).

The outcrop belt of the Jackson Group, which is dominated by the Yazoo Clay, is shown in Figure 5-11, as is the subsurface trend where predominantly clay sections thicker than 75 m occur at moderate depth. The Jackson Group essentially parallels the coastline and thickens

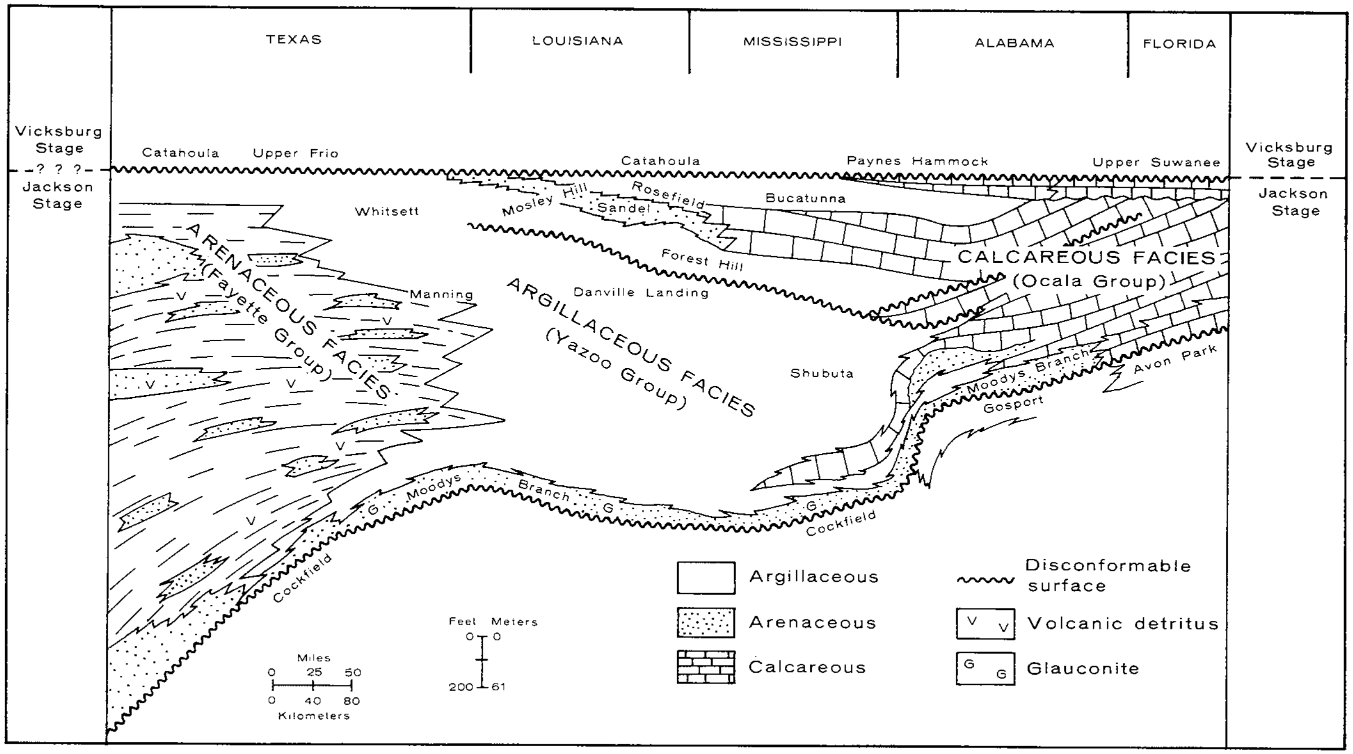

FIGURE 5-9. DIAGRAM SHOWING STRATIGRAPHIC RELATIONSHIPS OF YAZOO CLAY AND OTHER JACKSON AND VICKSBURG UNITS (MODIFIED FROM MURRAY, 1961)

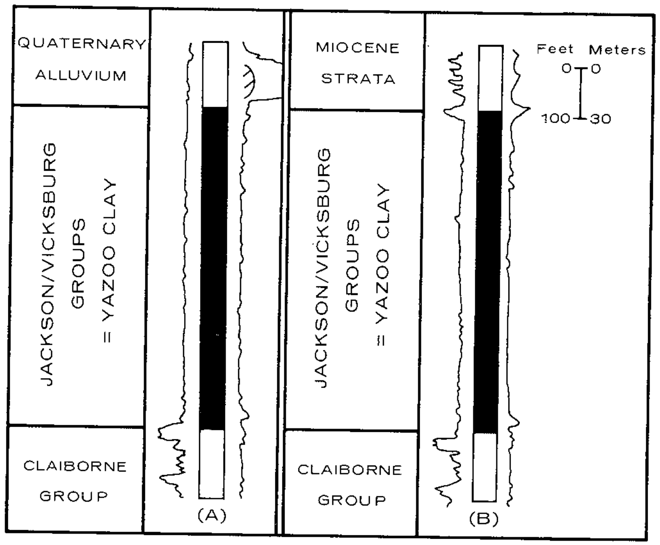

FIGURE 5-10. DIAGRAM SHOWING TYPICAL ELECTRIC-LOG RESPONSE OF JACKSON AND VICKSBURG GROUPS (= YAZOO CLAY) WHERE OVERLAIN BY ALLUVIUM (A) AND BY MIOCENE STRATA (B). (MODIFIED FROM ROLLO, 1960)

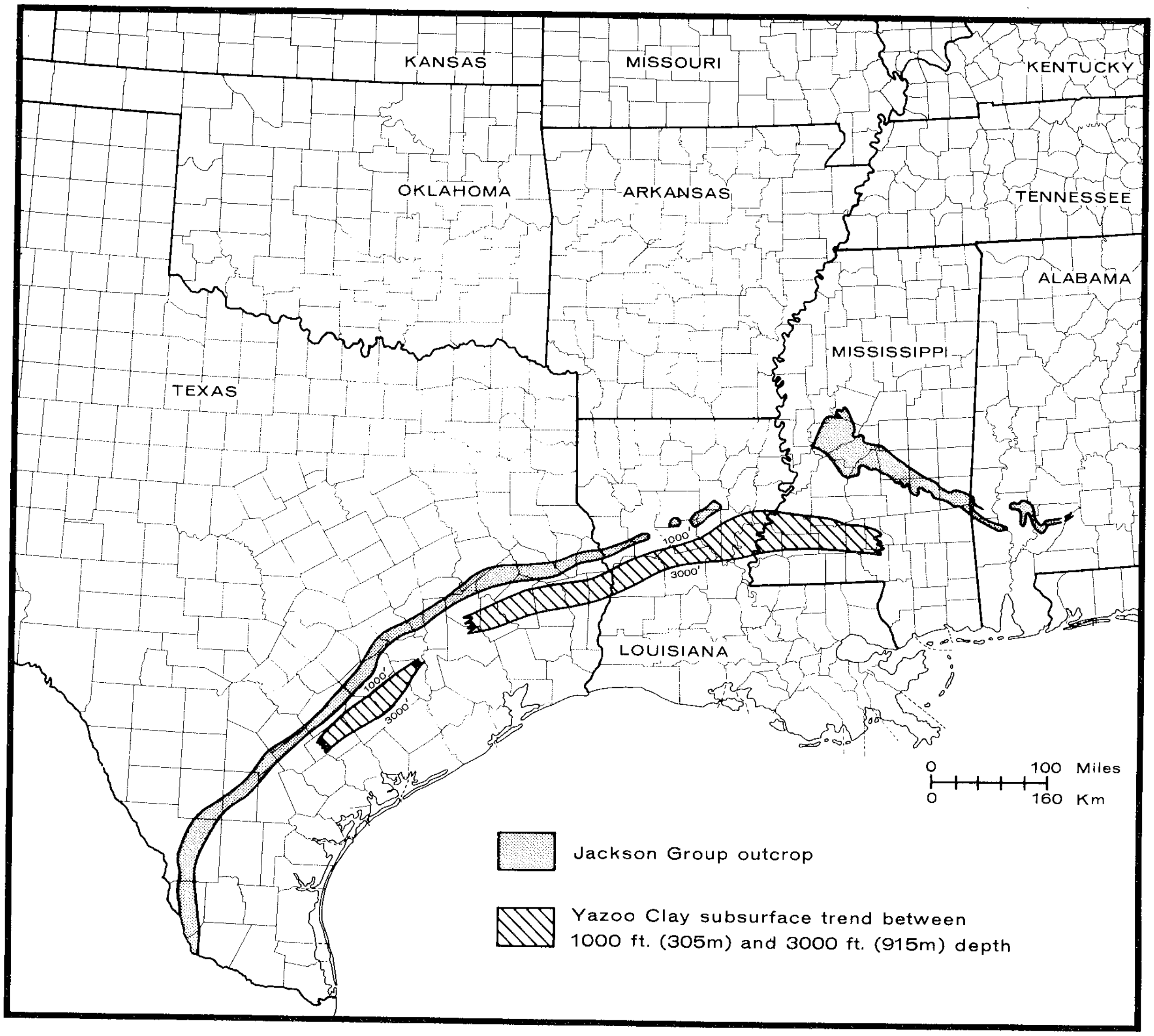

FIGURE 5-11. MAP SHOWING OUTCROP OF JACKSON GROUP AND DISTRIBUTION OF YAZOO CLAY WITHIN THE MODERATE DEPTH RANGE

gulfward. In Texas, this interval ranges from 245 to 300 m thick in outcrop and is more than 300 m thick in the area of the moderate depth. Owing to the variation in thickness of sand units within the section, less than 300 m of vertical clay is generally present. The map of the Yazoo Clay in the subsurface of Mississippi is terminated eastward where the unit becomes less than 75 m thick and increases in sand and lime content. As indicated in Figure 5-9, the Yazoo Clay exhibits an abrupt facies change to become a totally calcareous unit in Alabama.

Based upon the persistence of a thin bentonite layer in the upper Yazoo Clay, Mellen (1940) determined that the formation had undergone some slumping in western Mississippi. In addition, he reported that another near-surface characteristic was the development of gypsum, which is absent in boreholes along the outcrop below the depth of oxidation.

5.4.5.3 Mineralogy and Rock Properties

A partial analysis of a sample of Yazoo Clay from surface exposures in Sabine Parish, Louisiana, indicated it to be rich in montmorillonite and unsuitable for ceramic products (Dixon, 1967). A test for predicting the potential heave in the Yazoo Clay at Clinton, Mississippi, produced the determinations of the physical properties shown graphically in Figure 5-12 (Johnson, 1978). Buck (1957), using X-ray diffraction to analyze an unweathered core sample of Yazoo Clay from near Jackson, Mississippi, found that the sample was predominantly composed of clay minerals (90 percent). Kaolinite, montmorillonite, and illite accounted for 45, 30, and 15 percent, respectively, of the total mineralogy. Principal nonclay minerals included quartz, feldspar, and carbonate.

5.4.5.4 Hydrology

The Yazoo Clay is a persistent confining layer throughout the Gulf Coast. Field tests for swelling properties of surface exposures of the unit determined a permeability coefficient of 3.5×10^{-8} cm/s (Johnson, 1978). No other hydrologic data are available for this unit.

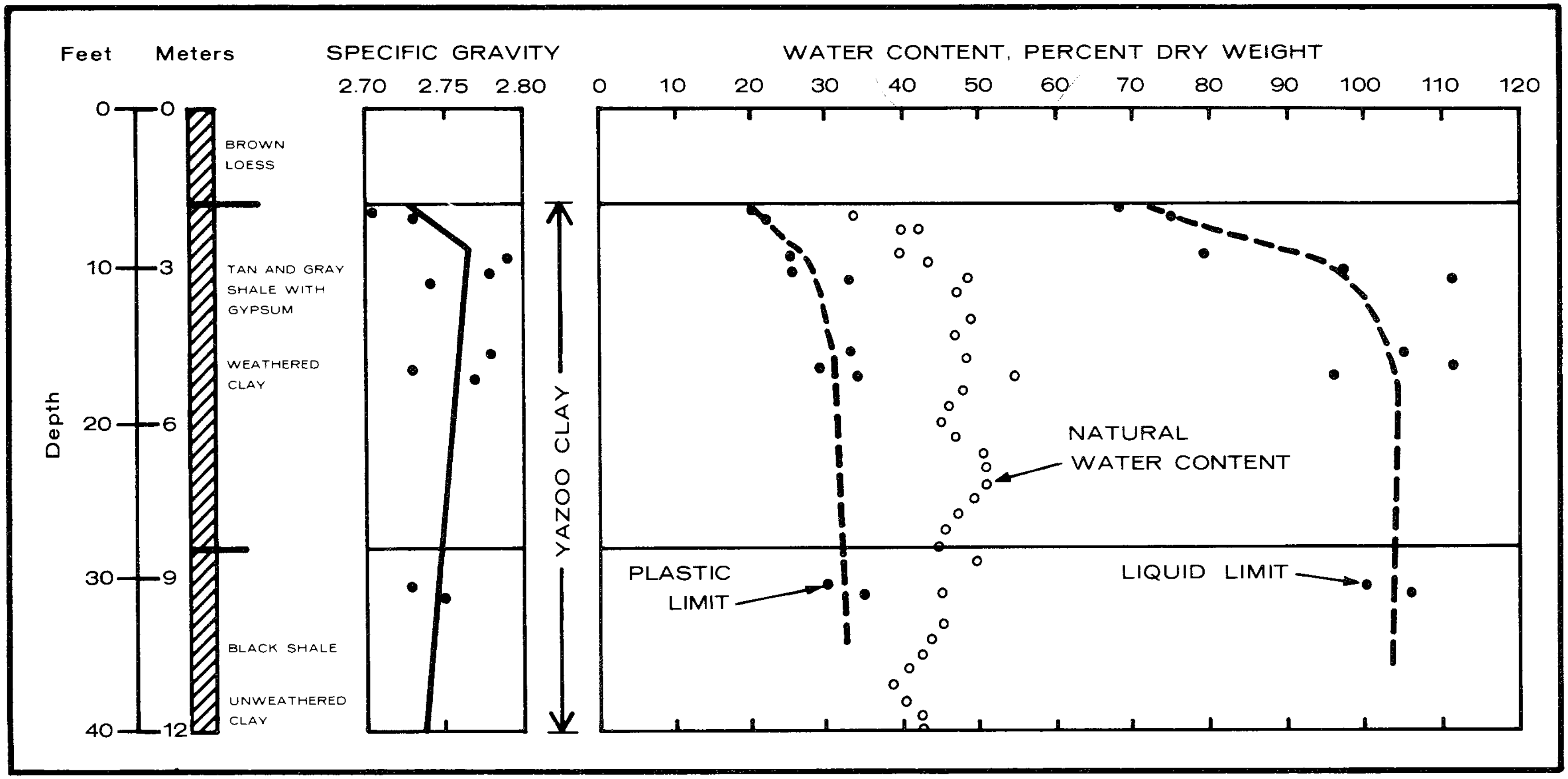

FIGURE 5-12. PLOTS OF SOME PHYSICAL CHARACTERISTICS OF YAZOO CLAY AS MEASURED IN CORE SAMPLE FROM CLINTON, MISSISSIPPI (MODIFIED FROM JOHNSON, 1978)

In Mississippi, Louisiana, and Texas, the Yazoo clay and its equivalents are overlain by Miocene, Pliocene, and Quaternary aquifers containing fresh water. The Oligocene Forrest Hill Sand, various shallower undifferentiated Miocene sands, the underlying Moodys Branch Marl, and the Cockfield aquifer all contain fresh water in Mississippi. Where the Yazoo Clay is 305 to 915 m deep in Mississippi and in east Texas, the unit is below the base of fresh water. At these depths in Louisiana, the Yazoo Clay is both overlain and underlain by fresh ground-water sources.

5.4.5.5 Mineral Resources

Economic utilization of the Yazoo Clay is limited to material collected at the outcrop and used for fired clay products. Actual figures for the production from and location of the many small active mines are not included here. Development within the downdip portion of this unit is limited to oil and gas production in south Texas, where the Jackson Group contains several sands.

5.4.6 Other Units

5.4.6.1 Shale Diapirs

In addition to the normal-bedded, Tertiary clay formations in the Gulf Coast, isolated accumulations of contorted shale occur as diapirs in the coastal areas of both Texas and Louisiana. Twelve piercement shale diapirs were reported (Bishop, 1977) in several south-central coastal counties of Texas (Figure 5-13). Two other shale diapirs, one clearly associated with a salt dome (Figure 5-14), are known from coastal Louisiana (Atwater and Forman, 1959; Roach, 1962).

These shale structures resulted from the clay masses having moved vertically and having uplifted and, in some cases, pierced the overlying clastic sediments. Movement in the Texas diapirs is thought to have been initiated by density differences that developed when thick, sandy

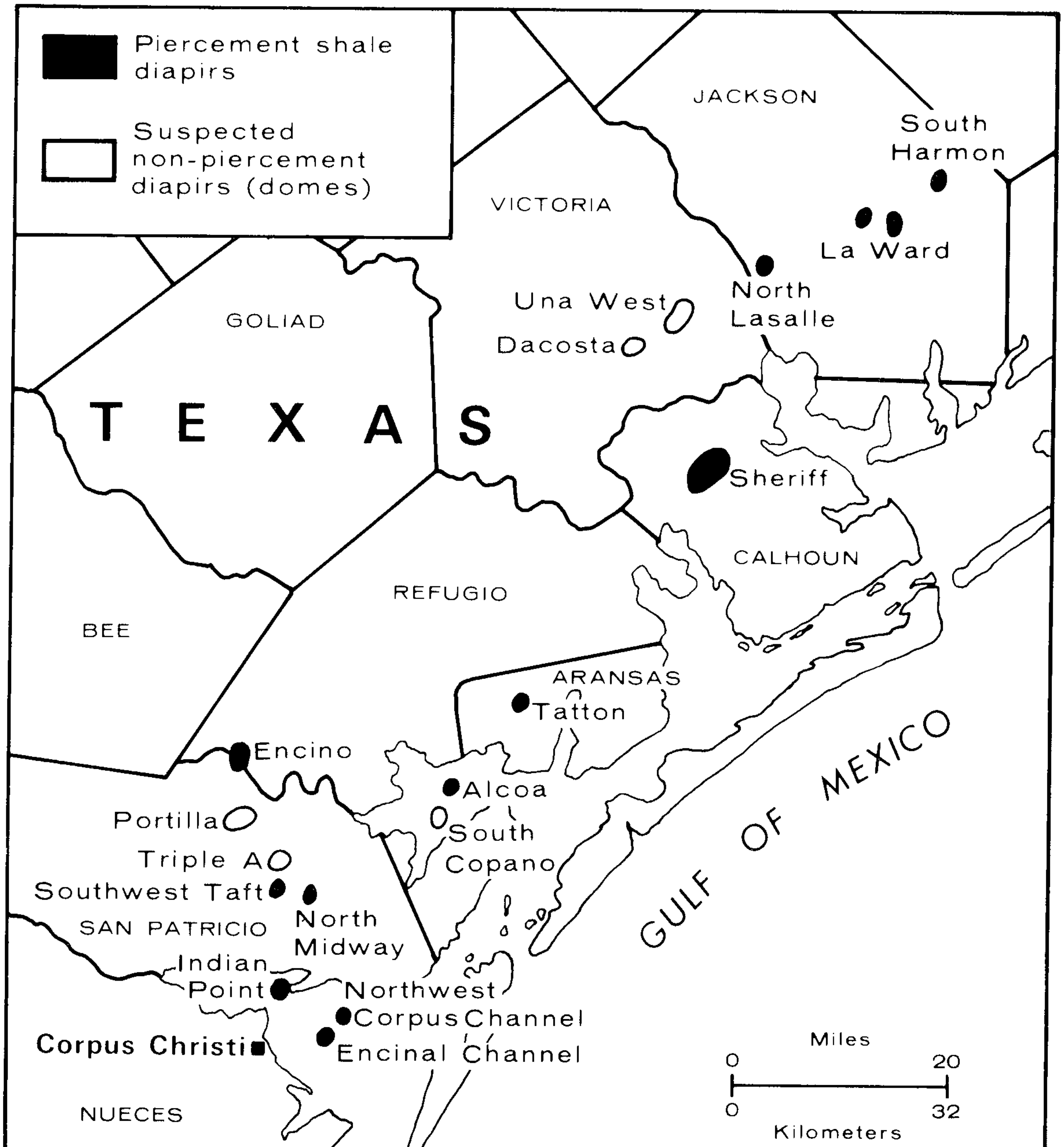

FIGURE 5-13. MAP SHOWING SEVERAL COUNTIES IN COASTAL TEXAS WHERE SHALE DIAPIRS (BOTH PIERCEMENT AND NONPIERCEMENT OR DOMAL) HAVE BEEN REPORTED (MODIFIED FROM BROONER, 1967)

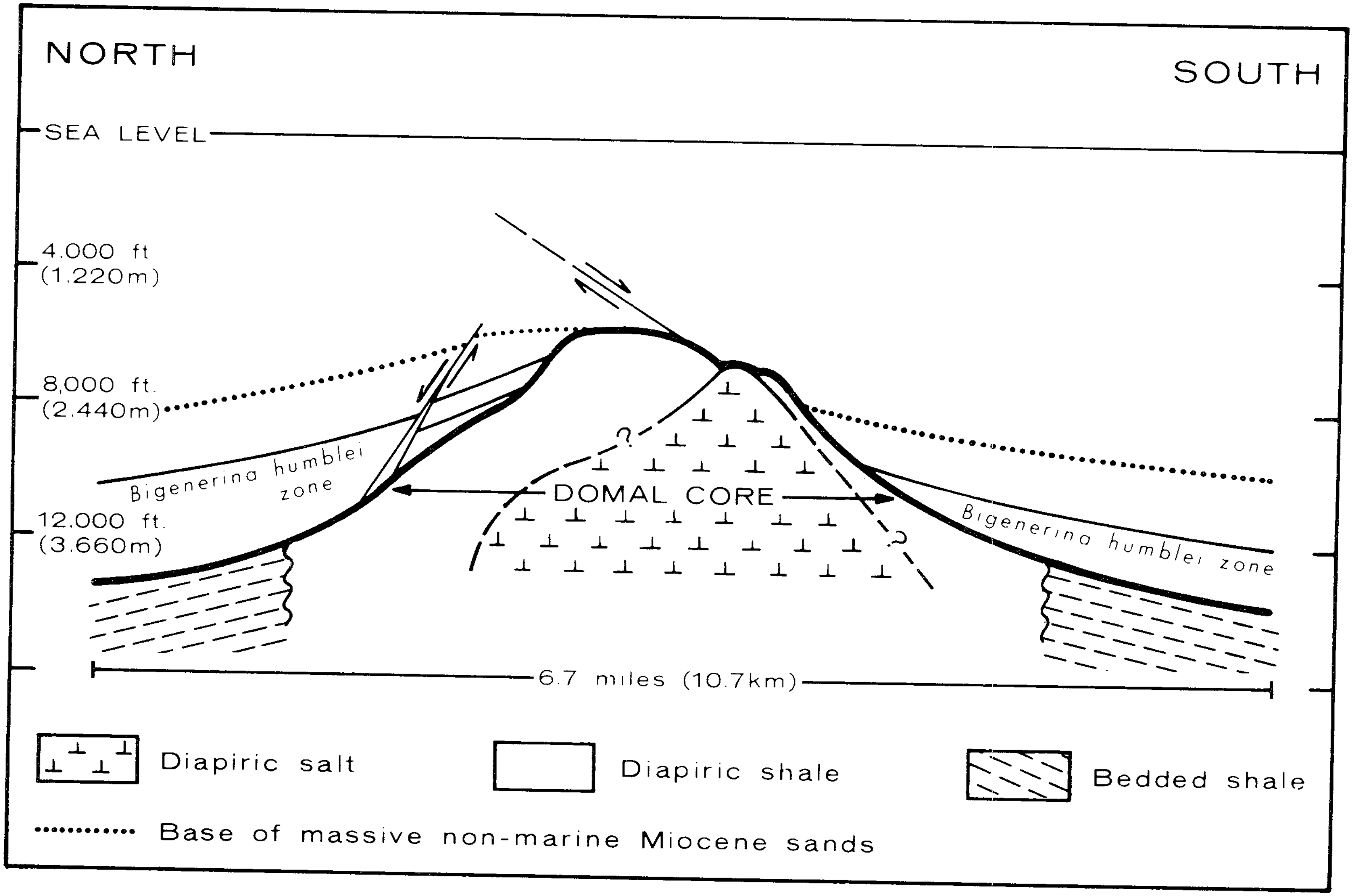

FIGURE 5-14. NORTH-SOUTH STRUCTURAL CROSS SECTION THROUGH VALENTINE SALT DOME, LA FOURCHE PARISH, LOUISIANA, SHOWING RELATIONSHIP OF DIAPIRIC SHALE MASS TO SALT CORE AND SURROUNDING NORMAL-BEDDED STRATA (MODIFIED FROM ATWATER AND FORMAN, 1959)

sediments accumulated above the less dense, muddy substratum (Bishop, 1977). Atwater and Forman (1959) determined that the shale diapirs associated with salt in south Louisiana were forced upward by the buoyancy of the mobile salt. According to Atwater and Forman (1959), diapiric shale is characterized by a high degree of contorted bedding, brecciation, and fracturing, which resulted from internal movement during intrusion. Such shale masses are further discernible when encountered in drilling by the "occurrence of abnormally high pressures accompanied by high-pressure salt-water flows containing minor amounts of gas and oil." The shaly material also has a tendency to heave or flow into and up wellbores.

Shale diapirs have several general characteristics of importance for this report: (1) all identified diapirs are deeper than 1,500 m; (2) shale diapirs and domes are likely to be geopressured and to display low structural strength; (3) these diapirs are associated with fault zones that could permit vertical fluid migration or recurrent differential movement; (4) owing to their fault-bounded nature, precise definition of their lateral limits is difficult; (5) these structural features are either proved sites for commercial hydrocarbon accumulations or potential sites for future exploration; and (6) their exact dimensions and internal structure are not as well known as normal-bedded shales and clays found in simpler structural settings.

5.5 REGIONAL SUMMARY

The Porters Creek Clay is the thickest and oldest of the Cenozoic argillaceous units within the Gulf Coast province. Electric logs indicate that the unit in the subsurface is consistently clay-rich and relatively free of silt and sand layers. The younger clays are less extensive and thinner and are likely to be less compacted and higher in contained water. In most cases, the younger clays are also more likely to be in contact with freshwater aquifers. Except for the Yazoo Clay, these other units also tend to contain permeable silts and sands within their subsurface extents.

In each unit, the structurally simplest areas are the Arkansas-Mississippi-north Louisiana portion of the central Mississippi Embayment and the southern flank of the Sabine Uplift. Remaining areas generally coincide with the complex structures of the regional fault systems and salt-dome basins.

Information about the physical or chemical properties of the various Cenozoic clay units is very scant. The older units would, however, be expected to be more compacted, and hence, less porous and permeable.

Each of the Cenozoic clay units lies beneath important aquifer systems that presently supply water or store undeveloped, potentially useful supplies of fresh to brackish water. The clays are known to be permeable, even though hydraulic conductivity values may be less than 1×10^{-8} cm/s (= 3 m/1000 years). Even under these conditions, if a head differential exists between the clay formation and nearby aquifers, owing either to natural or man-made pressure differences or more subtle potential differences related to thermal gradients or osmotic pressure, ground-water flow from the clay into the aquifer could occur; such a flow process would be extremely slow.

Cenozoic clays in the Gulf Coast are also coincident with extensive areas of oil and gas development. Productive fields are generally well below the depths of the clay formations considered here. In certain regions of Louisiana, Texas, Mississippi, and Arkansas, where a given clay unit falls within the depth and thickness ranges given in Chapter One, numerous exploratory holes nevertheless have been drilled through it. A higher degree of hydrologic integrity is clearly indicated where exploratory drilling has been minimal. Three regions that lack significant hydrocarbon production are central Louisiana and adjacent areas of east Texas, central Arkansas, and northern Mississippi.

6. GREAT PLAINS

6.1 STRUCTURE AND GEOLOGIC FRAMEWORK

The Great Plains Province is a large area embracing much of the west-central United States. As defined by Fenneman (1931), it is bounded by the Rocky Mountains and the Basin and Range Provinces on the west and mainly by the Central Lowlands and the Coastal Plains Provinces on the east and southeast. As used in this report, the term "Great Plains" refers to all of the Great Plains Province as defined by Fenneman, as well as portions of the Central Lowlands west of the Mississippi River and the Ouachita Province (Figure 6-1). These regions are grouped together in this discussion because some of the argillaceous strata are common to two or three provinces, and because there is a general similarity in the geologic setting and history of the regions.

The Great Plains are flat to gently rolling lands throughout vast areas, and local relief commonly is slight. Several isolated mountain systems in the region are the Black Hills, Wichita Mountains, Arbuckle Mountains, Ouachita Mountains, and Llano Uplift. In general the land surface slopes toward the east, with elevations of about 1,200 to 1,500 m above sea level in the foothills of the Rocky Mountains on the west to elevations of about 300 to 500 m in the Central Lowlands on the east.

The Great Plains are characterized by gently dipping Paleozoic, Mesozoic, and Cenozoic strata that were developed upon a stable basement of Precambrian igneous and metamorphic rocks. For the last billion years the basement and its overlying sedimentary cover have been affected only locally by sharp uplift and downwarp, and thus this largely undisturbed region is characterized by moderately shallow to deep sedimentary basins separated by broad arches or the several mountain systems mentioned previously. Among the principal basins are the Williston, Powder River, Denver, Salina, Forest City, Anadarko, Arkoma, Palo Duro, Fort Worth, Midland, and Delaware Basins (Figure 2-2).

The cover of sedimentary rocks, normally less than 1,200 m thick over some of the arches and uplifts, reaches thicknesses of nearly 1,500 m in

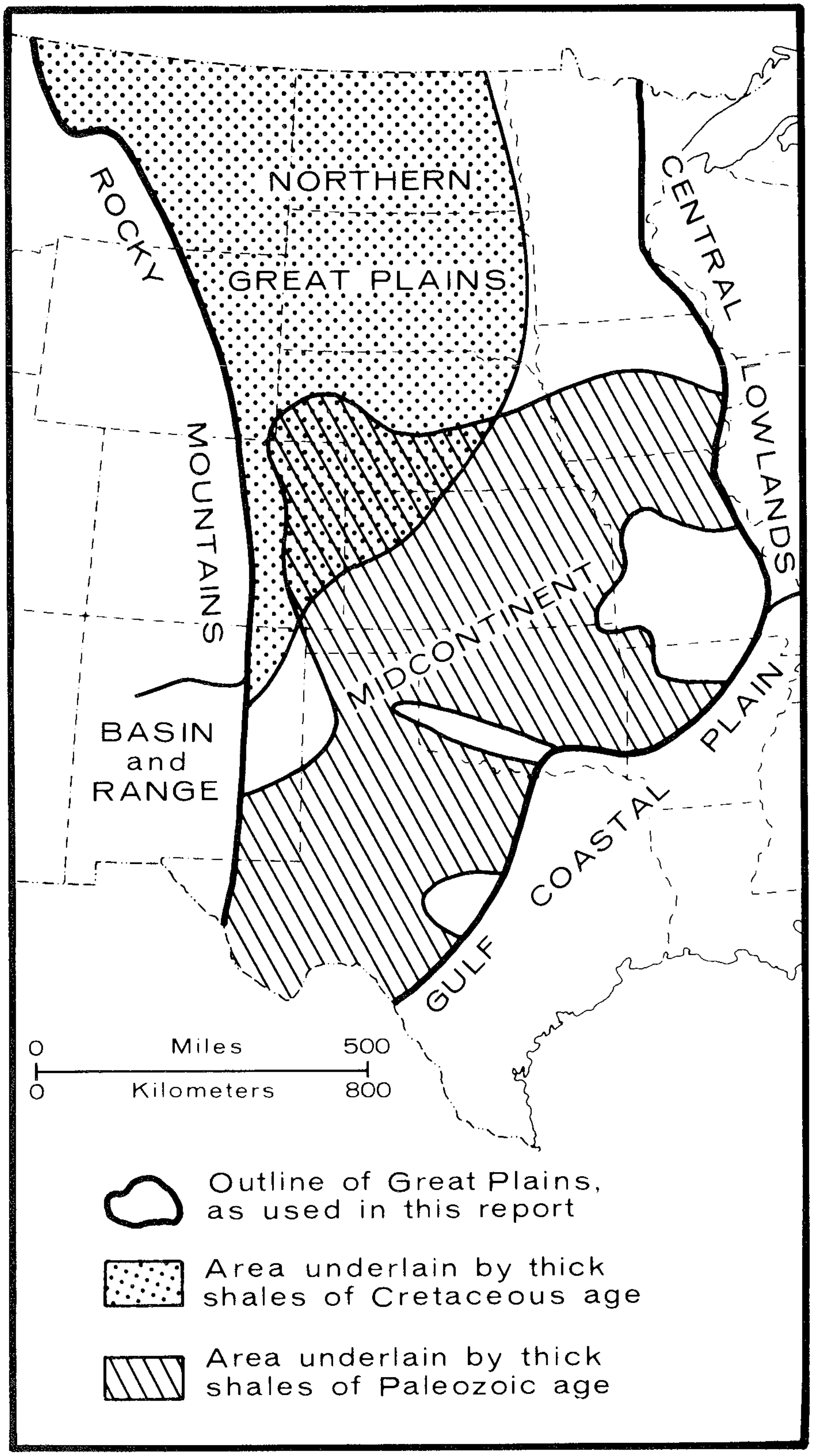

FIGURE 6-1. MAP OF WEST-CENTRAL UNITED STATES, SHOWING OUTLINE OF GREAT PLAINS AND AREAS UNDERLAIN BY THICK SHALES OF PALEOZOIC AND CRETACEOUS AGE

the Salina and Forest City Basins; 3,000 to 4,500 m in the Denver, Palo Duro, Midland, and Fort Worth Basins; 4,500 to 7,000 m in the Williston, Powder River, and Delaware Basins; and 9,000 to 12,000 m in the Arkoma and Anadarko Basins. Over much of the region the rocks dip about 1/2°, although locally on the flanks of some of the uplifts the strata dip 10 to 20°, and within some of the mountain ranges the strata are complexly folded, faulted, and overturned.

Throughout most of the Great Plains the Paleozoic tectonic record is epeirogenic, having been characterized by episodes of widespread marine sedimentation punctuated by periods of broad uplift, gentle folding, and some erosion before the next marine incursion (Ham and Wilson, 1967). Exceptions to the epeirogenic movements are found mainly in the transverse belt of mountains and deep basins that extend across southern Oklahoma and parts of northern Texas. This orogenic belt, including the Ouachita, Arbuckle, and Wichita Mountains, and the Arkoma, Ardmore, Marietta, and Anadarko Basins, was tectonically active mainly during the Pennsylvanian Period, although episodes of sharp uplift and downwarp extended from Late Mississippian through Early Permian time (Ham et al., 1964; Ham and Wilson, 1967).

Early and Middle Paleozoic sedimentation throughout the Great Plains region was dominated by limestones and dolomites laid down in shallow seas that extended across most parts of the craton. These carbonates are generally thin over the arches and broad uplifts owing to nondeposition or epeirogenic uplift and erosion, and are several thousand meters thick in some of the deep basins in Oklahoma. Late Paleozoic sedimentation was characterized by widespread and thick sequences of shales and mudstones interbedded with sandstones, limestones, and evaporites, and interfingered with conglomerates and coarse sandstones in areas bordering the principal mountain uplifts.

The Mesozoic Era was characterized by alternating marine and continental sedimentation in the Great Plains region. Triassic and Jurassic strata are mainly of continental origin, whereas Cretaceous strata include thick marine shales deposited in a major seaway that extended across most parts of the Great Plains. The principal tectonic activity in the region involved uplift of the Rocky Mountains just to the west in Late Cretaceous and Early Tertiary time, with a resulting broad uplift of the Great Plains and retreat of marine waters from the western interior of the United States.

The Cenozoic Era was characterized by continued epeirogenic uplift in the western part of the Great Plains and downwarping of the region toward the Mississippi Embayment and Gulf Coastal Plain to the east and southeast. Continental sediments laid down across most of the region were deposited from east- and southeast-flowing streams that drained the Rocky Mountains and flowed to the Mississippi River and the Gulf of Mexico.

6.2 REGIONAL SEISMICITY

Recorded seismic activity in the Great Plains is low, in comparison with most other parts of the United States. A total of only some 80 earthquakes of Modified Mercalli Intensity V (MMI V) or greater have been recorded in this extensive region through 1970 (Figure 1-2). The maximum intensity of these seismic events is MMI VII. Earthquake activity is widely scattered throughout most parts of the region, except to the south in Texas and to the north in North Dakota and Montana, where the activity is virtually nil. Among the reports dealing with seismic activity in the region are those of Docekal (1970), Northrop and Sanford (1972), Coffman and van Hake (1973), Lawson et al. (1979), and Luza and Lawson (1979). Additional data are being generated under a program initiated several years ago by the U.S. Nuclear Regulatory Commission in which the state geological surveys of Oklahoma, Kansas, Nebraska, and Iowa are investigating the seismicity and tectonic relationships throughout a large part of the Great Plains.

The most intense earthquakes in the Great Plains include seven events of MMI VII (Coffman and von Hake, 1973). The earliest recorded event of MMI VII was at Lawrence, Kansas, in 1867, and this was followed by another in eastern Nebraska in 1877 and one at Manhattan, Kansas, in 1906. More recent earth quakes of MMI VII include those at El Reno, Oklahoma, in 1952, at Catoosa, Oklahoma, in 1956, and in northwestern Nebraska in

1964. An MMI VII earthquake near Denver, Colorado, in 1967 was one of a series of events induced by the subsurface injection of liquid wastes.

Almost all parts of the Great Plains are in seismic risk zone 1, accord ing to the map prepared by S. T. Algermissen (ESSA/Coast and Geodetic Survey, 1969) (Figure 1-3). An elongate area covering the Nemaha Uplift in parts of Oklahoma, Kansas, and Nebraska is considered in zone 2 (moderate damage can be expected), and so also is a part of central Montana because of its proximity to the area of more intense activity in the Rocky Mountains just to the west. A small area in the far south, in central Texas, is classed as zone 0. Seismic risk, expressed in statistically significant values of ground shaking, is similarly low throughout most of this vast region (Figure 1-3b).

6.3 REGIONAL HYDROLOGY

6.3.1 Surface Water

Surface drainage consists mainly of east- and southeast-flowing streams whose headwaters lie in the eastern part of the Rocky Mountains or in the Great Plains Province itself. Principal river systems crossing the region are, starting on the north: Red (of North Dakota-Minnesota), Missouri, Yellowstone, North Platte, Arkansas, Canadian, Red (of Texas-Oklahoma), Colorado (of Texas), and Pecos. All of these rivers except the Colorado and Pecos are tributaries to the Mississippi River, and all surface flow eventually empties into the Gulf of Mexico. Streams draining the region are mostly supplied by precipitation (both rainfall and melting snow) and runoff, but some base flow is supplied by spring-water discharge from sandstones, limestones, and other aquifers.

Average annual precipitation ranges from about 30 to 40 cm in the west to about 60 to 100 cm in most eastern parts of the province. Moisture-laden air masses coming from the Pacific Ocean drop most of their water content while crossing the high Rocky Mountains. Thus, the precipitation is meager on the Great Plains just east of the mountains but increases eastward across the plains states where southerly winds circulate moist air from the Gulf of Mexico.

Streams crossing most parts of the region contain fresh water that is suitable for most purposes. Streams in the northern half of the Great Plains (Missouri River Basin) typically have a dissolved-solids concentration of less than 1,000 mg/l, although the concentration ranges from 1,000 to 4,000 mg/l for most streams in the western Dakotas, the lower South Platte River Valley in Colorado and Nebraska, and the upper Powder River Valley in central Wyoming (Missouri Basin Interagency Committee, 1969).

In the south half of the Great Plains (Arkansas River Basin and farther south) the streams and rivers contain fresh water in the High Plains where they flow across Tertiary strata. Such surface waters are, however, degraded by natural emissions of sodium-chloride brines at many salt plains and salt springs in Kansas, western Oklahoma, north-central Texas, and southeastern New Mexico where the rivers cross shallow deposits of Permian rock salt (Ward, 1963; Swenson, 1973, 1974; Johnson and Gonzales, 1978; Gustavson, 1979). In all cases, local meteoric water appears to have migrated down to the salt beds, then dissolved some of the salt to form brine, and finally returned to the surface as partly or fully saturated brine.

Most of the flow of surface water occurs during the spring from melting snows and from seasonally high rainfall. Many lakes and reservoirs have been constructed in order to retain much of this peak flow for use during the rest of the year. These reservoirs store water for a variety of purposes, includ ing irrigation, municipal supply, power generation, and recreation. Among the largest of the reservoirs in the Great Plains are Fort Peck in Montana, Sakakawea in North Dakota, Oahe in South Dakota, and Eufaula and Texoma in Oklahoma.

6.3.2 Ground Water

A number of summary appraisals have been prepared on the ground-water resources for various regions throughout the Great Plains. These include reports on the Missouri Basin Region (Taylor, 1978), Souris-Red-Rainy Region (Reeder, 1978), upper Mississippi region (Bloyd, 1975), Arkansas-White-Red Region (Bedinger and Sniegocki, 1976), Rio Grande Region (West and Broadhurst, 1975), and Texas-Gulf Region (Baker and Wall, 1976).

Ground water in the northern half of the Great Plains (essentially the Missouri Basin region) occurs in a variety of aquifers that have been classified as alluvial deposits of sand and gravel, glacial deposits, dune-sand deposits, and basin-fill deposits of sand and gravel; and as bedrock formations of sandstone, siltstone, fractured sandy clay, limestone, and dolomite (Taylor, 1978). Pleistocene and Holocene alluvium is generally located along major stream valleys, except in central Nebraska where Pleistocene alluvium is areally extensive. Pleistocene glacial deposits occur mainly in a broad band along the Missouri River. A major dune-sand aquifer of Pleistocene and Holocene age is spread across north-central Nebraska. The Ogallala, Arikaree, and Brule aquifers of Pliocene, Miocene, and Oligocene age underlie parts of Wyoming, South Dakota, Colorado, and Nebraska; in addition, the Ogallala Formation is an important aquifer in much of western Kansas.

A large number of sandstone aquifers are widespread in the Missouri Basin region, except in southwestern Montana and most of Nebraska, Kansas, Missouri, and parts of Wyoming and Colorado (Taylor, 1978). The age of these sandstone aquifers ranges from Cretaceous to Late Cambrian. Among the more important sandstones are the Judith River, Dakota, Kootenai, Swift, Inyan Kara, Sundance, Minnelusa, and Deadwood aquifers. The Madison Limestone aquifer of Early Mississippian age underlies much of the Montana-North Dakota-South Dakota-Wyoming portion of the Great Plains, but it is largely untested. Limestone and dolomite aquifers of Permian and Pennsylvanian age are also present in eastern Nebraska and Kansas, as well as in nearby parts of Iowa and Missouri.

In the southern half of the Great Plains, major aquifers include stream-valley alluvium, areally extensive terrace deposits, carbonates, gypsum, and sandstone (West and Broadhurst, 1975; Bedinger and Sniegocki, 1976; Baker and Wall, 1976). Although many of the bedrock formations contain moderately to strongly saline water at depth where they are in proximity to the extensive salt deposits of the Permian Basin, there are a number of excellent freshwater aquifers in the region. The Ogallala Formation of Tertiary age is the major source of ground water throughout the High Plains region and is widely used for municipal and irrigation water (Irwin and Morton, 1969). Large yields of freshwater also are obtained from the Dakota Sandstone in parts of Kansas and from the Rush Springs, Elk City, Garber, and Vamoosa Sandstones in Oklahoma. In parts of Texas and New Mexico, principal fresh-water aquifers include the Santa Rosa Sandstone of the Triassic Dockum Group, the Edwards-Trinity aquifer of Cretaceous age, and the Capitan Limestone and Rustler Formation of Permian age. Throughout the region, thick deposits of Quaternary terrace and alluvial material also yield large supplies of fresh water along present-day and ancient courses of the major rivers.

6.4 SHALES AND ARGILLACEOUS UNITS

6.4.1 Introduction

Throughout the vast area of the Great Plains, many thick shales and other argillaceous units occur. The shales of this region fall into two general categories and exist in two separate parts of the Great Plains: Paleozoic-age shales in the Midcontinent region of the southern and south-central Great Plains; and Cretaceous-age shales in the northern and north-central Great Plains.

Principal Paleozoic shales of the Midcontinent region include the Woodford (Chattanooga) Shale of Late Devonian-Early Mississippian age, as well as many shale units interbedded with Late Mississippian, Pennsylvanian, and Permian strata. The Midcontinent region underlain by these shales embraces parts of Texas, Oklahoma, Arkansas, New Mexico, Colorado, Kansas, Missouri, Nebraska, and Iowa (Figure 6-1).

Cretaceous shales that are thick and widespread in the northern and central Great Plains include, in ascending order, the Skull Creek (Kiowa), Mowry, Belle Fourche (Graneros), Carlile, Marias River, and Pierre

("Lewis"-Steele-Cody-Bearpaw-Clagget) Shales. The Skull Creek (Kiowa) and Mowry Shales are Lower Cretaceous units, whereas the remainder are Upper Cretaceous units placed in the Colorado Group (Belle Fourche, Carlile, and Marias River) or the overlying Montana Group (Pierre and equivalent units). The Pierre Shale is an exceptionally thick unit (typically 150 to 1,800 m thick) that is undisturbed, at moderate depth, and widespread in the northern and central Great Plains. The area underlain by thick Cretaceous shales includes parts of Montana, North Dakota, South Dakota, Wyoming, Nebraska, Colorado, and New Mexico (Figure 6-1).

6.4.2 Woodford Chattanooga Shale

6.4.2.1 Stratigraphy

The Woodford (Chattanooga) Shale is a relatively widespread marine unit in the Midcontinent region of the central and southern Great Plains Province (Figures 6-2, 6-3). The term "Woodford" usually is employed in Texas and most of Oklahoma. However, in eastern Oklahoma and in Arkansas, Missouri, Kansas, Nebraska, and Iowa, it is called the Chattanooga (partly or wholly equivalent to the "Kinderhook" of former subsurface usage).

The age of the Woodford (Chattanooga) Shale has been agreed upon generally as both Late Devonian and earliest Mississippian (Kinderhookian) (Figures 6-4, 6-5). The unit is roughly equivalent to the Chattanooga Shale of the Southeast, the New Albany Shale of the Illinois Basin, the Antrim Shale of the Michigan Basin, and other black-shale units in the Appalachian region. The Woodford or Chattanooga is partly correlative with the Arkansas Novaculite in the Ouachita Mountains of Oklahoma and Arkansas. It also is at least partly equivalent to the Caballos Novaculite of the Marathon region, west Texas, and the Percha Shale, which crops out in the El Paso area and adjoining areas of New Mexico (Amsden et al., 1967).

The lithology of the Woodford (Chattanooga) Shale is typically black, carbonaceous, pyritic, fissile shale that contains locally abundant zones of the alga Tasmanites (commonly identified as "spores"). The formation

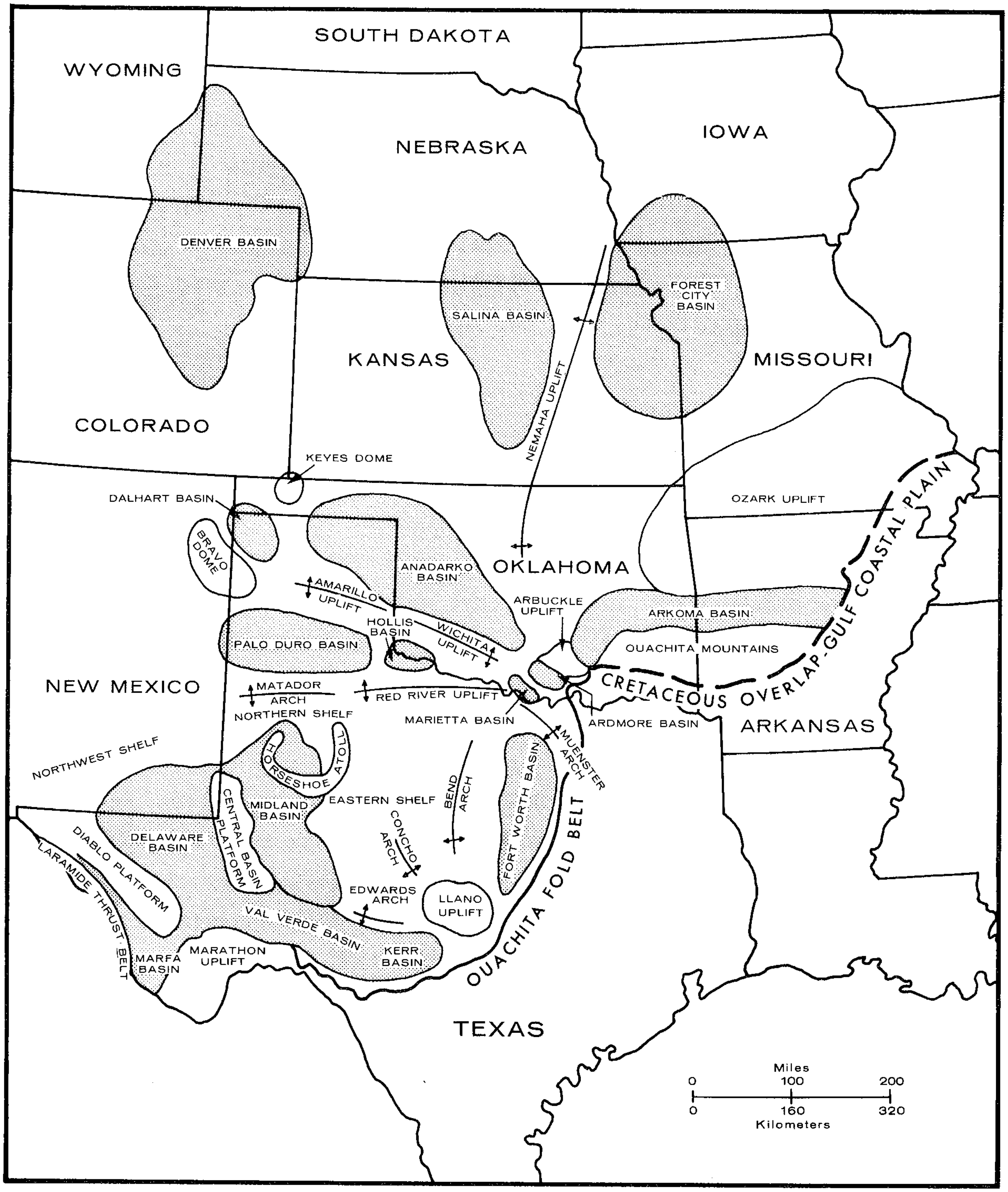

FIGURE 6-2. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION SHOWING PRINCIPAL GEOLOGIC FEATURES

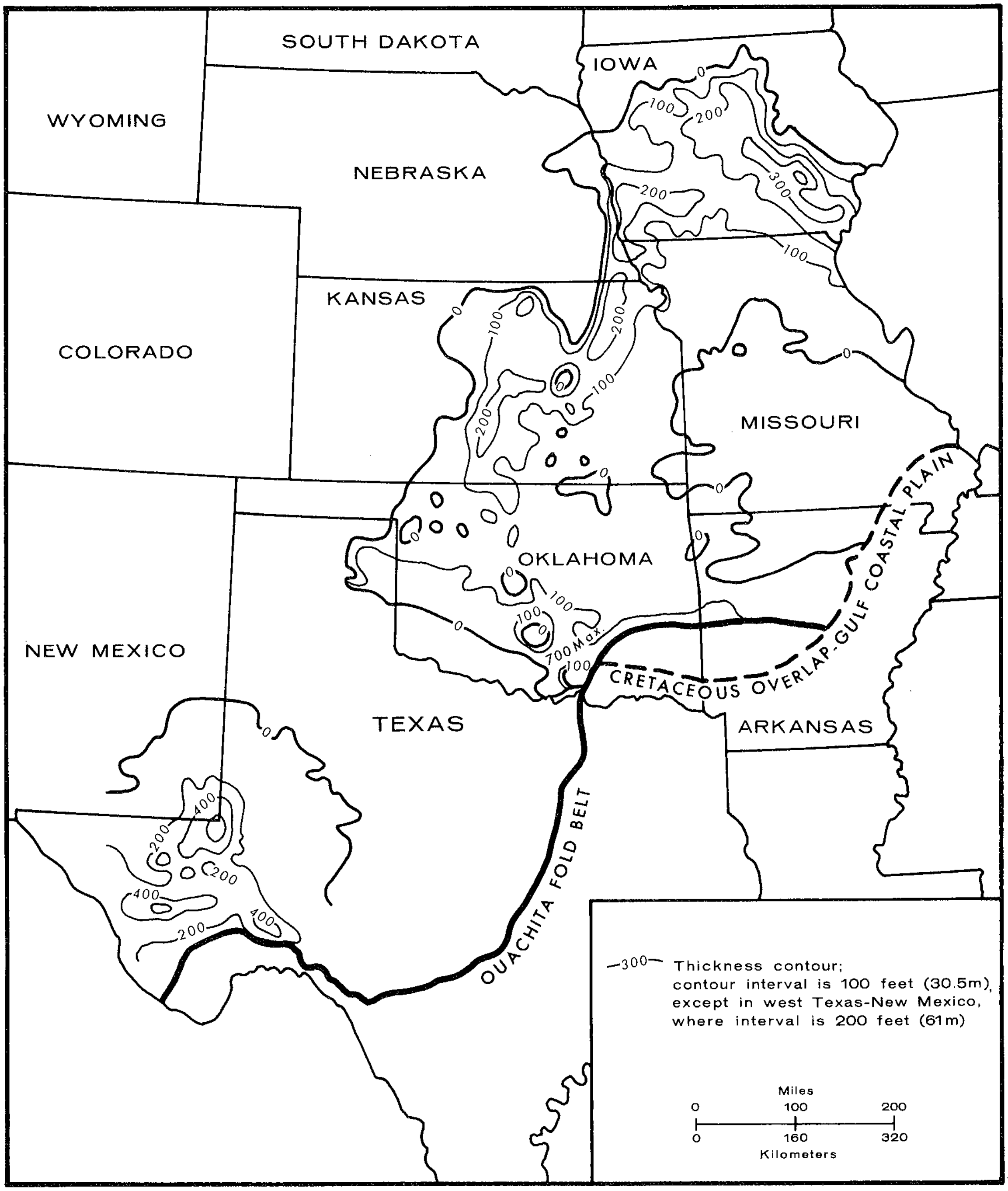

FIGURE 6-3. MAP OF MIDCONTINENT REGION, SHOWING DISTRIBUTION AND THICKNESS OF WOODFORD (CHATTANOOGA) SHALE AND EQUIVALENTS (MODIFIED FROM HUFFMAN, 1959: AMSDEN ET AL., 1967; HILL, 1971; ALDER, 1971; AMSDEN, 1975, 1980)

SYSTEM	SERIES	NEBRASKA-KANSAS	IOWA-MISSOURI	TEXAS-OKLA. PANHANDLES	SOUTHERN OKLAHOMA	CENT. and N. OKLA.	ARKANSAS
		(Quaternary and Tertiary in all states; Cretaceous, Jurassic and/or Triassic present in various states)					
PERMIAN	Guadalupian	Guad. Undif.		Guad. Undif.		Guad. Undif.	
	Leonardian	Nippewalla Gp.		El Reno Group			
		Sumner Gp.		Hennessey Formation			
				Wellington Formation			
	Wolfcampian	Wolf Undif.		Wolfcampian Undifferentiated			
PENNSYL-VANIAN	Virgilian	Wabaunsee, Shawnee, and Douglas Groups			Virgilian Undifferentiated		
	Missourian	Lansing, Kansas City, and Pleasanton Groups			Hoxbar Gp.	Ochelata Gp.	
						Skiatook Gp.	
	Desmoinesian	Marmaton Group			Deese Gp.	Marmaton Gp.	
		Cherokee Group				Cherokee Group	
	Atokan	Atokan Undifferentiated		"Atoka"	Dornick Hills Group	"Atoka"	
	Morrowan	Kearny		"Morrow"		"Morrow"/Bloyd	Bloyd
MISSIS-SIPPIAN	Chesterian	Chester. Undif.		Chester. Undif.	Goddard/"Springer"		Fayetteville
					Delaware Creek/"Caney"		
	Meramecian	Meramecian Undifferentiated					
	Osagean	Osagean Undifferentiated					
	Kinderhookian	Boice		Kinderhookian Undifferentiated			
DEVONIAN	Upper	Chattanooga		Woodford Formation			Chattanooga
		(Middle Devonian through Cambrian strata)					

FIGURE 6-4. CORRELATION CHART FOR CENTRAL MIDCONTINENT REGION

SYSTEM	SERIES	WEST TEXAS and EASTERN NEW MEXICO	NORTH-CENTRAL TEXAS
		(Quaternary, Tertiary, Cretaceous, Jurassic, and Triassic strata)	
PERMIAN	Ochoan	Ochoan Undif.	
	Guadalupian	Guadalupian Undifferentiated	
	Leonardian	Clear Fork Group	Clear Fork Group; Vale / Arroya
	Wolfcampian	Wolfcampian Undifferentiated	
PENNSYL-VANIAN	Virgilian	Cisco Group	
	Missourian	Canyon Group	
	Desmoinesian	Strawn Group	
	Atokan	Atokan Undif.	"Atoka"/Smithwick
	Morrowan	Morrowan Undifferentiated	
MISSIS-SIPPIAN	Chesterian	Barnett	
	Meramecian	Barnett	
		? — ? — ? — ?	
	Osagean	Osagean Undifferentiated	
	Kinderhookian	Kinderhookian Undifferentiated	
DEVONIAN	Upper	Woodford Formation	
		(Middle Devonian through Cambrian strata)	

FIGURE 6-5. CORRELATION CHART FOR SOUTHERN MIDCONTINENT REGION

bears varying amounts of chert, principally in parts of Oklahoma, Arkansas, and west Texas. Beds of chert are common in southern and southeastern Oklahoma, especially in the upper part.

At the base of the Woodford (Chattanooga) sequence a lenticular sandstone is present in some areas of Oklahoma, Arkansas, Kansas, and Missouri. This sandstone is usually called the Misener in the Oklahoma and Kansas subsurface and the Sylamore to the east. Where present, the Misener (Sylamore) Sandstone is generally less than 6 m thick and represents a basal sandy facies of the Woodford or Chattanooga Shale (Amsden, 1980).

The Woodford (Chattanooga) Shale attains its greatest thickness, or about 215 m, locally in the deepest parts of the Anadarko Basin and in the Marietta Basin to the southeast, both in the southern Oklahoma folded belt (Amsden, 1975) (Figure 6-3). In Winkler County, Texas, near the southeastern corner of New Mexico, the unit reaches a maximum thickness of about 190 m (Ellison, 1950) (Figure 6-3). Figure 6-6 shows the change in character and thickness of the Woodford Shale northward from Winkler County into Andrews County, Texas, as determined from electric logs.

Other areas of significantly thick Woodford (Chattanooga) Shale occur in southcentral Oklahoma north of the Arbuckle Uplift, where Amsden (1975, 1980) reported at least 75 m, and in the Salina and Forest City Basins, where thicknesses of 80 m and 85 m were recorded by Wells and McCracken (1964) and Amsden et al. (1967), respectively. In the Aylesworth Field of Bryan County, Oklahoma, Gahring (1959) reported a Woodford thickness of up to 118 m, with an upper 21 m consisting of hard, dark-brown shale with thin beds of dark-brown chert, a middle 85 m of hard, coffee-brown shale with abundant "spores" (probably Tasmanites), and a basal 12 m of green silty shale. The Chattanooga Shale is more than 100 m thick in parts of eastern Iowa.

In northeastern Kansas the Chattanooga is gray to green, micaceous, "spore-bearing" shale (Brandt, 1967), and northward it contains interbeds of gray dolomite and argillaceous limestone (Amsden et al., 1967). At places in the Salina and Forest City Basins, the Chattanooga is overlain by a Kinderhookian shale unit, the Boice, which is composed of dark- to

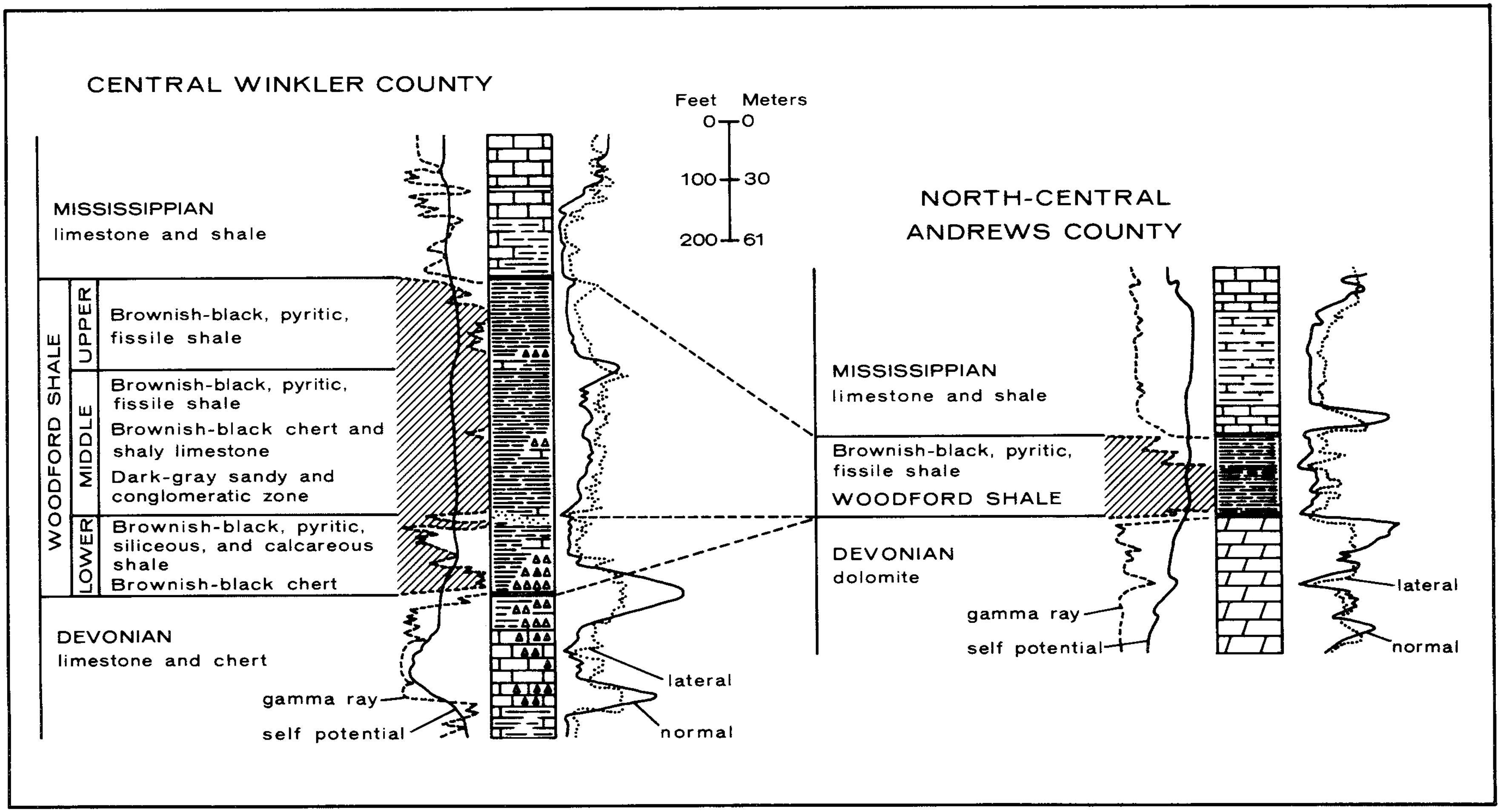

FIGURE 6-6. LOG SECTION SHOWING LITHOLOGY AND CHANGE IN THICKNESS OF WOODFORD SHALE FROM WINKLER COUNTY NORTHEASTWARD TO ADJOINING ANDREWS COUNTY, WEST TEXAS (MODIFIED FROM ELLISON, 1950)

light-greenish-gray silty or dolomitic shale containing basal beds of red shale or ferruginous oolite (Lee, 1956; Zeller, 1968). The thickness values for the Chattanooga Shale in Figure 6-3 include the Boice in this area.

6.4.2.2 Geologic Setting

A thick section of Woodford Shale occurs in the depocenter of the Early and Middle Paleozoic Tobosa Basin (Galley, 1958), in the vicinity of the southeastern corner of New Mexico (Figure 6-3). But in this area the Woodford lies at depths ranging mostly from 750 to 4,500 m below sea level (Figure 6-7). Only in the southwestern part of the area, near the outcrop, is there a possibility of finding a reasonable thickness of Woodford Shale at moderate depths. However, in this area, from Brewster County, Texas, northwestward into Culberson County, there are numerous faults and folds associated with the Marathon fold belt; these and related structural features make occurrences of Woodford deposits difficult to predict (Renfro et al., 1973).

In the area of thick Woodford deposits in southern Oklahoma, the structural complexity of the southern Oklahoma folded belt, coupled with the greater amounts of chert in the formation, makes the presence or absence of thick shale intervals difficult to assess (Figure 6-8). The structural attitude of the Woodford Shale in Oklahoma (Figure 6-7) indicates that no thick shale sections are present at moderate depths except in the areas of intense tectonic activity. The Woodford Shale is at least 75 m thick in a relatively undisturbed area in south-central Oklahoma north of the Arbuckle Uplift, where it lies at depths ranging from about 920 to 3,400 m (Amsden, 1975).

Perhaps the main areas where the Chattanooga and (or) Chattanooga-Boice intervals are thick and undisturbed are the Salina Basin in Kansas and the Forest City Basin in northeastern Kansas, northwestern Missouri, southwestern Iowa, and southeastern Nebraska. In each of these areas, the shale intervals reach a maximum thickness of 75 to 85 m (Amsden et al., 1967). Figure 6-9 indicates a Chattanooga or Chattanooga-Boice thickness

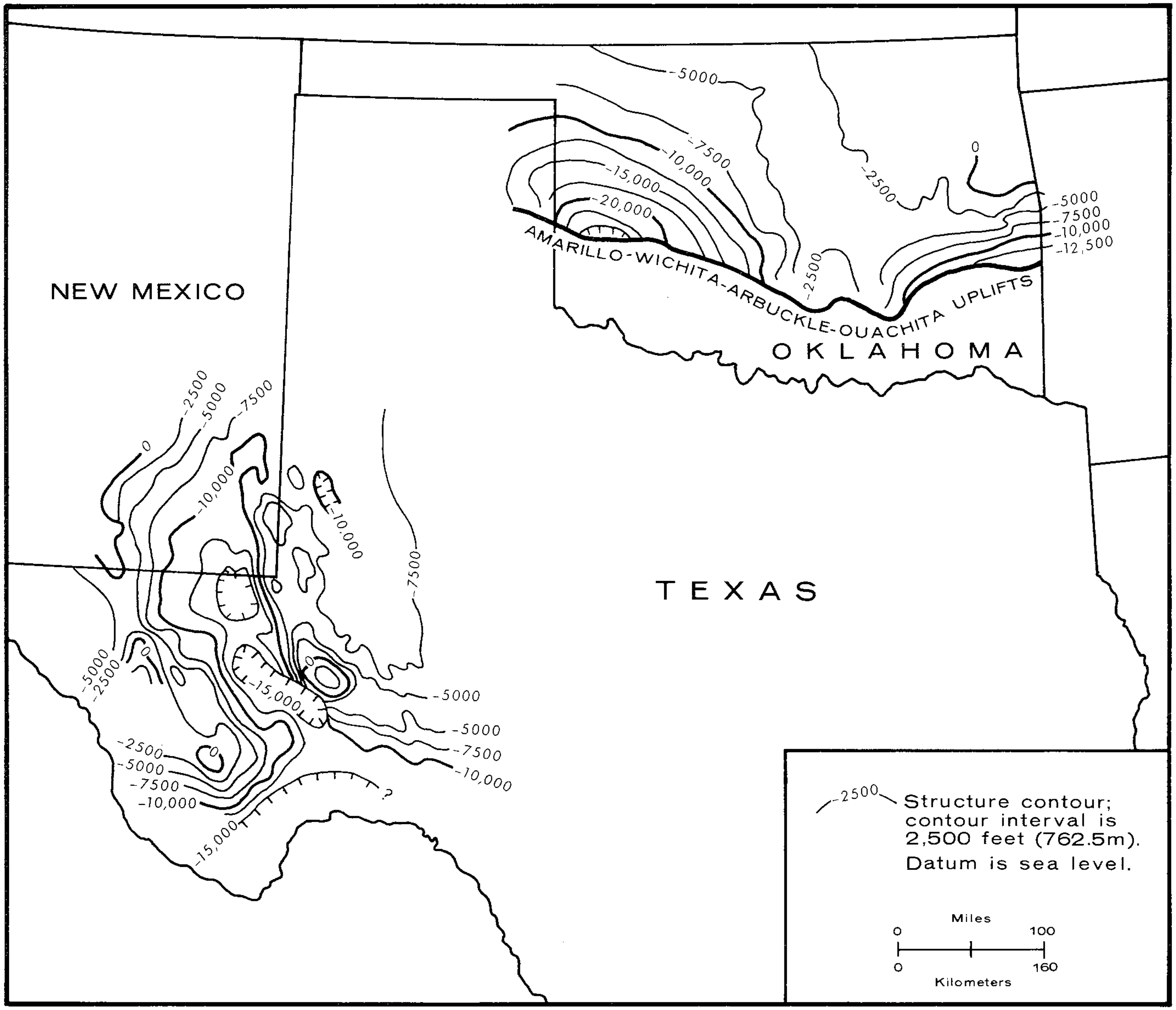

FIGURE 6-7. STRUCTURE MAP ON BASE OF WOODFORD (CHATTANOOGA) SHALE IN OKLAHOMA, WEST TEXAS, AND SOUTHEASTERN NEW MEXICO. CONTOURS PARTIALLY RESTORED WHERE WOODFORD HAS BEEN ERODED (MODIFIED FROM SALISBURY, 1968; AMSDEN, 1975, 1980)

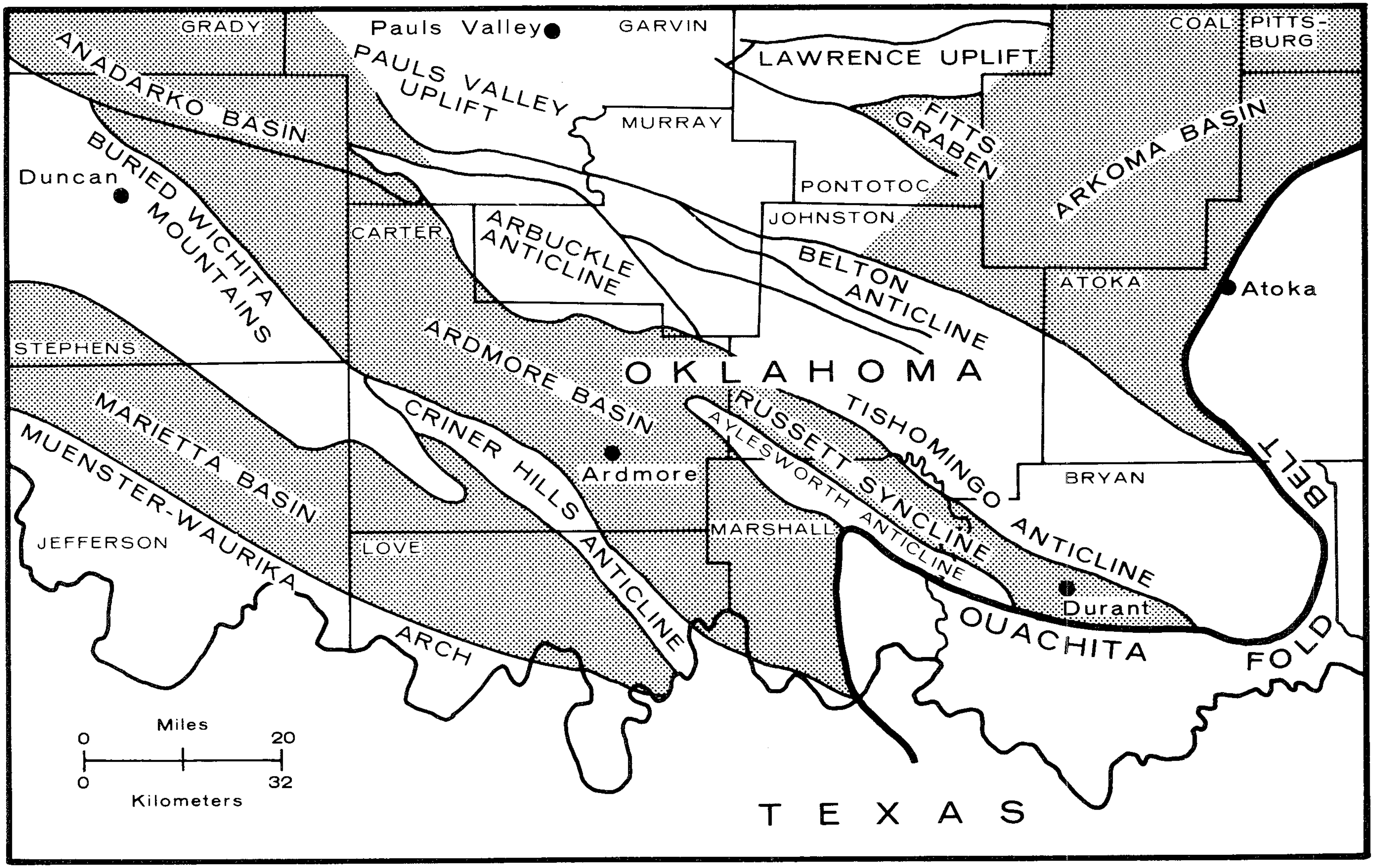

FIGURE 6-8. MAP OF SOUTHERN OKLAHOMA FOLDED BELT, SHOWING STRUCTURAL PROVINCES (MODIFIED FROM HICKS, 1971); STIPPLING INDICATES PRINCIPAL BASINS AND SYNCLINES

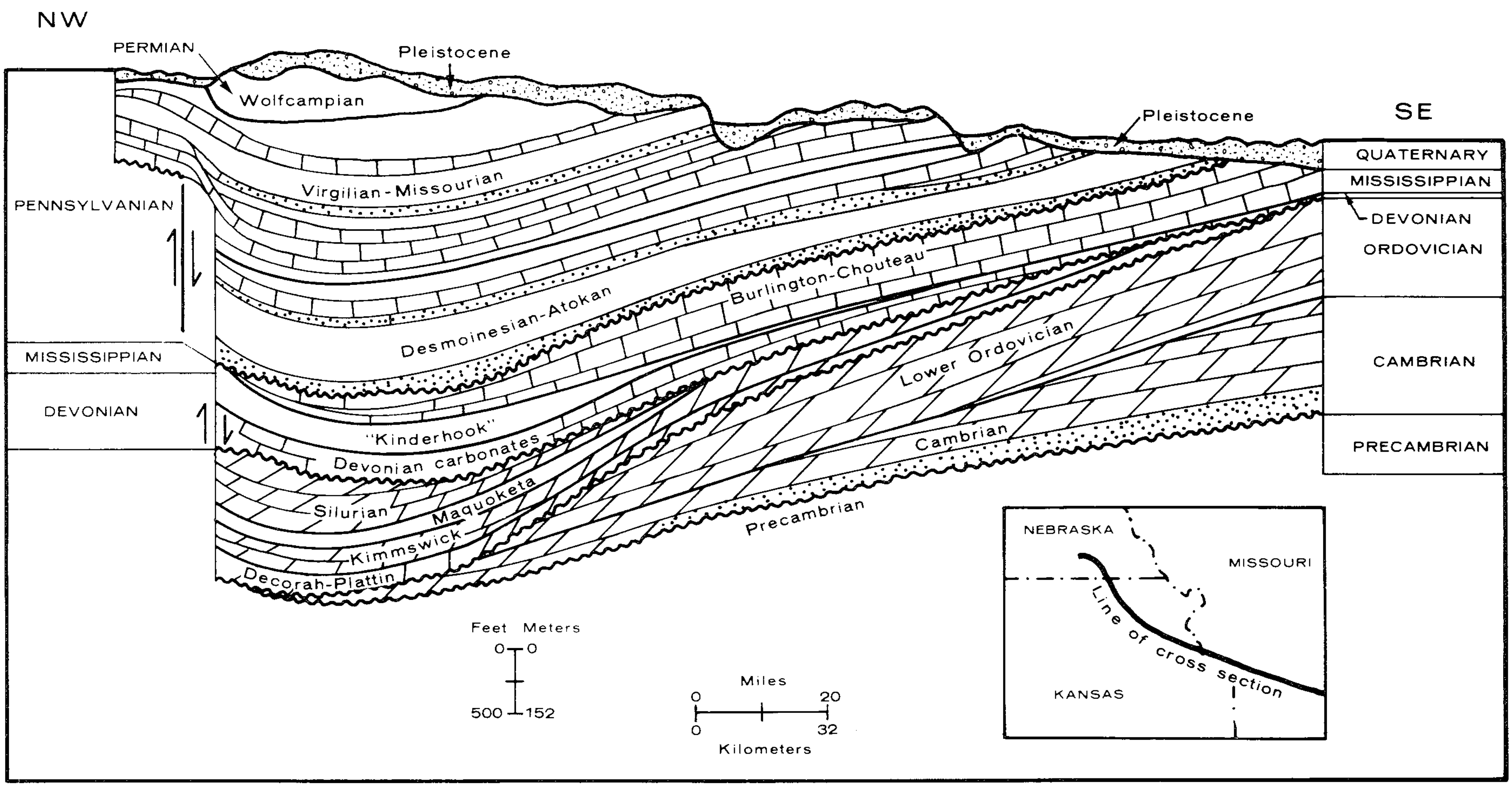

FIGURE 6-9. DIAGRAMMATIC NORTHWEST-SOUTHEAST LITHOLOGIC CROSS SECTION OF FOREST CITY BASIN (MODIFIED FROM WELLS, 1971)

of 75 m near the center of the Forest City Basin at depths ranging from about 700 to 850 m. Figure 6-10 shows a Chattanooga-Boice sequence in the Forest City Basin of 60 to 75 m at depths between 600 and 700 m. In eastern Iowa, the 100-m-thick sequence of Chattanooga Shale is mainly at depths of less than 300 m below the land surface, and only locally is it more than 300 m deep.

Sets of vertical joints are common in the Woodford (Chattanooga) Shale and are readily apparent at most outcrops. This tendency toward jointing, combined with fractures developed from tectonic movement, especially in the bedded cherts of Oklahoma and Texas, locally makes the formation fairly brittle and increases its permeability to ground water.

6.4.2.3 Mineralogy and Rock Properties

The Woodford (Chattanooga) Shale is well known as a fissile, marine shale that is rich in organic matter and commonly contains nodules of pyrite and marcasite. Weaver (1958) characterized the unit as also being rich in illite and mixed-layer illite-montmorillonite but containing little or no kaolinite. Johnson and Luza (1980) noted, in addition to illite, a content of illite-chlorite and chlorite for occurrences in Oklahoma; these argillaceous zones exhibit medium plasticity and low shrink-swell potential. Duncan and Swanson (1965), reporting on shale-oil resources of the world, noted that the Woodford (Chattanooga) Shale and its equivalents contain organic matter ranging from 5 to 25 percent of the shale. The phosphatic content of the Woodford (Chattanooga) Shale also has been mentioned (Heckel, 1977).

6.4.2.4 Hydrology

Where the Woodford (Chattanooga) Shale is at moderate depths in the region of the Forest City Basin, principal aquifers are Pleistocene glacial drift and Pleistocene and Holocene alluvium of the Missouri River and its tributaries (Bayne and Ward, 1967; Dorheim, 1970; Gann et al., 1973; Taylor, 1978). Aquifers of lesser importance are carbonate rocks of

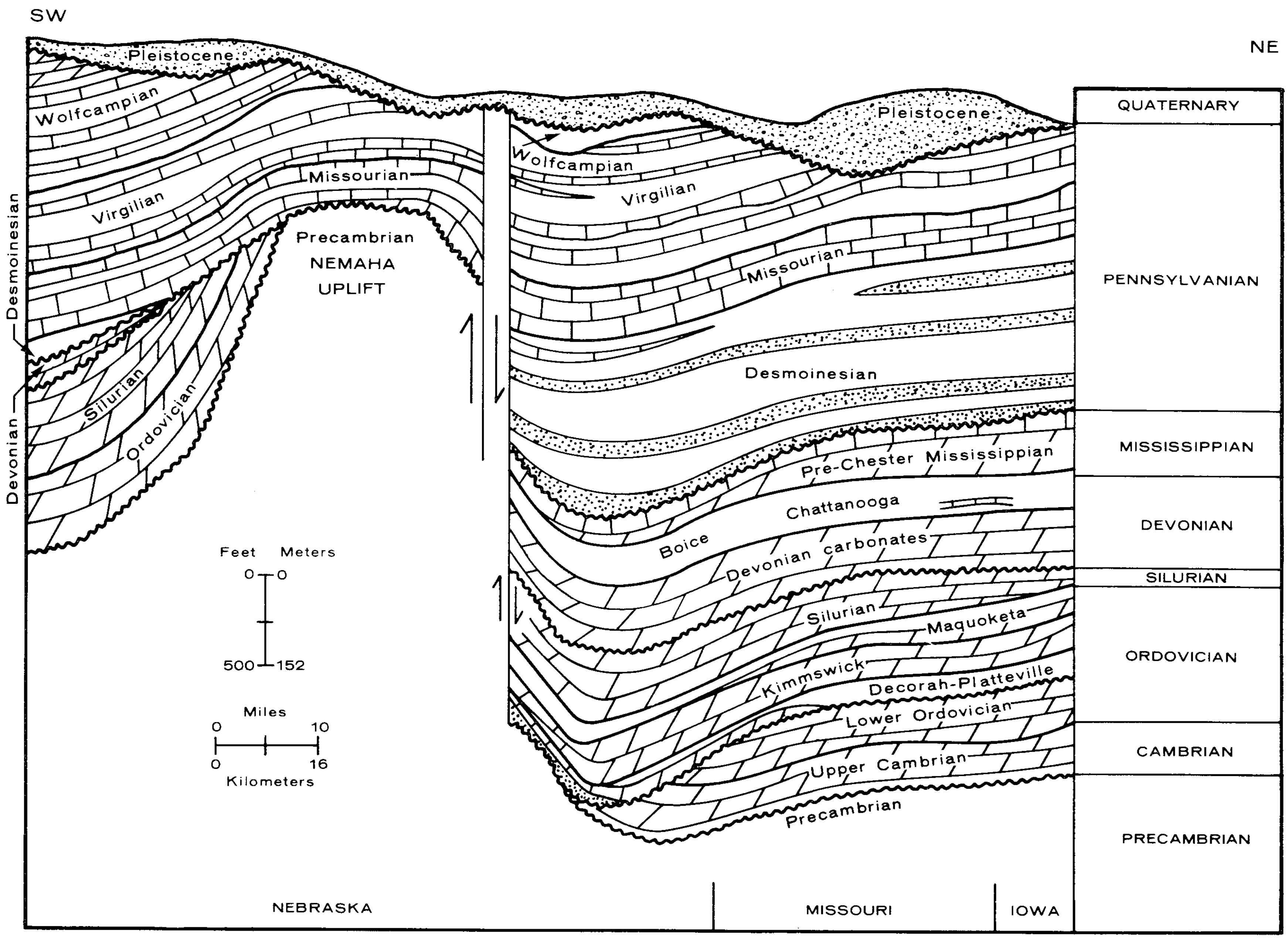

FIGURE 6-10. DIAGRAMMATIC SOUTHWEST-NORTHEAST LITHOLOGIC CROSS SECTION FROM SALINA BASIN THROUGH NEMAHA UPLIFT AND FOREST CITY BASIN (MODIFIED FROM CARLSON, 1971)

Pennsylvanian age (Dorheim, 1970; Taylor, 1978). In the Salina Basin, the source of most ground water is sandstone from the Cretaceous Dakota Formation and Pleistocene terrace deposits (Bayne and Walters, 1959; Hodson, 1959; Taylor, 1978).

In eastern and southern Oklahoma, the fractured Woodford (Chattanooga) Shale itself yields limited amounts of water of fair to poor quality (Marcher, 1969; Marcher and Bingham, 1971; Hart, 1974).

6.4.2.5 Mineral Resources

Most of the Midcontinent region has undergone intense exploration for and development of mineral resources, principally oil and gas (Figure 6-11) and coal. The Forest City Basin, however, has not received as great an exploratory effort for petroleum deposits as have some of the other basins, in large part owing to a lack of significant discoveries. Another reason is that the basin does not appear to have been as favorable a locale for the entrapment of hydrocarbons as it was for their generation, as evidenced by the numerous heavy-oil occurrences in Pennsylvanian rocks of Desmoinesian and Missourian age (Anderson and Wells, 1968). There has been repeated interest in these heavy-oil deposits as potentially producible by thermal-recovery techniques (Wells and Anderson, 1968). Some oil and gas production has been developed from older rocks, such as the Hunton Group (Silurian and Devonian), which underlies the Chattanooga Shale (Reed et al., 1958).

Other mineral resources in production from the Forest City Basin include bituminous coal and limestone (Frye et al., 1951; Kisvarsanyi, 1965; Dorheim, 1970). Resources of lesser potential are Pennsylvanian clays and shales.

Westward and southwestward across the Nemaha Uplift, in the Salina Basin of Kansas, principal mineral resources, aside from oil and gas, are gypsum, salt, and clays and shales from both Pennsylvanian and Permian rocks (Frye et al., 1951; Hardy, 1970).

The Woodford Shale itself produces oil and gas at various places in Kansas, Oklahoma, and Texas, either from fractured chert beds (Huffman

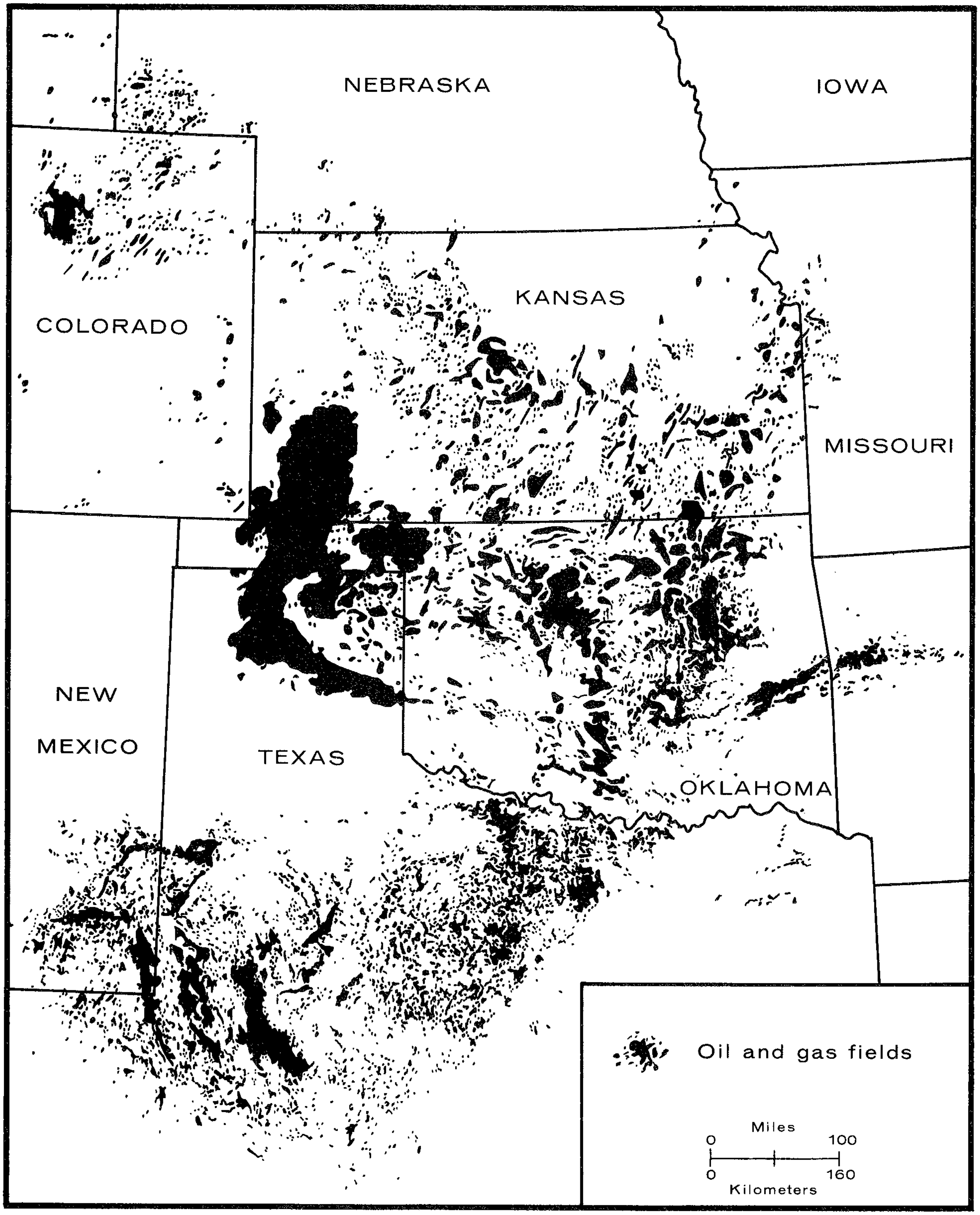

FIGURE 6-11. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION SHOWING DISTRIBUTION OF OIL AND GAS FIELDS (MODIFIED FROM SMITH, 1977)

et al., 1978; Morrison, 1980) or from its basal sandy facies, the Misener or Sylamore Sandstone (Amsden and Klapper, 1972). The carbonaceous oil shales of the Woodford (Chattanooga) Shale, moreover, remain a potential low-grade source of either oil or gas.

6.4.3 Upper Mississippian Shales

6.4.3.1 Stratigraphy

Several marine-shale formations, principally of Late Mississippian (Chesterian) age, can be conveniently considered together. These units include the Delaware Creek Shale ("Caney" of subsurface usage) and the overlying Goddard Shale ("Springer" of subsurface usage) in southern Oklahoma, the Fayetteville Shale of eastern Oklahoma and western Arkansas, and the Barnett Formation of north, central, and west Texas and southeastern New Mexico (Figures 6-4, 6-5). These units are roughly correlative with the argillaceous flysch deposits of the Stanley Group in the Ouachita Mountains of southeastern Oklahoma and western Arkansas (Fay et al., 1979), and at least the lower part of the Tesnus Formation of the Marathon area (Renfro et al., 1973).

In the Anadarko Basin of Oklahoma and in the Ardmore Basin to the southeast, the Delaware Creek-Goddard sequence is as much as 1,200 m thick (Huffman, 1959) (Figure 6-12). In the Arkoma Basin to the east, a thickness of more than 150 m was recorded in Oklahoma (Huffman, 1959), whereas the correlative Fayetteville Shale reaches a maximum of 227 m in Arkansas (Haley et al., 1979). The Barnett Formation, considered mainly Chesterian by Mapel et al. (1979), but thought to be also Meramecian and partly Osagean by Kier et al. (1979), occurs in thicknesses greater than 75 m in the Fort Worth Basin of north-central Texas and in the Midland and Delaware Basins of west Texas. This unit is truncated over much of the Central Basin Platform as the result of one or more Early Pennsylvanian erosional periods.

The Delaware Creek Shale of southern Oklahoma is a dark-gray and brownish-black fissile shale, whereas the overlying Goddard Shale is a

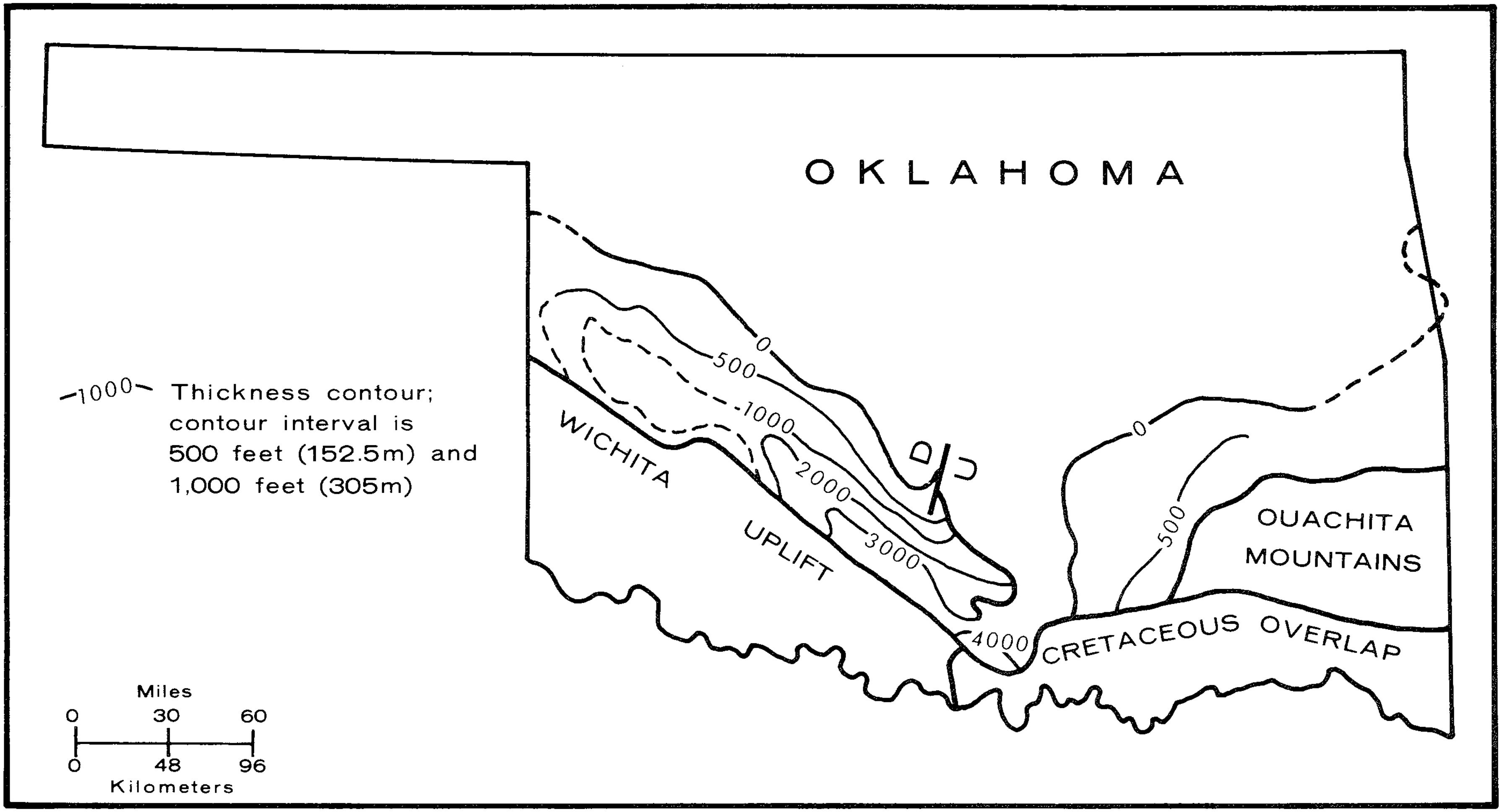

FIGURE 6-12. MAP OF OKLAHOMA, SHOWING THICKNESS OF COMBINED SEQUENCE OF DELAWARE CREEK AND GODDARD SHALES (MODIFIED FROM HUFFMAN, 1959)

dark-gray to black bituminous shale with thin sideritic layers and concretions (Westheimer, 1956; Huffman, 1959; Huffman et al., 1978; Fay et al., 1979). Both units contain several lenticular sandstones, many of which produce oil and gas. The following named sandstone members occur in the Goddard within the Ardmore Basin area (ascending): Redoak Hollow, Rod Club, and Overbrook (Fay et al., 1979).

The Fayetteville Shale is predominantly a gray to black, carbonaceous, fissile shale, at least partly equivalent to the Delaware Creek-Goddard sequence. At places it contains the lenticular Wedington Sandstone Member as well as other sandstone lenses in the subsurface of the Arkoma Basin (Croneis, 1930; Huffman et al., 1966; Fay et al., 1979).

The typical shale lithology of the Barnett Formation is a dark-brown to gray to black, highly bituminous, fissile shale (Sellards et al., 1932). On electric logs the Barnett Formation is expressed by unusually high resistivity for a predominantly shale unit.

At most places, especially on outcrop, the various Upper Mississippian shale formations rest unconformably on underlying rocks, principally Meramecian Limestones. Either these shales are overlain conformably by uppermost Chesterian carbonate formations, such as the Pitkin Limestone in eastern Oklahoma and Arkansas and the Comyn Limestone in north-central Texas, or they are overlain unconformably by Lower Pennsylvanian rocks. In parts of the deep basins, such as the Anadarko, Ardmore, and Arkoma, deposition apparently was continuous, as reflected in controversies about the age of the "Springer" and the placement of the Mississippian-Pennsylvanian boundary.

6.4.3.2 Geologic Setting

Although thick Upper Mississippian shales are present in several basins of Oklahoma and Texas, they lie mostly deeper than 900 m and have been subjected to moderate to intense tectonic deformation, especially throughout the southern Oklahoma folded belt (Figure 6-8) and eastward into the Arkoma Basin of Arkansas. In these deformed areas, the shales commonly are fractured and jointed.

Southeastward from the Ardmore Basin, Huffman et al. (1978) found the Delaware Creek Shale and overlying Goddard Shale present in steep folds beneath thrust faults, where the entire sequence attains a maximum thickness of 900 m and ranges in depth from about 150 to 2,000 m. Branan (1968) pointed out that the several types of folding and faulting in the Arkoma Basin, as caused predominantly by the Ouachita orogeny, include anticlinal and synclinal axes, minor faults in the northern shelf areas, major block faults in deep beds along the Oklahoma-Arkansas line, and tight folds and thrust faults along the deep-basin axis parallel to and just north of the Ouachita Mountain front. The Delaware Creek-Goddard Shales and the Fayetteville Shale are thin along the relatively undisturbed northern shelf of the Arkoma Basin, but thicken basinward as noted above.

In the deep part of the Anadarko Basin, the Delaware Creek-Goddard sequence is at least 900 m thick and lies at depths approaching 5,000 m (Oklahoma City Geological Society, Stratigraphic Committee, 1971). Along the southern margin of the basin, Takken (1968) documented the presence of 75 m of Goddard Shale at a depth of 820 m along the Kiowa-Washita County line in southwestern Oklahoma; however, the rocks in this area are folded and faulted. Toward the east in Caddo County, Adkison (1960) noted up to 275 m of shale in the Goddard Shale between the depth range of 760 and 1,035 m.

The Barnett Formation in Texas and southeastern New Mexico generally is either thin (less than 75 m) or deep (more than 900 m). Eastward into the Fort Worth Basin, the Barnett Formation thickens to more than 90 m but occurs at depths ranging from 1,650 to 2,400 m (Turner, 1957). In north Texas the Barnett Formation thins from about 180 m in Grayson County westward to less than 75 m in Archer County at depths between 2,500 m on the east and 1,950 m on the west (North Texas Geological Society, 1954a). In the Midland Basin the Barnett Formation ranges in thickness from 75 to 200 m but lies at depths of 2,400 to 3,600 m (West Texas Geological Society, Stratigraphic Problems Committee, 1949; West Texas Geological Society, 1960). Although the Barnett Formation is truncated beneath younger formations over the Central Basin Platform, it is present along the edges of the platform and reaches 260 m in thickness at depths of 2,400 to 3,500 m (West Texas Geological Society, Stratigraphic Problems Committee, 1949, 1951; West Texas Geological Society, 1960).

6.4.3.3 Mineralogy and Rock Properties

The principal clay minerals of the Delaware Creek Shale are illite, chlorite, and kaolinite. The plasticity of the Delaware Creek Shale is medium, and the shrink-swell potential varies from low to high (Weaver, 1960; Johnson and Luza, 1980).

The Goddard Shale is a bituminous shale and contains kaolinite, montmorillonite, and illite (Johnson and Luza, 1980). Weaver (1960) determined a montmorillonite-mixed-layer clay facies in the Ardmore Basin; from the southeastern part of the basin eastward into the Arkoma Basin, he noted a change to an illite-chlorite-kaolinite-mixed-layer facies. The plasticity of the Goddard Shale is medium, and its shrink-swell potential is low to high (Johnson and Luza, 1980).

The Fayetteville Shale is characterized by mixed-layer illite-chlorite-montmorillonite, illite, kaolinite, and chlorite (Johnson and Luza, 1980). Weaver (1958) described a mixed-layer illite-montmorillonite facies in the Arkoma Basin of Arkansas, with lesser amounts of kaolinite, chlorite, and illite. The plasticity of the Fayetteville Shale in Oklahoma is medium, and the shrink-swell potential is probably low (Johnson and Luza, 1980).

The Barnett Formation is richly organic at many places, including the Llano Uplift region, where it was tested for its petroliferous content (Plummer, 1940). Weaver (1958) inferred that the Barnett Formation, as an organic-matter-rich marine shale containing pyrite, could be expected to be rich in illite and mixed-layer illite-montmorillonite and to contain little kaolinite.

6.4.3.4 Hydrology

A major aquifer in southern Oklahoma is the Trinity aquifer, or Antlers Sandstone, of Early Cretaceous age, which overlies Upper

Mississippian shale deposits in the Marietta Basin and along the east and south flanks of the Ardmore Basin (Johnson et al., 1972; Hart, 1974). Other important aquifers include alluvial and terrace deposits of Tertiary and Quaternary age along the Red River; the Rush Springs Sandstone of Permian age, which extends from the central part to the northern part of the Anadarko Basin in west-central Oklahoma; and alluvial and terrace deposits of the Arkansas River in the Arkoma Basin of Oklahoma and Arkansas (Arkansas Geological and Conservation Commission, 1959; Johnson et al., 1972). Hart (1974) reported that in south-central Oklahoma the Delaware Creek and the Goddard Shales themselves probably yield limited amounts of water of poor to fair quality, presumably from both sandstone lenses and fractures.

Major aquifers in Texas overlying areas where the Barnett Formation is thicker than 75 m include the Trinity aquifer in a region surrounding the Dallas-Fort Worth area, where it reaches a maximum thickness of 366 m and extends to depths of about 1,600 m; alluvial and terrace deposits along major streams; and the Tertiary Ogallala aquifer of the High Plains of West Texas-New Mexico, which attains thicknesses of more than 150 m (Baker and Wall, 1976). In the Pecos Valley, important aquifers include limestone and, locally, gypsum of Permian age and thick deposits of Quaternary valley fill (West and Broadhurst, 1975).

6.4.3.5 Mineral Resources

Oil and gas are the principal mineral resources of the region underlain by Mississipian Shales (Figure 6-11). Principal reservoirs in the Anadarko Basin and the southern Oklahoma folded belt in general are Pennsylvanian sandstones, the lenticular "Springer" sandstones of the topmost Goddard Shale sequence, Lower Mississippian rocks, carbonates of the Hunton Group (mainly Silurian-Devonian), sandstones of the Simpson Group (Middle Ordovician), and the limestones and dolomites of the Arbuckle Group (Lower Ordovician) (Parker, 1956; Rutledge, 1956; Hicks, 1971; Huffman et al., 1978; Fay et al., 1979). The Arkoma Basin is largely a dry-gas province, with most of the production from Atokan and Morrowan sandstones (Lower Pennsylvanian) (Caplan, 1957; Arkansas Geological and Conservation Commission, 1959). Rock units considered to have promise for future discoveries in the Arkoma Basin mainly include deeper carbonates of Mississippian, Devonian, and Ordovician age; possible sandstone units are the Wedington Sandstone Member of the Fayetteville Shale and sandstones of the Middle Ordovician Simpson Group (Sheldon, 1954; Caplan, 1957; Schramm and Caplan, 1971). In Texas, most oil and gas are produced from Permian, Pennsylvanian, and Mississippian rocks (St. Clair et al., 1976).

Another important mineral resource of the southern Midcontinent region is Pennsylvanian bituminous coal, which crops out extensively throughout the Arkoma Basin and also in north-central Texas (Arkansas Division of Geology, 1952; Johnson, 1969; St. Clair et al., 1976).

Developed resources of lesser importance include Permian gypsum in the central and western Anadarko Basin of Oklahoma, scattered asphalt deposits in southern Oklahoma, scattered deposits of caliche in west Texas and southeastern New Mexico, cement materials from Cretaceous beds in the Dallas-Fort Worth area, and industrial sand in north-central Texas (Johnson, 1969; Garner et al., 1979). Uranium mineralization in sandstones of Permian age in north Texas may also have energy-resource potential (St. Clair et al., 1976). Likewise, shales of the Barnett Formation, especially in outcrops along the north flank of the Llano Uplift, constitute a low-grade oil-shale resource.

6.4.4 Pennsylvania Shales

In this section, thick shale deposits of Pennsylvanian age have been divided into stratigraphic groupings that approximate the provincial series divisions developed in the Midcontinent portion of the Great Plains Province. These divisions comprise, from oldest to youngest, Morrowan, Atokan, Desmoinesian, Missourian, and Virgilian.

Classification of thick shale sequences within these broad stratigraphic divisions is preferable to defining them more specifically within individual formations because of the many facies changes that have resulted from various depositional environments, not only between basins but also within basins and shelf areas. These striking and commonly abrupt facies changes are especially prevalent in those basins associated with the Ouachita fold belt and the Southern Oklahoma and Delaware Aulacogens (Handford et al., 1980). Pennsylvanian deposition on the Eastern Shelf and westward into the Midland Basin, which was characterized by clastic wedges of terrigenous fluvial and delta systems, has been especially well documented (Brown, 1969; Wermund and Jenkins, 1969; Galloway and Brown, 1972, 1973; Brown et al., 1973; Erxleben, 1975; Wermund, 1975).

In the shelf areas and shallow basins north of the Anadarko and Arkoma Basin--in central and northern Oklahoma, northwestern Arkansas, southeastern Colorado, Kansas, Nebraska, northwestern Missouri, and southwestern Iowa--deposition was of a more regular cyclic nature (both terrigenous and marine). As a result, clastic units, including shale, are much thinner.

In some areas, thick shale deposits extend from one series division to another, notably in some of the deep basins, where no stratigraphic break can be detected. Moreover, no well-defined break is recognized between the Mississippian and the Pennsylvanian or the Pennsylvanian and the Permian Systems throughout much of the region; thus, some shale sequences appear to extend unbroken across these systemic boundaries. These conditions generally have been noted in the various descriptions of the shale units that follow.

The general characterizations of the lithologies and thicknesses of the rocks of each provincial series of the Pennsylvanian by McKee and Crosby (1975) have been drawn upon liberally in the preparation of this part of the report. Detailed studies, such as geophysical (electric) log cross sections, also have been utilized in the discussions of lithologic and thickness data. Where McKee and Crosby (1975) characterized thick stratigraphic sequences as containing argillaceous strata in a ratio of at least 4:1 to other rock types, more detailed studies commonly reveal that some of the same intervals contain either zones of sandstone and limestone or zones of noticeably sandy or silty shale. Therefore, the discussions of specific lithologic and thickness determinations given here are usually based upon more detailed information than that presented by McKee and Crosby (1975).

6.4.4.1 Shales of the Morrowan Series

6.4.4.1.1 Stratigraphy. Rocks of the Morrowan Series occur in the Midcontinent Region principally in and on the flanks of several of the deep basins, such as the Anadarko, Ardmore, Marietta, Arkoma, Palo Duro, Hollis, Delaware, and Fort Worth Basins (McKee and Crosby, 1975) (Figure 6-2). Also, Morrowan rocks extend from the northern shelf of the Anadarko Basin northward and westward into western Kansas, northeastern New Mexico, and eastern Colorado (McKee and Crosby, 1975). In addition, Morrowan flysch sediments were deposited in the Ouachita trough.

Named formations and members of the Morrowan Series containing thick shale intervals include the Bloyd Shale in eastern Oklahoma and western Arkansas; the Dornick Hills Group, which contains the Golf Course Formation, in the Ardmore area; the Kearny Formation in western Kansas; and the "Morrow" Formation in southern Oklahoma (Figure 6-4). These units are at least partially equivalent to the Jackfork Formation of the Ouachita Mountains and the upper part of the Tesnus Formation of the Marathon Uplift (McKee and Crosby, 1975).

Predominantly argillaceous Morrowan rocks occur principally in the deep basins of the southern Oklahoma folded belt--the Anadarko, Ardmore, Marietta, and Arkoma Basins--and extend eastward through the Arkansas portion of the Arkoma Basin (McKee and Crosby, 1975); thick bodies of Morrowan Shale also extend northward from the Anadarko Basin through western Oklahoma and southwestern Kansas (Figure 6-13). Scattered thick shale sequences also occur in southeastern Colorado, in the northern Texas Panhandle, in northwestern Oklahoma, and in parts of the Fort Worth Basin (Figure 6-13). These argillaceous sequences range up to more than 1,800 m in thickness in the deepest part of the Anadarko Basin in western Oklahoma, and from 300 to more than 1,500 m in the Arkoma Basin of Oklahoma and Arkansas (McKee and Crosby, 1975). Some of these shale sequences in the Anadarko and Ardmore Basins include rocks of the

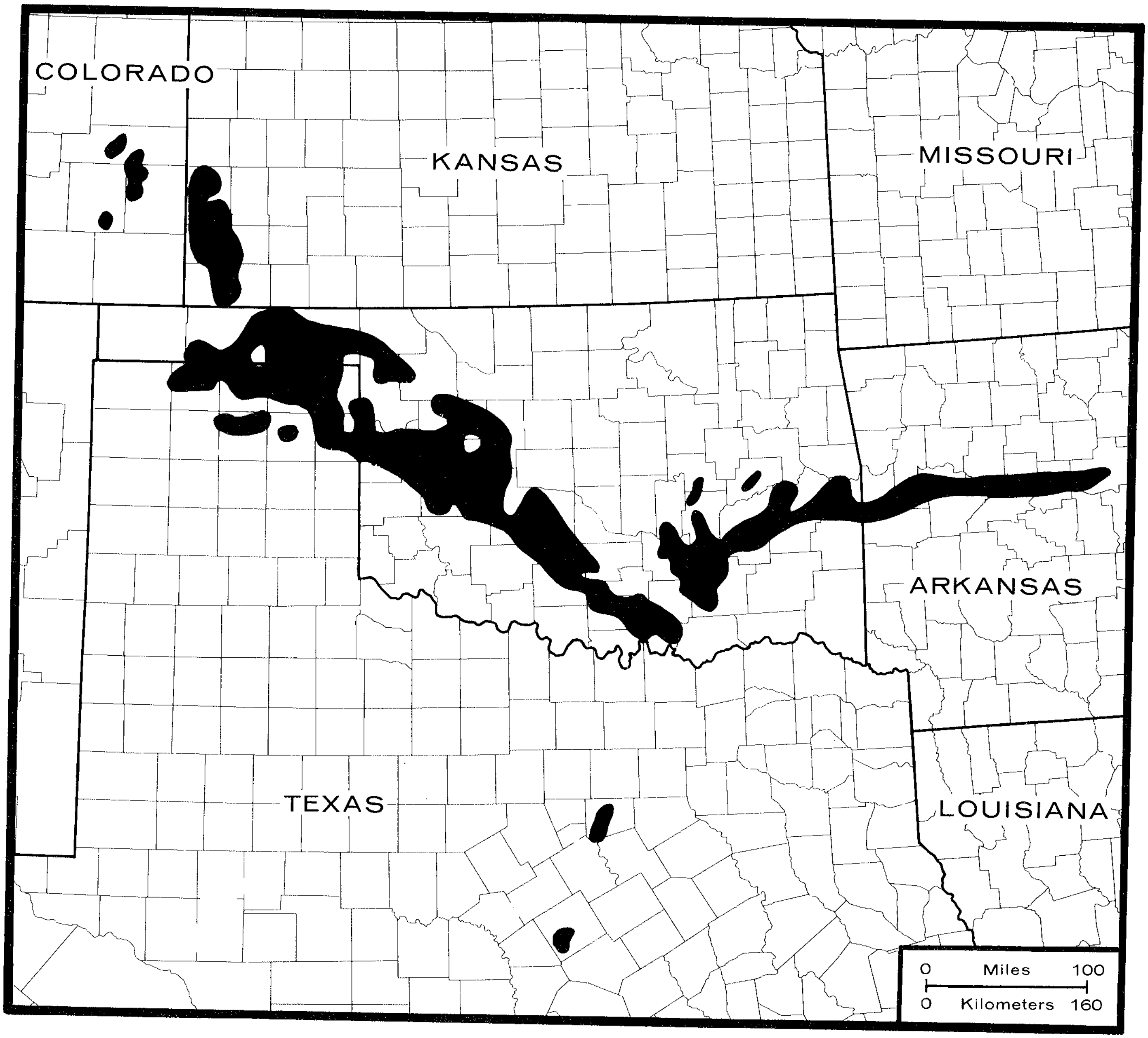

FIGURE 6-13. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION SHOWING DISTRIBUTION OF ARGILLACEOUS FACIES, IN A RATIO OF AT LEAST 4:1, OF MORROWAN ROCKS MORE THAN 75 M THICK (MODIFIED FROM MCKEE AND CROSBY, 1975)

"Springer" Formation, which were assigned to the Upper Mississippian in a preceding section.

In the Ardmore Basin and the eastern Anadarko Basin of Oklahoma, the lower part of the Dornick Hills Group is considered Morrowan and comprises the Golf Course Formation, which contains several thick shale units. Gahring (1959) recorded 215 to 520 m of strata consisting essentially of shale in Bryan County. Adkison (1960) noted 180 m of shale in Caddo County. An Ardmore Geological Society (1956d) cross section depicts up to 360 m of shale in the Golf Course Formation in Carter County. In Stephens County, shales in the Golf Course Formation range up to 400 m in thickness (Ardmore Geological Society, 1956c; Harlton, 1956). In the western Anadarko Basin of Oklahoma and the Texas Panhandle, shales in the upper "Morrow" Formation thicken southward into the basin from about 120 to 210 m (Forgotson et al., 1966).

A north-south cross section (Panhandle Geological Society, Stratigraphic Committee, 1952) indicates 90 m of Morrowan calcareous shale in Beaver County, in the Oklahoma Panhandle, and 107 m of Morrowan shale in Ochiltree County, in the Texas Panhandle. In Stevens County of southwestern Kansas, a Morrowan shale at least 90 m thick was recorded, but it possibly contains some silty or sandy zones (Liberal Geological Society, 1956). Shale of the Bloyd Formation thickens from about 30 to 120 m southward into the Arkoma Basin in Okfuskee County of east-central Oklahoma (Laudon, 1959).

Shales of the Dornick Hills Group of southern Oklahoma have been described as gray to black, finely textured, and sideritic; they commonly appear splintery and flaky to papery (Harlton, 1956; Gahring, 1959). Other Morrowan shales are typically gray to black and contain varying amounts of silt.

Many of the Morrowan shales are correlative with sandstone bodies, which appear at numerous stratigraphic positions and include some commercial petroleum reservoirs. In the deep basins of southern Oklahoma and western Arkansas, Morrowan rocks containing thick shales rest conformably upon underlying Upper Mississippian units, whereas northward in the Platform areas these rocks rest unconformably upon both Upper and Lower Mississippian units (Branson, 1962; Glick, 1975).

6.4.4.1.2 Geologic Setting. Where Morrowan shales are thick they are usually deeper than 900 m; an exception is isolated occurrences in the tectonically complex southern Oklahoma folded belt. In the Anadarko and Ardmore Basins, thick shales were noted to range from 910 to 4,000 m in depth (Panhandle Geological Society, Stratigraphic Committee, 1952; Ardmore Geological Society, 1956a, 1956c, 1956d; Adkison, 1960; Forgotson et al., 1966). Farther north, in Stevens County, Kansas, at least 90 m of shale is present at depths ranging from 1,600 to 1,800 m (Liberal Geological Society, 1956). The two occurrences of thick Morrowan shale in the Fort Worth Basin are both deeper than 900 m.

As was noted in a previous section on Upper Mississippian shales, structural complexity in varying degrees characterizes the southern Oklahoma folded belt and adjacent areas of Arkansas and Texas. This region includes the Anadarko, Ardmore, Marietta, and Arkoma Basins.

6.4.4.1.3 Mineralogy and Rock Properties. Weaver in 1958 determined the clay content for Morrowan shales in the Ardmore Basin and the western part of the Arkoma Basin as montmorillonite and/or mixed-layer clay plus illite and chlorite. In 1960 he noted that Morrowan shales from the Ardmore Basin eastward to the Ouachita Mountains contrastingly contain an illite-chlorite-kaolinite mixed-layer clay facies.

Flawn et al. (1961) identified the clay facies of Morrowan rocks in the Anadarko, Ardmore, and Arkoma Basins as comprising illite and chlorite plus montmorillonite and/or mixed-layer clay.

6.4.4.1.4 Hydrology. The Ogallala Formation of Tertiary age is the principal aquifer in the western part of the region of thick Morrowan shales; this aquifer extends from southeastern Colorado eastward and southward through southwestern Kansas into western Oklahoma and Texas (Baker and Wall, 1976; Bedinger and Sniegocki, 1976; Taylor, 1978). Throughout the region, alluvium and terrace deposits of Holocene and

Pleistocene age are also important aquifers. According to Bedinger and Sniegocki (1976) and Havens (1977), gypsum beds of Permian age in southwestern Oklahoma also constitute productive aquifers. The Antlers Sandstone of Early Cretaceous age is another important aquifer in southern Oklahoma (Johnson et al., 1972; Hart, 1974). Other principal aquifers include the Rush Springs Sandstone of Permian age in west-central Oklahoma and the Elk City Sandstone of Permian age in western Oklahoma (Johnson et al., 1972; Carr and Bergman, 1976).

6.4.4.1.5 Mineral Resources. Oil and gas constitute by far the most important mineral resources found within the region containing thick, dominantly argillaceous rocks of the Morrowan Series (Figures 6-11, 6-13). Principal reservoir rocks occur in and on the flanks of the Anadarko, Ardmore, Marietta, and Arkoma Basins, where lenticular Morrowan sandstones are some of the most important producing zones. Other pay zones include Permian carbonates (mainly in the Panhandle-Hugoton Field and nearby fields of the Oklahoma and Texas Panhandles and southwestern Kansas), younger Pennsylvanian sandstones, Mississippian carbonates and sandstones, carbonates of the Hunton Group (mainly Silurian-Devonian), Middle Ordovician sandstones, and carbonates of the Arbuckle Group (Lower Ordovician) (Parker, 1956; Rutledge, 1956; Caplan, 1957; Arkansas Geological and Conservation Commission, 1959; Hicks, 1971; St. Clair et al., 1976; Huffman et al., 1978; Fay et al., 1979).

Other mineral commodities produced include gypsum in western Oklahoma and bituminous coal in eastern Oklahoma and western Arkansas (Arkansas Geological and Conservation Commission, 1959; Johnson, 1969). Two areas of thick Pennsylvanian shales occur in the Fort Worth Basin, where cement materials and sand and gravel have been produced (Garner et al., 1979).

6.4.4.2 Shales of the Atokan Series

6.4.4.2.1 Stratigraphy. Rocks of the Atokan Series, which generally overlie those of the Morrowan Series conformably, also overlap pre-Pennsylvanian rocks unconformably in parts of the Midcontinent. In addition to depocenters in the Anadarko, Ardmore, Marietta, Arkoma, Palo Duro, Hollis, Delaware, and Fort Worth Basins, which typified distribution of the Morrowan sediments, Atokan sediments also were deposited in the Forest City Basin and adjacent shelf areas, the Midland Basin, the Val Verde and Kerr Basins, and the shelf area of north-central Texas west of the Fort Worth Basin (McKee and Crosby, 1975).

The main named units of the Atokan Series that consist largely of shale are the "Atoka" Formation in the Anadarko, Arkoma, and Fort Worth Basin areas; the Smithwick Shale in the Fort Worth Basin area; and the upper part of the Dornick Hills Group (the lower part being Morrowan), which contains the Lake Murray Formation, in the Ardmore Basin (see correlation charts, Figures 6-4, 6-5). These units are considered equivalent to the argillaceous flysch deposits of the "Atoka" Formation of the Ouachita Mountains and the Dimple Formation and the lower part of the Haymond Formation of the Marathon Uplift area (Fay et al., 1979; Kier et al., 1979).

Principal areas where argillaceous Atokan rocks thicker than 75 m and in a ratio of 4:1 or greater are present include the deep parts of the Anadarko, Ardmore, Marietta, and Arkoma Basins (Figure 6-14). Other areas with thick argillaceous Atokan rocks are the west and north flanks of the Fort Worth Basin, the Hollis Basin, and scattered sites in the Texas Panhandle and the Forest City Basin. The greatest thickness of Atokan shales occurs in the Arkoma Basin, where as much as 3,600 m was recorded, and where 1,000 m or more is common (McKee and Crosby, 1975). Atokan shales range up to 1,500 m thick in the deep part of the Anadarko Basin. In the Fort Worth Basin, these shales range up to 1,500 m thick also, and in the other areas, up to 120 m.

Along the entire length of the Arkoma Basin, the "Atoka" Formation thickens abruptly from less than 100 m to several thousand meters southward into the deepest part of the basin, just north of the Ouachita Mountain front.

In the Arkoma Basin a number of cross sections have shown the character of the "Atoka" Formation. Frezon (1962) reported intervals of clay shale up to 100 m thick in Coal County, Oklahoma; eastward into

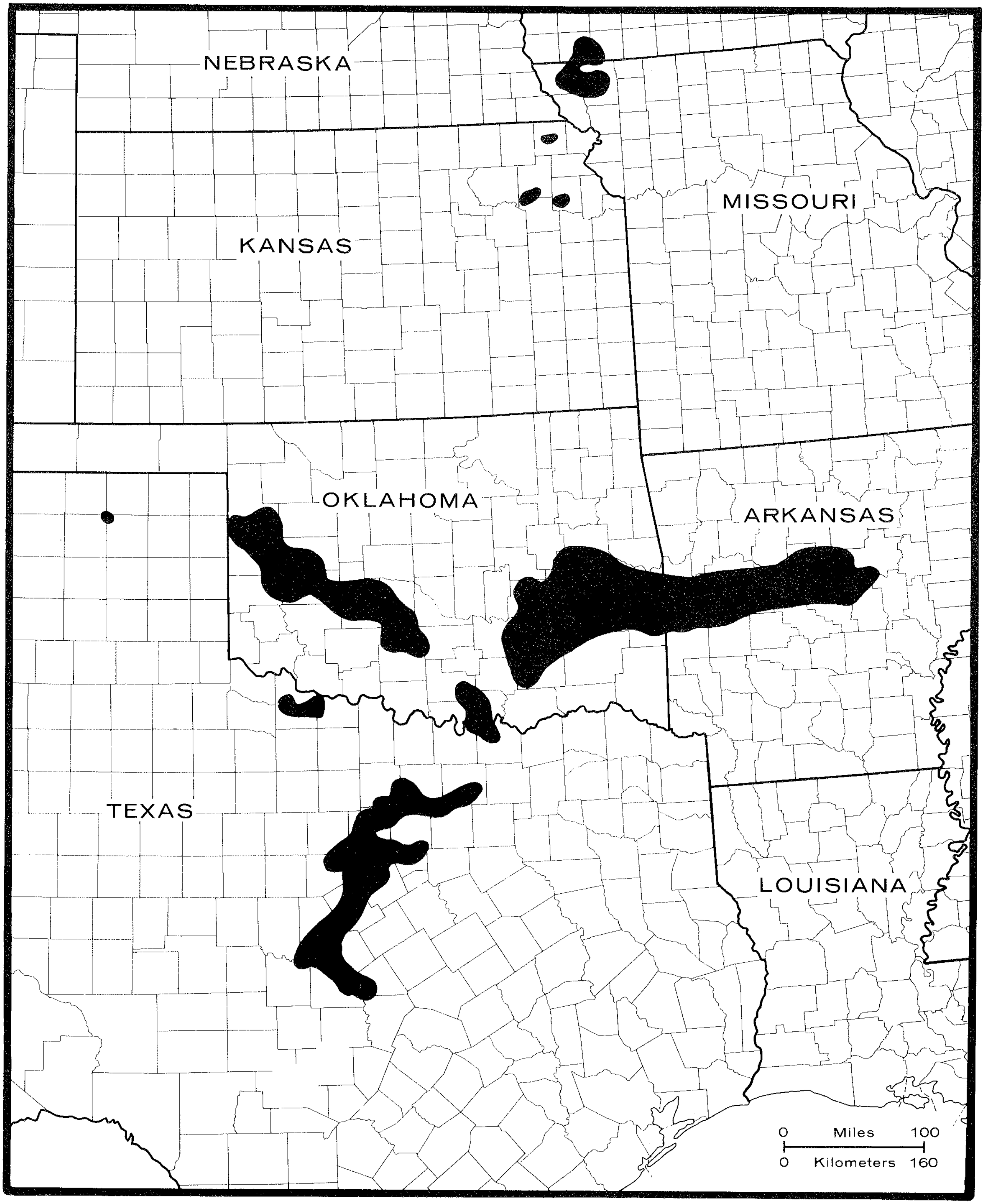

FIGURE 6-14. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION, SHOWING DISTRIBUTION OF ARGILLACEOUS FACIES, IN A RATIO OF A LEAST 4:1, OF ATOKAN ROCKS MORE THAN 75 M THICK (MODIFIED FROM MCKEE AND CROSBY, 1975)

Arkansas the shales are sandier and contain interbeds of siltstone and sandstone. Scull et al. (1959) presented a series of electric-log sections extending from the shelf southward into the basin: in Pittsburg, Hughes, and Coal Counties, Oklahoma, the "Atoka" Formation is represented by as much as 1,500 m of shale with essentially no sandstone content; further eastward in Oklahoma the intervals of "Atoka" shale range up to 1,000 m in thickness, and in Arkansas most of the shale intervals are silty to sandy.

In the Kansas portion of the Forest City Basin, shales in the Atokan Series are interbedded with cherty limestones; the whole interval ranges up to 150 m in thickness (Zeller, 1968). In southeastern Nebraska, shales up to 75 m thick were recorded in Richardson County (Burchett and Reed, 1960).

In the Ardmore Basin, Fay et al. (1979) defined a maximum thickness of 228 m for the upper shale member of the Lake Murray Formation of the upper Dornick Hills Group.

In the southern part of the Marietta Basin, in Grayson County, Texas, Atokan shales were noted, ranging in thickness from 60 to 90 m (North Texas Geological Society, 1954a).

In the Fort Worth Basin and adjacent shelf area to the west, several moderately thick Atokan shale intervals have been recorded, ranging from 60 to 120 m (North Texas Geological Society, 1954b; Ng, 1979).

The Smithwick Shale thickens from the outcrop around the Llano Uplift in central Texas to more than 300 m eastward in the subsurface toward the Ouachita Fold Belt (Barnes, 1948; McBride and Kimberly, 1963). In Brown County, north of the Llano Uplift, on the west flank of the Fort Worth Basin, the Smithwick Shale attains a thickness of 75 m (Morey, 1955). Turner (1957) considered the Smithwick Shale to be the basinward shaly facies of several carbonate shelf units westward, including the Marble Falls, Big Saline, and Caddo strata. He noted thicknesses of at least 600 m for Atokan shales in the Fort Worth Basin.

In southern Oklahoma, western Arkansas, and the Fort Worth Basin area of Texas, the "Atoka" Formation was described as consisting of dark shales, some silty, some micaceous, and some carbonaceous, with intercalated gray, tan, brown, and black siltstones and very fine grained and fine-grained sandstones; however, at places this entire interval is composed of shale (Scull et al., 1959; Oakes, 1977). Several zones of lenticular sandstone produce oil and gas. In Kansas, rocks of the Atokan Series were characterized as mainly interbedded dark-gray, black, and dark-brown cherty limestones and dark-gray to black shales (Zeller, 1968).

At its type locality in the Llano Uplift area the Smithwick Shale was described by McBride and Kimberly (1963) as dark-gray claystone grading upward into flyschlike interbedded sandstone and claystone. Also in this area, Plummer (1943) characterized the shale as a black, fissile, siliceous shale with its upper part consisting of a thick section of black, soft, slightly ferruginous and gypsiferous shale containing thin lentils of hard siltstone and sandstone. In the Fort Worth Basin, Turner (1957) described the Smithwick Shale as an essentially homogeneous section of dark-gray to black shales, containing a few interbedded sandstones, comparable to the Smithwick on outcrop.

6.4.4.2.2 Geologic Setting. In areas where Atokan shales are thicker than 75 m, they are usually deeper than 900 m. This is the case particularly in the deep basins of the southern Oklahoma folded belt and adjacent areas of Texas and eastward into the Arkansas portion of the Arkoma Basin. However, some thick Atokan shales are present at moderate depths along the north flank of the Arkoma Basin: in McIntosh County, Oklahoma, Oakes and Koontz (1967) recorded shale intervals up to 275 m thick, but containing several sandy or silty zones, at depths of 460 to 1,150 m; Frezon (1962) reported zones of clay shale up to about 100 m thick in Oklahoma ranging from 610 to 910 m deep; Edwards and Downey (1967) showed 490 m of shale in Oklahoma at a depth of 550 m, and 60 to 180 m of shale from 150 to 1,500 m deep; McQuillan (1977), in his many log sections in the southwestern part of the basin, recorded shales up to 1,800 m thick at depths ranging from 600 to 3,000 m; and Merewether and Haley (1961) noted several shale intervals in Logan County, Arkansas, from 30 to 90 m thick ranging in depth from 300 to 1,800 m.

Most sections through the Fort Worth Basin indicate depths greater than 900 m for thick Atokan shales, but Turner (1957) recorded about 600 m of "Atoka" shale at a depth of 700 m in Dallas County and 90 m of "Atoka" shale at a depth of 390 m in Bosque County. Also, Turner (1957) depicted several thick shale sequences in the Smithwick Shale: several wells in Comanche County penetrated shale intervals ranging from 90 to 240 m in thickness and 610 to 880 m in depth, and in Erath County shale intervals were found to range from 150 to 390 m in thickness and 550 to 910 m in depth.

Moderately thick Atokan shales in the Forest City Basin range in depth from about 240 to 640 m (Burchett and Reed, 1960; Anderson and Wells, 1968). As described in earlier sections, the basins of the southern Oklahoma folded belt, including adjacent areas in Texas and Arkansas, were subjected to varying amounts of structural deformation. The Forest City and Fort Worth Basins, on the other hand, have been relatively undisturbed, except that the latter is bounded on the east, at its deepest part, by the intensely deformed Ouachita Fold Belt.

6.4.4.2.3 Mineralogy and Rock Properties. Johnson and Luza (1980) characterized the "Atoka" shales of Oklahoma as containing the clay minerals illite, chlorite, kaolinite, and mixed-layer illite-montmorillonite. They noted that these shales exhibit a light to medium plasticity and a low to medium shrink-swell potential. Weaver (1958) determined that the "Atoka" shales of the Anadarko, Ardmore, and Arkoma Basins were characterized by illite and chlorite and by montmorillonite and/or mixed-layer clay. Weaver (1960) noted that Atokan sedimentary rocks in southern Oklahoma generally contain a larger proportion of southward-derived montmorillonite detritus than those of the Morrowan, and that in the western part of the Anadarko Basin a distinctive mixed-layer chlorite-vermiculite clay had first made its appearance, later becoming abundant by Desmoinesian time.

For claystone in the Smithwick Shale, McBride and Kimberly (1963) recorded chiefly illite with minor amounts of quartz and muscovite silt plus minute plant fragments; they noted that the silt occurs mostly in laminae. In the Llano Uplift area, Plummer (1943) described the following minute mineral grains in the Smithwick Shale: montmorillonite, kaolinite, chlorite, mica, quartz, limonite, pyrite, and organic material.

6.4.4.2.4 Hydrology. In the Anadarko Basin area, principal aquifers are, from west to east, the Ogallala Formation of Tertiary age, the Elk City Sandstone of Permian age, the Rush Springs Sandstone of Permian age, gypsum beds of Permian age, and alluvium and terrace deposits of Quaternary age along major streams (Johnson et al., 1972; Bedinger and Sniegocki, 1976; Carr and Bergman, 1976). Overlying parts of the Marietta and Ardmore Basins in southern Oklahoma and adjoining parts of Texas is the Antlers Sandstone, or Trinity aquifer, of Early Cretaceous age, a principal aquifer of the region (Johnson et al., 1972; Hart, 1974; Bedinger and Sniegocki, 1976). Eastward into the Arkoma Basin of Oklahoma and Arkansas, alluvium and terrace deposits along the Arkansas River constitute principal aquifers (Arkansas Geological and Conservation Commission, 1959; Johnson et al., 1972).

The Trinity aquifer of Early Cretaceous age overlies most of the Fort Worth Basin and is a major aquifer in the north-central Texas region; overlapping the Trinity aquifer to the east, and lying along the north flank of the Fort Worth Basin, is the Woodbine aquifer of Late Cretaceous age (Baker and Wall, 1976).

In the Forest City Basin, major aquifers include glacial drift of Pleistocene age and Holocene alluvium along the Missouri River and its principal tributaries (Bayne and Ward, 1967; Dorheim, 1970; Gann et al., 1973; Taylor, 1978).

6.4.4.2.5 Mineral Resources. As noted in previous sections, oil and gas make up by far the most important mineral resources of the region (Figure 6-11). The Atokan rocks themselves are important hydrocarbon producers, principally from lenticular sandstones which occur at various stratigraphic intervals both below and above thick shale zones. Other important petroleum reservoirs in southern Oklahoma and western Arkansas and adjacent parts of Texas include younger Pennsylvanian sandstones, both sandstones and carbonates of the Mississippian system, carbonates of the Hunton Group (principally of Silurian-Devonian age), sandstones of the Simpson Group (Middle Ordovician), and limestones and dolomites of the Arbuckle Group (Lower Ordovician) (Parker, 1956; Rutledge, 1956; Caplan, 1957; Arkansas Geological and Conservation Commission, 1959; Hicks, 1971; St. Clair et al., 1976; Huffman et al., 1978; Fay et al., 1979). In the eastern and southern parts of the Fort Worth Basin, only a little oil and gas have been produced (St. Clair et al., 1976); pay zones of both Pennsylvanian and Mississippian age have produced both oil and gas, and several once-productive fields have been abandoned. The small, scattered oil and gas fields of the Forest City Basin have produced small amounts of oil and gas from Hunton rocks (Reed et al., 1958) and from younger Pennsylvanian rocks of Desmoinesian and Missourian age (Anderson and Wells, 1968). It is thought that an effective means of petroleum entrapment was lacking in much of the Forest City Basin, as reflected in the many occurrences of heavy oil; however, interest remains active in developing thermal-recovery techniques for future production of this oil (Anderson and Wells, 1968; Wells and Anderson, 1968).

Other mineral resources of the region containing thick Atokan shales are bituminous coal beds in younger Pennsylvanian rocks in the Arkoma Basin area in Oklahoma and Arkansas, along the northwest flank of the Fort Worth Basin, and in the Forest City Basin; industrial sand, cement materials, and sand and gravel in younger rocks of the Fort Worth Basin; Permian gypsum in western Oklahoma; and limestone, clay, and shale in the Forest City Basin (Frye et al., 1951; Arkansas Geological and Conservation Commission, 1959; Kisvarsanyi, 1965; Johnson, 1969; Dorheim, 1970; Garner et al., 1979).

6.4.4.3 Shales of the Desmoinesian Series

6.4.4.3.1 Stratigraphy. Desmoinesian sedimentation in the Midcontinent was characterized in general by continued deposition in areas of previous Pennsylvanian sedimentation, but it was much more widespread in most of these areas, spilling over the basins and overlapping older rocks throughout most parts of the shelf areas (McKee and Crosby, 1975). For the first time, Pennsylvanian sediments covered the north-central part of the region, extending northward from Oklahoma through Kansas and Nebraska into the Dakotas. In Texas, Desmoinesian sediments covered the Eastern shelf, most of the Texas Panhandle, and much of the Central Basin Platform.

Named Desmoinesian units containing substantial amounts of argillaceous rocks generally have been assigned to the Deese Group in the Ardmore and Marietta Basins; the Cherokee Group in Oklahoma, the Texas Panhandle, Kansas, Missouri, Nebraska, and Iowa; the Marmaton Group in Oklahoma, Kansas, Missouri, Nebraska, and Iowa; and the Strawn Group in most of Texas (Figures 6-4, 6-5). In Oklahoma and Missouri, the Cherokee Group has been divided into the Krebs and Cabaniss Subgroups. Within these groups, specific formations containing thick shale sequences include the McAlester, Savanna, and Boggy Formations in eastern Oklahoma and western Arkansas; the Stuart Shale in the Arkoma Basin of Oklahoma; and the Senora Formation, Wetumka Shale, Wewoka Formation, Nowata Shale, and Holdenville Shale in the northern shelf area of eastern Oklahoma (Figure 6-4).

The main area where Desmoinesian argillaceous rocks thicker than 75 m are present in a ratio of 4:1 or greater extends from north-central Texas northward through Oklahoma, Kansas, and Missouri into Nebraska and Iowa (Figure 6-15). The thickest shales are present in the principal basin areas: up to about 2,800 m in the Ardmore and Marietta Basins, 1,500 m in the Arkoma Basin, 1,300 m in the Fort Worth Basin, and 1,200 m in the Anadarko Basin. Thicknesses of 100 m or more are common elsewhere (McKee and Crosby, 1975).

In addition to shale, Desmoinesian rocks contain many sandstone and limestone units as well as most of the commercial coal beds of the Midcontinent. Also, some of the Desmoinesian sandstones constitute major reservoirs for hydrocarbon production.

In eastern Oklahoma, the McAlester Formation consists predominantly of dark silty shale, separated at wide intervals by four named sandstones and the McAlester or Stigler coal; individual shale intervals range up to

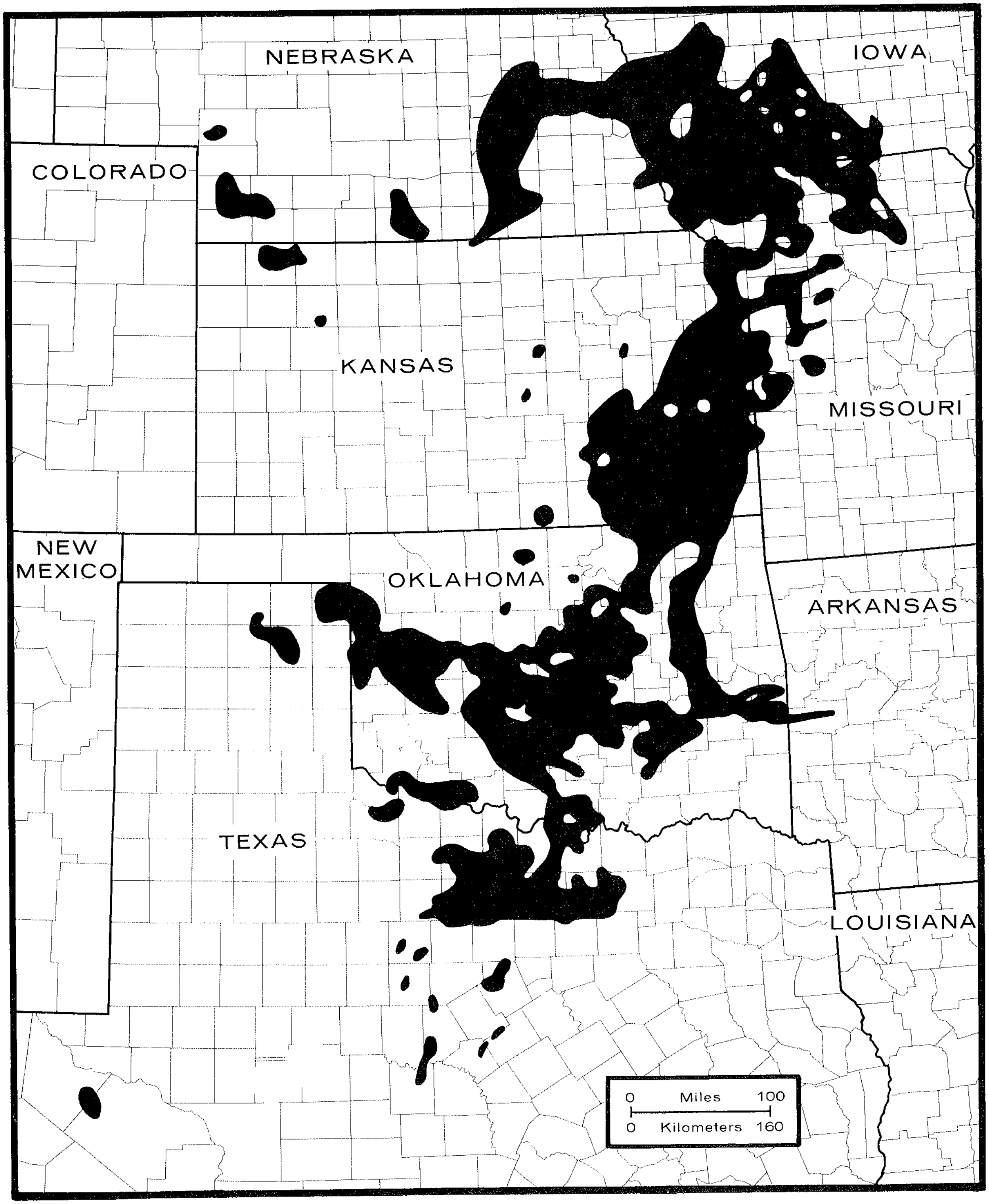

FIGURE 6-15. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION, SHOWING DISTRIBUTION OF ARGILLACEOUS FACIES, IN A RATIO OF AT LEAST 4:1, OF DESMOINESIAN ROCKS MORE THAN 75 M THICK (MODIFIED FROM MCKEE AND CROSBY, 1975)

150 m in thickness (Oakes, 1977; Johnson and Luza, 1980). The overlying Savanna Formation is composed mostly of dark-gray clayey to sandy shale with some fissile shale and contains several limestone and sandstone units as well as several commercial coal beds; the shale zones vary in thickness from about 30 m in the northern Oklahoma shelf area to 120 m in the Arkoma Basin (Oakes and Koontz, 1967; Oakes, 1977; Fay et al., 1979). The overlying Boggy Formation in the Arkoma Basin consists of up to 210 m of predominantly sandy, silty shale with thin sandstone units and the Secor coal bed; the gray to dark-gray Stuart Shale lentil at the top of the formation attains a maximum thickness of 115 m (Oakes and Koontz, 1967; Fay et al., 1979; Johnson and Luza, 1980). Shales in the overlying Senora Formation of the Arkoma Basin and northern shelf area in eastern Oklahoma are mainly gray and silty to sandy; the whole formation contains fine-grained micaceous sandstones, limestones, and several commercial coal beds and ranges in thickness from about 55 to 280 m (Bingham and Moore, 1975; Oakes, 1977; Johnson and Luza, 1980). Several formations of the overlying Marmaton Group have notably thick shale sequences, either singly or in combination: The Wetumka-Wewoka-Nowata-Holdenville interval of the northern Oklahoma shelf and adjacent parts of Kansas and Missouri consists principally of gray to dark-gray clay shale with several silty and sandy zones, where the argillaceous intervals range up to 240 m in thickness (Shawnee Geological Society, 1949a, 1949b; Ries, 1954; Tanner, 1956; Oakes and Jordan, 1959; Bingham and Moore, 1975; Fay et al., 1979).

In the Ardmore and Marietta Basins, gray micaceous shale intervals in the Deese Group range in thickness from 85 to 120 m (Ardmore Geological Society, 1956d; Parker, 1956). In the Oklahoma and Texas Panhandles, shale and calcareous shale in the Cherokee Group up to 165 m thick were recorded (Panhandle Geological Society, Stratigraphic Committee, 1952).

The Strawn Group in Texas is roughly the rock-stratigraphic equivalent of the Desmoinesian Series (Figure 6-5). Along the Eastern shelf and in north-central Texas, Strawn and younger Pennsylvanian and Permian rocks have been intensively studied, particularly with respect to their depositional systems (Brown, 1969; Wermund and Jenkins, 1969; Galloway and Brown, 1972, 1973; Brown et al., 1973; Erxleben, 1975;

Wermund, 1975). Argillaceous intervals in the Strawn Group range up to 330 m in this area (Abilene Geological Society, Stratigraphic Committee, undated, d; North Texas Geological Society, 1954a), with abrupt variations in lithology and thickness being common.

6.4.4.3.2 Geologic Setting. Desmoinesian shales thicker than 75 m crop out in the eastern part of the Midcontinent and are at moderate depths at many places in the shelf areas; a few basin areas contain shale intervals at moderate depths. In much of the western part of the Midcontinent, Desmoinesian shales lie below 900 m.

In the area of the Oklahoma portion of the Arkoma Basin and northern Oklahoma shelf, thick shales have been recorded as follows, generally from south to north: in Latimer County and vicinity, 300 m in the Cherokee Group from 180 to 480 m deep, and 60 to 120 m in the Marmaton Group from 60 to 185 m deep (Edwards and Downey, 1967); in McIntosh County, 90 to 120 m from 330 to 520 m deep (Oakes and Koontz, 1967); in Seminole County, shales in the Wewoka Formation up to 245 m with some sandy and silty zones from 600 to 900 m deep and 1,350 to 1,520 m deep (Tanner, 1956); in Okfuskee County, shales spanning the Wewoka Formation and Holdenville Shale up to 210 m from 600 to 900 m deep (Ries, 1954); in Creek County, shales covering the Wetumka-Wewoka-Holdenville interval up to 210 m from 245 to 520 m deep, and also shales in the Nowata-Lenapah-Holdenville interval up to 90 m from 90 to 670 m deep, all in the Marmaton Group (Oakes and Jordan, 1959).

Westward, in central Oklahoma, a cross section through Lincoln County indicates a shale sequence from the Wewoka Formation and Holdenville Shale (Marmaton Group) through the overlying Seminole Formation of the basal Skiatook Group of Missourian age (Shawnee Geological Society, 1949a). This shale unit is about 107 m thick at a depth of 790 to 897 m; some zones may be sandy or silty.

On the northeast flank and in the eastern part of the Anadarko Basin, the following thick Desmoinesian shale sequences were recorded: in Cleveland County, 90 to 110 m of shale ranging in depth from 1,950 to

2,130 m (Oklahoma City Geological Society, 1952c); in Canadian County, 120 to 150 m of shale in both the Marmaton Group and overlying Skiatook Group of the Missourian Series from 2,800 to 2,980 m deep (Adkison, 1960); and in Grady County, 245 m of shale from 4,030 to 4,275 m (Ardmore Geological Society, 1956b). Farther west in the Anadarko Basin, well logs from Beaver County, Oklahoma Panhandle, and Roberts County, Texas Panhandle, depict 75 m of calcareous shale at a depth of 1,850 m, and 165 m of shale and calcareous shale at a depth of 2,475 m, both from the Cherokee Group (Panhandle Geological Society, Stratigraphic Committee, 1952).

In the Ardmore Basin, 85 to 90 m of Desmoinesian (Deese) shale was noted in Carter County, Oklahoma, between 1,100 and 1,490 m deep (Ardmore Geological Society, 1956a; Parker, 1956). In the Marietta Basin, in Jefferson County, Oklahoma, and Montague County, Texas, Desmoinesian (Deese) shales from 105 to 135 m thick were indicated at depths between 1,170 and 1,330 m (Ardmore Geological Society, 1956c, 1956d).

Many cross sections have been recorded in the highly variable lithology of the Strawn Group to the south, in north and north-central Texas and along the Eastern Shelf. Those depicting significant thicknesses of shale are listed as follows.

In north Texas, thick Strawn shales were noted, from east to west: in Grayson County, 60 to 185 m of shale at depths of 1,160 to 1,560 m; in Cooke County, 90 m of shale spanning the upper Strawn and lower Canyon Groups at a depth of 245 m; in Denton County, at least 100 m of shale in the Strawn Group from 1,160 to 1,400 m deep; in Wise County, at least 100 m of shale from 520 to 1,560 m deep; in Clay County, 75 to 330 m of shale, some silty to sandy, from 820 to 1,830 m deep; in Archer County, 75 to 90 m of shale in the Strawn Group from 1,200 to 1,500 m deep, and 300 m of shale spanning the Strawn-Canyon boundary at a depth of 670 m; in Baylor County, 90 to 330 m of shale with a few zones of silty to sandy shale in the Strawn and Canyon Groups from 1,100 to 1,650 m; in Knox County, 75 to 245 m of shale in the Strawn and Canyon Groups from 1,190 to 1,780 m deep; and in Foard County, 75 to 120 m of shale from 1,370 to 1,670 m deep (North Texas Geological Society, 1954a, 1954b, 1962).

Farther south, in north-central Texas, thick Strawn Shales were noted in Palo Pinto County, where at least 100 m of shale with some silty to sandy zones is present from about 790 to 900 m deep; in Stephens County, 120 m of shale occurs at a depth of 910 m; in Comanche County, shale intervals 90 to 210 m thick are present at depths of 185 to 460 m; and in Brown County, shales 75 to 305 m thick lie at depths between 305 and 520 m (North Texas Geological Society, 1954a; Turner, 1957).

Along the northeast margin of the Midland Basin, 60 to 75 m of gray shale in the Strawn Group was recorded in southwestern Haskell County, and Strawn shales ranging up to 330 m thick at depths of 1,520 to 2,000 m were indicated in southeastern Stonewall County (Abilene Geological Society, Stratigraphic Committee, undated, b; undated, d).

6.4.4.3.3 Mineralogy and Rock Properties. On a regional basis, Weaver (1960) characterized Desmoinesian shales in the western part of the Anadarko Basin as exhibiting a distinctive mixed-layer chlorite-vermiculite clay mineralogy in relative abundance. In the area of the Arkoma Basin and adjacent shelf areas to the north in Oklahoma, nine formations that contain thick shale sequences are characterized (Johnson and Luza, 1980) in Table 6-1.

6.4.4.3.4 Hydrology. In the Forest City Basin area, important aquifers include Holocene alluvial deposits along the Missouri River and its major tributaries and Pleistocene glacial drift (Bayne and Ward, 1967; Dorheim, 1970; Gann et al., 1973; Taylor, 1978). Westward in Nebraska, Pleistocene alluvial aquifers occur not only along major streams but extend throughout much of the central and eastern parts of the state (Taylor, 1978). Valley-fill alluvial aquifers of Pleistocene and Holocene age are present along principal streams in southern and southwestern Nebraska and northwestern Kansas (Taylor, 1978). The Ogallala aquifer of Miocene and Pliocene age is present in upland areas throughout southwestern Nebraska and western Kansas and extends southwestward through western Oklahoma and the Texas Panhandle (Johnson et al., 1972; Bedinger and Sniegocki, 1976; Taylor, 1978). Extending from the western periphery

TABLE 6-1. PROPERTIES OF DESMOINESIAN SHALE UNITS IN EASTERN OKLAHOMA (DESCENDING) (MODIFIED FROM JOHNSON AND LUZA, 1980)

Formation	Principal Clay Minerals	Plasticity	Shrink-Well Potential
Holdenville Shale	Mixed-layer illite-montmorillonite, illite, and kaolinite	Medium	Low
Nowata Formation	Illite, kaolinite, vermiculite, and chlorite	Slight to medium	Probably low
Wewoka Formation	Illite, mixed-layer illite-montmorillonite, and kaolinite	Medium	Low
Wetumka Shale	Mixed-layer illite-montmorillonite, illite, and kaolinite	Medium	Low
Senora Formation	Illite and kaolinite	Slight to medium	Low
Stuart Shale	Illite, mixed-layer illite-vermiculite, mixed-layer illite-montmorillonite, and kaolinite	Medium	Low
Boggy Formation	Illite, kaolinite, montmorillonite, and mixed-layer illite-montmorillonite	Medium	Low to moderate
Savanna Formation	Illite, kaolinite chlorite, and vermiculite	Medium	Low
McAlester Formation	Illite, kaolinite, and mixed-layer illite-montmorillonite	Slight to medium	Low to moderate

of the Forest City Basin southward and southwestward through southeastern Nebraska and east-central Kansas is the Dakota aquifer of Cretaceous age; aquifers of secondary importance in the Forest City Basin area are limestone and dolomite aquifers of Permian and Pennsylvanian age (Taylor, 1978).

In addition to the Ogallala aquifer, other principal aquifers in the Anadarko Basin are alluvial and terrace deposits (Quaternary), the Elk City Sandstone (Permian) in western Oklahoma, and the Rush Springs Sandstone (Permian) in west-central Oklahoma (Johnson et al., 1972; Carr and Bergman, 1976). The Wichita Formation (Permian) is an important aquifer in scattered areas around the Ardmore Basin, and Permian gypsum beds yield some water to wells throughout western Oklahoma and Texas (Johnson et al., 1972; Hart, 1974; Bedinger and Sniegocki, 1976; Carr and Bergman, 1976).

In the area of Cretaceous overlap, in the Marietta Basin and in north Texas, the chief aquifer where thick Desmoinesian shales are present is the Antlers or Trinity aquifer of Early Cretaceous age; scattered alluvial aquifers are present elsewhere (Johnson et al., 1972; Baker and Wall, 1976).

Throughout the region, some lenticular sandstones in the Desmoinesian, as well as a few limestones, yield poor to fair amounts of water of poor quality (Marcher, 1969; Gann et al., 1973; Hart, 1974).

6.4.4.3.5 Mineral Resources. Although oil and gas make up the principal resources of the Midcontinent, bituminous coal beds constitute an almost equally important resource in the eastern part of the region. Desmoinesian strata, in fact, contain most of the commercially mined coals of the Pennsylvanian System along their outcrop belt and in the shallow subsurface extending southward from the Forest City Basin through eastern Kansas and eastern Oklahoma into north-central Texas (Ebanks et al., 1979; Fay et al., 1979; Kier et al., 1979; Thompson, 1979). Other important coals mined throughout the region occur in rocks of the overlying Missourian and Virgilian Series. Whereas much of the coal mined in the past was recovered by underground methods, virtually all the coal now mined is recovered by surface stripping. Many of the Desmoinesian coal deposits considered too deep for economic recovery at present, however, constitute potentially recoverable resources.

As stated in previous sections, oil and gas are produced in many areas within the region (Figure 6-11). Lenticular sandstones in the Desmoinesian rocks themselves are important hydrocarbon producers, including beds stratigraphically equivalent and adjacent to thick shale deposits. In the Forest City Basin, which has yielded little commercial production so far, heavy-oil accumulations in Desmoinesian and Missourian sandstones have long been considered a potential hydrocarbon resource (Wells and Anderson, 1968). Other pay zones include Permian carbonates (principally in western Oklahoma and the Texas Panhandle), older Pennsylvanian sandstones, both carbonates and sandstones of the Mississippian System, carbonates of the Hunton Group of Silurian-Devonian age, sandstones of the Simpson Group of Middle Ordovician age, and Lower Ordovician carbonates of the Arbuckle and Ellenburger Groups (Parker, 1956; Rutledge, 1956; Hicks, 1971; St. Clair et al., 1976; Ebanks et al., 1979; Fay et al., 1979; Kier et al., 1979).

Other mineral resources produced from Desmoinesian and other Pennsylvanian beds include clay, shale, and limestone throughout the region (Avcin and Koch, 1979; Burchett, 1979; Ebanks et al., 1979; Fay et al., 1979; Kier et al., 1979; Thompson, 1979). Among the other developed resources are Quaternary volcanic ash in central and southern Nebraska, central Kansas, and western Oklahoma; Permian gypsum in central and southern Kansas and western Oklahoma; industrial-sand deposits of Cretaceous age in north-central Texas (Frye et al., 1951; Johnson, 1969; Burchett, 1973; Garner et al., 1979). St. Clair et al. (1976) noted an area of scattered low-grade uranium occurrences within red beds of the Wichita Group (Permian, Leonardian) in north Texas, which apparently extends northward into Oklahoma.

Several underground caverns for the storage of liquefied petroleum gas have been excavated in argillaceous Pennsylvanian rocks. One of these is in Douglas County, central eastern Nebraska, where Desmoinesian shale of the Cherokee Group was excavated by the room-and-pillar method (Cobbs

Engineering, 1975). The depth to this cavern is 90 m; the cavern's capacity is 150,000 42-gallon barrels of liquid, or 23,800 m^3. The cavern has performed successfully since its operation began in 1960, with no evidence of water inflow or structural failure (Cobbs Engineering, 1975). Excavation of a second cavern in Cherokee Group shale was attempted 14 km to the north, but a severe floor upheaval caused the cavern to be lost; however, at the same site another cavern was successfully excavated in underlying Mississippian limestone (Cobbs Engineering, 1975).

6.4.4.4 Shales of the Missourian Series

6.4.4.4.1 Stratigraphy. Deposition throughout the Midcontinent during the Missourian Epoch continued in much the same pattern as that of the preceding Desmoinesian time (McKee and Crosby, 1975). The distribution of dominantly argillaceous rocks more than 75 m thick shifted toward the south and the southwest, centering principally in western Oklahoma, north-central Texas, the Texas Panhandle, and west-central Texas along the Eastern Shelf (Figure 6-16).

Rock groups in these areas containing significant thicknesses of argillaceous beds include, in Oklahoma, the Hoxbar Group in the area of the Ardmore and Marietta Basins, and the Skiatook and Ochelata Groups in the remainder of the state; in Kansas, the Kansas City and Lansing Groups; and in Texas, the Canyon Group (Figures 6-4, 6-5). The uppermost part of the Canyon Group is now considered Virgilian in age (Kier et al., 1979). Formations within the Skiatook Group containing thick shale sequences include the Seminole, Coffeyville, and Nellie Bly Formations in east-central Oklahoma (Figure 6-4). In north-central Texas, thick shale intervals occur in the Wolf Mountain, Placid, and Colony Creek Shales of the Canyon Group (Figure 6-5).

The argillaceous units of the Missourian Series considered in this report (Figure 6-16) range in thickness from 75 to 910 m (McKee and Crosby, 1975). The thickest sequences occur in the Ardmore and Marietta Basins, and in north and north-central Texas. Along the east margin of

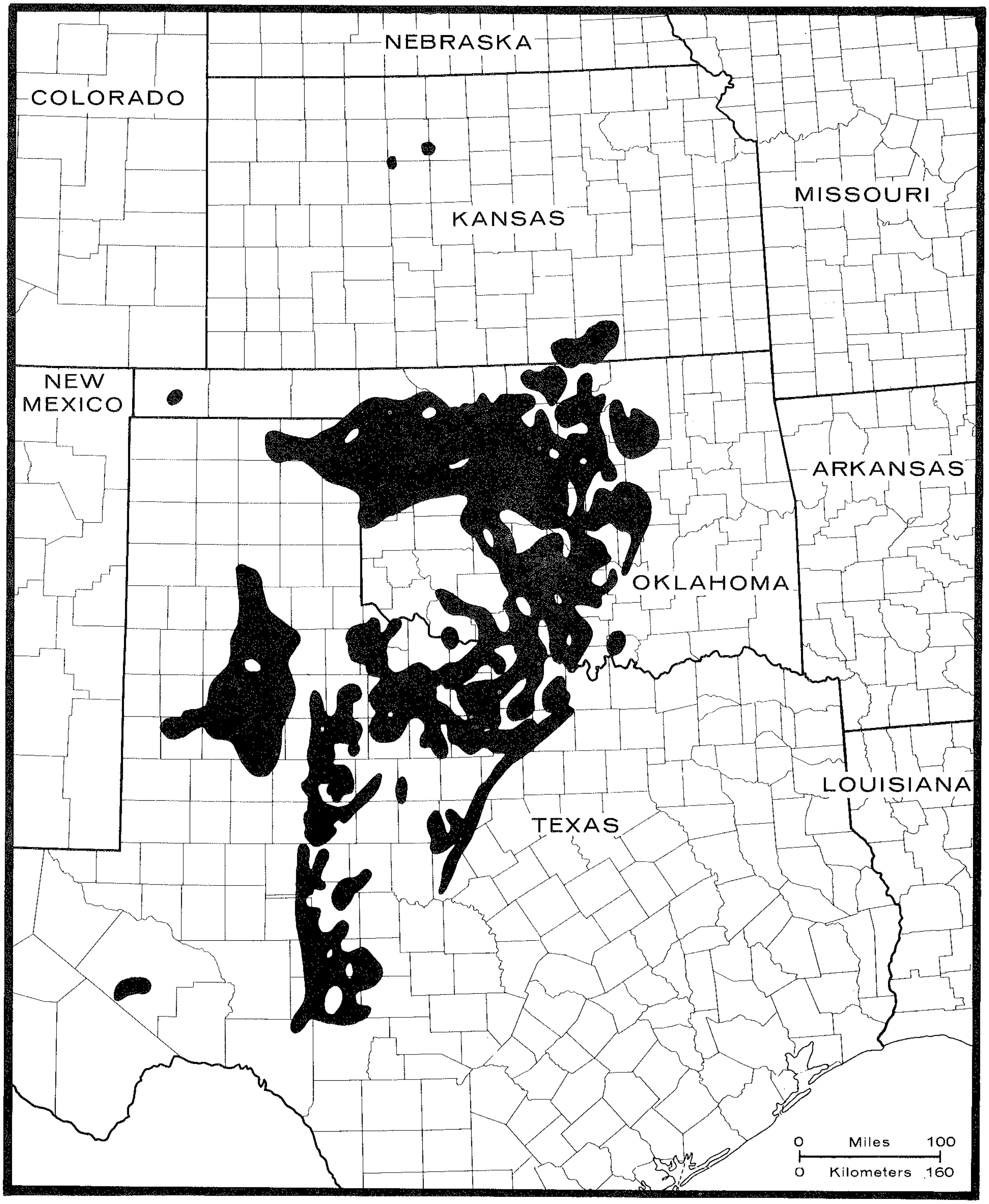

FIGURE 6-16. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION, SHOWING DISTRIBUTION OF ARGILLACEOUS FACIES, IN A RATIO OF AT LEAST 4:1, OF MISSOURIAN ROCKS MORE THAN 75 M THICK (MODIFIED FROM MCKEE AND CROSBY, 1975)

the Fort Worth Basin, shale units vary in thickness from 75 to 600 m; in the Anadarko Basin and northern shelf areas of Texas, Oklahoma, and southern Kansas, these rocks are mostly 75 to 300 m thick, although in Pawnee County, Oklahoma, they attain a thickness of 730 m (McKee and Crosby, 1975). In the Palo Duro Basin and Northern Shelf, in Texas, argillaceous rocks range from 75 to 300 m in thickness; and along the Eastern Shelf they range from 90 to 300 m. Other scattered areas of argillaceous rocks occur in northwest-central Kansas, with a thickness of 75 m; Cimarron County, in the Oklahoma Panhandle, with 90-120 m; and Pecos County, southwest Texas, with 75 to 150 m.

Missourian rocks of the Midcontinent contain, in addition to shale, beds of limestone, lenticular sandstones that constitute many of the region's hydrocarbon reservoirs, and several commercial coal seams. Distribution of these Missourian lithologies is typical of other Pennsylvanian units in being characterized by abrupt facies changes.

In Oklahoma, the Seminole Formation of the Skiatook Group is composed of gray and brown shale interbedded with sandstone, conglomerate, and one important coal bed in the northern part of the state (Johnson and Luza, 1980). The overlying Coffeyville Formation consists of blue-gray shale interbedded with sandstone, conglomerate, and locally, a thin coal bed; the next argillaceous unit above, the Nellie Bly Formation, is made up of mainly gray-brown shale with many fine-grained sandstone and limestone beds locally in the upper part (Bingham and Moore, 1975; Johnson and Luza, 1980).

The Hoxbar Group in Carter County, southern Oklahoma, in the area of the Ardmore and Marietta Basins, consists of gray micaceous shales with thin streaks of fine-grained sandstones (Parker, 1956).

In Sumner County, central southern Kansas, and in Kay County, central northern Oklahoma, argillaceous beds in the Kansas City and Lansing Groups consist of gray-green to black shale with a little siltstone and sandstone (Kansas Geological Society, Study Group Committee, undated; Brandt, 1967).

In Texas, argillaceous rocks generally have been assigned to the undifferentiated Canyon Group or Missourian Series. According to Kier et al. (1979), sedimentation of the Canyon Group in north-central Texas was characterized by less terrigenous influx and more carbonate shelf and bank deposition than that of the underlying Strawn (Desmoinesian) and overlying Cisco (Virgilian) Groups. A general facies change occurs from deltaic deposits in the east (updip) to thick platform and open-shelf limestone deposits westward and finally to shelf-edge reef and bank deposits at the east edge of the Midland Basin. Wermund (1975) described Missourian rocks in north-central Texas as consisting of red to gray terrigenous mudstone, with some sandstones, limestones, and thin coal beds. He noted that limestones commonly persist for 160 km along sedimentary strike but that the sandstones are erratically distributed; he identified a dense, black, pyritic shale in the central part of the Midland Basin as being equivalent to bank limestones of late Desmoinesian and early Missourian age eastward at the edge of the Eastern Shelf. Missourian shales in the Texas portion of the Marietta Basin were described by Bakker (1968) as predominantly gray shale, with some maroon shale, containing fine- to medium-grained sandstone and thin stringers of limestone.

6.4.4.4.2 Geologic Setting. Several areas of complex structure interrupt the distribution of thick sequences of Missourian shales. These complex areas are centered principally along the Southern Oklahoma and Delaware Aulacogens (Handford et al., 1980) and involve such structural features as the Amarillo-Wichita Uplifts, the Ardmore and Marietta Basins, and the Matador-Red River Uplifts (Figure 6-2). Elsewhere, structural influences have been less pronounced.

The thick argillaceous rocks in northwest-central Kansas (Figure 6-16) lie at depths of about 600 to 800 m (Merriam, 1963). Farther south, depths of these rocks range from the shallow subsurface in east-central Oklahoma to at least 2,000 m in western Oklahoma and the Texas Panhandle along the axis of the Anadarko Basin (Johnson and Roberts, 1980). Farther south in Texas, in the area of the Palo Duro Basin and the Northern Shelf, Upper Pennsylvanian shales generally are deeper than 1,300 m (Dutton et al., 1979). In north and north-central Texas, argillaceous rocks of the Canyon Group range in depth from the shallow subsurface near the eastern outcrop to 400 to 600 m in the central part of the area to more than 1,200 m in the western part (Wermund and Jenkins, 1969). In the eastern part of the Fort Worth Basin, argillaceous units range in depth from the shallow subsurface to about 450 m (Wermund and Jenkins, 1969). Along the Eastern Shelf, argillaceous units apparently lie at depths greater than 1,000 m (Wermund and Jenkins, 1969).

Specific thicknesses and corresponding depths of largely argillaceous sequences have been recorded in many electric-log and lithologic sections. Some of these occurrences at moderate depths are noted as follows.

In central southern Kansas and central northern Oklahoma, shales up to 90 m thick in the Lansing Group range in depth from 610 to 1,040 m (Kansas Geological Society, Study Group Committee, undated; Brandt, 1967). Southward in Oklahoma, in the area of the eastern part of the Anadarko Basin and the Ardmore Basin, 75 m and 135 m of shale were noted in the Hoxbar Group at depths of 520 m and 135 m, respectively, in Carter County (Ardmore Geological Society, 1956a; Parker, 1956). In Stephens County, several Missourian shale units were recorded on electric logs, ranging in thickness from 90 to 150 m and in depth from 565 to 1,290 m (Ardmore Geological Society, 1956c).

In north Texas, several well logs indicate Canyon argillaceous units as follows, from east to west: in Cooke County, 90 m of shale in an interval spanning the Strawn-Canyon boundary at a depth of 245 m; in Montague County, a Canyon shale interval of 120 m at a depth of 670 m; in Clay County, shale zones of 90 and 120 m at depths of 670 and 640 m, respectively; in Archer County, Canyon shale intervals of 120 to 210 m at depths from 670 to 730 m, and a Strawn-Canyon sequence of 305 m at a depth of 670 m; in Baylor County, a Canyon shale 120 m thick at a depth of 790 m, and a Strawn-Canyon shale 330 m thick at 1,040 m; and in Knox County, 245 m of Strawn-Canyon shale at a depth of 1,200 m (North Texas Geological Society, 1954a).

In north-central Texas, a well in Young County drilled through two intervals of about 75 m each of unbroken interdeltaic shale at depths of about 300 and 600 m (Erxleben, 1975). In Stephens County, 120 m of Canyon shale was recorded at a depth of 460 m (Turner, 1957).

In the Eastern Shelf area of Texas, several well logs from Runnels County indicated Canyon shale intervals as follows: 60 m at a depth of 910 m, 120 m at a depth of 940 m, 90 m at a depth of 975 m, and 75 m at a depth of 1,160 m (Morey, 1955).

6.4.4.4.3 Mineralogy and Rock Properties. No mineralogic studies were located that give comprehensive treatment to the shales of the Missourian Series in the Midcontinent. A few stratigraphic units in Oklahoma have been characterized in terms of clay mineralogy, however.

The chief clay minerals of the Seminole Formation are illite, kaolinite, vermiculite, and mixed-layer illite-vermiculite; shale zones exhibit slight to medium plasticity and low shrink-swell potential (Johnson and Luza, 1980). In Osage County, shales of the overlying Coffeyville Formation are characterized by illite and chlorite with minor amounts of kaolinite; in Tulsa County, Coffeyville shales have a plasticity of 21 to 32 percent and a drying shrinkage of 5 to 10 percent (Sheerar and Redfield, 1932; Bellis, 1976). In Oklahoma, shales of the Nellie Bly Formation contain the clay minerals illite, kaolinite, and minor amounts of vermiculite; the plasticity of these shales is medium, and the shrink-swell potential is low (Johnson and Luza, 1980).

6.4.4.4.4 Hydrology. Terrace and alluvial deposits of Quaternary age along major streams constitute important aquifers (West and Broadhurst, 1975; Baker and Wall, 1976; Bedinger and Sniegocki, 1976). Other important aquifers include the Ogallala aquifer of Tertiary age in the high-plains region of western Kansas, Oklahoma, and Texas; the Rush Springs Sandstone, the Garber Sandstone, and the Wellington Formation of Permian age in western and central Oklahoma; and the Vamoosa Sandstone of Late Pennsylvanian (Virgilian) age in east-central Oklahoma (Johnson et al., 1972; Bingham and Moore, 1975; West and Broadhurst, 1975; Baker and Wall, 1976; Bedinger and Sniegocki, 1976; Carr and Bergman, 1976).

In southern Oklahoma and north-central Texas, the Trinity aquifer of Early Cretaceous age is an important ground-water resource (Johnson et al., 1972; Baker and Wall, 1976). Three major aquifers have been developed along the Eastern Shelf in west-central Texas--the Santa Rosa aquifer of Triassic age in the north, the Edwards-Trinity aquifer of Cretaceous age in the Edwards Plateau in the central and southern part of the area, and the Hickory Sandstone of Cambrian age along the southeast edge, near the west flank of the Llano Uplift (Baker and Wall, 1976).

Some of the Missourian sandstones and siltstones are thought to yield limited amounts of water of fair to poor quality, at least in south-central Oklahoma (Hart, 1974).

6.4.4.4.5 Mineral Resources. Oil and gas constitute by far the most important developed mineral resources of the central and southern Midcontinent (Figure 6-11). Intensive petroleum exploration and development have continued throughout the area where thick Missourian shales lie at moderate depth (Figure 6-16). One area, however, in the lower Texas Panhandle has experienced few discoveries and, therefore, little development. This area includes part of the Palo Duro Basin, which has yielded almost no oil or gas thus far. Dutton (1980) believes that fair to good source rocks are present in the basin in the form of Pennsylvanian and Lower Permian basinal shales and that potential hydrocarbon reservoirs are likewise present. Thick Missourian shale sequences are deeper than 900 m here, however.

Generally throughout the central and southern Midcontinent, lenticular Missourian sandstones as well as Missourian carbonate banks are important reservoirs for oil and gas. Other important productive units include Permian and Pennsylvanian carbonates, Permian and Pennsylvanian sandstones, Mississippian sandstones and carbonates, Hunton Group carbonates (Silurian-Devonian), Simpson Group sandstones (Middle Ordovician), carbonates of the Arbuckle and Ellenburger Groups (Lower Ordovician), and Cambrian sandstones in the southeastern part of the Eastern Shelf (Parker, 1956; Rutledge, 1956; Hicks, 1971; St. Clair et al., 1976; Fay et al., 1979; Kier et al., 1979).

A resource probably second in importance to petroleum is bituminous coal, which has been mined extensively at and near the outcrop at the east edge of the area where thick Missourian shales occur (Fay et al., 1979;

Kier et al., 1979). These coal deposits, which include commercial beds in Missourian strata, dip beneath younger rocks westward. Where they occur in the deep subsurface their development is currently considered noncommercial, but they nevertheless constitute a potentially recoverable resource.

Other developed mineral resources in Missourian and other Pennsylvanian rocks include limestone, clay, and shale in the eastern parts of the region (Fay et al., 1979; Kier et al., 1979). In addition, Quaternary volcanic ash has been developed in western Oklahoma, Permian gypsum in western Oklahoma and Texas, and Permian copper deposits in southwestern Oklahoma; Permian copper mineralization is also present in north-central Texas, in the San Angelo Formation (Johnson, 1969; Garner et al., 1979).

Red shales of the Wichita Group (Permian) constitute a possible source of low-grade uranium ore in north Texas, apparently extending northward into Oklahoma (St. Clair et al., 1976).

Several caverns for the storage of liquefied petroleum gas have been excavated in shales of the Missourian Series in the Midcontinent. In Tulsa County, northeastern Oklahoma, a cavern was excavated by the room-and-pillar method in shales of the Coffeyville Formation at a depth of 116 to 123 m (Cobbs Engineering, 1975). The capacity of the cavern is 250,000 42-gallon barrels of liquid or 39,675 m^3. Since its completion in 1966, the cavern has served satisfactorily. The analysis of core samples revealed an unusually uniform compressive strength for shale intervals. No water inflow or structural failure is evident (Cobbs Engineering, 1975).

Another cavern was excavated in Seminole County, central Oklahoma, in shale of the Nellie Bly Formation at a depth of 94 to 101 m by mining a single drift around a central pillar (Cobbs Engineering, 1975). The capacity of the cavern is 110,000 42-gallon barrels of liquid, or 17,460 m^3. The cavern has performed successfully since its completion in 1954, with no evidence of water entry or structural failure (Cobbs Engineering, 1975).

The first two caverns ever excavated for LPG storage were constructed in 1950 and 1952 at a site in Stephens County, north-central Texas (Cobbs Engineering, 1975). The caverns were excavated by the room-and-pillar method in shale of the Canyon Group of Missourian age at a depth of 76 to 82 m; this Canyon shale extends to a depth of about 430 m and is overlain by shale of the Cisco Group of Virgilian (Late Pennsylvanian) age. The caverns are near the axis of the Bend Arch (Figure 6-2). The capacity of one cavern is 20,000 42-gallon barrels of liquid, or 3,170 m^3, and that of the other is 30,000 42-gallon barrels, or 4,755 m^3. Jointing or fracturing in the shale allowed leakage of the high-pressure product, so the caverns have now been converted to low-pressure storage for plant-residue gas for use by the city of Breckenridge (Cobbs Engineering, 1975).

6.4.4.5 Shales of the Virgilian Series

6.4.4.5.1 Stratigraphy. Virgilian deposition and distribution of lithologies closely paralleled those of the underlying Missourian Series (McKee and Crosby, 1975), with thick argillaceous sequences arranged in much the same pattern (Figure 6-17). The principal change was an additional concentration of thick shales near and at the outcrop in the Forest City Basin area, in northeastern Kansas, including scattered areas around the periphery, plus a small occurrence in southwestern Nebraska. In the central and southern Midcontinent, the contact between the Pennsylvanian and Permian Systems (the Virgilian-Wolfcampian contact) commonly is gradational (Crosby and Mapel, 1975; Frezon and Dixon, 1975).

In the area under consideration (Figure 6-17), thick argillaceous beds of the Virgilian Series generally have been referred to as the Douglas, Shawnee, and Wabaunsee Groups in the central Midcontinent and to the Cisco Group in Texas (Figures 6-4, 6-5). Recently, however, Kier et al. (1979) considered that the Virgilian Series comprises strata of both the upper Canyon and lower Cisco Groups, with the upper Cisco Group being placed in the Wolfcampian Series (Lower Permian). This report will follow the more traditional usage of previous literature.

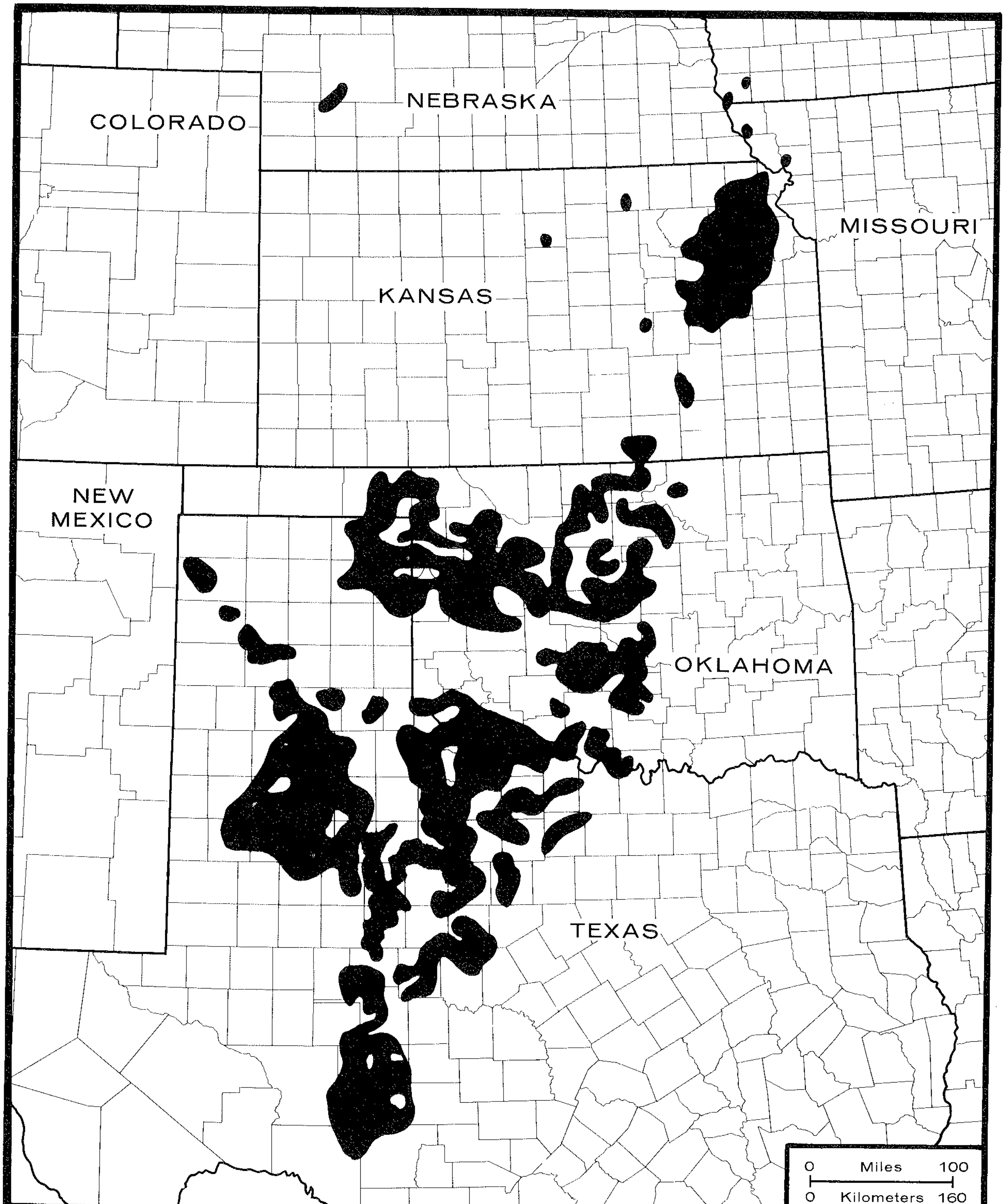

FIGURE 6-17. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION, SHOWING DISTRIBUTION OF ARGILLACEOUS FACIES, IN A RATIO OF AT LEAST 4:1, OF VIRGILIAN ROCKS MORE THAN 75 M THICK (MODIFIED FROM MCKEE AND CROSBY, 1975)

Sequences of argillaceous rocks, in a ratio of at least 4:1, range up to 1,070 m in thickness in the Midcontinent, in the eastern and southeastern parts of the Anadarko Basin in central Oklahoma (McKee and Crosby, 1975). The minimum thickness considered for argillaceous intervals in the region is 75 m. Argillaceous sequences attain thicknesses of 840 m in the Marietta Basin; 460 m in other parts of the Anadarko Basin, in northwestern Oklahoma and the Oklahoma and Texas Panhandles; 460 m in an area in central southern Kansas and central northern Oklahoma; 350 m in the Forest City Basin area in northeastern Kansas near and at the outcrop; 300 m in north and north-central Texas; 200 to 300 m in scattered areas of north- and east-central Kansas; 150 m in the area around the Palo Duro Basin and along the Eastern Shelf in west Texas; and 75 to 90 m in a small area in southwestern Nebraska.

Abrupt lateral facies variations are common in the rocks of the Virgilian Series, as in those of the underlying Pennsylvanian Series. In Kansas, the Douglas Group is made up predominantly of shale and sandstone, and subordinate thin limestone and coal beds; the Shawnee Group consists of alternating clastic units (mainly shale) and limestone units; and the Wabaunsee Group contains a greater proportion of sandy shale, also with thin coal beds, than does the Shawnee Group, and it contains several limestones as well (Ebanks et al., 1979). In Oklahoma, the Vamoosa Formation, the lowermost Virgilian unit, contains significant argillaceous intervals; the formation is composed of brown and light-gray shales and light-gray limestones in the northern part of the state (Fay et al., 1979).

In the Texas portion of the Marietta Basin, in Cooke and Grayson Counties, Bakker (1968) described rocks of the Virgilian Series as consisting of maroon to gray shale, fine- to medium-grained sandstone, and thin stringers of limestone, all up to 900 m thick.

In north-central Texas, sedimentation of the Cisco Group was characterized by a change from the predominating carbonate shelf and bank deposition of the underlying Canyon Group to renewed deposition of terrigenous clastic material and the dominance of fluvial and deltaic environments; downdip toward the edge of the Eastern Shelf, along the periphery of the Midland Basin, the clastic facies intertongues with extensive shelf and shelf-edge limestones (Kier et al., 1979). Galloway and Brown (1972) noted that the fluvial-deltaic Cisco sediments were derived from highlands to the east and northeast; they determined that the bulk of the interdeltaic embayment facies consists of mudstones, which typically are blocky and massive but at some places are fissile and splintery with sparse marine fauna or well-preserved plant fragments.

In the Palo Duro Basin of Texas, Upper Pennsylvanian strata have not been separated into formal subdivisions. According to Dutton et al. (1979), a large, well-defined, mud-filled basin developed, rimmed by shelf-margin carbonate buildups.

6.4.4.5.2 Geologic Setting. The major areas of structural complexity where thick Virgilian argillaceous sequences were deposited are associated with the Southern Oklahoma and Delaware Aulacogens (Handford et al., 1980) and include such structural features as the Hollis, Ardmore, and Marietta Basins along the Oklahoma-Texas border (Figures 6-2, 6-17). A subordinate structure is the Nemaha Uplift, which extends from central Oklahoma northward through Kansas and into southeastern Nebraska and which separates the Salina and Forest City Basins.

All occurrences of Virgilian shales thicker than 75 m in the Forest City Basin appear to be shallower than 300 m (Merriam, 1963; Ebanks et al., 1979). One small area of thick shales in the Salina Basin, in Mitchell County, north-central Kansas (Figure 6-17), appears to be at moderate depth (Merriam, 1963). The thick shales in southwestern Nebraska are deeper than 900 m (Reed, 1955).

In central Oklahoma, thick Virgilian shales generally lie at moderate depths a short distance west of their outcrop; these shales dip westward into the Anadarko Basin, where they are deeper than 900 m (Johnson and Roberts, 1980).

In north and north-central Texas, thick Virgilian argillaceous deposits range in depth from the shallow subsurface along the east edge of their occurrence to 300 to 900 m westward through the Eastern Shelf toward the Midland Basin; these shales are deeper than 900 m at the western edge of the Eastern Shelf (Wermund and Jenkins, 1969). In the area around the

Palo Duro Basin, in the lower Texas Panhandle, thick Virgilian shales apparently occur below 900 m (Dutton et al., 1979). The three areas of thick Virgilian shale to the northwest in the Texas Panhandle (Figure 6-17) appear to be deeper than 900 m (Panhandle Geological Society, 1960).

Several stratigraphic sections have been recorded that show Virgilian shales at moderate depths. In Pawnee County, north-central Oklahoma, as much as 75 m of shale in the Vamoosa Formation was recorded at a depth of 290 m (Greig, 1959). Farther south, in the area of the Ardmore Basin, in Stephens and Carter Counties, Oklahoma, Virgilian shale sequences (identified as "Cisco") from 120 to 185 m thick were noted at depths ranging from 550 to 730 m (Ardmore Geological Society, 1956a, 1956c).

In north Texas, 90 m of Cisco shale was identified in Baylor County at a depth of 940 m; farther west, in King County, 70 m of Cisco shale was noted at a depth of 1,160 m (North Texas Geological Society, 1954a). In Foard County, 75 m of Cisco shale was recorded at a depth of 1,010 m (North Texas Geological Society, 1962).

6.4.4.5.3 Mineralogy and Rock Properties. Sparse information is available about the mineralogy of Virgilian shales in the Midcontinent. Bellis (1976) indicated that Upper Pennsylvanian shales in Osage County, central northern Oklahoma, are characterized by the clay minerals illite and kaolinite.

Speights and Brunton (1961), in a study of clay-mineral distribution in undifferentiated Pennsylvanian-Permian shales of the Val Verde Basin and adjoining areas in southwest Texas, where some thick Virgilian argillaceous deposits are present (Figures 6-2, 6-17), identified a three-tiered vertical zonation of clay-mineral occurrence. The lower zone, which begins at the base of the Pennsylvanian strata, contains illite, chlorite, kaolinite, mixed-layer clay, and small amounts of montmorillonite; the middle zone (which perhaps includes the Virgilian shales) is characterized by illite and minor amounts of chlorite, kaolinite, and mixed-layer clay, the latter more abundant than in the lower zone; and the upper zone, which extends to the base of the overlying

Cretaceous shale, contains illite, chlorite, kaolinite, montmorillonite, vermiculite(?), and mixed-layer clay. The clay-mineral composition of the upper zone is more variable, both vertically and laterally, than that of the other two zones.

6.4.4.5.4 Hydrology. The area where thick deposits of Virgilian shales are at moderate depths is confined to Oklahoma and Texas, except for southern Mitchell County, north-central Kansas (Figure 6-17). Ground-water aquifers of importance in these areas include alluvial and terrace deposits of Quaternary age along major streams; the Ogallala aquifer of Miocene and Pliocene age in upland areas of western Kansas, Oklahoma, and Texas; the Rush Springs Sand stone, Garber Sandstone, and Wellington Formation, all of Permian age, in western and central Oklahoma; and sandstone of the Vamoosa Formation of Virgilian age in east-central Oklahoma (Johnson et al., 1972; Bingham and Moore, 1975; West and Broadhurst, 1975; Baker and Wall, 1976; Bedinger and Sniegocki, 1976; Carr and Bergman, 1976). Additional aquifers are Permian gypsum beds in western Oklahoma and west Texas and the Wichita Formation of Permian age at scattered places in south-central Oklahoma (Johnson et al., 1972; Hart, 1974; Bedinger and Sniegocki, 1976; Carr and Bergman, 1976).

Farther south, in southern Oklahoma and north-central Texas, the Trinity aquifer of Cretaceous age constitutes a major source of ground water (Johnson et al., 1972; Baker and Wall, 1976). Along the Eastern Shelf, in west-central Texas, three aquifers are of considerable importance: the Santa Rosa aquifer of Triassic age, the Edwards-Trinity aquifer of Cretaceous age, and the Hickory Sandstone of Cambrian age (Baker and Wall, 1976).

As was already noted, sandstone of the Vamoosa Formation of Virgilian age constitutes a principal aquifer in the shallow subsurface, extending in a belt from east-central Oklahoma northward into Kansas; well yields are as high as 600 l/min, although the dissolved-solids content of the water is moderate to high (Johnson et al., 1972; Bingham and Moore, 1975). Other Virgilian units probably yield only small amounts of water to wells (Hart, 1974).

6.4.4.5.5 Mineral Resources. The most important developed mineral resources in the area under consideration are oil and gas (Figure 6-11). Virtually all areas where thick argillaceous deposits of Virgilian age are present at moderate depths have undergone intense oil and gas exploration and development. An exception is the small area in north-central Kansas. Almost no oil or gas has been discovered in and north of the Palo Duro Basin, but here thick Virgilian shales are deeper than 900 m.

Several of the lenticular Virgilian sandstones serve as hydrocarbon reservoirs themselves. Major petroleum reservoirs in the central and southern Midcontinent also include carbonates and sandstones of Permian and Pennsylvanian age, sandstones and carbonates of Mississippian age, Silurian-Devonian carbonates of the Hunton Group, Middle Ordovician sandstones of the Simpson Group, Lower Ordovician carbonates of the Arbuckle and Ellenburger Groups, and Cambrian sandstones in the southeastern part of the Eastern Shelf (Parker, 1956; Rutledge, 1956; Hicks, 1971; St. Clair et al., 1976; Fay et al., 1979; Kier et al., 1979).

Bituminous coal makes up a resource of subordinate importance at present but nevertheless of high potential. Although most of the commercially developed beds belong to the underlying Missourian and Desmoinesian Series of the Pennsylvanian System, several Virgilian coals have been worked, at least in the past, especially in north-central Texas (St. Clair et al., 1976; Fay et al., 1979; Kier et al., 1979).

Several other mineral resources have been developed in the area where thick Virgilian shales are present: volcanic ash of Quaternary age in western Oklahoma, gypsum and salt of Permian age in western Oklahoma and west Texas, and copper-bearing shales of Permian age in southwestern Oklahoma (Johnson, 1969; Garner et al., 1979). Undeveloped resources of possible potential in north-central Texas include low-grade copper shales in the San Angelo Formation of Permian age and red beds of the Wichita Group of Permian age, which contain uranium mineralization and which apparently extend northward into southwestern Oklahoma (St. Clair et al., 1976; Garner et al., 1979).

A cavern for the storage of liquefied petroleum gas was excavated in shale of the Vamoosa Formation of Virgilian age at a depth of 124 to 130 m in Creek County, northeast-central Oklahoma (Cobbs Engineering, 1975). The cavern was developed in 1964 by the room-and-pillar method and was abandoned about 10 years later because a small inflow of water from overlying siltstones weakened the roof, causing a heavy roof fall and continued roof problems. The capacity of the cavern was 225,000 42-gallon barrels, or 35,615 m^3 (Cobbs Engineering, 1975).

6.4.5 Permian Shales

6.4.5.1 Stratigraphy

This section describes thick argillaceous deposits in three of the four series of the Permian Period in the Midcontinent region: Wolfcampian, Leonardian, and Guadalupian (youngest). The terminology used herein is mainly general, because many lithostratigraphic sequences have not been divided into formal groups or formations, especially in some of the basins of Oklahoma, west Texas, and southeastern New Mexico, such as the Anadarko, Hollis, Palo Duro, Delaware, Midland, and Val Verde Basins (Figure 6-2). In these areas especially, many of the argillaceous rocks of the Wolfcampian and Leonardian Series clearly are marine, and some of the Guadalupian deposits appear to be. Elsewhere, other environments of deposition prevailed, including: restricted marine and marine mudflat, which accounted for the evaporites formed during the Permian Period; marginal marine; and terrigenous, including deltaic and fluvial. In west Texas and southeastern New Mexico, several great carbonate banks and reefs were formed, such as the Guadalupe Reef, the Central Basin Platform, and the Horseshoe Atoll (or Scurry Platform). Obviously, the marine shales are more uniform in lithology and composition than nonmarine shales; the latter commonly contain considerable silt and sand, exhibit greater lateral variation, and tend toward jointing or fracturing.

In most of the basin areas and some of the shelf areas of the Midcontinent region, deposition appears to have been continuous from Late Pennsylvanian into Early Permian time (Oriel et al., 1967; Dixon, 1967; MacLachlan, 1967; Mudge, 1967). But, beginning with Wolfcampian deposition, Permian deposits covered many structural uplifts that thus far had received no Late Paleozoic sediments. One of these buried structures is the Amarillo Uplift, lying beneath Permian and younger rocks in the Texas Panhandle (Figure 6-2).

The stratigraphic divisions followed in this report (Figures 6-4, 6-5) follow mainly the correlation chart given in McKee et al. (1967b).

Argillaceous deposits of the Wolfcampian Series thicker than 75 m, and in a ratio of at least 4:1, are concentrated mainly in southeastern Colorado, western Oklahoma, north-central Texas, and southwest Texas, with smaller areas in southeastern Nebraska, eastern Kansas, west Texas, and eastern New Mexico (Figure 6-18). In southeastern Nebraska and eastern Kansas, these shales occur at the outcrop and are up to 100 m thick (McKee et al., 1967b). In western Oklahoma and north-central Texas, these shales attain thicknesses of 600 m in the vicinity of the Anadarko and Hollis Basins and range up to 150 to 450 m elsewhere (McKee et al., 1967b). Although not shown on the map giving the distribution of argillaceous facies in the Midcontinent region (Figure 6-18), thick Wolfcampian shales are present in the Palo Duro Basin, in the Texas Panhandle (Dutton et al., 1979). In southwest Texas, Wolfcampian shales range in thickness from 300 m in the north to 3,000 m in the deepest part of the Val Verde Basin (McKee et al., 1967b). In eastern New Mexico, these shales are up to 460 m thick. They are up to 220 m thick in southeastern Colorado.

Typical of the lithology of the argillaceous rocks of the Wolfcampian Series is black to red and green shale and mudstone, at some places containing thin interbeds of siltstone and sandstone.

Argillaceous rocks of the Leonardian Series thicker than 75 m occur in three main areas of the Midcontinent: in the Wyoming-Nebraska-Colorado-Kansas area, in western Oklahoma and north Texas, and in southwest Texas (Figure 6-19). In the southern part of the first area, these shales attain thicknesses of 460 m, and in the northern part, thicknesses of 350 m; typically they are 100 to 150 m thick (McKee et al., 1967b). In western Oklahoma and north Texas, Leonardian argillaceous deposits generally range in thickness from 150 to 750 m; in the deepest part of the Anadarko Basin, they are more than 1,000 m thick (McKee

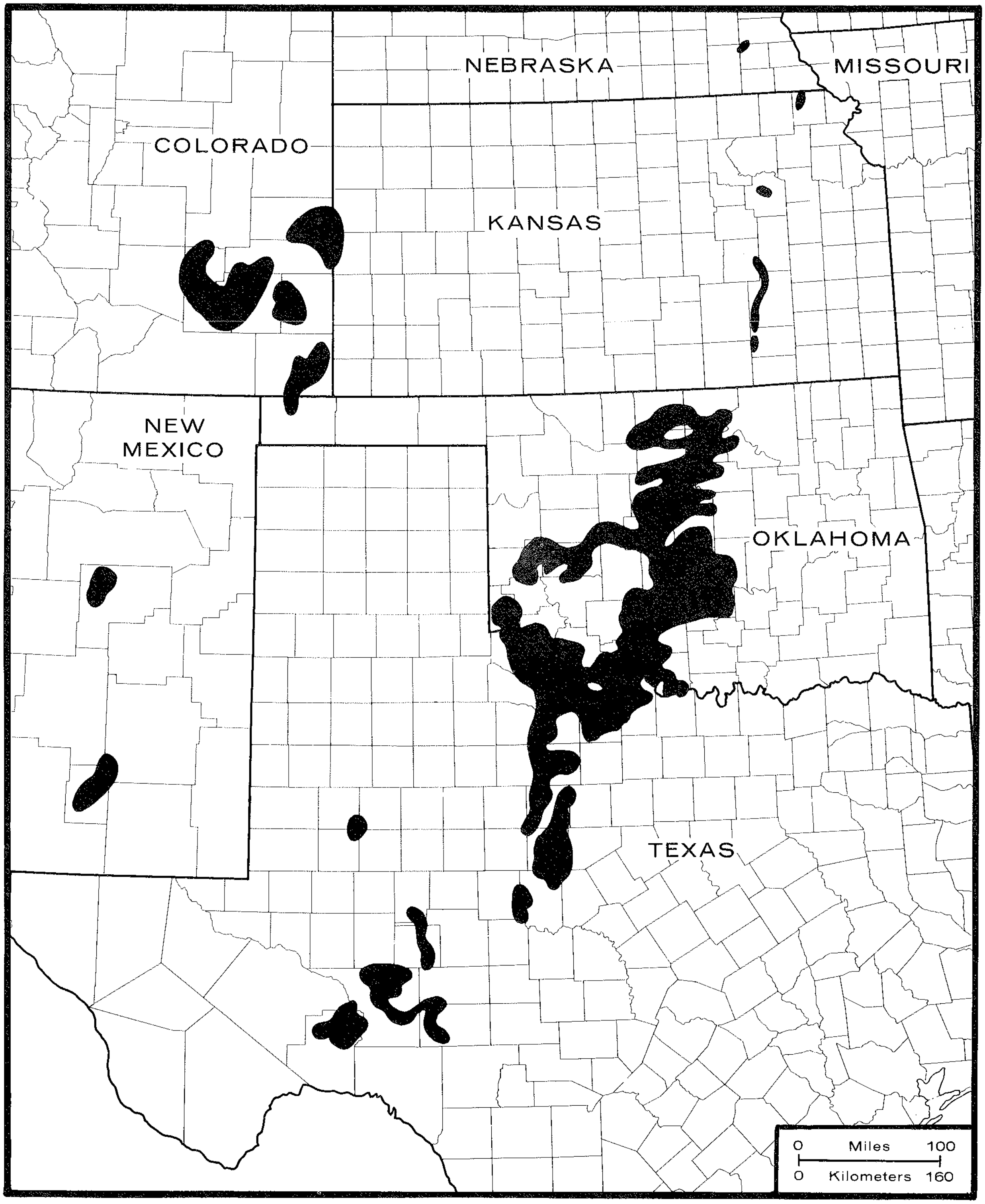

FIGURE 6-18. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION, SHOWING DISTRIBUTION OF ARGILLACEOUS FACIES, IN A RATIO OF AT LEAST 4:1, OF WOLFCAMPIAN ROCKS MORE THAN 75 M THICK (MODIFIED FROM MCKEE AND CROSBY, 1967b)

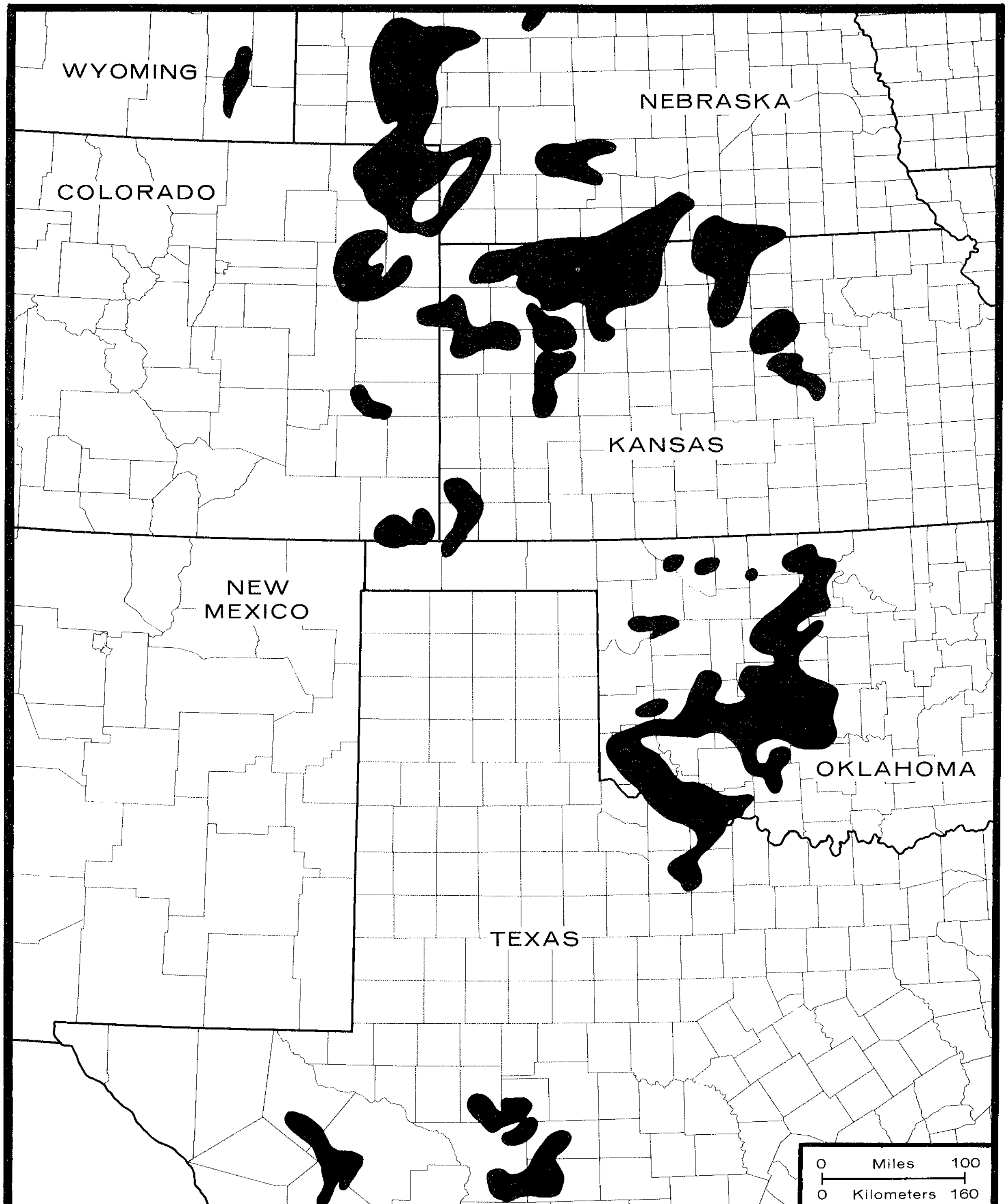

FIGURE 6-19. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION, SHOWING DISTRIBUTION OF ARGILLACEOUS FACIES, IN A RATIO OF AT LEAST 4:1, OF LEONARDIAN ROCKS MORE THAN 75 M THICK (MODIFIED FROM MCKEE ET AL., 1967b)

et al., 1967b). In the Val Verde and Kerr Basins of southwest Texas, typical thicknesses of these shales range from 300 to 900 m, and the greatest thickness is about 1,250 m in the Kerr Basin (McKee et al., 1967b).

Stratigraphic units in the Leonardian Series that contain significant thicknesses of shale are, in Kansas and Nebraska, the Wellington Formation and the Ninnescah Shale, in the Sumner Group, and the Harper Formation, at the base of the overlying Nippewalla Group (Figure 6-4). Separating the Ninnescah Shale and the Harper Formation is the Stone Corral Anhydrite at the top of the Sumner Group, correlative with the Cimarron evaporite bed to the south in Oklahoma, which is one of the most regionally persistent markers in the Permian Period of the Midcontinent Region. In Oklahoma, thick shale sequences occur in the Wellington Formation, Hennessey Shale, Flowerpot Shale, and Dog Creek Shale (Figure 6-4). Southward, in north-central Texas, thick shales are present in the Arroyo Formation and overlying Vale Formation of the Clear Fork Group; the Clear Fork Group, undifferentiated, has been designated for other occurrences of thick shales in Texas.

The Wellington Formation is estimated to contain 245 m of shale in Oklahoma, where the shale is reddish brown and interbedded with thin layers of siltstone, sandstone, and dolomite (Johnson and Luza, 1980). In Kansas the Wellington Formation consists mainly of gray to greenish-gray and red to maroon and purple shale with minor amounts of limestone and dolomite, siltstone, gypsum, and anhydrite; it contains thick beds of salt in the subsurface (Zeller, 1968). The Hennessey Shale in Oklahoma is reddish brown and contains some thin beds of greenish-gray siltstone and orange-brown siltstone and sandstone; it is about 150 m thick (Carr and Bergman, 1976). The overlying Flowerpot Shale is about 30 to 135 m thick in Oklahoma and consists of red-brown blocky shale with thin interbeds of siltstone, sandstone, gypsum, and dolomite (Johnson and Luza, 1980). The Dog Creek Shale in Oklahoma consists of 30 to 75 m of reddish-brown, blocky clay shale, with thin interbeds of siltstone, sandstone, gypsum, and dolomite; the Dog Creek thins to about 9 m northward in southern Kansas (Fay, 1964; Johnson and Luza, 1980). In Haskell and Stonewall Counties, north-central Texas, the Arroyo Formation and overlying Vale

Formation of the Clear Fork Group consist chiefly of red shale (Abilene Geological Society, Stratigraphic Committee, undated, b; undated, d).

The Ninnescah Shale in southern Nebraska and northeastern Colorado contains 13 m of dark-red shale with some light-gray streaks and 17 m of underlying red silty shale, partly gypsiferous (Condra and Reed, 1959). Mudge (1967) described the Ninnescah in Kansas as a unit attaining local thicknesses of 107 m and consisting of red anhydritic mudstone with sandstone and sandy mudstone as well as scattered salt.

Guadalupian shales thicker than 75 m are concentrated in the central Midcontinent region (Figure 6-20). Thicknesses range up to 185 m (McKee et al., 1967b).

The restricted-marine and marine-mudflat environments that characterized Leonardian deposition continued into Guadalupian time, resulting in the formation of continued evaporite sequences and the intertonguing of evaporites and mainly clastic units (MacLachlan, 1967). Many of the predominantly argillaceous units of the Guadalupian Series have not been formally named in the subsurface.

6.4.5.2 Geologic Setting

Most of the areas in the central and southern Midcontinent region where thick Permian shales were deposited have been structurally stable, except for the complex structures of the southern Oklahoma folded belt and the Red River Uplift to the south in Texas (Southern Oklahoma and Delaware Aulacogens) and the deep Val Verde and Kerr Basins a short distance north of the Ouachita fold belt (Figure 6-2).

Thick Wolfcampian shales generally lie at moderate depths in southeastern Colorado (Oetking et al., 1967). In much of western Oklahoma, these shales appear to be at moderate depths (Oklahoma City Geological Society, Stratigraphic Committee, 1971). In north-central Texas, most thick Wolfcampian shales probably are shallower than 300 m, except for scattered areas to the west (Hartman and Woodard, 1971; Renfro et al., 1973). On the south flank of the Val Verde Basin of southwest Texas, thick Wolfcampian shales lie beneath the pre-Cretaceous

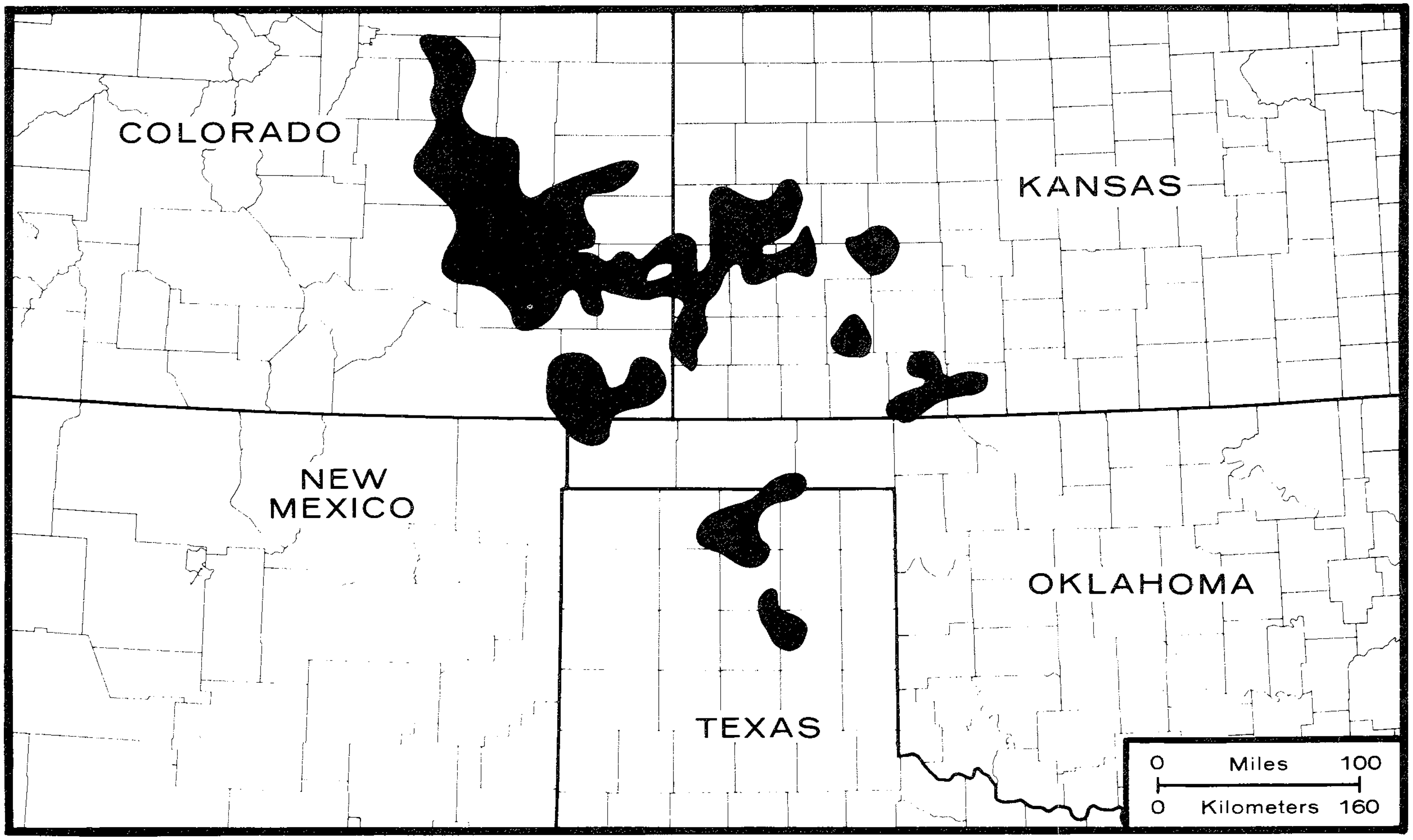

FIGURE 6-20. MAP OF CENTRAL AND SOUTHERN MIDCONTINENT REGION, SHOWING DISTRIBUTION OF ARGILLACEOUS FACIES, IN A RATIO OF AT LEAST 4:1, OF GUADALUPIAN ROCKS MORE THAN 75 M THICK (MODIFIED FROM MCKEE ET AL., 1967b)

unconformity at moderate depths, dipping northward into the basin, away from the Ouachita Fold Belt; farther into the basin, however, and in the Midland Basin to the north, they are deeper than 900 m (West Texas Geological Society, Stratigraphic Problems Committee, 1962; Hartman and Woodard, 1971; Renfro et al., 1973).

Thick Leonardian shales in the Denver Basin area lie at moderate depths at some localities in western Nebraska and northeastern Colorado, but they are much deeper in southeastern Wyoming (Reed, 1955; Renfro and Feray, 1972). In western Kansas, these shales probably occur at moderate depths, but in central Kansas some areas are probably shallower than 300 m (Merriam, 1963). Thick Leonardian shales occur at generally moderate depths in southeastern Colorado (Oetking et al., 1967). These shales are probably at moderate depths in many areas of western Oklahoma. In the Val Verde Basin area of southwest Texas, thick Leonardian shales dip northward beneath the pre-Cretaceous unconformity somewhat more basinward than those of the Wolfcampian, but they lie deeper than 900 m northward into the Midland Basin (West Texas Geological Society, Stratigraphic Problems Committee, 1962; Hartman and Woodard, 1971; Renfro et al., 1973).

Where thick Guadalupian shales occur in the central Midcontinent region, they appear to lie either somewhat less than 300 m deep or else just below 300 m (Oetking et al., 1966, 1967).

Many stratigraphic sections throughout the Midcontinent record specific thicknesses and depths of various units. Thick Permian shale sequences of the Wolfcampian, Leonardian, and Guadalupian Series occurring at moderate depths are listed in the following paragraphs. Some of the areas where thick shales are present are not shown on the maps in Figures 6-18, 6-19, and 6-20 (which are taken from McKee et al., 1967b), presumably because the argillaceous content for the entire rock sequence of a particular series division amounts to less than a 4:1 ratio.

In Kingman, Harper, and Barber Counties, central southern Kansas, about 100 m of red shale occurs in the Ninnescah Shale and the overlying Harper Formation of the Leonardian Series; this shale sequence ranges in depth from outcrop to 275 m, dipping to the southwest (Lee, 1949). In Scott, Kearny, and Hamilton Counties, western Kansas, 45 to 60 m of red shale is present in the base of the Nippewalla Group, ranging in depth from 460 to 700 m (Maher, 1946, 1947).

In Canadian County, central Oklahoma, in the Anadarko Basin, 90 m of reddish-brown shale, containing some siltstone and very fine-grained sandstone, is present in the Hennessey Shale (Leonardian) at a depth of 260 m (Adkison, 1960).

In Gray County, Texas Panhandle, 105 m of a Leonardian shale sequence identified as Ninnescah occurs at a depth of 520 m; this shale contains anhydrite and salt to the north (Panhandle Geological Society, Stratigraphic Committee, 1952). And in Ochiltree County, to the north, a similar 105-m shale unit lies at 640 m, underlying a salt bed (Panhandle Geological Society, Stratigraphic Committee, 1952). Also in the Texas Panhandle, in Oldham County, 70 m of Guadalupian shale occurs at a depth of about 305 m, and 60 m of Leonardian shale, at 1,130 m (Panhandle Geological Society, 1960). Dutton et al. (1979) indicated Wolfcampian shale thicknesses of at least 300 m filling the Palo Duro Basin; however, these shales lie deeper than 900 m. In Stonewall County, north-central Texas, 75 m of red shale in the Vale Formation of the Clear Fork Group (Leonardian) occurs at depths of 305 to 430 m (Abilene Geological Society, Stratigraphic Committee, undated, d).

In west Texas, in the Val Verde Basin, well logs recorded Wolfcampian shales ranging up to 300 to 600 m in thickness at depths of 1,170 to 1,670 m (West Texas Geological Society, 1960). Farther north, in Irion County, Midland Basin, up to 200 m of gray-black Leonardian shale of the Clear Fork Group was noted at a depth of 790 m; this shale grades into reef-bank limestone eastward along the Eastern Shelf (San Angelo Geological Society, undated).

6.4.5.3 Mineralogy and Rock Properties

No systematic study of the mineralogy of Permian argillaceous rocks was discovered in the course of this investigation. Speights and Brunton (1961), however, analyzed the clay-mineral distribution of undifferentiated Pennsylvanian-Permian shales of the Val Verede Basin and adjacent areas in southwest Texas. They distinguished a three-layered vertical zonation of the clay minerals in these beds. The lower zone consisted of samples from Pennsylvanian strata; the middle zone (which possibly contains some Permian beds) contains illite and minor amounts of chlorite, kaolinite, and mixed-layer clay, the latter more abundant than in the lower zone; and the upper zone (perhaps entirely Permian), which extends to the base of the overlying Cretaceous, is characterized by illite, chlorite, kaolinite, montmorillonite, vermiculite(?), and mixed-layer clay. The clay-mineral composition of the upper zone is more variable, both vertically and laterally, than that of the other two zones.

Johnson and Luza (1980) reported on the clay mineralogy of several Leonardian units containing argillaceous rocks in Oklahoma, as follows, from oldest to youngest. The Wellington Formation is characterized by illite, kaolinite, chlorite, and montmorillonite. The plasticity of the shales is medium, and shrink-swell potential is low to medium. The Hennessey Shale contains chiefly illite, with lesser amounts of mixed-layer illite-chlorite. The shale exhibits medium plasticity and a low shrink-swell potential. The principal clay mineral of the Flowerpot Shale is illite, with lesser amounts of kaolinite, chlorite, and montmorillonite. The shale's plasticity is medium, and its shrink-swell potential is low. The Dog Creek Shale contains illite, kaolinite, mixed-layer chlorite-vermiculite, and mixed-layer chlorite-montmorillonite. The plasticity is medium, and the shrink-swell potential is low to medium. Bellis (1976) reported that the chief clay mineral of the Wolfcampian shales of Osage County, central northern Oklahoma, is montmorillonite.

6.4.5.4 Hydrology

Principal Permian aquifers in Oklahoma and Kansas are the Elk City Sandstone, the Rush Springs Sandstone, the Garber Sandstone, and the Wellington Formation (Johnson et al., 1972; Hart, 1974; Bingham and Moore, 1975; Bedinger and Sniegocki, 1976). The Garber-Wellington units combined constitute an especially good aquifer in central Oklahoma; the Garber

Sandstone underlies the Hennessey Shale. Of local significance are several Permian gypsum aquifers (Bedinger and Sniegocki, 1976; Carr and Bergman, 1976).

Other major aquifers in the region include valley-fill deposits of Quaternary age in eastern Colorado, eastern New Mexico, and west Texas; alluvium and terrace deposits of Quaternary age along principal streams and their tributaries; dune sand of Quaternary age in northwestern and north-central Nebraska; the Ogallala Formation of Miocene and Pliocene age in northwestern Nebraska, southeastern Wyoming, northeastern Colorado, and in the high-plains region of Kansas, Colorado, Oklahoma, New Mexico, and Texas; mainly artesian aquifers in the Cheyenne Sandstone Member of the Purgatoire Formation and the Dakota Sandstone, both of Early Cretaceous age, in southeastern Colorado; the Edwards-Trinity aquifer of Early Cretaceous age in the Edwards Plateau area of west Texas; and the Madison aquifer of Early Mississippian age in southeastern Wyoming and northeastern Colorado (U.S. Geological Survey, 1968; West and Broadhurst, 1975; Baker and Wall, 1976; Bedinger and Sniegocki, 1976; Taylor, 1978).

6.4.5.5 Mineral Resources

Chief among the developed mineral resources of the central and southern Midcontinent region is oil and gas (Figure 6-11). Many thick Leonardian shales occur in western Nebraska outside the area of principal petroleum development in the Denver Basin, however. Thick Leonardian shales in northeastern Colorado occur mainly in the Denver Basin, where wells produce mostly from Upper Cretaceous reservoirs (U.S. Geological Survey and Colorado Geological Survey, 1977). Less oil and gas development has occurred in southeastern Colorado where thick Permian shales are present; here, mostly gas is produced, with a subordinate amount of oil, from Permian, Pennsylvanian, and Mississippian reservoirs (U.S. Geological Survey and Colorado Geological Survey, 1977). Likewise, in western Kansas, several occurrences of thick Permian shales are outside the principal producing region.

Elsewhere in the Midcontinent region, some of the main producing zones include Permian carbonate and sandstone units of Guadalupian, Leonardian, and Wolfcampian age. Leonardian and Wolfcampian reservoirs predominate in the central Midcontinent, whereas Guadalupian reservoirs are probably of equal importance in west Texas. Other important producing zones include carbonates and sandstones of Pennsylvanian age, carbonates and sandstones of Mississippian age, carbonates of the Hunton Group of Silurian-Devonian age, sandstones of the Simpson Group of Middle Ordovician age, and carbonates of the Arbuckle and Ellenburger Groups of Early Ordovician age (Parker, 1956; Rutledge, 1956; Hicks, 1971; St. Clair et al., 1976; Fay et al., 1979; Kier et al., 1979).

Another important Permian resource of the Midcontinent region is gypsum, which has been mined at many localities in east-central Kansas, western Oklahoma, and west-central Texas (Johnson, 1969; Hardy, 1970; Garner et al., 1979). Permian bedded salt underlies much of western Nebraska, western Kansas, western Oklahoma, and west Texas; although not yet produced in quantity, this vast resource possibly will be of greater importance in the future (Johnson, 1969; Hardy, 1970; Burchett, 1973; Garner et al., 1979). In addition to bedded salt, Burchett (1973) indicated areas of potassium salt where some thick Leonardian shales occur in northwestern Nebraska.

Other Permian mineral resources include copper-bearing shales in southwestern Oklahoma and north-central Texas, and red beds of the Wichita Group, which contain low-grade uranium mineralization and which apparently extend northward into southwestern Oklahoma (Johnson and Croy, 1976; St. Clair et al., 1976; Garner et al., 1979). Also, various carbonate, clay, shale, and sand resources occur in Permian rocks (Johnson, 1960; Hardy, 1970; Garner et al., 1979).

In 1961 a cavern was excavated at Ponca City, Kay County, Oklahoma, in undifferentiated Permian rocks for the storage of liquefied petroleum gas (Cobbs Engineering, 1975). The cavern was constructed at a depth of 107 to 115 m by conventional room-and-pillar techniques in rocks of varying lithologies, including red sandy shale, siltstone, and sandstone. A slight inflow of water encountered during excavation was later controlled by pressure grouting. The analysis of core samples for unrestrained compressive strength showed an average of 39.7 MPa; the standard deviation was 26.1 MPa, or 65.6 percent. The capacity of the cavern is 300,000 42-gallon barrels, or 47,630 m^3. Since operation began, the cavern has performed satisfactorily (Cobbs Engineering, 1975).

6.4.6 Pierre Shale and Equivalent Upper Cretaceous Shales

6.4.6.1 Stratigraphy

The Pierre Shale, which makes up most of the Montana Group of Late Cretaceous age, is one of the thickest and most widespread shale units in the United States. It crops out or is in subsurface in almost all parts of the northern Great Plains, and equivalent shales are present in substantial parts of the Rocky Mountain and Colorado Plateau Provinces (Figure 6-21). The Pierre Shale is part of the great thickness of Upper Cretaceous strata that are more than 1,500 m thick in parts of Montana, Wyoming, South Dakota, Nebraska, Colorado, Utah, New Mexico, and Arizona, and that range up to nearly 6,000 m thick in parts of Wyoming (Reeside, 1944). Among the principal studies providing stratigraphic data on the Pierre in the Great Plains are those of Weimer (1960), Tourtelot (1962), Izett et al. (1971), Gill et al. (1972), McGookey et al. (1972), Gill and Cobban (1973), Rice (1976b, 1977), Irwin (1977), Merewether et al. (1977a, 1977b, 1977c, 1977d), Shurr (1977), Kiteley (1978), Rice and Shurr (1980), and Schultz et al. (in press). Most of these reports are part of a long-term study conducted by the U.S. Geological Survey on the geochemistry, mineralogy, and physical properties of the Pierre Shale in the northern Great Plains.

The Pierre Shale and equivalent strata were deposited during the last major incursion of marine waters across interior parts of the United States. The widest extent of the Cretaceous sea in the region was during the early part of Late Cretaceous time (Weimer, 1960), and during the remainder of the period the dominant movement of the shoreline was toward the east (McGookey et al., 1972). Thus an intertonguing relationship of

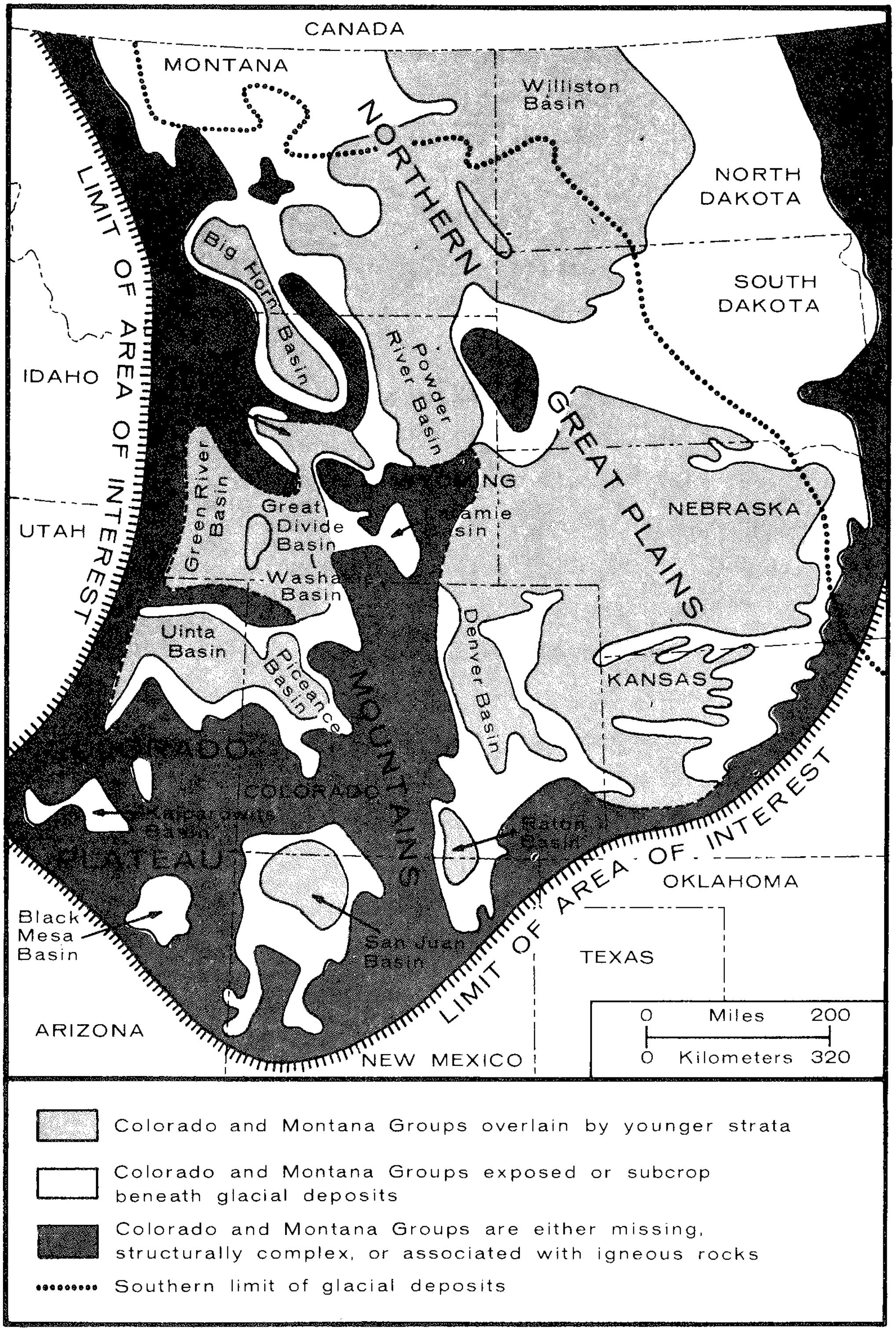

FIGURE 6-21. MAP SHOWING DISTRIBUTON OF SHALE UNITS IN COLORADO AND MONTANA GROUPS (UPPER CRETACEOUS) IN NORTHERN GREAT PLAINS, ROCKY MOUNTAINS, AND COLORADO PLATEAU PROVINCES OF WESTERN UNITED STATES (MODIFIED FROM KING AND BEIKMAN, 1974)

four principal facies was established in the region (Figures 6-22, 6-23, 6-24, 6-25): (1) white and gray limestone and marlstone were deposited in the offshore, deeper marine environment in the east; (2) gray and black shale was deposited in the shallow marine environment that extended across most of the central area; (3) white, gray, and tan massive sandstone was deposited along the shore to the west and south; and (4) lenticular interbeds of sandstone, shale, coal, and conglomerate were deposited in the nonmarine swamp, lagoon, coastal plain, and inland environments of the far west (Weimer, 1960).

Owing to the great thickness and widespread distribution of the Pierre Shale and equivalent strata, many different formation and member names have been given to the same units in different areas (Figures 6-22, 6-23, 6-24, 6-25). The term Pierre Shale is used for these strata in most parts of the Great Plains, although the terms "Lewis", Steele, Cody, Bearpaw, and Claggett Shales are also used for significant portions of the unit in parts of Wyoming and Montana. For simplicity, we will commonly use the term Pierre Shale when referring to the Pierre or equivalent shales in the Great Plains Region.

The Pierre Shale is typically a gray to black clay shale that locally contains thin interbeds of sandstone, limestone, and volcanic ash (bentonite). Calcareous shale and marl are present in the lower part of the Pierre Shale in most areas and in the upper part of the unit in some of the northeastern area in the Dakotas. There also are units of organic-rich black shale and of siliceous shale (Shurr, 1977). Minor lithologic breaks in the shale are represented by bentonite beds, thin beds of siltstone and sandstone, and some zones of calcareous and ferruginous concretions.

The thickness of the Pierre Shale increases toward the west in most parts of the Great Plains (Figure 6-26). The unit is typically less than 150 m thick only in the eastern parts of Nebraska and the Dakotas, and it increases to as much as 750 m in the Williston Basin, 1,300 m in the Powder River Basin, and 1,800 m in the Denver Basin. In the northwest, across most of Montana, massive sandstones divide the Pierre Shale into an upper shale (Bearpaw Shale), about 300 m thick, and several lower shales

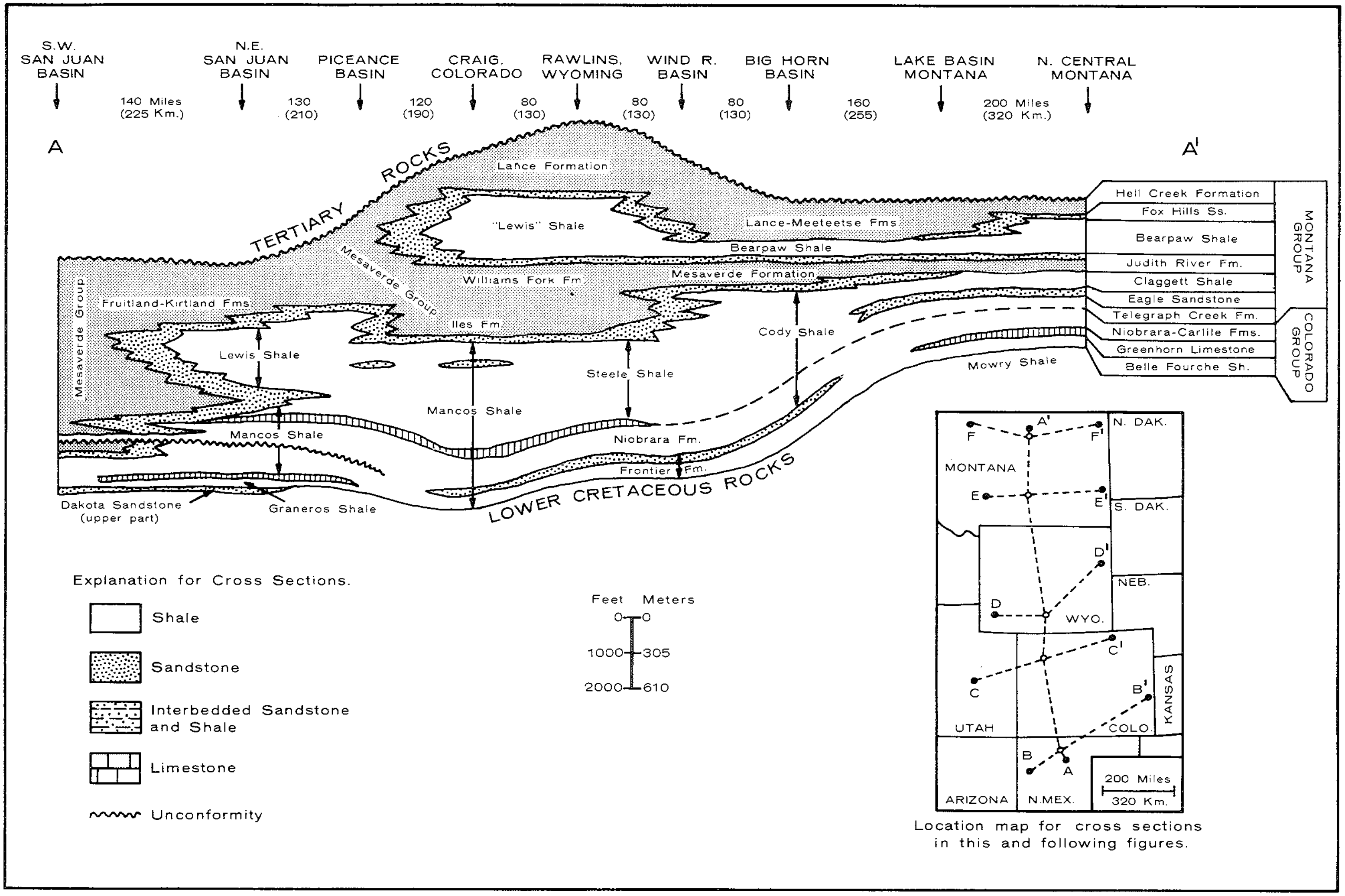

FIGURE 6-22. GENERALIZED STRATIGRAPHIC CROSS SECTION A-A', SHOWING UPPER CRETACEOUS SHALES AND ASSOCIATED STRATA IN NORTHERN GREAT PLAINS, ROCKY MOUNTAINS, AND COLORADO PLATEAU (MODIFIED FROM WEIMER, 1960; MCGOOKEY ET AL., 1972). SEE FOLLOWING FIGURES FOR OTHER CROSS SECTIONS

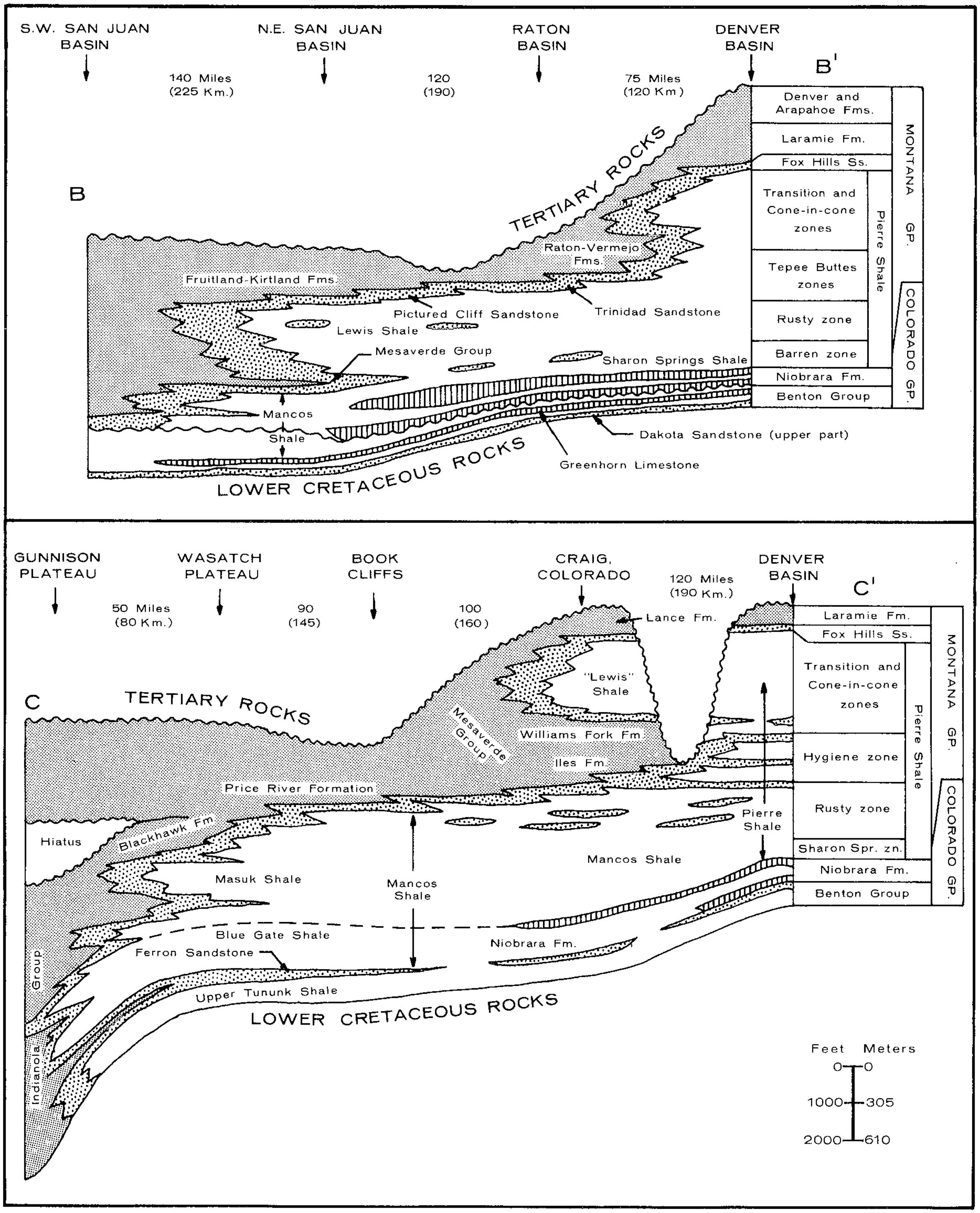

FIGURE 6-23 GENERALIZED STRATIGRAPHY CROSS SECTIONS B-B' AND C-C', SHOWING UPPER CRETACEOUS SHALES AND ASSOCIATED STRATA IN NORTHERN GREAT PLAINS, ROCKY MOUNTAINS, AND COLORADO PLATEAU (MODIFIED FROM WEIMER, 1960; MCGOOKEY ET AL., 1972). SEE PRECEDING FIGURE FOR LOCATION MAP AND EXPLANATION.

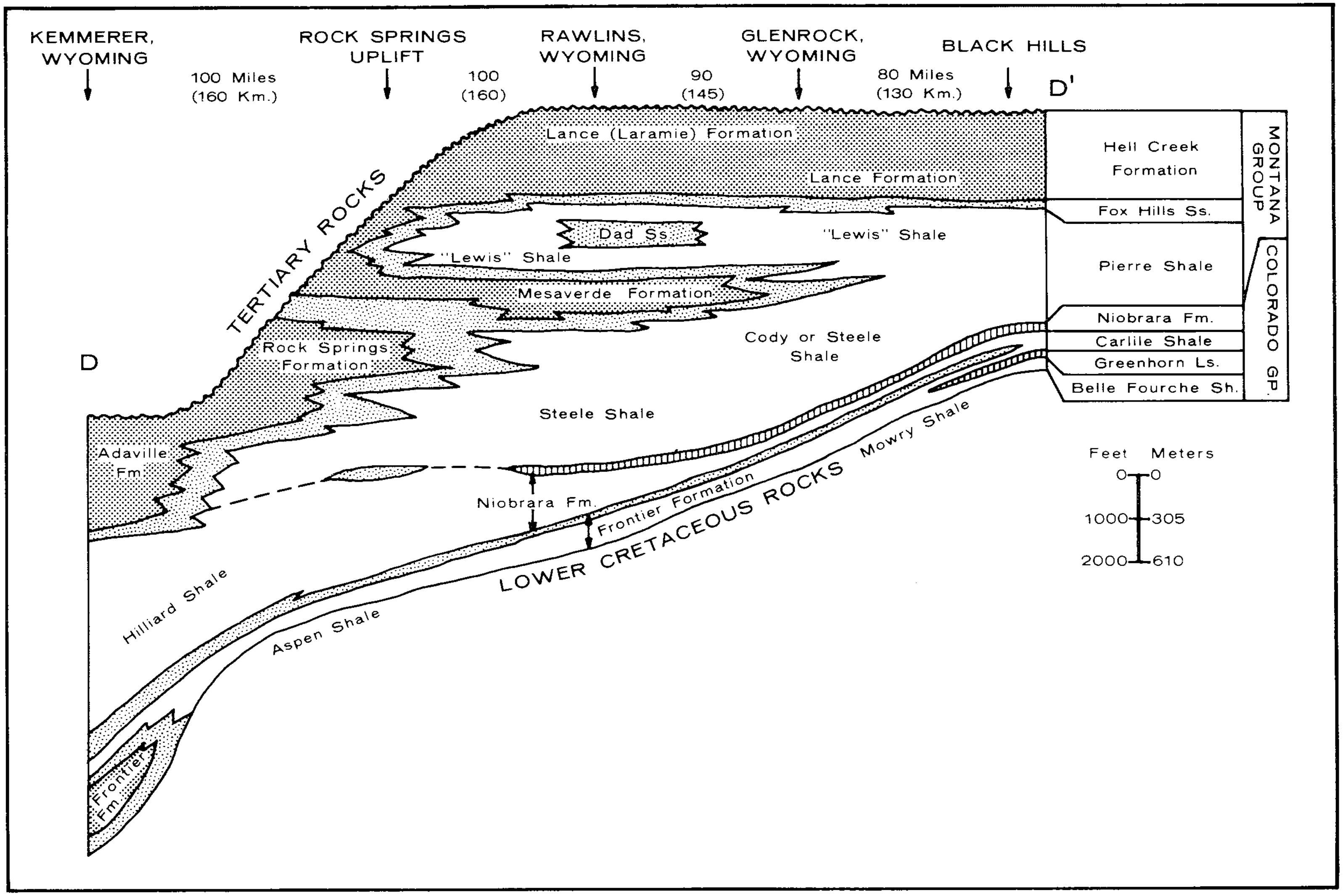

FIGURE 6-24. GENERALIZED STRATIGRAPHIC CROSS SECTION D-D', SHOWING UPPER CRETACEOUS SHALES AND ASSOCIATED STRATA IN NORTHERN GREAT PLAINS AND ROCKY MOUNTAINS (MODIFIED FROM WEIMER, 1960; MCGOOKEY ET AL., 1972). SEE FIGURE 6-22 FOR LOCATION MAP AND EXPLANATION

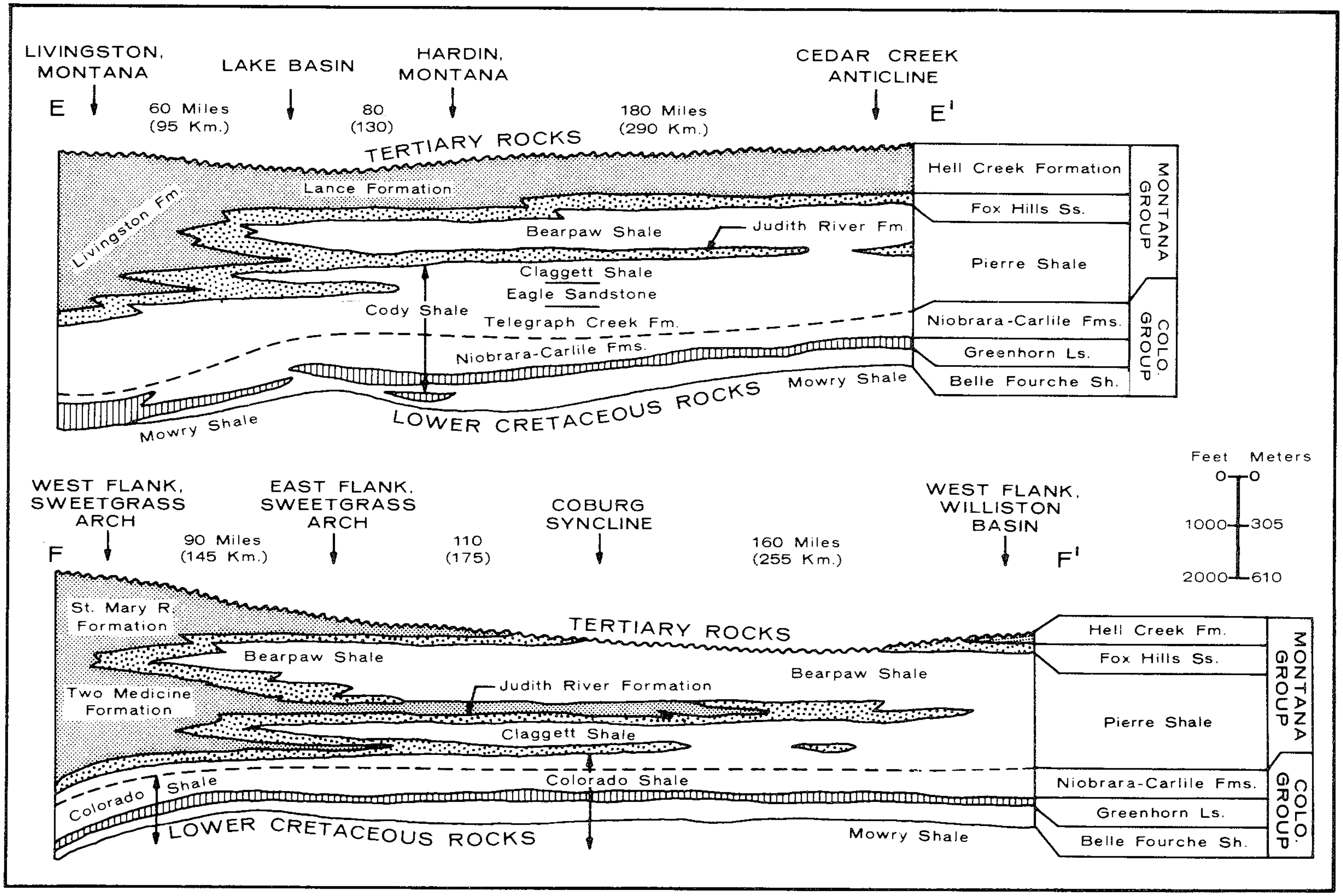

FIGURE 6-25. GENERALIZED STRATIGRAPHIC CROSS SECTIONS E-E' AND F-F', SHOWING UPPER CRETACEOUS SHALES AND ASSOCIATED STRATA IN NORTHERN GREAT PLAINS AND ROCKY MOUNTAINS (MODIFIED FROM WEIMER, 1960; MCGOOKEY ET AL., 1972). SEE FIGURE 6-22 FOR LOCATION MAP AND EXPLANATION

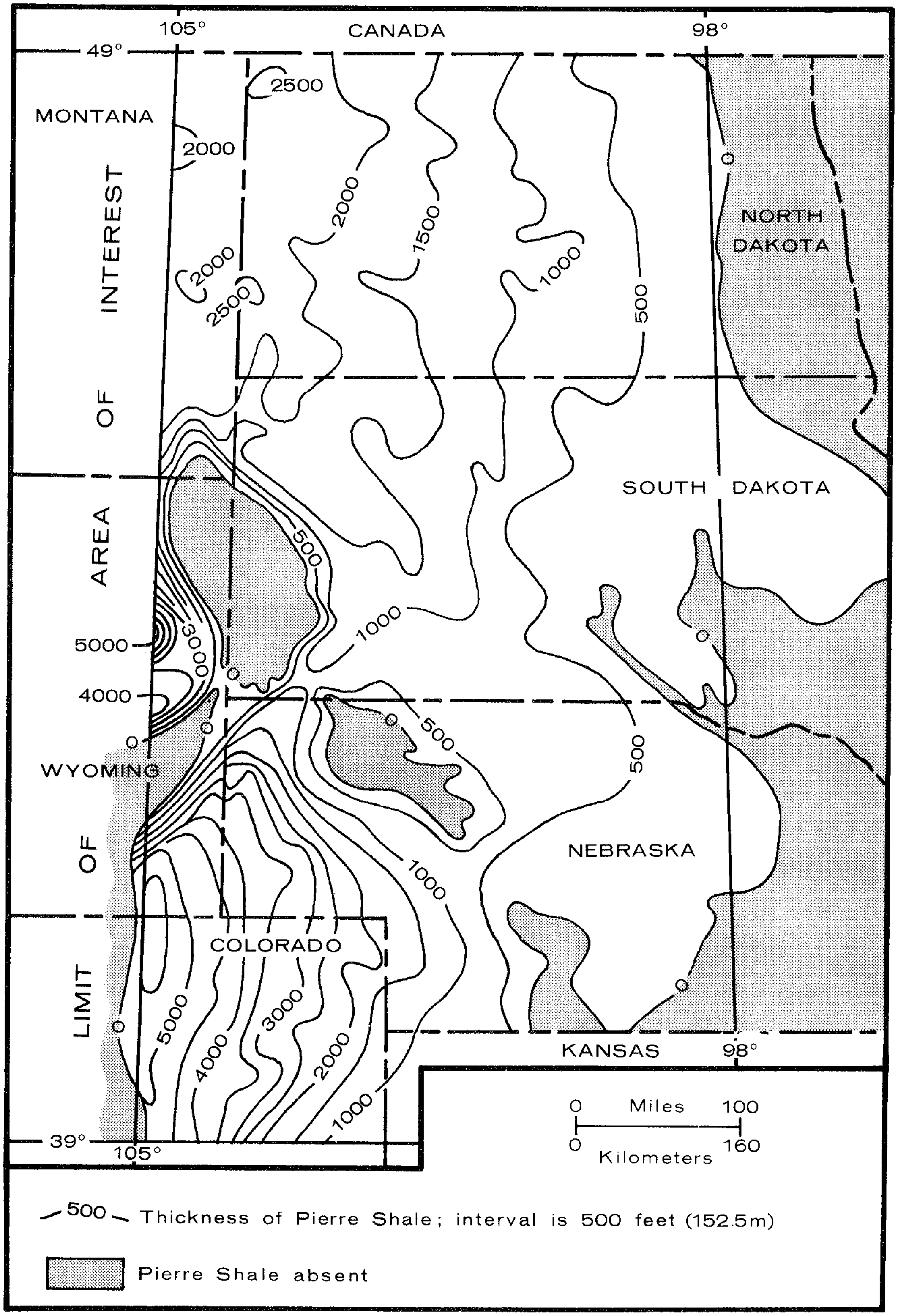

FIGURE 6-26. MAP SHOWING THICKNESS OF PIERRE SHALE IN NORTHERN GREAT PLAINS (MODIFIED FROM SHURR, 1977)

that are somewhat thinner (Figure 6-25, F-F'). The Pierre Shale is eroded along its eastern edge in the vicinity of the 98th meridian, and also where it has been uplifted over the Black Hills of South Dakota and Wyoming, over the Chadron Arch of northwestern Nebraska, and over the Hartville uplift of southeastern Wyoming (Figure 6-26).

Underlying the Pierre Shale are limestones, marls, and shales of the Niobrara Formation and other units of the Colorado Group (Figures 6-22, 6-23, 6-24, 6-25). Some of these units, such as the Carlile, Colorado, and Belle Fourche Formations, are predominantly shales, and when added to the thickness of the Pierre Shale, they increase by several hundred meters the thickness of shales of the Upper Cretaceous.

In many areas the Pierre Shale contains eastward-thinning wedges of sandstone deposited along the western shore of the Late Cretaceous seaway (Figures 6-22, 6-23, 6-24, 6-25). Units such as the Mesaverde and Judith River Formations break the vertical continuity of the thick shales in some areas.

Overlying the Pierre Shale in most parts of the Great Plains is the Fox Hills Sandstone, and this in turn is overlain by other Late Cretaceous sandstones and shales that are variously called the Laramie, Hell Creek, or Lance Formation. In some areas, particularly in Nebraska and adjacent parts of surrounding states, these Late Cretaceous sandstones are absent and the Pierre Shale is overlain by sands and clays of Tertiary age (Figure 6-27).

6.4.6.2 Geologic Setting

The geologic structure of Cretaceous and younger sediments in most parts of the Great Plains is relatively simple, and thus the Pierre Shale and equivalent strata are only little deformed, except along the margins of the principal uplifts and in much of central Montana. The regional dips are toward the several major basins, such as the Williston, Powder River, and Denver Basins (Figure 6-28) where the Pierre Shale is thickest, and typically these dips are less than 1 degree. Faults, flexures, and folds are widely scattered throughout the Great Plains, but there are many

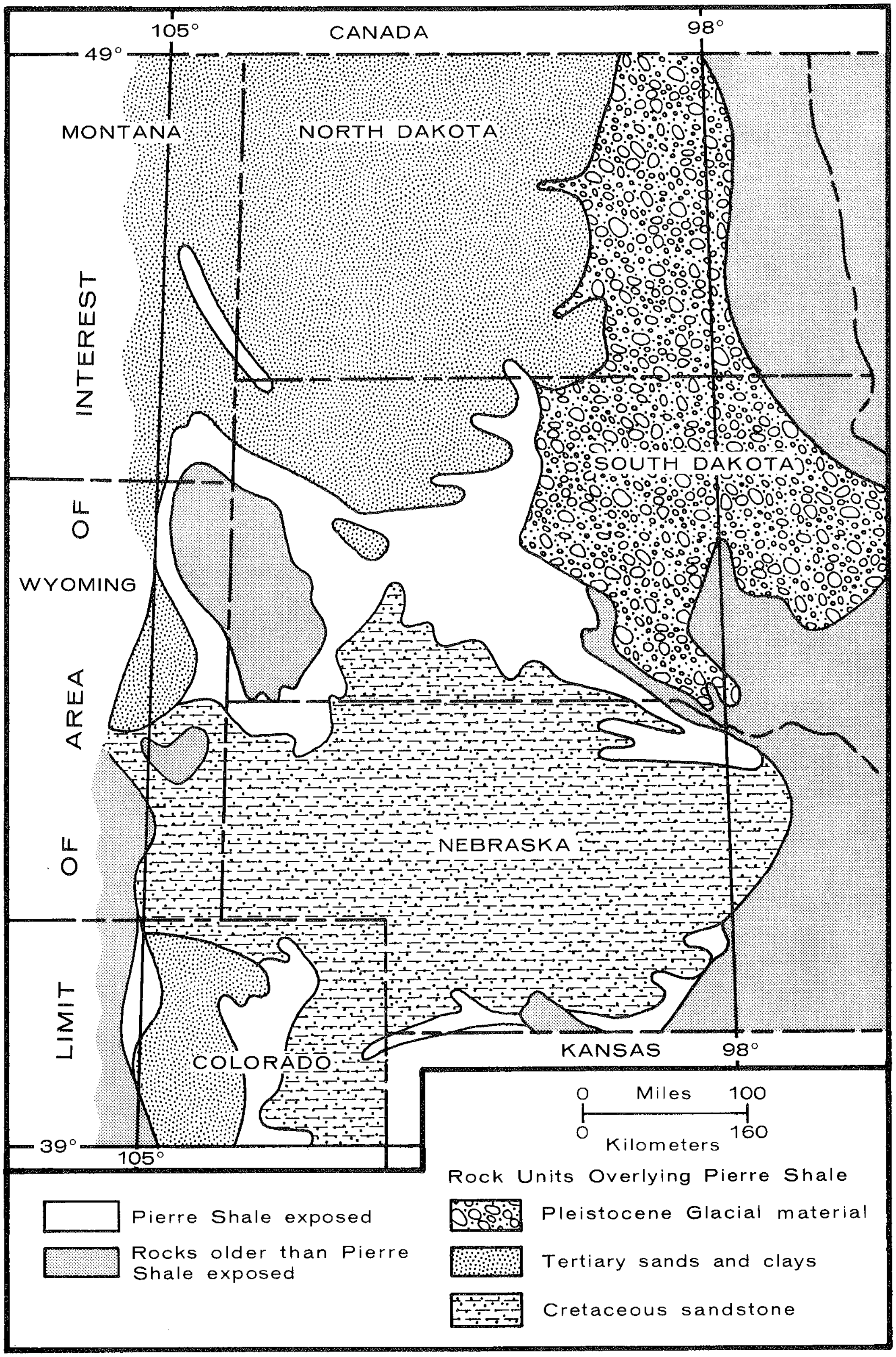

FIGURE 6-27. MAP SHOWING DISTRIBUTION OF PIERRE SHALE OUTCROPS AND LITHOLOGY, AND AGES OF ROCK UNITS OVERLYING PIERRE SHALE IN NORTHERN GREAT PLAINS (MODIFIED FROM SHURR, 1977)

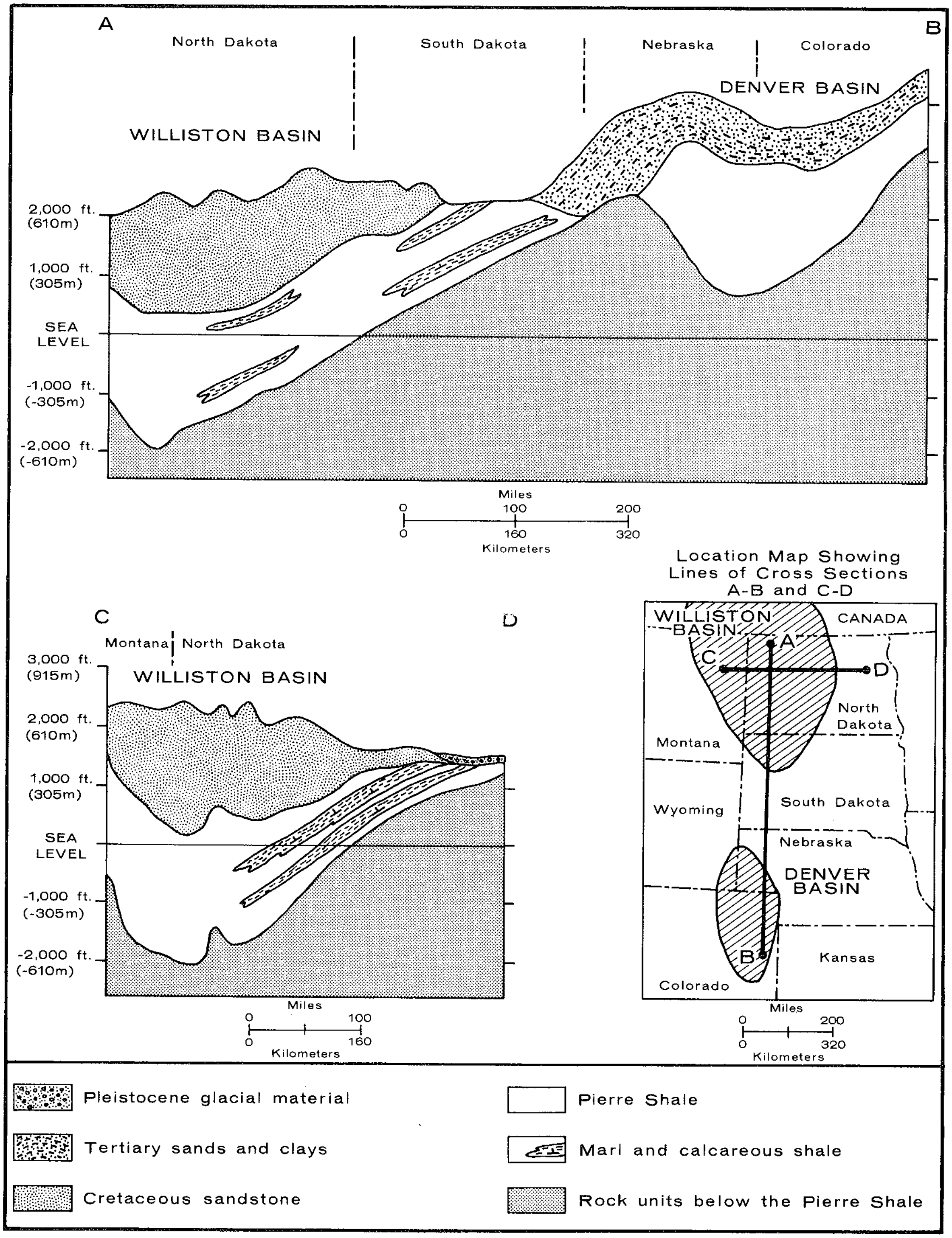

FIGURE 6-28. GENERALIZED CROSS SECTIONS SHOWING PIERRE SHALE AND OVERLYING STRATA IN NORTHERN GREAT PLAINS (MODIFIED FROM SHURR, 1977)

substantial areas where thick sections of the shale are far removed from these smaller structures.

The Pierre Shale is at fairly shallow depths in most parts of the northern Great Plains (Figure 6-29). The shale crops out over a substantial part of central South Dakota and central Montana, and around the margins of the Black Hills. The top of the shale is less than 300 m deep in most of the eastern parts of the region and in almost all parts of central and eastern Montana. The shale dips down to its greatest depths in the three major basins of the region: the top of the shale is typically 300 to 600 m deep in the Williston Basin, 300 to 1,200 m deep in the Denver Basin, and 300 to 2,000 m deep in the Powder River Basin. Sedimentary rocks directly above the Pierre Shale include lithified Cretaceous sandstones and shales, unlithified Tertiary sands and clays, and unlithified glacial deposits (Figure 6-27).

Owing to the great thickness of the Pierre Shale, there are large areas where the shale crops out, or is at shallow depth, and where the lower parts of the shale unit may still be thick and at a depth of less than 1,000 m. Thus a separate map showing the depth to the base of the Pierre Shale is presented (Figure 6-30). On this map it is clear that the base of the Pierre Shale is more than 1,000 m deep only in the deep parts of the Williston, Denver, and Powder River Basins.

Comparison of those maps showing the thickness of the Pierre Shale and the depth to the top and base of the shale (Figures 6-26, 6-29, 6-30) enables preparation of a composite map (Figure 6-31) that shows the large areas of the northern Great Plains where the Pierre Shale is thick, at moderate depths, and is not penetrated by a large number of boreholes. Such areas include substantial parts of the western halves of Nebraska, South Dakota, and North Dakota, parts of northeastern Colorado, southeastern Wyoming, and eastern Montana (Figure 6-31).

6.4.6.3 Mineralogy and Rock Properties

The Pierre Shale is characteristically a clay shale in the Great Plains Region, but it also includes substantial thicknesses of interbedded

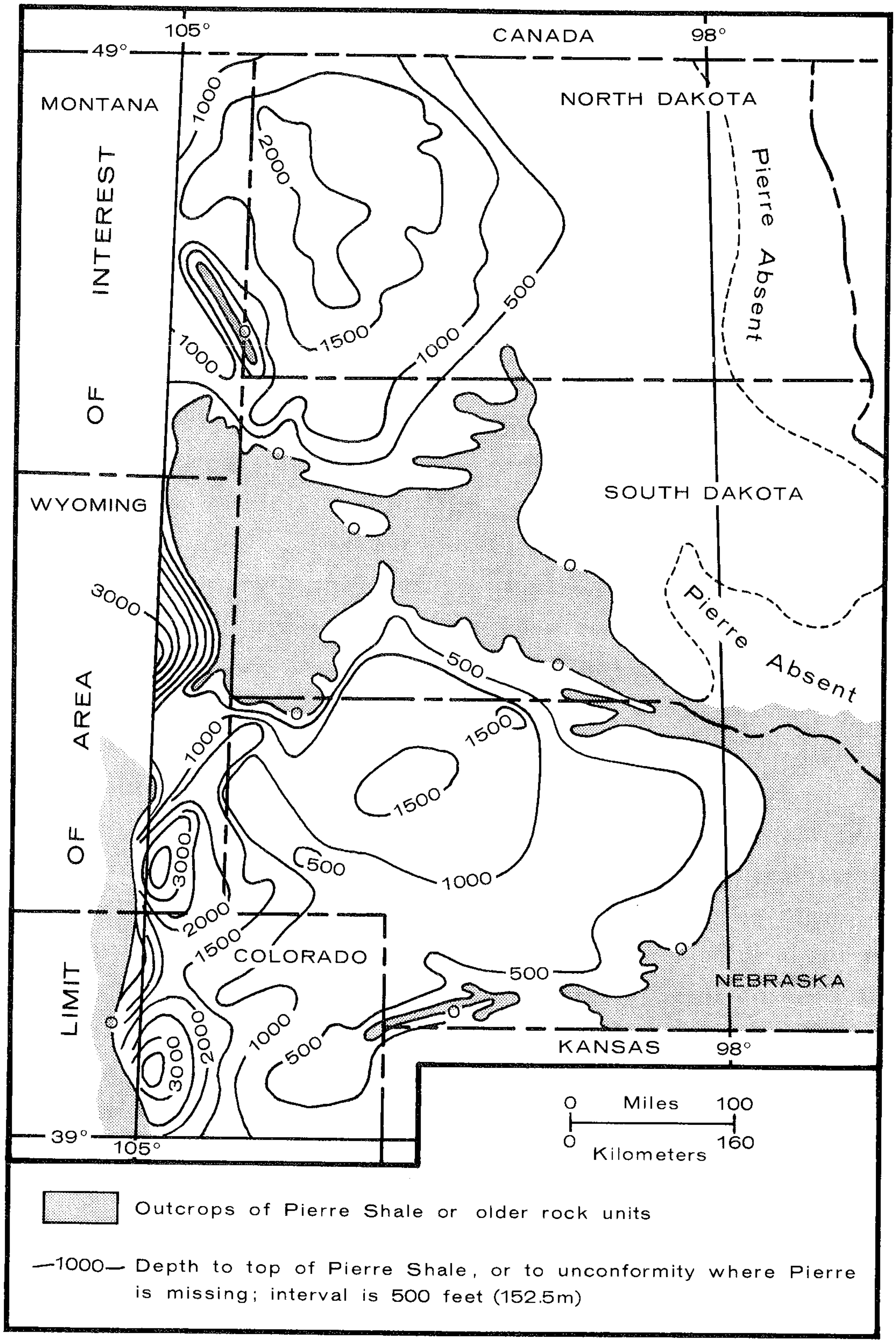

FIGURE 6-29. MAP SHOWING DEPTH FROM SURFACE TO TOP OF PIERRE SHALE IN NORTHERN GREAT PLAINS (MODIFIED FROM SHURR, 1977)

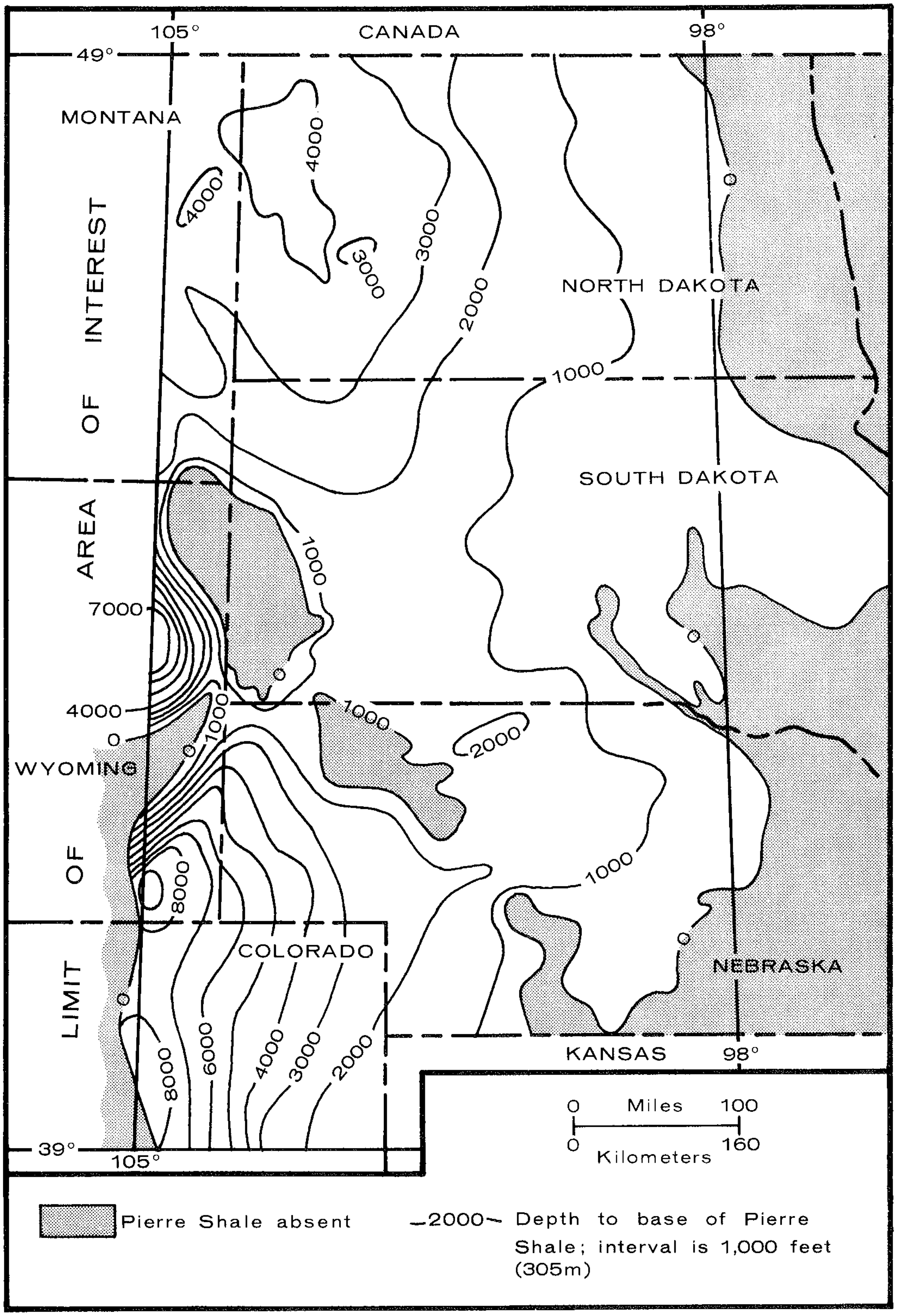

FIGURE 6-30. MAP SHOWING DEPTH FROM SURFACE TO BASE OF PIERRE SHALE IN NORTHERN GREAT PLAINS (MODIFIED FROM SHURR, 1977)

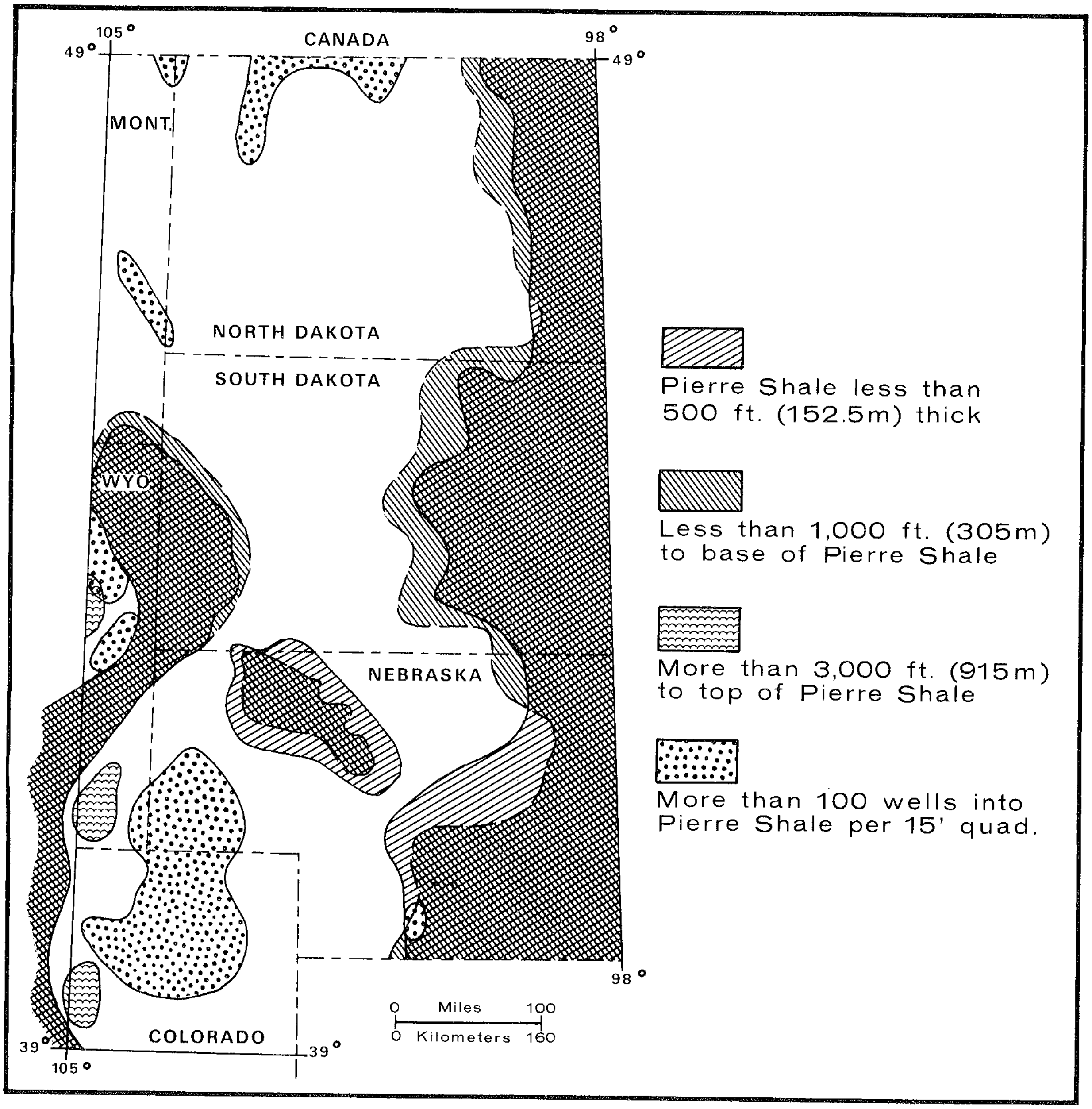

FIGURE 6-31 MAP OF NORTHERN GREAT PLAINS SHOWING AREAS WHERE PIERRE SHALE IS THICK, AT MODERATE DEPTHS, AND HAS NOT BEEN PENETRATED BY MANY BOREHOLES

sandstone and siltstone in the west and some interbeds of marl in the east (Shurr, 1977). In addition, some of the shale is siliceous or organic rich.

The gross mineralogy of shale units in the Pierre Shale in various parts of the Great Plains has been described by Tourtelot et al. (1960), Tourtelot (1962), Schultz (1965, 1978), Gill et al. (1972), and Schultz et al. (in press). Shales consist mainly of clay minerals, although locally they contain as much as 25 percent quartz, a few percent feldspar, and minor amounts of calcite, dolomite, biotite, pyrite, jarosite, clinoptilolite, and organic matter.

Of the clay minerals, which typically make up 60 to 80 percent of the shales, mixed-layer illite-montmorillonite is dominant. There also are moderate amounts of montmorillonite and illite and minor amounts of kaolinite and chlorite. The percentage of mixed-layer illite-montmorillonite decreases eastward across the region, whereas the percentage of illite and montmorillonite increases in that direction. The principal stratigraphic trend is that illite and mixed-layer illite-montmorillonite are more abundant in the lower part of the Pierre Shale, whereas the amount of montmorillonite increases upward through the unit.

The average chemical composition of 17 samples of Pierre Shale from Montana, Wyoming, and South Dakota is as follows (Tourtelot, 1962): SiO_2 (59.68 percent), Al_2O_3 (15.40), Fe_2O_3 (4.56), FeO (0.96), MgO (2.11), CaO (1.52), Na_2O (1.09), K_2O (2.49), H_2O^- (3.73), H_2O^+ (4.77), CO_2 (0.87), P_2O_5 (0.15), acid-soluble S as SO_3 (0.85), insoluble S as S (0.21), Cl (0.01), F (0.07), MnO (0.19), and BaO (0.08). These averages differ only in minor ways from the average compositions of other shales, and thus the Pierre Shale is not an extraordinary shale unit in terms of its chemistry.

Tourtelot (1962) also tested 22 samples for their plastic limits and liquid limits. The plastic limits ranged from 20 to 62, but most of the samples had plastic limits of 30 to 40. The liquid limits ranged from 36 to 113 and generally are much higher than those for kaolin clays, glacial clays, and gumbo clays, but are not as high as those for bentonite.

Marls and calcareous shales in the Pierre Shale range up to 75 percent calcium or magnesium carbonate content, whereas the siliceous shales locally contain as much as 40 percent cristobalite. Although most shales in the sequence contain less than 0.5 percent organic carbon, the few units that are organic rich may contain as much as 15 percent organic matter.

A comprehensive discussion of the physical properties and the history of surface and subsurface excavations of the Pierre Shale was presented by Abel and Gentry (1975). Their data (Table 6-2) show that the shale is a fairly weak rock that is plastic and is nearly impermeable. Previous excavation experience shows that the formation tends to deteriorate rather rapidly if not protected from drying and wetting cycles that cause alternate shrinking and swelling (Abel and Gentry, 1975). Faults and joints encountered in subsurface excavations have led to failure and fallout of blocks of rock.

Excavation of the Pierre Shale produces both instantaneous and long-term rebound (Abel and Gentry, 1975). Surface excavation of a maximum 60 m of Pierre Shale at the Oahe Dam in South Dakota resulted in 20 cm of vertical rebound, 90 percent concurrent with excavation and 10 percent occurring later at a decreasing rate. Removal of a maximum of 49 m of Pierre Shale at Fort Peck Dam in Montana resulted in nearly 15 cm of rebound during excavation, followed by a decreasing, but still continuing, 70 cm of additional rebound over a period of 35 years. Underground excavations have also produced rebound in the Pierre Shale (Abel and Gentry, 1975). In one tunnel 1.8 m wide by 2.4 m high, unweathered shale expanded 2.5 to 7.5 cm over a 1.5-year period. However, only 2.5 cm of rebound (apparently instantaneous) was measured in a 9.1-m-diameter tunnel in Pierre Shale where the humidity was maintained at a high and constant level.

Based upon evaluation of various excavation techniques, Abel and Gentry (1975) suggested that tunnel-boring machines would probably be most successful for underground mining in the Pierre Shale with minimum damage to surrounding rock.

TABLE 6-2. PHYSICAL PROPERTIES OF PIERRE SHALE IN NORTHERN GREAT PLAINS (MODIFIED FROM ABEL AND GENTRY, 1975)

Compressive strength	70–2,530 psi
Elastic modulus	0.02–0.014 x 10^6 psi
Cohesion	2–30 psi
Internal friction angle	8° to 25°
Plastic limit	22–39
Liquid limit	55–202
Plasticity index	30–110
Permeability	10^{-6}–10^{-10} cm/s
Dry density	95–110 lb/cu ft
Natural moisture content	18–38% (27% near outcrop; 18% below depths of 60 m)
Swell potential	3–5% (2–20% for samples from Canada)

6.4.6.4 Hydrology

Freshwater aquifers overlie or underlie the Pierre Shale in most parts of the northern Great Plains (U.S. Geological Survey, 1969b, 1973, 1975; Reeder, 1978; Taylor, 1978). Aquifers above the shale include alluvium and terrace deposits of Pleistocene and Holocene age along the principal rivers and streams of the region. Related to these deposits are the areally extensive Pleistocene alluvial and dune-sand aquifers of central and western Nebraska (Taylor, 1978). Similar unconsolidated-sand aquifers include the Tertiary Ogallala, Arikaree, and Brule Formations that are locally as much as 120 m thick and underlie parts of Kansas, Colorado, Nebraska, South Dakota, and Wyoming. The dissolved-solids concentration of waters in all these young aquifers is normally less than 500 to 1,000 mg/l, and thus the water is generally suitable for most common purposes. Individual wells in each of the formations yield as much as 8,000 l/min locally and are used for irrigation and for municipal and industrial water supplies.

Pleistocene glacial deposits contain some significant aquifers in a broad area that covers much of the northern and northeastern parts of the region (Reeder, 1978; Taylor, 1978). The glacial deposits locally are more than 200 m thick, and they contain sand and gravel aquifers in the form of buried channel deposits, extensive outwash deposits, and lenticular outwash deposits. The quality of water in these aquifers is variable, and the dissolved-solids concentration ranges from 300 to 30,000 mg/l. Wells locally yield as much as 8,000 l/min.

Sandstone aquifers overlie the Pierre Shale in most parts of the Dakotas, Montana, and Wyoming, and also in the Denver Basin area (Taylor, 1978). Upper Cretaceous units are the Fox Hills, Hell Creek, Lance, Laramie, and Arapahoe aquifers; Upper Cretaceous-Paleocene units are the Fort Union, Denver, and Dawson aquifers; and an Eocene unit is the Wasatch aquifer. Wells in these aquifers typically yield 50 to 2,000 l/min of water with dissolved-solids concentrations of 500 to 2,000 mg/l.

Sandstones interbedded with the Pierre Shale and equivalent shales locally are aquifers in the western part of the northern Great Plains.

These units, including the Mesaverde, Eagle, and Judith River Formations, yield water in much of Montana and in the Powder River Basin area. Yields of 40 to 800 l/min can be attained from individual wells. In addition, in some places the shales in the Pierre equivalents are fractured and yield small quantities of water. The fractures, where present, may extend almost 100 m below the land surface, but generally they are too small to yield significant amounts of water below depths of 30 m (U.S. Geological Survey, 1973). In such areas of fractures, the shale normally yields less than 20 l/min; however, where the fractures are unusually large, the pumping rates can range up to 200 to 400 l/min.

Sandstone aquifers of Early Cretaceous to Late Cambrian age underlie the Pierre Shale in most parts of the Dakotas and Montana and in the Powder River-Black Hills area of Wyoming (Taylor, 1978). Principal units in these areas include the Frontier, Dakota, Inyan Kara, Sundance, Minnelusa, Red River, and Deadwood aquifers. These aquifers are highly variable, but generally they yield 20 to several thousand l/min of water that contains 500 to 20,000 mg/l of dissolved solids. The Dakota aquifer is especially important in South Dakota (Schoon, 1971), where an estimated 25 percent of the population obtains water supplies from the Dakota aquifer.

The major limestone aquifer underlying the Pierre Shale in the region is the Madison Limestone of Early Mississippian age (Swenson et al., 1978; Taylor, 1978). The aquifer underlies the northwestern half of the northern Great Plains region, but it is largely untested. Wells generally yield 1,000 to 10,000 l/min and the dissolved-solids concentration is as low as 300 mg/l where the aquifer is at shallow depths.

6.4.6.5 Mineral Resources

Many mineral resources are present within, above, and below the Pierre Shale in the northern Great Plains (Osterwald et al., 1966; U.S. Geological Survey, 1968c, 1969b, 1973, 1975). The principal resources within the Pierre Shale are the bentonite deposits, 0.5 to 2 m thick, that are mined from open pits in the Powder River Basin and Black Hills areas

(Osterwald et al., 1966). Other uses of the shale that may have some potential in the future include manufacture of cement, recovery of aluminum, and recovery of uranium from the black shale units.

In some parts of the Great Plains, important coal resources are present in the rocks and sediments that overlie the Pierre Shale (Averitt, 1969, 1972). Subbituminous coals occur in Tertiary sediments in parts of the Denver Basin, Powder River Basin, and central Montana; locally these coals are more than 30 m thick, and they are presently being strip mined at many localities. Lignite beds, typically 1 to 3 m thick, also are being strip mined from uppermost Cretaceous and Lower Tertiary sediments at places in many parts of the Williston Basin. Other rock and mineral resources above the Pierre Shale that are being, or might be, developed by surface mining include sand and gravel and stone.

Petroleum is being produced in the northern Great Plains chiefly from rock units within or below the Pierre Shale, although locally there is production from overlying Upper Cretaceous and Tertiary sands (Lumb et al., 1972; Rice and Shurr, 1980). Principal producing areas include parts of the Denver, Powder River, and Williston Basins as well as parts of central Montana and the Central Kansas Uplift-Las Animas Arch area of northwest Kansas and adjacent states. Shurr (1977) prepared a map showing the distribution of oil and gas test holes that penetrate the Pierre Shale in each quadrangle whose dimensions are 15 minutes of latitude and longitude (Figure 6-32).

Other major mineral resources that underlie the Pierre Shale and may be developed on a wider scale at some future date are salt (halite) and potash (Hite, 1972; Johnson and Gonzales, 1978). Salt deposits are present beneath the Williston, Powder River, and northern Denver Basins and also beneath parts of northwestern Kansas. Potash resources are limited to bedded deposits in the northern part of the Williston Basin and to potash-bearing brines in the Nebraska Panhandle.

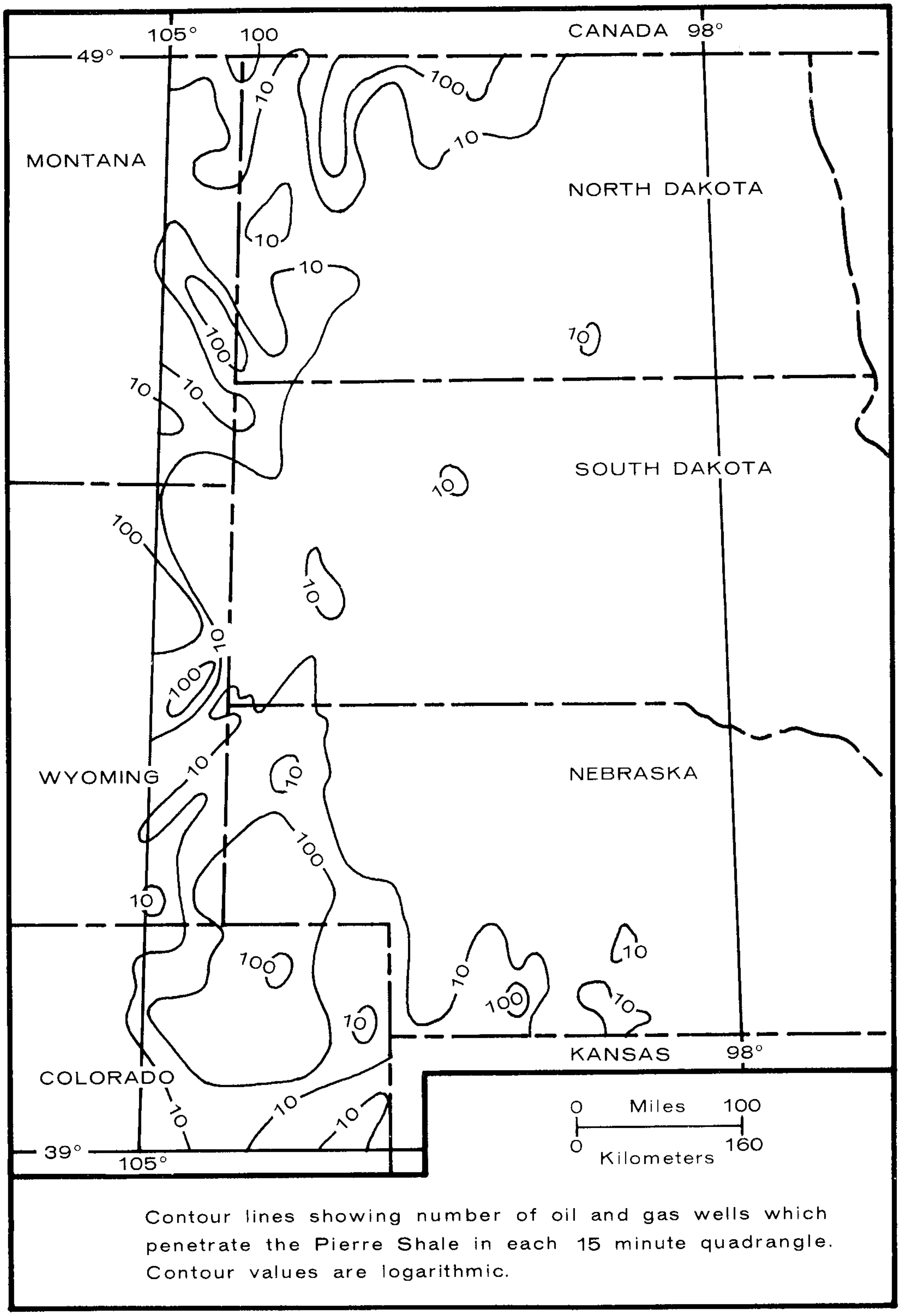

FIGURE 6-32. MAP SHOWING NUMBER OF OIL AND GAS WELLS THAT PENETRATE PIERRE SHALE IN NORTHERN GREAT PLAINS (MODIFIED FROM SHURR, 1977). BASED ON RECORDS OF 33,000 WELLS

6.4.7 Lower Cretaceous Shales

6.4.7.1 Stratigraphy

Rocks of Early Cretaceous age in the Great Plains consist generally of an eastern facies of sandstones, typified by the Dakota Formation, and a central and western facies of shales characterized by the Skull Creek, Kiowa, and Mowry Shales. The total thickness of the shale-bearing strata in the region ranges from about 30 to 100 m in Kansas on the southeast to 150 to 300 m in Montana and the northern Black Hills area. Principal outcrops are limited to an eastern belt about 15 to 50 km wide in central Kansas and eastern Nebraska, several areas in northeastern New Mexico, and narrow belts along the Rocky Mountain front and around the Black Hills. The shale units and equivalent strata are widespread and underlie almost all parts of the northern Great Plains, but in most areas they lie at considerable depth below the surface. References dealing with the stratigraphy of these Lower Cretaceous shale units in the Great Plains region include Hansen (1955), Condra and Reed (1959), Reeside and Cobban (1960), Wulf (1962), Merriam (1963), Bolyard and McGregor (1966), McGookey et al. (1972), Rice (1976b, 1977), Irwin (1977), and Berman et al. (1980).

The first of several major Cretaceous marine invasions of the Great Plains and Rocky Mountains occurred in Early Cretaceous (Albian) time. The Skull Creek Shale was deposited across most parts of the northern Great Plains and the Denver Basin area, while the equivalent Kiowa Shale was laid down to the southeast in Kansas. These Skull Creek and Kiowa Shales are typically gray to black: they can be differentiated with ease from underlying strata because of their sharp lithologic contrast with the underlying fluvial sandstones of the Fall River Sandstone and equivalent units. The thickness of the Skull Creek Shale ranges from 30 to 75 m in much of Montana and North Dakota, but the formation grades into sandstone toward the southeast and consists of 30 to 50 m of shale in parts of the Powder River Basin and northwestern South Dakota. Farther south, the Skull Creek Shale is typically 30 m thick in the Denver Basin and is as much as 60 m thick in northwestern Nebraska. In Kansas, the Kiowa Shale averages about 30 m thick but also locally is as much as 115 m thick.

The Skull Creek Shale is characterized as a fissile black shale that contains some light-gray to bluish-gray bentonite beds and volcanic-ash beds that locally are 1 to 2 m thick. The Kiowa Shale is predominantly medium- to dark-gray, silty, carbonaceous shale that contains some limestone, sandstone, and bentonite.

Overlying the Skull Creek and Kiowa Shales are sandstone units that typically are 15 to 60 m thick and are variously called the Newcastle, Dynneson, Muddy, Birdhead, and "J" Sandstones.

The next episode of marine inundation of the region took place near the end of Early Cretaceous time, when the moderately thick Mowry Shale was deposited over a large area extending northward from northeastern Colorado to the Canadian border and beyond (McGookey et al., 1972). The Mowry Shale is a hard, dark-gray, porcelaneous shale with many interbeds of bentonite and numerous scattered fish scales and bones. It is recognizable in subsurface mainly by its hardness and its high resistivity and high bentonite content as seen on electric logs. The high silica content of the unit is attributed to the large volume of volcanic ash that settled into the Mowry sea from eruptions that accompanied emplacement of the Boulder Batholith in Idaho. The lower part of the Mowry Shale contains 15 to 45 m of sandstone (the Dynneson Sandstone) in much of the Williston Basin area (Wulf, 1962), whereas the upper part of the Mowry Shale grades into the Dakota Sandstone to the east and southeast in South Dakota, Nebraska, and other areas on the east side of the Mowry seaway. The top of the Mowry Shale is placed at the base of a regionally persistent marker bed called the Clay Spur Bentonite.

The thickness of the Mowry Shale increases toward the west across the northern Great Plains. The shale is typically 15 to 40 m thick in the western part of the Dakotas and increases to 60 to 120 m thick in the Powder River Basin and to 75 to 175 m thick in parts of central Montana.

6.4.7.2 Geologic Setting

Lower Cretaceous strata are nearly flat lying or dip at low angles in most parts of the Great Plains Region. The regional dip is toward such major basins as the Williston, Powder River, and Denver Basins. The few areas where these strata are deformed are (1) along the flanks of major uplifts, (2) in much of central Montana, and (3) near folds, faults, and flexures that are widely scattered throughout the Great Plains.

In a fairly wide band, stretching northward from northwestern Kansas through parts of Nebraska and the Dakotas, the top of the Lower Cretaceous shales is at moderate depths. In northwestern Kansas and most parts of the western half of Nebraska, the Skull Creek or Kiowa Shale is 300 to 900 m deep, with the greater depths in the west, where strata dip into the Denver Basin. The shale typically is about 30 m thick in much of this area, but it is reported locally to be as much as 115 m thick in Kansas (Merriam, 1963) and up to 60 m thick in northwestern Nebraska (Condra and Reed, 1959).

In South Dakota, the top of the Lower Cretaceous shales (top of Mowry Shale) is more than 300 m below the surface in the entire western two-thirds of the state (essentially west of the 99th meridian), except in a narrow zone encircling the Black Hills, where Lower Cretaceous strata crop out or are at shallow depth. The only part of the state where the Lower Cretaceous shale is deeper than 900 m is in the northwest, in Harding, Perkins, and Corson Counties, on the south side of the Williston Basin. Thus in most parts of South Dakota the Mowry and Skull Creek Shales are 300 to 900 m below the surface, but it is only in the northwestern third of the state that these units are locally as much as 60 to 75 m of shale. The Mowry Shale is about 60 m thick in the northwestern corner of the state, but it thins to the east-southeast and is only about 30 m thick in the vicinity of the 102d meridian (Wulf, 1962). The Skull Creek Shale, on the other hand, generally thickens southeastward from about 60 m in the northwestern corner of the state to more than 120 m in the vicinity of Bateland-Kadoka-Pierre-Gettysburg. However, the amount of sandstone in the Skull Creek Shale also increases to the southeast across this area (Wulf, 1962), and thus the thickness of the shale unit alone is probably not much more than 60 to 75 m in any part of the area.

The Skull Creek and Mowry Shales are 300 to 900 m deep in a narrow belt around the flanks of the Black Hills. This belt, which is generally 15 to 25 km wide, extends mainly through South Dakota but also passes through parts of northeastern Wyoming and southeastern Montana. In the Wyoming and Montana areas the Skull Creek Shale is about 60 m thick, and the Mowry Shale is 60 to 75 m thick.

Lower Cretaceous strata dip uniformly to the west across North Dakota toward the Williston Basin. The top of the Lower Cretaceous sequence is 300 to 900 m below the land surface in the central one-third of the state, in the area between approximately the 98th and 101st meridians. Within all parts of this area the Mowry Shale is no more than 30 m thick. In most parts of central North Dakota, the deeper Skull Creek Shale is 30 to 50 m thick, but in the south, in parts of Sioux, Morton, Emmons, and McIntosh Counties, the thickness of the Skull Creek Shale is 60 to 70 m (Wulf, 1962). North of this southern area the Newcastle Sandstone, which normally separates the Skull Creek and Mowry Shales, is missing (Hansen, 1955; Carlson and Anderson, 1965; Rice, 1977); thus the combined thickness of the Skull Creek and Mowry Shales is 60 to 90 m in much of central North Dakota (Figure 6-33).

The Lower Cretaceous units are at moderate depths in several parts of Montana. In north-central Montana, on the Bowdoin Dome in Phillips County, the top of the Lower Cretaceous is about 700 to 900 m below the surface: in this area, the Skull Creek Shale is about 50 to 60 m thick and the shallower Mowry Shale is about 140 to 150 m thick. Farther west, the top of the Lower Cretaceous is 300 to 900 m deep in a fairly large area over the Sweetgrass Arch: here, the Taft Hill Member (equivalent to the Skull Creek Shale) is about 60 to 120 m of siltstone, shale, and sandstone (Cobban et al., 1959; Billings Geological Society, 1966; Rice, 1976b), and the Bootlegger Member (equivalent to the Mowry Shale) is about 60 to 120 m of interbedded shale, siltstone, sandstone, and tuffaceous bentonite. The other principal area where Lower Cretaceous shales are at moderate depths is in the vicinity of the Central Montana Uplift (Big

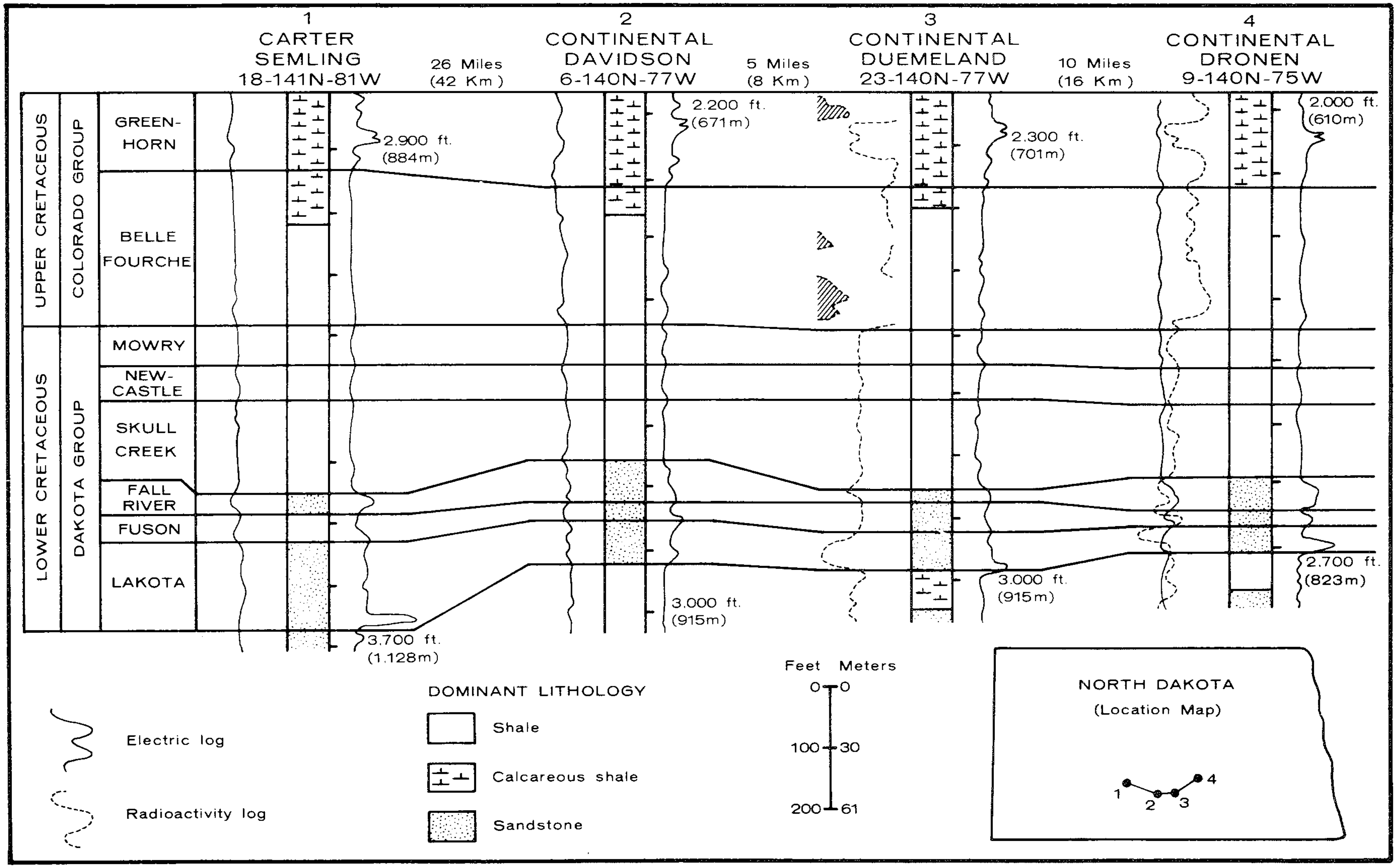

FIGURE 6-33. CORRELATION OF CRETACEOUS SHALES IN SKULL CREEK, NEWCASTLE, MOWRY, AND BELLE FOURCHE FORMATIONS OF SOUTH-CENTRAL NORTH DAKOTA (MODIFIED FROM HANSEN, 1955)

Snowy Anticlinorium and nearby uplifts and domes); however, the structure in this area is relatively complex.

6.4.7.3 Mineralogy and Rock Properties

Shales of the Lower Cretaceous typically are gray to black in color, and they normally contain a moderate amount of volcanic ash and/or bentonite. Although they commonly are fairly soft and not well indurated, the Mowry Shale is somewhat siliceous, and it is more resistant and harder than the other shales. The Mowry Shale contains an average of 50 percent quartz, 5 percent feldspar, and 2 percent organic carbon; the remainder consists of clay minerals and minor zeolites (Davis, 1970). Mixed-layer clays are predominant in the Mowry Shale, although the lower part of the formation contains kaolinite and the upper part is enriched with montmorillonite.

The organic content of some of the Lower Cretaceous shales is moderate, and the rocks are considered potential local source beds for petroleum in several areas. The Mowry Shale, in particular, contains as much as 3 percent organic carbon in the eastern part of Wyoming (Schrayer and Zarrella, 1963; Nixon, 1973) and may be the source of some of the nearby oil accumulations.

6.4.7.4 Hydrology

Lower Cretaceous shales have low permeabilities and typically contain no significant amounts of ground water, except at and near the outcrop, where weathered and fractured shale locally contains small amounts of fresh water. Thin interbeds of sandstone within the shales also locally contain fresh water at shallow depths.

Aquifers in rocks and sediments that overlie Lower Cretaceous shales are mainly Upper Cretaceous, Tertiary, and Holocene sandstones, sands, and gravels. Aquifers that underlie the Lower Cretaceous shales are mainly sandstones of Late Cambrian through Early Cretaceous age, and the Madison Limestone of Mississippian age. A discussion of these aquifers is given earlier in Section 6.4.6.4 for the Pierre Shale and equivalent Upper Cretaceous shales in the Great Plains Region, and the reader is referred to that earlier discussion.

6.4.7.5 Mineral Resources

Mineral resources in areas underlain by Lower Cretaceous shales are the same as those discussed in Section 6.4.6.5 for the Pierre Shale and equivalent Upper Cretaceous shales in the Great Plains Region, and the reader is referred to that discussion for information and references.

6.4.8 Colorado Shale and Equivalent Upper Cretaceous Shales

6.4.8.1 Stratigraphy

The Colorado Shale and equivalent strata make up the oldest group of rocks in the Upper Cretaceous of the Great Plains Region. They overlie the Mowry Shale of the Lower Cretaceous, and they are in turn overlain by the Montana Group, which contains the widespread and thick Pierre Shale. The total thickness of the Colorado Shale and equivalent strata typically is 150 to 300 m, and the sequence contains several principal argillaceous units in various parts of the Great Plains. The Colorado Shale is considered of group rank by most workers, and its two principal argillaceous units are the Belle Fourche Shale at the base and the Carlile Shale in the upper part (Figure 6-34). In the northwestern part of Montana, these shales, along with intervening units, are referred to as the Marias River Shale. Principal studies of the Colorado Group in the Great Plains include Reeside (1944), Hansen (1955), Condra and Reed (1959), Weimer (1960), Hattin (1962, 1965), Merriam (1963), McGookey et al. (1972), Rice (1976b, 1977), Irwin (1977), and Rice and Shurr (1980).

The inundation of the Great Plains region that brought about widespread deposition of the Mowry Shale near the end of Early Cretaceous time continued through most of Late Cretaceous time. As a result, a thick sequence of predominantly shale units was laid down in most parts of the

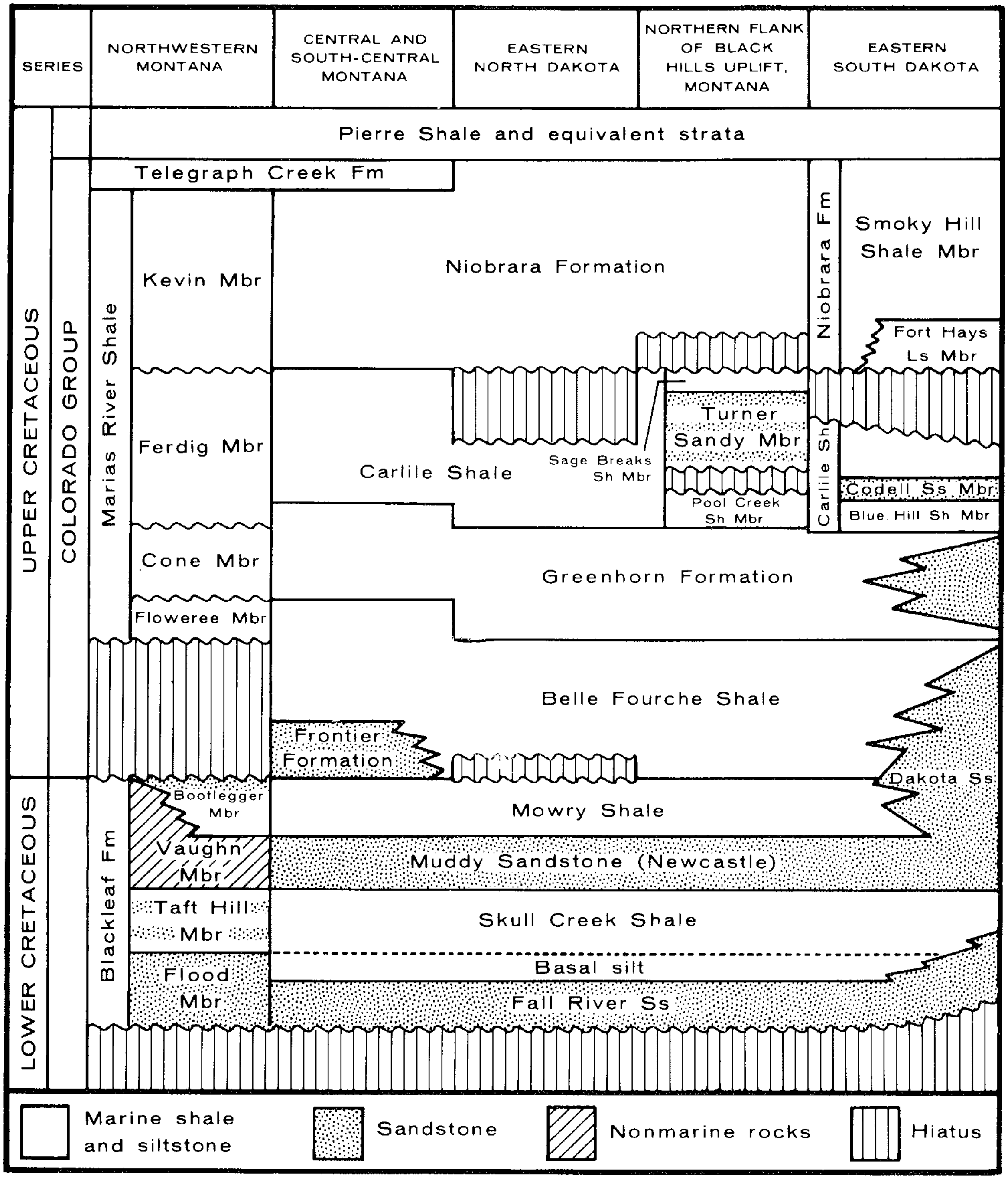

FIGURE 6-34. CORRELATION CHART OF COLORADO GROUPS AND ASSOCIATED STRATA IN NORTHERN GREAT PLAINS (MODIFIED FROM RICE, 1976a)

Great Plains, with several sandstone or carbonate units separating the shales.

The Belle Fourche Shale, with the Clay Spur Bentonite at the bottom, is the basal unit of the Colorado Group in most parts of the northern Great Plains. The shale is typically 30 to 75 m thick in much of the Dakotas and northern Montana, but in southern Montana and the Powder River Basin-Black Hills area, the unit is typically 90 to 210 m thick. Farther south, in Nebraska, Kansas, and the Denver Basin area, equivalent strata are called the Graneros Shale, and typically they are 15 to 30 m thick except in northwestern Nebraska and nearby areas, where they are as thick as 180 m. The shale in most areas is gray to black, and locally it is calcareous, sandy, and silty. Bentonite layers are fairly common in some parts of the Great Plains.

Overlying the Belle Fourche Shale is the Greenhorn Formation, which commonly consists of interbeds of limestone, calcarous shale, and chalk. The thickness of the Greenhorn Formation is typically 30 to 60 m in most parts of the region.

Above the Greenhorn Formation is an argillaceous unit called the Carlile Shale in all parts of the Great Plains except in northwestern Montana, where the unit is named the Ferdig Member of the Marias River Shale. The Carlile Shale is typically about 30 to 60 m thick in the south, southeast, and northeast (Denver Basin, Kansas, eastern Nebraska, and North Dakota). The unit thickens to the north and west, toward the depocenter of the Late Cretaceous seaway, and reaches a thickness of 90 to 150 m in most other areas. The Carlile Shale commonly is a gray shale throughout the region, but locally it contains interbeds of sandstone or chalk, some of which are given formal member status. Thin beds of bentonite are present in parts of the region.

Overlying the Carlile Shale in most areas is the Niobrara Formation, consisting mainly of limestone, chalk, calcareous shale, and some sandstone. The unit ranges from about 30 to 60 m thick in the eastern and central parts of the region, but it thickens to 60 to 150 m in the Denver and Powder River Basins and southern Montana and is as thick as 200 m in northwestern Kansas and adjacent areas (Merriam, 1963).

In northwestern Montana, the Carlile Shale and Niobrara Formation grade into a thick sequence of shales referred to as the Maria River Shale (Cobban et al., 1959; Rice, 1976b). The Marias River is about 250 to 325 m of dark-gray marine shale with numerous thin interbeds of bentonite.

6.4.8.2 Geologic Setting

As with underlying and overlying Cretaceous strata, the Colorado Shale and equivalent units are little disturbed in most of the Great Plains. Regional dips are at low angles toward the structural lows in the Williston, Powder River, and Denver Basins. Principal areas where these strata are somewhat disturbed are (1) along the flanks of major uplifts, (2) in much of central Montana, and (3) near some of the folds, faults, and flexures present at widely scattered places in the region.

Shales of the Colorado Group are fairly thick and at moderate depths in large areas of the Great Plains. The depth to the top of the Colorado Group is shown in Figure 6-30, inasmuch as the base of the Pierre Shale is equivalent to the top of the Colorado Group (top of Niobrara Formation). Thus it can be seen that the Colorado Group shales are 300 to 900 m below the surface in large areas of the Dakotas and Nebraska and in smaller areas of eastern Colorado and northwestern Kansas. The shales also are at similar depths in much of Montana and in a narrow band on the east side of the Powder River Basin. They are more than 900 m deep in most parts of the Williston, Powder River, and Denver Basins (Figure 6-30).

In that part of North Dakota where the Colorado Group is at moderate depth, the Carlile Shale typically is less than 60 m thick. However, the deeper Belle Fourche Shale locally is as thick as 75 m, and in much of the area, it, together with the underlying Mowry and Skull Creek Shales, forms a nearly unbroken sequence of shale 100 to 150 m thick (Rice, 1977). In most of central and western South Dakota and northwestern Nebraska, the Carlile Shale is 90 to 150 m thick and lies at depths of 300 to 900 m below the surface. The Belle Fourche Shale is commonly 30 to 75 m thick in these same areas, but in western South Dakota and northwestern Nebraska the combined thickness of the Belle Fourche Shale and the underlying Mowry Shale is 120 to 225 m.

Still farther south, in Colorado, Kansas, and eastern Nebraska, the Carlile Shale is typically only 30 to 60 m thick, and the Belle Fourche Shale is normally only 15 to 30 m thick.

In much of southeastern, central, and northwestern Montana, the top of the Colorado Shale and its equivalents are 300 to 900 m below the surface. The Carlile Shale is more than 75 m thick only in the south, where the thickness ranges from 90 to 150 m. The Belle Fourche Shale, on the other hand, when combined with the underlying Mowry Shale, is 130 to 175 m thick in the north and is 200 to 350 m thick across the southern part of the state. In the vicinity of the Sweetgrass Arch, the Marias River Shale is 250 to 325 m thick and ranges from 300 to 900 m below the surface in a fairly large area.

6.4.8.3 Mineralogy and Rock Properties

The Colorado Shale and equivalent units typically are gray to black in color, and beds of bentonite are common in some areas. The shales commonly are fairly soft and not well indurated. Although detailed information on the mineralogy and rock properties of the Colorado Shale are not readily available, it is assumed that these properties are probably somewhat similar to those of the overlying Pierre Shale and equivalent Upper Cretaceous shales, and the reader is referred to that earlier discussion.

6.4.8.4 Hydrology

The Colorado Shale and equivalent shales have low permeabilities, and typically they lack significant quantities of ground water at moderate depths below the surface. Small quantities of water are locally present where the shales are weathered or fractured at and near the outcrop, or where thin sandstone layers are interbedded with the shale.

Aquifers that overlie the Colorado Shale in various areas consist of sandstones, sands, and gravels of Late Cretaceous, Tertiary, and Holocene age. Aquifers that locally underlie the Colorado Shale are sandstones and limestones of Late Cambrian through Early Cretaceous age. Discussion of these aquifers was given in the discussion of the Pierre Shale, and the reader is referred to Section 6.4.6.4 on hydrology for the Pierre Shale and equivalent strata in the Great Plains Region.

6.4.8.5 Mineral Resources

Important mineral deposits in areas underlain by the Colorado Shale are the same as those discussed in Section 6.4.6.5, Mineral Resources, for the Pierre Shale and equivalent Upper Cretaceous shales in the Great Plains region, and the reader is referred to that discussion.

6.4.9 Other Units

6.4.9.1 Sylvan Shale

The Sylvan Shale of Late Ordovician age, and its equivalent, the Maquoketa Formation, is a widespread shale that locally is moderately thick. The term Sylvan generally is used in Oklahoma and parts of Texas, whereas the term "Maquoketa" is used mostly in Kansas, Nebraska, Missouri, and Iowa. To the south, the unit consists typically of calcareous or dolomitic shale, overlain by gray to green shale (Rutledge, 1956; Adkison, 1960). Northward and eastward, the carbonate content of the formation increases, and in Iowa, in the shallow subsurface and on outcrop, the lower part is high in organic content (Howe, 1961; Zeller, 1968; Parker, 1971).

The Sylvan Shale attains thicknesses of more than 75 m at depths considerably greater than 900 m in the Anadarko, Ardmore, and Marietta Basins of southern Oklahoma (Ardmore Geological Society, 1956a, 1956d; Rutledge, 1956; Amsden, 1975; Huffman et al., 1978), but argillaceous rocks in the Sylvan Shale and Maquoketa sequence seldom attain thicknesses of as much as 60 m elsewhere in the Midcontinent region, either at moderate depths or on outcrop. Eastward in Illinois, however, the argillaceous portion of the Maquoketa Formation thickens, and the reader is referred to Section 3.4.2.

6.4.9.2 Paleozoic Shales of Ouachita Geosyncline

Several argillaceous flysch sequences deposited in the Ouachita Geosyncline are thick, but are also structurally complex because of intense deformation, fractures, tight folds, and other features resulting from tectonic stresses associated with the present Ouachita Fold Belt. These argillaceous units include the Womble and Mazarn Shales of Ordovician age, the Stanley Shale or Group of Late Mississippian age, and the Johns Valley Shale and "Atoka" Formation of Early Pennsylvanian age, all in the Ouachita Mountains of Oklahoma and Arkansas; and the Tesnus Shale of Mississippian and Pennsylvanian age in the Marathon Uplift area. Some of these units are several thousand meters thick (Fay et al., 1979; Haley et al., 1979; Kier et al., 1979). Merewether et al. (1973), in a reconnaissance study of thick argillaceous rocks suitable for the underground emplacement of waste, listed the Mazarn, Stanley, and Johns Valley as possible prospects.

6.4.9.3 Otter and Tyler Formations

Carlson and Anderson (1965) and Carlson (1967) recorded variegated shales and mudstones of the Otter Formation of the Big Snowy Group (Upper Mississippian) and overlying Tyler Formation (Mississippian-Pennsylvanian?) attaining combined thicknesses of 75 to 120 m in the subsurface of parts of the Williston Basin of western North Dakota and eastern Montana. Where these units are present, however, they lie at depths considerably greater than 900 m.

6.4.9.4 Spearfish Formation

Red and green mudstone of the Spearfish Formation of Permian age thickens from the Black Hills outcrop area northward into the Williston Basin (Maughan, 1967). Evidence to verify its presence at moderate depths and in thicknesses of at least 75 m could not be found, however.

6.4.9.5 Middle Cambrian Shales

Two shales of Middle Cambrian age are reported to be 50 to 100 m thick in parts of central and western Montana (Lochman-Balk, 1972; Shell Oil Co., 1975). The shales are the Wolsey Shale (below) and the Park Shale (above), and they are separated in the west by the Meagher Limestone. The shales are underlain by and grade laterally into the Cambrian Flathead Sandstone in all parts of Montana. They are overlain by the Pilgrim Limestone and equivalent strata. In most parts of Montana, the Wolsey and Park Shales are 1,000 to 3,000 m below land surface. The shales crop out or are at shallow depth in several of the fold belts or uplifts, and typically they are somewhat disturbed in these complex areas.

6.5 REGIONAL SUMMARY

The Great Plains is a vast region with diverse geology. Thick marine shales were deposited mainly during Late Paleozoic time in the Midcontinent region and nearby parts of the region, and during the Cretaceous Period in the northern part of the Great Plains. These shales are thick and at moderate depths in various parts of the region.

The Great Plains region is part of the stable cratonic interior east of the Rocky Mountains, and it has been generally tectonically stable since Pennsylvanian time. Most earth movements have been broad epeirogenic upwarps or downwarps. Seismic activity is generally low; almost all parts of the region are in seismic-risk zone 1 (minor quake damage can be expected), with the principal exception being the seismic-risk zone 2 area along the Nemaha Uplift in Oklahoma, Kansas, and

Nebraska. Although there are a number of major cities and population centers within the region, most lands in the Great Plains are sparsely populated and are used mainly for agriculture and pasture.

A large number of major ground-water aquifers underlie large parts of the Great Plains, and they are an important water supply for municipal, irrigation, industrial, and domestic purposes. Owing to the sparse rainfall and runoff in most parts of the region, the surface-water supply is somewhat limited.

Petroleum is the major mineral resource that might compete with repository siting in the Great Plains. Large areas in the region are major petroleum provinces, particularly in the Midcontinent and Permian Basin. Oil and/or gas are being produced and actively explored for within and around such important petroleum provinces as the Williston, Powder River, Denver, Anadarko, Arkoma, Ardmore, Fort Worth, Delaware, and Midland Basins. Petroleum exploration and production also are important on and near some of the arches and uplifts, such as the Sweetgrass, Bearpaw, Central Kansas, Nemaha, Las Animas, Wichita-Amarillo, Bend, and Concho positive features.

The Permian Basin, including the Palo Duro and Dalhart Basins on the north, contains several thick shale units, but in most places they are more than 900 m deep and are in areas characterized as major petroleum provinces. The Woodford and Barnett Shales are more than 75 m thick in different areas, but in these areas they are more than 900 m deep; locally the Woodford Shale is thick and at moderate depth, but the unit is complexly folded. Missourian and Virgilian shales are 75 to 300 m thick in the Permian Basin, but generally they are more than 900 m deep; thick Missourian shales are present 400 to 1,200 m below the surface in parts of the Eastern Shelf. Permian shales are more than 75 m thick in parts of the Val Verde Basin in the southeast and along the Eastern Shelf, but typically these shales are more than 900 m deep.

The Fort Worth Basin area of north-central Texas contains several thick Pennsylvanian shales at moderate depths. Shale units in the Atokan, Desmoinesian, Missourian, and Virgilian Series are locally 75 to 600 m thick and occur at depths of 300 to 900 m, chiefly in the northern part of the basin. Oil and gas occur in large quantities in the basin, mainly in the northern part of the basin.

The basins of Oklahoma and Arkansas contain the thickest Paleozoic shale units in the Great Plains Province; these basins are structurally complex in much of the area, and represent sources of present and future oil and gas production. Thick shales are present in the Woodford and Late Mississippian units, along with each of the series of Pennsylvanian and Permian age. In most areas where the Woodford Shale is 75 to 200 m thick, the unit is structurally complex, fractured, cherty, and is either less than 300 m deep or greater than 900 m deep; the areas where the unit is between 300 and 900 m deep are narrow and commonly are structurally complex. Late Mississippian units (the Delaware Creek and Goddard Shales) are 100 to 1,200 m thick, but they are more than 900 m deep in most basins of the area or are shallow and in structurally complex parts of the southern Oklahoma folded belt, where the units typically are fractured and jointed.

Pennsylvanian shales in the basins of Oklahoma and Arkansas include Morrowan units that are 100 to 1,800 m thick, but these shales typically are more than 900 m deep and are present mainly in the southern Oklahoma folded belt. Atokan shales are 90 m to more than 500 m thick in many areas and are at depths of 300 to 900 m locally in the Arkoma Basin of Oklahoma and Arkansas. Desmoinesian shales are 75 to 300 m thick at depths of 300 to 900 m in shelf areas of the Anadarko and Arkoma Basin and locally in other basins of southern Oklahoma. Missourian shale units are 75 to 300 m thick and extend to depths of 100 to 2,000 m from central Oklahoma into the Anadarko Basin; they are up to 910 m thick in parts of the Ardmore and Marietta Basins. Virgilian shales are more than 75 m thick and locally are at moderate depths in central and western Oklahoma, but in most parts of the area the shales are more than 900 m deep. Permian shales in western Oklahoma are 75 to 1,000 m thick and range in depth from about 100 to 900 m, but typically they are interbedded with other rocks such as sandstones, siltstones, and evaporites.

The Salina and Forest City Basins contain several thick shale units at moderate depths. The Chattanooga Shale is 60 to 85 m thick at depths of 600 to 850 m in the western part of the Forest City Basin; although the unit is thicker farther east in Iowa, the Chattanooga Shale is generally less than 300 m deep in this area. Pennsylvanian shales of the Atokan and Desmoinesian Series are more than 75 m thick and are at depths of 300 to 900 m in parts of both basins. Shales in the Virgilian Series also are as thick as 350 m in the Forest City Basin, but the shales typically are less than 300 m deep. Petroleum is being produced from the southern and western parts of both the Salina and Forest City Basins.

Central and western Kansas contains a number of scattered small areas where Desmoinesian, Missourian, and Virgilian shales are more than 75 m thick and at depths of 300 to 900 m. Thick Permian shale units are more widespread and at depths of 300 to 900 m in central and western Kansas, and these units also extend into parts of southeastern Colorado. Oil and gas production is widespread and important in central and western Kansas and is sporadic in southeastern Colorado.

The Pierre Shale and other argillaceous units of Cretaceous age are of major thick shales in the northern part of the Great Plains. The region underlain by Cretaceous shales is characterized by simple structure with little deformation: faults, flexures, and folds are widely scattered, and there are vast areas that are undisturbed. The Pierre Shale is 100 to 1,800 m thick in the northern Great Plains, and the formation typically is 100 to 750 m thick and 300 to 900 m below the land surface in most areas of the region. Such areas embrace substantial parts of the western halves of Nebraska, South Dakota, and North Dakota, along with parts of northeastern Colorado, southeastern Wyoming, and large parts of Montana.

Other Cretaceous shales are also thick and at moderate depths in parts of the central and northern Great Plains. Lower Cretaceous shales (Skull Creek, Kiowa, and Mowry Shales) are fairly thick and moderately deep in northwestern Kansas, western Nebraska, northwestern South Dakota, central North Dakota, and scattered areas of Montana. The Upper Cretaceous Colorado Shale (locally termed the Belle Fourche, Carlile, and Marias River Shales) are fairly thick and moderately deep in northwestern Nebraska, central and western South Dakota, central North Dakota, and much of Montana.

The Pierre Shale and other Cretaceous shales typically have mixed-layer illite-montmorillonite and montmorillonite as the dominant clay minerals, and they contain interbeds of volcanic ash and bentonite. The Upper Cretaceous shales also contain some interbeds of sandstone, mainly to the west. These interbeds disrupt the homogeneity of the thick shales. Other discontinuities include joints and fractures, mainly in the weathered zone at and near the outcrop.

Ground water is present locally in sandstone interbeds and in weathered zones of the Pierre Shale and other Cretaceous shales, but the water is present typically only at and near the land surface and not where the shale is at moderate depths. Other aquifers are present in overlying Tertiary, Pleistocene, and Holocene sediments, and also in underlying units of Late Cambrian through Cretaceous age.

Excavation of the Pierre Shale can lead to swelling and deterioration of the shale if the rock is not protected from alternate drying and wetting cycles. Both instantaneous and long-term rebound occur as a result of excavation, but the expansion or rebound of unweathered shale can be minimized by maintaining a high humidity in an underground opening. Experience has shown that tunnel-boring machines would be effective in underground mining in the Pierre Shale.

The Pierre Shale and other Cretaceous shales are relatively free of mineral resources suitable for development. Major petroleum provinces in the region include the Denver, Powder River, and Williston Basins, along with parts of northwestern Kansas and southwestern Nebraska, and the Bowdoin, Bearpaw, Sweetgrass, and Central Montana Uplifts of Montana. Petroleum is being produced chiefly from rock units within or below the Cretaceous System, although locally there is production from overlying Upper Cretaceous and Tertiary sands. There are areas with numerous boreholes. Coal seams stratigraphically above and below the Pierre Shale and other Cretaceous shales are important resources that have been, or may be, strip mined locally. Sand and gravel, stone, bentonite, and other minerals also have been, or may be, strip-mined locally in areas underlain by thick Cretaceous shales.

7. ROCKY MOUNTAINS

7.1 STRUCTURE AND GEOLOGIC FRAMEWORK

The Rocky Mountain Province consists of a series of mountain ranges and sedimentary basins that extend southward from the Canadian border across parts of Idaho, Montana, Wyoming, Utah, Colorado, and northern New Mexico (see Figure 2-2). The province is bounded on the east by the Great Plains and on the west by the Colorado Plateau, the Basin and Range Province, and the Columbia Plateaus. Many workers divide the United States portion of the Rockies into three subprovinces: Northern Rocky Mountains, Middle Rocky Mountains (including the Wyoming Basins), and Southern Rocky Mountains; this subdivision is followed generally in this discussion.

The region was characterized by both marine and continental sedimentation during long periods of Paleozoic and Mesozoic time, and nonmarine-basin filling during the Tertiary Period. Early episodes of orogenic uplift occurred during the Pennsylvanian and Permian Periods in the Ancestral Rocky Mountains, chiefly in Colorado and parts of adjacent states. The main period of mountain building occurred during the Late Cretaceous-Early Tertiary Laramide orogeny, when many parts of the province were the sites of sharp uplift, compressive folds and faults, igneous intrusion, and volcanism. Among the more comprehensive discussions of the Rocky Mountain Province are those by Eardley (1962), Haun and Kent (1965), and King (1977), and the Geologic Atlas of the Rocky Mountain Region by Mallory et al. (1972).

Some of the mountain ranges in the Rocky Mountain system reach elevations greater than 4,000 m, and many of the mountain peaks are more than 2,000 m above the nearby basins and plains areas. The mountain ranges typically contain a core of Precambrian igneous or metamorphic rocks exposed by erosion of overlying Paleozoic and Mesozoic strata.

A number of sedimentary and structural basins are present between the mountain ranges in the province, particularly in Wyoming (Figure 7-1). The basins have been somewhat passive in their history, inasmuch as they

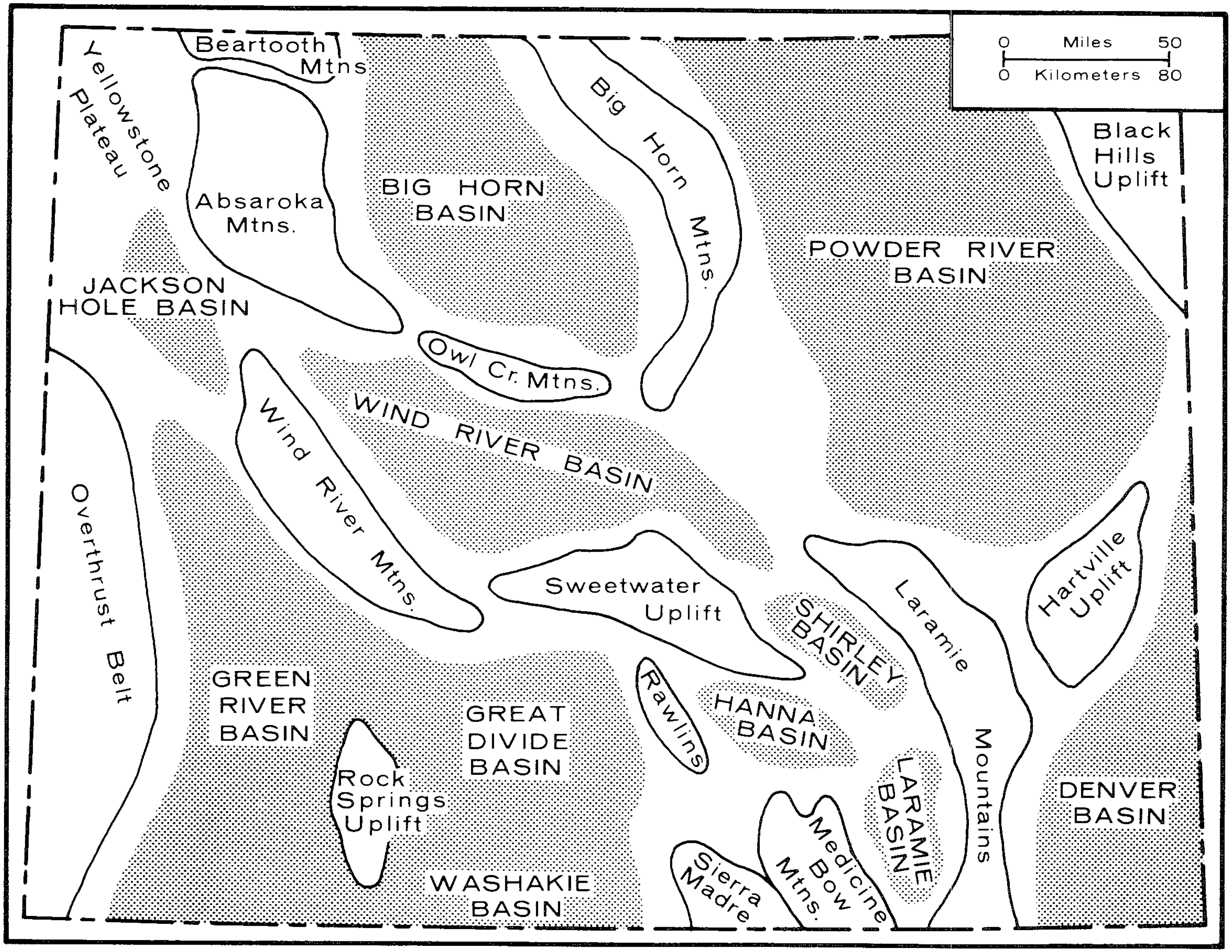

FIGURE 7-1. MAP OF WYOMING SHOWING MAJOR BASINS AND UPLIFTS IN CENTRAL PART OF ROCKY MOUNTAIN PROVINCE (MODIFIED FROM GLASS ET AL., 1975)

remained relatively stable while the nearby mountain ranges were being uplifted. Principal basins include, starting in the north, the Big Horn, Wind River, Green River (sometimes divided into the Green River in the west and the Great Divide or Red Desert, Washakie, and Sand Wash in the east), Laramie, North Park, South Park, and San Luis Basins. The central parts of these basins normally contain as much as 3,000 to 10,000 m of sedimentary rocks. Strata generally are little deformed in the central parts of the basins, where the dip normally is 1° to 5°, but near the margins of the basins the rocks commonly are folded and faulted.

Cambrian through Mississippian strata in most parts of the Rocky Mountain Region consist mainly of marine carbonates, sandstones, and shales. Tectonic activity in the Ancestral Rockies interrupted the widespread shallow seas during Pennsylvanian and Permian time. These uplifted blocks supplied coarse clastic sediments to nearby basins, while, farther from land, sandstones, shales, evaporites, and carbonates were deposited. Parts of the Ancestral Rockies persisted as land areas into Triassic and Jurassic time, and continental deposits accumulated in most of the province during these periods.

During Early Cretaceous time, seas again invaded the Rocky Mountain region, creating a great seaway that also extended eastward across most of the Great Plains. Thick marine shales, deposited across much of the region during the remainder of Cretaceous time, intertongue with nonmarine sandstones derived mainly from rising land masses in the west. The total thickness of Cretaceous strata in the region typically ranges from about 2,000 m in some of the eastern areas to 6,000 m in southwestern Wyoming.

The Laramide orogeny began in latest Cretaceous time and lasted until the end of the Eocene. By a series of orogenic pulses, each in a more easterly position than the last, the entire region was raised above sea level, forcing the sea to retreat. During the Laramide orogeny, there developed a series of mountain ranges and basins, caused in part by vertical movements and in part by thrusting and lateral movements. Thrust faulting was dominant in the western area.

The sedimentary basins of the Rocky Mountain Region became isolated during the Tertiary Period. The basins received thick accumulations of

Paleocene and Eocene continental sediments, including some significant deposits of lacustrine shale.

Late Cretaceous and Tertiary igneous activity, including both intrusive and extrusive events, was widespread in the Rockies but was more concentrated in the Northern and Southern Rocky Mountain subprovinces. Normal faulting, regional uplift, mountain glaciation, and development of the modern drainage system characterize the Late Tertiary and Holocene history of the region.

7.2 REGIONAL SEISMICITY

Recorded seismic activity in the region ranges from high in the Northern Rocky Mountains to fairly low in the Central and Southern Rocky Mountains. Principal reports dealing with earthquake activity in the Rocky Mountains are those of Simon (1972) and Coffman and von Hake (1973). About 200 earthquakes of Modified Mercalli Intensity V (MMI V) or greater have been recorded in the Northern Rockies through 1970 (Figure 1-2), with the most intense being the Hebgen Lake event (MMI X) in southwestern Montana in 1959. Earthquakes in the Northern Rockies occur mainly in the Overthrust Belt, a complex system of thrust faults extending through parts of Montana, Idaho, Wyoming, and Utah. Most parts of the Northern Rockies are in seismic-risk zones 2 and 3 (see Figure 1-3a).

Seismic events in the Central and Southern Rocky Mountain subprovinces through 1970 number only about 12 (see Figure 1-2), with all of these earthquakes being of MMI V to MMI VII intensity. All parts of the Central and Southern Rockies are considered to be in seismic-risk zone 1, according to Algermissen (see Figure 1-3a). On the other hand, Simon (1972) indicated that parts of central and north-central Colorado and southeastern Wyoming are "regions of greater seismicity," where the frequency of earthquakes is greater than in surrounding areas.

7.3 REGIONAL HYDROLOGY

7.3.1 Surface Water

Surface drainage in the Rocky Mountain Province is characterized by small, fast-moving, clear streams in the mountainous headwaters, and larger streams in some of the broad basins and plains areas where the streams leave the province. The Continental Divide, which separates drainage systems flowing to the Atlantic and Pacific Oceans, extends in a north-northwesterly direction through the Rocky Mountain Province. Major river systems that have their headwaters in the Rocky Mountains include (clockwise from the north) the Missouri, Yellowstone, Platte, Arkansas, Canadian, Pecos, Rio Grande, Colorado, Green, Snake, and Columbia Rivers. The first seven rivers flow into the Mississippi or directly into the Gulf of Mexico; the last four flow southwestward or westward and empty into the Pacific Ocean. Most of the surface flow in these river systems results from melting of snow in the spring and from seasonally high rainfall.

Average annual precipitation ranges from 50 cm to more than 100 cm in most of the mountain ranges in the province, but precipitation is typically only 15 to 50 cm per year at lower elevations in the major sedimentary basins and plains. Air carrying moisture from the Pacific Ocean drops most of its water as it crosses the high mountain ranges of the Rockies.

Streams in the Rocky Mountains contain fresh water that is suitable for most purposes, and current development of the region's water resources has been limited almost entirely to surface water (Price and Arnow, 1974; Taylor, 1978). Surface water in most areas has a dissolved-solids concentration of less than 1,000 mg/l, although the concentration is between 1,000 and 3,000 mg/l in a large part of the Green River Basin of southwestern Wyoming.

7.3.2 Ground Water

The Rocky Mountain Region contains large supplies of ground water, mainly in the sedimentary and structural basins of the region. Sedimentary rocks of Cretaceous, Tertiary, and Quaternary age are the major aquifers, but other aquifers of local importance are in the Ordovician, Mississippian, Pennsylvanian, Permian, and Jurassic Systems. Regional appraisals of ground-water resources have been made by Welder and McGreevy (1966), Whitcomb and Lowry (1968), U.S. Geological Survey (1968b, 1969b), Welder (1968), Lohman and Petersen (1972), Lowry et al. (1973, 1975), Price and Arnow (1974), and Taylor (1978).

In most parts of the Rocky Mountain region, ground-water yields are less than 200 l/min, but in some of the basins local yields are between 200 and 2,000 l/min. The quality of ground water is typically less than 1,000 mg/l dissolved solids, although in some areas, such as the Green River Basin, the quality ranges from 1,000 to more than 3,000 mg/l dissolved solids.

Most of the important aquifers in the Rocky Mountain Region are sandstones, sands, and gravels deposited in the various sedimentary basins. The units were deposited in both marine and nonmarine environments, and now they are preserved in the intermontane basins developed in Late Cretaceous-Early Tertiary time. Recharge is through the upturned edges of the aquifers along adjacent uplifts, or through downward percolation from precipitation or streamflow within the basin areas.

More than 25 separate aquifers have been identified in Wyoming alone (Price and Arnow, 1974; Taylor, 1978). These aquifers are mainly of Cretaceous and Tertiary age, but they range in age from Ordovician through Quaternary. Depth to the aquifers is less than 30 m in some parts of the region, but in many areas the depth is from 30 m to more than 150 m below the land surface.

Alluvium and terrace deposits along present-day and earlier streams contain large quantities of water that generally is of high quality and at shallow depth. Yields of more than 2,000 l/min have been obtained in some wells, and in most areas the water table is within 15 m of the land surface.

7.4 SHALES AND ARGILLACEOUS UNITS

7.4.1 Introduction

A number of shales and argillites are more than 75 m thick in various parts of the Rocky Mountain Region. Some area are structurally complex and the depth to the shales is great in other areas.

Among the thick argillites in the region are the Milligen Formation and Copper Basin Group of Devonian-Mississippian-Pennsylvanian age in Idaho. Individual argillite units are 60 to 200 m thick and are exposed in the fault-block mountain ranges of south-central Idaho.

Marine shales of Early and Late Cretaceous age extend across most parts of Wyoming and adjacent areas. These shales are in large part a westward extension of equivalent shales that are so widespread in the Great Plains Province. Lower Cretaceous shales include the Thermopolis, Shell Creek, and Mowry Shales, whereas the Upper Cretaceous shales are in the Frontier, Cody (Steele), and Lewis Formations. Most of these units reach a maximum thickness of only 100 to 200 m, but the Cody or equivalent units are typically 600 to 1,200 m thick in Wyoming and nearby areas.

Thick Tertiary shales include the Waltman Shale Member of the Fort Union Formation in the Wind River Basin and the Green River shales in the Green River and Washakie Basins. The Waltman Shale is locally as thick as 900 m, whereas the Green River Formation is typically 500 to 1,000 m thick.

7.4.2 Milligen Formation and Copper Basin Group

7.4.2.1 Stratigraphy

The Milligen Formation and Copper Basin Group make up a thick sequence of Devonian-Mississippian-Pennsylvanian strata exposed in several mountain ranges of south-central Idaho (Figure 7-2). These strata are approximately 6,500 m thick and contain several thick units of argillite in the region.

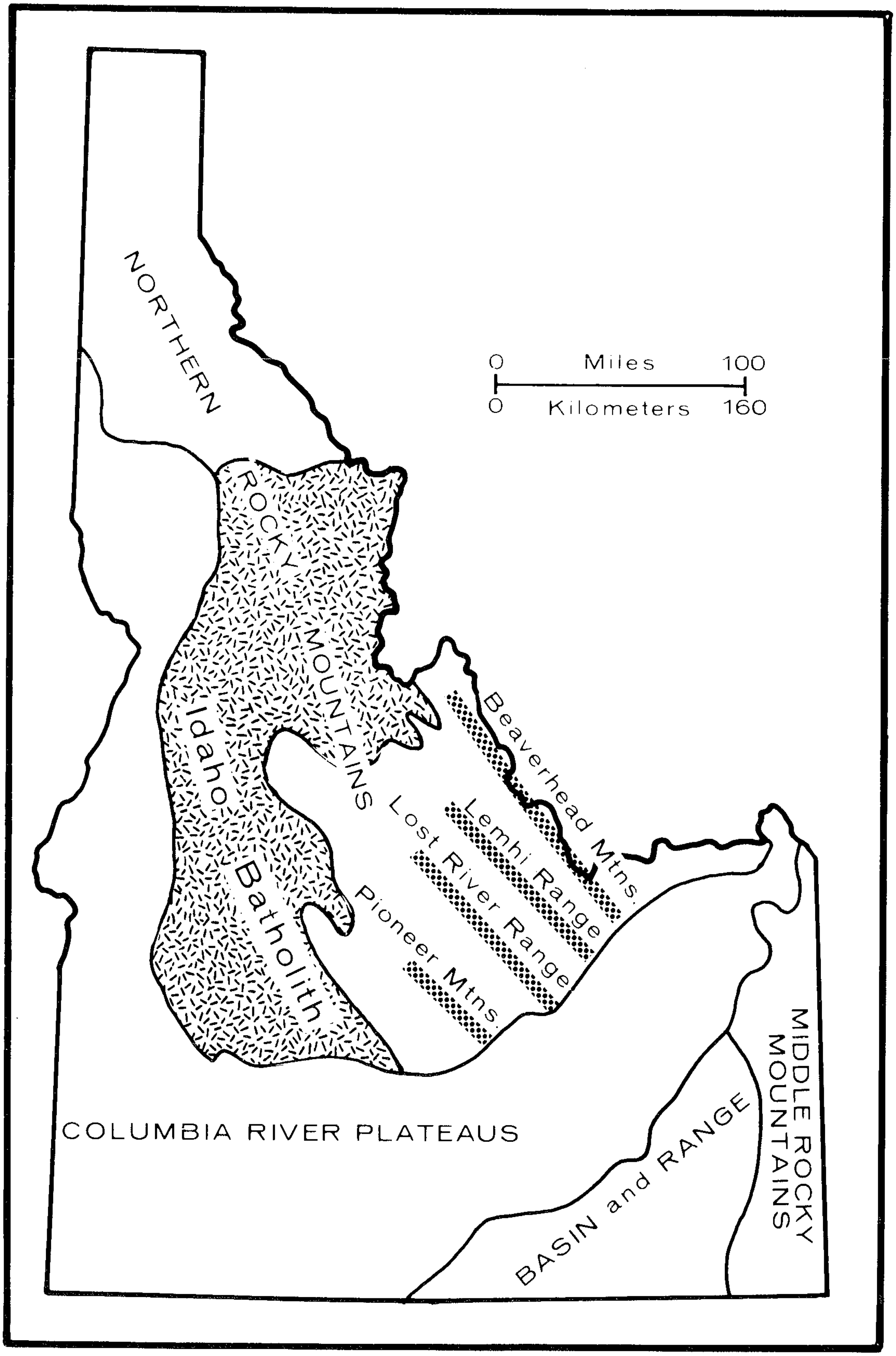

FIGURE 7-2. MAP OF MAJOR PHYSIOGRAPHIC AND GEOLOGIC PROVINCES OF IDAHO, SHOWING FOUR PRINCIPAL MOUNTAIN RANGES IN NORTHERN ROCKY MOUNTAINS THAT CONTAIN OUTCROPS OF MILLIGEN FORMATION AND COPPER BASIN GROUP

The Milligen Formation was originally named by Umpleby et al. (1930), and the term was applied to a thick sequence of predominantly dark-gray to black carbonaceous argillite exposed at Milligen Creek in Blaine County, Idaho. The thickness of the formation is assumed to be approximately 1,000 m, and the age of the unit is considered to range from Middle(?) Devonian to Early(?) Mississippian. The name Milligen was later extended into central Idaho (Ross, 1934) and eventually was applied broadly to similar-aged rocks in the several mountain ranges between the Snake River Plain, the Idaho Batholith, and the Beaverhead Mountains (Figure 7-2). General discussions of the Milligen Formation are found in the work by Ross (1937, 1947, 1961), Paull et al. (1972), and Paull and Gruber (1977).

The Copper Basin Formation of Ross (1962b) was raised to group rank by Paull et al. (1972). This was supported in later work by Paull and Gruber (1977) but was not adopted in the reports by Skipp et al. (1979) and Roberts (1979). The Copper Basin Group consists of about 5,500 m of Lower(?) Mississippian to Lower(?) Pennsylvanian strata, according to Paull et al. (1972), but Skipp et al. (1979) contend that this includes a duplicating thrust fault and that the true thickness is perhaps more like 4,000 m.

Paull and Gruber (1977) divided the Copper Basin Group into six separate formations (Figure 7-3). General lithologies of the group include, in ascending order: (1) 1,100 m of dark argillite with interbeds of quartzite and conglomerate; (2) 800 m of limestone with interbeds of argillite and sand stone; (3) 1,100 m of conglomerate and quartzite; (4) 1,265 m of dark-gray argillite with small amounts of quartzite, conglomerate, and limestone; (5) 650 m of conglomerate and quartzite; and (6) 460+ m of dark-gray argillite and shale with few interbeds of conglomerate and quartzite (Paull et al., 1972). Thus, more than half of the Copper Basin Group at the type section in the Pioneer Mountains is argillite, with small amounts of interbedded quartzite and conglomerate. Principal recent studies of this group include those by Ross (1962a, 1962b), Dover (1969), Paull et al. (1972), Paull and Gruber (1977), Nilsen (1977), Skipp et al. (1979), and Roberts (1979).

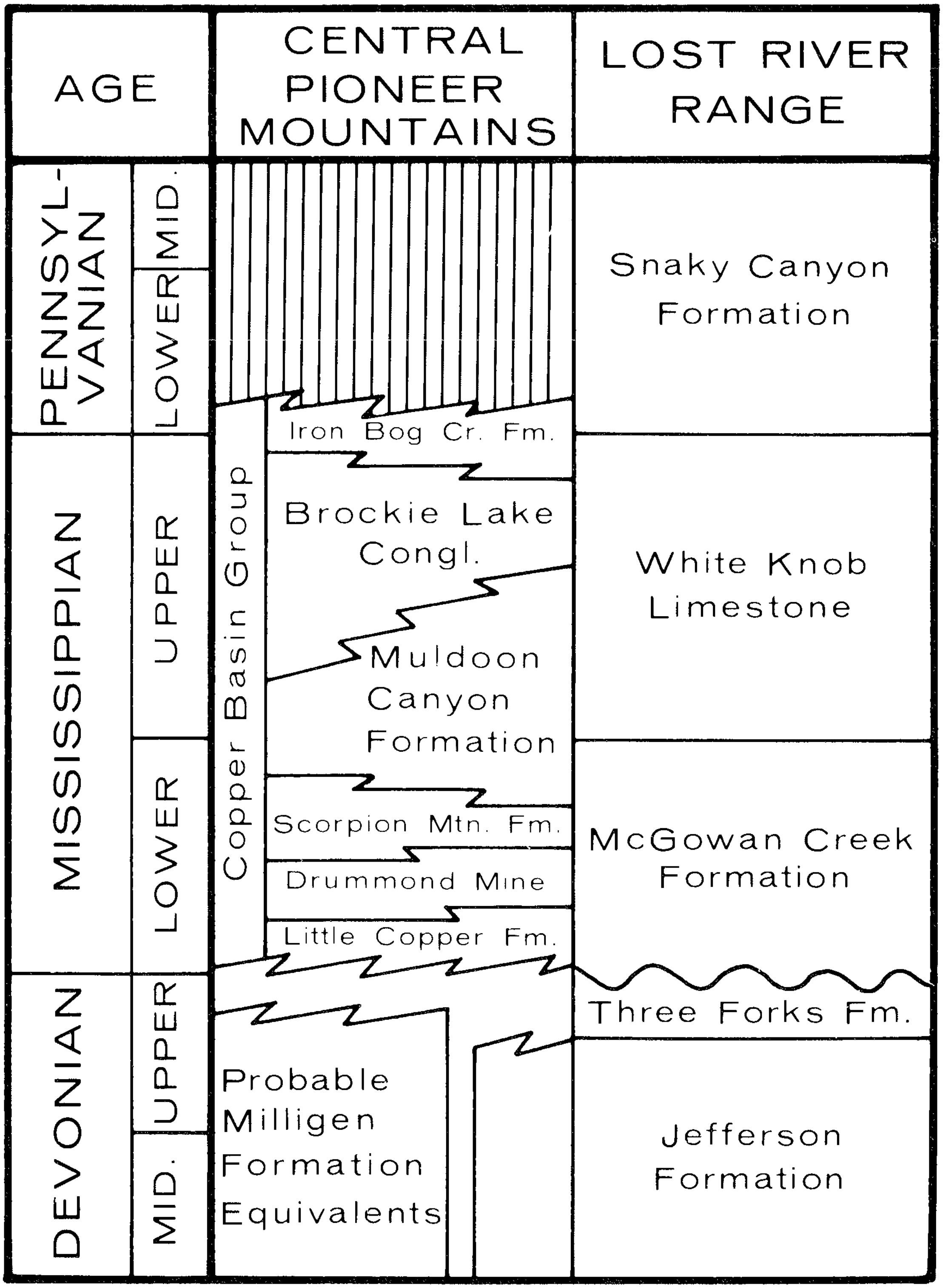

FIGURE 7-3. CHART SHOWING GENERALIZED STRATIGRAPHIC NOMENCLATURE FOR DEVONIAN-MISSISSIPPIAN-PENNSYLVANIAN OF SOUTH-CENTRAL IDAHO (MODIFIED FROM PAULL AND GRUBER, 1977)

Two formations contain the principal argillites in the Copper Basin Group (Paull et al., 1972). The Little Copper Formation at the base is a thick sequence of argillite that overlies and apparently has a gradational contact with the underlying Milligen Formation. In the middle of the Copper Basin Group is the Muldoon Canyon Formation, a unit consisting of at least 900 m of predominantly argillite strata.

7.4.2.2 Geologic Setting

The Milligen Formation and Copper Basin Group are fairly widespread stratigraphic units deposited over much of south-central Idaho. Substantial thicknesses of both units are dark-colored thin to thick-bedded argillites. Individual argillite units are 60 to 200 m thick in outcrops (Paull et al., 1972), and some thicker units contain only a few interbeds of quartzite or conglomerate. Data on depth, thickness, and distribution of these argillites come almost entirely from outcrops, inasmuch as few boreholes have been drilled through the Devonian-Mississippian-Pennsylvanian strata in the area.

Based upon regional studies, however, it is known that these strata crop out and are in shallow subsurface mainly in a series of fault-bounded mountain ranges north of the Snake River Plain. The rocks making up these mountain ranges are typically folded and faulted. Folds are, in general, closely spaced and have northwest trends, and many of them are overturned toward the northeast. Some of the deformation is due to Paleozoic disturbances, but the major episodes of deformation were during the Jurassic and Cretaceous Periods. Intrusive igneous rocks in the area include the Idaho Batholith of Late Cretaceous age, and a series of small stocks of Tertiary age to the east of the Idaho Batholith. The Challis volcanics of Tertiary age are widespread andesitic flows and tuffs that were deposited in and around the mountain ranges containing shales of the Milligen Formation and Copper Basin Group. Studies dealing with major structural features in the area include those of Ross (1934, 1937, 1947, 1961), Ross et al. (1964), Skipp et al. (1979), and Roberts (1979). The same Paleozoic strata also extend south of the Snake River Plain where they are thinner, and are exposed in a series of complex mountain ranges in southeastern Idaho.

Seismic activity in the Idaho portion of the Rocky Mountains is high. The eastern half of Idaho, including the area with Paleozoic argillites, is in seismic-risk zone 3 (expected major damage) (see Figure 1-3). Among the highest intensity earthquakes in Idaho are MMI VII events that occurred near Shoshone (1905), at Boise City (1916), and near Seafoam (1944). Earthquakes of MMI VI intensity occurred near Sand Point (1942), near Clayton (1945), near Wallace (1957), in southeastern Idaho (1960), in central Idaho (1963), and near Ketchum (1969).

7.4.2.3 Mineralogy and Rock Properties

The Milligen Formation consists mainly of dark-gray, thin- to thick-bedded argillite, with few interbeds of quartzite and conglomerate (Paull et al., 1972). Quartzite is present sporadically throughout, but conglomerate is present only in the middle or upper part of the formation. Locally, calcareous sandstone and argillaceous limestone are interbedded with argillite in a 120-m-thick interval, about 610 m below the top of the formation.

Argillites of the Milligen Formation are dark gray to medium light gray and consist of about 50 percent clay-size matrix of illite and some chlorite, and about 50 percent silt-size and sand-size quartz, chert, and siliceous rock fragments (Paull et al., 1972). Minor amounts of carbonaceous material and pyrite also are present. Ross (1962a) reported that in a few places, beds of "graphitic anthracite" have been prospected but that the "coal" is so graphitic that it cannot be burned as a fuel. Underground mining in the Milligen Formation has been hampered by relatively abundant gas (Ross, 1962a).

The argillite generally is well bedded, but locally jointing and blocky weathering obscure bedding. Bedding thickness ranges from 3 to 150 cm but generally is 15 to 30 cm. The interbedded quartzite is dark gray to dark yellowish-brown and weathers moderate brown to medium dark gray. Most quartzite beds are 30 cm to 150 cm thick.

In most respects, argillites of the Copper Basin Group are similar to those described above for the Milligen Formation (Paull et al., 1972). Visible laminae of angular to subrounded, silt-size quartz and chert are common, however, and all gradations from almost pure mudstone to laminated siltstone are present.

7.4.2.4 Hydrology

The principal sources of ground water in south-central Idaho are the intermontane valleys (Kinnison, 1955; Travis et al., 1964). These valleys contain deposits of alluvial sand and gravel and glacial outwash 15 to 90 m thick. In addition, basalts and tuff deposits in the valleys and in the mountain ranges are highly porous and permeable, and they also are good aquifers. The Paleozoic rocks that make up most of the mountain ranges in south-central Idaho are generally poor aquifers, and thus these units are little studied, and few data are available on the hydrogeology of the argillites or interbedded strata.

7.4.2.5 Mineral Resources

The mountains of south-central Idaho have had a long history of mining activity since 1860, and mining districts are scattered throughout the area. The principal metals mined include gold, silver, copper, lead, zinc, molybdenum, antimony, and mercury. Ores occur as replacement deposits in Paleozoic rocks, lodes within the granitic intrusive rocks, and lodes associated with the Challis volcanics. Pleistocene sand and gravel and older Tertiary alluvial deposits are sources of some of the placer gold mined in this region. Ross (1963a) provided a summary of the mining history of south-central Idaho.

A number of thermal springs, with temperatures that range from 38 to 74°C, occur in central Idaho. Thermal springs flow from rocks as old as Precambrian and as young as Quaternary age. A number of springs are associated with Tertiary faulting and with igneous activity (Ross, 1971).

Commercial quantities of oil or natural gas have not yet been produced in south-central Idaho, although parts of southwestern Idaho and southeastern Idaho have been explored for hydrocarbons (Savage, 1964).

7.4.3 Mowry Shale and Other Lower Cretaceous Shales

7.4.3.1 Stratigraphy

Lower Cretaceous strata in the Rocky Mountains are characterized by a lower sequence of continental sandstones and shales and an upper sequence of marine shales and sandstones. The marine shales include, in ascending order, the Thermopolis, Shell Creek, and Mowry Shales (Figure 7-4), with these units being widespread in most of the Wyoming basins and nearby areas. The shales are stratigraphically just below the Colorado Group, and thus their general distribution is approximately shown on the map of the Colorado and Montana Groups in the Rocky Mountains (see Figure 6-21). The total thickness of the shale-bearing strata in the Lower Cretaceous ranges from 150 to 1,200 m in various parts of the region (Haun and Kent, 1965). Principal references to these shales in the region include Wyoming Geological Association (1956), Reeside and Cobban (1960), Curry (1962), Eicher (1962), Moberly (1962), Weimer (1962), Young (1970), McGookey et al. (1972), and Berman et al. (1980).

Continental sediments at the base of the Cretaceous strata are referred to as the Cloverly Group in most parts of Wyoming (McGookey et al., 1972). These interbedded sandstones and shales were deposited over an extensive lowland region bordered on the east by the low-lying craton of the central United States and on the west by the Mesocordilleran geanticline highland (MacKenzie and Ryan, 1962). At the top of this sequence is the Fall River Sandstone and equivalent strata, normally about 15 m thick, laid down as deltaic, tidal-flat, and shallow-marine deposits in a transgressive sea invading from the north.

The Thermopolis Shale, the oldest of the marine Cretaceous shales in the region, is typically 30 to 70 m thick in the Rocky Mountains. The unit is equivalent to the Skull Creek Shale in the Great Plains. The

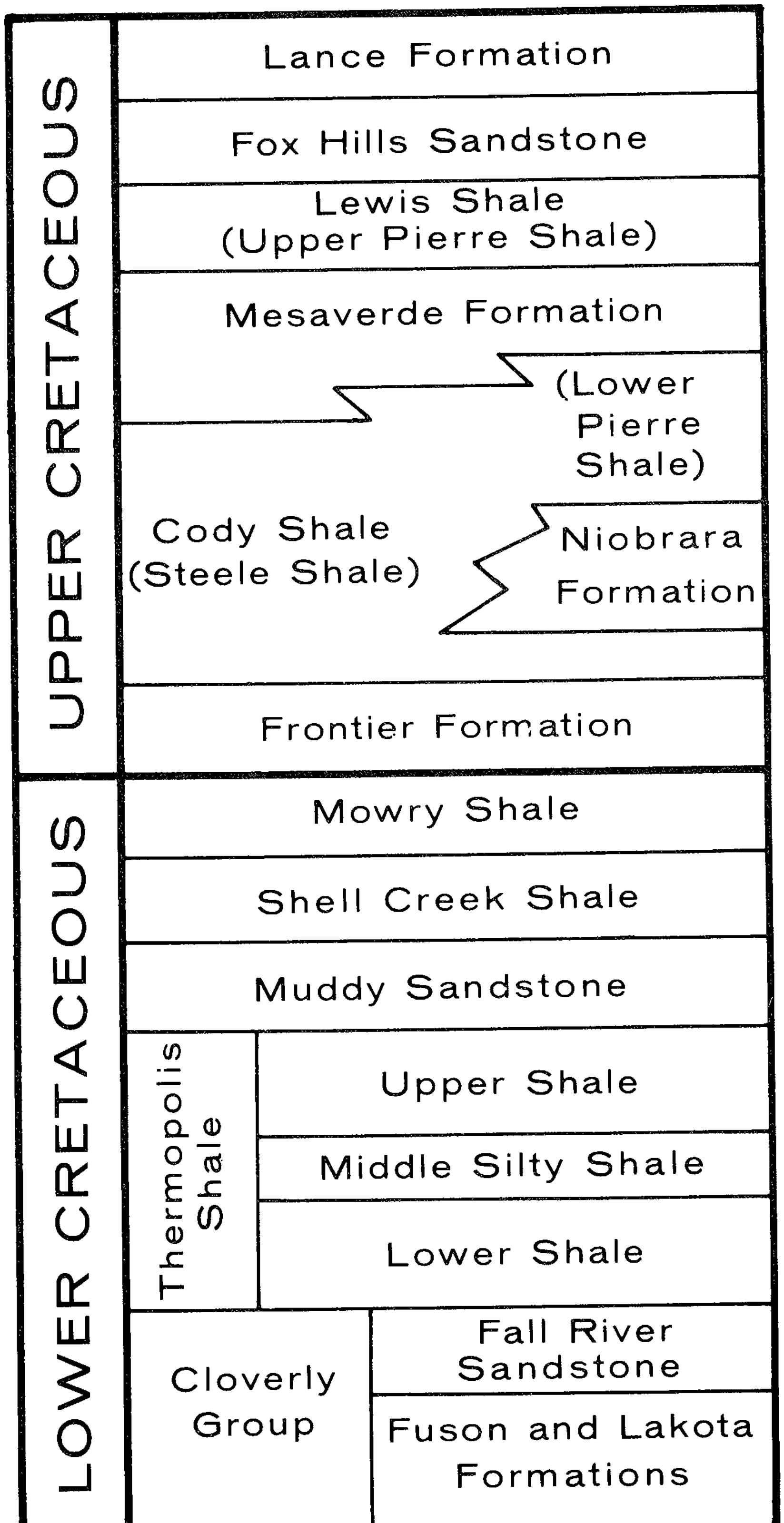

FIGURE 7-4. CHART SHOWING GENERALIZED STRATIGRAPHIC NOMENCLATURE FOR CRETACEOUS STRATA IN WYOMING BASINS AND NEARBY AREAS OF ROCKY MOUNTAINS (MODIFIED AFTER MCGOOKEY ET AL., 1972). VERTICAL DIMENSIONS ARE UNRELATED TO THICKNESS OF FORMATIONS

shale overlies the Fall River Sandstone or the equivalent Rusty Beds that had once been considered a part of the Thermopolis Shale. The shale is commonly divided into a lower and upper shale, separated by a middle silty shale (Eicher, 1962; McGookey et al., 1972). Shales are typically fissile, black to gray, and slightly silty. They locally contain thin beds of limestone, ironstone, and sandstone, and they also contain a few beds of bentonite and concretions of dahllite, a resinous, yellowish-white carbonate-apatite mineral.

Above the black shales of the Thermopolis Shale is the Muddy Sandstone, a highly variable unit consisting of siltstone, sandstone, shale, bentonite, lignite, and chert-pebble conglomerate. The Muddy Sandstone ranges up to 30 m thick, but in most areas it is 10 to 15 m thick.

Overlying the Muddy Sandstone in the Big Horn Basin and nearby areas is a dark-gray to black shale referred to by Eicher (1962) as the Shell Creek Shale. The unit contains a few ironstone beds and concretions and a few prominent bentonite beds up to 3 m thick. The total thickness of the formation ranges from about 60 to 100 m in most parts of the Big Horn Basin, but the unit thins southeastward across Wyoming and pinches out in the southern part of the state.

The youngest and thickest of the Lower Cretaceous shales is the Mowry Shale. The unit overlies the Shell Creek Shale in much of Wyoming and southern Montana, but it rests upon the Muddy Sandstone and equivalent strata in southern Wyoming and nearby parts of Colorado. The Mowry Shale is equivalent to the Aspen Shale of north-central Utah (McGookey et al., 1972). Shales of the Mowry are extremely hard and weather to silver-gray ridges because they are composed of a high proportion of silica. The shale contains appreciable amounts of organic matter and numerous interbeds of bentonite. The top of the Mowry Shale is the base of the regionally persistent Clay Spur Bentonite. The thickness of the Mowry Shale is typically about 30 to 45 m in the eastern part of Wyoming, but the thickness increases westward across the state and is typically 75 to 120 m in the Big Horn and Wind River Basins.

7.4.3.2 Geologic Setting

Although several Lower Cretaceous shales are moderately thick in the Big Horn and Wind River Basins of the Middle Rocky Mountains, the region typically is fairly complex in areas where these shales are at moderate depths. The areas that are structurally simple are generally in the central parts of the major basins, where the shales are at great depth (Figure 7-5). The geologic structure of Lower Cretaceous strata is most complex within and adjacent to the principal uplifts and mountain ranges, because the major episodes of uplift were along these tectonic boundaries after deposition of the shales (Lumb et al., 1972).

In the Big Horn Basin of northwestern Wyoming and adjacent Montana, the Shell Creek and the Mowry Shales are the only Lower Cretaceous shales that are at least 75 m thick. The Shell Creek Shale typically ranges in thickness from 60 to 100 m (Eicher, 1962), whereas the Mowry Shale has a fairly constant thickness of about 110 m (Wyoming Geological Association, 1956). Together, the Shell Creek and overlying Mowry Shales are typically 150 to 200 m thick in most parts of the basin. Along the flanks of the Big Horn Basin, the Shell Creek and Mowry Shales are at shallow to moderate depths, but in most parts of the basin the units are 1,000 to 6,000 m below the land surface (Figure 7-5). Structures in the basin include not only simple folds, faulted folds, and domes, but also low-angle thrusts, steep monoclines, reverse faults, and some major lineaments.

In the Wind River Basin, the Mowry and Shell Creek Shales together range from about 150 to 180 m in the west to about 75 m in the east (Wyoming Geological Association, 1956). The shales are at shallow to moderate depths mainly along the southwestern flank of the basin, where the structure is generally more complex, and are at depths as great as 7,500 m along the northeast side of the basin (Figure 7-5).

7.4.3.3 Mineralogy and Rock Properties

Shales of the Lower Cretaceous Period commonly are fairly soft and not particularly indurated, although the siliceous nature of the Mowry

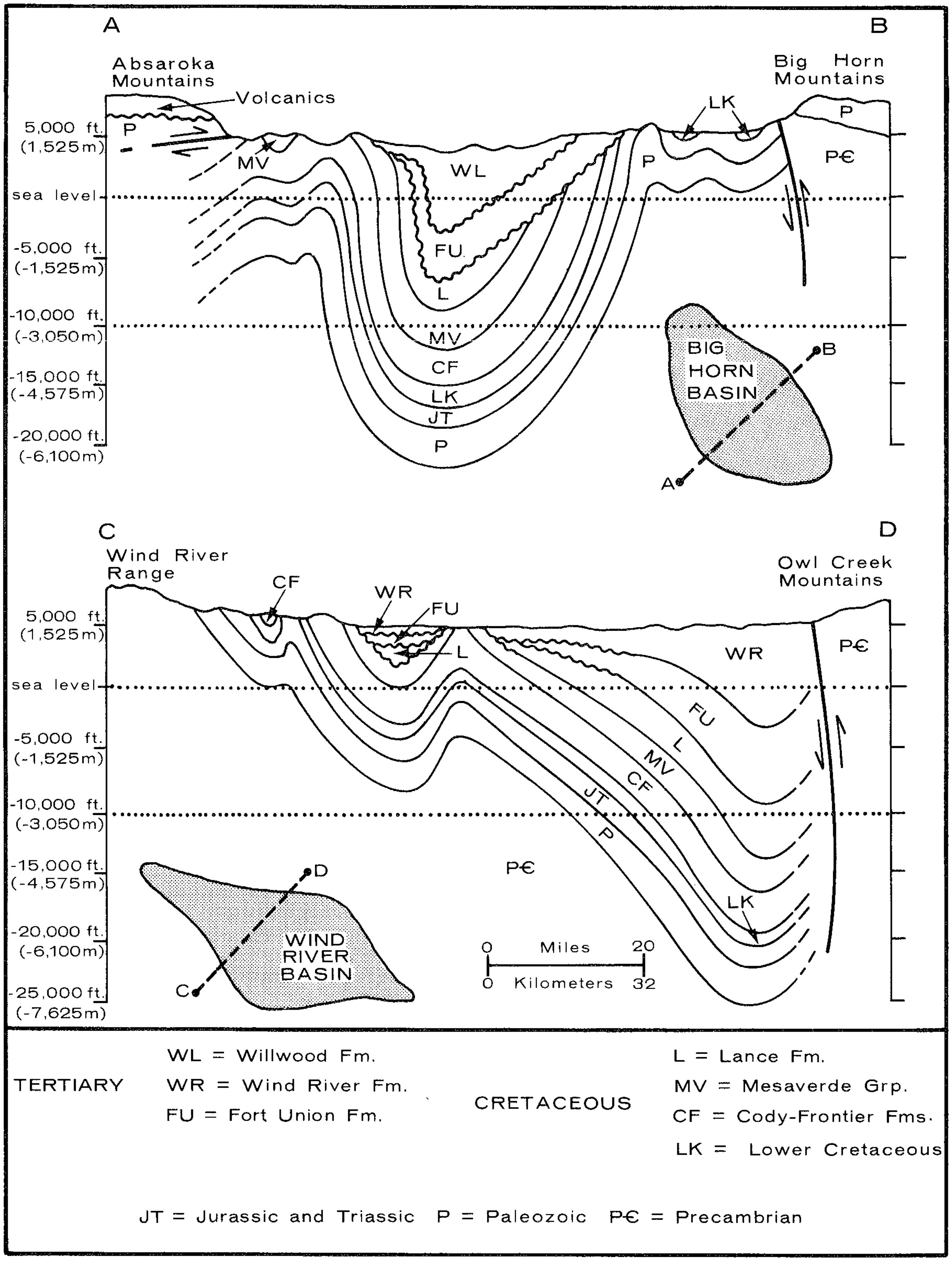

FIGURE 7-5. DIAGRAMMATIC CROSS SECTIONS THROUGH BIG HORN BASIN (SECTION A-B) AND WIND RIVER BASIN (SECTION C-D) OF WYOMING (MODIFIED FROM STAUFFER, 1971)

Shale generally makes it a more resistant and hard rock unit. Bentonite beds are present in parts of all these shales, and in some areas the bentonite makes up a significant part of the shales, particularly the Mowry Shale (Slaughter and Earley, 1965).

The Mowry Shale contains an average of 50 percent quartz, 5 percent feldspar, and 2 percent organic carbon; the remainder consists of clay minerals and minor zeolites (Davis, 1970). Mixed-layer clays are predominant in the Mowry Shale, although the lower part of the formation contains kaolinite and the upper part is enriched in montmorillonite.

Some of the Lower Cretaceous shales are dark gray to black, and they are considered potential local source beds for petroleum in the several basins. This is especially true for the Mowry Shale, which is reported to have an organic carbon content that ranges from about 1 percent in the western one-third of Wyoming to as much as 3 percent in the eastern one-third (Schrayer and Zarrella, 1963; Nixon, 1973).

7.4.3.4 Hydrology

The Lower Cretaceous shales generally contain no significant amounts of ground water, although locally they are interbedded with sandstones that contain fresh water at shallow depths. Most aquifers in the region are of Cretaceous, Tertiary, and Quaternary age and thus generally overlie the Lower Cretaceous shales, but several Paleozoic aquifers are also present (Price and Arnow, 1974; Taylor, 1978).

Principal aquifers in the Big Horn Basin include, in ascending order, the Amsden, Tensleep, Cloverly, Frontier, Mesaverde, Lance, and Fort Union (Lowry et al., 1975). These aquifers are recharged mainly by precipitation, streamflow, and leakage from other aquifers. Ground-water supplies are being used currently for municipal, industrial, and irrigation purposes. Additional data needed to evaluate ground-water conditions in the basin include results of aquifer testing and preparation of potentiometric maps for each aquifer (Taylor, 1978).

The Wind River Basin contains numerous sandstone aquifers that contain large volumes of ground water (Whitcomb and Lowry, 1968).

Principal aquifers include, in ascending order, the Amsden, Tensleep, Wind River, Wagon Bed, White River, and Arikaree Formations. Some of the sandstones in the basin are fractured locally, thus increasing aquifer transmissivity and well yield. Data still needed for an assessment of the geohydrology of the Wind River Basin include potentiometric maps, results of aquifer testing, and determination of water quality (Taylor, 1978).

In southeast Wyoming, the ground-water resources of the Laramie, Hanna, and Shirley Basins and nearby areas were assessed by Lowry et al. (1973). The basins contain many formations that consist partly or completely of sandstone. Principal aquifers include, in ascending order, the Casper, Nugget, Sundance, Mesaverde, Medicine Bow, Hanna, Wind River, Wagon Bed, White River, and Arikaree. Not all these aquifers are present in each basin, but the presence of several aquifers in any basin may represent a considerable thickness of sandstone and a large volume of stored ground water (Taylor, 1978).

The geohydrology of the Green River, Great Divide, and Washakie Basins of southwestern Wyoming and adjacent Colorado were studied by Welder and McGreevy (1966) and Welder (1968). Principal aquifers, in ascending order, include the Bighorn, Madison, Nugget, Mesaverde, Rock Springs, Wasatch, Green River, Bridger, and Browns Park. The depth to ground water in the multibasin area is commonly less than 30 m, but there are a few areas where it is 30 to 150 m (Price and Arnow, 1974).

In addition to the bedrock aquifers mentioned above for each basin, alluvium and terrace deposits are significant freshwater aquifers locally. These deposits typically are 10 to 30 m thick and contain relatively high purity water.

7.4.3.5 Mineral Resources

Principal mineral resources in areas underlain by thick Lower Cretaceous shales of Wyoming and adjacent areas include petroleum, coal, and uranium (Osterwald et al., 1966; Wyoming Geological Survey, 1970; Glass et al., 1975). These energy resources are prospected and produced mainly in the major basins of the region. Other minerals that are or may be of considerable importance locally in these basins include oil shale, trona, sodium sulfate, sodium carbonate, potash, halite, gypsum, bentonite, clay, limestone, titanium, and sand and gravel.

Oil and gas are produced from reservoir rocks as old as Cambrian and as young as Tertiary age, representing every geologic period except the Silurian, Devonian, and Quaternary. Production is chiefly from anticlinal traps around the perimeter of the basins, although a number of major stratigraphic traps have been found also. Oil is the principal hydrocarbon being produced in the Big Horn and Laramie Basin areas, whereas both oil and natural gas are produced in significant quantities in the other basins. A good summary of the petroleum activity and potential in the various basins was given by Lumb et al. (1972).

Coal resources in the basins of Wyoming are Cretaceous and Tertiary in age. These coals are subbituminous in rank in all areas except in the northern Big Horn Basin and locally on the margins of the Hanna, Washakie, and Green River Basins, where they are medium- and high-volatile bituminous (Averitt, 1969, 1972). Because of the great depth of the basins, and the presence of thick strata overlying the coals, readily available coal reserves occur mainly at and near the outcrops around the margins of the basins. Coal bearing strata dip below strippable depths only a few kilometers back from the outcrop in most areas, and thus the areas of potential coal mining are relatively small parts of the basins (Glass et al., 1975). The maximum thick nesses of individual coal beds in each basin are (Osterwald et al., 1966): 3 m in the Big Horn Basin, 5.5 m in the Wind River Basin, 7 m in the Hanna Basin, and 8 m in parts of the Green River-Washakie-Great Divide Basins area.

Uranium deposits in Wyoming and nearby areas are almost all of the sandstone type, and they occur mainly in the Madison Formation of Mississippian age, the Fall River and Lakota Formations of Early Cretaceous age; the Wasatch, Battle Spring, and Wind River Formations of Eocene age, and the Browns Park Formation of Miocene(?) age. Principal mining districts in areas underlain by thick shales include the Crooks Gap-Green Mountain, Ketchum Buttes, Baggs, and Shirley Basin districts (Glass et al., 1975). Mining of uranium in sandstone-type deposits is by surface-mining methods, with some of the open pits extending to depths greater than 100 m. Additional information on uranium in this region is given in reports by Osterwald et al. (1966), Harshman (1968), Anderson (1969), Melin (1969), and Butler (1972).

Oil shale, trona, and halite occur in the Green River Formation of Eocene age in parts of the Green River and Washakie Basins. Trona is being mined in underground shaft mines at the present time, whereas the oil shale and halite resources are not currently being extracted. Potash, sodium sulfate, and sodium carbonate are present at scattered places in the Great Divide Basin and Rock Springs Uplift area (Osterwald et al., 1966).

Gypsum, bentonite, limestone, clay, and sand and gravel are present in many parts of Wyoming. Most of these resources are abundant around the margins of the basin where Cretaceous and pre-Cretaceous strata crop out (Osterwald et al., 1966; Wyoming Geological Survey, 1970). They are all being mined from surface pits at various places in the region, but each of the mines typically occupies an area of less than 1 km^2. The bentonite resources are chiefly interbedded with Cretaceous shales and to a lesser extent with Tertiary shales (Osterwald et al., 1966): commercial deposits up to 3 m thick occur mainly in the Mowry and Frontier Formations, with other deposits also being present in the Thermopolis and Wind River Formations. Although this resource occurs within the thick shale units, it is minable only at the outcrop.

7.4.4 Cody Shale and Other Upper Cretaceous Shales

7.4.4.1 Stratigraphy

Upper Cretaceous strata in the region include several principal thick units of marine shale interbedded with coarser grained clastic rocks. These thick shales include, in ascending order, the Frontier Formation, the Cody or Steele (Lower Pierre) Shale, and the Lewis (Upper Pierre) Shale (Figure 7-4). These shales are widespread in the basins and mountain areas of Wyoming and nearby states. The present distribution of these units, both in outcrop and in subsurface where they are overlain by younger strata, is shown elsewhere in this report (Figure 6-21).

The total thickness of Upper Cretaceous strata in the Rocky Mountain region generally ranges from 1,500 to 6,000 m (Reeside, 1944; Haun and Kent, 1965), and much of this thickness consists of the marine shales herein considered. Among the principal references on the stratigraphy of the Upper Cretaceous shales of the region are the reports by Reeside (1944), Rich (1958), Weimer (1960, 1961), Haun (1961), Weichman (1961), Goodell (1962), Miller et al. (1965), Roehler (1965), Barlow and Haun (1966), Gill and Cobban (1966a, 1966b), Asquith (1970), McGookey et al. (1972), Merewether et al. (1975, 1979), Rea and Barlow (1975), and Shell Oil Co. (1975).

The greatest extent of the Cretaceous seas in the Rocky Mountain region was during the early part of the Late Cretaceous Epoch. From this time on, the dominant movement of the shoreline (and thus, in general, the sandstone-shale facies boundary) was one of eastward marine regression (Figures 6-22, 6-24, 6-25). However, this pattern was interrupted intermittently by several widespread westward incursions of the sea.

The position and extent of the Late Cretaceous seaway was established near the end of Early Cretaceous time, and this determined the location of depocenters for the thick marine shales to be deposited during the remainder of Cretaceous time. The earliest of the Late Cretaceous sediments was the Frontier Formation, a sequence of dark-gray shales and interbedded sandstones derived from a westerly source area (Goodell, 1962). The total thickness of the formation is typically 150 to 300 m in most areas. The Frontier Formation consists mainly of shale in the southeastern quarter of Wyoming, and in this area (embracing parts of the Laramie and Hanna Basins and nearby areas) the thickness of the formation is commonly 150 to 225 m (Goodell, 1962).

Overlying the Frontier Formation in most areas is a thick shale sequence generally referred to as the Cody Shale but also locally called the Steele Shale or the Hilliard Shale (see Figures 6-22, 6-24, 6-25). This shale is also largely equivalent to the lower part of the Pierre Shale of the Great Plains Region. Eastward, the lower part of this shale grades into the calcareous shales, argillaceous limestones, and limestones of the Niobrara Formation. The Cody Shale and its equivalents are commonly 600 to 1,200 m thick in most parts of Wyoming and nearby parts of the Rocky Mountain Region, and they are typically dark gray to black in color.

Much intertonguing took place between the Cody Shale and the overlying Mesaverde Group, and the contact between these two units is younger toward the east. The Mesaverde consists of several hundred meters of sandstones with minor amounts of interbedded shales and coals. Sandstones in this unit also have produced petroleum in various parts of the region.

The Lewis Shale is a dark-gray shale that locally contains thin beds of sandstone, siltstone, and calcareous concretions. It is equivalent to the Bearpaw Shale of Montana and to the upper part of the Pierre Shale to the east in the Great Plains. The shale is typically 200 to 400 m thick across much of the Rocky Mountain Region, but it grades into sandstone to the west in western Wyoming and to the south in the northern part of Colorado (see Figures 6-22, 6-24, 6-25). The Lewis Shale contains several bentonite beds that are useful locally for correlation purposes.

Overlying the Lewis Shale and its equivalents is the Fox Hills Sandstone, a transgressive unit deposited as the Late Cretaceous sea withdrew eastward toward the Great Plains. The thickness of the Fox Hills Sandstone is typically only 30 to 100 m.

Above the Fox Hills Sandstone is the Lance Formation, the youngest Cretaceous unit in most parts of the Rocky Mountains (McGookey et al., 1972). Freshwater and brackish-water sandstones and other clastic sediments characterize the Lance Formation in many areas.

7.4.4.2 Geologic Setting

Upper Cretaceous shales are thick and are widespread in most parts of the Middle Rocky Mountains. Individual shale units range from 150 to 1,200 m thick in various parts of Wyoming and nearby areas, but in much of this region the structure is moderately complex or else the shales are at great depth. Areas where the thick shales are at shallow to moderate depths, and have undergone relatively minor amounts of disturbance, are on the Casper Arch (parts of Natrona and Johnson Counties, Wyoming), in the Laramie-Hanna Basin area, along the east flank of the Great Divide and Washakie Basins, and near the Rock Springs Uplift in southwestern Wyoming (Figure 7-1). Each of these areas is represented by a relatively broad outcrop of Upper Cretaceous strata in Figure 6-21.

The Cody and Lewis Shales are deeply buried at depths of 1,000 to 6,000 m in most parts of the Big Horn and Wind River Basins (Figure 7-5). However, along the flanks of both basins these shales are 100 to 1,000 m deep, and it is possible that locally they may be structurally undisturbed. Structural disturbances scattered around the margins of the basins may include folds, faults, domes, and both low-angle and high-angle thrusts.

Outcrops on the Casper Arch consist chiefly of the thick Cody Shale. In this area the Cody Shale consists of about 900 m of gray calcareous shale with some interbeds of sandstone and siltstone. The structural geology of the Casper Arch is relatively simple, with dips generally ranging from 1 to 5 degrees. Although the top of the Cody Shale is eroded over most parts of the arch, there is a substantial area where a thick sequence of shale is at depths of 300 to 900 m below the surface. Studies of the geology of this area include those by Crist and Lowry (1972) and Hodson et al. (1973).

In the Laramie and Hanna Basin areas, as well as along the east side of the Great Divide and Washakie Basins, the thick Lewis and Steele Shales crop out and are present at shallow to moderate depths over fairly large areas (Welder and McGreevy, 1966; Lowry et al., 1973). These shales typically are light gray to dark gray, and they contain some beds of siltstone and sandstone. The strata dip at low to moderate angles into the basin from adjacent uplifts and generally are at moderate depths in areas that are 5 to 10 km wide and extend for several tens of kilometers along the basin margins. The Frontier Formation also contains thick shale in this region, but in general it is at great depth in most areas.

The Rock Springs Uplift, between the Great Divide Basin and the Green River Basin, contains outcrops of a thick unit locally called the Baxter Shale. The Baxter Shale, which is equivalent to the Steele Shale farther east and the Hilliard Shale to the west, is about 1,100 m of dark-gray gypsiferous silty shale that contains a 150-m-thick sandstone member in the upper part (Smith, 1961; Welder and McGreevy, 1966). Although a number of faults and several Tertiary intrusives are present in the northern half of the Rock Springs Uplift, there is a fairly large area in the southern half of the uplift where the thick Baxter Shale is at moderate depths.

7.4.4.3 Mineralogy and Rock Properties

X-ray diffraction studies of clay-sized material in Upper Cretaceous rocks of southwestern Wyoming show that all the common clay minerals (illite, kaolinite, montmorillonite, chlorite, and mixed-layer illite-montmorillonite) are present (Weaver, 1961). All of these minerals are commonly present in the same samples, although the relative proportions are variable, and any of these minerals, except chlorite, can predominate in a given sample.

Although each of the thick shales of the Upper Cretaceous is characterized as silty, light to dark gray, and not particularly indurated, the shales do contain well-cemented beds locally and may also contain sparse to locally abundant interbeds of sandstone and siltstone.

A single cavern was excavated near Rawlins, in Carbon County, Wyoming, for underground storage of liquefied petroleum gas (Cobbs Engineering, 1975). The facility was constructed at a depth of 130 to 136 m in the Frontier Formation on the flanks of the Rawlins Uplift where the strata are strong, but brittle, and have a dip of 14° and a well-developed joint system. Construction was by conventional room-and-pillar mining methods. All core holes and the access shaft encountered artesian flow from the fractured Frontier Formation, and water flows exceeded 1,200 l/min. With extensive grouting, the water inflow was controlled but not stopped. However, the cavern failed to pass final air-pressure acceptance tests and was abandoned. Thus, although the cavern withstood the stress of construction and large water inflows without detectable deterioration, the extensive fracture system made the cavern unsuitable for its intended purpose.

7.4.4.4 Hydrology

Upper Cretaceous shales typically have low permeabilities and contain no significant amounts of ground water. Most of the aquifers in areas underlain by thick Upper Cretaceous shales are of Cretaceous, Tertiary, and Quaternary age (Price and Arnow, 1974; Taylor, 1978), and a discussion here of these aquifers in the various basins would be similar to the discussion presented in Section 7.4.3.4, Hydrology, for the Mowry Shale and other Lower Cretaceous shales in the Rocky Mountain Region. The reader is referred to that discussion for pertinent information.

7.4.4.5 Mineral Resources

Mineral resources in areas underlain by Upper Cretaceous shales are similar to those discussed in Section 7.4.3.5, Mineral Resources, for the Mowry Shale and other Lower Cretaceous shales of the Rocky Mountain Region, and the reader is referred to that discussion for information and references.

7.4.5 Tertiary Shales

7.4.5.1 Stratigraphy

Tertiary strata contain some thick shales in the basins of central and southwestern Wyoming and northwestern Colorado, including the Wind River, Green River, Great Divide, and Washakie Basins. Principal shales and argillaceous units in the Tertiary strata of this region are the Waltman Shale Member of the Fort Union Formation and the shales in the Green River Formation. Principal references on these and associated units are the work by Keefer (1961, 1965), Bradley (1964), McDonald (1972), Wyoming Geological Association (1973), and Netherland, Sewell and Associates (1975b).

The major features of the region at the beginning of Tertiary time were the group of mountains and associated deep basins that originated in Late Cretaceous time and continued their development through Paleocene and Eocene time. This period of mountain building, which has been called the Laramide orogeny, caused the rise of ranges that rimmed the basins and were the primary sources of sediments deposited in the basins.

The Fort Union Formation of Paleocene age extends across central and southwestern Wyoming, and equivalent strata were deposited farther north in the Big Horn Basin and other areas. The Fort Union Formation consists of a variety of lithologies, with sandstones and interbedded conglomerates and shales being dominant. The formation is typically 600 to 1,200 m thick in most of the southwestern Wyoming areas. In the Wind River Basin, however, the formation is as thick as 2,500 m, and it can be divided into two general lithologic units: a lower unit of sandstone, conglomerate, shale, and carbonaceous shale deposited in a fluvial environment, and an upper unit of fine-grained clastic strata deposited in and adjacent to a large body of water, referred to as Waltman Lake (Keefer, 1961, 1965).

The upper sequence of the Fort Union Formation in the Wind River Basin consists of two members. The Shotgun Member, deposited along the margins of the lake, is characterized by dull gray and tan claystone, siltstone, and shale and minor amounts of sandstone, carbonaceous shale, and coal. The Waltman Shale Member was deposited as an offshore unit in the lake, and thus it is a homogeneous dark-brown to black, silty, micaceous shale. The Waltman Shale Member has a maximum thickness of 900 m in the northeastern part of the Wind River Basin, but it thins to extinction along the southern and western margins of the basin.

The Green River Formation of Eocene age contains several members that are predominantly shale and marlstone in the Green River and Washakie Basins. This formation also contains well-known oil shales, although the deposits here are "leaner" than the oil-shale beds in the nearby Uinta and Piceance Basins of the Colorado Plateau. In simple terms, the Green River

Formation is a thick lens of fine-grained, generally calcareous, lacustrine strata forming part of a large body of sandy mudstone deposited in an intermontane basin (Bradley, 1964; McDonald, 1972; van West, 1972; Netherland, Sewell and Associates, 1975b). The Green River Formation is typically 500 to 1,000 m thick and generally is divided into three members in the Green River Basin. These units are, in ascending order, the Tipton Shale, Wilkins Peak, and Laney Shale Members (Figure 7-6). The Tipton Shale Member consists of oil shale and calcareous sandstone and lesser amounts of siltstone, marlstone, and limestone. The Wilkins Peak Member consists of marlstone, claystone, oil shale, tuff, sandstone, limestone, and saline minerals. Principal rock types in the Laney Shale Member include marlstone, oil shale, tuff, limestone, and sandstone.

Underlying the Green River Formation is the Wasatch Formation, whereas the overlying unit is the Bridger Formation. Both of these formations embracing the Green River are mixed fluvial and alluvial sequences.

7.4.5.2 Geologic Setting

The Waltman Shale was deposited only in the Wind River Basin of central Wyoming. The basin is asymmetrical and contains as much as 9,000 m of sedimentary rocks along its depocenter in the northern and northeastern parts of the basin (Keefer, 1969). Black organic shales and siltstones of the Waltman Shale are restricted to the northeastern side of the basin. The unit is locally more than 900 m thick, but typically it is at depths of 1,000 to 2,500 m and is less than 1,000 m deep only toward the southwest, where the unit thins abruptly (Figure 7-5, cross section C-D).

The Green River Shale is restricted, in the Rocky Mountain Province, to the Green River and Washakie Basins of southwestern Wyoming (the same unit is also present in the Piceance and Uinta Basins of the northern part of the Colorado Plateau). Strata in these basins range from 4,000 to 9,000 m thick, and they range in age from Precambrian to Holocene. The total thickness of the Green River Formation is commonly about 600 to

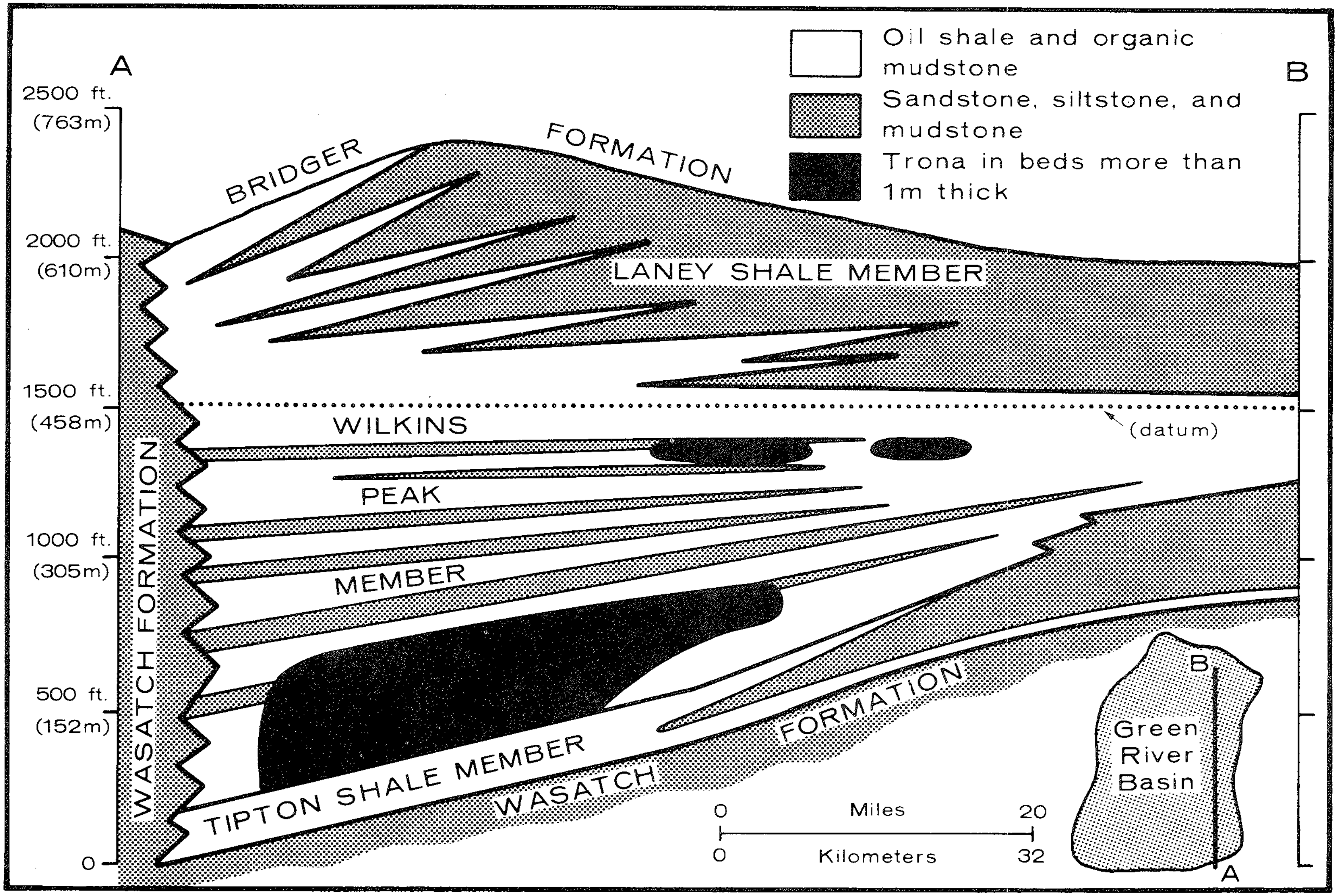

FIGURE 7-6. STRATIGRAPHIC CROSS SECTION OF GREEN RIVER FORMATION IN GREEN RIVER BASIN OF SOUTHWESTERN WYOMING (MODIFIED FROM NETHERLAND, SEWELL AND ASSOCIATES, 1975b)

900 m, although the upper part of the formation crops out and is eroded at many places, and thus the thickness locally is reduced to less than 300 m.

In the central parts of the Green River and Washakie Basins, the Green River Shale is overlain only by several hundred meters of the Bridger Formation; thus there are large areas in both basins where thick shales are at moderate depths. Locally, however, the Green River Formation beds and other strata are faulted; this is especially true in the far west near the Overthrust Belt, in the vicinity of the Rock Springs Uplift, and in the south-central part of the Washakie Basin near the Colorado state line.

7.4.5.3 Mineralogy and Rock Properties

The Waltman Shale consists of dark-brown to black, silty, siliceous shale and claystone that locally contain some sandstone beds at the top and base (Keefer, 1965). Clay minerals make up about 30 to 40 percent of most samples, with other minerals being quartz, feldspar, pyrite, glauconite, and mica. The dark color of the shale results mainly from the high organic-matter content: two samples that were tested contained 2.5 and 6.5 percent organic matter (Keefer, 1965).

Oil shales of the Green River Formation are not true shales but have the composition of dolomitic marlstones (Bradley, 1964; van West, 1972). Mineralogically, the oil shales consist of combinations of illite, dolomite, calcite, quartz, and saline minerals. Organic matter is a common constituent in certain beds and zones within the Green River Shale, and these oil-shale beds or zones are typically a few meters to as much as 50 m thick. The organic matter contained in the oil shales is mainly kerogen, a rubbery solid that when heated to temperatures of about 485°C, will break down in a short period of time to liquid and gaseous hydrocarbons. Upon such distillation in a retort, the better-grade oil-shale beds in southwestern Wyoming will yield about 40 to 80 liters of oil per metric ton of shale (10 to 20 gallons per ton). This is less productive than the good oil-shale beds of the Uinta and Piceance Basins of the Colorado Plateau (Section 8.4.3.3).

Owing to the potential importance of oil shales as a source of fuels, they have been the subject of engineering studies as summarized by Netherland, Sewell and Associates (1975b). The compressive strength and stability of oil shales decrease with an increase in kerogen content, temperature, or thickness of oil-shale beds. Underground room-and-pillar mines have been opened successfully in oil shales in the Colorado Plateau, but none has been operated in the Wyoming basins yet.

Low-grade, or lean, oil shales and similar lithologies lacking kerogen should have a compressive strength of about 138 to 172 MPa, a Poisson's ratio of 0.15 to 0.20, and a Young's modulus greater than 21,000 MPa; high-grade oil shales (greater than 100 liters per metric ton) have a compressive strength of 35 to 138 MPa, a Poisson's ratio of 0.2 to 0.3, and a Young's modulus of 7,000 to 17,500 MPa (Netherland, Sewell and Associates, 1975b). Kerogen can be converted to liquid and gaseous hydrocarbons in a matter of minutes at a retort temperature of 485°C; however, the same distillation can be accomplished over a period of 100 hours at temperatures as low as 345°C, and at even lower temperatures over a longer period of time.

7.4.5.4 Hydrology

Ground-water resources in the Wind River Basin occur mainly in sandstone beds that are younger than the Waltman Shale (Whitcomb and Lowry, 1968; Taylor, 1978). Principal aquifers below the Waltman Shale are, in ascending order, the Amsden, Tensleep, and Casper, whereas those that overlie the Waltman Shale are the Indian Meadows, Wind River, Battle Spring, Wagon Bed, White River, Arikaree, and alluvial aquifers. These aquifers are recharged mainly from precipitation or by interaquifer leakage. Although large volumes of water are present in these aquifers, many additional data are needed to evaluate properly the character of this ground water and its possible interaction with the Waltman Shale.

Ground water in the Green River and Washakie Basins is mainly present in certain high-transmissivity clastic wedges in the Green River Formation and the underlying Wasatch Formation (Welder and McGreevy, 1966; Welder, 1968; Price and Arnow, 1974; Netherland, Sewell and Associates, 1975b). These sandstone aquifers are recharged along their outcrops at the basin margins, and the water-saturated beds dip down into the basins, containing water under artesian pressure. Aquifers have been encountered at depths between 15 and 300 m, and wells into these aquifers have potentials of 40 to 2,400 l/min.

Wasatch aquifers in the Green River Basin contain water with a dissolved-solids content of 200 to 3,700 mg/l, whereas water in the Green River aquifers have a dissolved-solids content of 650 to 4,200 mg/l (Welder and McGreevy, 1966). In the Washakie Basin, Wasatch aquifer waters have a dissolved-solids content of 500 to 2,000 mg/l. Oil-shale units in the Tipton, Wilkins Peak, and Laney Members are interbedded with low-transmissivity beds containing mineralized water.

Some ground water has been encountered during deep shaft mining for trona in the Green River Basin (Netherland, Sewell and Associates, 1975b). Longwall mining at depths of 400 to 600 m has encountered some water invasion, thought to be from fractures caused by the method of mining. In addition, some water has entered through the vertical shafts.

3.4.5.5 Mineral Resources

The major mineral resource in the Wind River Basin area underlain by the Waltman Shale is petroleum. Natural gas and some crude oil have been produced from rocks of Tertiary and Late Cretaceous age in the northeastern part of the basin (Lumb et al., 1972; Glass et al., 1975). Another mineral known to be present in the area is subbituminous coal of Cretaceous and Tertiary age, although this resource is too thin and too deep to be of commercial value except along the outcrop at the margin of the basin. In addition, uranium has been mined from surface and near-surface sandstone-type deposits at several places in the Wind River Basin.

The Green River and Washakie Basins contain several important mineral resources, including oil shale, trona, petroleum, and uranium (Wyoming Geological Survey, 1970; Glass et al., 1975; Netherland, Sewell and

Associates, 1975b). Other resources in the basins include coal and tar sands.

Oil shales in southwestern Wyoming contain about 40 to 80 liters of oil per ton (10 to 20 gallons per ton) of oil shale, with principal resources being in the Tipton Member (Green River Basin) and the Laney Member (Washakie Basin). In general, oil shales in these units are in rather widely spaced beds that are interbedded with lean oil shales or other types of rocks. Although this resource has a potential for development at some time in the future, the grade of these oil shales makes them of secondary importance when compared to the much richer oil shales of the neighboring Uinta and Piceance Basins.

The abundant and thick beds of trona in the lower part of the Wilkins Peak Member in the Green River Basin make this the nation's leading producing area for sodium bicarbonate, an important chemical for a variety of chemical and manufacturing industries. It has been estimated that about 100 billion tons of bedded trona and associated halite are present in the basin (Culbertson, 1966), and four companies are now mining trona at depths of 400 to 600 m (Netherland, Sewell and Associates, 1975b). Mining is mainly by the longwall-mining technique. This method of mining apparently has opened up fractures into nearby aquifers, because flows greater than several hundred liters of water per minute have been encountered in mined-out areas. Also, flows of 40 to 120 l/min have occurred around working and ventilation shafts (Netherland, Sewell and Associates, 1975b).

Oil and gas are important resources in parts of the Green River and Washakie Basins, but most of the current production is from areas not underlain by the oil-shale portion of the Green River Formation. Oil and gas production are mainly from Cretaceous strata, but other Mesozoic and Paleozoic reservoirs are productive in scattered localities. In addition to such proved production, substantial reserves of natural gas are present in "tight" Upper Cretaceous and Lower Tertiary sands that underlie the Green River Formation.

Uranium deposits have been identified and mined at a number of places along the margins of the basins in southwestern Wyoming and adjacent

Colorado (Osterwald et al., 1966; Glass et al., 1975). These deposits are mainly in Cretaceous and Tertiary sands, although some of them are closely associated with the oil shales.

Subbituminous coals underlie the oil shales in the Green River and Washakie Basins, and tar sands occur below the oil shale on the western flank of the Washakie Basin. These materials are locally important resources that might be developed in surface or near-surface mines.

7.4.6 Other Units

7.4.6.1 Middle Cambrian Shales

Several shales of Middle Cambrian age are reported to be 100 to 150 m thick in parts of northern Wyoming and southwestern Montana (Lochman-Balk, 1956, 1972; Shell Oil Co., 1975). These shales are called the Park and Wolsey Shales in Montana and are referred to as the Park and Wolsey Shales of the Gros Ventre Group or the Depass Formation in Wyoming. The units consist mainly of shale with some interbeds of siltstone and fine-grained sandstone.

Underlying and interfingering with the shale in most areas is the Flathead Sandstone, the basal clastic unit deposited during transgression of the Cambrian seas across the region. Westward, the shales grade into a thick sequence of limestones and dolomites typified by the Death Canyon Limestone. The youngest Cambrian shales are overlain by, and interfinger with, the Du Noir and Pilgrim Limestones of Late Cambrian age.

In most areas underlain by Cambrian shales, the shales are deep below the land surface. Shales crop out in the uplifts that surround the Big Horn and Wind River Basins, but they plunge to depths of 2,000 to 6,000 m in most parts of these and other basins. In outcrop areas the shales typically are disturbed by faults and folds.

7.4.6.2 Horseshoe Shale Member of Amsden Formation

In parts of the Big Horn and Wind River Basins of northwestern Wyoming, the Horseshoe Shale Member at the base of the Amsden Formation consists of 20 to 50 m of red mudstone. The shale unit is in the Morrowan Series of the Pennsylvanian System. Regional studies providing information on the Horseshoe Shale are given in Mallory (1972) and McKee and Crosby (1975). In most parts of the basins this Pennsylvanian shale is 3,000 to 6,000 m below the land surface.

7.4.6.3 Satanka Shale Member of Goose Egg Formation

The Satanka Shale of Leonardian (Permian) age consists of 60 to 150 m of red-bed shale, siltstone, and sandstone in the Laramie Basin and northern Denver Basin area of southeastern Wyoming (Rascoe and Baars, 1972; Lane, 1973). The unit is considered the basal member of the Goose Egg Formation. Few data are available on this predominantly shale unit, but the shale is apparently 1,000 to 3,000 m deep in most parts of the Laramie and northern Denver Basins.

7.4.6.4 Morrison Formation

The Morrison Formation of Late Jurassic age consists of 60 to 150 m of continental mudstones and interbedded sandstones throughout most parts of the Rocky Mountain Region (Love et al., 1945a, 1945b; McKee et al., 1956; Burk, 1957; Mirsky, 1962; Peterson, 1972). The formation was deposited as a region-wide blanket of variable lithologies, although red, green, gray, and tan shales are predominant. It is possible that in some areas of the Rocky Mountain Province the formation consists almost entirely of shale.

In most of the Rockies, the Morrison Formation overlies sandstones and shales of the Swift and Sundance Formations, and typically is overlain in the region by conglomerate, sandstone, and shale of the Cretaceous Kootenai, Cloverly, and Lakota Formations.

The Morrison Formation is at great depths in most basins of the Rocky Mountain Region. The unit typically is 1,000 to 5,000 m below the surface in the basins and is at shallower depths only along the margins of the basins and on the flanks of mountain uplifts.

7.5 REGIONAL SUMMARY

The Rocky Mountain region is characterized by: (1) the presence of thick shales, mainly of Cretaceous and Tertiary age, over a fairly large part of the Rockies; (2) a low seismicity for most parts of the region, with most areas being in seismic-risk zone 1; (3) a sparse population in large parts of the region; and (4) the ownership and/or administration of large tracts of land in the region by federal or state government bodies.

However, many parts of the Rocky Mountain region that are underlain by thick shales: (1) the geology is structurally complex and includes folds, faults, thrust faults, and fractured rock, mainly along the margins of the basins where the shales commonly are at shallow to moderate depths; (2) sedimentary or structural basins are structurally simple mainly in their central areas, where the thick shales typically are more than 1,000 m below the land surface; (3) the geohydrology of most basins is poorly known; (4) the energy resources and other mineral resources of the region are extremely important to the nation's future, particularly such resources as petroleum, uranium, coal, oil shale, trona, and bentonite; (5) bentonite and montmorillonite are common, particularly in the Cretaceous shales, and these clay minerals typically contain interlayer water that might be released upon heating; (6) most of the shales are generally soft and plastic, and little is known about their behavior if they were to be mined underground; and (7) the one underground cavern in the region was located in strong, but brittle and fractured, Upper Cretaceous shale at a depth of 130 to 136 m, and although it withstood the stress of construction, it had significant inflow of water and failed to pass the final air-pressure tests.

Lower Cretaceous and Upper Cretaceous shales locally appear to be at moderate depths and with little structural complication at some places around the margins of the Big Horn or Wind River Basin. The Upper Cretaceous Cody Shale is quite thick and at moderate depths over a large part of the Casper Arch, and the Lewis and Steele Shales appear to be moderately thick and at appropriate depths in parts of the Laramie and Hanna Basins and along the east side of the Great Divide and Washakie

Basins. The Upper Cretaceous Baxter Shale also is quite thick and at moderate depths on and near the Rock Springs Uplift.

Thick Tertiary shales that locally appear present at moderate depths and are structurally undeformed include the Waltman Shale in the southern part of the Wind River Basin and the Green River Shales around the perimeter of the Green River Basin and in the Washakie Basin.

The Milligen Formation and Copper Basin Group of Idaho are very complex structurally. Other thick shales that have been considered in the Rocky Mountain region are generally at great depths within the basins or are structurally complex where they are at moderate depths along the margins of the basins.

8. COLORADO PLATEAU

8.1 STRUCTURE AND GEOLOGIC FRAMEWORK

The Colorado Plateau embraces large parts of Arizona, Utah, Colorado, and New Mexico that are characterized by major structural basins and broad uplifts (Figure 2-2). The structure of the region is significantly less complex than that of the Rocky Mountains to the north and east, or the Basin and Range Province to the south and west. Rocks of the Colorado Plateau typically are undisturbed or gently flexed and folded, and thus large areas of the nearly flat-lying strata are interrupted only by widely spaced monoclines and uplifts. The geomorphology of the region is characterized by plateaus, escarpments, and canyons, all on a grand scale, and most parts of the region are sparsely populated desert country. Many reports have been prepared on the Colorado Plateau Region, and included among the more comprehensive discussions of the region are those by Eardley (1962), Haun and Kent (1965), Barwin et al. (1971), Schneider et al. (1971), Sanborn (1971), King (1977), and the Geologic Atlas of the Rocky Mountain Region by Mallory et al. (1972).

The Colorado Plateau was part of the vast eastern shelf of the Cordilleran Miogeosyncline during most of the Early and Middle Paleozoic. A basal transgressive sandstone of Cambrian age is overlain by younger Cambrian, Devonian, and Mississippian limestone, dolomite, and shale units. The total thickness of these strata is more than 1,000 m in the west; they thin abruptly toward the east across the plateau and are absent from the Uncompahgre Uplift and the southeastern part of the region.

Pennsylvanian rocks of the Colorado Plateau include red-bed sandstones and shales in the southwest and north, with carbonates in the San Juan and Paradox Basins and a thick section of evaporites in the central part of the Paradox Basin and in the Eagle Basin in the northeast. Pennsylvanian strata are more than 2,000 m thick in the Paradox Basin and more than 3,000 m thick in the Eagle Basin. Diapiric flow of the evaporites in both these basins has created a series of salt-cored anticlines and other complex structures.

Permian strata were deposited in a variety of continental and marine environments. Vertical and lateral facies changes caused interbedding of arkoses, sandstones, shales, carbonates, and evaporites. The greatest thickness of Permian strata is at the northeastern margin of the Paradox Basin, where more than 2,000 m of coarse and fine clastics were deposited adjacent to the Uncompahgre Uplift, and in the southwestern part of the region, where about 700 to 900 m of sandstones and shales were laid down.

Triassic and Jurassic sediments in the region are chiefly red-bed sandstones and shales deposited in continental environments including mudflat, eolian, alluvial, and lacustrine environments. The thickness of Triassic and Jurassic strata ranges from 1,000 to 2,500 m in parts of the west, and they thin eastward to about 400 to 900 m in the southeast and 100 to 200 m in the northeast.

During Early Cretaceous time, most parts of the Colorado Plateau were lowland areas from which sand and other coarse clastics were derived. Near the end of the Early Cretaceous time and throughout much of the Late Cretaceous time, the region was inundated by a vast inland sea in which were deposited the thick shales of the Mowry (in the north), Mancos, and Lewis (in the southeast) Formations. The total thickness of the Cretaceous strata ranges from 600 to 1,200 m in the south, 1,500 to 3,000 m in the northeast, and 3,000 to 6,000 m in the northwest. The thickness of the predominantly marine-shale sequence ranges from 300 to 1,500 m in the region, with interbeds of sandstone being abundant to the west and southwest.

The Laramide orogeny, of Late Cretaceous and Early Tertiary age, was the cause of much of the broad folding and flexing of rocks in the Colorado Plateau. These crustal movements also brought about development of the Uinta, Piceance, and San Juan Basins, with each of these basins becoming the site for accumulation of thick sections of Tertiary strata.

Tertiary strata of the region are mainly lacustrine and alluvial shales and sandstones deposited in interior basins. Major depocenters are the Uinta Basin, with about 3,000 m of strata, the Piceance Basin, with about 1,500 m of strata, and the San Juan Basin, with about 1,000 m of strata. The Uinta and Piceance Basins contain well-known oil shales of the Green River Formation.

Igneous activity, including both intrusive and extrusive events, occurred in the region during Late Cretaceous and Tertiary time. Events of Late Cretaceous through Middle Tertiary (Miocene) time were scattered widely through the central and eastern parts of the Colorado Plateau, whereas the late Cenozoic events were limited to the periphery of the region, chiefly along the entire southern boundary from the Jemez Mountains in New Mexico to the San Francisco Peaks in Arizona.

8.2 REGIONAL SEISMICITY

Recorded earthquake activity in the Colorado Plateau is low in most areas, particularly in the central part of the region away from bordering tectonic features such as the Overthrust Belt on the west and the Rocky Mountains on the east. Principal summaries of seismic activity in the Colorado Plateau are presented by Simon (1972) and Coffman and von Hake (1973). Approximately 20 earthquakes with Modified Mercalli Intensities of V through VIII (MMI V-VIII) have occurred through 1970 (see Figure 1-2), with almost all of the epicenters being near the perimeter of the plateau. Most parts of the region are considered in seismic-risk zone 1, where minor earthquake damage can be expected, although much of the western and southern areas are in zone 2, where moderate damage can be expected (see Figure 1-3a). The low seismicity of the Colorado Plateau is consistent with the general lack of complex structural and tectonic features in the region.

8.3 REGIONAL HYDROLOGY

8.3.1 Surface Water

The Colorado River and its tributaries dominate the drainage system of the Colorado Plateau. Major rivers, such as the Escalante, Dirty Devil, Green, San Rafael, Duchesne, Yampa, White, Gunnison, Dolores, and San Juan, are typically deeply entrenched into the broad plateaus. Although these rivers normally carry water throughout the year, their tributaries have cut deep, narrow, intricate canyons mainly as a result of the spring snowmelt or the intermittent and ephemeral flow of flash floods during brief but heavy rainstorms.

The average annual precipitation in the region typically is low, and most of the plateau has an arid to semiarid climate. The annual precipitation is 15 to 25 cm in most of the lowland areas near the major rivers and is less than 50 cm in almost all parts of the Colorado Plateau. The principal areas where precipitation exceeds 50 cm per year are the isolated mountain peaks that are widely scattered through the region.

Development of the water resources of the region has been limited almost entirely to the development of surface water (Price and Arnow, 1974; West and Broadhurst, 1975; Davidson, 1979). Surface water in most areas has a dissolved-solids concentration of less than 1,000 mg/l, although much of the Green River drainage area is characterized by concentrations of 1,000 to 3,000 mg/l. A series of multipurpose dams built on some of the major rivers has created reservoirs that are used for flood control, recreation, and municipal and irrigation supplies. The demands for water from the Colorado River are heavy, including the need to allow large quantities of fresh water to reach Mexico.

8.3.2 Ground Water

Large supplies of ground water underlie many parts of the Colorado Plateau, but owing to the sparse population of the region, there has been little exploration for, or characterization of, ground-water resources. Approximately 35 different rock formations have been identified as important aquifers in various parts of the region (Price and Arnow, 1974; West and Broadhurst, 1975; Davidson, 1979), with most of them being sandstones of Triassic, Jurassic, and Cretaceous age. Among the more widespread aquifers are the Wingate, Navajo, Carmel, Entrada, and Dakota Sandstones. Regional studies of ground-water resources, in addition to the three mentioned above, are those done by the U.S. Geological Survey (1964, 1965, 1969a, 1969b), Cooley et al. (1969), Coffin et al. (1971), Boettcher (1972), McGavock and Edmonds (1974), Pearl (1974), and Brown (1976).

The depth to ground water is unknown in most areas, although where it has been tested, the water typically is more than 30 m deep and is more than 150 m deep in the vicinity of the Colorado River. In almost all parts of the plateau region the potential yield of water wells is less than 200 l/min. The quality of ground water is less than 1,000 mg/l dissolved solids in most parts of the region; the dissolved-solids content ranges from 1,000 to 3,000 mg/l in much of the San Juan Basin area and in broad areas across the northern part of the region, where the thick outcropping Cretaceous shales yield small quantities of somewhat mineralized water.

Owing to the great potential for ground-water resources and the heavy demands already being placed on surface water in the Colorado River and its tributaries, the geohydrology of the Colorado Plateau will need additional studies, well beyond the reconnaissance-level studies done to date. Such detailed studies are being conducted locally around the few population centers of the region and in the vicinity of the several areas in the Paradox Basin where salt beds of the Pennsylvanian Paradox Formation are being investigated as potential host rocks for underground storage of radioactive waste.

8.4 SHALES AND ARGILLACEOUS UNITS

8.4.1 Introduction

Several of the Upper Cretaceous and Tertiary shales are 100 to 1,500 m thick in one or more of the major basins in the Colorado Plateau. Major Upper Cretaceous shales include the Mancos Shale (and equivalent units, such as the Tununk, Blue Gate, Masuk, and Tropic Shales) and the younger Lewis and Kirtland Shales. These shales are at moderate depths and undeformed in parts of the Uinta, Piceance, Henry, Kaiparowits, Black Mesa, and San Juan Basins.

The major thick Tertiary shales of the region are in the Green River Formation of the Uinta and Piceance Basins. The Green River Formation contains significant thicknesses of oil shale (organic-rich marlstone) and shale, along with other rock types, and is at moderate depths in large parts of both basins.

8.4.2 Mancos Shale and Other Upper Cretaceous Shales

8.4.2.1 Stratigraphy

Upper Cretaceous shales, such as the Mancos, Lewis, Kirtland, and equivalent shales, are thick and widespread in the Colorado Plateau. The shale units are part of the Colorado and Montana Groups and are stratigraphically equivalent to much of the Pierre Shale of the Great Plains (see Figure 6-23). Upper Cretaceous shales crop out or are in the subsurface in parts of the Uinta, Piceance, Henry, Kaiparowits, Black Mesa, and San Juan Basins (see Figures 6-21, 8-1). In most of these areas, shale units 100 to 1,500 m thick make up a substantial part of the 1,200 to 3,000 m of Upper Cretaceous strata in the Colorado Plateau (Reeside, 1944; McGookey et al., 1972). The literature on these shales and equivalent argillaceous units is voluminous, but some of the principal studies are those by Repenning and Page (1956), Haun and Weimer (1959), Weimer (1960), Burger (1963), Willard (1964), Young (1966, 1973), Baltz (1967), Lamb (1968), Fassett and Hinds (1971), O'Sullivan et al. (1972), Fassett (1973), Irwin (1977), Kellogg (1977), Molenaar (1977), Peterson and Kirk (1977), and Peterson et al. (1980).

Shales of the Upper Cretaceous are mainly light gray to dark gray and calcareous. They were deposited in nearshore and offshore environments during the last major incursion of marine waters across the southwestern United States. The episodes of Late Cretaceous shale deposition across the Colorado Plateau involved southwestward marine transgression followed by northeastward regression. The shales thin to the southwest and west by interfingering with the underlying and overlying sandstones, and they grade, in those same directions, into a thick sequence of nonmarine

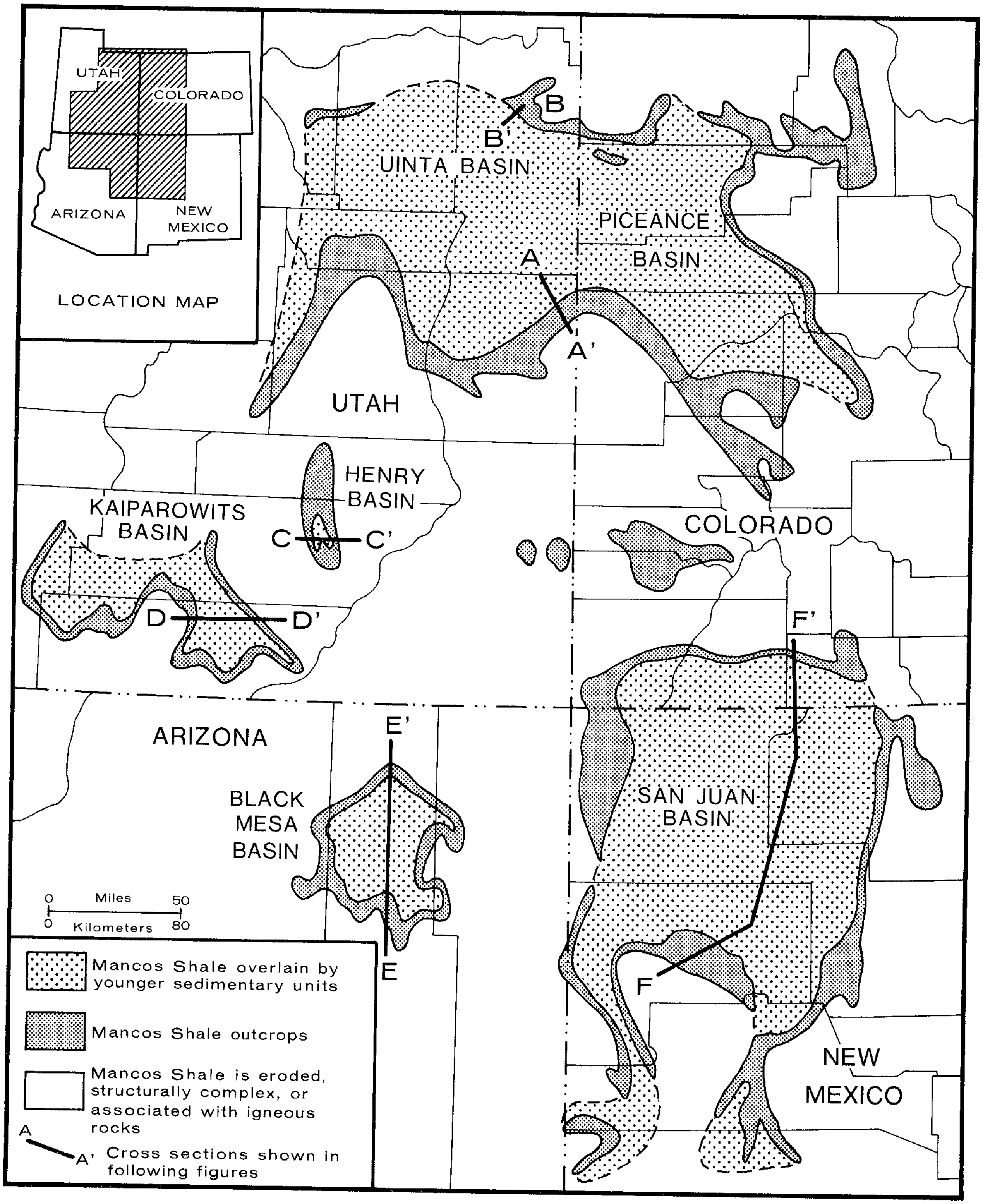

FIGURE 8-1. MAP SHOWING DISTRIBUTION OF MANCOS SHALE (UPPER CRETACEOUS) AND EQUIVALENT SHALES IN COLORADO PLATEAU REGION (MODIFIED FROM KING AND BEIKMAN, 1974)

coastal-plain strata consisting chiefly of sandstones, shales, and conglomerates (see Figures 6-22, 6-23).

Owing to the widespread distribution of Upper Cretaceous strata in separate parts of the Colorado Plateau, a number of different formation and member names have been given to equivalent strata in different areas. The term Mancos Shale is used for the lower part of the shale sequence in most areas, although other names, such as the Tununk, Blue Gate, Masuk, and Tropic Shales, are used for some parts of the Mancos Shale in southern Utah.

The upper part of the Upper Cretaceous in the San Juan Basin contains several additional important shale units; the Lewis Shale is separated from the Mancos by a thick wedge of sandstone in the Mesaverde Group, and the Kirtland Shale is a still younger argillaceous unit near the top of the Cretaceous. In northwestern Colorado, just northeast of the Piceance Basin, the "Lewis" Shale overlies the Mesaverde Group; the "Lewis" Shale is younger than the Lewis Shale of the San Juan Basin, and it is not present in the Piceance Basin or elsewhere to the south.

Underlying the Mancos Shale and equivalent shales are sandstones, thin shales, and conglomerates of the Dakota Sandstone, which was deposited in transitional shore and nearshore environments accompanying the transgression of the Mancos sea, and it interfingers with the Mancos Shale. The Dakota Sandstone is typically 10 to 60 m thick in the Colorado Plateau. Overlying the Mancos Shale is the Mesaverde Group, which consists of 300 to several thousand meters of sandstone, siltstone, shale, and coal. These same types of strata are also present as westward equivalents of the Mancos Shale, and several tongues of sandstone, such as the Gallup, Ferron, and Emery Sandstones, extend eastward into the Mancos Shale, enabling the thick shale to be subdivided into several members (see Figures 6-22, 6-23).

Overlying the Mesaverde Group in the San Juan Basin is the Lewis Shale, a unit of gray shale and siltstone locally as thick as 700 m. The Lewis Shale is in turn overlain by the Pictured Cliffs Sandstone and Fruitland Formation, and this sequence is overlain by the Kirtland Shale, which consists of greenish-gray mudstone with thin lenses of fine-grained sandstone. The Kirtland Shale is separated by the medial Farmington Sandstone Member into a lower shale member 100 to 300 m thick and an upper shale member 30 to 140 m thick.

8.4.2.2 Geologic Setting

In several large areas of the Colorado Plateau, the Upper Cretaceous shales are thick, undeformed, and are at moderate depths below the surface. The regional dip in most of these areas is typically less than 3, although the dip locally is 10° to 30° along monoclines or other flexures peripheral to the structural basins. Areas where the Upper Cretaceous shales are thick and generally undeformed include the Uinta, Piceance, Henry, Kaiparowits, Black Mesa, and San Juan Basins, and also several other areas that are peripheral to these basins (see Figure 8-1).

The Uinta Basin of northeastern Utah and the Piceance Basin of northwest Colorado are major structural depressions where the Mancos Shale crops out and is at moderate depths only around the perimeter of the basins. The shale unit plunges to depths greater than 1,000 m a short distance back from the outcrop, and it reaches depths of 4,000 to 6,000 m near the axes of the basins. The thickness of the Mancos Shale in both basins is typically 1,200 to 1,800 m (Young, 1966; Doelling, 1979; Doelling and Graham, 1972b). In the western part of the Uinta Basin, and southwest of the basin in the Wasatch Plateau area, the Mancos Shale consists of five shale and sandstone members: the Tununk Shale (150 to 240 m thick) at the base, Ferron Sandstone (100 to 240 m), Blue Gate Shale (450 to 600 m), Emery Sandstone (150 to 300 m), and Masuk Shale (100 to 300 m) (Doelling, 1972). In the central part of the Uinta Basin and eastward across the Piceance Basin, the sandstone interbeds are largely absent and the Mancos Shale is a thick sequence consisting almost entirely of shale.

The dip of the Mancos on the southern flanks of the Uinta and Piceance Basins is typically 1° to 3°, and there is a band about 500 km long and 15 to 25 km wide where the formation crops out or is at moderate depths beneath the overlying Mesaverde Group (Figure 8-2). Other areas in

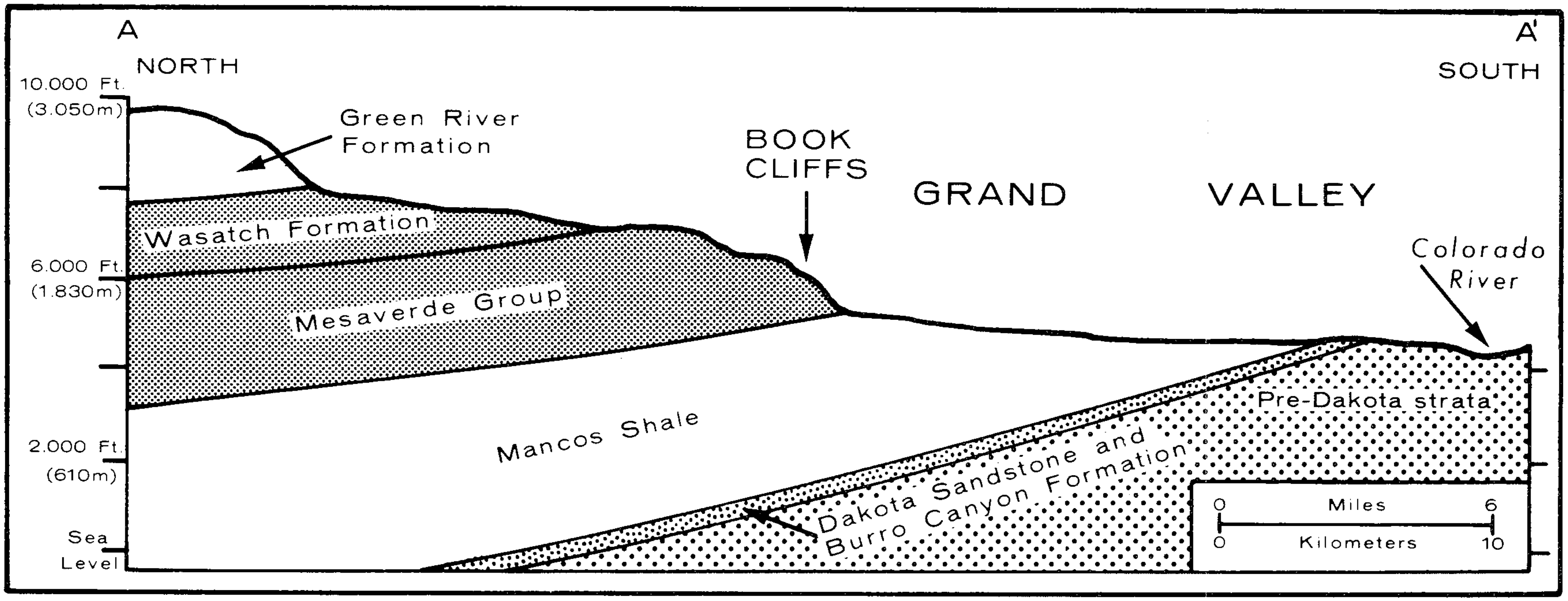

FIGURE 8-2. CROSS SECTION A-A', SHOWING MANCOS SHALE ON SOUTHERN FLANKS OF UINTA AND PICEANCE BASINS IN VICINITY OF UTAH-COLORADO STATE LINE (MODIFIED FROM CASHION, 1973)

northwestern Colorado where the Mancos Shale has a similar thickness and depth are at the southern end of the Piceance Basin in parts of Delta and Montrose Counties, and northeast of the Piceance Basin in parts of Routt and Rio Blanco Counties.

The dip of the Mancos Shale is typically 5° to 30° on the northern flank of the Uinta Basin and on the northern and eastern sides of the Piceance Basin. Thus in these areas, the Mancos Shale is at a depth of 300 to 900 m only in a narrow band (Figure 8-3), and the strata are moderately to steeply flexed.

The Henry Basin, on the west side of the Henry Mountains of southeastern Utah (Figure 8-1), contains the following subdivisions, in ascending order, of the Mancos Shale: Tununk Shale (150 to 200 m thick), Ferron Sandstone (45 to 105 m), Blue Gate Shale (450 m), Emery Sandstone (75 to 135 m), and Masuk Shale (180 to 240 m) (Doelling and Graham, 1972b; Doelling, 1975; Peterson et al., 1980). In a large area in the central part of the basin, the thick shales, particularly the Blue Gate and Tununk Shales, are flat lying, undisturbed, and at depths of 300 to 900 m (Figure 8-4). A sharp flexure, the Waterpocket Fold, is present along the western margin of the basin, and Tertiary intrusive stocks and laccoliths form the Henry Mountains on the eastern side of the basin. A small part of the western side of the Henry Basin is within Capitol Reef National Park.

The Kaiparowits Basin of south-central Utah embraces a fairly large area of Kane and Garfield Counties, where the Tropic Shale is 150 to 300 m thick (Doelling and Graham, 1972a; Doelling, 1975) and is at moderate depths (Figure 8-5). The Tropic Shale is correlative with the Tununk Shale of the Henry Basin area and is the only thick shale unit in this area equivalent to the Mancos Shale farther east. In most parts of the Kaiparowits Basin, the dip of the Tropic Shale is 1° to 3°, and the principal structures are broad folds and several sharp monoclines (Doelling and Graham, 1972a). Small areas at the northwestern edge of the basin are in Bryce Canyon National Park and in Dixie National Forest. In the area just west of the Kaiparowits Basin (Figure 8-1), the Tropic Shale is structurally more complex, is intruded by Tertiary igneous rocks, and partly underlies national forest lands.

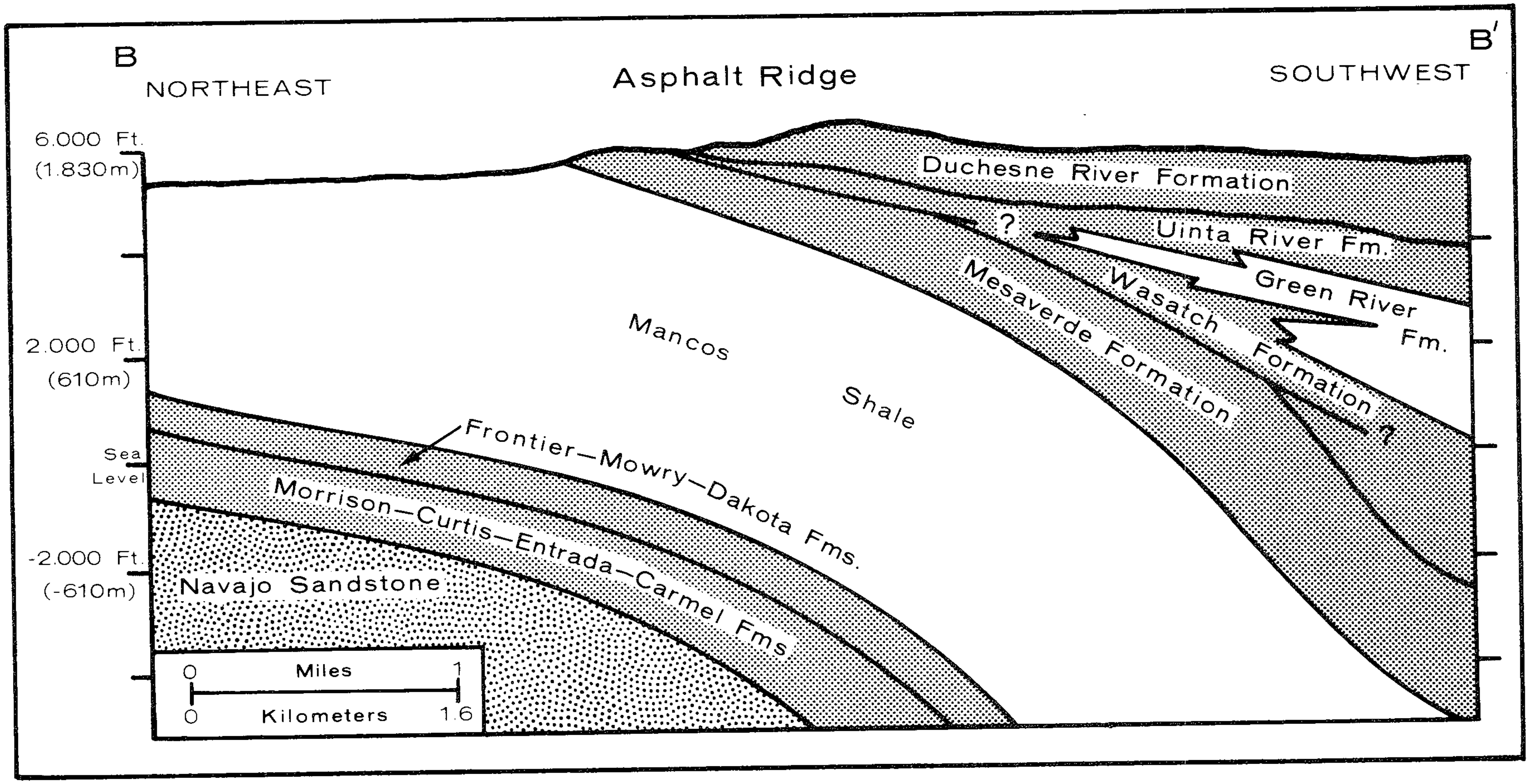

FIGURE 8-3. CROSS SECTION B-B', SHOWING MANCOS SHALE AT ASPHALT RIDGE NEAR VERNAL, UTAH, ON NORTHEASTERN SIDE OF UINTA BASIN (MODIFIED FROM COVINGTON, 1963)

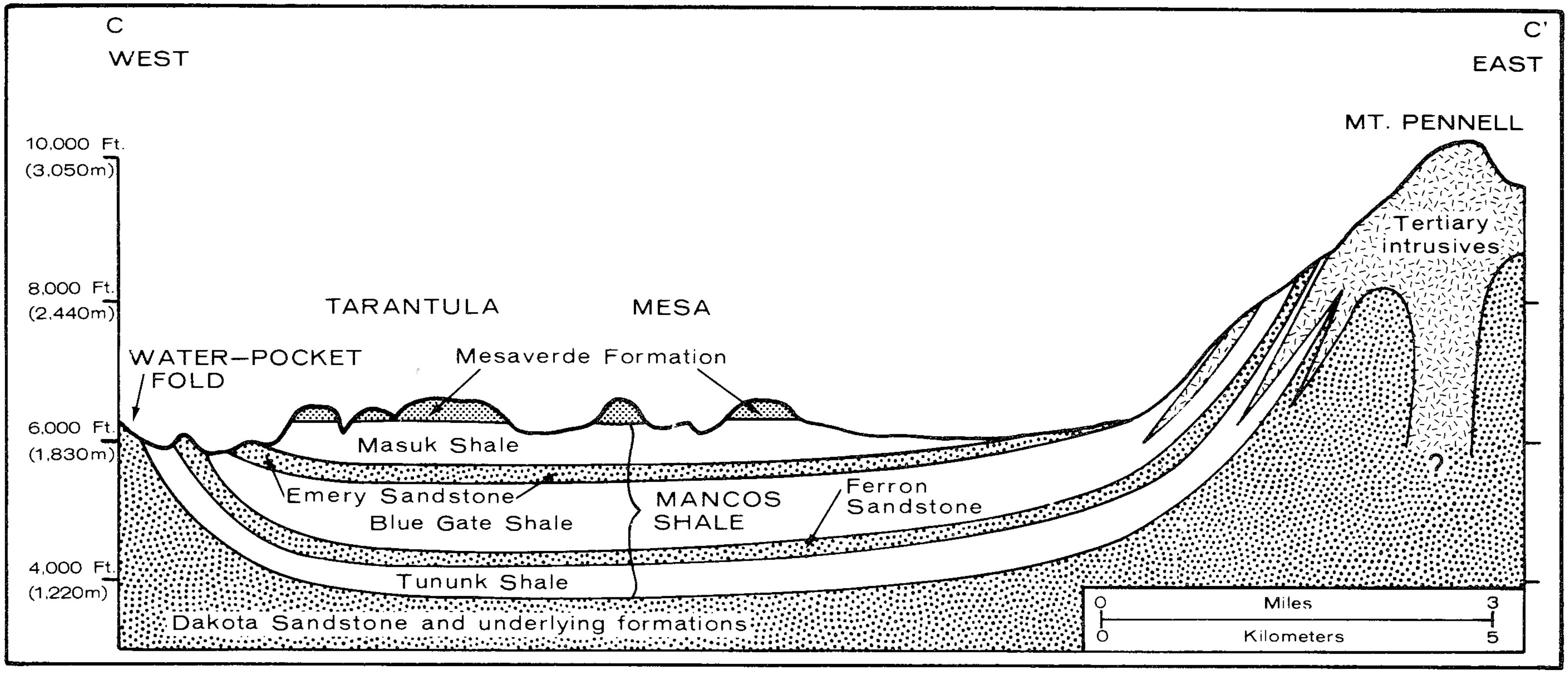

FIGURE 8-4. CROSS SECTION C-C', SHOWING MANCOS SHALE IN HENRY BASIN, WAYNE AND GARFIELD COUNTIES, UTAH (MODIFIED FROM DOELLING AND GRAHAM, 1972b)

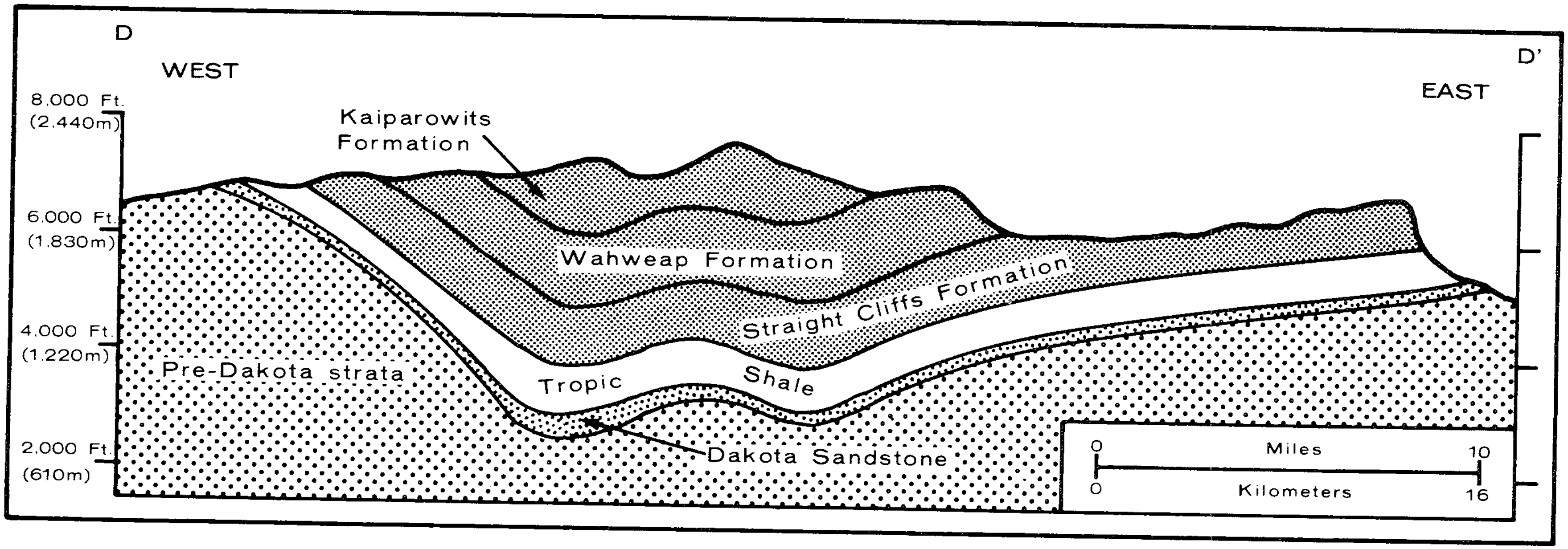

FIGURE 8-5. CROSS SECTION D-D' THROUGH KAIPAROWITS BASIN, KANE AND GARFIELD COUNTIES, UTAH, SHOWING RELATION OF TROPIC SHALE (EQUIVALENT TO LOWER PART OF MANCOS SHALE) TO ADJACENT SANDSTONES (MODIFIED FROM DOELLING AND GRAHAM, 1972b)

The Black Mesa Basin of northeastern Arizona lies mostly in Navajo County, but parts of the basin extend into Apache and Coconino Counties (Figure 8-1). The Mancos Shale in this basin is 120 to 210 m thick (Peirce et al., 1970; O'Sullivan et al., 1972), and the shale unit is equivalent only to the lower (Tununk) part of the Mancos Shale farther to the north and east (Peterson and Kirk, 1977). In most parts of the Black Mesa Basin, the top and base of the shale are less than 300 m below the land surface, but in some areas there is a sufficient cover of Mesaverde Group strata so that the lower half of the Mancos Shale is 300 to 450 m below the surface (Figure 8-6). The Mancos Shale is nearly flat lying in the area, with dips typically less than 1° and only a few gentle folds. The area underlain by Mancos Shale is mostly within the Hopi Indian Reservation, and the remainder of the area is on the Navajo Indian Reservation.

The San Juan Basin of northwestern New Mexico and the southwestern corner of Colorado is a highly asymmetrical basin, with its axis at the northern edge of the basin. Principal outcrops of thick shale are along the southern side of the basin, where the lower part of the Mancos Shale is 100 to 250 m thick, and along the western side of the basin, where the shale thickens from about 180 m in the south to about 600 m in the north (Willard, 1964; O'Sullivan et al., 1972; Young, 1973; Molenaar, 1977). In large areas on the south and west sides of the basin (Figure 8-1), the shale is undeformed, thick, and at depths of 300 to 900 m (Figure 8-7). From these areas the formation dips gently toward the basin center, and at depths greater than 1,000 m it is locally as thick as 700 m.

The Lewis Shale, which overlies the Mesaverde Group in the San Juan Basin, is 180 to 250 m thick and at depths of 700 to 900 m in most of the northeastern quarter of San Juan County, New Mexico (Peterson et al., 1965; O'Sullivan et al., 1972; Fassett, 1977) (Figure 8-7). To the south and west of this area the Lewis Shale is at moderate depths but is generally less than 75 m thick; to the north and east of this area the shale unit is typically 250 to 700 m thick but is at depths greater than 900 m.

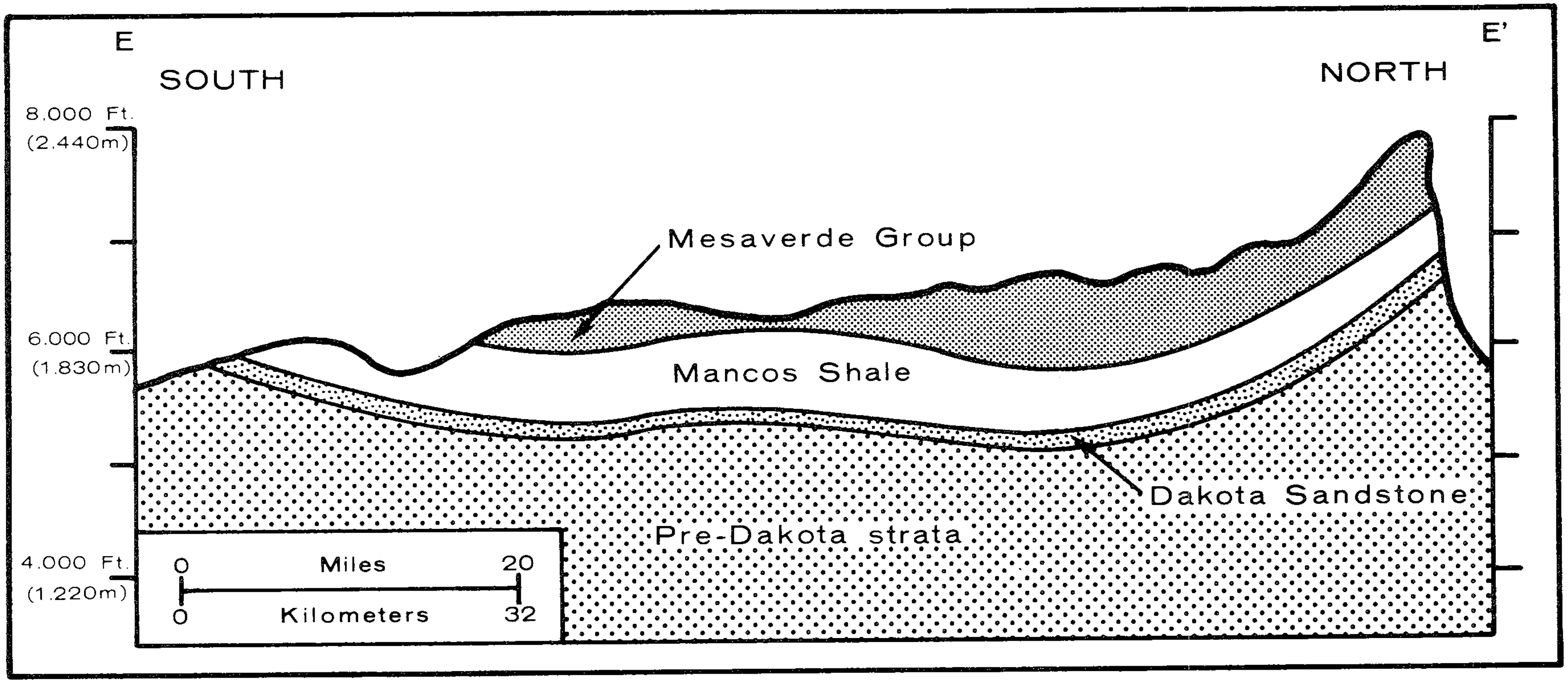

FIGURE 8-6. CROSS SECTION E-E', SHOWING MANCOS SHALE IN BLACK MESA BASIN OF NORTHEASTERN ARIZONA (MODIFIED FROM PIERCE ET AL., 1970)

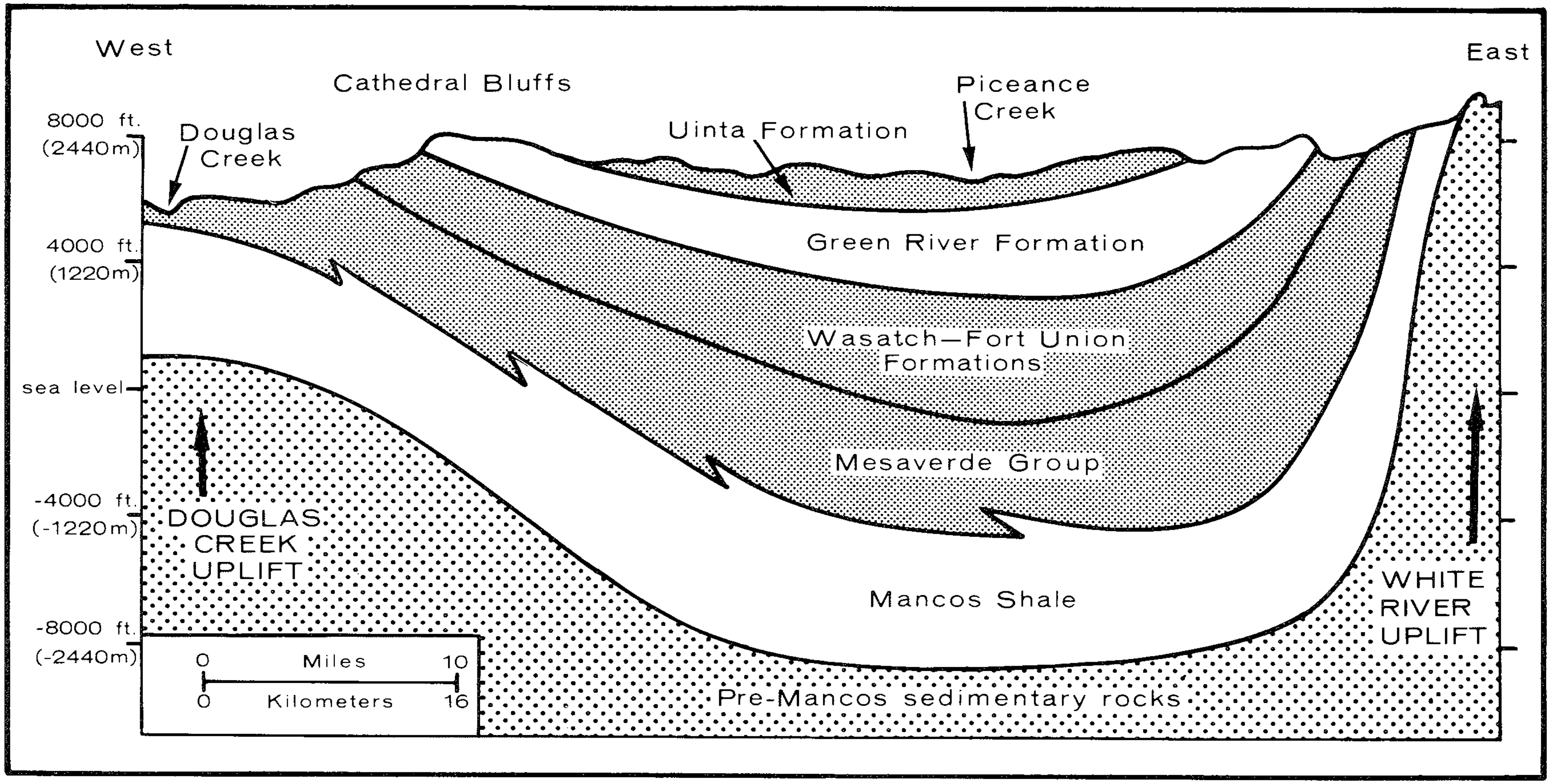

FIGURE 8-7. CROSS SECTION F-F' THROUGH SAN JUAN BASIN OF NORTHWESTERN NEW MEXICO, SHOWING RELATION OF MANCOS AND LEWIS SHALES TO ADJACENT SANDSTONES (MODIFIED FROM PETERSON ET AL., 1965)

The Kirtland Shale, near the top of the Cretaceous strata in the San Juan Basin, consists of 100 to 450 m of shale with a medial sandstone 30 to 140 m thick (Fassett and Hinds, 1971; O'Sullivan et al., 1972). The lower shale member is typically 60 to 150 m of gray shale with few thin interbeds of siltstone and sandstone, whereas the upper shale member is thicker but contains many more sandstone interbeds. The Kirtland Shale is undeformed and at depths of 300 to 900 m in most parts of northeastern San Juan County and western Rio Arriba County, New Mexico.

Most of the western third of the San Juan Basin is within the Navajo Indian Reservation, and the Colorado portion of the basin is primarily within the Southern Ute Indian Reservation. Along the eastern side of the northern half of the basin, much of the land is within the Jicarilla Apache Indian Reservation or Carson National Forest.

8.4.2.3 Mineralogy and Rock Properties

The Mancos Shale and other Upper Cretaceous shales are typically light-gray to dark-gray, silty, even-bedded claystones and mudstones that are carbonaceous (locally they are organic-rich) and contain few interbeds of sandstone and bentonite. Sandstone beds are commonly thin and discontinuous, although several thicker units deposited during major marine regressions to the north and east have been given member status (such as the Ferron and Emery Sandstone Members of the Mancos Shale in Utah). Bentonite beds or bentonitic clays, typically less than 1 m thick, are scattered in most Upper Cretaceous shales throughout the Colorado Plateau.

The Mancos Shale is calcareous in many areas, and locally it contains thin beds of coal near the lower and upper boundaries of the formation and near the interbedded sandstone members in the south and west. On the western side of the San Juan Basin, kaolinite is the major clay mineral in some Mancos Shale samples, whereas montmorillonite is dominant in other samples (Willard, 1964). X-ray diffraction of the Tropic Shale in the Kaiparowits Basin shows that the most abundant minerals are quartz, montmorillonite, calcite, dolomite, and kaolinite (Lawrence, 1965).

The Mancos Shale has yielded commercial quantities of oil from fractured shales in several areas of the Colorado Plateau, chiefly around the perimeter of the San Juan Basin, in the north part of the Piceance Basin, and in the area northeast of the Piceance Basin (Mallory, 1977). Fractures occur mainly in the parts of the Mancos Shale that are calcareous or dolomitic, whereas other parts of the formation yield plastically to stresses. It is believed that the oil present in these fractured-shale reservoirs is derived locally from the organic matter in the shale (Mallory, 1977).

8.4.2.4 Hydrology

The Mancos Shale and other thick Upper Cretaceous shales of the Colorado Plateau typically have low permeability and yield little or no water. The shales act mainly as aquicludes between aquifers in the Dakota and Mesaverde Sandstones, and only the few sandstone interbeds within the shales contain moderate amounts of ground water. Water confined to the sandstone aquifers below, within, or above the thick shale units is under artesian pressure in much of the area, and it is recharged mainly in the topographic uplands in the Colorado Plateau.

Principal reports dealing partly with the hydrology of rock units closely associated with the Mancos Shale and other thick Upper Cretaceous shales are those by the U.S. Geological Survey (1964, 1965, 1969a, 1969b), Cooley et al. (1969), Coffin et al. (1971), McGavock and Edmonds (1974), Price and Arnow (1974), and Davidson (1979). Most of these reports, however, are regional in scope and provide few details on the geohydrology of the shales and associated sandstones. There exists a major need for hydrologic studies in any area where the Upper Cretaceous shales warrant further study.

8.4.2.5 Mineral Resources

The mineral resources of the Colorado Plateau region are vast, with petroleum, coal, uranium, and oil shale being among the most important and widespread (U.S. Geological Survey, 1964, 1965, 1969a, 1969b). Most of these energy resources are in rock layers younger than, or stratigraphically above, the Mancos Shale and other Upper Cretaceous shales, but some resources are in rock layers beneath the thick shales, and their development locally requires drilling boreholes or sinking mine entries through the thick shales.

Major oil and gas fields exist in parts of the Uinta, Piceance, and San Juan Basins (Sanborn, 1971, 1977; Schneider et al., 1971; Lumb et al., 1972). Production in these basins is mainly from sandstones in the Mesaverde Group and in the Tertiary System that overlie the shales, but some oil and gas also are produced from the underlying Dakota, Morrison, and Entrada Sandstones and from Pennsylvanian formations as well. At several places in the three basins the Mancos Shale itself yields oil and/or gas from sandstone interbeds or from fractured shales (Kellogg, 1977; Mallory, 1977). No petroleum has been produced yet from the Henry or Black Mesa Basin (Turner, 1968), and oil has been produced only from a small area of the Kaiparowits Basin.

Major coal resources of the Colorado Plateau are in Cretaceous and Tertiary strata, and coal is now being mined, or has the potential of being mined, in each of the six basins containing thick Upper Cretaceous shales (Peirce et al., 1970; Fassett and Hinds, 1971; Shomaker et al., 1971; Averitt, 1972; Doelling, 1972; Doelling and Graham, 1972a, 1972b; Jones et al., 1978). Significant reserves are present in the Mesaverde Group, and locally the Dakota Sandstone and even the Mancos Shale contain minable coal beds. The coal in the San Juan and Black Mesa Basins is subbituminous in rank, whereas in the remaining basins it is bituminous in rank. The coal beds typically are 1 to 6 m thick and are being mined both at the surface and underground, where the beds are typically at depths less than 300 m.

Uranium is present in some of the sandstones of the Colorado Plateau, with the major resources being in the Morrison (Jurassic) and Chinle (Triassic) Formations (Finch, 1967; Butler, 1972). Minable uranium deposits are scattered throughout many districts in most of the basins that contain Upper Cretaceous shales.

The nation's greatest reserves of oil shale are in the Green River Formation (Tertiary) in the Piceance and Uinta Basins (van West, 1972; Murray, 1974). The oil shales are about 1,500 to 2,000 m stratigraphically above the Mancos Shale in these basins.

Resources locally associated with the Mancos Shale and other thick Cretaceous shales include bentonite, bentonitic clays, and the shale itself, all of which are generally surface-mined at shallow depths. Other resources such as gypsum, nahcolite, dawsonite, and sand and gravel are locally present in or around the perimeter of basins in the Colorado Plateau, and some of these minerals are now being mined.

8.4.3 Green River Formation

8.4.3.1 Stratigraphy

The Green River Formation is a thick sequence of shale, organic-rich marlstone (a mixture of calcite, dolomite, and clay minerals), and sandstone, along with some conglomerate, nahcolite, dawsonite, and salt in local areas. These strata were deposited in a lacustrine environment that persisted in the Uinta and Piceance Basins during much of Eocene (Early Tertiary) time. The organic-rich marlstones are commonly referred to as "oil shales," and the deposits in this region, especially those in the Piceance Basin, are regarded as the largest and most important oil-shale resources in the United States. Owing to the importance of these oil shales, many studies have been made of their stratigraphy, including those by Bradley (1931, 1964), Dane (1954), Picard (1955), Donnell (1961), Cashion (1967), Trudell et al. (1970), McDonald (1972), Van West (1972), Murray (1974), and Netherland, Sewell and Associates (1975b).

The Green River Formation is underlain by the Wasatch Formation, which consists of interbedded shales and sandstones of fluvial origin, and is overlain by the Uinta Formation, consisting of sandstones and shales of fluvial and lacustrine origin. The Green River Formation has been divided into five members which vary considerably in lithology and thickness: the Douglas Creek, Garden Gulch, Parachute Creek, Evacuation Creek, and Anvil

Points Members (the Evacuation Creek Member was considered part of the overlying Uinta Formation by Cashion and Donnell, 1974).

The Douglas Creek Member consists mainly of shale and sandstone, but it also contains some limestone and beds of "lean" oil shale. The unit is generally 300 to 600 m thick in the Uinta Baisn and is 120 to 240 m thick in the Piceance Basin. The overlying Garden Gulch Member consists chiefly of shale, siltstone, and oil shale. The member is 60 to 300 m thick in the Piceance Basin, and it is restricted to the eastern side of the Uinta Basin, where the unit is 0 to 70 m thick.

The Parachute Creek Member consists mainly of oil shale and marlstone, and it contains the major part of the rich oil-shale deposits in the region. Individual beds in the member are generally thin and even-bedded, with most strata ranging in thickness from 2 cm to paper thin. The thickness of the Parachute Creek Member typically ranges from about 150 to 400 m in both basins. Several stratigraphic zones in the member are rich in oil shale, and locally as much as 300 m of strata in the middle of the Piceance Basin have an average of about 100 liters of oil per metric ton of rock (about 25 gallons per ton). An unusually rich oil-shale unit known as the Mahogany Ledge locally contains as much as 320 liters per ton and averages about 220 liters per ton throughout the deeper parts of the Piceance Basin. The Parachute Creek Member also contains the potentially important nahcolite, dawsonite, and salt resources in the Piceance Basin (Beard et al., 1974; Dyni, 1974).

Overlying the Parachute Creek Member is the Evacuation Creek Member, which consists mainly of sandstone, siltstone, shale, and marlstone. This member is commonly 150 to 300 m thick and is now considered by some to be part of the Uinta Formation. The Anvil Points Member is restricted to the eastern side of the Piceance Basin, where it crops out and extends basinward only a short distance. It interfingers with the Douglas Creek, Garden Gulch, and lower Parachute Creek Members and consists of shale, sandstone, marlstone, and limestone interbeds that are as thick as 450 m.

8.4.3.2 Geologic Setting

The Green River Formation is restricted, in the Colorado Plateau, to the Uinta Basin of northeastern Utah and the Piceance Basin of northwestern Colorado (Figure 8-8); the unit is also present in the Green River and Washakie Basins of southwestern Wyoming (Rocky Mountain Province). Deposition of the oil shale, shale, and sandstone occurred in, and peripheral to, a large lake (referred to as Lake Uinta) that extended across both basins during much of Eocene time. Lake Uinta was surrounded by broad plains and uplifted mountain blocks. The major environments ranged from freshwater lacustrine, fluvial, and swamp conditions to saltwater lacustrine conditions.

The Uinta Basin is a broad asymmetrical syncline containing as much as 4,000 m of Tertiary sedimentary rocks. Along the southern margin of the basin, strata dip northward at only 1° or 2°, whereas on the eastern, western, and northern margins the beds dip more steeply. Faults are present at widely scattered places in the Uinta Basin, with the larger and more numerous faults occurring in the northern part of the basin. A well-developed fracture system is present in the basin, and some of these fractures have opened and filled with gilsonite, a solid bitumen, or asphaltite. Several hundred meters of the Green River Formation are structurally undisturbed and are at moderate depths in the southern part of the Uinta Basin, particularly in southern Uintah County and nearby areas. In general, the depth of the Green River Formation ranges from 150 to 1,000 m in most areas.

The Piceance Basin is one of the major structural features of northwestern Colorado. The basin has an irregular shape; its axis extends northwest to southeast, with the southern and western flanks being relatively simple and undisturbed (beds dip at rates of only a few degrees) and the northern and eastern flanks being marked by sharp monoclines (Figure 8-9). The total thickness of Tertiary strata in the basin is as much as 2,000 m, with about half the thickness being the Green River Formation. The top of the main sequence of shales and oil shales in the Parachute Creek Member of the Green River Formation is typically 150

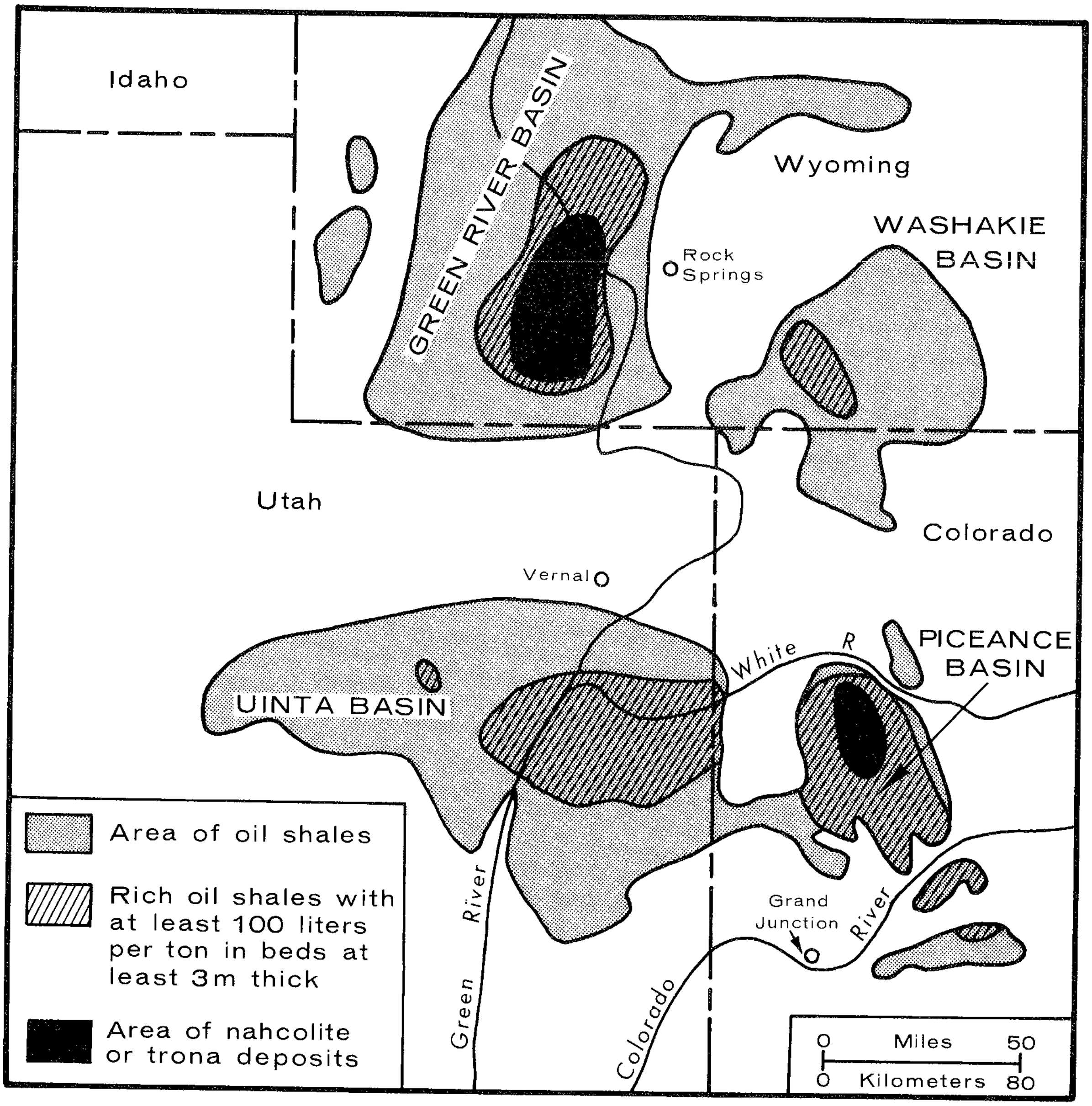

FIGURE 8-8. AREAS UNDERLAIN BY OIL SHALES OF GREEN RIVER FORMATION IN COLORADO, UTAH, AND WYOMING (MODIFIED FROM ASH, 1974)

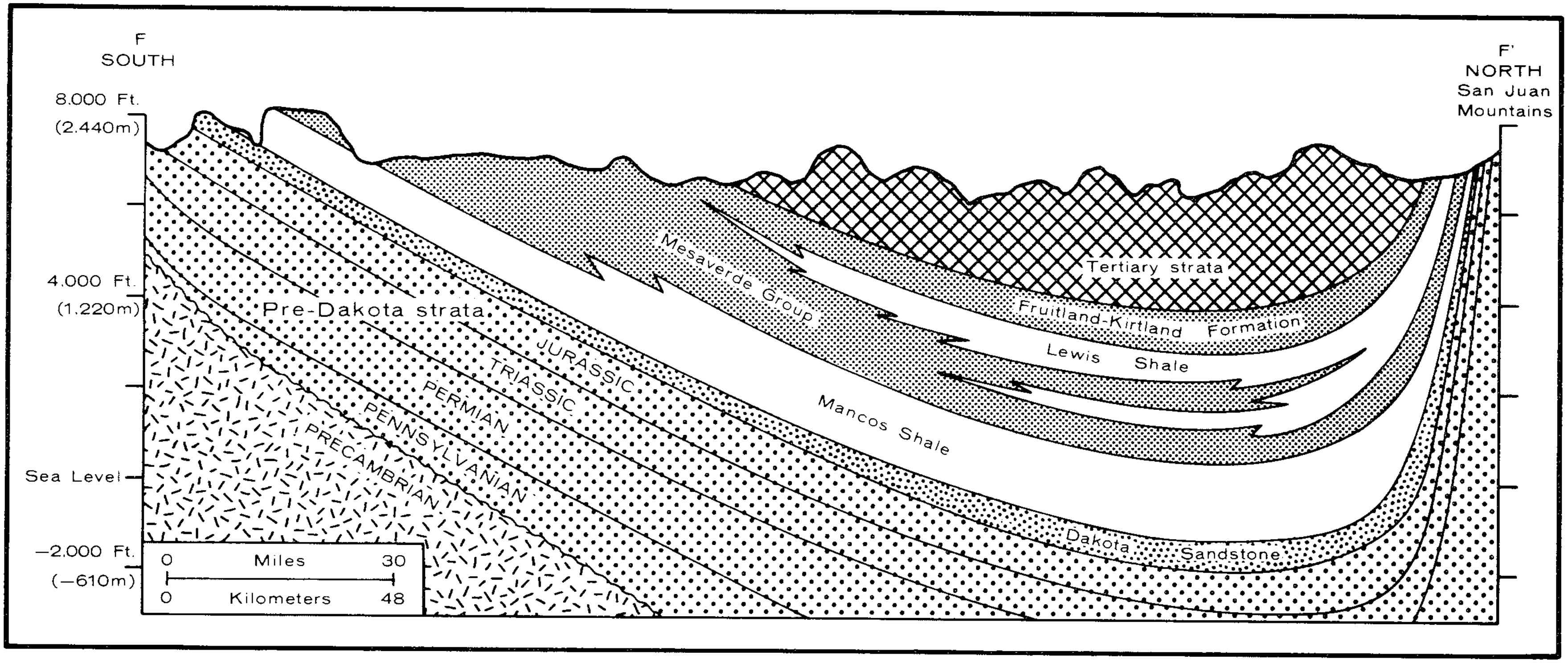

FIGURE 8-9. SCHEMATIC WEST-EAST CROSS SECTION THROUGH PICEANCE BASIN, SHOWING POSITION OF OIL SHALES IN GREEN RIVER FORMATION

to 400 m below the land surface in the Piceance Basin, and thus there are large areas where these strata are at moderate depths.

Faults are not common in the Piceance Basin, but there are many joints and other fractures in the surface and near-surface strata of the basin. The joints result in part from tectonic stresses built up in the basin, and in part from leaching of soluble minerals present in the Parachute Creek Member at shallow depths. Joints tend to close at a depth of about 300 m in the Piceance Basin, and this joint system has the effect of conducting meteoric water down at least to this depth in parts of the basin.

Both the Uinta and Piceance Basins are free of significant seismic activity and are considered to be in seismic-risk zone 1 according to the work by Algermissen (see Figure 1-3a). Moderate amounts of low-intensity seismic activity have, however, been triggered by injection of water in secondary-recovery operations at Rangely Oil Field in the northwestern corner of the Piceance Basin.

8.4.3.3 Mineralogy and Rock Properties

Oil shales of the Green River Formation consist mainly of dolomite, calcite, quartz, illite, and feldspar and thus are best regarded as dolomitic marlstones (Bradley, 1964; van West, 1972). Detailed discussions of the mineralogy and geochemistry of the formation are given by Smith (1969, 1974), Brobst and Tucker (1973), Desborough and Pitman (1974), and Robb and Smith (1974). Organic matter is an important constituent in certain beds and zones of the Green River Formation, particularly in the Parachute Creek Member, and these oil-shale units typically are a few meters to as much as 50 m thick. In some parts of the Piceance Basin almost, 300 m of the Parachute Creek Member is considered high-grade oil shale.

Upon distillation in a retort, the better-grade oil-shale beds in the Uinta Basin will yield about 60 to 100 liters of oil per metric ton of shale (15 to 25 gallons per ton), and those in the Piceance Basin will yield about 100 to 120 liters per metric ton (25 to 30 gallons per ton).

These resources, especially those in the Piceance Basin, are regarded as the most important oil-shale deposits in the United States, and currently they are being explored and tested.

At several places in both basins, government and industry have conducted experimental underground mining and retorting to establish the economic viability of oil-shale mining and processing (Murray, 1974; Netherland, Sewell and Associates, 1975b). Commercial-scale room-and-pillar mining of oil shale has already been demonstrated by the U.S. Bureau of Mines at Anvil Points, and by Colony Development Operation and Union Oil Co. at their Parachute Creek sites. Also, underground mining related to proposed in situ processing has been conducted by Occidental Oil Shale Corp. at Logan Wash and at the Colorado-b lease tract, and by Rio Blanco Oil Shale Co. at the Colorado-a lease tract. The U.S. Bureau of Mines is also sinking a deep, vertical shaft in the central part of the Piceance Basin. Typical room-and-pillar mines in the oil shale have rooms and pillars about 20 m square, 10 to 23 m in height (developed in one or two benches), at depths as great as 450 m, with removal of about 50 to 70 percent of the mined zone.

Netherland, Sewell and Associates (1975b) summarized a number of engineering studies that have been conducted on the oil shales. The compressive strength and stability of oil shales decrease with an increase in kerogen content, in thickness of oil-shale beds, or in temperature. The engineering properties and distillation characteristics of oil shale are presented earlier (Section 7.4.5.3).

8.4.3.4 Hydrology

Ground water in the Uinta and Piceance Basins occurs at shallow depths in many formations, including the Wasatch, Green River, Uinta, and (in the Uinta Basin) Duchesne River Formations (Coffin et al., 1971; Weeks, 1974; Price and Arnow, 1974; Netherland, Sewell and Associates, 1975b). Ground water is recharged mainly through joints and fractures that cut the outcropping rock units, and through the exposures of permeable sandstones and siltstones that are interbedded with the shales. Recharge is derived mainly during the spring from the melting of snow.

Strata overlying the oil-shale sequence, especially the Evacuation Creek Member and the Uinta Formation, consist mainly of coarser-grained clastics that contain moderate amounts of ground water. These units, along with the fractured Parachute Creek Member above the Mahogany Ledge (an aquitard), make up a moderately transmissive upper aquifer system with fresh to slightly brackish water. Wells completed in the upper aquifer yield as much as 1,200 l/min, although yields of less than 400 l/min are more common.

Water quality in the upper aquifer generally is more degraded with depth and in the direction of flow (Weeks, 1974). The water is classified as a sodium bicarbonate water that contains moderate amounts of sulfate and low concentrations of chloride and fluoride. The concentration of dissolved solids averages about 950 mg/l and ranges from 250 mg/l to more than 2,000 mg/l.

The lower aquifer system in the Piceance Basin consists of fractured oil shale and marlstone of the Parachute Creek Member, underlying the Mahogany Ledge. Secondary porosity and permeability of the lower aquifer are greatly enhanced by the dissolution of soluble minerals, chiefly nahcolite and halite (Weeks, 1974). The lower aquifer commonly is referred to as the "leached zone" because of the leaching or dissolution of soluble minerals by circulating ground water. Water wells drilled into the lower aquifer yield as much as 4,000 l/min for short periods, although 800 to 1,600 l/min is typical.

Water in the lower aquifer is also classified as a sodium bicarbonate water, with dissolved solids concentrations that are moderate to extremely high. Total dissolved-solids greater than 30,000 mg/l are common in the northern part of the Piceance Basin where the aquifer is underlain by nahcolite, dawsonite, and halite deposits. Around the margins of the basin the dissolved-solids concentration in the water in the lower aquifer near its outcrop is generally about 1,000 mg/l.

8.4.3.5 Mineral Resources

The Green River Formation contains the major oil-shale resources of the United States, and the richest deposits of oil shale underlie an area about 12,000 km^2 in the Piceance and Uinta Basins (van West, 1972; Murray, 1974; Netherland, Sewell and Associates, 1975b). Important oil shales in the Piceance Basin commonly yield about 100 to 140 liters of oil per ton (25 to 35 gallons per ton) of shale, whereas those of the Uinta Basin yield about 60 to 100 liters per ton (15 to 25 gallons per ton). The principal oil-shale resources are in the Mahogany Ledge and in other parts of the Parachute Creek Member.

The rich zones of oil shale are typically 15 to 60 m thick, and they are interbedded with zones of lean oil shale or other types of rocks. Owing to the high grade of these oil shales, particularly those in the Piceance Basin, many research and development programs have been conducted in the region by industry and the federal government to determine the economic feasibility of opening up this vast resource. Major efforts are still being made in both basins to evaluate in situ retorting of oil shale at moderate depths and surface retorting of oil shale after it has been extracted from surface or underground mines.

Large amounts of nahcolite (sodium bicarbonate mineral) and dawsonite (sodium aluminum hydroxyl carbonate) are present in the rich oil shales of the Green River Formation, chiefly in the Piceance Basin (Beard et al., 1974; Dyni, 1974). These minerals, which may be by-products of future oil-shale production, are regarded as potential sources of sodium and aluminum. Halite is another evaporite mineral also present in the Green River Formation of the Piceance Basin, but the halite is not present in sufficient quantity or purity to be considered a potential mineral resource at this time.

Oil and gas are important resources being developed in many parts of the Piceance and Uinta Basins (Sanborn, 1971, 1977; Lumb et al., 1972), and both basins are regarded as major petroleum provinces that will continue to see intensive exploration for many years to come. The biggest fields in the region are Rangely, in the Piceance Basin, and Bluebell-Altamont, in the Uinta Basin. Petroleum is now being produced from strata in every geologic system from Pennsylvanian through Tertiary, and the major producing zones are in the Pennsylvanian, Cretaceous, and Tertiary Systems. Most production is from porous sandstone reservoirs in structural traps, but it is believed that the potential for future reserves lies mainly in lenticular stratigraphic traps in strata of Pennsylvanian, Cretaceous, and Tertiary age (Sanborn, 1977). Substantial reserves of natural gas also are known in "tight" Upper Cretaceous and Lower Tertiary sands of the region, and attempts to produce this gas on a commercial basis have been made through nuclear stimulation and massive hydraulic fracturing in parts of the Piceance Basin.

Commercial deposits of gilsonite, an asphaltite that is a solid, tar-like hydrocarbon, occurs in veins 1 to 7 m wide and 2 to 22 km long in the north eastern part of the Uinta Basin. These veins cut vertically through Tertiary strata overlying the Green River Formation and extend down to depths greater than 500 m. Gilsonite has been mined commercially for many years from surface pits and deep mines, and it continues to be an important mineral resource in the area.

Other important mineral resources that have been developed locally around the perimeter of the basins are bituminous coals and tar sands. Both of these resources occur in strata older than the oil shales; their development has been mainly in surface or near-surface mines.

8.4.4 Other Units

8.4.4.1 Bright Angel Shale and Ophir Formation

The Bright Angel Shale of northwestern Arizona and the equivalent Ophir Formation of western Utah is a Middle Cambrian argillaceous unit that is as thick as 100 m in the Grand Canyon area (McKee, 1945; Palmer, 1971; Lochman-Balk, 1972). The unit consists of interbedded shale, siltstone, and sandstone deposited as a transgressive sequence as the Cambrian seas encroached on the craton. It is possible that this unit locally may be at least 75 m thick and at moderate depths in an undeformed area, but few subsurface data are available for the unit in the western part of the region.

8.4.4.2 Hermit and Organ Rock Formations

The Hermit Formation and equivalent Organ Rock Formation constitute a thick sequence of Early Permian red-bed clastics in southern Utah and northern Arizona (Baars, 1962; Bissell, 1968; Rascoe and Baars, 1972; Blakey, 1979). The dominant lithology is quartz siltstone with a red-stained matrix of clay and iron oxide and abundant carbonate cement. In some places the carbonate is dominant, and the rock is properly classified as silty limestone or dolomite. Shale or mudstone also makes up a significant part of the Hermit and Organ Rock Formations, but these fine-grained strata are irregularly interbedded with sandstones and other lithologies deposited in the alluvial and flood-plain environments of the two formations. The thickness of the Hermit and Organ Rock Formations is 50 to 250 m in the east, and it increases to 300 to 450 m near the Nevada border (Blakey, 1979).

8.4.4.3 Morrison Formation

The Morrison Formation of Late Jurassic age consists mainly of interbedded continental sandstones and mudstones. The total thickness of the formation typically is 100 to 250 m in most parts of the Colorado Plateau, but the unit is 300 to 450 m thick in the northwest (Craig et al., 1955; Keller, 1962; Cadigan, 1967; Peterson, 1972). The Morrison was laid down as a blanket-like sequence, and is largely recognized by its red, green, gray, tan, and purple shales. The formation consists mainly of sandstones in the southern and western parts of the region, but the formation may contain some moderately thick shales locally in other parts of the region. The principal argillaceous unit is the Brushy Basin Member at the top of the formation; the member is typically 30 to 125 m thick and consists mainly of siltstone, claystone, and mudstone.

The Morrison Formation is one of the major uranium-bearing formations in the Colorado Plateau, particularly in the Uravan and Grants Mineral Belts (Finch, 1967; Fischer, 1968; Butler, 1972). Uranium ores occur mainly in the sandstones, although other rock types also contain uranium locally, and they still are being prospected in many parts of the region.

8.4.4.4 Moenkopi and Chinle Formations

The Moenkopi Formation and overlying Chinle Formation of Triassic age are mainly red-bed argillaceous units that are widespread throughout the Colorado Plateau (McKee, 1954; Averitt et al., 1955; Repenning et al., 1969; O'Sullivan, 1970; MacLachlan, 1972; Stewart et al., 1972). Interbedded with the argillaceous strata are a number of beds of sandstone, siltstone, and conglomerate deposited in a complex system of marine and continental environments. The total thickness of the clastic sequence is commonly 300 to 600 m, but individual mudstone or argillaceous units typically are only 5 to 15 m thick.

In the southern part of the Colorado Plateau, the Petrified Forest Member of the Chinle is as thick as 300 m and consists mainly of silty shale and siltstone units that are red, brown, green-gray, and purple (Stewart et al., 1972; O'Sullivan, 1974). Much of this shale is bentonitic and montmorillonitic and was derived from the alteration of volcanic debris.

In most parts of the Colorado Plateau, the Moenkopi and Chinle Formations are surrounded by important ground-water aquifers (Repenning et al., 1969). The formations commonly overlie the Permian Coconino Sandstone aquifer and are in turn overlain by the Triassic(?) and Jurassic Navajo Sandstone aquifer.

8.4.4.5 Tertiary Shales of the San Juan Basin

The Nacimiento and overlying San Jose Formations of Paleocene and Eocene age are thick units of somewhat eratically distributed shale and sandstone deposited in alluvial, flood-plain, deltaic, and lacustrine environments in the northeastern part of the San Juan Basin of New Mexico. The Nacimiento Formation ranges from 250 to more than 500 m in thickness (Baltz et al., 1966; Baltz, 1967). In the southern part of the area the formation consists mainly of silty clay shale with some interbedded sandstone; to the north the amount of sandstone increases to as much as 50 percent of the formation. The San Jose Formation, the youngest Tertiary sequence in the basin, is 60 to 540 m thick and consists of shale, sandstone, and conglomerate. Study of the ground water in Tertiary rocks shows that there are a number of aquifers in the Nacimiento and San Jose Formations and that these aquifers can yield 140 to 800 l/min to water wells (Brimhall, 1973).

8.5 REGIONAL SUMMARY

The Colorado Plateau is a tectonically stable region with several sedimentary and structural basins that contain thick sequences of Upper Cretaceous and Tertiary shales that are flat lying or gently folded and that are at moderate depths in fairly large areas. The Upper Cretaceous Mancos Shale, in particular, is a thick, blanket-like marine shale deposited over the entire Colorado Plateau.

Basins containing thick shales are the Uinta, Piceance, Henry, Kaiparowits, Black Mesa, and San Juan Basins. All these basins are characterized by an arid to semiarid climate. The quality and quantity of ground water in each basin is not well understood, although water is known in the sandstone aquifers that commonly overlie and/or underlie the shales. Thus, a study of the geohydrology is an important part of any further examination of shales in the region. Current and future development of major energy resources is especially important in the Uinta, Piceance, and San Juan Basins, whereas the potential for development of significant mineral resources is much less in the Henry, Kaiparowits, and Black Mesa Basins.

The Uinta and Piceance Basins contain thick shales in both the Cretaceous and Tertiary Systems. The Mancos Shale is typically 1,200 to 1,800 m thick in both basins, and thick sections of the shale are present at depths of 300 to 900 m in a wide, undisturbed belt about 500 km long on the south side of both basins. To the west, the Mancos is divided by sandstone interbeds into the Tununk, Blue Gate, and Masuk Shales, which range in thickness from 100 to 600 m. On the northern and eastern sides of the basins, the strata dip rather steeply into the basins, and the Mancos Shale is at moderate depths in a relatively narrow belt. In most other parts of the basins, the shale is 1,000 to 6,000 m below the surface.

Tertiary shales in the Uinta and Piceance Basins are in the Green River Formation and include the organic-rich marlstones or oil shales. Individual members of the Green River Formation typically are 100 to 400 m thick, and most of them contain shale, marlstone, and oil-shale units that are locally more than 75 m thick. The depth to the top of the Green River Formation is commonly 150 to 1,000 m in the Uinta Basin and is commonly 150 to 400 m in the Piceance Basin. The strata are generally flat lying, and only locally are the shales faulted. There are well-developed sets of fractures in both basins, and locally these are filled with solid hydrocarbons (gilsonite) or are potential pathways for meteoric water that might migrate into the subsurface.

Mineral resources of the Uinta and Piceance Basins are important and they will be developed in the future. Both basins are major petroleum provinces, with production coming mainly from strata of Pennsylvanian, Cretaceous, and Tertiary age. The Green River Formation in both basins also contains the major oil-shale reserves of the United States, and in the Piceance Basin the formation contains potentially valuable deposits of nahcolite and dawsonite. Coal, asphaltite, tar sands, and other mineral resources are important in various parts of both basins.

The Henry Basin is tectonically stable, although a sharp flexure is present on the western margin of the basin and Tertiary intrusive rocks are present on the east. The basin is near the boundary of seismic-risk zones 1 and 2. The Tununk, Blue Gate, and Masuk Shales are 150 to 450 m thick, and in the central part of the basin these shales are flat lying, undisturbed, and are at depths of 300 to 900 m. Important coal deposits are known in the basin; mining of these coals or the bentonite and other known mineral deposits will be at shallow depths. Petroleum has not been discovered in the basin.

The Kaiparowits Basin contains 150 to 300 m of the Tropic Shale (equivalent to the lower part of the Mancos Shale) at depths of 300 to

900 m. The shale beds typically have gentle dips, and the simple structures of the basin consist of broad folds and several sharp monoclines. The basin is in seismic-risk zone 2. Coal resources are locally important in the basin, and mining of them or other known mineral resources generally will not involve the shale unit. Oil has been produced only from a small part of the Kaiparowits Basin, and the basin is not regarded as an important petroleum province.

The Black Mesa Basin contains a single shale unit, the Tununk Shale, which is 120 to 210 m thick. In most parts of the basin the shale is less than 300 m below the land surface, but in some areas the lower half of the shale is 300 to 450 m below the surface. Strata in the basin are nearly flat lying, with only a few gentle folds, and the basin is near the boundary of seismic-risk zones 1 and 2. Surface-minable coal deposits are locally important in the basin. Petroleum has not been discovered in the basin.

The San Juan Basin contains several thick Upper Cretaceous shales that are relatively undisturbed and at moderate depths. The Mancos Shale is 100 to 600 m thick and 300 to 900 m below the surface in the southern and western parts of the basin; the Lewis Shale is 180 to 250 m thick and 700 to 900 m deep in the central and north-central parts of the basin; and the Kirtland Shale consists of 100 to 450 m of shale, with a medial sandstone, at depths of 300 to 900 m in the north-central part of the basin. The San Juan Basin is a major petroleum province, with most of the production coming from the northern half of the basin. Coal, uranium, and other minerals also are locally important in the basin.

9. GREAT BASIN OF NEVADA AND UTAH

9.1 STRUCTURE AND GEOLOGIC FRAMEWORK

Thick shale formations of Devonian and Mississippian age crop out in some of the numerous mountain ranges of the Great Basin Region in Nevada and western Utah (Figure 9-1). Other argillaceous units of Cambrian age also are locally thick. The Great Basin, which is part of the Basin and Range Province, is characterized by elongate, subparallel, block-faulted mountain ranges separated by broad, nearly flat-floored valleys or basins filled with alluvium (Osmond and Elias, 1971).

In Late Precambrian and Early Cambrian time, a broad seaway, the Cordilleran Geosyncline, formed in parts of Nevada and west-central Utah to receive a sequence of predominantly clastic sediments. These deposits, mostly derived from lower Precambrian metamorphic terranes to the east, are typically 60 to 120 m thick along the eastern flank of this seaway and thicken westward to 3,000 to 3,700 m. In Middle Cambrian time, sedimentation was characterized by the deposition of carbonates in shallow seas, particularly in eastern Nevada. In central Nevada, the carbonates are interbedded with shales and siltstones in a transitional belt, and farther west the transitional rocks grade into chert, shale, sandstone, and volcanic rocks. The three major assemblages, that is, carbonates, transitional rocks, and siliceous/volcanic rocks, were laid down in these different parts of the seaway without significant interruptions from Middle Cambrian to the end of Devonian time (Stewart, 1964; Stokes, 1979).

In Late Devonian time, the Antler orogeny, a major mountain-building phase, began in western Nevada. This orogeny was culminated by the movement eastward of a number of thrust plates that reached points along a line from Austin to Eureka and then to Mountain City, and covered a belt about 140 km wide. Subsequent deformation and erosion have resulted in local removal of the overthrust plate, thus exposing rocks of the lower plate in windows.

During the episodes of uplift in the Antler orogenic belt in central Nevada, several major depositional troughs developed east of the uplift

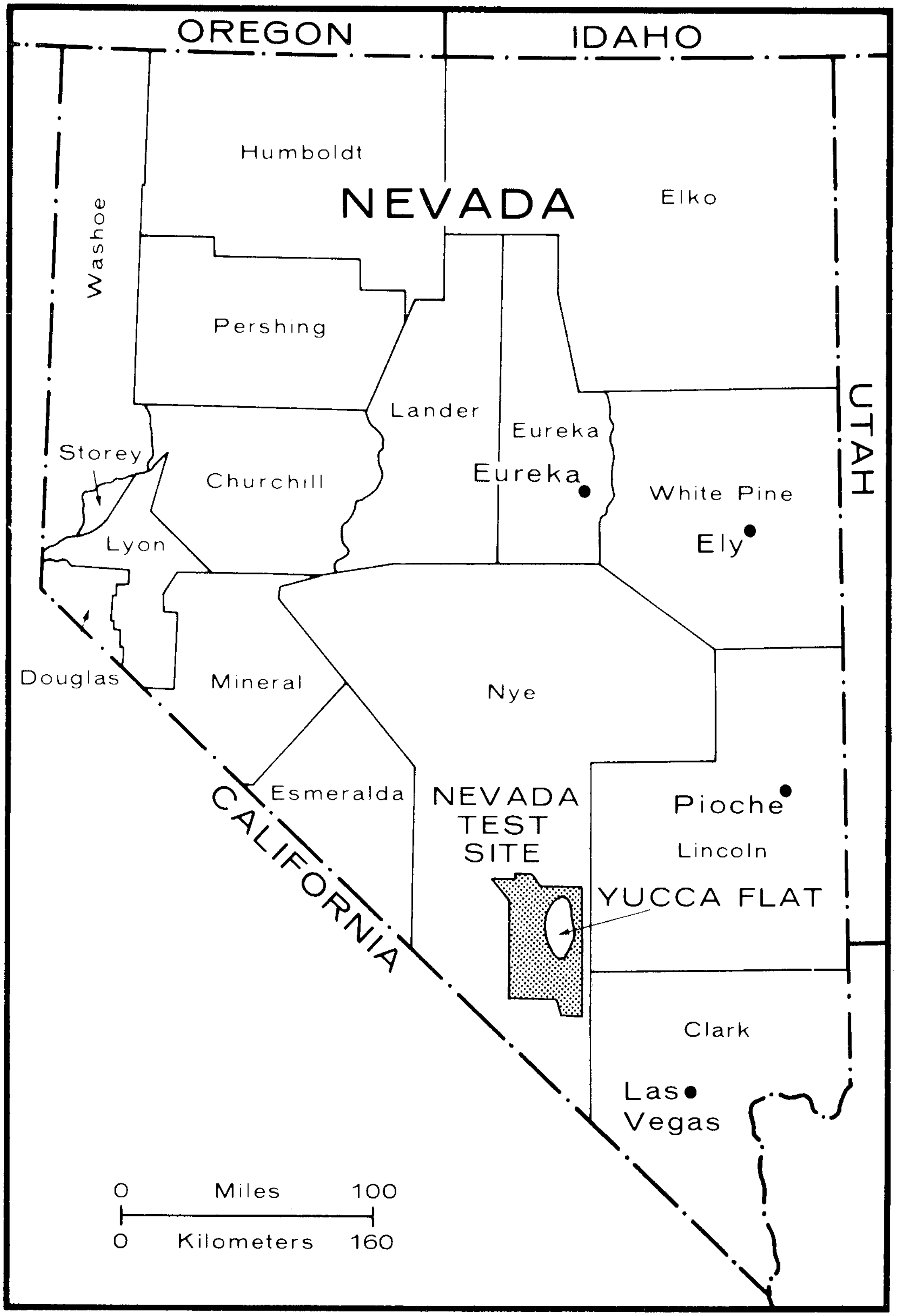

FIGURE 9-1. MAP SHOWING COUNTIES AND SEVERAL CITIES IN NEVADA AND LOCATION OF NEVADA TEST SITE IN SOUTHERN NYE COUNTY

(Figure 9-2): the Chainman-Diamond Peak Trough on the north and the Eleana Trough on the south received great thicknesses of fine-grained clastics from latest Devonian time through the entire Mississippian Period. These clastic wedges are somewhat coarse-grained and conglomeratic on the west, adjacent to the uplift, and they have been called the overlap assemblage (Roberts et al., 1958) where they overlap the orogenic belt and flank older rock units. These strata are represented predominantly by shales and argillites in the central part of the troughs, where the sequence is more than 2,000 m thick, and they grade eastward into shales and limestones only 300 to 600 m thick (Nolan et al., 1956) in easternmost Nevada and western Utah (Figure 9-2).

By Middle Pennsylvanian time the Antler orogenic belt was largely eroded, leaving only a few islands projecting above the sea. Late Pennsylvanian and Early Permian limestone and associated rock assemblages were then deposited over much of Nevada. In Late Permian time, uplift and mountain building in western Nevada began again and culminated in the movement of another thrust plate eastward onto the roots of the Antler orogenic belt. This younger period of mountain building, the Sonomo orogeny, also resulted in a flood of coarse clastics into the marine waters that still covered eastern Nevada (Silberling and Roberts, 1962). At the end of the Permian Period, much of eastern and central Nevada was uplifted just above sea level.

A broad belt of western North America, including the Great Basin Region, was uplifted during the Mesozoic Era, and the Cordilleran Geosyncline was destroyed. The Meso-Cordilleran High, occupying the site of the former geosyncline, reached its maximum elevation during the Cretaceous Period, and only a few small patches of nonmarine rocks representing the system are still preserved.

The Tertiary Period was characterized by igneous activity, by deposition of large volumes of ash-flow tuff, and by block faulting. The start of volcanism coincided with the development of numerous north-south normal faults, and the formation of horsts and grabens, which are primarily responsible for the development of elongated mountain ranges and intervening flat valleys (Albers, 1964; Eaton, 1979). During the last few

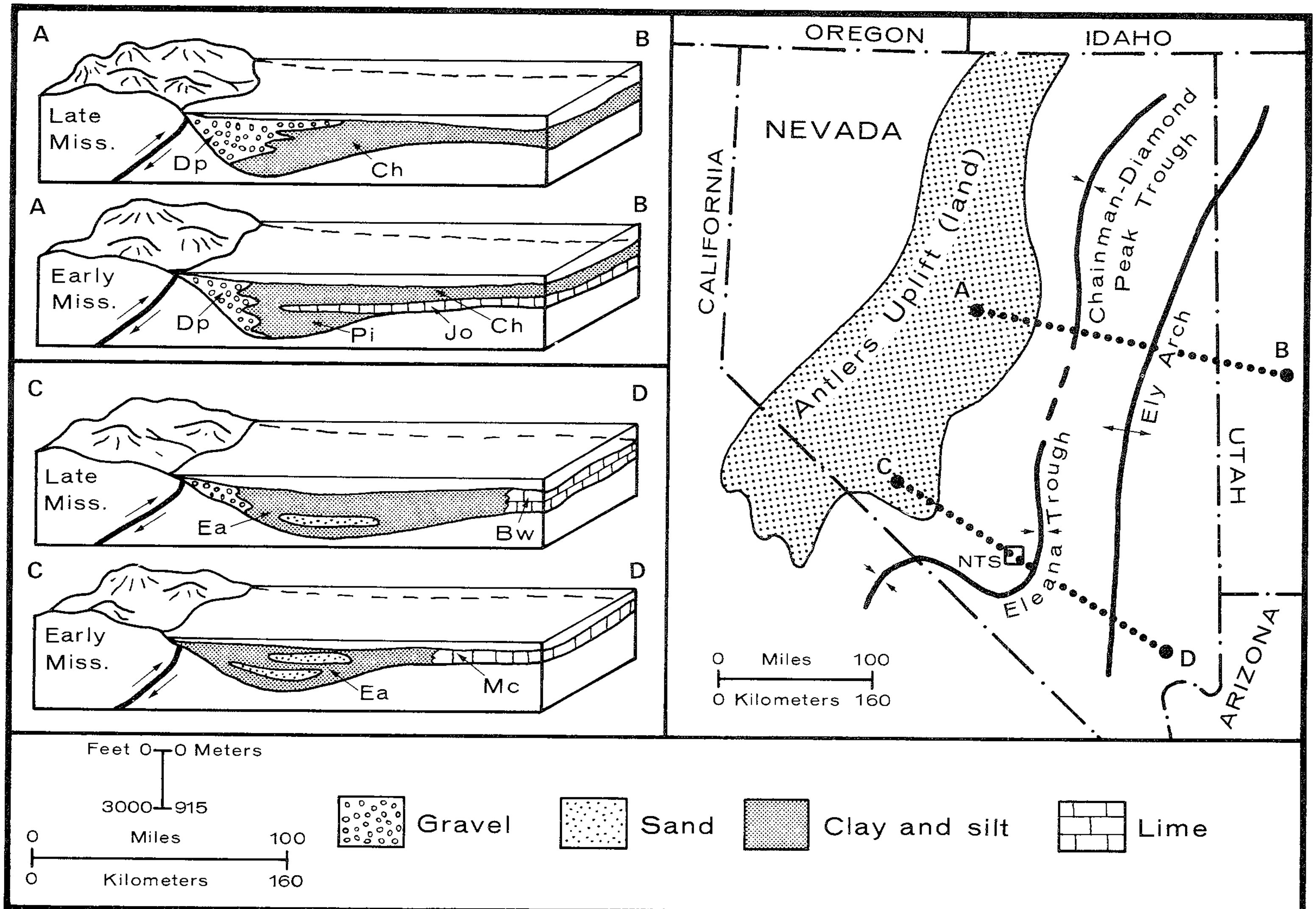

FIGURE 9-2. PALEOTECTONIC MAP AND BLOCK DIAGRAMS, SHOWING MISSISSIPPIAN SEDIMENTARY UNITS FORMED IN GREAT BASIN AREA (MODIFIED FROM LARSON AND LANGENHEIM, 1979). ABBREVIATIONS: DP, DIAMOND PEAK FORMATION; Ch, CHAINMAN FORMATIONS; Pi, PILOT SHALE; Jo, JOANA LIMESTONE; Ea, ELEANA FORMATION; Bw, BATTLESHIP WASH FORMATION; Mc, MONTE CRISTO FORMATION

million years the rock record of the Great Basin includes localized extrusion of basic lavas, continued accumulation of continental clastics (including many lacustrine facies in the valley trenches), and local glacial activity.

9.2 REGIONAL SEISMICITY

Western Nevada and western Utah are situated in seismic-risk zone 3, where major damage may be expected, whereas the remaining portion of the Great Basin is in seismic-risk zone 2, where moderate damage may be expected (Algermissen, 1969). Since 1852, more than 30 earthquakes of Modified Mercalli Intensity VI (MMI VI) or greater have occurred in western Nevada, and at least three of these were classified as MMI X. In addition, seven earthquakes of MMI VI or greater were centered in the eastern part of the state. Almost 2,000 other earthquakes have been cataloged in nearly 125 years of historical records. Thus, Nevada ranks among the most seismically active states in the nation (Figures 1-3a and 1-3b).

A number of the larger earthquakes have produced some spectacular examples of surface faulting, including the earthquakes that occurred at Pleasant Valley (1951), Cedar Mountain (1932), Excelsior Mountain (1934), Rainbow Mountain (1954), and Fairview Peak-Dixie Valley (1954). Slemmons et al. (1965) tabulated more than 1,000 earthquakes with epicenters within the state from 1852 to 1961, and additional detailed information on Nevada earthquakes was provided by Coffman and von Hake (1973) and von Hake (1974).

9.3 REGIONAL HYDROLOGY

9.3.1 Surface Water

The Great Basin is a major subdivision of the Basin and Range Province in which surface water discharges into enclosed basins rather than discharging into the sea. Drainage finds an outlet to the sea only in the southeastern part of the region through the Colorado River system and in some of the northern part of the region through the Snake River system. Precipitation ranges from 10 to 40 cm per year in most parts of the region, and locally it is 40 to 150 cm per year in the high mountain ranges (Eakin et al., 1976). Most of the precipitation falls during the winter and spring months to form a mountain snowpack, and most of the streamflow occurs during the spring melt-and-runoff period.

The largest river in the basin is the Humboldt River, which derives most of its water from the Ruby and East Humboldt Ranges. It flows generally westward then turns south to drain into the Humboldt and Carson Sinks, where its water eventually evaporates. The Walker, Carson, and Truckee Rivers drain the eastern flank of the Sierra Nevada Mountains in California and flow eastward to enclosed basins in Nevada: the Carson River to the Carson Sink, the Walker River to Walker Lake, and the Truckee River to Pyramid Lake (Thomas, 1964).

9.3.2 Ground Water

Ground-water resources in the Great Basin occur in thick alluvium that fills the intermontane basins or in consolidated rock units that are present both in the mountains and beneath the valley alluvium (Thomas, 1964; Price et al., 1974; Eakin et al., 1976). Only a few areas in the region have been studied in sufficient detail to permit a good understanding of the ground-water system, but general observations can be made about both the valley-fill and bedrock aquifers.

Valley-fill aquifers occur in alluvium and fan deposits that partly fill the structural depressions and intermontane basins. These deposits consist of sand and gravel that serve as the main aquifers, although interbeds of silt and clay locally are water saturated and yield minor amounts of water to wells. In most valleys, ground water occurs in porous alluvium in a zone of continuous saturation, and the water table is typically at shallow depths in topographically low parts of the valleys (Eakin et al., 1976). The depth to water increases toward the mountains and may be 100 m or more beneath the upper parts of some alluvial fans.

Data on the thickness of valley-fill aquifers generally are not available. The maximum thickness probably varies greatly from basin to basin and even within certain basins. Available data indicate that aquifers commonly may be as much as 300 m thick in the larger basins, but no generalized statements can be made about the smaller areas (Eakin et al., 1976).

A large amount of ground water also is stored in consolidated carbonate and volcanic rocks that make up part of the mountain ranges and that underlie the intermontane basins. These reservoirs generally are not continuous and are difficult to evaluate. Local barriers, consisting of faults or low-permeability rock units, inhibit the downward or lateral flow of ground water and thus create isolated ground-water bodies in the mountains (Eakin et al., 1976). Many mountain springs and streams are fed by these perched ground-water bodies.

The chemical quality of the ground water is less than 1,000 mg/l dissolved solids in most alluvium (Eakin et al., 1976). Saline water does occur, however, near some thermal springs and in areas where an aquifer is adjacent to soluble salts. Also, in sink areas, such as Great Salt Lake, Sevier Lake, and Carson Sink, the ground water is highly saline, owing to evaporation of surface water that recharges the ground water, and the dissolved-solids concentration locally exceeds that of ocean water.

9.4 SHALES AND ARGILLACEOUS UNITS

9.4.1 Introduction

Shales and argillites of the Great Basin Region are chiefly of Cambrian and Late Devonian through Mississippian age. The Eleana Formation (Late Devonian and Mississippian) has been studied more extensively on the Nevada Test Site in southern Nye County than has any other argillaceous unit in the region, and thus it deserves a full discussion in this report. The other principal thick and widespread units in the region are the Pilot and Chainman Shales, which are largely correlative with the Eleana Formation but were deposited in a different depocenter farther north.

Several other shale formations that are less understood but deserve mention are the Pioche, Secret Canyon, and Dunderberg Shales, all of Cambrian age. Additional clay-rich units present in widely scattered places in the region were summarized by Simpson et al. (1979).

9.4.2 Eleana Formation

9.4.2.1 Stratigraphy

The Eleana Formation is a thick sequence of diverse rock types that crop out on, or adjacent to, the Nevada Test Site in southern Nye County, Nevada. Argillite, a term used for a somewhat indurated rock derived from shale, claystone, or mudstone by slight metamorphism, is the dominant rock in the Eleana Formation, although sandstone, quartzite, conglomerate, and limestone also are present. The Eleana Formation of Late Devonian and Mississippian age (Figure 9-3) was named by Johnson and Hibbard (1957) and was further described by Poole et al. (1961, 1965), Cornwall (1972), Poole and Sandberg (1977), Larson and Langenheim (1979), and Skipp (1979). Stratigraphic information is largely derived from the major outcrops in the Eleana Range and Quartzite Ridge on the northwestern side of Yucca Flat at the test site, and from the several other smaller exposures on Shoshone Mountain, Mine Mountain, Bare Mountain, and Cactus Range. Exposures on the northern side of Bare Mountain were originally named the Meiklejohn Formation by Cornwall and Kleinhampl (1961), but these strata later were included in the Eleana Formation by Cornwall (1972) and the name Meiklejohn Formation was abandoned.

The Eleana Formation was deposited in a north-northeast-trending trough, the Eleana Trough, that developed in southern Nevada just east of the Antler uplift (Figure 9-2). The trough was about 100 km wide and 200 km long, and it persisted from latest Devonian time throughout the entire Mississippian Period. A wedge of coarse clastic sediments apparently was deposited west of the present outcrops, and these coarse

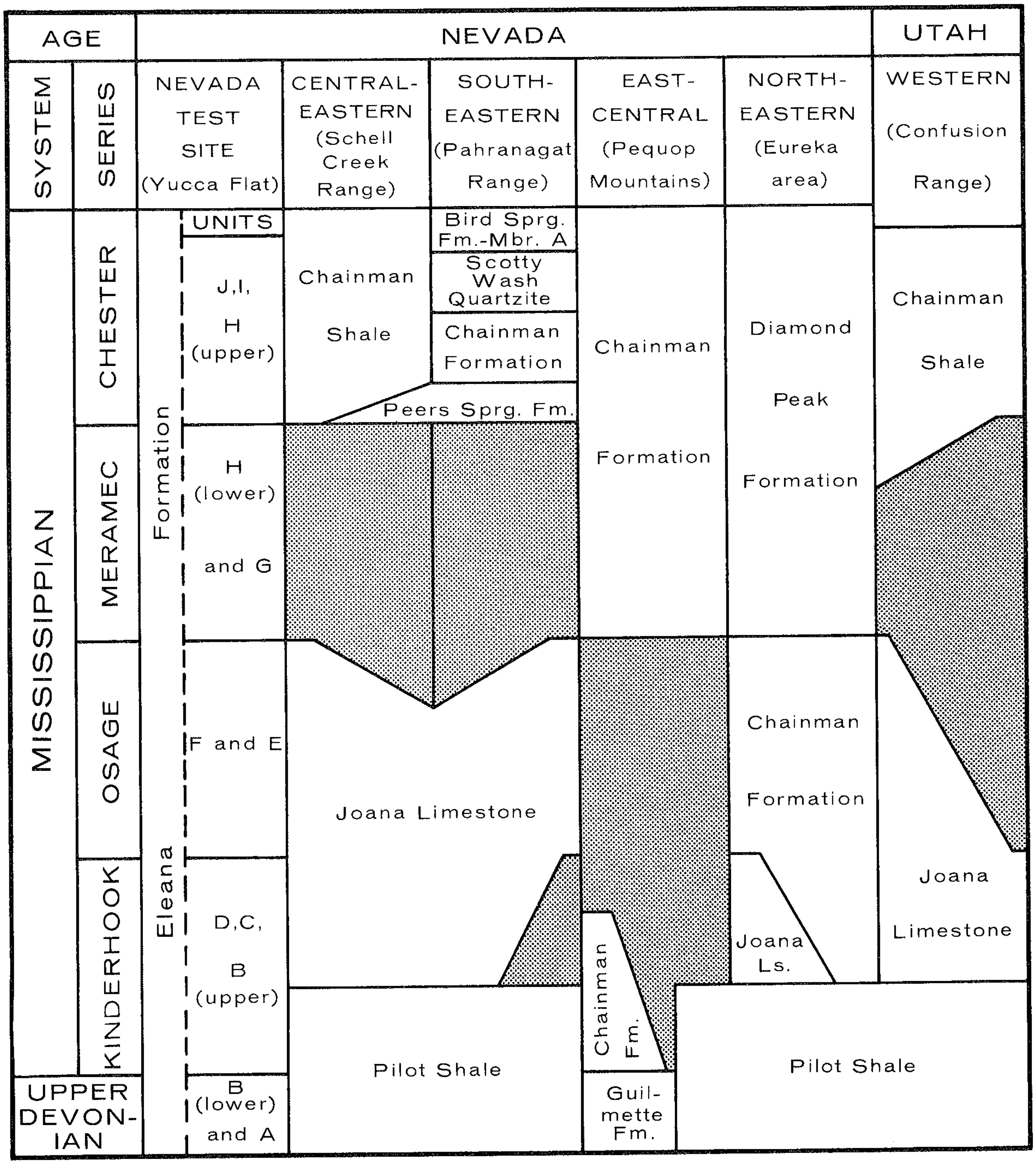

FIGURE 9-3. CORRELATION CHART OF MISSISSIPPIAN ROCKS IN GREAT BASIN REGION OF NEVADA AND WESTERN UTAH (MODIFIED FROM CRAIG ET AL., 1979)

sediments graded eastward into a thick sequence of finer-grained clastics across the Nevada Test Site area. The formation is partly conglomeratic to the west in both the Cactus Range and in the vicinity of Beatty.

The stratigraphy of the Eleana Formation, which is at least 2,350 m thick, is represented by a composite section consisting of partial sections measured in the various outcrops (Figure 9-4). Further work at Syncline Ridge, on the western side of Yucca Flat, shows that about 2,160 m of strata are present in just the upper half of the Eleana Formation (Hodson and Hoover, 1979), and thus the total thickness of the formation may well be greater than 3,000 m. Correlation from outcrop to outcrop is difficult, owing to facies changes, structural complexities, and partial cover by younger sediments, and thus the proposed stratigraphic sequence is uncertain (Poole et al., 1961; Cornwall, 1972).

The four major rock types that make up the Eleana Formation are (1) argillite, (2) siliceous siltstone and sandstone, (3) quartzite and conglomerate, and (4) limestone (Poole et al., 1961). The formation has been divided into 10 major lithologic units, referred to as A through J in ascending order (Figure 9-4). These units consist of the following: unit A is limestone and limestone conglomerate; unit B is argillite; unit C is quartzite and conglomerate; unit D is argillite and quartzite; unit E is argillite; unit F is quartzite, argillite, and conglomerate; unit G is quartzite, conglomerate, and argillite; unit H is argillite; unit I is limestone and argillite; and unit J is argillite. It appears that some of the argillite units can be traced over a distance of at least 13 km, and thus further examination and coring may establish some lateral continuity in these important units.

Argillite in the Eleana Formation is typically yellowish-brown to pale red and laminated, and commonly it contains iron oxide pseudomorphs after pyrite, plant-stem fragments, and light-colored sinuous markings on bedding planes that have been interpreted as worm trails and borings (Poole et al., 1961).

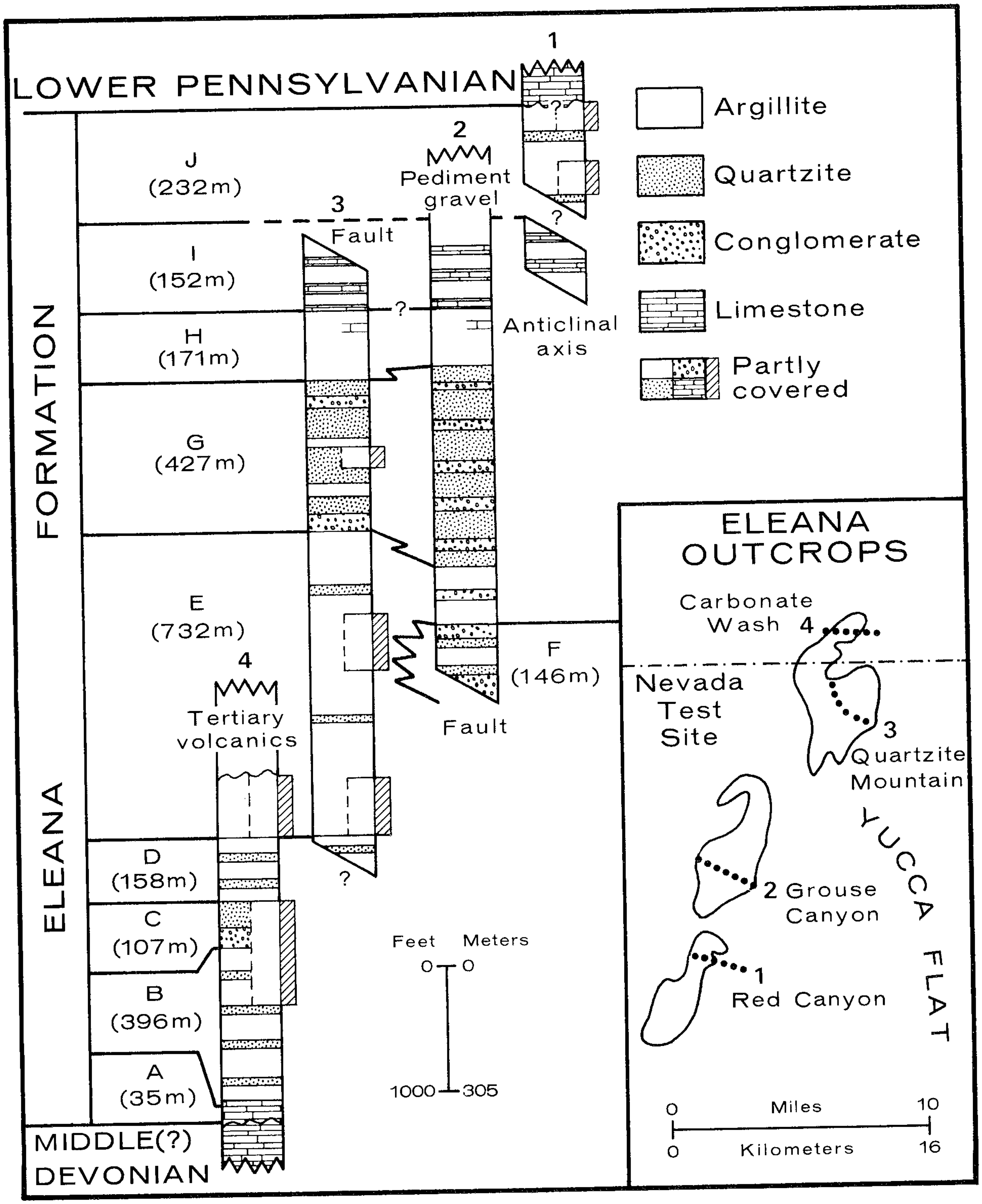

FIGURE 9-4. COMPOSITE STRATIGRAPHIC SECTION OF LATE DEVONIAN-MISSISSIPPIAN ELEANA FORMATION AT YUCCA FLAT ON NEVADA TEST SITE, NYE COUNTY, NEVADA (MODIFIED FROM POOLE ET AL., 1961). UNITS A THROUGH J ARE THE MAJOR LITHOLOGIC DIVISIONS

9.4.2.2 Geologic Setting

The geology of southern Nye County and the area embracing outcrops of the Eleana Formation is moderately complex (Johnson and Hibbard, 1957; Ekren, 1968; Cornwall, 1972) (Figures 9-5, 9-6). Structural deformation was divided by Cornwall (1972) into the following types: (1) folds, thrust faults, tear faults, and strike-slip (wrench) faults; (2) cauldron subsidence, domes, and high-angle faults related to volcanic activity; (3) Basin and Range type of high-angle normal faults; and (4) gravity slides.

Folds, thrusts, and other faults are most intense in the Late Precambrian and Paleozoic rocks of Bare Mountain and Spring Mountains, but other mountain ranges have similar patterns of deformation. Cornwall (1972) believed that this deformation is related to development of the Las Vegas Valley shear zone in Middle Cretaceous time, as described by Longwell (1960). The Las Vegas Valley shear zone extends to the southern boundary of the Nevada Test Site.

Volcano-tectonic activity during Miocene and Pliocene time in southern Nye County caused development of large calderas, or circular, graben-like structures containing some or all of the following features: domes, elevated blocks, and normal faults. Calderas in the vicinity of the Nevada Test Site are Belted Range, Timber Mountain, and Silent Canyon (Ekren, 1968). These and other volcanic centers in and around the Nevada Test Site have produced great amounts of volcanic ash, tuff, and lava that range in age from about 7.5 to 26.5 m.y.

Basin and Range normal faults that range in age from Miocene to Holocene are abundant in southern Nye County, and they bound most of the mountains and ranges. North-trending faults are most common in the area, but other trends also are locally prevalent.

Gravity slides occur in several places in Nye County (Cornwall, 1972). These slides probably range in age from Cretaceous to Pliocene and represent movement of large masses of rock through distances of 0.50 to 10 km.

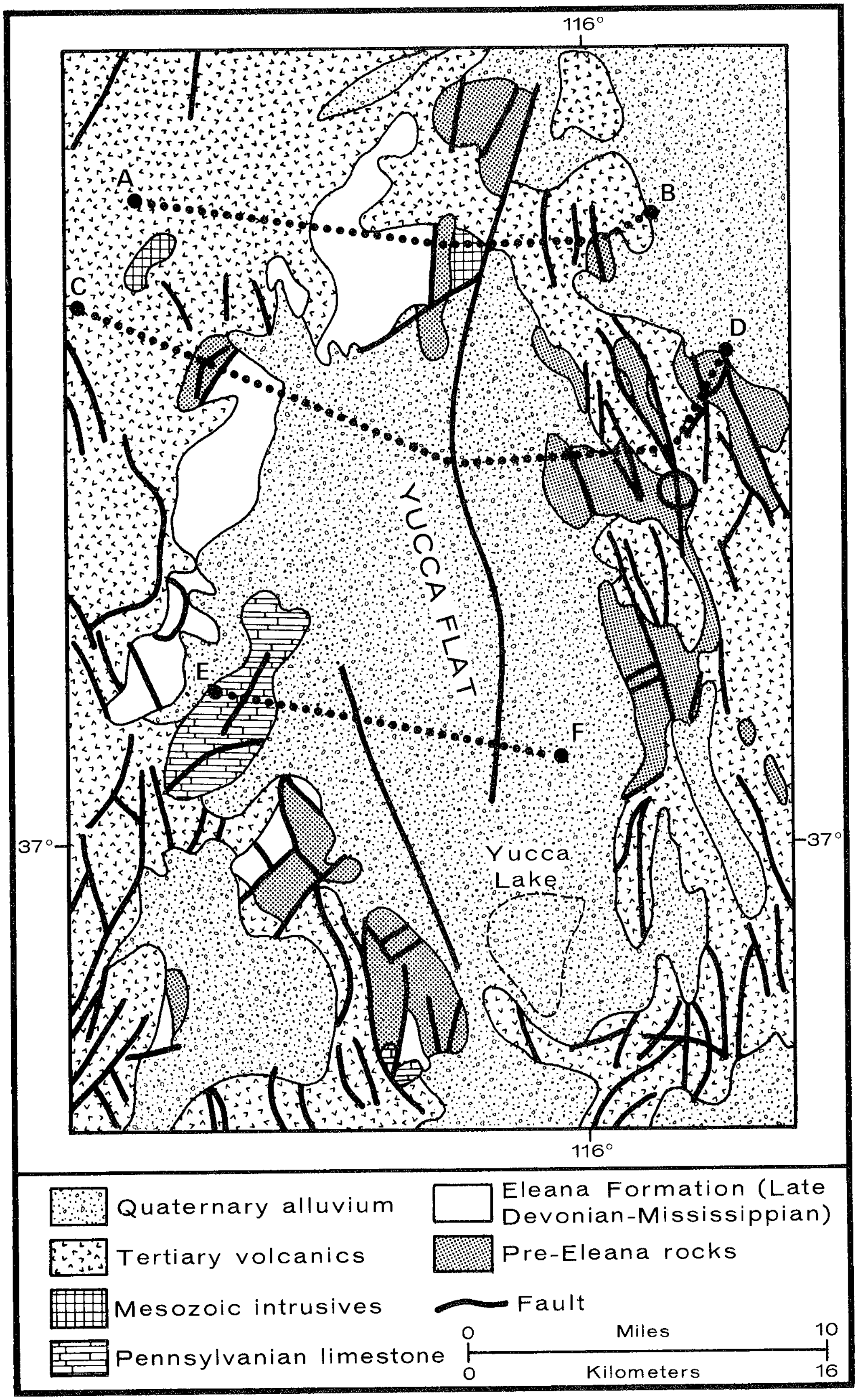

FIGURE 9-5. GENERALIZED GEOLOGIC MAP OF YUCCA FLAT AREA OF NEVADA TEST SITE, NYE COUNTY, NEVADA (MODIFIED FROM CORNWALL, 1972). CROSS SECTIONS A-B, C-D, AND E-F ARE SHOWN IN NEXT FIGURE

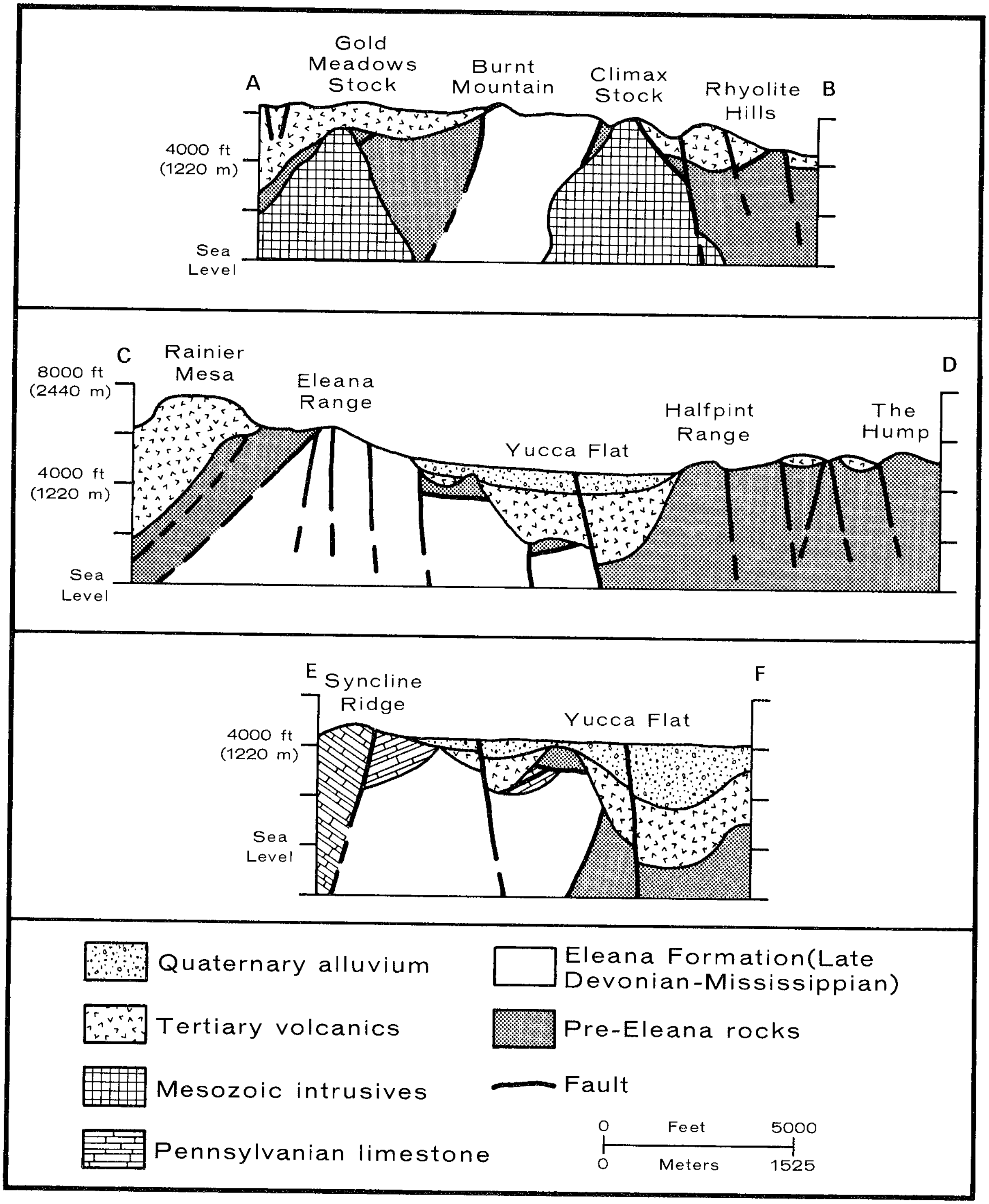

FIGURE 9-6. GENERALIZED GEOLOGIC CROSS SECTIONS THROUGH YUCCA FLAT AREA OF NEVADA TEST SITE, NYE COUNTY, NEVADA. SECTIONS A-B AND C-D ARE MODIFIED FROM HINRICHS (1968), AND SECTION E-F IS MODIFIED FROM WINOGRAD AND THORDARSON (1968). LOCATION OF CROSS SECTIONS IS SHOWN IN PREVIOUS FIGURE

The largest area that contains exposures of the Eleana Formation is in the Eleana Range-Twin Peaks-Quartzite Ridge area on the northwestern side of Yucca Flat on the Nevada Test Site (Figures 9-5, 9-6). The outcrop belt is generally 2 to 6 km wide and extends about 25 km to the north-northeast from Tippipah Spring. Strata within this outcrop belt generally dip 20° to 40° to the southeast, but in the vicinity of faults the strike and dip are highly variable. Other outcrops of the Eleana Formation in southern Nye County are more intensely folded and faulted, and the areas of exposure do not exceed several square kilometers.

Deformation of Late Precambrian and Paleozoic rocks around Yucca Flat has been complex and consists of broad folds, thrusts, and high-angle reverse faults and normal faults. Folds on the western side trend northeast, and thrust faults are most pronounced west of Yucca Flat. Prominent high-angle normal faults trending, for the most part, northeast, north, and north-northwest have displaced the Precambrian and Paleozoic rocks and also Miocene-Pliocene tuffs. A recently reactivated north-trending normal fault in Yucca Flat offsets alluvium and tuff as much as 360 m, with the eastern side down. Southwest of Yucca Flat, along the eastern flank of Skull Mountain (southeast of Shoshone Mountain), a prominent northeast-trending left-lateral strike-slip fault has ruptured the Salyer and Washmonie Formations and younger rocks. In this area and to the northwest around Jackass Flats, the Miocene and Pliocene volcanic rocks are ruptured by numerous high-angle normal faults probably related to both tectonic and volcanic activity.

Paleozoic rocks, including the Eleana Formation, extend under the Tertiary volcanics and unconsolidated alluvium that underlie Yucca Flat (Figure 9-6). Depths to the Paleozoic rocks beneath Yucca Flat are generally about 300 to 1,000 m (Healey, 1968).

9.4.2.3 Mineralogy and Rock Properties

Mineralogical analyses of the Eleana argillite indicate a wide variation in mineral constituents. The general assemblage is characterized by quartz and illite as dominant minerals, with lesser amounts of kaolinite, chamosite, pyrophyllite, chlorite, vermiculite, siderite, calcite, ferroan dolomite, and pyrite (Lappin and Olsson, 1979). The quartz content ranges from approximately 15 to 50 weight percent. Bulk x-ray analysis of powdered samples indicates that the illite contains up to 10 percent interlayering of chlorite and 60 to 80 percent illite. The remainder of the illite is interlayered with montmorillonite and vermiculite.

Several cores have been drilled into the J unit at Syncline Ridge, on the western side of Yucca Flat, and at Calico Hills, in the southwestern part of the Nevada Test Site (Hodson and Hoover, 1978, 1979; Maldonado et al., 1979). In these cores the argillite is typically gray, dark gray, and black, and it contains numerous shear planes and foliated structure. Many fractures are present in the cores, with most fractures being parallel to bedding. In one core, there are generally two to nine fractures per meter of rock, with the number of fractures decreasing at depths below 500 m, whereas in the other cores fractures average 13 to 15 per meter. In addition, numerous faults and brecciated zones were penetrated in the cores.

The natural-state bulk density of argillite in the cores generally ranged from 2.44 to 2.71 g/cm^3 and averaged about 2.60 g/cm^3. The porosity of the argillite generally was 8 to 16 percent in the top 500 m of one core and 6 to 12 percent at depths of 500 to 914 m in the same hole; in another hole the porosity averaged 11 percent. The moisture content of the argillite in several cores was typically about 2 to 4 percent. Geomechanical measurements also were made on samples from some of the cores.

Thermomechanical studies of Eleana Formation argillite indicate that in situ thermal conductivities are reduced at temperatures greater than 100°C (Lappin and Olsson, 1979). Heating causes contraction of the rock, which in turn causes opening of joints, with a resulting increase in permeability and a decrease in thermal conductivity. The contraction is believed to be due to the presence of small amounts of expandable clays.

9.4.2.4 Hydrology

Precipitation in the Yucca Flat area of the Nevada Test Site averages 10 to 20 cm per year, although it ranges from 20 to more than 40 cm per year in some of the high mountain ranges that are adjacent to and drain into Yucca Flat (Eakin et al., 1976). The area is one of internal drainage, where ephemeral streams and washes carry runoff to Yucca Lake, an intermittent or playa lake from which ponded water evaporates or seeps down into the valley-fill alluvium.

The principal bedrock aquifers in the Yucca Flat area are the Cambrian through Devonian carbonate rocks that make up a substantial part of the bedrock underlying alluvium and Tertiary volcanics in the basin (Winograd and Thordarson, 1968). These carbonates, present at depths of 300 to 1,500 m below Yucca Flat, have fracture transmissibilities that range from 4,000 to 4,000,000 l/day per foot, according to pumping-test analysis at various parts of the Nevada Test Site and vicinity. The permeability of the carbonates here is further shown by the low hydraulic gradient of these aquifers in Yucca Flat; the potentiometric surface within the carbonate aquifers varies by only 11 m throughout the valley (Winograd and Thordarson, 1968). The carbonate aquifers beneath Yucca Flat are probably hydrologically continuous with overlying alluvium and volcanics, but they may be isolated from other carbonate aquifers in adjacent valleys by the bordering clastic aquitards such as the Eleana Formation.

The permeability of the unit appears to be low, and the formation acts as an aquitard in the Yucca Flat area (Winograd and Thordarson, 1968). The fracture transmissibility of this thick clastic sequence in various parts of the Nevada Test Site is less than 4,000 l/day per foot, according to hydraulic tests. In addition to outcrops on the west side of the valley, the Eleana Formation underlies the valley-fill material at depths of 100 to 600 m in much of the central and western half of Yucca Flat. The potentiometric level within the unit is several hundred meters higher than that of the carbonate aquifer, and the hydraulic gradient appears to be about 50 to 175 m/km (Winograd and Thordarson, 1968).

Two test holes drilled into the Eleana Formation at Syncline Ridge showed that the hydraulic heads increase markedly with depth, indicating a likelihood for upward flow of ground water through the formation (Dinwiddie and Weir, 1979). Also, water in the Eleana is predominantly sodium bicarbonate water, and the age of the water, uncorrected, was determined to be as much as 21,000 years.

9.4.2.5 Mineral Resources

Approximately 23 mining districts in southern Nye County have produced minerals or metals at one time (Cornwall, 1972). Most of the districts have gold and silver deposits in quartz veins in Tertiary volcanic rocks, although in a few districts the veins are in Paleozoic or Precambrian sedimentary and metamorphic rocks. In several districts gold is disseminated in part in dolomite beds in the Johnnie Formation and Sterling Quartzite.

The Bare Mountain district has produced fluorspar valued at more than $2 million, along with a little mercury, volcanic cinder, ceramic silica, pumicite, gold, and silver. The fluorspar occurs in dolomite of the Nopah Formation in a structurally complex area with prominent northeast-trending, steeply dipping, right-lateral tear faults and gently northwest-dipping thrust faults.

The Mine Mountain and Oak Spring districts occur close to Yucca Flat. The Mine Mountain district, on the southwestern margin of Yucca Flat, contains silver, mercury, and lead in brecciated fault zones within the Devils Gate Limestone. The Oak Spring mining district, at the northern end of Yucca Flat, contains tungsten and molybdenum deposits in a tactite formed by metamorphism of limestone in the Ninemile Formation of the Pogonip Group near a granodiorite-quartz monzonite intrusive complex. Gold with lesser amounts of silver, gem-quality chrysocolla, and sparse pyrite, galena, chalcopyrite, and sphalerite have been reported.

9.4.3 Pilot Shale and Chainman Shale

9.4.3.1 Stratigraphy

The Pilot Shale of Late Devonian-Early Mississipian age (Figure 9-3), consists mainly of platy, slope-forming, olive-gray dolomitic siltstone, interbedded with silty shale that weathers dusky yellow gray. At some places the formation contains thin beds of nodular limestone and clay shale. The unit is the lower part of a thick wedge of clastic rocks deposited in the Chainman-Diamond Peak Trough in eastern Nevada (Figure 9-2). The Pilot Shale, defined by Spencer (1917) in the Ely District, also has been recognized in the Eureka area (Nolan et al., 1956), in White Pine County (Hose et al., 1976), and in Lincoln County (Tschanz and Pampeyan, 1970). Other recent reports that summarize the character of the Pilot Shale are those by Larson and Langenheim (1979) and Skipp (1979).

The thickness of the Pilot Shale ranges from 96 to 130 m in the Eureka district. The unit rests with a sharp and apparently conformable contact upon the Devils Gate Limestone and is overlain by the Joana Limestone (Figure 9-2). On the southern side of Diamond Peak and on the western slopes of the Pancake Range the Joana is absent, and the basal shales of the Chainman formation rest directly upon shales believed to be assignable to the Pilot Shale. The Pilot Shale either is absent or is very thin locally in parts of White Pine and Lincoln Counties.

The thickest sections of Pilot Shale are in the northeastern part of White Pine County. Fritz (1960) reported the shale to be 187 m thick in the southern Cherry Creek Range, Dechert (1967) reported 213 m in the northern Schell Creek Range, and Hose et al. (1976) estimated that the unit is 290 m thick in the Red Hills. Its basal contact is marked by a contrast between the slope-forming shales and the resistant beds of Devonian limestone that underlie them. The Pilot Shale in the vicinity of Eureka is regarded by Nolan et al. (1956) to be Devonian and Mississippian in age, which is comparable to the age of the unit in western Utah (Hose, 1966) and the southern Snake Range (Whitebread, 1969).

The Chainman Shale, like the Pilot Shale, was originally defined by Spencer (1917) in the Ely district. The unit is assigned an Early to Late Mississippian age in various parts of the Great Basin (Figure 9-3). The Chainman Shale is widely recognized in eastern Nevada and western Utah and crops out in some part of nearly every mountain range in White Pine and Lincoln Counties, Nevada. The rocks mapped as Chainman Shale are overlain in the Diamond Mountains, Ruby Mountains, and parts of the White Pine Range by the Diamond Peak Formation, but are overlain elsewhere by the Ely Limestone.

The Chainman Shale consists mainly of pyritiferous claystone and clayey siltstone interbedded with some sandstone and conglomerate in the Eureka area. The unit consists of dark-gray to black shale and olive-gray siltstone or silty shale in most parts of White Pine County (Hose et al., 1976). The Chainman Formation was part of the thick sequence of fine-grained clastic rocks deposited east of the Antlers Uplift in the Chainman-Diamond Peak Trough (Figure 9-2). Recent summaries of the general character of the Chainman Shale are those by Larson and Langenheim (1979), Skipp (1979), and Welsh and Bissell (1979).

Because the Chainman Shale consists mainly of soft, incompetent rocks, it has been more severely deformed than the units below and above it and is, in general, poorly exposed. For these reasons, it is difficult to obtain reliable measurements of the thickness of the unit or to determine its precise relation to the underlying and overlying formations. Roberts et al. (1967) reported possible thicknesses of approximately 1,500 m in eastern Eureka County, but they stated that the true thickness is probably much less. The shale also is reported to be 120 to 457 m thick in the Ely area (Bauer et al., 1964), 287 to 390 m thick in the Bald Mountain-Buck Mountain Ranges (Rigby, 1960), as much as 488 m thick in the northern Cherry Creek Range (Hose et al., 1976), and 60 to 305 m thick in Lincoln County (Tschanz and Pampeyan, 1970). In general, the unit thins toward the south and east.

In Lincoln County, Tschanz and Pampeyan (1970) subdivided the Chainman Shale into three informal members. A black shale facies, which is characteristic of the Chainman Shale in central White Pine County, forms the middle member. The lower member consists of a fairly resistant calcareous siltstone or silty limestone that weathers brown but commonly is black on fresh exposures. The upper member of the formation is a silty unit that contains several olive-gray fossiliferous limestone beds, some sandy beds, and much gray shale.

A major facies change occurs in the Chainman Shale in the Meadow Valley Mountains, where the thick black shale thins drastically within a few miles southeastward and interfingers with thin reddish-weathering shaly limestone and limestone conglomerate that resembles the basal unit of the Bird Spring Formation. Another pronounced facies change appears to occur between the Spotted Range and the Nevada Test Site, although thrust faults or unconformities may be responsible for these apparent facies changes. The Chainman Shale is correlated with the upper part of the Eleana Formation in the Nevada Test Site (Figure 9-3).

9.4.3.2 Geologic Setting

Exposures of the Pilot Shale and the Chainman Shale are found in almost every mountain range in White Pine and north-central Lincoln Counties, Nevada. Outcrop areas extend the full length of some of the mountain ranges and normally are 1 to 5 km in width. Generally, the strata have moderate to steep dips and are interrupted by numerous faults. Long, intermontane basins separate the mountain ranges from each other. These valleys contain Tertiary and Holocene sediments that vary from a few tens of meters to several kilometers in thickness.

The structure of eastern Nevada is quite complex because of the several episodes of deformation that have taken place since Middle Paleozoic time. The Antler orogeny of Late Devonian to Early Pennsylvanian age was probably the first major orogenic episode to involve rocks of Paleozoic age in north-central Nevada; others followed in Permian, Jurassic, and Cretaceous or Eocene time (Roberts et al., 1958). Each succeeding orogeny affected the Devonian and Mississippian rocks and caused more pronounced folding of earlier structures.

The major regional structures in eastern Nevada are thrust faults, north-east-trending strike-slip faults, and north-trending normal faults. In Lincoln County, at least two periods of thrust faulting coincided with the Laramide orogeny of Cretaceous or Eocene age. The major thrust faults are generally older than the strike-slip faults, which are Miocene in age or younger. Normal faults, which produced the present basins and ranges, are also later in the major thrust faults. At some places the normal faults cut beds of Pliocene-Pleistocene age.

9.4.3.3 Mineralogy and Rock Properties

The Pilot Shale contains quartz silt at most places and typically is interbedded with thick siltstone units. Both the shale and siltstone are calcareous in parts of the region, and thin beds of limestone also are reported. In Lincoln County, the Pilot Formation consists mainly of thin-bedded or platy limestone, and it contains only minor amounts of shale. In some parts of southern Lincoln County, the upper part of the formation contains dark-gray carbonaceous shale with limestone concretions.

The Chainman Shale is mainly shale and argillaceous siltstone, although sandstone and conglomerate are also present in some parts of the region. Pyrite is present in the formation in a number of places, and beds of bituminous limestone are interbedded with the shale in much of White Pine County.

9.4.3.4 Hydrology

Few data are available on the ground water in that area of the Great Basin that contains the Pilot and Chainman Shales, mainly because the sparse population has not required detailed studies of ground-water resources. The mountain ranges containing outcrops of these shales receive an average annual precipitation of 30 to 60 cm, and there are no major drainage systems except the White River, Muddy River, and Meadow Valley Wash, which flow through parts of White Pine and Lincoln Counties and empty into Lake Mead on the Colorado River.

Alluvium-filled valleys undoubtedly contain the principal ground-water supplies in this area of eastern Nevada and western Utah. However, significant amounts of carbonate-rock units make up the mountain ranges in this area (Eakin et al., 1976), and it is likely that some of these units (such as the Joana Limestone) contain perched ground water. The few data available indicate that the ground water in this area has a low dissolved-solids concentration (Eakin et al., 1976). Many additional data are needed on all aspects of hydrology in order to adequately characterize the geohydrology of the area.

9.4.3.5 Mineral Resources

Production of mineral fuels in eastern Nevada and western Utah has been relatively small. There are no commercial coal deposits, although attempts have been made in the past to mine low-grade coals in Tertiary lake beds. Several wells have been drilled for oil and gas in eastern Nevada (Lintz, 1957; Schilling and Garside, 1968; Osmond and Elias, 1971; Garside and Schilling, 1977; Garside et al., 1977). The Trap Spring Field and the Eagle Springs Field, northern Nye County, are the only producing fields in Nevada. Principal drilling activity has taken place in Eureka, White Pine, Lincoln, Clark, and northern Nye Counties (Garside and Schilling, 1977).

Gold, silver, lead, zinc, copper, iron, and tungsten are being mined in eastern Nevada. Most of the metallic deposits in Nevada are related to intrusive rocks, generally granodiorite to quartz monzonite in composition. Ore bodies are found in the intrusive rock as well as in the adjacent wall rocks. Fluorspar, bentonite, lightweight aggregate, limestone, and barite are some of the major industrial-mineral commodities mined in eastern Nevada (Payne and Papke, 1977). More detailed information on the mineral resources of eastern Nevada is found in many reports of the Nevada Bureau of Mines and Geology.

9.4.4 Other Units

9.4.4.1 Pioche Shale

The Pioche Shale is an Early and Middle Cambrian unit consisting of micaceous, sandy, and clayey shales and siltstone with some thin sandstone beds and many limestone interbeds as thick as 15 m (Simpson et al., 1979) (Figure 9-7). The Pioche Shale is typically 180 to 270 m thick in parts of Lincoln and White Pine Counties, Nevada. The unit has been well studied in the Bristol-Highland Range area of Lincoln County because of its relation to production of zinc, lead, silver, and manganese ores from the Pioche mining district (Tschanz and Pampeyan, 1970). Most areas containing outcrops of the Pioche Shale are complex mountain ranges containing both thrust faults and normal faults; thus, there are not enough data to characterize this unit fully in the region.

9.4.4.2 Secret Canyon Shale

The Middle Cambrian Secret Canyon Shale consists of several subunits, of which the lowest subunit is gray to black shale 150 m to more than 250 m thick in parts of Eureka and White Pine Counties, Nevada (Simpson et al., 1979). The shale is in part papery and argillaceous, and in part micaceous, thin bedded, and calcareous. Thick deposits of the Secret Canyon Shale are reported in several of the block-faulted and thrust-faulted mountain ranges where the geology is complex.

9.4.4.3 Dunderberg Shale

The Dunderberg Shale of Late Cambrian age consists of 150 to 550 m of fissile claystone or shale in parts of northern Nye County and White Pine County, Nevada (Simpson et al., 1979). The shale contains interbeds of limestone and calcareous shales, and in some areas the limestone predominates over the shale. Mountain ranges where the Dunderberg Shale crops out have been disturbed by both thrust faulting and normal faults,

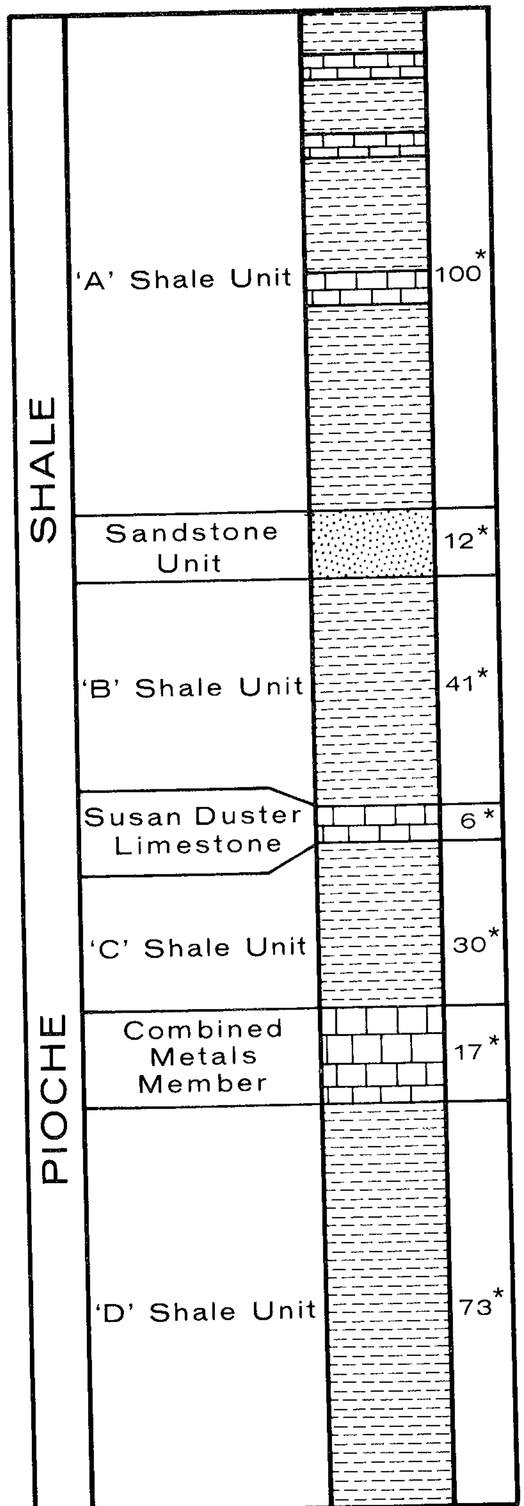

FIGURE 9-7. STRATIGRAPHIC COLUMN OF CAMBRIAN PIOCHE SHALE IN PIOCHE MINING DISTRICT, LINCOLN COUNTY, NEVADA (MODIFIED FROM TSCHANZ AND PAMPEYAN, 1970)

and the lateral extent of undisturbed blocks of shale in the mountains is uncertain.

9.5 REGIONAL SUMMARY

Several of the shales and argillites of the Great Basin are thick, extensive, and structurally very complex. Uplift, folding, and thrust faulting during Late Paleozoic, Mesozoic, and Cenozoic time have segmented the originally continuous blankets of shale into a series of fault-bounded blocks wherein lateral continuity of an undisturbed mass cannot be ensured.

The Eleana Formation is the best known of the shale units in the region because of the extensive study being undertaken by the U.S. Department of Energy and the U.S. Geological Survey on the geology and hydrology of the Nevada Test Site. The Eleana Formation has been folded, thrust faulted, and fractured in most parts of this area, and volcanic activity has further complicated an already complex setting.

The most widespread of the units, the Pilot and Chainman Shales, extend over most of eastern Nevada and nearby parts of Utah. These shales are exposed in many of the elongate mountain ranges, but almost no subsurface data are available on them within the mountains or where they are deeply buried in the intermontane basins.

Few data are available on the ground water as it relates to any of these shales. Principal mineral resources of the region are gold, silver, lead, zinc, copper, and other metallic and nonmetallic materials. Petroleum has been discovered at only a few places in the region.

10. GREAT VALLEY OF CALIFORNIA

10.1 STRUCTURE AND GEOLOGIC FRAMEWORK

The Great Valley of California, also called the Central Valley of California, is a nearly flat alluvial plain west of the Sierra Nevada and east of the Coast Ranges (Figure 10-1). The valley, which extends from the Tehachapi Mountains on the south to the Klamath Mountains on the north, is about 720 km long and has an average width of about 80 km. Elevations of the alluvial plain are generally 100 to 300 m above sea level. The only prominent feature is Marysville (Sutter) Buttes, a Pliocene volcanic plug that rises abruptly 600 m above the surrounding valley floor. The northern portion of the valley is also referred to as the Sacramento Valley, and the southern portion is called the San Joaquin Valley.

Many reports have been prepared on selected parts of the Great Valley over the years, but we have relied heavily in the following discussions on the comprehensive regional reports by Repenning (1960), Bailey (1966), U.S. Geological Survey (1966), Hackel (1966), Rudkin (1968), and Safonov (1968).

The Great Valley is a large, elongate, northwest-trending asymmetric structural trough that has been filled with a thick sequence of sedimentary rocks ranging in age from Jurassic to Holocene. In general, rocks of Jurassic and Cretaceous age are more widespread in the Sacramento Valley, and Tertiary rocks are more widespread in the San Joaquin Valley. The deepest part of the trough is along the western edge of the valley, where as much as 9.5 km of sedimentary rocks have accumulated in the Sacramento Valley. This asymmetrical geosyncline has a wide and stable eastern shelf, supported by the subsurface continuation of the Sierra Nevada granitic basement, and a narrow western flank, containing the upturned edges of the basin sediments. The basin has a regional southward tilt, which is interrupted by two significant cross-valley faults. The northernmost fault, the Stockton Fault, generally is used to separate the Great Valley into the Sacramento and San Joaquin subbasins. The other

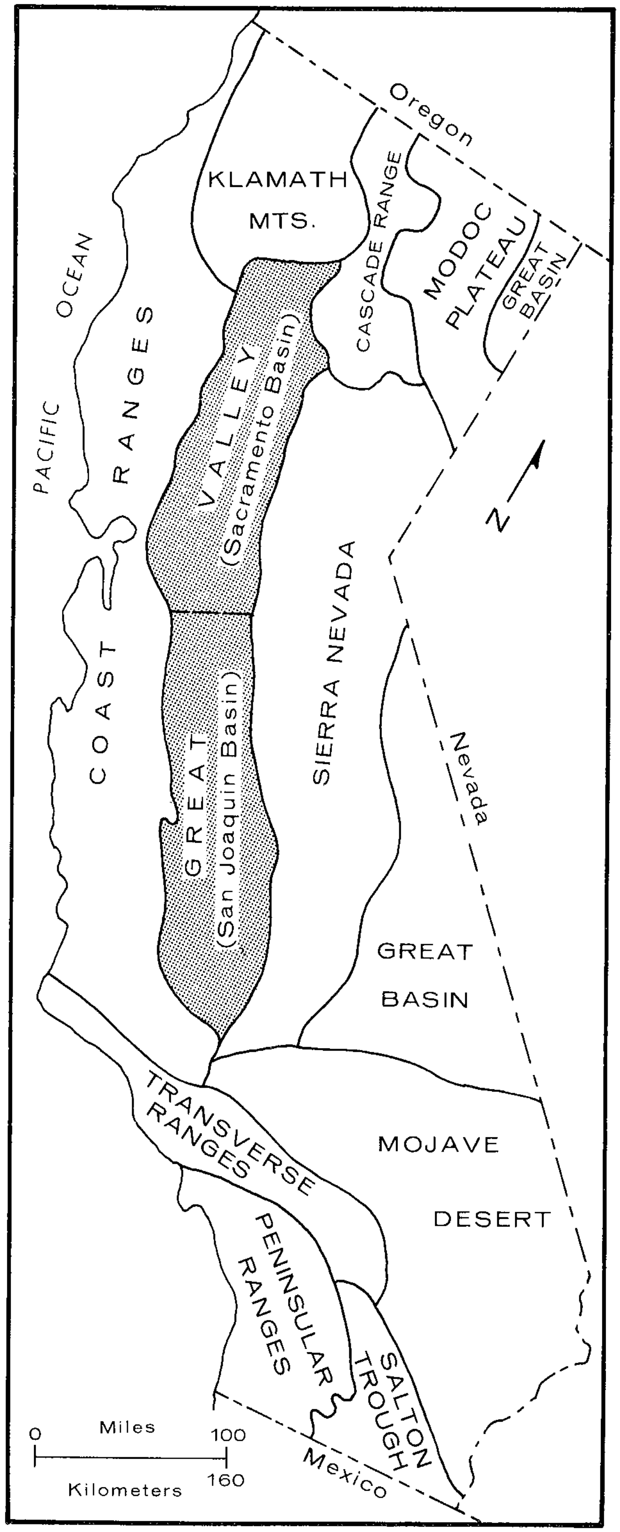

FIGURE 10-1. MAP SHOWING LOCATION OF GREAT VALLEY (SAN JOAQUIN AND SACRAMENTO BASINS) AND OTHER GEOLOGIC PROVINCES OF CALIFORNIA

great cross-valley fault lies near the southern end of the basin and has been named the White Wolf Fault (Repenning, 1960; Hackel, 1966).

Mesozoic rocks are thickest along the western side of the Sacramento Basin, indicating that their depocenter was probably west of the present structural trough. During the Tertiary Period, however, the thickest accumulation was along the southwestern part of the San Joaquin Basin, about at the present position of the structural low. The sedimentary sequence rests on a basement floor of metamorphic and igneous rocks in the eastern half of the valley. These basement rocks, which are exposed in the Sierra Nevada foothills, are composed of Paleozoic and Mesozoic metasediments and volcanics as well as Jurassic and Cretaceous granites. Along the western margin of the valley, where the thick Mesozoic strata are present, basement rocks have not been observed (Hackel, 1966).

Jurassic, Cretaceous, and Tertiary rocks are, for the most part, of marine origin, though significant amounts of continental strata are present in the Tertiary section. Throughout the stratigraphic sequence the rocks are mostly clastic units, with siltstone, claystone, and sandstone, in that order, the dominant lithologic types. Carbonate rocks are virtually absent. Volcanic rocks compose about 10 percent of the Franciscan Formation (Jurassic and Cretaceous) and are present in minor amounts in the Tertiary strata. The Cretaceous System is characterized by similar lithologies over great distances in the Great Valley. On the other hand, Tertiary strata in the region are extremely variable, and rock units change facies over short distances.

The sediments that form the thick valley section were largely derived by erosion of land areas east of the depositional trough. The major part of the Jurassic and Cretaceous sediments of the valley seem to have been derived from the batholiths of the Klamath Mountains and the Sierra Nevada. There is evidence to indicate that the Diablo Range was periodically emergent during later parts of the Late Cretaceous and that this area contributed sediments to the Late Cretaceous sea. The arkosic nature of the Tertiary sediments indicates that the principal source area was the elevated granitic batholiths of the Sierra Nevada and Tehachapi Mountains. Coarse arkosic sediments in the upper Miocene of the western

San Joaquin Basin, however, indicate a different granitic source area. Other localized areas in the Coast Ranges probably contributed debris into the Tertiary seas.

The Mesozoic depocenter covered a larger area than just the Great Valley Trough. Jurassic and Cretaceous rocks either are exposed in or underlie large portions of the region between the valley and the Pacific Ocean. In contrast, the Tertiary basins were much more restricted and distinct; they had relatively narrow and limited connections to the open western sea.

10.2 REGIONAL SEISMICITY

A comprehensive listing of the earthquake history for California can be found in Coffman and von Hake (1973). This information is supplemented by annual publication of U.S. Earthquakes published by the National Ocean and Atmospheric Administration (NOAA), Environmental Data Service Area, for 1970 to 1972 and subsequently published jointly by the U.S. Department of Commerce, NOAA, and the U.S. Geological Survey since 1973. The California Division of Mines and Geology established an earthquake-catalog program in 1973, and as part of this program Real et al. (1978) completed a California earthquake catalog covering the years 1900 to 1974. Bolt and Miller (1975) completed a comprehensive catalog of northern California earthquakes, and Hileman et al. (1973) compiled earthquake data for the southern California region.

Coffman and von Hake (1973) reported that earthquakes in California and western Nevada may represent approximately 90 percent of the seismic activity of the contiguous United States. Most of these earthquakes occur at relatively shallow focal depths of 16 to 24 km and along known rupture zones or faults. The San Andreas fault zone, which extends more than 965 km from north of San Francisco to the Mexican border, has been responsible for the great earthquakes of 1857 (near Fort Tejon) and 1906 (San Francisco) and many of the events of lesser magnitude. The first known strong earthquake occurred in the Los Angeles region in 1769. Since then, thousands of California earthquakes have been cataloged including many prominent earthquakes of Modified Mercalli Intensity VII (MMI VII) or greater (Table 10-1).

The Great Valley is in seismic-risk zone 2 (moderate damage expected) and seismic-risk zone 3 (major damage expected) on the seismic-risk map prepared by Algermissen (see Figure 1-3a). Most of the large California earthquakes have occurred adjacent to the Great Valley Region, which partly accounts for the high seismic risk of this area. Richter (1959) estimated the probable maximum seismic intensity to be expected for most of the Great Valley to be MMI VIII or more.

The evaluation of earthquake sensitivity of the Central Valley varies with depth as well as area, because the estimated probable seismic intensity is largely based upon surficial rock types. Repenning (1960) reported that at an average depth of about 1,600 m in the Central Valley, consolidated rocks are more prevalent than unconsolidated rocks and would have a lower probable seismic intensity. Therefore, below 1,600 m, almost all the area within the Great Valley would be included in the MMI VII maximum-intensity scale, or less, except for the southern end of the San Joaquin Valley. This area, essentially south of the Bakersfield Arch, is composed largely of poorly consolidated Pliocene and Pleistocene sediments at this depth. In addition, the southern basin is partly encompassed and crossed by fault zones that are known to be active. The southern basin, therefore, is estimated to have a probable maximum seismic intensity of MMI VIII or occasionally MMI IX even at a depth of 1,600 m (Repenning, 1960).

10.3 REGIONAL HYDROLOGY

10.3.1 Surface Water

Average annual precipitation in the Sacramento Valley is about 90 cm, whereas average annual precipitation for the San Joaquin Valley is about 50 cm. About 85 percent of the annual precipitation can be expected in the six months from November to April. In most of the region, the rainfall in the four hottest months (June to September) is less than 5 percent of the annual total (Thomas and Phoenix, 1976).

TABLE 10-1. PROMINENT CALIFORNIA EARTHQUAKES FROM 1769 THROUGH 1976 (VON HAKE, 1971; COFFMAN, 1979)

	Date	Region	Modified Mercalli Intensity
1769	July 28	Los Angeles region	
1812	Dec. 8	Southern California	VIII-IX
	Dec. 21	Off coast of southern California	X
1836	June 10	San Francisco Bay	IX-X
1838	June	San Francisco region	X
1855	July 10 or 11	Los Angeles County	VIII
1857	Jan. 9*	Near Fort Tejon	X-XI
1858	Nov. 26	San Jose	VIII
1860	Nov. 12	Humboldt Bay	VIII
1861	July 3	Near Livermore	VIII
1865	Oct. 1	Fort Humboldt-Eureka area	VIII-IX
	Oct. 8	Santa Cruz Mountains	VIII-IX
1868	Oct. 21	Hayward	IX-X
1872	Mar. 26*	Near Lone Pine	X-XI
1892	Apr. 19	Vacaville	IX
	Apr. 21	Winters	IX
1893	Apr. 4	Northwest of Los Angeles	VIII-IX
1897	June 20	Near Hollister	VIII
1898	Apr. 14	Mendocino area	VIII-IX
1899	July 22	San Bernadino County	VIII
	Dec. 25	San Jacinto-Hemet area	IX
1902	July 27 and 31	Santa Barbara County	VIII
1906	Apr. 18**	San Francisco region	XI
	Apr. 18‡	Brawley, Imperial Valley	VIII
1909	Oct. 28‡	Humboldt County	VIII
1915	Jan. 11	Los Alamos	VIII
	June 22‡	El Centro-Calexico-Mexicall area	VIII
1918	Apr. 21‡	San Jacinto-Hemet area	IX
1920	June 21	Inglewood	VIII
1922	Mar. 10‡	Cholame Valley	IX
1925	June 29‡	Santa Barbara area	VIII-IX
1926	Oct. 22‡	Monterey Bay	VIII
1927	Aug. 20	Humboldt Bay	VIII
	Nov. 4†	West of Point Arguello	IX-X
1930	Feb. 25	Westmorland	VIII
	Mar. 1	Brawley	VIII
1932	June 6‡	Humboldt County	VIII
1933	Mar. 10‡	Near Long Beach	IX
1934	June 7‡	Parkfield	VIII
1940	May 18†	Imperial Valley	X
1941	June 30	Santa Barbara-Carpinteria area	VIII
1946	Mar. 15‡	North of Walker Pass	VIII
1950	July 29	Imperial Valley	VIII
1952	July 21†	Kern County	XI
	Aug. 22	Bakersfield	VIII
1954	Apr. 25	East of Watsonville	VIII
	Dec. 21‡	Eureka	VII
1968	Apr. 8‡	Northeast San Diego County	VII
1969	Oct. 1	Santa Rosa	VII-VIII
1971	Feb. 9	San Fernando	XI
1975	Aug. 1	Oroville	VIII

* Possibly Magnitude 8.
** Magnitude 8 or above
† Magnitude 7 to 7.9
‡ Magnitude 6 to 6.9

Drainage from the Sacramento Valley is southward through the Sacramento River to its confluence with the San Joaquin River, near Suisan Bay, and then westward through San Francisco Bay to the Pacific Ocean. The northern part of the San Joaquin Valley drains northward through the San Joaquin River, but the southern part of the valley is a basin of interior drainage, where ephemeral lakes occupy the trough of the valley. These ephemeral lakes are known as Kern, Buena Vista, and Tulare Lakes (Poland and Evenson, 1966).

River flood plains and channels flank the Sacramento, San Joaquin, and Kings Rivers in the middle of the valleys and along other major streams on the eastern side of the valley. Those rivers that are incised below the general land surface have well-defined flood plains, but in the middle of valleys the rivers are flanked by low-lying land where the flood-plain and channel deposits are confined to the stream channel and natural levees slope away from the river (Poland and Evenson, 1966). Several major surface reservoirs, such as Oroville, Don Pedro, and Auburn Lakes, are in the Sierras along major tributaries that drain westward into the valley.

10.3.2 Ground Water

Great Valley ground-water reservoirs include numerous shallow gravel-and-sand aquifers formed by the interstream sediments as well as deep, confined aquifers that are separated from the shallow aquifers by extensive beds of clay. The level of precipitation and surface recharge is generally greater in the north, which is responsible for many variations in ground-water occurrence. For overall water-resource planning in California, the Great Valley drainage basin is subdivided into the Sacramento Basin to the north and the San Joaquin Basin southeast of the valley's outlet to San Francisco Bay. The San Joaquin Basin is further subdivided to form the delta, where the valley floor is approximately at sea level, and the Tulare Basin, where interior drainage occurs at the southern end of the Great Valley (Thomas and Phoenix, 1976).

In the Sacramento Valley, water for irrigation, public supply, and industry is obtained primarily from surface-water sources but in part from wells. These wells generally range in depth from 30 to 150 m, although some wells are as deep as 300 m. Most wells of large capacity are used for irrigation and for public supply; their yields range from 750 to 7,500 l/min. Estimated withdrawal of ground water for irrigation in the Sacramento Valley during 1964 was approximately 3,000 hm^3 (cubic hectometers). The estimated total rechargeable storage capacity to a depth of 60 m is about 34,500 hm^3 (Poland and Evenson, 1966).

In the San Joaquin Valley, water for irrigation is supplied both from surface-water sources and from wells, with most coming from wells. Well water is the source for half the irrigated land in the valley, and it supplies nearly all municipal, industrial, and domestic needs. Depths of water wells range widely, from 30 to 1,050 m, depending either on the permeability of the aquifers or on the water-quality controls. For example, well depths range from 30 to 150 m in the highly permeable alluvial-fan deposits derived from the Sierra Nevada granite complex, whereas at the southern end of the valley, south of the Kern River fan, well depths average about 300 m and range from 180 to 600 m (Poland and Evenson, 1966). Yields of irrigation wells in the San Joaquin Valley also vary widely, ranging from 370 to 11,000 l/min, but most wells yield 2,000 to 6,000 l/min. Estimated storage capacity of the aquifers between 3 and 60 m in depth is approximately 115,000 hm^3. Locally, the reservoir has been dewatered to a depth greater than 100 m (Poland and Evenson, 1966).

10.4 SHALES AND ARGILLACEOUS UNITS

10.4.1 Introduction

The Great Valley was the site of marine sedimentation during much of Cretaceous and Tertiary times, and thick shales and clays were deposited in both the Sacramento and San Joaquin Basins during these marine incursions. Individual shales and clays typically range from 75 to 600 m thick, although some units are locally as much as 1,500 m thick. In addition to blanket-like shales laid down over substantial areas in each basin, several thick clays were deposited in gorges that had been cut into underlying sediments.

Owing to the abundance of shales and clays throughout the Great Valley and the general similarity of the geologic setting, mineralogy, rock proper ties, hydrology, and mineral resources for each of these units, the discussion that follows is in a different format than that used for other regions.

10.4.2 Stratigraphy

10.4.2.1 Jurassic Shales

The oldest thick shale-bearing unit in the vicinity of the Great Valley is the Franciscan Formation of Late Jurassic to Late Cretaceous age. The formation is a thick sequence of diverse rock types exposed in the Coast Ranges on the western side of the Great Valley, and it represents a eugeo synclinal facies of equivalent miogeosynclinal strata deposited in the Great Valley itself (Hackel, 1966).

The Franciscan Formation consists of graywacke, dark shale, volcanic rocks of submarine origin, chert, limestone, and some metamorphic rocks (Hackel, 1966). Although this constitutes a heterogeneous assemblage of rocks, it is so typical and distinct that most Franciscan Formation outcrops are readily recognized. The total thickness of the Franciscan Formation is unknown because of deformation and the fault-contact relationships it has with other rock units, but it is believed to have a minimum thickness of 15,000 m (Bailey et al., 1964).

The Knoxville Formation of Late Jurassic age is the oldest known unit that is considered part of the Great Valley sedimentary sequence (Figure 10-2). The formation includes a large variety of clastic rocks ranging from shale to conglomerate, but dark-gray to black shale or mudstone predominates (Hackel, 1966). The greatest thickness is in the Sacramento Valley, where the unit is about 6,000 m thick near Paskenta. Massive, lenticular conglomerates up to 1,000 m thick are erratically

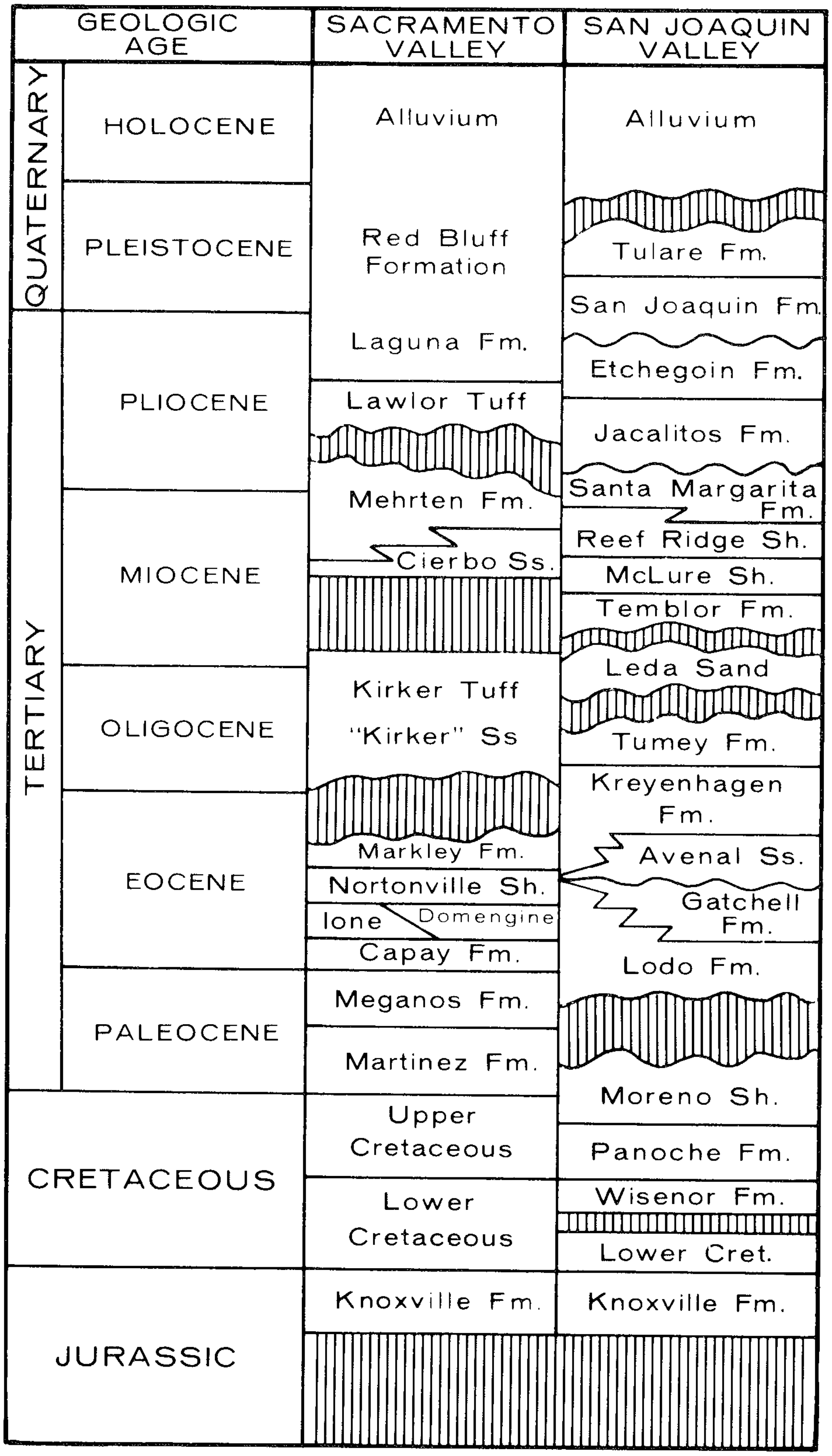

FIGURE 10-2. GENERALIZED STRATIGRAPHIC CHART FOR STRATA IN GREAT VALLEY OF CALIFORNIA (MODIFIED FROM U.S. GEOLOGICAL SURVEY, 1966)

distributed in the mudstone. The sandstones are dark gray and of the graywacke type. The lower part of the section at some places contains volcanic flows, tuff beds, and chert. The basal contact of the Knoxville Formation is usually faulted against Franciscan or associated rocks. In most areas, the upper contact with overlying Cretaceous rocks is gradational with similar lithologies above and below. At the north end of the Sacramento Valley, however, buried Knoxville rocks are presumed to be overlapped by Lower Cretaceous strata that in outcrop rest on basement (Hackel, 1966).

10.4.2.2 Cretaceous Shales

Lower Cretaceous rocks are widely exposed along the western margin of the Great Valley, and although they extend beneath the valley, they do not reach the eastern outcrop belt (Figure 10-3). In the older literature, Lower Cretaceous beds are called the Shasta "series," and Upper Cretaceous beds are referred to as the Chico "series." The Lower Cretaceous sequence generally is thought to overlie the Knoxville Formation conformably, and generally is overlain conformably by Upper Cretaceous units, except locally at the margins of the depositional basin where Upper Cretaceous rocks overlap the older units. The Lower Cretaceous sequence consists of more than 6,000 m of mudstone, siltstone, conglomerate, graywacke, and minor limestone. The mudstones cover large areas and are the dominant rock type, and in parts of the section the mudstones and sandstones are rhythmically interbedded. The graywacke sandstones occur in limited amounts, whereas the conglomerates attain great thicknesses but are highly lenticular. The finer-grained strata are more common in the southern part of the Great Valley, where much of the section consists of mudstones and turbidites (Hackel, 1966).

Upper Cretaceous strata crop out along the western side of both the Sacramento and San Joaquin Basins, and they extend eastward in the subsurface across the basins to exposures in the foothills of the Sierra Nevada Mountains, where the strata are much thinner (Hackel, 1966). The Upper Cretaceous strata have been subdivided into numerous formal and

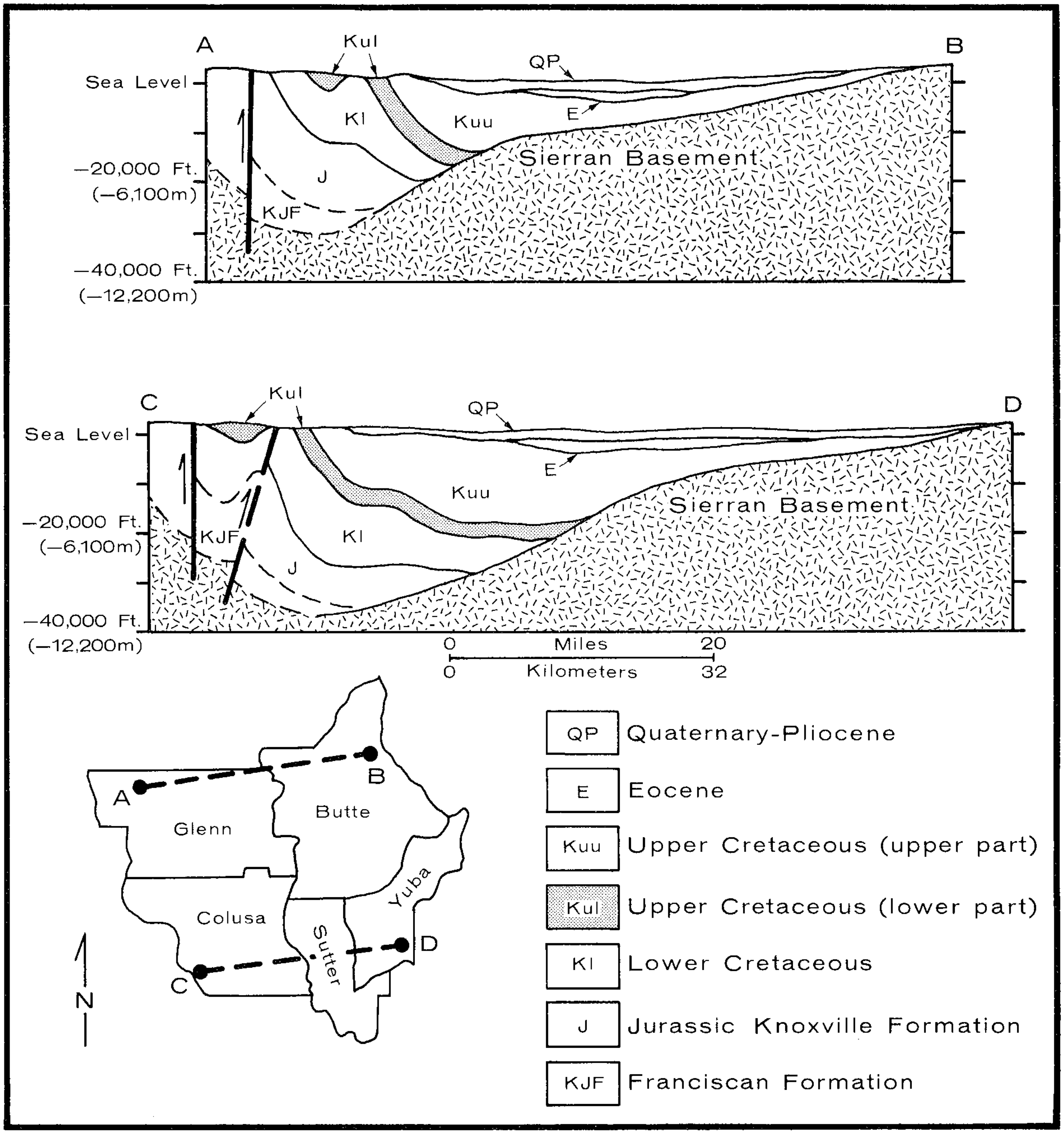

FIGURE 10-3. SCHEMATIC CROSS SECTIONS THROUGH NORTHERN AND CENTRAL PARTS OF SACRAMENTO BASIN IN CALIFORNIA (MODIFIED FROM SAFONOV, 1968)

informal units, and facies changes in various parts of the Great Valley have given rise to a number of names having been applied to the same units in different areas. In general, sandstone and conglomerate are the dominant lithologies in the northern part of the Great Valley, whereas shale and mudstone are dominant in the south. The maximum thickness of Upper Cretaceous strata is more than 7,000 m, and this great thickness is present in the southern part of the Great Valley.

A major part of the Upper Cretaceous sequence on the western side of the Sacramento Basin was described by Kirby (1943). Principal units, including the Venado, Yolo, Sites, Funks, Guinda, and Forbes Formations, consist of interbedded sandstone, siltstone, and shale, with the finer clastics being slightly predominant. The maximum thickness of the Upper Cretaceous in the Sacramento Valley is along Putah Creek, on the Solano-Yolo County line, where about 5,000 m of strata is present.

Most of the Upper Cretaceous formations are predominantly shale or mudstone in at least some places in the subsurface of the Sacramento Valley, but the most persistent shale-bearing unit appears to be the Forbes Formation which typically ranges from 300 to 1,200 m thick, although locally it is truncated by overlying Tertiary strata (Safonov, 1968). The formation is mainly shale, with some scattered interbeds of sandstone, and in places the upper part grades laterally into the overlying Kione Formation, which is predominantly sandstone.

Other units that are mainly shale in parts of the Sacramento Basin include the Dobbins, Sacramento, Winters, Tracy, Sawtooth, Ragged Valley, and Azevedo Shales. Most of these shales are thinner and sandier toward the northern part of the basin.

In the San Joaquin Valley, most of the Upper Cretaceous strata are placed in the Panoche Formation (Figure 10-2), which was described and subdivided by Payne (1962). In the type area, the Panoche formation consists of shale, sandstone, and conglomerate, with shale predominating, and the unit has a total thickness of more than 6,600 m. Shales equivalent to the Panoche Formation, such as the "Winters shales," extend northward to the southern end of the Sacramento Valley.

Overlying the Panoche Formation is the Moreno Formation, which consists of about 900 m of organic-rich shale interbedded with fine-grained sandstone, with a sand-to-shale ratio of about 0.12 (Hackel, 1966). Payne (1951) divided the Moreno Formation into four members, named the Dosaclos Sand and Shale, the Tierra Loma Shale, the Marca Shale, and the Dos Palos Shale. In the lower part of the formation there are many beds of sandstone, locally containing poorly developed concretions, whereas the upper half of the formation is predominantly shale. Calcareous shale, siliceous shale, and limestone nodules are present locally. The contact between Cretaceous and Tertiary strata is gradational and has been placed within the Moreno Formation.

10.4.2.3 Tertiary Shales

Tertiary rocks ranging from Paleocene to Pleistocene in age, and of both marine and continental origin, were deposited continuously at one place or another in the Great Valley. The greatest accumulation of these strata is in the San Joaquin Basin, where locally they are more than 10,500 m thick. In the Sacramento Basin, at least 3,600 m of Tertiary strata occurs in the southern part, or Delta area. The depositional history of the Tertiary sequence in the Great Valley is complex. Abrupt lateral changes of lithology are common, and, as a result, a large number of units have been named, both formally and informally (Hackel, 1966).

Paleocene strata in the Sacramento Basin include the Martinez Formation and the lower part of the Meganos Formation (Figure 10-2). Both of these units locally contain some shale, and in fact the Martinez Formation consists of 600 m of silty claystone with thin interbeds of sandstone and conglomerate in its type-area outcrops, but both units are predominantly sandstone. In the southern part of the Sacramento Basin, a deep gorge of late Paleocene age was filled with clay and sand referred to as the "Meganos Gorge Fill" (Edmondson, 1972). This unit consists mainly of marine shale and is commonly 50 to 200 m thick. In the San Joaquin Basin, Paleocene units include the upper part of the Moreno Shale and the lower part of the Lodo Formation. The Moreno Shale contains shales as described in the section on Cretaceous stratigraphy.

Lower Eocene rocks in the Sacramento Basin are referred to the Capay Formation and part of the underlying Meganos Formation, whereas in the San Joaquin Basin they are referred to the upper part of the Lodo Formation and to the Yokut Sandstone. Lower Eocene rocks are exposed along the western side of the Sacramento Basin, but they are buried in the central part of the basin, where they are confined largely to a deep, narrow, subsurface gorge that has been named the Capay Gorge. The Capay Formation consists of gray-green to dark-gray shale that is compact and brittle, and it appears to have been deposited in a basin with stagnant bottom conditions. The thickness of the Capay Formation generally increases from 90 to 120 m in the northern part of the Sacramento Basin to about 300 to 360 m in the south. At the type locality the Capay Formation is about 750 m thick and fills the so-called Capay Gorge to depths of 600 m.

Lower Eocene strata are discontinuous to the south across the Stockton Arch. In the San Joaquin Basin the Lodo Formation is similar lithologically to the Capay Formation but contains a much higher sand content. The Lodo Formation has been subdivided into the lower Cerros Shale, the intermediate Cantua Sandstone, and the upper Hondo Shale. The formation has a maximum thickness of 1,500 m in western outcrops, but in many areas it is less than 300 m thick. The Lodo Formation pinches out eastward, owing to thinning from the bottom and truncation at the top by the Yokut Sandstone, which is about 60 m thick.

Upper Eocene strata in the Sacramento Basin contain one fairly widespread shale, called the Nortonville Shale, and a thick shaly unit called the Markley Gorge Fill that was deposited in a buried channel (Hackel, 1966). The Nortonville Shale consists mainly of dark-brown shale that is brittle and platy; locally, it contains fine-grained sandstone lenses. The unit typically is 60 to 120 m thick. The Markley Gorge Fill consists of thick sequences of shale and sandstone that overlie and locally cut into or through the Nortonville Shale. Shales of the Markley Gorge Fill are typically brown and carbonaceous. On the northern flank of Mount Diablo, the Markley Formation consists of a lower sandstone unit

600 m thick, a middle shale unit 210 m thick, and an upper sandstone member 150 m thick.

Upper Eocene shaly strata to the south in the San Joaquin Basin include a widespread sequence of brown to white gypsiferous and diatomaceous shales referred to as the Kreyenhagen Shale. The shale, which also is partly Oligocene in age, is one of the most lithologically consistent Tertiary units in the San Joaquin Valley. The lower two-thirds of the unit commonly is brown siltstone and claystone interbedded with some sandstone layers that are more abundant toward the base. Sandstone units typically contain grains of black and white chert and are referred to as "salt-and-pepper sandstone." Outcrops along the western side of the valley contain 180 to 300 m of strata from the Kettleman Hills northward, and the thickness increases sharply to more than 1,200 m farther south in the Devils Den area, where the thick Point of Rocks sandstone is present in the lower part of the Kreyenhagen Shale. In the McKittrick area, and eastward across the basin, the average thickness of the Kreyenhagen Shale and Point of Rocks units is about 300 m. Toward the eastern edge of the valley these formations intertongue with, and are replaced by, undifferentiated continental beds usually called the Walker Formation.

Argillaceous strata of Oligocene age in the Sacramento Basin appear to be restricted to the upper part of the Markley Gorge (Hackel, 1966). Marine strata in the Markley unit are limited to a narrow trough-like sequence extending from Sacramento south-southwestward to the Mount Diablo area.

The Oligocene shale in the San Joaquin Basin is named the Tumey Shale (Figure 10-2). This unit is present in the western and central parts of the basin, extending from the Panoche Hills southward to the Bakersfield Arch. In outcrops, the Tumey Shale consists of an upper shale unit as thick as 210 m and a basal sandstone as thick as 240 m.

Miocene strata in the Great Valley of California have complex facies relationships, and the formal and informal stratigraphic nomenclature reflects the great lateral and vertical variation. Clays and shales are largely restricted to the major area of marine sedimentation in the southern half of the San Joaquin Basin, whereas continental sandstones and related sediments predominate in all other parts of the San Joaquin and Sacramento Basins (Hackel, 1966). In general, the southern part of the San Joaquin Basin contains nonmarine sands, clays, and conglomerates along its margins, and marine, deep-water shales and sands in the west-central part of the basin. The total thickness of Miocene strata in the deep part of the San Joaquin Basin is typically about 3,000 m.

Miocene shales in the San Joaquin Basin include, in ascending order, the Salt Creek, Santos, Media (Freeman), Gould, Reef Ridge, McClure, and Antelope Shales (Hackel, 1966). The Reef Ridge and McLure Shales are 120 to 240 m thick, and they are exposed along the southeastern side of the Diablo Range. The Reef Ridge-McClure sequence commonly is underlain by sandstones of the Temblor Formation and is overlain by sandstones of the Pliocene Etchegoin Formation (Addicott, 1972; Church, 1972; Dibblee et al., 1972; Stinemeyer, 1972).

Marine rocks of Pliocene age also are restricted to the southern half of the San Joaquin Basin (Hackel, 1966). As much as 1,500 m of claystone, sandstone, and conglomerate accumulated during this last episode of marine deposition in any part of the Central Valley of California. The most extensive marine unit in the lower and middle parts of the Pliocene strata is the Macoma Claystone, a subsurface unit that is part of the Etchegoin Formation. The Macoma Claystone extends far to the east of the main depocenter for the Etchegoin Formation, and it separates the nonmarine Chanac Formation from the overlying Kern River Formation. The upper part of the marine Pliocene strata has been named the San Joaquin Formation.

10.4.3 Geologic Setting

Strata in the Sacramento and San Joaquin Basins have complex stratigraphic relationships and have been subjected to a complex structural and tectonic history. Marine shales of Jurassic, Cretaceous, and Tertiary age generally grade laterally into sandstones and conglomerates and have been folded and faulted during four major periods of tectonism in Late Cretaceous (post-Moreno), Late Eocene, pre-Pliocene, and mid-Pleistocene times (Hackel, 1966). The most intense episode of deformation was in mid-Pleistocene time.

The mid-Pleistocene orogeny created many flexures in the Great Valley, and it also rejuvenated a number of folds that had formed during previous orogenic periods. Much of the disturbance took place along the mobile western flank, where numerous folds and faults are now particularly evident. Many of these flexures are asymmetric and are associated with reverse-type compressional faults. The magnitude of the folds decreases eastward, but folds do extend out to, and even beyond, the basin axis (Figure 10-3). The eastern shelf is relatively free of folds, and normal faults are typical in this region. Some of the folds in the central part of the valley are evident at the surface, but because of the thick alluvial deposits many flexures are known only from seismic data and well-bore information.

Faults are numerous in the Great Valley. In the Sacramento Basin the most prominent faults are (1) those associated with the Willows-Beehive Bend trend, (2) reverse faults at the northern flank of the Dunnigan Hills, (3) faults north of Mount Diablo near Willow Pass, and (4) the Midland Fault, which traverses the Rio Vista Gas Field (Hackel, 1966). In the San Joaquin Basin, faults with considerable displacement are common. The Stockton and White Wolf Faults are associated with cross-valley structural highs. Reverse or thrust faults include such faults as (1) the McKittrick Thrust in western Kern County, (2) the Pleito Thrust in the Tejon Embayment, and (3) the Edison Fault in the outcrops southeast of Bakersfield. Large normal faults are the Kern Gorge Fault, the Round Mountain and Mount Poso Faults, and the group of faults in the Edison and Mountain View Oil Fields.

Tectonic activity, though reaching its climax in the mid-Pleistocene, is still continuing in the Great Valley, as borne out by seismic disturbances such as the destructive earthquake of 1952 that originated along the White Wolf Fault. In spite of the great amount of tectonic disturbance in the Great Valley, the regional dip of strata is typically quite low, generally less than a few degrees. These low-angle dips are most common in areas removed from the western side of the valley or from the midvalley faults and folds.

Jurassic shales in the Franciscan and Knoxville Formations are at great depth and are generally somewhat disturbed in and near the Great Valley. Jurassic shales are restricted to the western parts of the two basins, and they are at moderate depths only in a structurally complex narrow band before plunging eastward to depths of 10,000 m.

Cretaceous shales are more widespread in the basins than those of Jurassic age, and some of them extend to outcrops on the eastern side of the Great Valley. In the Sacramento Basin the 300- to 1,200-m-thick shales of the Forbes Formation are locally 600 to 1,000 m below the land surface in parts of Sutter, Colusa, Butte, and Tehama Counties (American Association of Petroleum Geologists, 1951-1969; Safonov, 1968; Alkire, 1968; Vaughan, 1968), but in much of the rest of the basin the top of the unit is more than 1,000 m deep. Other Cretaceous shales in the Sacramento Basin are younger and at shallower depths than the Forbes Formation, but these units are much thinner than is the Forbes Formation.

Cretaceous shales in the San Joaquin Basin occur in the Panoche and Moreno Formations. These shales are quite thick, and they crop out at a number of places in anticlines and fault blocks on the western side of the basin. From these outcrop areas the shales dip steeply to the east and are buried beneath Tertiary sediments at depths greater than 900 m in most parts of the basin (Hoffman, 1964). In the southern part of the basin, the shales generally are thickest, but in this area the Cretaceous strata plunge to depths well below 2,000 m.

Thick Tertiary clays and shales in the Sacramento Basin are of Eocene age, and they are at moderate depths at least locally in almost all counties of the basin. Most of the shales are thickest, however, in the southern part of the basin. Principal information on thickness and depth of these shales in the region is from the American Association of Petroleum Geologists (1951-1969), Ditzler and Vaughan (1968), Harding (1968), Safonov (1968), and Morrison et al. (1971). Examples of areas where thick shales are at depths of 300 to 900 m are as follows: the Capay Shale is 90 to 120 m thick to the north in parts of Glenn, Butte, and Sutter Counties and is typically 300 to 360 m thick farther south in parts of Solano and Contra Costa Counties; the Princeton Gorge Fill is 150 to 600 m thick in parts of Glenn and Butte Counties; the Nortonville Shale is 90 to 180 m thick in parts of San Joaquin and Solano Counties; the Markley Formation-Nortonville Shale, undifferentiated, contains shale units 90 to 300 m thick in parts of San Joaquin, Sacramento, and Solano Counties; and the Markley Formation, or Markley Gorge Fill, is predominantly shale for a thickness of 300 to 600 m in parts of Solano, Sacramento, and Contra Costa Counties.

In the San Joaquin Basin, thick Tertiary clays and shales are at moderate depths in the southern part of the basin, mainly in parts of Kern and Fresno Counties. Thick shales are distributed through a considerable range of the stratigraphic section and occur in Eocene, Miocene, and Pliocene formations. Principal information on the thickness and depths of Tertiary shales in the region is from the American Association of Petroleum Geologists (1951-1969), Rudkin (1968), and Callaway (1971). The following are examples of areas where thick Tertiary shales are at depths of 300 to 900 m below the land surface: in parts of Fresno County the Eocene Kreyenhagen Shale is about 300 m thick, and the Miocene McLure Shale is about 210 m thick; in Kern County the Miocene Media (Freeman) Shale is 150 to 300 m thick, the Miocene Antelope Shale is up to 1,500 m thick, the Miocene Reef Ridge Shale is 150 to 300 m thick, and the Pliocene Etchegoin and San Joaquin Formations each contain about 600 m of shale with some interbeds of sandstone.

10.4.4 Mineralogy and Rock Properties

Ojakangas (1968) examined the mineralogy of the Upper Jurassic-Cretaceous section in the Cache Creek-Rumsey Hills area, Sacramento Valley. The mudstones in this sequence are blocky, dark gray to black, and commonly laminated. They contain abundant angular, silt-sized grains of quartz, mica, organic material, and opaque minerals. Chlorite, montmorillonite, and fine-grained mica are the dominant clay minerals.

The Moreno Formation, near its type locality on the eastern flank of the Panoche Hills, is composed predominantly of thin-bedded, rather brittle, brownish and lavender-colored shales, that weather into small flake-like fragments. The lower part of the formation contains numerous beds of sandstone, whereas the upper half of the formation is composed mostly of organic-rich shale. Calcareous shale, limestone nodules, and layers of semiporcelaneous siliceous shale occur locally (Payne, 1951).

The type section of the Martinez Formation, exposed at the town of Martinez about 8 km upstream from the head of San Pablo Bay, consists of about 600 m of dark silty claystone with thin, hard sandstone and some conglomerate (Repenning, 1960). Southeast of the type section, toward Mount Diablo, the Martinez thins to 210 m of calcareous shale and brown to green sandstone.

The Capay Formation is composed of greenish-brown to gray shale, perhaps organic rich, with phosphatic nodules and beds containing disseminated pyrite. In some areas the Capay Formation contains a glauconitic sandy conglomerate at its base. In the San Joaquin Valley, the Lodo Formation is composed of siltstone and claystone with some interbedded sandstone. Its lower member, the Cerros Shale, is highly glauconitic and sandy in its lower part but is similar to the upper member of the Lodo, the Arroyo Hondo Shale Member (Repenning, 1960).

The Kreyenhagen Shale is composed of a sequence of brown to white gypsiferous and diatomaceous shale. The shale is one of the most lithologically consistent units in the Tertiary section of the San Joaquin Valley. In general, the lower two-thirds of the section is a brown siltstone and claystone interbedded with some medium- to coarse-grained sandstone that is increasingly abundant toward the base. In most areas the sandstone units contain grains of black and white chert. The upper third of the formation is a near-white, highly diatomaceous and gypsiferous shale and diatomite (von Estorff, 1930; Repenning, 1960).

The Tumey Shale, which may be equivalent to the upper part of the Kreyenhagen Shale, has a 240-m-thick basal sandstone member that is overlain by a 210-m-thick shale unit. The shale unit intertongues with variegated shale and sandstone of the Walker Formation along the eastern margin of the valley, and toward the southern end of the valley the marine beds intertongue with thick sandstone and siltstone of the San Emigdio Formation.

Miocene marine sandstone units of the San Joaquin Basin are interbedded with shales that range from 30 to 300 m thick. These shale units, such as the Reef Ridge and McLure Shales, are typically brownish mudstones that have an appreciable percentage of silt and variable quantities of fine sand. Some are siliceous, and, for the most part, thick sections of claystone are absent (Repenning, 1960).

10.4.5 Hydrology

Rocks and sediments containing fresh ground water in the Great Valley are principally unconsolidated continental deposits of Pliocene to Holocene age that overlie the marine shales and extend to depths ranging from less than 30 m to more than 1,050 m (Poland and Evenson, 1966; U.S. Geological Survey, 1966; Thomas and Phoenix, 1976). Locally, marine sediments contain fresh ground water, and in other areas some of the continental deposits contain saline water, but such conditions are not common. Thus, only minor amounts of fresh ground water are likely to be present in sands associated with marine shales and clays of the region, and these fresh waters are likely to occur mainly in areas where the sands are fairly shallow.

Unconsolidated continental deposits of the region consist mainly of alluvium but in some areas include widespread lacustrine and estuarine sediments. These deposits are Late Cenozoic fill in the structural and depositional troughs. Folds and minor faults are present in water-bearing strata, but these structural features have had no significant barrier effect on ground-water movement.

Consolidated rocks form the boundaries beneath and on the flanks of productive ground-water reservoirs in the unconsolidated deposits. Only minor quantities of water occur in joints or fractures in the consolidated rocks in the Sierra Nevada, and stream runoff passes over these rocks and infiltrates into the unconsolidated aquifers. Owing to the moderately plastic state of the Cretaceous and Tertiary clays and shales, these strata generally do not contain open fractures and hold little or no ground water.

Ground water occurs under both confined (artesian) and unconfined (water-table) conditions in the Great Valley. The degree of confinement varies widely because of the heterogeneity of the continental deposits (Poland and Evenson, 1966). In the big alluvial fans on the eastern side of the San Joaquin Valley, the ground water is unconfined. The most extensive confined aquifer is a major Pliocene-Early Pleistocene aquifer system overlain by the Corcoran Clay Member of the Tulare Formation. Recharge of the various ground-water aquifers results from infiltration of rainfall; infiltration from streams, canals, and ditches; infiltration of excess irrigation water; and underflow entering the valley from tributary stream canyons.

Large amounts of ground water have been produced for irrigation and municipal purposes, and this has caused substantial overdraft in the central part of the western side and in much of the southern part of the valley, where replenishment is small compared to withdrawal (Poland and Evenson, 1966). As a result, water levels have declined 30 m to more than 120 m in the same formation in Kern County south of the Kern River fan. As a result of such heavy ground-water use, three extensive areas between Sacramento and the southern end of the Great Valley have experienced major subsidence of the land surface. These three areas constitute roughly one-third of the valley lands south of Sacramento. Maximum subsidence in different areas ranges from 3 m south of Bakersfield to 7 m southeast of Los Banos (Poland and Evenson, 1966).

10.4.6 Mineral Resources

The Great Valley is an important petroleum province (Figure 10-4). Large amounts of oil and gas have been produced from approximately 50 separate fields that extend through all parts of the region (Wright, 1957; Hart, 1966; U.S. Geological Survey, 1966; Rudkin, 1968; Safonov, 1968; Callaway, 1971; Morrison et al., 1971). Almost all the oil is produced

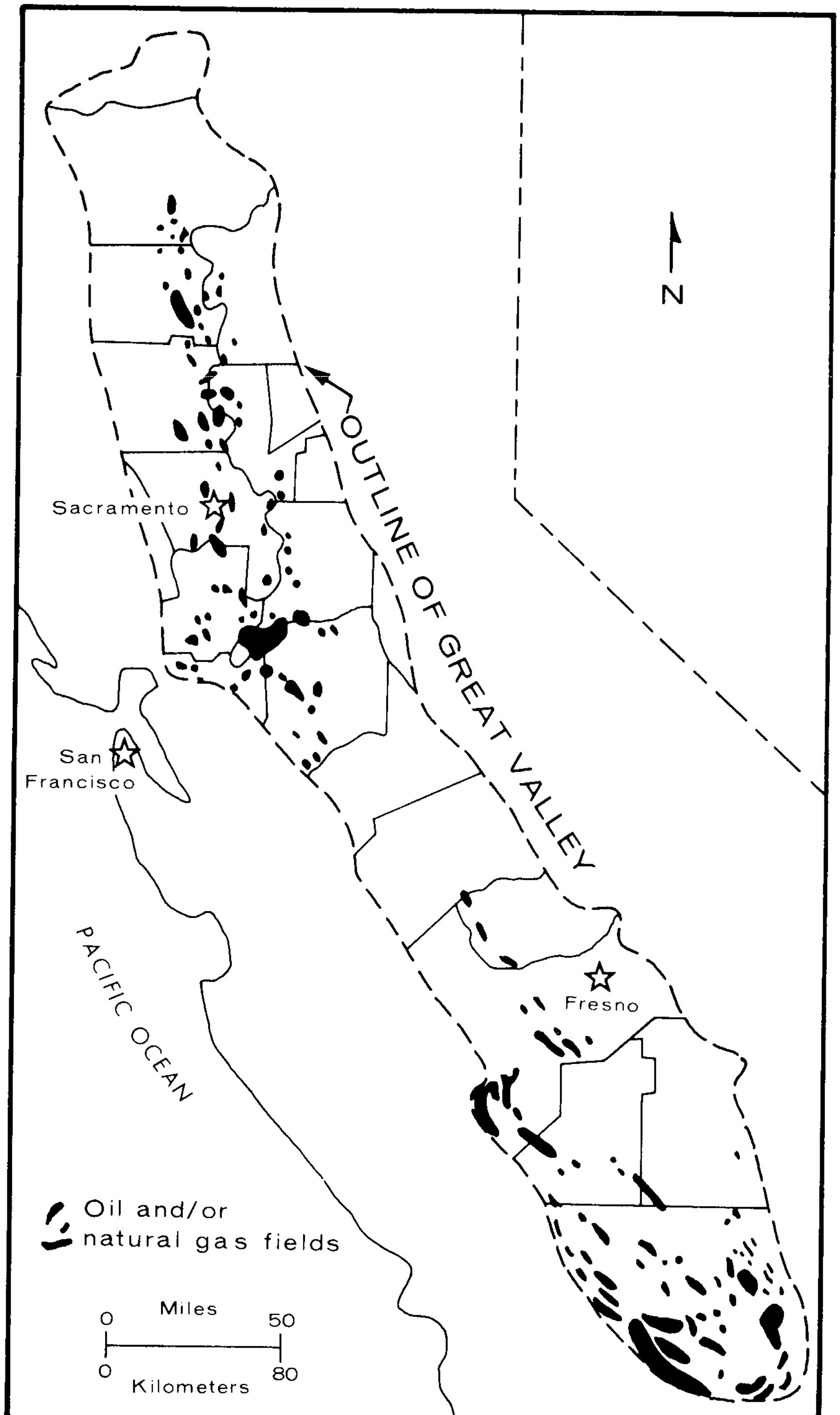

FIGURE 10-4. MAP OF GREAT VALLEY OF CALIFORNIA, SHOWING LOCATION OF OIL AND (OR) NATURAL GAS FIELDS (MODIFIED FROM HART, 1966)

from fields in the San Joaquin Basin, and the chief area of such production is in the south in Kern, Kings, and Fresno Counties. Natural gas is produced mainly in the Sacramento Basin to the north, but some natural gas also is produced in the San Joaquin Basin. Most of the petroleum accumulations are controlled structurally and occur in anticlines or in fault blocks.

Petroleum production in the San Joaquin Basin comes chiefly from sand reservoirs and, to a lesser extent, fractured shale reservoirs of Cenozoic age; Miocene and Pliocene strata are the most productive Cenozoic units. A large amount of oil also comes from jointed and fractured metamorphic rocks of pre-Cretaceous age. The Cretaceous sands of the San Joaquin Basin have yielded only minor amounts of oil.

Large quantities of "wet" natural gas are produced from the oil reservoirs in the San Joaquin Basin. "Dry" natural gas occurs mainly in the northern part of the San Joaquin Basin and the full extent of the Sacramento Basin. The dry gas is produced mainly from sands of Late Cretaceous and Tertiary (chiefly Eocene) age.

New discoveries of oil and gas can be expected in the Great Valley region. Although major structural trends already have been delineated and drilled, deeper production is anticipated from some of these features as well as from more subtle structural and stratigraphic traps. Because of the extensive program of petroleum exploration and production in the Great Valley, there is a large number of boreholes in the two basins.

Other important mineral resources in the Great Valley include clays, placer gold, gypsum, and sand and gravel (Hart, 1966; U.S. Geological Survey, 1966). Each of these resources has been, and still is being, mined by open-pit methods at some place in the Great Valley.

The Ione Formation of Eocene age has yielded most of the clay produced in the Great Valley (Hart, 1966). The formation contains clay-sand mixtures, with local lenses of clay, shale, gravel, and lignite deposited in a lagoon environment. The Ione clay has been produced from numerous pits, mainly near Lincoln in Placer County, near Ione and Bueno Vista in Amador County, and near Valley Springs in Calaveras County. Smaller deposits have been worked near Wheatland in Yuba County, Michigan

Bar in Sacramento County, and Knights Ferry and LaGrange in Stanislaus County. Clay from the Ione consists mainly of kaolin minerals and is used as fireclay (refractory, structural, and whiteware), although the Stanislaus County deposits are used as ball clay and probably contain some montmorillonite. Most of the other clays being worked in the Great Valley are present in alluvial deposits.

10.5 REGIONAL SUMMARY

The Great Valley of California contains a number of thick Cretaceous and Tertiary shales and clays at moderate depths. Individual shales range from 75 m to as much as 1,500 m thick in areas where the top of the shale unit is 300 to 900 m below the land surface.

In the Sacramento Basin the Cretaceous Forbes Formation consists of 600 to 1,200 m of predominantly shale strata at moderate depths in the central part of the basin, and the Capay Shale (Eocene) is 90 to 360 m thick over a substantial part of the basin. All other shales that are at least 75 m thick in the Sacramento Basin are also of Eocene age and include the Nortonville Shale, the Markley Formation, and several thick gorge-filling shales.

Thick shales in the San Joaquin Basin are of Tertiary age, and the areas where they are at moderate depths are limited largely to Kern and Fresno Counties in the southern part of the basin. These units include the Kreyenhagen Shale of Eocene age; the Media (Freeman), Antelope, McLure, and Reef Ridge Shales of Miocene age; and the Etchegoin and San Joaquin Shales of Pliocene age.

The region has undergone four major episodes of tectonism from Late Cretaceous time until the mid-Pleistocene, and the most intense episode was the last one, which followed deposition of all the marine shales herein described. Thus, the shales are affected by a number of faults and folds, mainly along the western margins of the Great Valley but also at places in the central parts of the Sacramento and San Joaquin Basins. There still is, in fact, continuing tectonic activity within the basins, as attested by the 1952 earthquake along the White Wolf Fault. All portions of the Great Valley are considered in seismic-risk zones 2 and 3, and this determination results in part from the fact that most of the large historical earthquakes in California have occurred adjacent to the valley.

The Great Valley is a major petroleum province in the western United States. Natural gas is being produced from many fields scattered throughout most parts of the Sacramento Basin and from a few fields in the San Joaquin Basin. Crude oil, on the other hand, is virtually limited to the southern part of the San Joaquin Basin, with major production in Kern County and lesser production in Fresno, Kings, and Tulare Counties.

Ground water is another major resource of the Great Valley. Water is critical to continued growth of agriculture, industry, and municipalities in the region, and ground water is relied upon heavily to supply this resource, especially in the San Joaquin Valley.

11. PACIFIC NORTHWEST

11.1 STRUCTURE AND GEOLOGIC FRAMEWORK

Western Oregon and Washington at the beginning of the Tertiary Period were the site of an eugeosyncline that occupied the present area of the Olympic Mountains, the Coast Ranges, and the Willamette-Puget Lowlands (Figure 11-1). This linear depositional basin was about 650 km long, extending from Vancouver Island on the north to the Klamath Mountains on the south. The eastern margin may have extended beneath the present site of the Cascade Range, and the western margin may have been several kilometers west of the present coastline.

Early in the history of the geosyncline, a thick sequence of basaltic pillow lavas and breccia erupted from numerous volcanic centers onto the floor of the rapidly subsiding trough. These early Eocene volcanic units intertongue complexly with dark-gray, fossiliferous, tuffaceous siltstones that contain graded beds of volcanic, feldspathic, and lithic wackes. In Middle Eocene time, volcanic activity in the basin was somewhat restricted and a major uplift south of the geosyncline resulted in an influx of great quantities of arkosic, volcanic, and lithic detritus into the basin.

By Late Eocene time, areas of local uplift and active volcanism divided the geosyncline into several separate basins where sediments accumulated in an open-marine environment characterized by tuffaceous silts and clays rich in organic matter. Local unconformities are common along the margins of uplifts and volcanic centers, but in the deeper parts of the basin sedimentation was essentially continuous. Rapid, but intermittent, downwarping of the basins produced interfingering of nearshore marine and coal-bearing strata in a coastal belt 50 to 65 km wide principally in the King County, Centralia, and Coos Bay, Oregon, areas.

In Early and Middle Oligocene time, mild regional uplift of the southern part of the geosyncline shifted the strandline northward from the position it held during the Late Eocene. Regional subsidence took place in the northern part of the geosyncline, and in places marine Oligocene

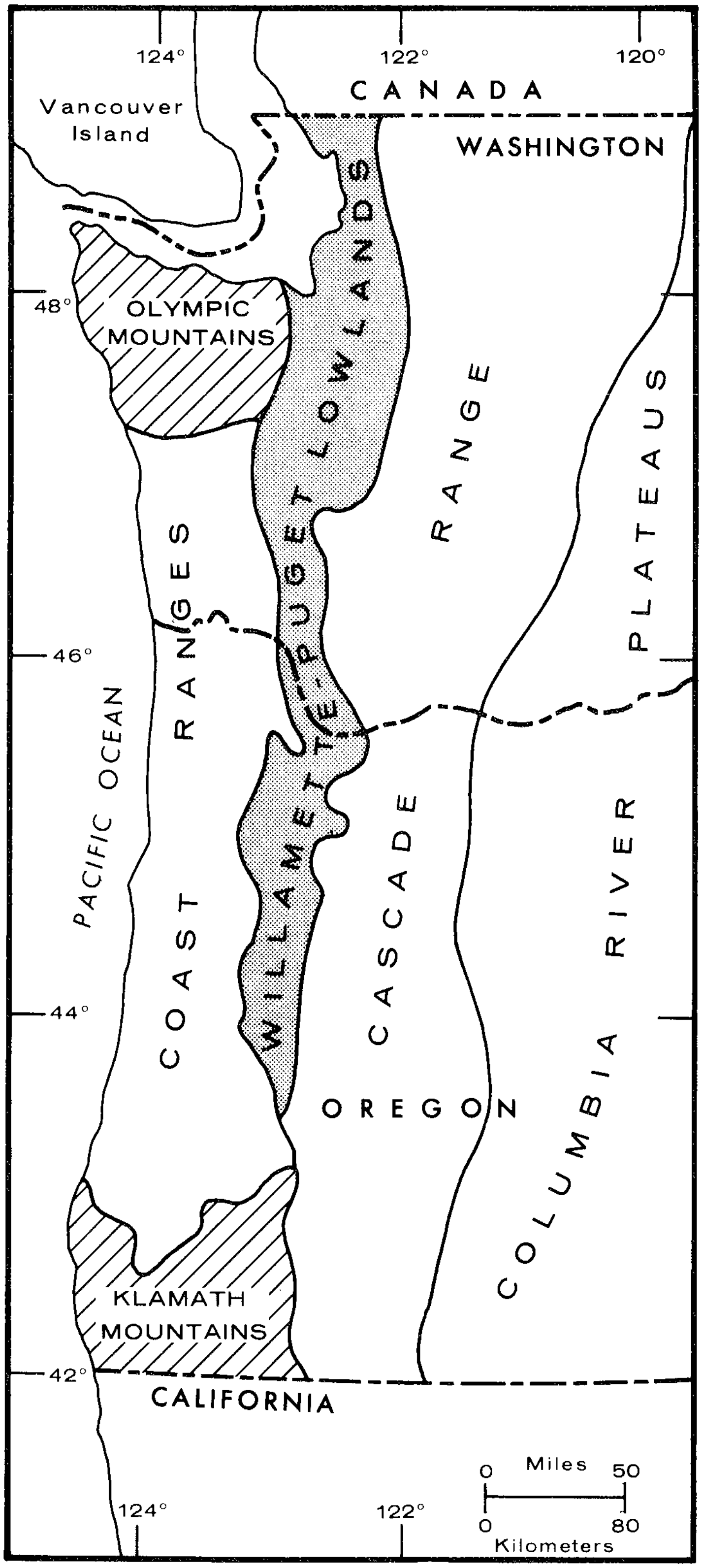

FIGURE 11-1. MAP OF PACIFIC NORTHWEST REGION, SHOWING MAJOR TECTONIC-PHYSIOGRAPHIC PROVINCES

beds overlap upper Eocene strata and rest unconformably on lower Eocene rocks. Vigorous pyroclastic volcanism adjacent to the eastern margin of the geosyncline brought about a marked change in the type of sediments that were being deposited in the marine basins. Streams, whose headwaters were constantly choked with pyroclastic debris, transported large quantities of pumice-rich detritus to the nearshore marine environment. In places, these streams constructed steep-fronted deltas, and some of this material was carried by submarine landsliding into the deeper parts of the basins. Typical Oligocene rocks consist of massive tuffaceous siltstone and fine-grained sandstone with intercalated beds of pumiceous tuff and glauconite.

Early Miocene deposition was similar to that of the Late Oligocene, but by the Middle Miocene the older Tertiary strata and volcanics had been folded and faulted along generally northeasterly structural trends in Oregon and along northwesterly trends in Washington. Erosion of the land areas elevated by this period of deformation furnished clastic debris that characterizes much of the sedimentary rocks of Middle Miocene age. At the same time, basalt flows and breccias were extruded onto the sea floor from north-south trending groups of vents and fissures near the strandline. In Late Miocene time, large shallow lakes formed in local structural basins along the Willamette-Puget Lowlands. Sedimentation in these basins kept pace with downwarping and as much as 300 m of lacustrine clay, fluvial sand, and volcanic mudflow deposits accumulated. Near the close of the Miocene Epoch, marked regional uplift of the Coastal Ranges and intense deformation in the Olympic Mountains further reduced the area of marine deposition in this region.

Only the eastern fringe of Pliocene marine deposition is available for study in the Coos Bay, Oregon, and Gray Harbor, Washington, structural embayments. In these basins, more than 1,000 m of shallow-water-marine strata rests unconformably upon older Tertiary rocks. During Late Pliocene time, the Olympic Mountains and Coast Ranges probably attained their present elevations.

Principal sources of information on the geologic framework of western Oregon and Washington are Snavely and Wagner (1963), Baldwin (1964), Wagner and Snavely (1966), Corcoran (1969), and Snavely et al. (1969).

11.2 REGIONAL SEISMICITY

From 1841 to 1970, many earthquakes of intensity MMI V or greater occurred in Washington and Oregon (see Figure 1-2). Others that were felt were centered either offshore in the Pacific Ocean to the west, in British Columbia to the north, or in neighboring states. Rasmussen (1967) reported that 850 earthquakes were felt in the State of Washington between 1841 and 1965, thus making Washington one of the most seismically active states in the nation. Most of this activity has occurred in the western part of the state, with the strongest shocks reported in the vicinity of Puget Sound. The Puget Sound area is almost entirely within seismic-risk zone 3 (major damage expected) on the seismic-risk map prepared by S. T. Algermissen (Environmental Sciences Services Administration/Coast and Geodetic Survey, 1969) (see Figure 1-3). Five earthquakes of MMI VI or greater have occurred in this region. Two earthquakes, one near Olympia in 1949 (MMI VIII) and the other near Seattle in 1965 (MMI VII-VIII), are the largest known earthquakes to have occurred in Washington. In the vicinity of nearby Clallam County, at least 10 earthquakes of MMI V-VI have been recorded. Five of these events occurred in the Victoria-Vancouver Island area of British Columbia; events of MMI VI occurred in 1864, 1865, and 1896, whereas events of MMI V occurred in 1904 and 1926. The remaining earthquakes--in 1891 (MMI V), in 1895 (MMI V-VI), in 1896 (MMI VI), in 1955 (MMI V), and in 1959 (MMI V)--occurred within or adjacent to Clallam County, Washington. Crosson (1974, 1975) and Crosson and Millard (1975) published a compilation of earthquake hypocenters in western Washington from July 1970 to December 1972, and for 1973 and 1974, respectively.

Oregon, although situated between two states (California and Washington) that have many violent earthquakes, is much less active seismically. Most of Oregon is in either seismic-risk zone 1 (minor damage expected) or seismic-risk zone 2 (moderate damage expected). Nineteen earthquakes of MMI V or greater occurred in the vicinity of Portland, with the most notable events being in 1892 (MMI VI), 1961 (MMI VI), and 1962 (MMI VII) (near Vancouver, Washington). Of the remaining nine, three earthquakes--in 1957 (MMI VI), in 1961 (MMI VI), and in 1963 (MMI V)--occurred near Salem. The remaining earthquake epicentral locations are near Umatilla, in 1893 (MMI V); Craker Lake, in 1920 (MMI V); Cascadia, in 1921 (MMI V); near Perrydale, in 1930 (MMI V-VI); Talent, in 1931 (MMI VI); and Corvallis, in 1952 (MMI V).

The high level of seismicity that has been recorded in the Pacific Northwest, and the volcanic activity of Mount St. Helens and other active volcanoes, show that this part of the United States is still tectonically active.

11.3 REGIONAL HYDROLOGY

11.3.1 Surface Water

Average annual precipitation in Washington and Oregon ranges from about 500 cm in the Coast and Cascade Ranges to less than 25 cm in parts of east-central Oregon and Washington. In the Coast Ranges of Oregon, the average annual precipitation ranges from 150 cm south of Coos Bay to over 375 cm west of Dallas to approximately 200 cm near Astoria. Precipitation in the northern Olympic Peninsula also varies considerably, with average annual amounts reaching about 300 cm per year near the Pacific Ocean to 40 cm at the eastern end of the Peninsula. Most of the precipitation falls during the fall and early winter months; very little falls during the summer. Runoff is high and nearly equals precipitation rates (Phillips, 1969).

The Columbia River, which drains 70 percent of Washington and a sizable part of Oregon, is the major river system in the Pacific Northwest. The river enters Washington from Canada at the northeastern corner of Washington and flows southward and westward for about 700 km and then westward for about 500 km to the Pacific Ocean. The Snake River, the largest tributary of the Columbia River, enters Washington from Oregon and flows westward to join the Columbia River. Other principal tributaries of the Columbia include the Pend Oreille, Spokane, Yakima, Klickitat, Lewis, and Cowlitz Rivers in Washington, and the John Day, Deschutes, and

Willamette Rivers in Oregon. The remainder of this region outside the Columbia River basin is drained by many smaller streams flowing directly to Puget Sound or the Pacific Ocean. Some of the principal streams that drain the western slope of the Oregon Coast Range are the Nestucca, Siletz, Alsea, Siuslaw, Nehalem, Coos, and Umpqua Rivers. The Hoh and Saledwick Rivers, which flow westward and empty into the Pacific Ocean, and the Elwha, which flows northward and discharges into the Juan De Fuca Strait, are the principal rivers in the northern Olympic Peninsula area. The Hoh River basin drains approximately 18 km^2 of glaciers (Hidaka, 1966; Phillips, 1969).

Most of the surface water of western Washington and Oregon is of excellent quality and is suitable for municipal, industrial, and agricultural uses. The dissolved-solids content of most stream waters in this region is less than 250 mg/l (Hidaka, 1966; Phillips, 1969).

11.3.2 Ground Water

Holocene and Pleistocene alluvial sand and gravel and some Tertiary volcanic units are the principal ground-water aquifers in Oregon and Washington (Hidaka, 1966; Phillips, 1969; Foxworthy, 1979). Most of the coastal region is underlain by marine sedimentary units that do not readily yield water. In Oregon, natural recharge in the Coast Range is principally into Tertiary volcanic units, and these exhibit many springs that provide the base flow for numerous streams that drain the Coast Range. Sand dunes, which cover about 300 km^2 and range from sea level to 75 m in altitude, are also a source of ground water along the Oregon coast. They occur in a narrow strip that normally is less than 5 km wide. Most of the precipitation that falls on the dunes infiltrates readily. The water in the dunes is discharged through springs and seeps to many small lakes in the dune area or directly to the ocean (Phillips, 1969).

The Olympic Peninsula is situated in the Hoh River ground-water area. The Olympic Mountains cover most of the Hoh River area, and the remainder includes adjoining slopes and coastal plains. The area is mountainous, heavily forested, and drained by many perennial streams. The surface generally is underlain by fine-grained sedimentary rocks that are impermeable below the zone of weathering. In the mountains, ground water is restricted chiefly to gravel deposits in the major stream valleys. In the northeastern part of the peninsula, near Sequim, much ground water is pumped from wells that tap aquifers in sand and gravel deposits of glacial outwash. These wells are mostly less than 60 m deep, and many yield more than 800 liters of water per minute. Recharge is chiefly from precipitation and infiltration of irrigation water. Water quality is generally excellent; it contains less than 200 mg/l of dissolved solids and ranges from soft to moderately hard (Hidaka, 1966).

11.4 SHALES AND ARGILLACEOUS UNITS

11.4.1 Introduction

Several thick Tertiary argillaceous rock formations of Eocene to Early Miocene age are present in the western parts of the Pacific Northwest. These shale-bearing formations include the Bastendorff and Toledo Formations and Nye Mudstone in western Oregon, and the Twin River Formation in northern Washington (Figure 11-2).

11.4.2 Bastendorff Formation

11.4.2.1 Stratigraphy

The Bastendorff Formation of Late Eocene-Early Oligocene age originally was termed the "Bastendorff shale" by Schenck (1927), who designated exposures at Bastendorff Beach south of Coos Bay, Oregon, as the type locality (Figure 11-3). Exposures of the Bastendorff Formation are restricted to the Coos Bay area along the Pacific Coast in Coos County (Figure 11-2). The area, in the southern part of the Coast Range, includes the South Slough Syncline, the Sumner Syncline, and the Riverton Syncline south of Beaver Hill (Baldwin et al., 1973). Near Bastendorff

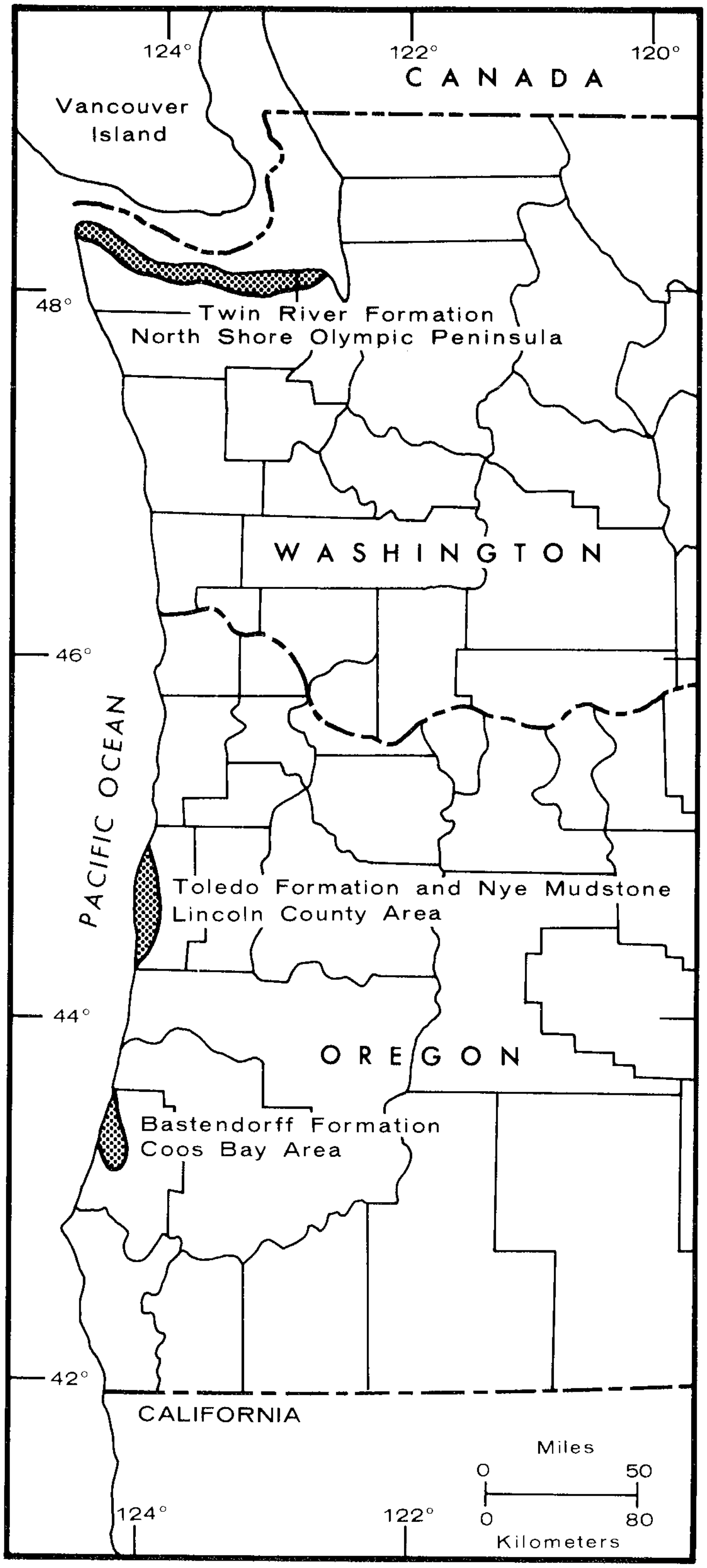

FIGURE 11-2. MAP OF PACIFIC NORTHWEST REGION, SHOWING LOCATION OF PRINCIPAL THICK SHALES OF TERTIARY AGE

Beach the unit consists of 560 m of shale, an 18-m-thick sandstone member, and approximately 300 m of fine-grained strata, presumably shale, giving a total thickness for the Bastendorff Formation of about 880 m. Most of the formation consists of thinly laminated, blue to steel-gray shale with some thin interbeds of carbonaceous sandy shale and feldspathic sandstone. Thin beds of light-yellowish-gray tuff are also present (Allen and Baldwin, 1944; Baldwin et al., 1973). The formation is easily eroded, which gives rise to a characteristically low-lying, subdued topography.

Bedding of the Bastendorff Formation appears to be conformable with the underlying Coaledo Formation and the overlying Tunnel Point Formation. The Coaledo Formation, approximately 1,800 m thick, consists of coal-bearing lower and upper sandstone members separated by a middle mudstone member (Beaulieu, 1971). The Tunnel Point Formation consists of approximately 250 m of fine-grained, massive, buff sandstone; the unit is commonly iron-stained and concretionary near the base and contains tuffaceous material, glauconite, and interbeds of brittle shale near the top.

11.4.2.2 Geologic Setting

Exposures of the Bastendorff Formation, which are found in approximately a 260-km^2 area, are limited to west-central Coos County, Oregon (Figure 11-2). Several outcrop areas, 1 to 30 km^2 in extent, extend from the coast inland for a distance of about 20 km. This unit is folded locally into a series of synclines and anticlines producing steeply dipping beds in places. Much of the unit has been removed by erosion, principally the anticlinal equivalents, which creates a discontinuous outcrop pattern. In the core of the synclines, such as the South Slough, the overburden depth may exceed 600 m.

Three major periods of folding in the Tertiary Period are recognizable in the Coos Bay area. The first apparently took place in post-Tyee time and affected the Umpqua and Tyee sediments; the second occurred during the Miocene Epoch, and may have included more than one movement; and the third took place during Middle or Late Pliocene or Early

Pleistocene time. Minor post-Pleistocene faulting and warping also has occurred. A major structural basin, which Allen and Baldwin (1944) referred to as the Coaledo Basin, occupies much of the Coos Bay area and consists of minor arches and basins. A detailed description of the individual folded elements was presented by Allen and Baldwin (1944).

Two general sets of faults are recognized: strike-slip faults, which trend generally north, and dip-slip faults, which strike generally slightly northwest and range in throw from a few meters to an estimated 200 to 300 m.

11.4.2.3 Mineralogy

Detailed mineralogy of the shale in the Bastendorff Formation is unknown. This unit locally contains tuffaceous material and is high in organic matter. Merewether et al. (1973) indicated that the dominant clay mineral is montmorillonite.

11.4.2.4 Hydrology

Ground water in the Coos Bay area occurs in sand dunes and marine terraces, and in fluvial terrace deposits along the Coos, Coquille, and Umpqua Rivers. Ground water is most abundant in the Coos-Umpqua dune sheet north of Coos Bay, where well yields in excess of 1,000 l/min are common. Yields in the terrace units and alluvium range from a few tens to 200 l/min, and yields in the bedrock units are low, seldom exceeding 20 l/min (Beaulieu and Hughes, 1975).

11.4.2.5 Mineral Resources

Black-sand deposits, which occur in marine terraces and beach sands along and near the coast, contain iron, chromium, gold, titanium, zirconium, platinum, and garnet. Marine-terrace deposits in the Brandon area have been mined for chromium, gold, and platinum (Baldwin et al., 1973; Beaulieu and Hughes, 1975). Principal nonmetallic resources in the area include sand and gravel, clay (alluvial), and crushed and broken rock (volcanics).

The Tertiary rocks of the Coos Bay area appear to be possible source rocks for oil and gas, but most of the potential reservoir rocks have low permeabilities and poor spatial relationships to potential source rocks. For the several exploratory tests that have been drilled, no commercial production was reported (Beaulieu and Hughes, 1975).

Coal in the Coos Bay area was mined commercially from 1854 to the close of World War II. The seams are most abundant in the upper member of the Coaledo Formation, but they also occur in the lower and middle members. Several mines and prospects are located near the contact between the upper Coaledo and lower Bastendorff Formation (Allen and Baldwin, 1944).

11.4.3 Toledo Formation and Nye Mudstone

11.4.3.1 Stratigraphy

Exposures of the Late Eocene-Early Oligocene Toledo Formation, as mapped by Vokes et al. (1949), extend along the west coast of Oregon in Lincoln County, near Yaquina Bay and the cities of Waldport, Newport, and Depoe Bay. In this area the formation is subdivided into the Moody Shale and an overlying sandstone unit (Figure 11-3).

The Late Eocene Moody Shale consists of 450 to 550 m of dark-gray to black, hard, tuffaceous mudstones, often intricately fractured, with scattered discontinuous, irregular, hard-cemented calcareous bands a few centimeters thick. Interbedded fine- to medium-grained sandstones containing much coarse pumiceous material and abundant glauconite occur at numerous horizons. Carbonaceous material and plant fragments are abundant in sandstones near the base. The rock weathers easily to form slopes of soft, light-gray to rust-colored, friable fragments, creating potential landslide conditions. This unit also has been referred to as the Nestucca Formation.

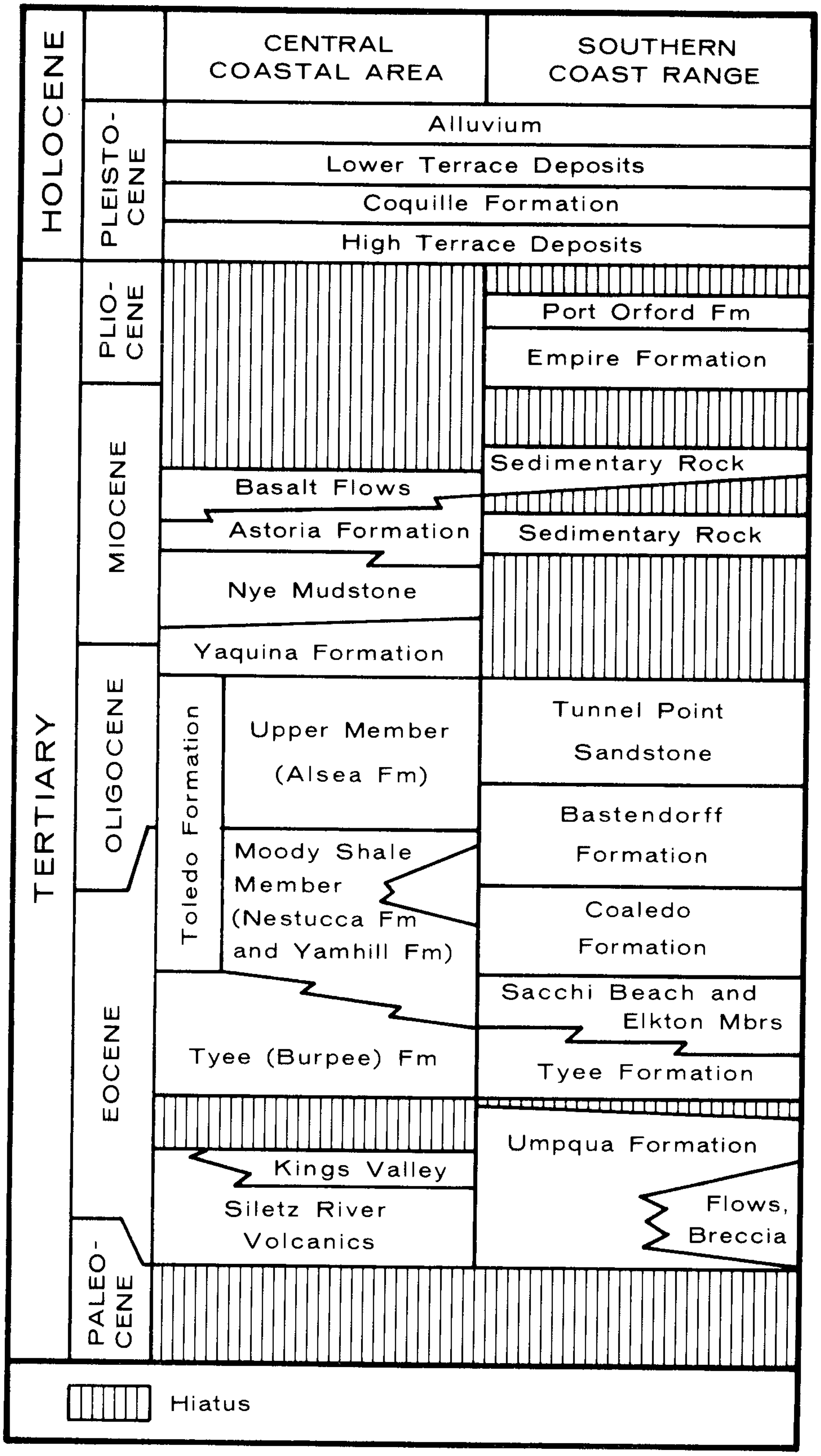

FIGURE 11-3. CORRELATION CHART OF TERTIARY FORMATIONS ALONG OREGON COAST (MODIFIED FROM BALDWIN, 1964; SNAVELY ET AL., 1975)

The upper member of the Toledo Formation is composed of fine-grained, greenish-gray to gray tuffaceous sandstones, tuffaceous siltstones and shales, and glauconitic sandstones. This member was referred to as the Alsea Formation of Early Oligocene age by Snavely et al. (1975).

The Early Miocene Nye Mudstone also is exposed along the coast in Oregon, in the vicinity of Yaquina Bay, Lincoln County, at the type section. The Nye Mudstone is 1,340 m thick at Yaquina Bay and thins to 150 m 6.5 km north of the Bay (Snavely et al., 1976a, 1976b, 1976c). The unit consists of indurated, dark-gray to black, massive to indistinctly bedded clayey siltstone rich in organic matter. Thin calcareous lenses and siltstone interbeds are common low in the section, and large concretions are present in the upper parts of the unit (Schlicker et al., 1973). Lateral variations within the unit are relatively pronounced. Along the Yaquina River the mudstone grades into a section of predominantly tuffaceous and micaceous sandstones. These sandstones are cross-bedded and contain pebble beds. Coal seams occur near the base of the section. The Nye Mudstone conformably overlies the Yaquina Formation and is overlain by the Astoria Formation (Figure 11-3). This unit is intruded locally by dikes and sills of fine-grained basalt.

11.4.3.2 Geologic Setting

The Nye Mudstone crops out in a belt some 50 km long from south of Yaquina Bay and northward to Siletz Bay along the central Oregon coast (Figure 11-2). The unit strikes north-northwest and dips westward on an average of 10 to 15, and thus the unit is more than 300 m below the surface a short distance away from the outcrop area. Exposures of the Nye Mudstone range from 800 to 2,400 m in width. Holocene beach, bar, and dune sand and Pleistocene coastal terrace deposits overlie this unit locally near the coast. Finely crystalline Miocene basaltic dikes and sills intrude this unit.

The Toledo Formation, including the Moody Shale, crops out in a 70- to 80-km-long arcuate belt along the central Oregon coast. The outcrop width ranges from 800 to 1,600 m. The unit strikes approximately north-south, and dips are generally westward 10 to 20 degrees. South of Alsea Bay this unit locally is intruded by Upper Eocene basaltic dikes.

The Nye Mudstone and the Toledo Formation are exposed in Lincoln County on the west flank of the Coast Range, a complex structural high with a predominant northerly trend but containing strong northeast-trending structural elements. The Siletz River Volcanics, the oldest rocks of the area, form the core of the northeast-trending anticlinal highs in the northeastern part of Lincoln County. Faulting is present in all of the bedrock units. Snavely et al. (1976a, 1976b, 1976c) indicated a complex of northwest- and northeast-trending normal faults in this region. Some faults have large vertical displacements, whereas other mapped faults exhibit considerable horizontal movement. The length of most faults is less than 16 km. Multiple periods of faulting are indicated; the youngest unit involved in faulting is Late Miocene ($\pm$20 m.y.). No faulting is noted in the marine terrace deposits, which range in age from Late Pliocene to Early Pleistocene, indicating that fault movement is older than 0.5 million years. Although elevated, the marine terrace deposits and entrenched channels of the major rivers provide evidence for uplift of the coastal region in Holocene time.

11.4.3.3 Mineralogy

Detailed mineralogy of the Toledo Formation and the Nye Mudstone has not been investigated. The Toledo Formation is locally calcareous and contains interbeds of tuffaceous sandstone. The Nye Mudstone is rich in organic matter and displays many lithologic variations. Merewether et al. (1973) indicated that the dominant clay mineral is montmorillonite.

11.4.3.4. Hydrology

The principal sources of ground water in this region include the marine terraces and possibly some dune-sand areas bordering the coast. Some alluvial terrace and flood-plain deposits bordering streams also serve as aquifers. Schlicker et al. (1973) reported 66 wells drilled into the Nye and Toledo (Alsea, Nestucca, and Yamhill) Formations. Yields range up to 200 l/min with an average of approximately 32 l/min. Ground water from these formations requires some treatment for iron, hydrogen sulfide, and/or salinity.

11.4.3.5 Mineral Resources

The principal mineral resources in this area include sand, gravel, and crushed stone. Because of the limited supply of sand and gravel in Lincoln County, crushed basalt is the principal source of aggregate.

Oil and gas exploration in Lincoln County up to 1973 was limited to three shallow wildcat wells drilled onshore and two deep test wells drilled on the bordering continental shelf (Schlicker et al., 1973). Folding and faulting of the sedimentary rocks in Tertiary time have, however, provided the necessary structural elements for entrapment of hydrocarbons, and gas shows are not uncommon in water wells. To date, Oregon's only gas well was completed in early 1979, in Columbia County (Newton, 1979).

11.4.4 Twin River Formation

11.4.4.1 Stratigraphy

The Twin River Formation, as defined by Brown et al. (1960) and Gower (1960), extends in age from the Late Eocene to the Early Miocene. This stratigraphic unit conformably overlies the Lyre Formation and crops out in a narrow belt along the north shore of the Olympic Peninsula from Kydiabbit Point to the Port Angeles area (Tabor and Cady, 1978). Gower (1960) subdivided the Twin River into three lithologic units and designated them as the lower, middle, and upper members (Figure 11-4).

The lower member of the Twin River Formation is characterized by thin to thick beds of olive-gray, lithic sandstone that contains poorly sorted sediments. The sandstone beds are interbedded with, and grade laterally into, well-indurated, light-olive-gray to medium-gray siltstone. Lenses

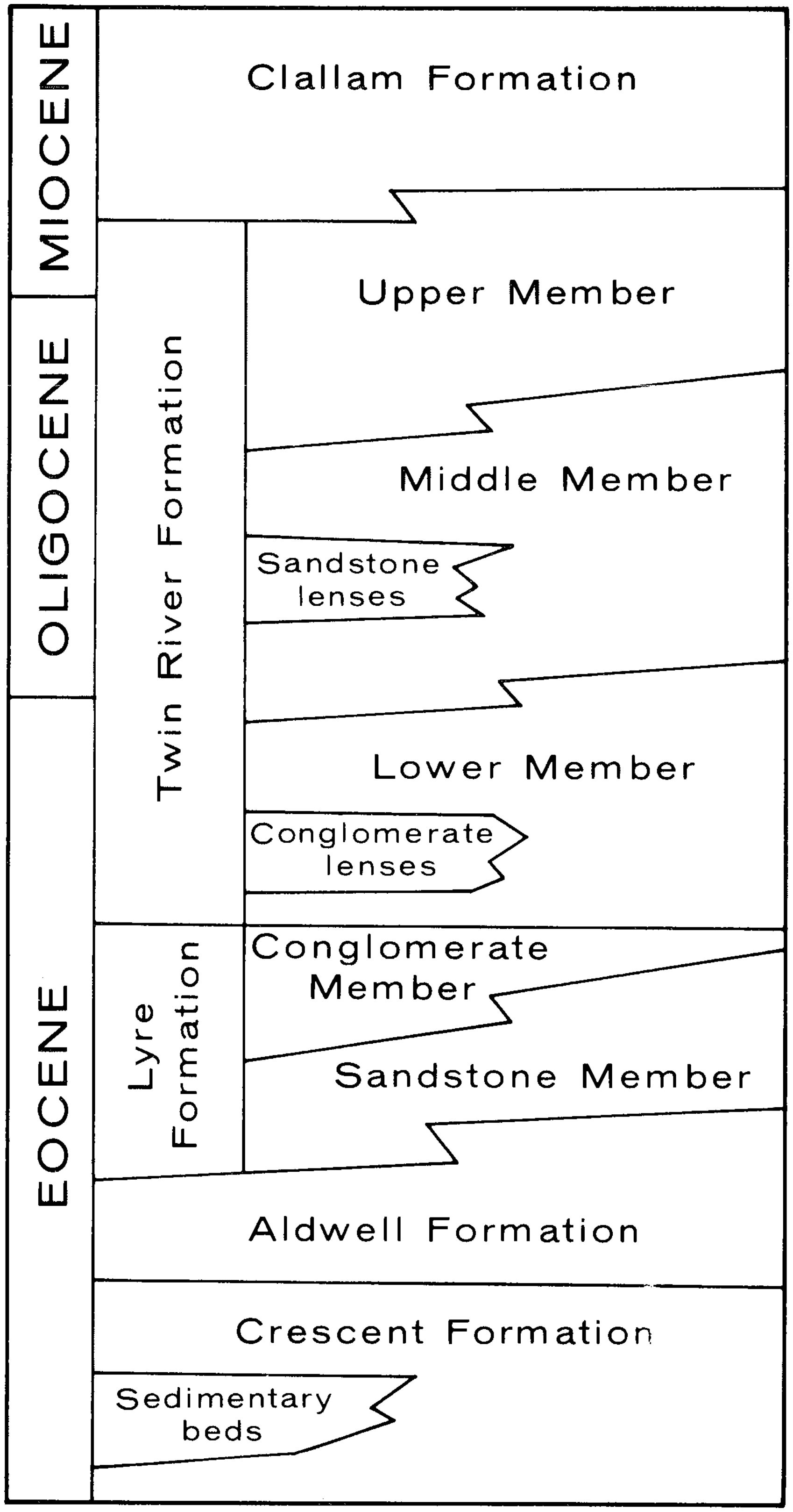

FIGURE 11-4. CORRELATION CHART OF TERTIARY FORMATIONS FOR NORTHERN PART OF OLYMPIC PENINSULA IN WASHINGTON (MODIFIED FROM GOWER, 1960)

of conglomerate up to 30 m thick and composed of basalt and sedimentary rock clasts occur in several places within the lower part of this member.

Massive, medium-gray to light-olive-gray mudstone and sandy siltstone make up most of the upper member of the Twin River Formation. Most of the clay-rich rocks are semi-indurated and contain spherical to elliptical calcareous concretions. Thin- to thick-bedded, light-gray, carbonate-cemented, lithic and feldspathic sandstone beds up to 30 m thick occur near the upper part of this member. In the central part of the outcrop belt, the upper member is poorly exposed and attains a thickness estimated to be about 1,000 m south of Lost Creek. Its thickness is, however, variable, as the unit also grades laterally into the middle member. The upper member is overlain by the Clallam Formation, a thick-bedded and cross-bedded, light-olive-gray, fine- to coarse-grained sandstone and pebble conglomerate. The Clallam Formation also contains coal beds. Glacial deposits composed of sand, gravel, silt, and clay locally overlie the upper member.

11.4.4.2 Geologic Setting

Exposures of the Twin River Formation occur within a zone some 140 km long and 6 to 10 km wide along the north shore of the Olympic Peninsula (Figure 11-2). Strata within the outcrop area generally strike west-northwest and dip toward the Strait of Juan de Fuca at angles that typically are 30° to 40° but locally range from 10 to 85 degrees. The upper member, which contains more clay-rich strata than the lower or middle members, is exposed throughout an area of up to 180 km^2. In the eastern half the upper member is overlain by glacial materials composed of moraine and stratified deposits. This member dips northward beneath the Strait of Juan de Fuca. Therefore, although the shale units in the Twin River Formation are at moderate depth a short distance north of their outcrop, this area is one that is close to or beneath the strait.

The Twin River Formation is folded generally along a N 80° W trend. Deformation by folding is greatest in rocks of Eocene age, but younger Tertiary units also are greatly folded locally and are overturned in places. Numerous faults occur in this region and generally parallel the fold axes and trend westward. Faults commonly show an apparent downward movement on the south side, but many show evidence of both vertical and horizontal components of movement. Deformation in this area probably began in Late Eocene time, as shown by the local unconformity within the lower member of the Twin River Formation. The major part of the orogeny that formed the present structure of the Olympic Peninsula took place in post-Middle Miocene time before the late Pleistocene Wisconsin glacial stage (Gower, 1960; Brown et al., 1960; Tabor and Cady, 1978).

11.4.4.3 Mineralogy

The lower and middle members of the Twin River Formation consist primarily of interbedded siltstones and lithic sandstones, whereas the upper member is composed of mudstone and sandy siltstone. No studies on the detailed mineralogy of these members appear to have been conducted to date.

11.4.4.4 Hydrology

Most of the Olympic Peninsula is in the Hoh River ground-water area, which is mountainous, heavily forested, and drained by many perennial streams (Hidaka, 1966). The land surface, where underlain by fine-grained sedimentary rocks, is relatively impermeable below the zone of weathering.

In the mountains, the occurrence of ground water is restricted chiefly to gravel deposited along major stream valleys. Along the northern coast of the Olympic Peninsula the Tertiary bedrock units are mantled by glacial deposits composed of marine and outwash deposits including sand, gravel, silt, and clay. These deposits provide an excellent source of ground water. Most wells are less than 60 m deep, and near Sequim many of them yield more than 800 1/min.

11.4.4.5 Mineral Resources

Commercial-grade manganese deposits have been mined on the Olympic Peninsula, and the principal ore mineral, hausmannite, occurs mainly in the Crescent Formation. No production has, however, been reported since the mid-1940s (Dorr, 1966). Thin stringers of coal and carbonaceous material are present in Oligocene and younger Tertiary strata, although no commercial deposits of coal have been found (Livingston, 1974). Test drilling for oil and gas in the Olympic Peninsula region has been concentrated along the west coast near known oil seeps. Rau and Wagner (1974) reported that several shallow to moderately deep oil and gas tests have been drilled along the peninsula's north shore, where there appear to be potential source and reservoir rocks as well as the potential for numerous structural traps.

11.5 REGIONAL SUMMARY

Several thick shales and argillaceous units of Tertiary age are present in coastal areas of the Pacific Northwest. The areas underlain by the thick shales are typically long and narrow strips along the coast (Figure 11-2), and the shales dip seaward beneath the Pacific Ocean or the Strait of Juan de Fuca. The character of the shales is known in outcrops only, and there are few data on the subsurface character and distribution of the shales. Areas underlain by thick Tertiary shales are structurally complex, with the shale units generally being folded and faulted and having dips ranging from 10 to 85 degrees. The region is characterized by a high level of seismicity, with much of the region being in seismic-risk zones 2 and 3. The high seismicity and the recorded history of volcanic activity show that the Pacific Northwest is still tectonically active.

12. PRECAMBRIAN ARGILLITES AND ASSOCIATED ROCKS

12.1 INTRODUCTION

Argillites and associated rocks of Precambrian age crop out in widely scattered locations of several geologic regions of the western United States (Figure 12-1), and they are discussed here in a separate section of this report because they share many common characteristics. In discussing such units, the major age subdivisions of the Precambrian used are those of current U.S. Geological Survey usage, expressed in billions of years, as: W = greater than 2.5; X = 1.6 to 2.5; Y = 0.8 to 1.6; and Z = 0.57 to 0.8.

Most argillaceous strata of W age have been thoroughly metamorphosed to high-grade rocks (King, 1976). Thus, no true argillites of W age, and only one of X age, are identified in Figure 12-1.

In a preliminary inventory of shales and argillites, Connolly and Woodward (1980) identified those Precambrian sequences that contain argillites and similar kinds of rocks whose thicknesses exceed 150 m. That study lists the location, general lithology, approximate maximum thickness, formation names, and outcrop areas for such Precambrian sedimentary and low-grade metamorphic terranes.

The discussion in this report is based upon the preliminary data assembled by Connolly and Woodward (1980). For each of the localities cited, the available literature was examined in detail, and the regional characteristics of the sequences evaluated to determine if any had the potential for inclusion here. Because the general data base and detailed descriptions about these Precambrian sequences are more limited than for most Phanerozoic stratigraphic units, less definitive discussion can be given here than is feasible for most of the younger argillaceous strata. Despite these limitations, two areas of Precambrian supracrustal rocks, one in the Northern Rocky Mountains, and the other in the southern Basin and Range Province, are described.

Although supracrustal rocks are generally thought of simply as "rocks that overlie the basement" (Bates and Jackson, 1980), the term as utilized

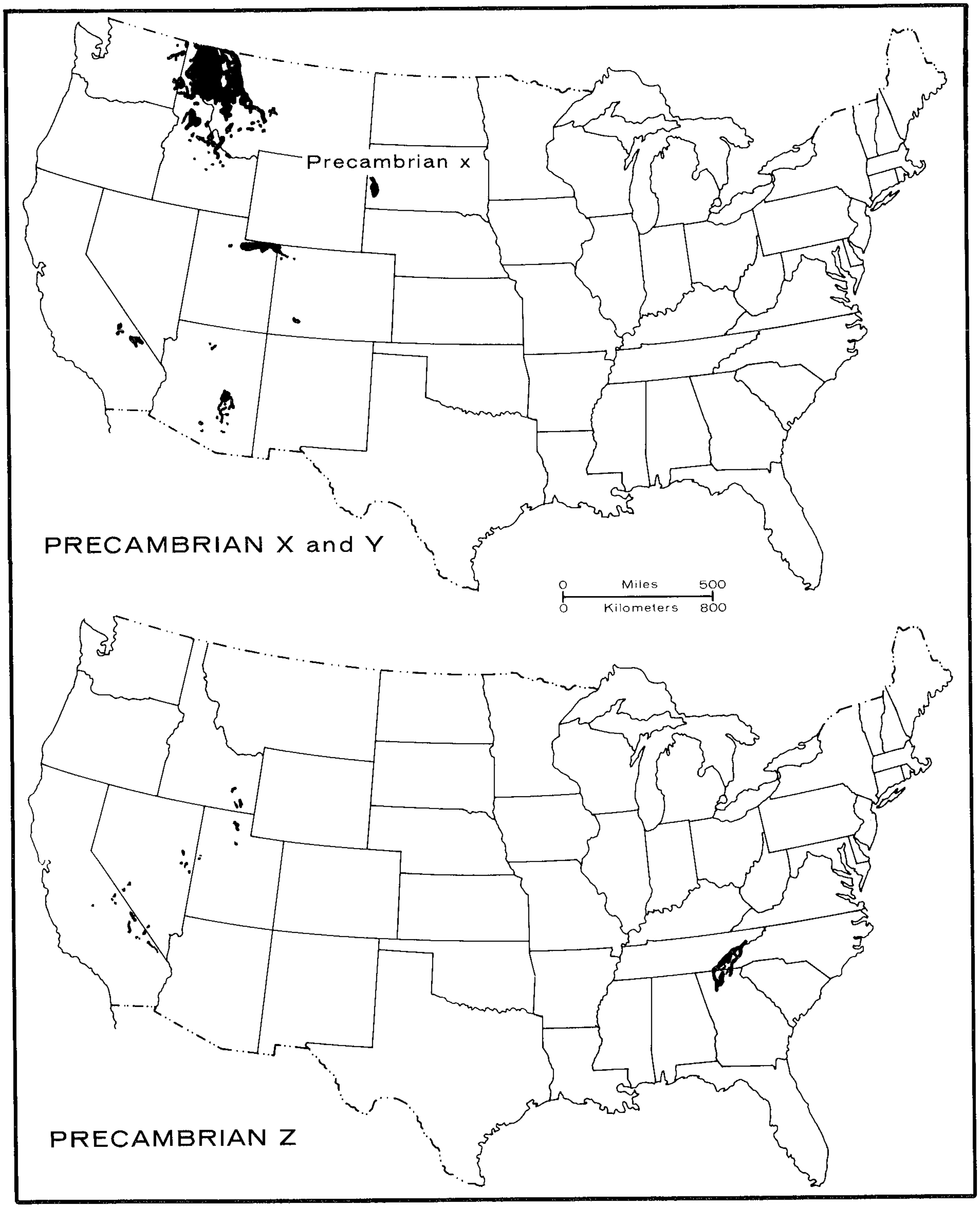

FIGURE 12-1. MAP SHOWING DISTRIBUTION OF PRECAMBRIAN SUPRACRUSTAL SEQUENCES THAT CONTAIN SIGNIFICANT UNITS OF SHALE, ARGILLITE, AND RELATED ROCKS IN CONTERMINOUS UNITED STATES (MODIFIED FROM KING, 1976; CONNOLLY AND WOODWARD, 1980)

by King (1976) refers to Precambrian sedimentary and volcanic rocks that were formed at the surface of the Earth and upon basement rocks that had more complex metamorphic and plutonic histories than the overlying younger sequences. Thus, rock units within these supracrustal sequences are ideally little deformed and metamorphosed, or in sharp contrast to the more enigmatic paragneisses and orthogneisses typical of many Precambrian terranes.

12.2 BELT SERIES IN NORTHERN ROCKY MOUNTAINS

12.2.1 Stratigraphy

The Belt Series (or Supergroup) is almost continuously exposed across an area of about 78,000 km^2 in the northern Rocky Mountains of western Montana, northern Idaho, and northeastern Washington (Figure 12-2). This same sequence of rocks is called the Purcell Supergroup in Canada, where some 26,000 km^2 is additionally exposed. The Belt Series (named after the Big and Little Belt Mountains in central Montana) represents the greatest expanse of well-preserved Precambrian supracrustal rocks in the United States (King, 1976). Throughout much of its extent, this sequence is simply tilted or broadly warped, broken into fault blocks, and only incipiently metamorphosed. The Late Precambrian Purcell Anticlinorium has combined with fault-block grabens developed during the Cretaceous and Tertiary Periods to create a nearly complete exposure of the various strata in the Belt Series (Figure 12-2).

Extensive regional studies, as summarized by Harrison (1972), have led to definitive correlation of the various stratigraphic units throughout the wide extent of the Belt Series (Figure 12-3). Among these units, the Prichard Formation and significant parts of the Ravalli and Missoula Groups were identified by Connolly and Woodward (1980) as containing clay-rich strata thicker than 150 m. In this report, the detailed stratigraphic information presented for each is from summary descriptions by Ross (1959, 1963b) and Harrison (1972).

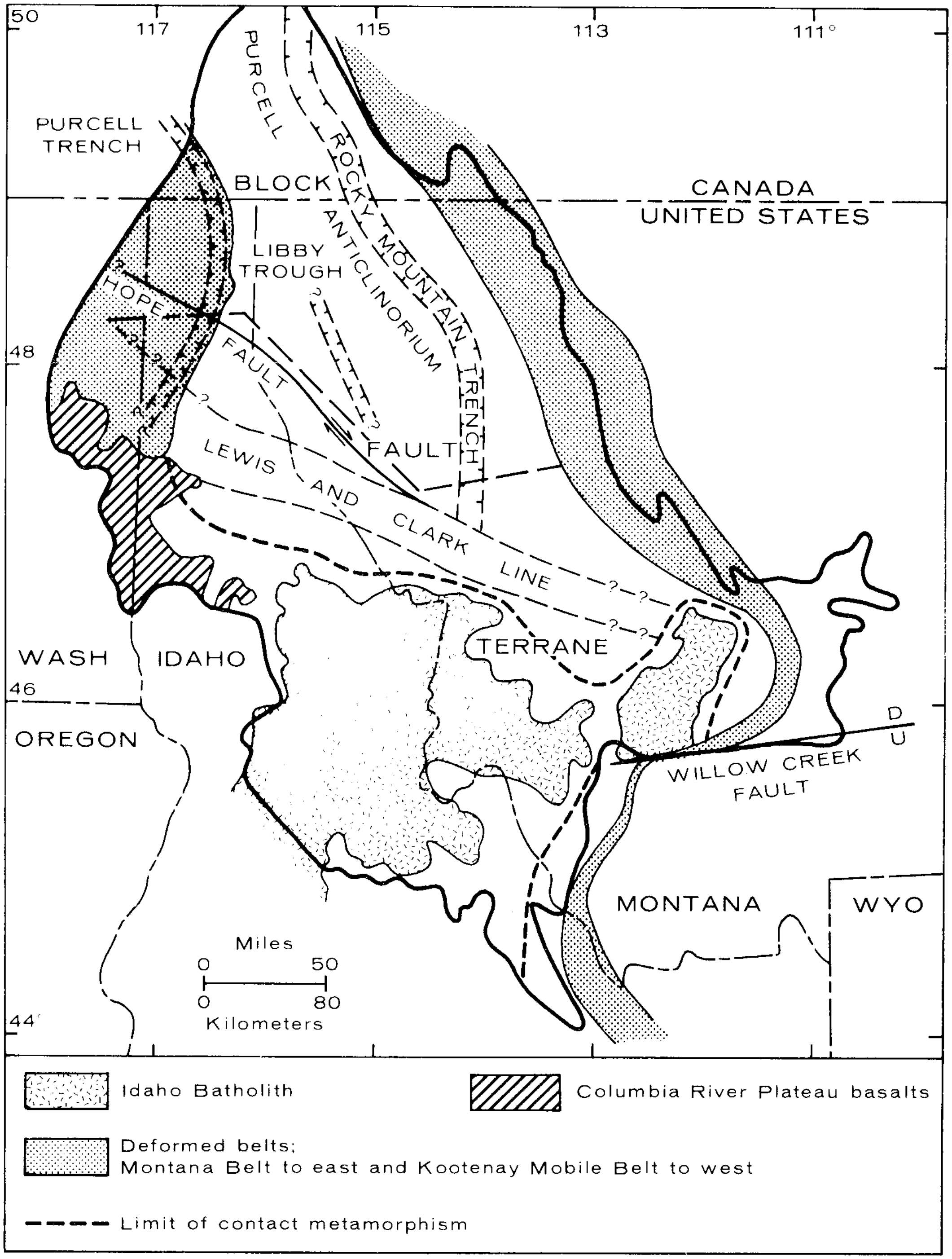

FIGURE 12-2. MAP SHOWING OUTCROP BELT AND REGIONAL TECTONIC SETTING OF THE BELT SERIES IN MONTANA, IDAHO, AND ADJACENT AREAS (MODIFIED FROM HARRISON, 1972)

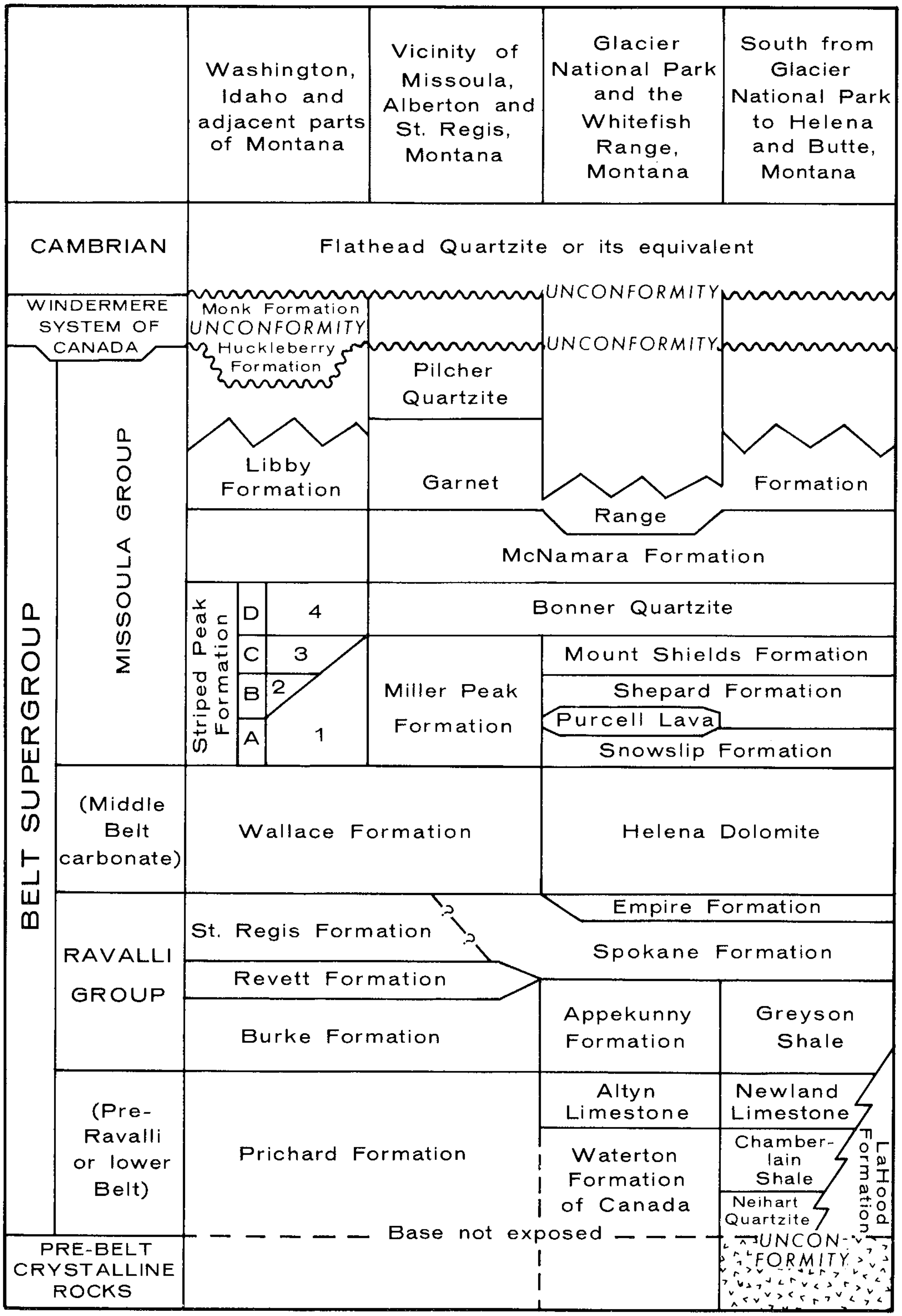

FIGURE 12-3. GENERALIZED STRATIGRAPHIC SEQUENCES OF BELT SERIES FOR AREAS IN WASHINGTON AND IDAHO AND THROUGHOUT WESTERN MONTANA (MODIFIED FROM ROSS, 1959, 1963b; HARRISON, 1972)

The Prichard Formation represents the lowermost exposed portion of the Belt Series, is conventionally called the Pre-Ravalli or lower Belt (Figure 12-3), and consists of an assemblage of argillaceous and arenaceous rocks lying upon the Neihart Quartzite (Ross, 1963b). The latter arenaceous unit in turn lies upon the granitic-gneiss basement in the Little Belt Mountains east of Helena, Montana, or essentially along the eastern outcrop edge of the Belt Series.

Descriptions of the Prichard Formation suggest that lateral variations are common and pronounced. In the Coeur d'Alene area, the thickness exceeds 2,400 m, and all but the uppermost part consists of dark-blue to gray argillite with imperfect slaty cleavage interbedded with sandstone. The upper part of the formation is increasingly more sandy.

Farther east along the Idaho state border, the Prichard Formation consists of fine-grained, medium-gray and green-gray quartzite and siliceous argillite. Individual beds range up to a few meters in thickness. The formation is similar to that exposed in the Coeur d'Alene region, except that it is more uniformly siliceous and contains fewer argillite beds. East of the 116th meridian (Libby Quadrangle), this formation consists mostly of dark-gray to blue-gray, sandy, laminated argillite, interbedded with sandstone, quartzite, and thin-bedded shale. The composite thickness approaches 3,000 m. Petrographic studies reveal that the argillite from this region consists largely of very fine-grained quartz and sericite. The strata in the Libby Quadrangle are probably representative for most of western Montana (Ross, 1963b). Other descriptions of this formation as presented in Ross (1963b) from localities to the south suggest that the rocks were subjected to moderate grades of metamorphism.

The Ravalli Group contains two sequences of interest, the basal Burke Formation, which lies directly upon the Prichard Formation, and the uppermost St. Regis Formation and its correlative unit, the Spokane Formation. Relationships between these units are depicted schematically in Figure 12-4. The middle unit, or Revett Formation, consists of thick-bedded quartzite in most regions.

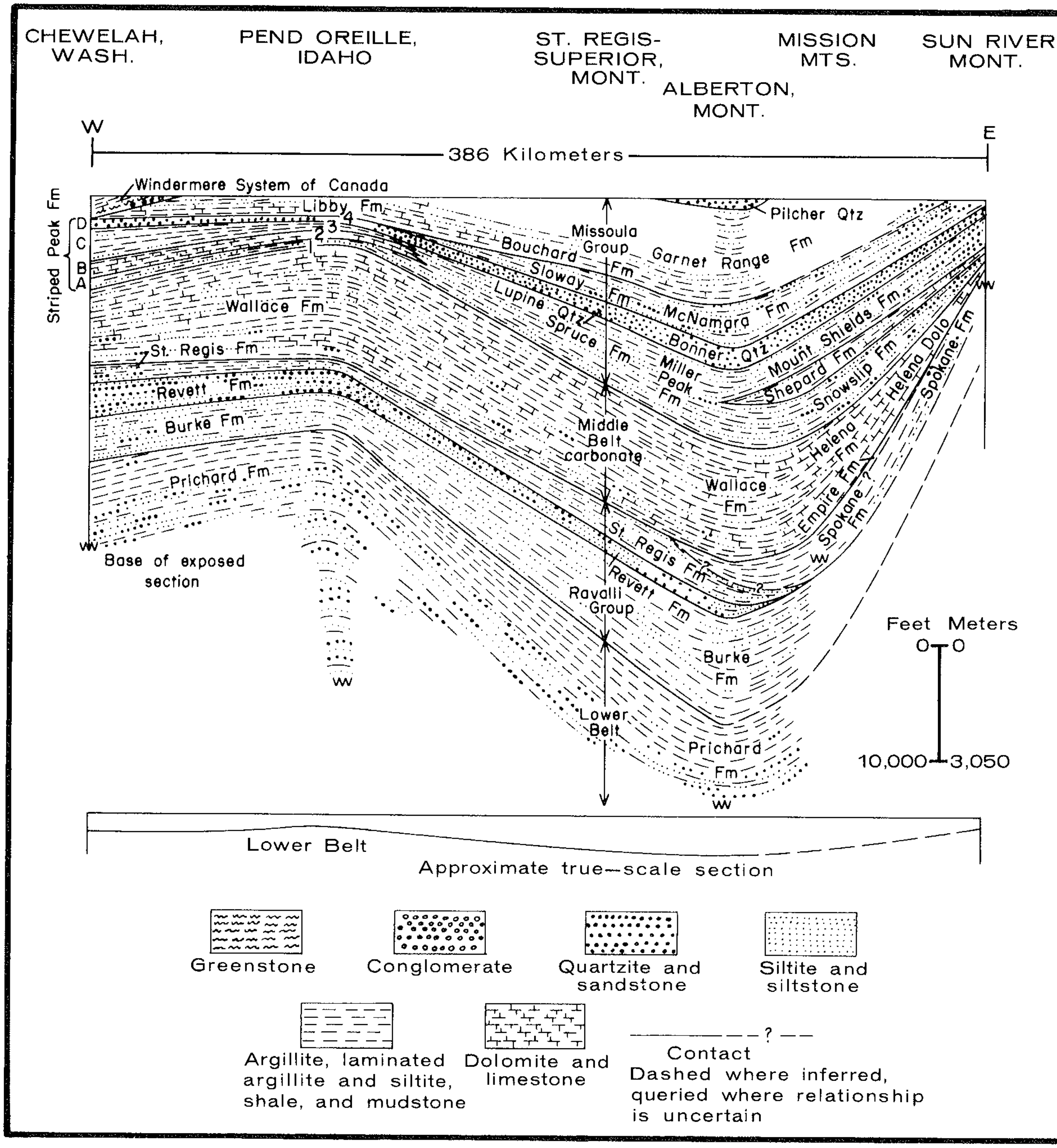

FIGURE 12-4. DIAGRAM SHOWING PALINSPASTIC RECONSTRUCTION OF BELTIAN AND WINDERMERE STRATIGRAPHY ALONG AN EAST-WEST SECTION (MODIFIED FROM HARRISON, 1972)

The Burke Formation, as described in western Montana (Mineral County), varies between fine-grained, green-gray quartzite and green-gray, thin-bedded, impure quartzite. Farther to the north and east in Glacier National Park, the stratigraphically equivalent Appekunny Argillite (Figure 12-3) consists of massive argillite that is mainly green but also red in certain intervals. Argillite makes up more than 90 percent of the 1,030 m of exposed strata, while light-colored quartzite is the only other lithology present.

The Greyson Shale is stratigraphically equivalent to the Burke Formation (Figure 12-3); outcrops near Helena, Montana, however, indicate little lithologic deviation from exposures of the latter unit at Glacier National Park. Ross (1963b) described outcrops in the Big Belt Mountains as containing appreciable shale of variable lithologic expression and "hard, compact greenish-gray and drab siliceous rock."

The younger St. Regis Formation is geographically restricted to Idaho and adjacent parts of western Montana, where this unit mainly contains argillaceous and quartzitic beds with lesser amounts of calcareous quartzite. Sedimentary structures indicative of shallow-water deposition such as interformational conglomerates, are present locally.

The Grinnell Argillite, which correlates with the Spokane Formation (Harrison, 1972) and hence in part with the St. Regis Formation, is dominantly argillite, as revealed by detailed lithologic descriptions given by Ross (1959) for exposures in Glacier National Park. Approximately 70 percent of a 930-m sequence on Red Eagle Mountain consists of argillite. Shales, which vary in coloration from purplish-red to red to green, and which are both siliceous and arenaceous, are also typical of the Spokane and Empire Formations near Helena, Montana (Figure 12-3).

The Missoula Group contains a number of formations composed of abundant fine-grained clastic lithologies that are interbedded with impure limestone. All gradations between argillite and quartzite exist among these clastic units. The more argillaceous sequences are found within the eastern extent of the Belt Series near Glacier National Park and Helena, Montana. In general, the argillites of the younger Missoula Group are less compact and less siliceous than those of the underlying Grinnell sequence.

The basal Snowslip Formation consists of monotonous green, calcareous argillite. Argillaceous strata exposed above the Siyeh Limestone (=Helena Dolomite of Figure 12-3) in Glacier National Park total some 1,600 m and are dominated by red, maroon, and green argillites. Some carbonates and minor quartzite are also present. Near Helena, Montana, the Marsh Shale is correlative and, although thinner, is predominantly red shale with minor amounts of calcareous and quartzite interbeds (Harrison, 1972).

The overlying Shepard Formation in the same area is primarily a pale yellow-brown to gray-orange sequence of argillaceous and siliceous rocks rich in dolomite (Ross, 1963b). Stratigraphically equivalent to the Snowslip and Shepard Formations is the Miller Peak Formation, which, in the vicinity of Missoula, Montana, is characterized by red to green, laminated silty argillite and lesser amounts of argillaceous quartzite. In this region the argillites resemble phyllites, owing to the presence of very fine-grained chlorite and sericite. Argillaceous siltstones and argillites are also abundant in the McNamara Formation, which is estimated to attain a thickness of more than 1,200 m near Missoula, Montana.

12.2.2 Geologic Setting

The various thicknesses and generalized lithologic composition of the divisions of the Belt Series are shown in Figure 12-4. Represented there is a reconstruction (palinspastic) of Beltian and Windermere stratigraphic successions as they appeared in this Late Precambrian depositional basin.

The Belt Series as exposed throughout a broad region (Figure 12-2) exhibits an outcrop belt defined in several ways as discussed by Harrison (1972). Thus, Belt Series strata (1) rest upon Precambrian crystalline rocks east of Helena, Montana, but are bounded by a fault (originally active in Belt time) in areas south of Helena; (2) are overlain by the younger supracrustal Precambrian Windermere System to the northwest and buried by Columbia River Plateau basalts to the west; (3) are complexly deformed and metamorphosed to high-grade rocks in the western and southwestern parts of the basin (Kootenay Mobile Belt) and adjacent to the intrusions of the Idaho and Boulder Batholiths to the south (Figure 12-2); and (4) are interrupted to the east by the Montana Disturbed Belt, an area characterized by numerous thrust faults that have displaced Beltian rocks eastward several tens of kilometers over younger Paleozoic and Mesozoic rocks in the Cordilleran Foreland. Harrison (1972), however, noted that the eastern edge of the Belt Series coincides approximately with the Montana Disturbed Belt.

The degree of metamorphism within the Belt Series increases across the basin from northeast to southwest, and with depth in the stratigraphic section. This is reflected by the increasing grain size of the micaceous minerals sericite and muscovite (Ross, 1963b). Other evidence involves mineralogic studies (x-ray diffraction analyses) denoting illite transformation to the 2M polymorph (Maxwell and Hower, 1967), an obvious increase in biotite content, and by reconnaissance oxygen-isotope geothermometry (Eslinger and Savin, 1973).

Studies by Maxwell and Hower (1967) on the Belt Series along the extreme eastern edge of the outcrop belt indicate that the deeper argillite sections (Prichard, Burke, St. Regis Formations) in Idaho and western Montana should more properly be considered metamorphic because of the relatively high percentage of the 2M illite polymorph. This is consistent with general descriptions given to these rocks where such terms as sericite schists are commonly used (Ross, 1963b).

In addition to those Beltian rocks which are exposed in the deeper sections within Idaho and adjacent parts of Montana and which have undergone low-grade metamorphism, rocks adjacent to the Idaho and Boulder Batholiths to the south are also clearly metamorphic (Figure 12-2). True argillites outside of these two settings are those exposed along the eastern and northeastern parts of the Belt Series outcrop area in Montana.

Several geologic and tectonic events that affected rocks of the Belt Series largely reflect Cretaceous and Tertiary events, although some exhibit remnant Precambrian tectonism. Movement on several faults, such as the Hope strike-slip fault and some parts of the faults that constitute the Lewis and Clark Line (Figure 12-2), as well as broad anticlinal warping such as in the Purcell Anticlinorium, has been documented to have occurred in the Precambrian time (Harrison, 1972). Rejuvenation of structural movement along Precambrian features occurred during the Cretaceous and Tertiary Periods and produced block-fault and graben structures, such as the Purcell Trench, the Libby Trough, and the Rocky Mountain Trench. Structural events that formed the Montana Disturbed Belt and the Kootenay Mobile Belt also appear to have been largely Cretaceous and Tertiary; the same holds for the emplacement of the Idaho and Boulder Batholiths.

The thickness of individual formations is well illustrated in Figure 12-4. In general, however, units are thinnest in the east. Near what was the probable center of the Belt depositional basin, or in the vicinity of Alberton, Montana, partial sequences probably exceed 20,000 m in thickness, while individual formations approach 3,000 m in thickness (Figure 12-4).

Isopach maps for several of the dominantly argillaceous units reveal that the middle part of the Ravalli Group (St. Regis-Spokane Formations) is regionally thickest in the northeastern part of the Belt Series in Montana (Figure 12-5). Of interest is that the metamorphic grade is lowest in this area. Likewise, the greatest thicknesses of the lowermost parts of the Missoula Group (to the top of the Bonner Formation) generally are developed in the east-central part of the outcrop area in Montana, or where metamorphic grade is also low (Figure 12-6).

12.2.3 Mineralogy and Rock Properties

Ross (1963b) noted that the clastic rocks of the Belt Series generally consist of fine-grained, silt- and clay-sized grains that range from a few thousandths to a few hundredths of a millimeter in diameter and are embedded in a matrix containing conspicuous flaky minerals. Quartzite units, although appearing coarse grained in outcrop, generally consist of grains a millimeter or less in diameter.

These clastic rocks basically consist of detrital quartz, clays, and other micaceous minerals, feldspars, and some ferromagnesium minerals.

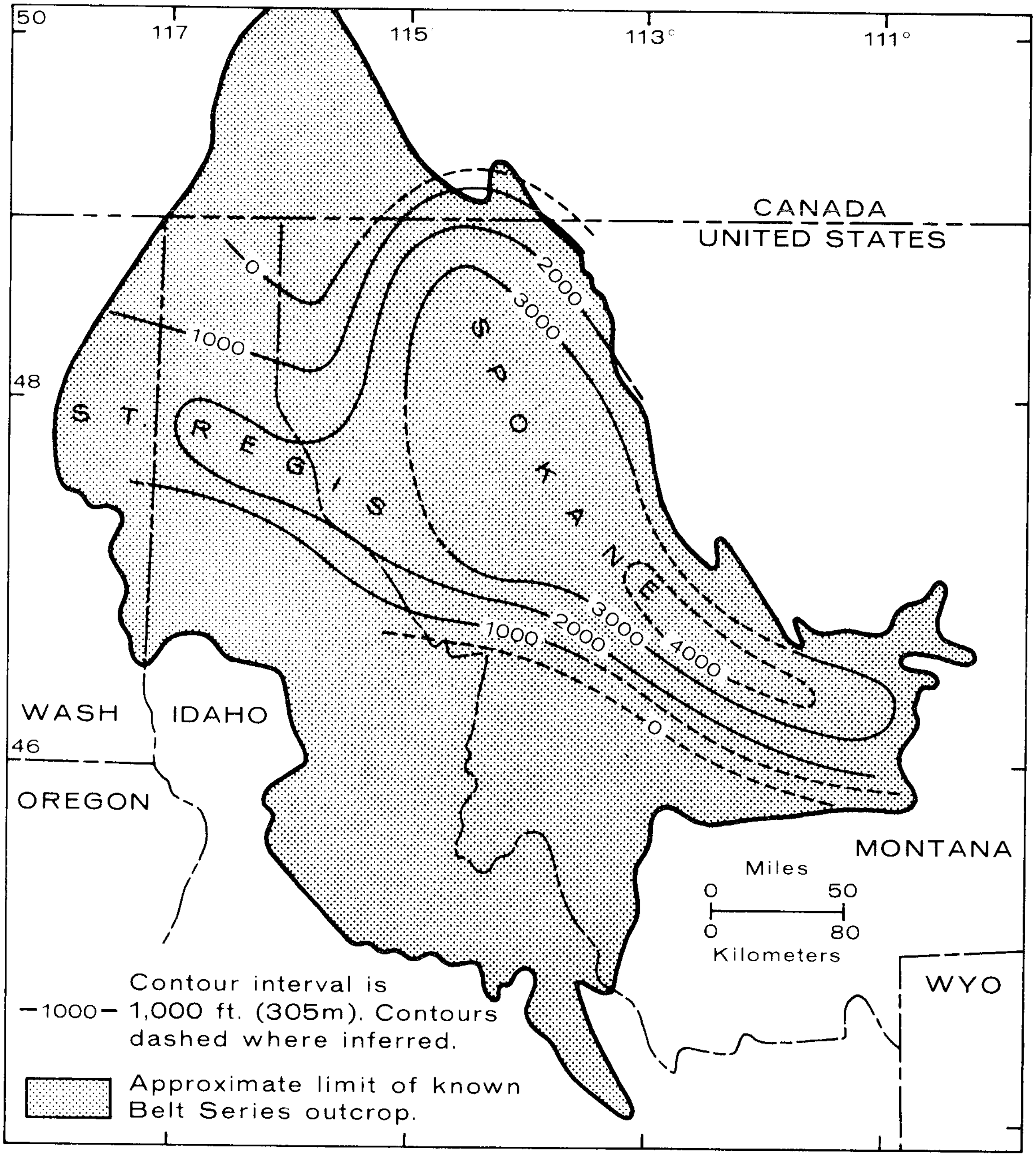

FIGURE 12-5. ISOPACH MAP OF RAVALLI GROUP OF BELT SERIES (MODIFIED FROM HARRISON, 1972)

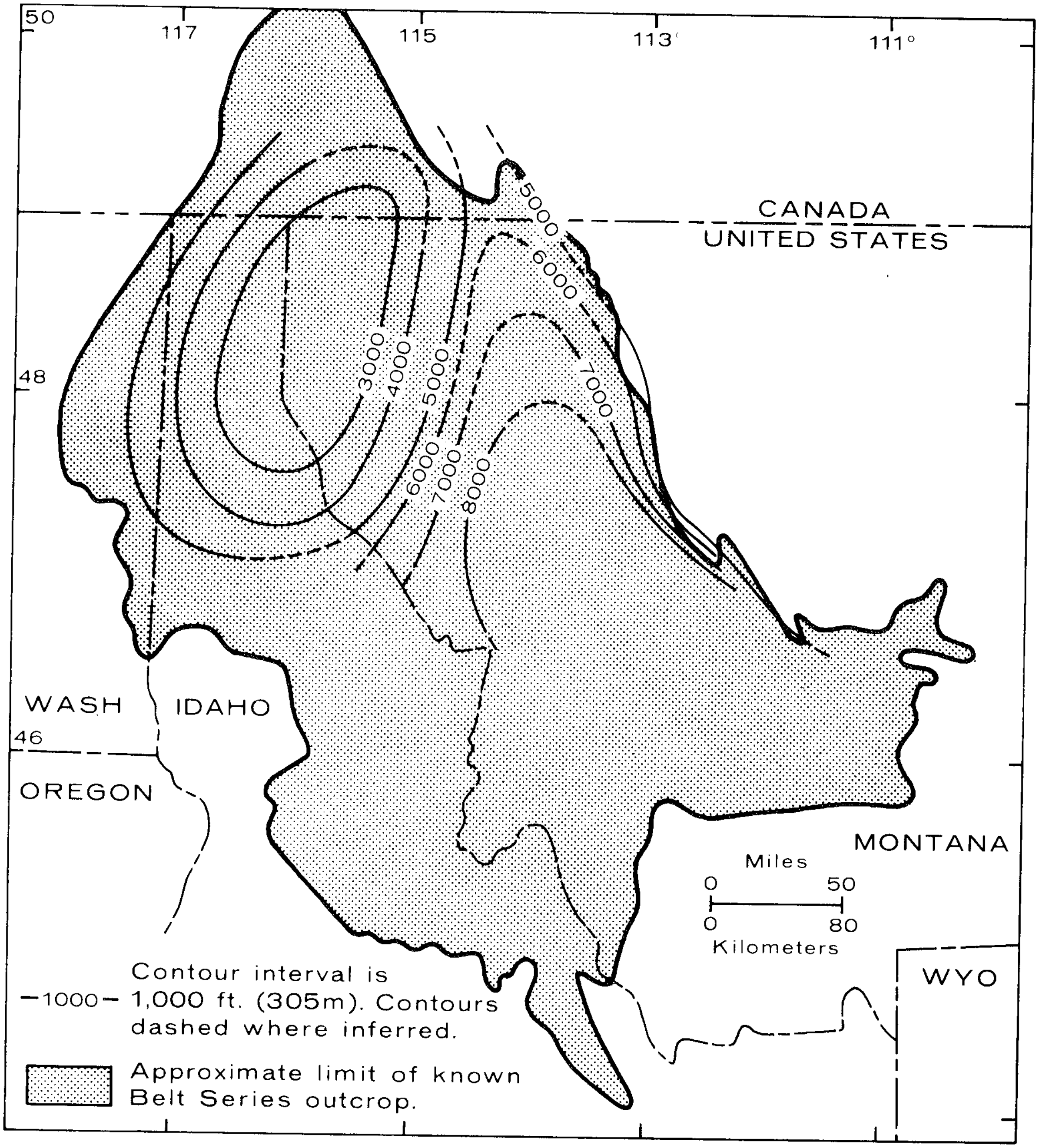

FIGURE 12-6. ISOPACH MAP OF MISSOULA GROUP OF BELT SERIES (MODIFIED FROM HARRISON, 1972)

Fragments of argillaceous rocks, though present, are rare, while carbonate minerals are common in the matrix. Most of the arenitic rocks are compositionally graywackes and subgraywackes, although they are finer grained and contain more rounded clasts than usual. Many of these rocks also exhibit cross bedding and ripple marks, features not normally associated with typical graywackes. Some of the coarser clastic units in the Belt Series are even arkosic.

In general, metamorphism has produced recrystallization of the sand grains, conversion of most clay minerals to micaceous phases, and generation of authigenic feldspars. On the basis of x-ray examination, most argillites are shown to contain relatively small quantities of clay and mica minerals. In analyzing 47 samples of argillite, a typical clay and mica content showed these percentage ranges: chlorite, 1 to 3 percent; mica, 1 to 2; illite, 2 to 3; montmorillonite, 3; and mixed-layer clays, less than 3 (Ross, 1963b).

Detailed x-ray diffraction studies by Maxwell and Hower (1967) of samples from Pend Oreille, Idaho, Glacier National Park, and the Little Belt Mountains in Montana indicated that the proportion of the 2M polymorph of illite increases with depth in various stratigraphic sequences and along an east to west gradient. This recrystallization from the detrital 1Md polymorph to the 2M form is a consequence of increasing grades of diagenesis and/or metamorphism. Kaolinite was noted only in the Spokane Formation from the Little Belt Mountains. Coincident with these mineralogic trends was a general pattern of increasing grain size together with increasing deorientation of the layered silicates from their parallelism to the bedding.

The physical properties of many Belt Series argillites might be expected to differ significantly from those observed in the Eleana Argillite owing to the general absence of montmorillonitic-type clays. Most of these argillites would not be expected to undergo an early contraction phase upon heating to 100°C as was noted in the Eleana studies by Lappin and Olsson (1979).

No studies appear to have been conducted on the argillites in the Belt Series with regard to standard rock-mechanical properties.

12.2.4 Hydrology

Extremely few data exist for ground-water resources within the outcrop area of the Belt Series. Some of the principal aquifers identified within the region occur in the vicinity and south of Kalispell and Missoula, Montana, and appear to be confined to restricted deposits of glacial till and alluvial sediments (Foxworthy, 1979).

12.2.5 Mineral Resources

Significant metallic mineral resources occur associated with or in the vicinity of the Belt Series (Kinkel and Peterson, 1962; McKnight et al., 1962). These include the major lead-zinc-silver vein deposits that occur in Belt Series rocks in the Coeur d'Alene district near Wallace, Idaho; major copper-zinc-lead-silver disseminated-type deposits primarily associated with the Boulder Batholith in the Butte district, Montana; important deposits of disseminated- and replacement-type copper deposits that occur in the Snowstorm district of Montana along the Idaho border; and important lead deposits contained within Belt Series rocks that occur in the Colorado district near Boulder, Montana.

Although not economically developed to date, significant strata-bound, sedimentary copper deposits are known to exist within fine-grained clastic units of the Revett Formation along a belt parallel to a broad band of domal structures of Precambrian age in western Montana (Harrison, 1972). Estimates suggest that as much as 900 million metric tons of ore having an average grade of 0.5 to 1.0 percent copper plus prolific submarginal reserves may be present (Cox et al., 1973).

Despite these areas of significant mineralization, there are large expanses within the outcrop area of the Belt Series where major mineral deposits do not appear to occur. The argillite units of interest to this report tend to be especially barren in this context for parts of the Revett Formation.

The Belt Series, lastly, is devoid of hydrocarbon and coal deposits as well as exploration wells and subsurface mines typical of other sedimentary basins that contain these energy resources.

12.3 CHUAR-UNKAR-APACHE GROUPS IN ARIZONA

12.3.1 Stratigraphy

Precambrian supracrustal rocks occur in separated exposures within the Grand Canyon, where the Colorado River has incised deeply into the overlying Paleozoic succession, and in numerous scattered localities throughout central Arizona. Of the several sequences having argillaceous units, the Sixty Mile Formation of the Chuar Group, the Hakati Shale of the Unkar Group, and the Pioneer Shale of the Apache Group were identified in a preliminary examination as containing significant thicknesses of shales and/or argillites (Connolly and Woodward, 1980). These units are assessed further in this report.

An effort to correlate approximately the basic stratigraphy of Precambrian supracrustal rocks from exposures in the Grand Canyon with those in central Arizona is presented in Figure 12-7. No detailed stratigraphic correlation has yet been possible, owing to the wide geographic separation between the two areas. The stratigraphic information presented is largely from Noble (1914), Shride (1967), and Ford and Breed (1973).

The Apache Group is exposed in numerous outcrops throughout central Arizona (Figure 12-8). Within this group, the Pioneer Shale attains a maximum formation thickness of 152 m, with the thickest sections exposed in the Sierra Ancha region. This shale locally includes at its base the Scanlan Conglomerate Member, which averages 9 m in thickness. Where the Pioneer Shale is greater than 45 m thick, mudstone ordinarily constitutes up to two-thirds of the upper part of the formation; the lower part consists of fine- to medium-grained arkosic or feldspathic sandstone intercalated with mudstone. Shride (1967) pointed out, however, that this so-called shale is actually a tuffaceous mudstone or siltstone that includes abundant fine-grained sand particles. The rock is typically laminated in beds up to 1 m thick. Much of the shale is described as firmly indurated, suggesting that argillite may be a more appropriate lithologic term.

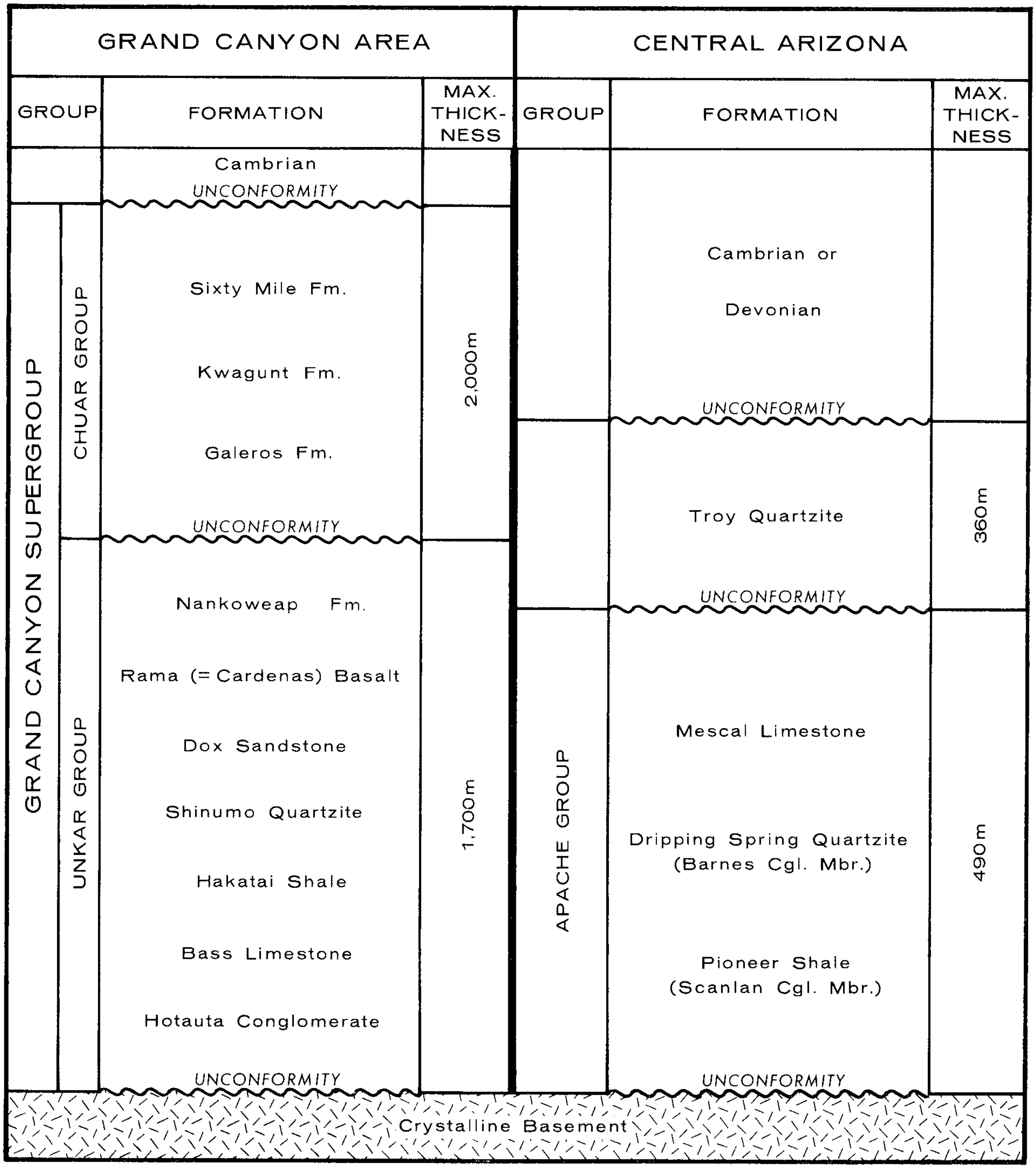

FIGURE 12-7. CHART SHOWING GENERALIZED CORRELATION OF PRECAMBRIAN SUPRACRUSTAL SEQUENCES EXPOSED IN GRAND CANYON AND IN CENTRAL ARIZONA (MODIFIED FROM KING, 1976)

Significant lateral variations occur within the Pioneer Shale only in the northwestern part of the region adjacent to where the unit thins to a feather edge (Figure 12-8). In this area, the unit becomes appreciably coarser grained, and lithologic variations extend up to several kilometers. This variation was apparently controlled by the height and local relief on the pre-Pioneer surface (Shride, 1967).

Within the Grand Canyon region, the Grand Canyon Supergroup (King, 1976) reaches an aggregate thickness of as much as 3,000 m locally and is divisible into the younger Chuar Group and the older Unkar Group. The Chuar Group is divisible, in ascending order, into the Galeros, Kwagunt, and Sixty Mile Formations (Figure 12-9). In turn the Galeros Formation has been subdivided, in ascending order, into the Tanner, Jupiter, Carbon Canyon, and Duppa Members. Members of the overlying Kwagunt Formation are the Carbon Butte, Awatubi, and Walcott. Although the youngest formation (Sixty Mile) is of insufficient thickness (36 m) for further consideration, several of the members listed above contain argillaceous strata of appreciable thickness.

The Tanner Member of the Galeros Formation consists of a basal massive, coarsely crystalline dolostone (18 m thick) overlain by 177 m of blue-gray shale. Ford and Breed (1973) described this shale as fissile and micaceous; a few siltstone beds, rarely thicker than a few centimeters, are also present. The Jupiter Member contains a basal carbonate unit whose maximum thickness is 13 m; above this is a thick shale section that reaches 453 m in thickness. This shale unit is more variable than the comparable argillaceous unit in the Tanner Member and ranges in color from blue-gray through light green-gray to red-brown. Numerous thin (5 to 10 cm) quartzose siltstone layers occur throughout this shale. The Carbon Canyon Member consists of a thick (472 m) sequence of alternating limestones, shales, and thin sandstones. Some measure of cyclic expression is evident among these lithologies. The uppermost Duppa Member is an intercalated mixture of thin limestones, calcareous sandstones, and purple to gray shales.

Within the Kwagunt Formation, the lowermost Carbon Butte Member is composed of a massive red sandstone whose maximum thickness reaches 29 m;

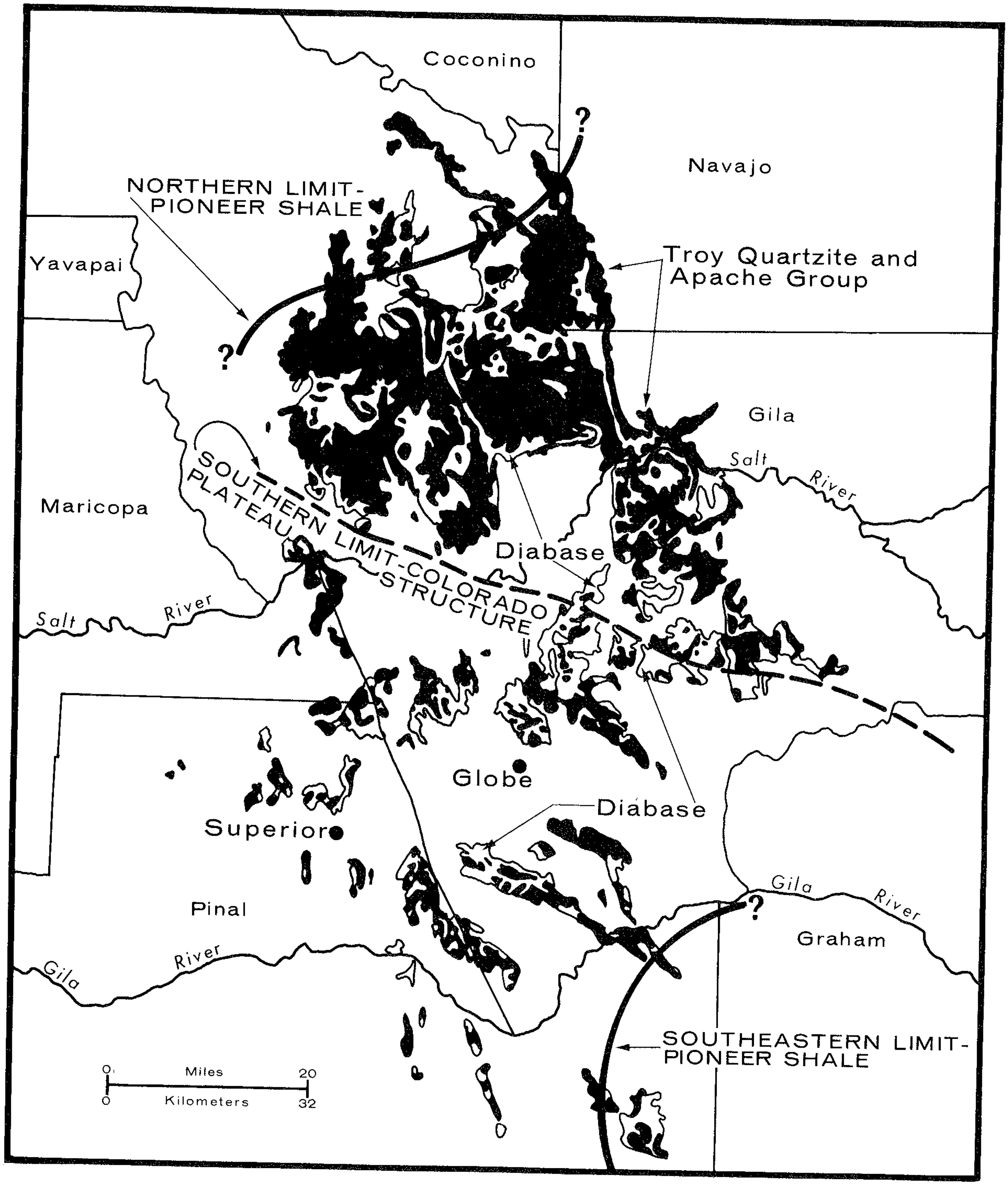

FIGURE 12-8. MAP SHOWING AREAS IN CENTRAL ARIZONA WHERE OUTCROPS OF PRECAMBRIAN APACHE GROUP (AND TROY QUARTZITE) AND ASSOCIATED DIABASIC INTRUSIONS ARE LOCATED (MODIFIED FROM SHRIDE, 1967)

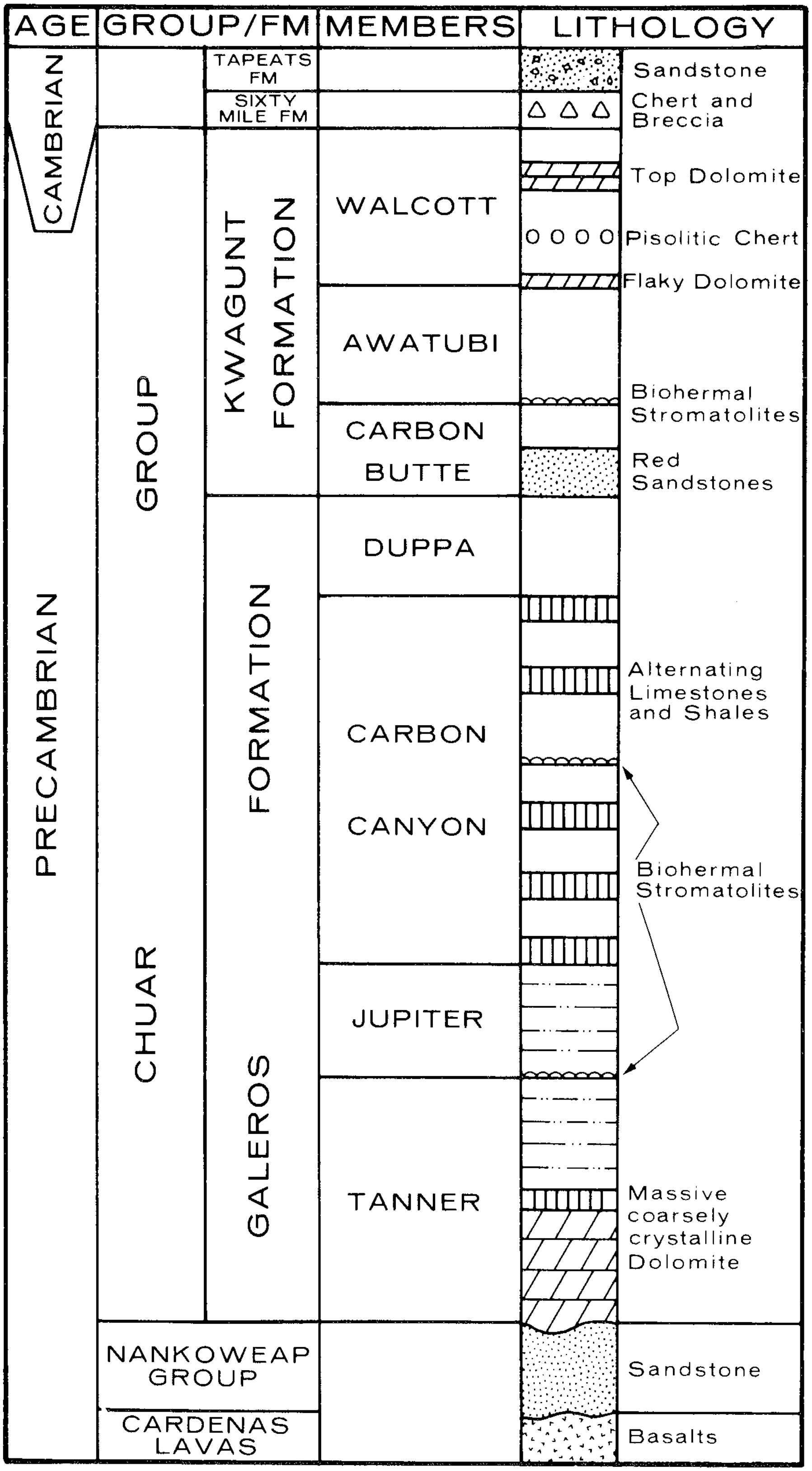

FIGURE 12-9. DIAGRAM SHOWING STRATIGRAPHIC SUCCESSION AND PRINCIPAL LITHOLOGIES WITHIN PRECAMBRIAN CHUAR GROUP, AS FOUND IN GRAND CANYON REGION (MODIFIED FROM FORD AND BREED, 1973)

some 24 m of purple-gray mudstone containing thin siltstone lenses overlies this basal arenaceous unit. A distinctive limestone bed only 4 m thick marks the base of the overlying Awatubi Member and is in turn overlain by some 340 m of varicolored shale beds. The uppermost Walcott Member is a diverse sequence that contains dolostone, shale, bedded chert, and dolomitic limestone.

Within the Unkar Group, which lies disconformably below the Chuar Group, there is one important thick argillaceous unit known as the Hakati Shale. Noble (1914) characterized this interval as consisting of shales that grade upward into arenaceous shales and sandstones. Quartzitic jasper beds are also developed in this sequence, which reaches 182 m in thickness in the Grand Canyon region. This unit is also affected by a diabasic intrusion and its associated contact metamorphism.

12.3.2 Geologic Setting

The Precambrian supracrustal sequence of central Arizona is best developed in the central Sierra Ancha, where the Troy Quartzite and Apache Group are collectively up to 854 m thick. In the southern part of the region, where only the Apache Group is present, the sequence thins appreciably. Despite these regional thickness variations, Shride (1967) believed that the entire sequence probably extended over an area up to 39,000 km^2.

Most individual units within the Apache Group exhibit little lateral variation in composition, texture, or stratification. Thus, Shride (1967) suggested that regional differences in thickness are due principally to erosion prior to the deposition of a succeeding unit. An alternative explanation invoked to explain the thickness variation of the Pioneer Shale is that the configuration of the basin was the controlling factor.

Precambrian strata in this region were intensely folded and displaced by both normal and reverse faults during the Grand Canyon disturbance along narrow, widely spaced, north-trending belts. Strata lying between these belts remained almost completely undeformed until the intrusion of extensive diabase sills, which affected major parts of Arizona

(Figure 12-8). In central Arizona, some diabase sills exceed 305 m in thickness. Concomitant with this intrusive activity, much of the Precambrian sedimentary sequence was wedged apart, faulted, and additionally displaced.

The geologic setting of the Precambrian supracrustal rocks in the Grand Canyon region is deduced entirely from limited exposures within the canyon proper. Ford and Breed (1973) noted that the Chuar Group is unconformably overlain by the Cambrian Tapeats Sandstone and that perhaps some 2,000 m of the Chuar and underlying Unkar Groups may have been eroded subsequent to tectonic activity in this area. As exposed in the Grand Canyon itself, the Precambrian supracrustal rocks lie beneath approximately 1,300 m of Paleozoic sedimentary rocks and extend laterally away for an unknown distance.

Regional normal faulting that affected the Precambrian strata in the Grand Canyon region occurred in two episodes, one in the Precambrian time and the other during Laramide (Cretaceous-Tertiary) time. In large part, these two periods of faulting occurred along the same trends. Broad Precambrian folding also took place in the region.

Although any correlation with the Belt Series rocks of the Northern Rocky Mountains is highly speculative, Ford and Breed (1973) suggested that the Apache Group may be equivalent to the main Belt Series and that the Chuar Group is probably correlative with the Windermere Group, which overlies the Belt Series in Montana and British Columbia. If this interpretation is correct, deposition of the sediments that formed the strata in the Chuar Group may have continued right up to the start of the Cambrian Period (Harrison and Peterman, 1971).

12.3.3 Mineralogy and Rock Properties

Although no detailed mineralogic studies have been conducted on the Precambrian supracrustal rocks of Arizona, brief field descriptions of the various stratigraphic units lead to the deduction that many argillaceous units are probably true argillites. For example, Ford and Breed (1973) described the upper part of the Tanner Member as a "fissile micaceous shale," while the upper shale unit in the Jupiter Member was described as "blue-gray beds that are micaceous."

Petrographic studies of argillaceous rocks from the Apache Group in central Arizona suggest a high degree of induration, which in all probability means the rocks are argillites. Shride (1967) noted that the mudstones of the Pioneer Shale consist of very fine-grained detrital feldspar and quartz, and of devitrified glass shards set in a matrix composed partly of platy muscovite (=sericite) aligned parallel to bedding. In a subsequent study, Shride (1967) also observed that the lithologies in the Apache Group are generally no more metamorphosed than those in the overlying Paleozoic sequence.

In summary, limited, extrapolated data suggest that the Precambrian supracrustal rocks in central Arizona were probably subjected to a lower grade of diagenesis than many parts of the Belt Series in Montana and Idaho. A tentative assumption is that micaceous minerals such as sericite probably represent diagenetically formed material. If true, this would qualify the more shaly rocks as true argillites.

12.3.4 Hydrology

Although the general hydrologic setting in Arizona where Precambrian supracrustal rocks occur was discussed by Ligner et al. (1963), specific data about the ground-water hydrology of these strata are extremely few. The occurrence of ground water within Precambrian units in central Arizona is restricted, owing to the high degree of consolidation (induration) of these rocks. Local, small accumulations of ground water occur where there are fractures; numerous springs also occur in the region.

The amount of ground water used in central Arizona is small. Several valleys along the Verde River south of the Mogollon Rim and in central Yavapai County represent the only important sources of ground water, and in both areas it is derived from unconsolidated alluvial material.

Within the Plateau Uplands in the vicinity of the Grand Canyon, the Coconino, Navajo, and Dakota Sandstones constitute significant bedrock aquifers. All of these sandstone units occur well up in the stratigraphic section that overlies the Precambrian strata; a considerable thickness of impermeable siltstones and mudstones separates these aquifers from the Precambrian units of interest.

12.3.5 Mineral Resources

Important mineral resources within the Precambrian supracrustal rocks of central Arizona include chrysotile asbestos in Gila County and iron ore deposits in the Sierra Ancha area and in the Canyon Creek-Fort Apache Indian Reservation area of southwestern Navajo County.

Younger Precambrian rocks also serve as the hosts for the Laramide-age deposits of copper, zinc, lead, and silver from a number of localities, such as the Superior and Globe districts (Figure 12-8). In these districts, porphyry-copper deposits are associated with Laramide-age stocks, where mineralization followed shattering of the intrusive bodies (Anderson, 1969). Major deposits occur in the area around Globe. The Mescal Limestone also was used extensively at the Roosevelt Dam site.

The asbestos deposits are restricted to locations where small dikes and sills of diabase have come in contact with the Mescal Limestone. Most of the minable material is concentrated at the contact zone in bodies up to 45 cm thick. Some 160 deposits scattered throughout central Arizona have been mined; the major mining areas are north and southeast of Young and north of Globe. Annual production of asbestos has ranged from a few thousand to several tens of thousands of metric tons. Shride (1969) estimated that minable, undiscovered resources probably were equal to 70,000 metric tons a decade ago. Also, some potential deposits of iron ore are found in this central Arizona region. Potentially large deposits of hematite appear to be present within the Mescal Limestone of Navajo and Gila Counties (Klemic, 1969). No commercial production of these metallic deposits has yet been undertaken. Within the Grand Canyon region, minor contact metamorphic asbestos deposits occur within the Late Precambrian supracrustal rocks, although none are being mined at the present time. No other economic commodities are presently obtained from this region.

12.4 OTHER UNITS

Connolly and Woodward (1980) identified several Precambrian supracrustal sequences that, according to their descriptions, contain thick argillaceous units. These eight stratigraphic sequences occur throughout the Rocky Mountains, Great Basin, and northern Great Plains (Black Hills), and are discussed briefly in this next section. They are considered together, even though they were formed in different geologic provinces. Available data for some sequences are scarce.

12.4.1 Units of Z Age

A number of isolated, relatively small exposures of supracrustal rocks of Z age (0.57 to 0.8 billion years) occur within the eastern Great Basin region, or in parts of California, Idaho, Nevada, and Utah (King, 1976). As cited by Connolly and Woodward (1980), the sequences include (1) red-purple quartzites and red and green shales of the Mutual Formation in north-central Utah, or near Great Salt Lake, where a thickness of some 360 m is present; (2) alternating quartzites and argillites up to 2,700 m in thickness that make up the McCoy Creek Group (Sheeprock Series) along the Nevada-Utah border and into southern Idaho; and (3) some 3,000 m of shales and argillites found in the Deep Spring, Wyman, and Johannie Formations that occur along the California-Nevada border. These supracrustal sequences all occur within a region characterized by numerous earthquakes and high seismic risk (zone 3; Figure 1-3a). Also, on a more localized basis, they are affected by active faulting and comparatively recent volcanism and associated tectonic disruption.

Z-age argillites in the eastern United States occur in the Ocoee Supergroup in the Blue Ridge Mountains of Tennessee, Georgia, and Alabama. These argillites are discussed briefly under "Other Units" in the chapter on the Eastern Interior region (Section 3.4.5.1).

12.4.2 Units of Y Age

In the same general areas discussed above, there also occur several supracrustal sequences that are older, or of Y age (0.8 to 1.6 billion years). Included in this sense are the thick (up to 5,000 m) sequence of quartzite and interbedded varicolored shales of the Big Cottonwood Formation in north-central Utah and the 1,200 m of alternating shales and quartzites of the Crystal Spring Formation in southeastern California. Although these older sequences also may have undergone slightly greater metamorphism, and the Crystal Spring sequence has been extensively intruded by diabases, the most significant objections to their potential are the same cited in the preceding section.

Other Y-age sequences within the western United States include the Uncompahgre Formation, known from the Needle Mountains in southwestern Colorado, and the Red Pine Shale, which is a division of the Uinta Mountain Group of eastern Utah and western Colorado (King, 1976). In the former sequence, up to 2,400 m of alternating quartzites and shales have been described, while the latter sequence contains some 1,500 m of shale, siltstone, and minor quartzite.

The Uncompahgre Formation actually is predominantly quartzite and has been severely deformed into tight isoclinal folds and is overlain by Tertiary San Juan volcanic rocks (King, 1976). Also, this region in southwestern Colorado is well known for numerous deposits of gold-silver mineralization, especially in the vicinity of Silverton, even though mining here has largely depleted the major ore bodies.

Wallace and Crittenden (1969) described the Red Pine Shale as consisting of thin-bedded units of shale and siltstone up to 13 m in thickness, alternating with arkosic to orthoquartzitic, lenticular quartzite units that range in thickness from 1 to 5 m. This small-scale interbedding of shale and quartzite units lessens the likelihood that a thick, homogeneous argillaceous unit is present in this sequence. Although the Uinta Mountain Group also extends northward into northern Wyoming, little is known about its thickness and depth characteristics (Wallace and Crittenden, 1969). A significant thickness of metasedimentary strata assignable to the Uinta Mountain Group is known, however, to underlie the Red Pine Shale, but this sequence is heterogeneous and consists of a complex of interfingering shale, quartzite, and arkosic units.

12.4.3 Units of X Age

The only X-age (1.6 to 2.5 billion years) Precambrian sequence identified by Connolly and Woodward (1980) is the Upper Kenoran sequence. This supracrustal assemblage consists of some 12,000 m of various sedimentary- and volcanic-rock types and is exposed in a north-trending oval area of approximately 2,300 km^2 within the Black Hills of South Dakota (King, 1976). Although the rocks are reported to be graywackes and slates, most have been moderately metamorphosed into phyllites and schists. The volcanic component is largely represented by pillow lava units. Steeply inclined folds have affected the entire sequence. On the basis of the relatively high degree of metamorphism and structural complexity, this series of rocks does not appear to contain low-grade lithologies such as argillite.

12.5 SUMMARY

Parts of the Precambrian (Y-age) Belt Series and, to a lesser degree, stratigraphic units in two supracrustal sequences of similar age in Arizona contain appreciable thicknesses of argillite or related, slightly metamorphosed argillaceous strata. Several areas or large expanses underlain by each sequence, however, may not be characterized by these conditions.

In the case of the Belt Series, strata in some areas display a higher grade of metamorphism (to greenschist grade or above) or are coincident with belts of high seismic risk (zone 3) and/or major regional tectonic features. North and east of the axis of the Purcell Anticlinorium and west of the Montana Disturbed Belt (Figure 12-2), metamorphic effects and seismic risk are less.

In this northeastern part of the Belt Series outcrop trend, several formations contain substantial thicknesses of argillite, but data on the regional depths of these thick argillaceous sections are not extensive enough to characterize fully the physical distribution of these units. Based on measured thicknesses where particular stratigraphic intervals are exposed, the Ravalli and Missoula Groups each contain thick argillaceous units. In particular, the Burke and Spokane Formations contain argillites whose combined thickness exceeds 1,000 m toward the eastern part of this region. Within the same general trend, but more westward, the exposed argillites within the Burke Formation also increase in thickness. Eastward, these units lie beneath the strata of the Spokane Formation, but data are not sufficient to determine subsurface depths.

Within this same region, the younger Missoula Group, especially its lower part, or the Snowslip and Shepard Formations, contains nearly 2,000 m of dominantly argillaceous strata. Again, data are insufficient to characterize these units fully in terms of their depth distribution.

Although the Prichard Formation, especially its upper part, is known to contain thick argillites that would extend throughout this region, data from exposures to the west show these units to be high in metamorphic grade. Because the relative depth of the Prichard Formation within the entire Belt Series is the probable cause for this higher level of metamorphic alteration, and these argillites occur at the same relative depth throughout this northeastern region, the metamorphic grade may be similarly high.

Potential copper mineralization is found in the Revett Formation (=upper Burke Formation); more subsurface data on this unit are needed to determine eastward extensions of this potentially commercial mineralization. The Burke and St. Regis Formations contain thick argillites, but the depth distribution for these units is not clearly established. These older and deeper argillaceous strata have experienced slightly greater incipient metamorphism than those in the Missoula Group.

Parts of the Missoula and possibly the Ravalli Groups are dominated by thick, structurally undeformed units of argillite within this northeastern region. A greater level of future regional exploration is required than for most post-Precambrian strata on which more subsurface data are generally available.

In central Arizona, the Pioneer Shale (Apache Group) reaches more than 150 m in thickness, at least half of which (the upper part) is argillite. Because of numerous diabasic intrusions and their associated contact-metamorphic effects on the Pioneer Shale and regional faulting, the geology is complicated. Few data, moreover, exist on the subsurface-depth relationships of the Pioneer Shale, and careful exploration would be needed to avoid areas affected by the intrusions and faulting cited above. The Pioneer Shale is, however, regionally extensive and thick, and there may be several small regions where detailed investigations would show a lack of intrusions and faulting.

Knowledge of the shale-rich strata found in the Grand Canyon region is unfortunately restricted largely to this historical, aesthetic site. Several thick units are dominated by argillaceous strata; their collective thickness approximates 1,300 m. The Galeros and Kwagunt Formations of the Chuar Group, and the Hakati Shale of the Unkar Group, principally account for this significant development of shale. Data on the lithologic character and thickness-depth relationships of these same units as they extend beneath the Colorado Plateau Province of northern Arizona are, however, not numerous enough to permit any definitive statement. At the Grand Canyon itself, the top of the Precambrian supracrustal sequence lies buried beneath more than 1,000 m of Paleozoic sedimentary strata. Whether any of these shale-rich units occur at moderate subsurface depths away from the Grand Canyon is purely conjectural. Also not known is the exact regional extent of these shales.

In summary, Precambrian supracrustal sequences in Arizona are known to contain thick to very thick units of shale and/or argillite. With regard to the Pioneer Shale in central Arizona, complex geology makes further characterization difficult, even if new data are gained in the future. Those strata known from the Grand Canyon occur at depths greater than 1,000 m. Little is known about their characteristics elsewhere.

13. OVERALL SUMMARY

Shales and other argillaceous strata collectively form a group of rocks that occur widely throughout the United States. The current study presents geologic and hydrologic data for a number of shales and other argillaceous rock units that are thick and occur at moderate depths throughout large regions of the conterminous United States. The geologic settings of these units, in terms of structural geology, seismicity, hydrology, and associated mineral resources, have been discussed for each of the major rock units. Many of these argillaceous units are found within large regions characterized by little structural deformation and by histories of stable to mild tectonics. Specific argillaceous units or formations have been listed and their characteristics summarized at the end of Chapters 3 through 12; no effort is made here to rediscuss these units.

Based upon the data available and the intended scope of this report, no attempt has been undertaken to discuss the relative merits of individual shales, clays, and argillites for repository siting. If detailed studies are conducted on these units in the future, it may then be appropriate to identify and to select the rock units that appear to be best suited as host rocks.

This report shows that there exist several geotechnical areas where data about argillaceous rocks are meager to nonexistent. To a degree, this is because shales and clays in the subsurface are not generally the focus of attention in most drilling and/or exploration programs. Neither are they typically tested for their hydrologic properties. Thus, very little information about hydraulic conductivity, a property whose determination is more aligned to permeable units such as aquifers, is either available or probably valid for clay-rich rocks. Additional hydrologic testing needs to be conducted upon shales and clays, not only to gather firm geotechnical data, but also to establish whether such units are or would act as impermeable barriers, as commonly perceived. Such properties as vertical versus lateral hydraulic conductivity should be determined and contrasted. The impact of differential hydraulic heads between aquifers that lie above and below a shale or clay, the effects of temperature gradients upon the ground-water regime relative to shales, and the nature of osmotic pressures on these rocks and the passage of fluids through them need to be studied and evaluated.

More information also is needed in the area of rock mechanical properties. This is especially necessary for argillaceous units that occur at depths of 300 to 900 m. Except for a few deep mines where shales are exposed in the roof or walls, almost no rock mechanics testing of shales has been done in this depth range. The thermo-mechanical response of clay-rich strata to in situ heater testing also needs additional study.

The ion-exchange capacity of clay minerals in soils and as pure mineral separates is well known; this same property for disaggregated commercial products also can be determined easily. However, the ion-exchange capacity of shales and other argillaceous strata has not been pursued as a research area. Other than studies about the swelling and heaving nature of bentonite-rich materials, little has been done on equating various physical properties in shales and clays with specific clay-mineral assemblages or compositions. Ion-exchange capacity, preferential absorption of elements (including radioisotopes), and the effect upon shales of wetting-drying cycles (as might exist in a subsurface excavation) all require additional study to determine the relationship between clay mineralogy and rock properties.

An important conclusion, therefore, is that relatively little is known about shales and clays with regard to geotechnical characteristics that are critical in evaluating these rocks for radioactive-waste disposal. A large number of data, thus, remains to be investigated.

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