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Salt Plains and Brines in Western Oklahoma Result from Dissolution of Permian Salt and Distinguishing those Brines from Oil-Field Brines

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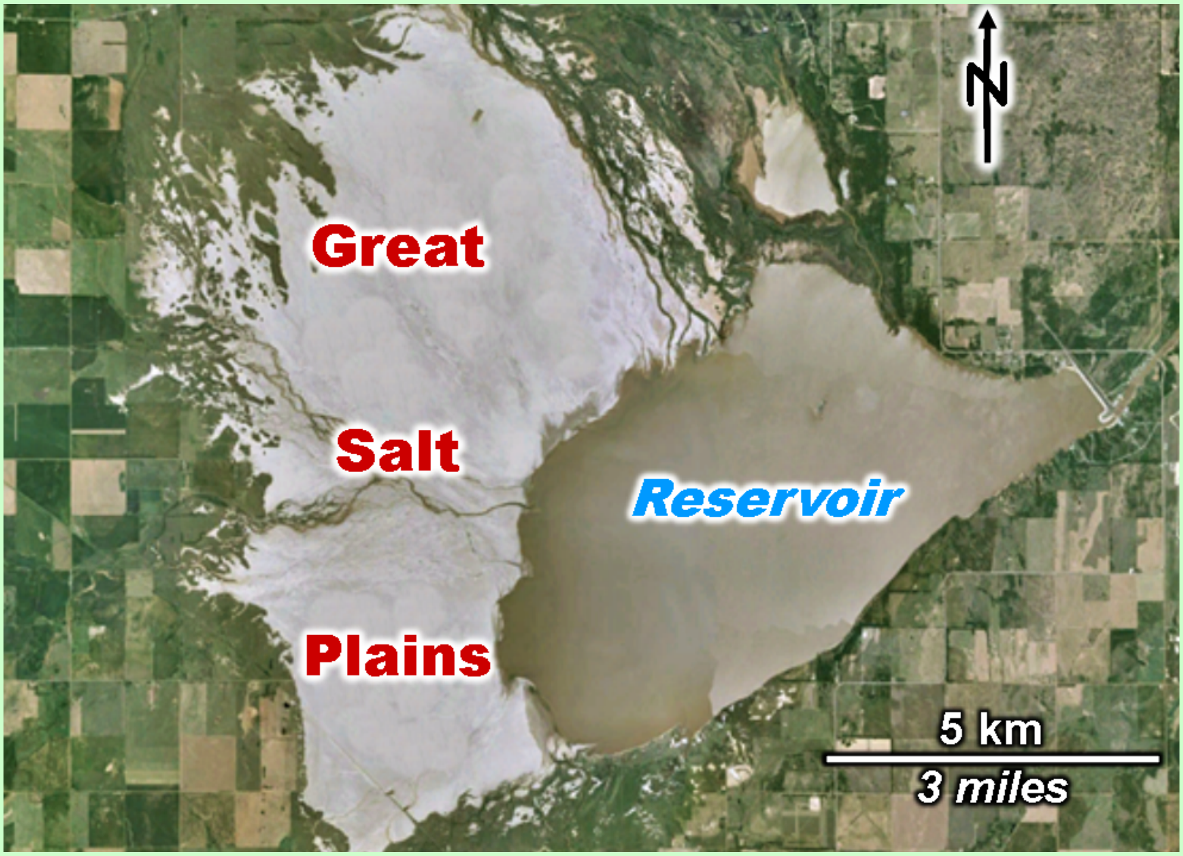

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TITLE PAGE ILLUSTRATION

Aerial view of the Great Salt Plains in Alfalfa County, northwest Oklahoma. This is the largest of Oklahoma’s 11 salt plains, measuring about 65 km^2. Photo is from Google Earth, dated September, 2010.

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Salt Plains and Brines in Western Oklahoma Result from Dissolution of Permian Salt and Distinguishing those Brines from Oil-Field Brines

Kenneth S. Johnson
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ABSTRACT. —Natural dissolution of Permian salt beds is occurring at shallow depths in western Oklahoma, and the resultant brine is coming to the land surface at 11 locations to form salt plains or salt flats in the Arkansas and Red River watersheds. Requirements for dissolution of salt are: 1) a deposit of salt (halite, NaCl) against which, or through which, water can flow; 2) a supply of water unsaturated with NaCl; 3) an outlet whereby the resulting brine can escape; and 4) energy (such as a hydrostatic head or density gradient) to cause water to flow through the system. Fresh groundwater migrates down and laterally, where it contacts salt beds at depths of 9 m to about 200 m below the surface and dissolves the salt to form brine. The brine is then forced laterally and upward by hydrostatic pressure through aquifers, karst features, or fractures in aquitards, until it is discharged at the surface, where the brine evaporates and salt is precipitated. This typically forms a salt crust about 0.5 to 3 cm thick, but crusts as much as 15 cm thick have occurred at some sites where brine bubbles to the surface. These natural salt plains are then partly flushed of their salt during rainfall or flooding events and, as a result, parts of the Arkansas and Red River systems are naturally degraded with salt.

Six of the salt plains are in the Arkansas River watershed (which includes the Cimarron River): Great Salt Plains, Big Salt Plain, Little Salt Plain, Salt Creek Canyon Salt Plain, Okeene Salt Plain, and Drummond Flats Salt Plain. The remaining five are in the Red River watershed: Boggy Creek Salt Plain, Salton (or Chaney) Salt Plain, Robinson Salt Plain, Kiser Salt Plain, and Sandy Creek Salt Plain. The largest salt plain is Great Salt Plains, which covers about 65 km^2, and the smallest are the Salton, Robinson, Kiser, and Sandy Creek Salt Plains, each of which covers from 1 to 4 hectares. The greatest salt emissions are from Big Salt Plain, which emits 2,600 to 4,870 tons of salt per day, and Great Salt Plains, which emits 2,310 to 3,300 tons of salt per day. The lowest emissions are from Boggy Creek and Drummond Flats Salt Plains, which respectively emit 33 and 83 tons of salt per day. Most of the salt plains emit high-salinity brines, with chloride concentrations of 150,000 to 205,000 ppm and salt concentrations of 255,000 to 337,000 ppm; at the higher concentrations, brine is saturated and salt is precipitated on the salt flat almost immediately after brine reaches the surface. Salt was harvested from most of the salt plains by Native Americans and early European settlers, and since about 1900 AD commercial salt has been produced at Big Salt Plain, Salt Creek Canyon Salt Plain, Boggy Creek Salt Plain, Salton Salt Plain, and Kiser Salt Plain.

In addition to natural salt-dissolution brines, as described above, another potential source of brines is oil-field brines or briny formation waters that can be released at or near the land surface and can contaminate freshwater sources. These brines can also have high concentrations of salt and dissolved solids, and it is important to distinguish them from salt-dissolution brines in order to determine the source of the brine—i.e., is a particular brine an oil-field brine or a salt-dissolution brine? The chief means of differentiating between these brines is comparing their sodium-chloride and calcium-sulfate ratios (Na/Cl and Ca/SO_4 ratios). Pure salt has a Na/Cl

ratio of 0.648, and 28 salt-dissolution-brine samples from western Oklahoma have Na/Cl ratios that mostly range from 0.60 to 0.70, and average 0.649. On the other hand, 29 oil-field brines from western Oklahoma have Na/Cl ratios between 0.45 and 0.59, and average about 0.50. Analyses of the 28 western Oklahoma salt-dissolution brines (which are all associated with gypsum and/or anhydrite) have Ca/SO_4 ratios mostly between 0.17 and 0.72, and average 0.4175—almost identical to the actual Ca/SO_4 ratio in gypsum and anhydrite (0.4167). This contrasts with results for 19 randomly selected western Oklahoma oil-field brines, which have Ca/SO_4 ratios that range from 3.2 to 251 and average 52; most of the values are between 20 and 80.

INTRODUCTION

In this report, the term "salt" refers to a rock consisting of the mineral halite—sodium chloride (NaCl). Permian-age salt deposits underlie a vast region extending across western Oklahoma and adjacent states, and a number of natural salt plains exist along the east side of this region in the watersheds of Arkansas River (which includes the Cimarron River) and Red River (Fig. 1, 2). These salt emissions result from natural dissolution of Permian salt deposits that underlie much of western Oklahoma and all of the Texas Panhandle, just to the southwest. Because of the large amount of salt entering these two major river systems, the Tulsa District of the US Army Corps of Engineers (USACE) was tasked to investigate and reduce this natural contamination and to improve water quality downstream from the salt plains. Efforts by the USACE are divided into studies of the Arkansas River Chloride Control Project (which includes six Oklahoma salt plains; Fig. 3, sites 1–6) and the Red River Chloride Control Project (which includes the five remaining Oklahoma salt plains; Fig. 3, sites 7–11).

A cooperative effort of the USACE and the Oklahoma Geological Survey provided basic information on the geologic framework in the vicinity of most of these salt-emission sites; this collaborative effort is the basis for much of this report, and no additional field work or sampling of emission areas was carried out in the study areas. Note: there are natural-brine emissions in the Kansas portion of Arkansas River drainage, and a number of salt plains and emission sites in the Texas portion of the Red River drainage, but this report is limited to the Oklahoma occurrences.

An early report on salt plains in Oklahoma by Gould

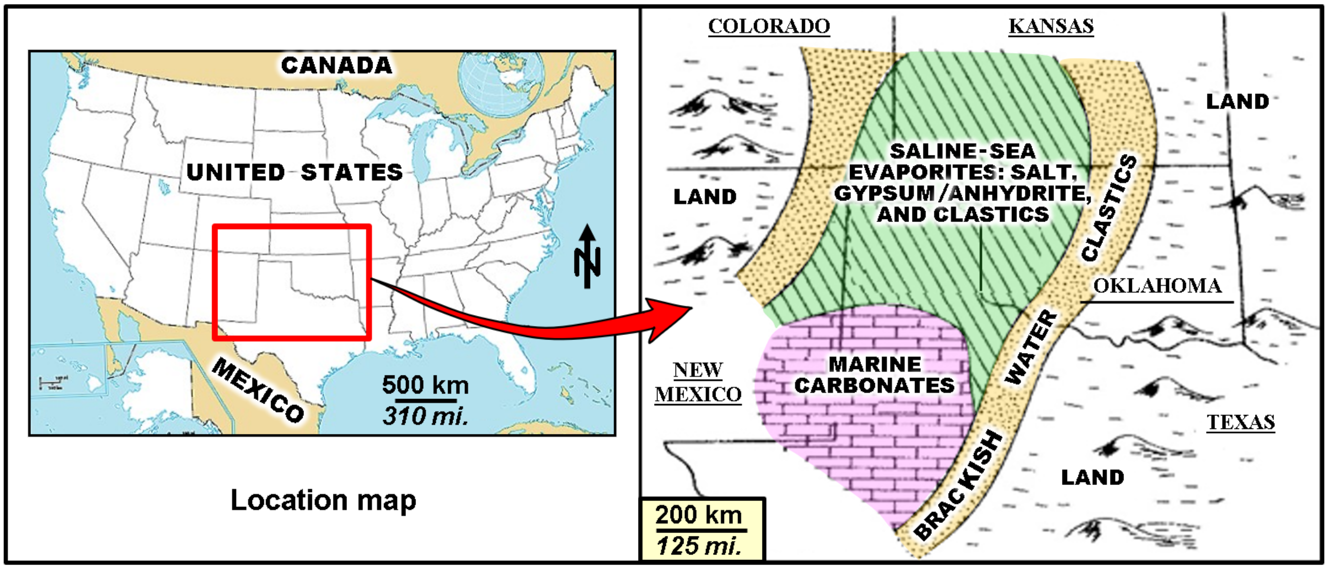


Figure 1. Simplified paleogeography and principal facies in the Greater Permian Evaporite Basin (GPEB) of southwestern United States during deposition of the evaporite facies (salt, gypsum/anhydrite, and clastics) of the Blaine Formation and Flowerpot Shale (modified from Johnson, 1981).

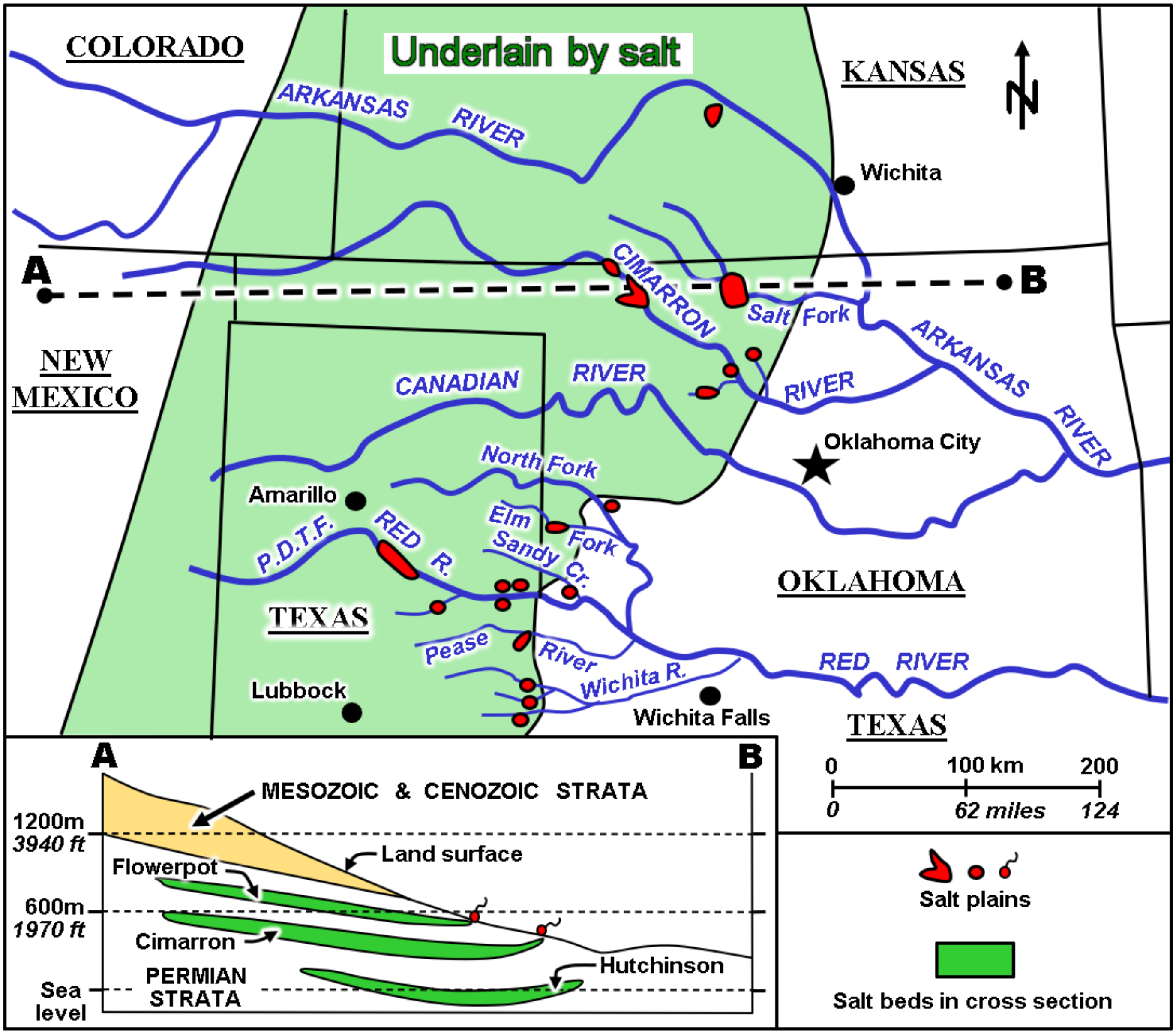


Figure 2. Map and schematic cross section showing area underlain by Permian salt deposits and distribution of salt plains in western Oklahoma and adjacent areas (modified from Johnson, 1981). The water quality of rivers is degraded by salt for some distance downstream from each of the salt plains.

(1901) focused on those in northwest Oklahoma, and a second report by Gould (1905) briefly discussed most of the major salt plains in the State (note—Gould referred to counties as they were in early 1900s: thus his “Woods County Plain” is Great Salt Plains in Alfalfa County, his “Roger Mills County Plain” is Boggy Creek Salt Plain in Beckham County, and his “Greer County Salt Plains” are the Salton, Robinson, and Kiser Salt Plains in Harmon County). A fairly detailed discussion of the major salt plains throughout Oklahoma is given by Snider (1913, p. 202–214): this report includes descriptions of each site, along with chemical analyses of the brines. A discussion of early salt works in Oklahoma by Foreman (1932) dealt mainly with brine seeps and salt production in eastern Oklahoma, but also briefly describes early activity at the salt plains in northwest Oklahoma. A later report by Theis (1934) provides general information on the geology of Great Salt Plains. Harris (1955) made an investigation of the salt plains of northwestern Oklahoma, and summarized much of the early development of their salt resources.

The most comprehensive study of all the salt plains in Oklahoma, Kansas, and north Texas was by Ward (1963a): he discussed the local geology of all the sites

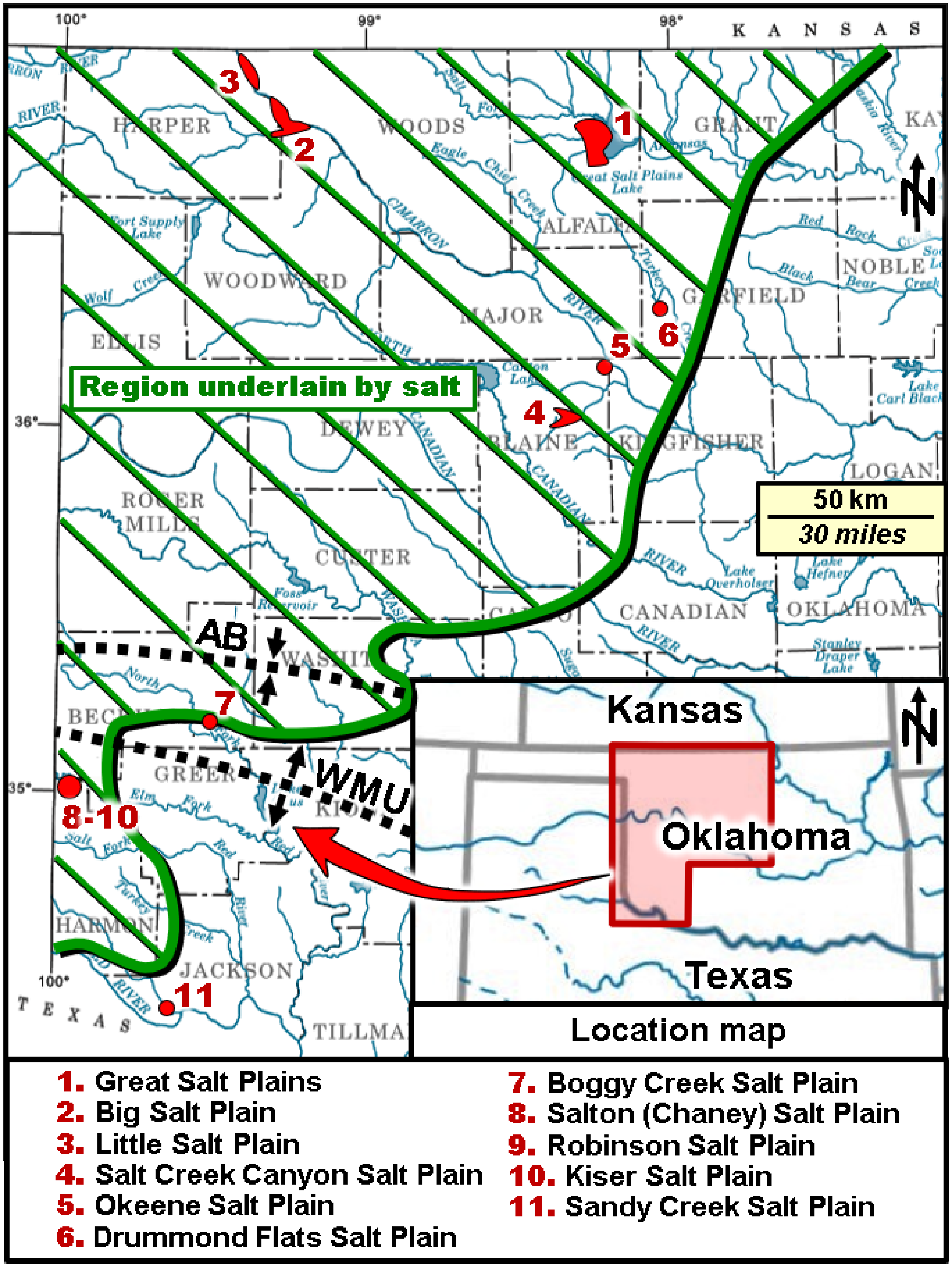


Figure 3. Map of western Oklahoma showing region underlain by salt and location of 11 salt plains formed by subsurface dissolution of Permian salts. Salt distribution modified from Johnson (1976). Also shown are approximate axes of Anadarko Basin (AB) and Wichita Mountain Uplift (WMU).

in Oklahoma, along with chemical analyses of brines, and the amount of salt and chloride emitted at most of the Oklahoma sites. Additional reports that came out of Ward's studies include those by Ward (1961a, b, 1962, 1963b), by Ward and Leonard (1961), and by Leonard and Ward (1962). US Department of Health (1964) also carried out a detailed study of many of the emission sites in Oklahoma, and provided chemical analyses of the brines at most sites. A comprehensive study of Oklahoma's subsurface salt deposits by Jordan and Vosburg (1963) contains a series of maps and cross sections showing the distribution, thickness, and depth of the principal Permian salt units, and a similar study of the Permian salts in Oklahoma and the Texas Panhandle was carried out later by Johnson (1976). Subsequent studies of the geology of Oklahoma's salt plains include: an overview of salt dissolution on the east flank of the Permian Basin (Johnson, 1981); geology and brines at Great Salt Plains (Johnson, 2013a, 2019c); salt plains in northern Harmon County (Johnson, 2019a); and salt plains on the Cimarron River in northwest Oklahoma (Johnson, 2019b).

Salt flats in Oklahoma are all located in topographically low areas (in stream or river valleys) and the brine, formed by groundwater dissolution of Permian salt beds, migrates up towards the surface where it saturates local bedrock and alluvium. Because of the hydrostatic head, and/or capillary action, brine then is brought to the surface and is evaporated to produce a salt crust on the bedrock and/or alluvium. Typically, some or all of the salt crust is dissolved by rain, but this is temporary and a crust is again formed after the rain stops. The crust reforms because: 1) the freshened water evaporates, so dissolved salt is thus concentrated and is again precipitated; and/or 2) new brine is brought to the surface and new salt is precipitated. A thicker crust forms during the hot and dry summer months. The thickness of most salt crusts is about 0.5 to 3 cm, but as much as 15 cm has occurred locally where brine is bubbling to the surface. These salt crusts were often used as a source of salt by Native Americans and early settlers in (what would become) Oklahoma and surrounding states. Several of the salt plains (Big Salt Plain, Salt Creek Canyon Salt Plain, Boggy Creek Salt Plain, and the Salton-Kiser Salt Plains area) have been developed as commercial sources of salt, and/or as sources of high-salinity brine for use in salt-based drilling muds for oil and gas wells drilled through salt beds in the Anadarko Basin.

The largest salt flat in Oklahoma is Great Salt Plains, located on Salt Fork Arkansas River in Alfalfa County (Fig. 3, site 1), where it covers about 65 km^2. Another major area of salt flats, also in the Arkansas River system, is along the Cimarron River and its tributaries: this includes Big Salt Plain, Little Salt Plain, Salt Creek Canyon Salt Plain, Okeene Salt Plain, and Drummond Salt Plain (Fig. 3, sites 2–6). The largest area of salt flats in the Oklahoma portion of the Red River drainage system are the three closely spaced salt plains in northern Harmon County: the Salton, Robinson, and Kiser Salt Plains (Fig. 3, sites 8–10). The remaining salt plains in southwest Oklahoma, the Boggy Creek and Sandy Creek Salt Plains (Fig. 3, sites 7 and 11, respectively), are relatively small and make only minor contributions of salt to local streams in the Red River system.

Based on cooperative efforts by the Oklahoma Geological Survey and the USACE, a series of reports have been released that characterize the geology, distribution of salt beds, and emission of brines at all the major salt plains (Johnson, 1981, 2013a, 2019a, b, c); these studies are the major source of information for much of the current report, and some data from these earlier reports are herein summarized or reproduced.

Being released in 2022, this publication is part of the celebration of the second year of the "International Year of Caves and Karst" (IYCK), which acknowledges the importance of karst in those parts of the world where carbonate and evaporite rocks are being dissolved at or near the Earth's surface. The IYCK is organized by the International Union of Speleology, the worldwide organization of cave and karst explorers, scientists, managers, and educators: the IYCK is being co-sponsored by about 150 national and international partner organizations.

Appreciation is extended to Leah E. Jackson, Tim K. Lowenstein, and James J. Zambito for critical review of the manuscript.

GENERAL GEOLOGIC SETTING

During the Permian Period, western Oklahoma was part of the Greater Permian Evaporite Basin (GPEB) (Fig. 4), a vast region of salt and gypsum and/or anhydrite deposition that covered about 650,000 km^2, extending from west Texas and southeast New Mexico, northward through western Oklahoma and the Texas Panhandle, and including western Kansas and southeast Colorado (Johnson, 2021). Normal marine water entered this large inland sea and was evaporated to produce thick sequences of salt and gypsum/anhydrite (meaning: "gypsum and/

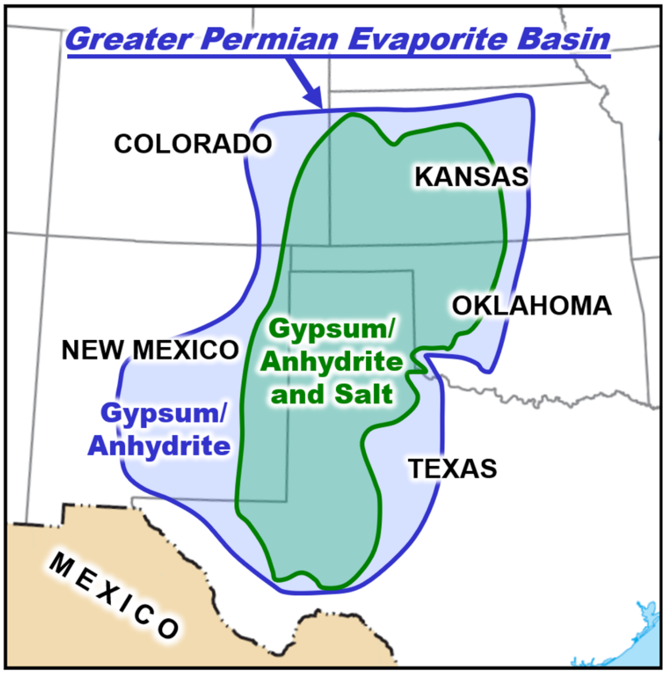


Figure 4. Approximate limits of Permian-age salt and gypsum/anhydrite deposits in the Greater Permian Evaporite Basin (GPEB) of Texas, New Mexico, Oklahoma, Kansas, and Colorado (cover illustration from Johnson and others, 2021).

or anhydrite"), interbedded with redbed shale, siltstone, and sandstone, as well as lesser amounts of limestone and dolomite. Figure 1 shows the paleogeography and principal facies in much of the GPEB during deposition of the Blaine Formation and Flowerpot Shale, two of the principal evaporite-bearing units in the northern and central parts of the GPEB. Salt units deposited in the Oklahoma portion of the GPEB include, in ascending order: 1) the Hutchinson Salt; 2) the Lower and Upper Cimarron salts; and 3) the Flowerpot, middle-Blaine, and Yelton salts (Fig. 5). Salt units that are now contributing to the various salt plains and brine springs in Oklahoma are the Lower and Upper Cimarron salts, and the Flowerpot salt.

Although the vast extent of the evaporite deposits of the GPEB appear to be entirely, or predominantly, of marine origin (deposition in a large, shallow, inland sea with somewhat restricted connections to the open ocean to the southwest), work by Benison and Goldstein (2001), Benison and others (2013, 2015), and Soreghan and others (2014) interprets deposition of the Nippewalla Group (including the Flowerpot salt of western Kansas) in a non-marine, saline-lake, and mudflat environment.

Outcropping rocks in most of western Oklahoma are strata of Permian age, and all the brine-emission sites are underlain by Permian bedrock. Therefore, the geology of Permian rocks in western Oklahoma is key to understanding the salt deposits and brine emissions in the region. At many places, bedrock is overlain by a veneer of Quaternary alluvium and terrace deposits. Major geologic provinces of western Oklahoma include the Anadarko and Hollis Basins, which are separated by the Wichita Mountain Uplift (Fig. 5, inset map). The Anadarko Basin is a large, east-west trending syncline extending across western Oklahoma and the Texas Panhandle; the Lower and Upper Cimarron salts and the Flowerpot salt are being dissolved to supply brine-emission sites in the Anadarko Basin (Fig. 3, sites 1–7). The Hollis Basin, an eastern extension of the Palo Duro Basin, contains a lesser amount of Permian salt: the Flowerpot salt is at shallow depths and yields brines at four sites in Harmon and Jackson Counties (Fig. 3, sites 8–11). The Wichita Moun-

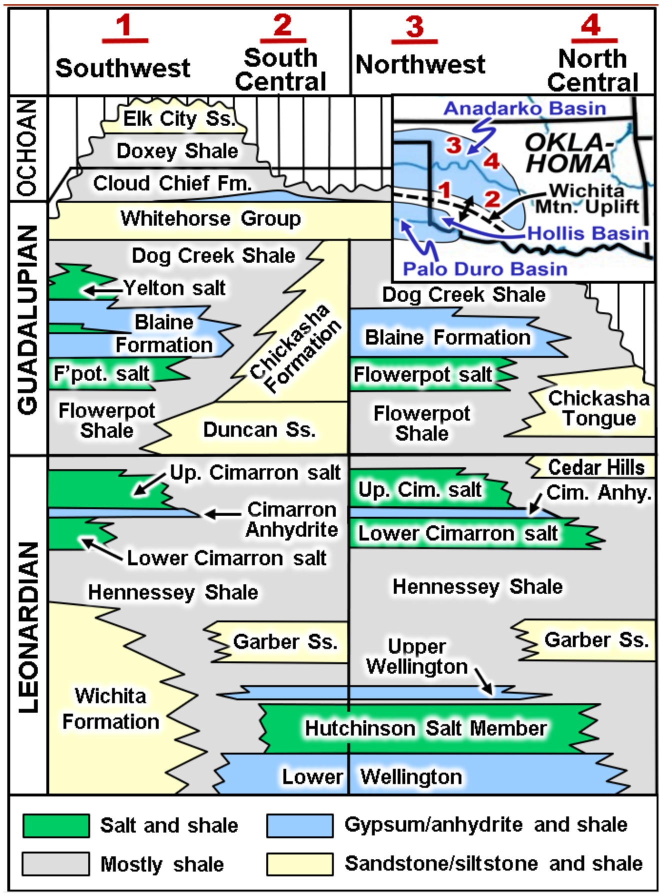


Figure 5. Stratigraphic nomenclature and lithology of Permian evaporites and associated strata in the Leonardian, Guadalupian, and Ochoan Series in four areas of Anadarko Basin in western Oklahoma. Modified from Miser (1954), Jordan and Vosburg (1962), and Johnson (2021).

tain Uplift, which separates the two basins, includes the Wichita Mountains in parts of Kiowa and Greer Counties: Permian strata onlap the uplift, and the mountain system plunges beneath Permian strata and is buried in western Greer County and farther to the west.

Permian outcrops throughout the region consist of shale, siltstone, sandstone, gypsum, and dolomite; they are interbedded with layers of salt in the subsurface immediately below, or downdip from, the various salt plains in both the Anadarko and Hollis Basins. Outcropping Permian strata in the region typically dip gently toward the axes of the Anadarko and Hollis Basins at about 2 to 6 m/km (about 0.1º to 0.3º). However, where salt beds are dissolved (referred to as "salt karst") in the subsurface, overlying strata commonly are disturbed and may dip chaotically at angles of 5º to 30º. This is especially true in parts of the north flank of the Anadarko Basin, where chaotic structures, collapse features, breccia pipes, and other evidence of disturbed bedding are present in Permian and Cretaceous strata that overly areas of salt karst (Suneson, 2012; Johnson, 2013b, 2017; Benison and others, 2015).

SUBSURFACE DISSOLUTION OF SALT

Salt is highly soluble—more soluble than any other rock in the Permian of western Oklahoma. Groundwater in contact with salt will dissolve some of the salt to form a brine, providing the water is not already saturated with NaCl. For extensive dissolution to occur, it is necessary for the brine thus formed to be removed from the salt, or else the brine becomes saturated and dissolution stops. Four basic requirements are necessary for extensive salt dissolution to occur (Johnson and others, 1977):

1) A deposit of salt against which, or through which, water can flow;
2) A supply of water unsaturated with NaCl;
3) An outlet whereby the resulting brine can escape; and
4) Energy (such as a hydrostatic head or density gradient) to cause water to flow through the system.

When all four of these requirements are met, and additional unsaturated water replaces the escaping brine, salt dissolution and brine transport can be extensive and quite rapid, in terms of geologic time.

As described earlier (Johnson, 1981; Richter and Kreitler, 1986), natural dissolution of bedded salt occurs at shallow depths at a number of places in western Oklahoma and north Texas. Fresh and saline groundwater moves laterally through aquifers, sandstone, or karstic gypsum, dolomite, or salt; it also moves vertically through fractures, sinkholes, and collapse features (Fig. 6). Fresh groundwater is generally recharged west of Oklahoma's salt plains, in upland areas where unconsolidated sands, sandstone, gypsum, dolomite, terrace deposits, or alluvium are at the surface. The water migrates down and laterally (generally to the east) where it contacts salt beds at depths of 9 m to 200 m below the surface, and dissolves the salt to form brine. The brine is then forced laterally and upward by hydrostatic pressure through aquifers, karst features, or fractures in aquitards, until it is discharged at the surface.

There are four principal ways for recharge of fresh groundwater in the region (Johnson, 1981) (Fig. 6):

1) Water seeps into the ground through permeable rocks and soils, such as where sandstone is at the surface;
2) Water enters the bedrock through highly permeable alluvium and terrace deposits along and near major streams and rivers;
3) Water enters the ground through sinkholes, caverns, and other karstic features in areas where gypsum, dolomite, or limestone is at the surface; and
4) Water enters the ground through joints and fractures present in the rocks, particularly where salt or gypsum beds are partly dissolved and overlying rock is fractured due to collapse.

After water has dissolved some of the salt, and has become brine, there are six principal ways whereby the brine moves underground and is eventually discharged at the surface (Johnson, 1981) (Fig. 6):

1) Brine moves through dissolution cavities in the salt or other soluble rocks;
2) Brine moves vertically and/or laterally through joints and fractures, particularly where rock is disrupted over dissolution zones;
3) Brine moves laterally through aquifers of sandstone, siltstone, or other permeable rock;
4) Brine may be discharged at a point-source, as a saline spring;
5) Brine may be discharged along the course of a stream bed and become part of the surface flow; and
6) Brine may enter the base of an alluvial deposit or soil, where it can be forced upward under hydrostatic pressure and then drawn up by capillary action as the brine evaporates. A crust of salt is then precipitated on the land surface as water (H_2O) is evaporated from the brine.

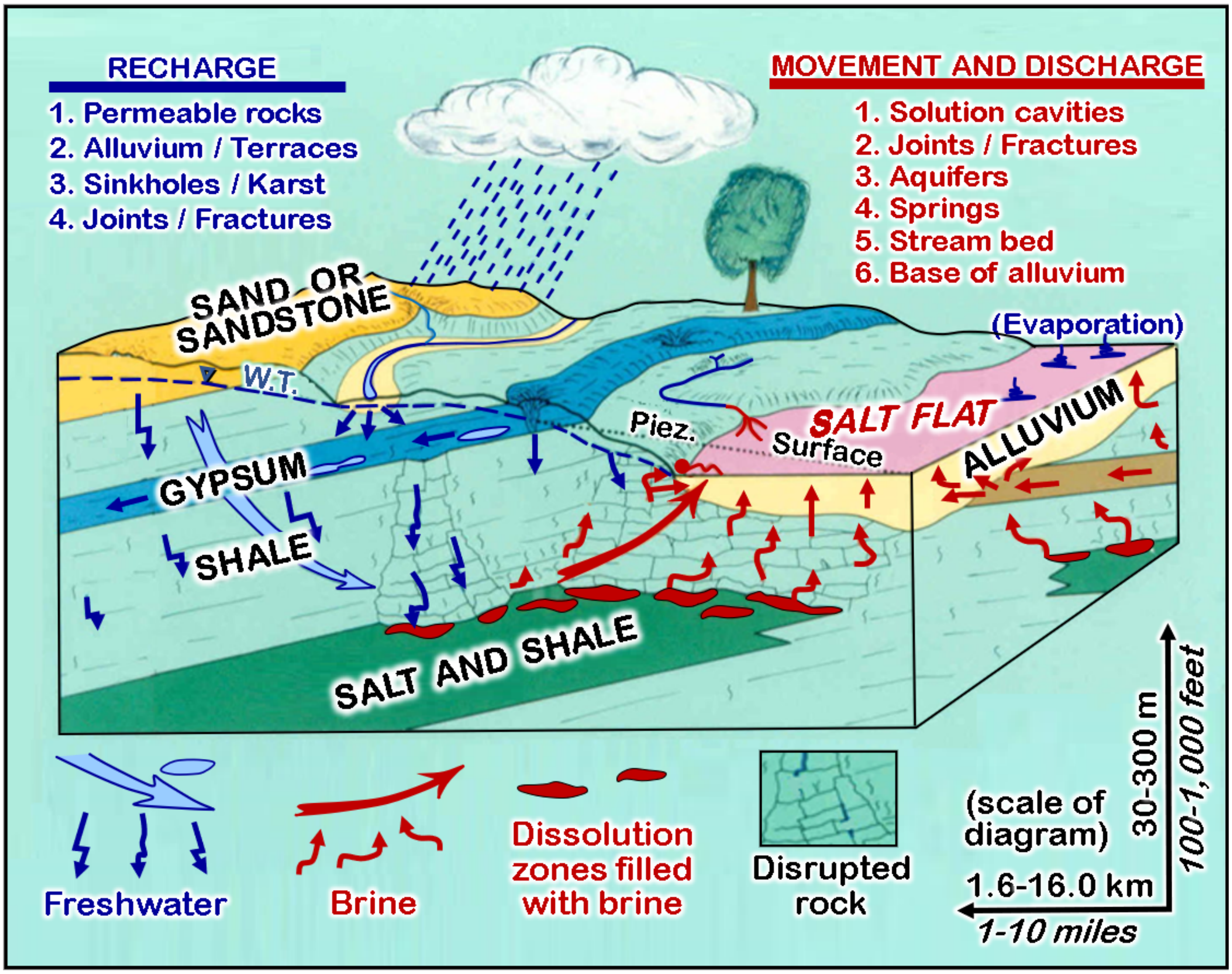


Figure 6. Schematic diagram showing circulation of freshwater and brine in areas of salt dissolution in western Oklahoma (modified from Johnson, 1981, 2019a). Evaporation of water from brine at the land surface results in a salt plain or salt flat.

In all cases mentioned above, the energy needed to cause flow of the water is the hydrostatic head created in the recharge area, with resultant brine moving laterally and upward toward the piezometric surface. When dissolution occurs, the resulting collapse, subsidence, and fracturing of overlying rock causes greater vertical permeability along joints and openings. Therefore, salt dissolution can produce a self-perpetuating cycle: dissolution can cause cavern development and land subsidence, with the result that this disrupted rock has a greater vertical permeability that allows increased water percolation and additional salt dissolution. As a result of the above-mentioned processes, a number of salt plains and brine springs have formed along the east side of the GPEB (Figs. 2, 3).

Tritium (^{3}H), a radioactive isotope of hydrogen with a half-life of about 12.3 years, was determined in five samples from brine springs in the region (Ward, 1963a): two of the springs were in Oklahoma (Big Salt Plain and Salton Salt Plain). The results indicate that those spring waters were at least partly meteoric in origin, and younger than 20 years. Atmospheric testing of nuclear weapons, starting in 1945, introduced increased amounts of tritium to the atmosphere, and it then fell with precipitation and was incorporated in groundwater. Considering the relatively low permeability of most Permian strata (mostly shales) in the region, it was therefore assumed that groundwater dissolving the salt and producing the brine springs fell to the ground in nearby areas and could not have travelled far. The water would likely be considerably older, with little or no tritium, if it had migrated over great distances.

Along with the salt plains and brine springs in Oklahoma, there are similar features in Kansas and north Texas along other parts of the Arkansas and Red River systems. The geology of some of these non-Oklahoma sites are described by Ward (1963a), US Department of Health (1964), Johnson (1981, 2019a), and Richter and Kreitler (1986).

AMOUNT OF SALT EMITTED AT SALT PLAINS

Different amounts of salt are emitted at the Oklahoma salt plains, and the amount emitted at each salt plain can vary widely, according to the season of the year, and over years and decades of time. The most comprehensive earlier studies of Oklahoma salt plains were by Ward (1963a) and the US Department of Health (1964): their estimates of the amount of salt emitted from each salt plain at the time of their measurements are presented in Table 1.

The salt flat with the largest area is Great Salt Plains, located on Salt Fork Arkansas River in Alfalfa County, with a flow of 2,310 to 3,300 short tons per day (Table 1). Another major area of salt flats, also in the Arkansas River system, is along the Cimarron River and its tributaries where daily emissions of salt are: Big Salt Plain, 2,600 to 4,870 short tons (the largest emission of salt in Oklahoma); Little Salt Plain, 160 to 990 short tons; Salt Creek Canyon Salt Plain, 160 to 360 short tons; Okeene Salt Plain area (including areas upstream and downstream of the salt plain), average of 1,525 short tons; and Drummond Flats Salt Plain, 83 short tons (Table 1).

The largest area of salt flats in the Oklahoma portion of the Red River drainage system are the three closely spaced salt plains in northern Harmon County: the Salton (also called Chaney), Robinson, and Kiser Salt Plains.

Salt Plain	County	Short tons per day[1]		Short tons per day[2]	
		Salt[3] (NaCl)	Chloride (Cl)	Salt[3] (NaCl)	Chloride (Cl)
Great Salt Plains	Alfalfa	3,300	2,000	2,310	1,400
Big Salt Plain	Woods & Woodward	2,600	1,600	4,870	2,950
Little Salt Plain	Woods & Harper	160	100	990	600
Salt Creek Canyon S.P.	Blaine	160	100	360	220
Okeene Salt Plain	Blaine	1,525[4]	925[4]	n.d.	n.d.
Drummond Flats S.P.	Garfield	n.d.	n.d.	83	50
Boggy Creek Salt Plain	Beckham	n.d.	n.d.	33	20
Salton Salt Plain	Harmon	490	300	410	250
Robinson Salt Plain	Harmon				
Kiser Salt Plain	Harmon				
Sandy Creek Salt Plain	Jackson	Few	Few	132	80

[1] Ward (1963a).

[2] US Department of Health (1964).

[3] Calculated from chloride emissions: chloride x 1.65 = salt.

[4] Average of data from Dunlap (1975) for 13-km stretch of Cimarron River that includes Okeene Salt Plain; salt load calculated from chloride emissions.

n.d. = No data.

Table 1. Estimated salt emissions from salt plains in western Oklahoma.

Together, these three sites emit an estimated 410 to 490 short tons of salt each day to the Elm Fork Red River (Table 1). The two remaining salt plains in southwest Oklahoma make smaller daily contributions of salt: Boggy Creek Salt Plain yields 33 short tons, and Sandy Creek Salt Plain contributes 132 short tons.

CHEMISTRY OF BRINES EMITTED AT SALT PLAINS

Brines emitted at the various salt plains in western Oklahoma are typically very high in sodium (Na), chloride (Cl), calcium (Ca), and sulfate (SO_4). This results from natural dissolution of salt (NaCl), gypsum ($CaSO_4 \cdot 2H_2O$), and anhydrite ($CaSO_4$), which are a closely associated group of evaporite rocks/minerals in the Permian of western Oklahoma and in the Greater Permian Evaporite Basin of Oklahoma and adjacent states. In many places the brines are saturated, or nearly saturated, with NaCl, and thus evaporation of just some of the water can result in rapid precipitation of salt on the land surface. Ward (1963a) reported chemical analyses of brines from five of the major salt plains in the State (Table 2). Four of his samples of brine came directly from the ground (the fifth sample, from Salt Creek Canyon, was collected downstream from the emission area, and was diluted by local freshwater stream flow), and these four undiluted samples show the following concentrations: chloride ranges from 114,000 to 190,000 ppm (parts per million), and averages 155,500 ppm; and salt ranges from 185,300 to 310,000 ppm, and averages 254,425 ppm. The three samples collected from actual brine springs or seeps (at the Big, Little, and Kiser Salt Plains) show even higher average concentrations of chloride (169,333 ppm) and salt (277,333 ppm). For comparison, sea water has a to-

Source	Great Salt Plains[1]	Big Salt Plain[2]	Little Salt Plain[3]	Salt Creek Canyon S.P.[4]	Kiser Salt Plain[5]
Date collected	5-14-59	11-17-59	11-17-59	11-16-59	6-21-59
Silica (SiO_2)	-----	1.5	2.5	4.0	-----
Calcium (Ca)	-----	1,120	1,280	1,700	1,480
Magnesium (Mg)	-----	896	758	578	2,000
Sodium and Potassium (Na+K)	71,300	100,000	104,000	52,100	120,000
Bicarbonate (HCO_3)	82	25	27	103	38
Sulfate (SO_4)	-----	3,750	3,800	3,200	3,720
Chloride (Cl)	114,000	156,000	162,000	82,600	190,000
Hardness as $CaCO_3$ Noncarbonate	5,240	6,460	6,290	6,540	11,900
Hardness as $CaCO_3$ Calcium, magnesium	70	20	20	80	0
Specific conductance (Micromhos at 25° C)	181,000	215,000	215,000	159,000	210,000
pH	6.9	6.7	6.7	7.4	6.4

[1] Hole 30 cm deep on Great Salt Plains, Alfalfa County.
[2] Spring at base of bluffs on south side of Big Salt Plain, Woodward County.
[3] Salt-water seep on Little Salt Plain, Woods County.
[4] Salt Creek, below Salt Creek Canyon Salt Plain, Blaine County.
[5] Spring at Kiser Salt Plain, Harmon County.

Table 2. Analyses of natural brines from various Oklahoma salt plains (Ward, 1963a). Results in parts per million, except as indicated.

tal salinity of only about 35,000 ppm: it contains about 19,500 ppm chloride and about 10,500 ppm sodium, or about 30,000 ppm salt (Na+Cl).

Additional brine samples were analyzed from most of the Oklahoma salt plains, and these other analyses are presented in the following discussions of each salt plain. In general, the highest concentrations of chloride and salt were measured in springs or wells at the Big, Little, Salton, Robinson, and Kiser Salt Plains.

Chloride concentrations mentioned in this report are those given in the various tables, and in most cases the salt concentrations mentioned are the sum of the sodium and chloride concentrations (Na+Cl) reported. However, some of the analyses report the chloride content, but not a specific value for the sodium content. In these cases, an estimation of the salt concentration is calculated to be the chloride concentration (Cl) x 1.65. The atomic weight of chloride is 35.45, and the atomic weight of Na+Cl is 58.43: therefore, Na+Cl ÷ Cl is 58.43 ÷ 35.45 = 1.65.

Some of the analyses shown herein on tables are expressed in ppm, and some are in mg/l (milligrams per liter). In dilute water solutions, 1 mg/l = 1 ppm; in highly concentrated solutions, such as these brines, the numerical value in mg/l or ppm is essentially equal (ppm values are only about 0.0014% higher than mg/l values) (see UnitConverters.net in references). Therefore, numerical values reported in mg/l on these tables will be considered as the same in ppm. Discussions in this paper will refer to concentrations in ppm, even when a chemical analysis presents the concentrations in mg/l.

SALT PLAINS IN OKLAHOMA

A total of 11 known salt plains or natural brine springs are present in western Oklahoma (Fig. 3). They include six sites in the Arkansas River drainage basin, and five sites in the Red River drainage basin. The largest salt plains, with the greatest amount of salt being emitted, are in the Arkansas River Basin, although the salt plains in the Red River Basin are also significant. Following is a description of these 11 brine-emission sites.

Great Salt Plains

Great Salt Plains, in Alfalfa County (Fig. 3, site 1), is a most-impressive landform. The 65 km^2 of flat, salt-encrusted land makes it the largest salt plain in Oklahoma, or in any part of the Arkansas River system (Figs. 7, 8). A dam, completed in 1941, created the Great Salt Plains Reservoir, and that lake now covers 36 km^2 of the original salt plain: therefore, Great Salt Plains originally covered 101 km^2. Lake-water salinity varies from 2 to 15 grams of dissolved solids per kilogram of water (2,000 to 15,000 ppm) (Johnson, 1972), with the higher salinities occurring when heavy rains dissolve and wash the adjacent salt crust into the lake. Lake salinity varies considerably, and the amount of salt that flows from the reservoir into Salt Fork Arkansas River ranges from 2,310 to 3,300 short tons per day (Table 1); this is second only to the amount of salt emitted at Big Salt Plain (up to 4,870 short tons per day). The present surface of the salt plain appears horizontal (Fig. 8), but it actually slopes down toward the reservoir at a rate of about 1 to 2 m/km. The following description of Great Salt Plains is modified from earlier reports by Johnson (2013a, 2019c). In USACE studies, Great Salt Plains is referred to as "Area I."

Great Salt Plains consists of loose Quaternary deposits saturated with high-salinity natural brine that is seeping up from underlying Permian rocks. Quaternary deposits consist of 3 to 8 m of alluvial and lacustrine sediments that were laid down upon, and now conceal, an irregular bedrock surface that was eroded by streams and rivers. Aspects of the geology and/or brines of Great Salt Plains have been discussed by Davis (1968), Johnson (1972, 2013a, 2019c), Slaughter and Cody (1989), and Evans (2017).

The origin of the brine here appears to result from groundwater dissolving the Lower Cimarron salt at moderate depths beneath, and just west of, the salt plains (Fig. 9). Brine then moves laterally and upward under artesian conditions through several porous aquifers and through fractures in the bedrock until it is discharged into the bottom of Quaternary sediments comprising the salt plains. Brine continues to rise through the Quaternary under artesian pressure, and finally capillary action brings the brine to the surface of the salt plain.

Surface Geology

Bedrock formations cropping out in the vicinity of Great Salt Plains include the Hennessey Shale (south and west of the salt plains) and the Nippewalla Group (north and east of the salt plains) (Miller and Stanley, 2003). These units consist chiefly of interbedded red-brown shales and siltstones, but also contain some layers of fine-grained sandstone and green-gray siltstone and shale. Beds of sandstone and siltstone are aquifers that bring brine up to the base of Quaternary deposits, where

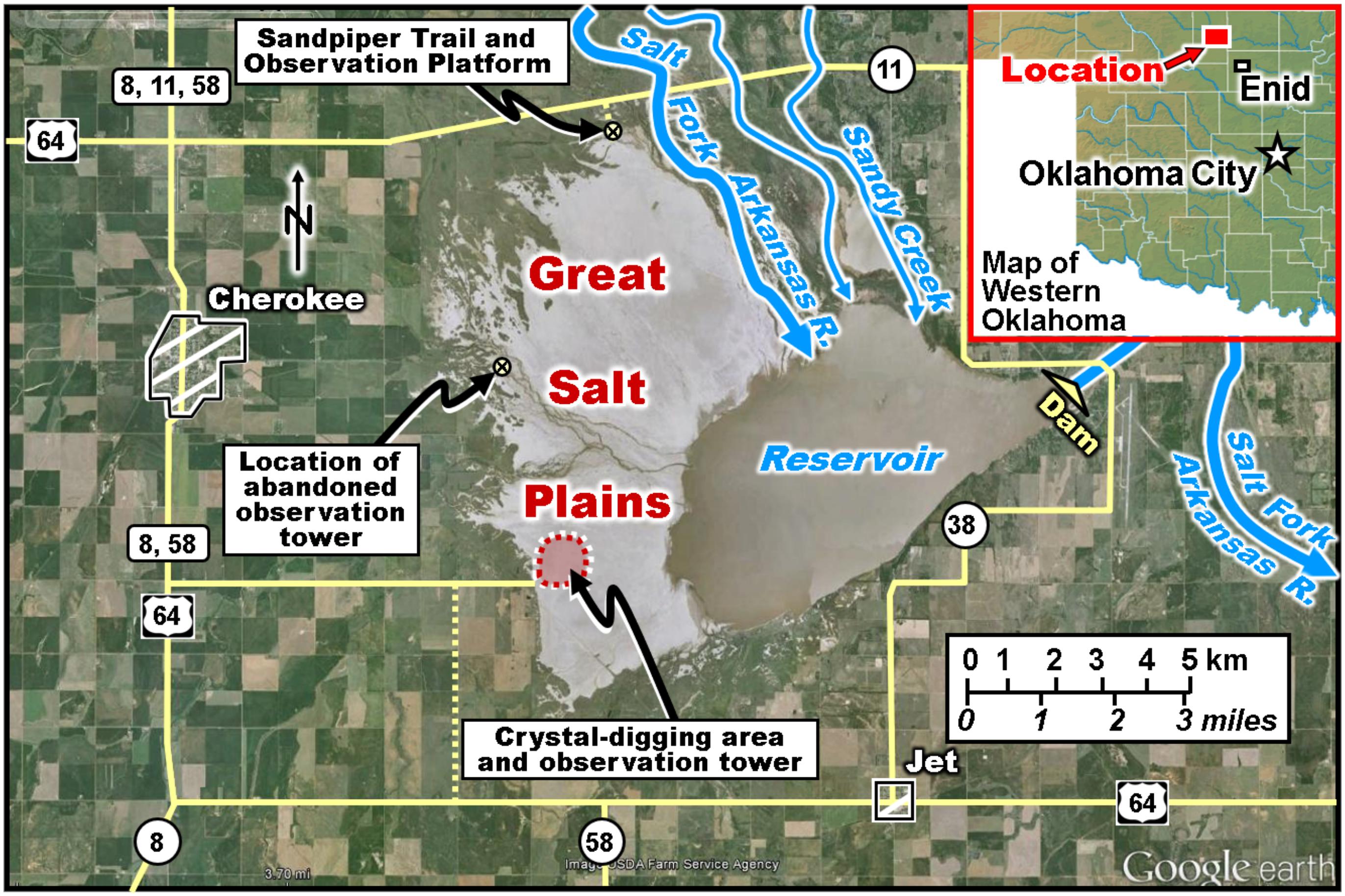


Figure 7. Aerial view of Great Salt Plains in Alfalfa County, northwest Oklahoma (modified from Johnson, 2013a). Air photo from Google Earth, dated September, 2010.

Figure 8. View of part of the 65-km^2 salt flats that comprise Great Salt Plains (courtesy Oklahoma Tourism Department).

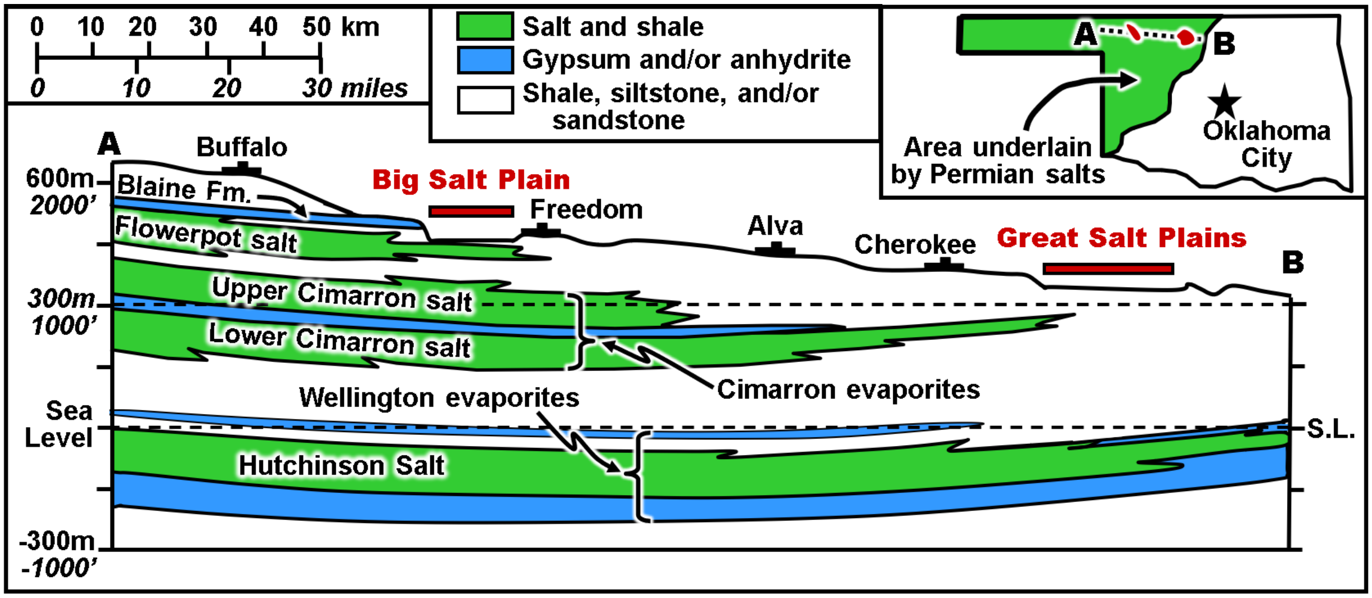


Figure 9. Regional cross section showing Permian evaporites in northwestern Oklahoma (based in part upon Jordan and Vosburg, 1963, plate 2; modified from Johnson, 2019b). The Flowerpot salt is the source of brine emissions at Big Salt Plain, and the Lower Cimarron salt is the source of brine emissions at Great Salt Plains.

the brine can then move upward to reach the surface of the salt plain.

Permian bedrock in the area dips gently to the southwest into the Anadarko Basin. The dip averages about 3 m/km (about 0.15º). This agrees well with the structure of deeper strata: the base of the Wellington evaporites, about 520 m below the salt flats, dips about 4 m/km (about 0.2º) to the southwest (Jordan and Vosburg, 1963, Map B). Although Quaternary sediments cover the bedrock in most of the area, there is no evidence of faults or erratic dips in the bedrock that might result from their collapse due to underground dissolution of salt or other evaporites.

Most of the land surface at and around the salt plains is mantled by unlithified Quaternary sediments: they are alluvial, lacustrine, and terrace deposits consisting chiefly of sand, silt, and clay laid down by Salt Fork Arkansas River and its main tributaries. These deposits are generally 3 to 8 m thick at the salt flats, but they are up to 15 m thick to the north and west, and Quaternary terrace deposits are as much as 27 and 40 m thick, respectively, to the southeast and northeast of the reservoir. Alluvial deposits are mantled by wind-blown sand dunes in some areas north, east, and south of the salt plains. The salt flats themselves are encrusted with deposits of salt that are locally up to 5 cm thick, especially after long hot and dry spells (Fig. 8).

Subsurface Salt Deposits

The Lower Cimarron salt is the shallowest salt at Great Salt Plains: it occurs in subsurface to the west of the area, and also beneath the western part of the salt flats (Figs. 10, 11). The total thickness of the Lower Cimarron salt ranges from 25 to 37 m in most parts of western Alfalfa County, but it decreases to only 5 m in core #11 beneath the salt flats, and is absent farther east (core #9) and in the northern part of the county (cores #22 and #23) (all cores drilled by the USACE from 1968 to 1970).

The Lower Cimarron salt consists chiefly of red-brown and gray shale and siltstone in Alfalfa County. Salt occurs mainly as veins, nodules, and isolated crystals or masses in most cores, but is also present as discrete layers of rock salt in beds 0.6 to 2.4 m thick farther west in core #16 (located in sec. 14, T. 27 N., R. 13 W., in Woods County). In core #16, salt comprises an estimated 40% of an interval that is 29 m thick (percentages and thickness of salt units in this and other cores are reported in US Army Corps of Engineers, 1971).

The amount of salt in the cores shown on Figure 10 is as follows: core #10 contains 20 to 30% salt in an interval 16.5 m thick; core #18 contains about 20% salt in an interval 24.4 m thick; core #7 contains about 10% salt in an interval 15.8 m thick; and core #11 contains about 10% salt in an interval 4.6 m thick.

Depth to the top of salt beneath and near the salt flats was also reported in US Army Corps of Engineers (1971): core #18 = 70.7 m deep; core #7 = 114.3 m deep; and core #11 = 82.6 m deep (note: depth to the original top of salt in core #11 should be much less, but, presumably, the

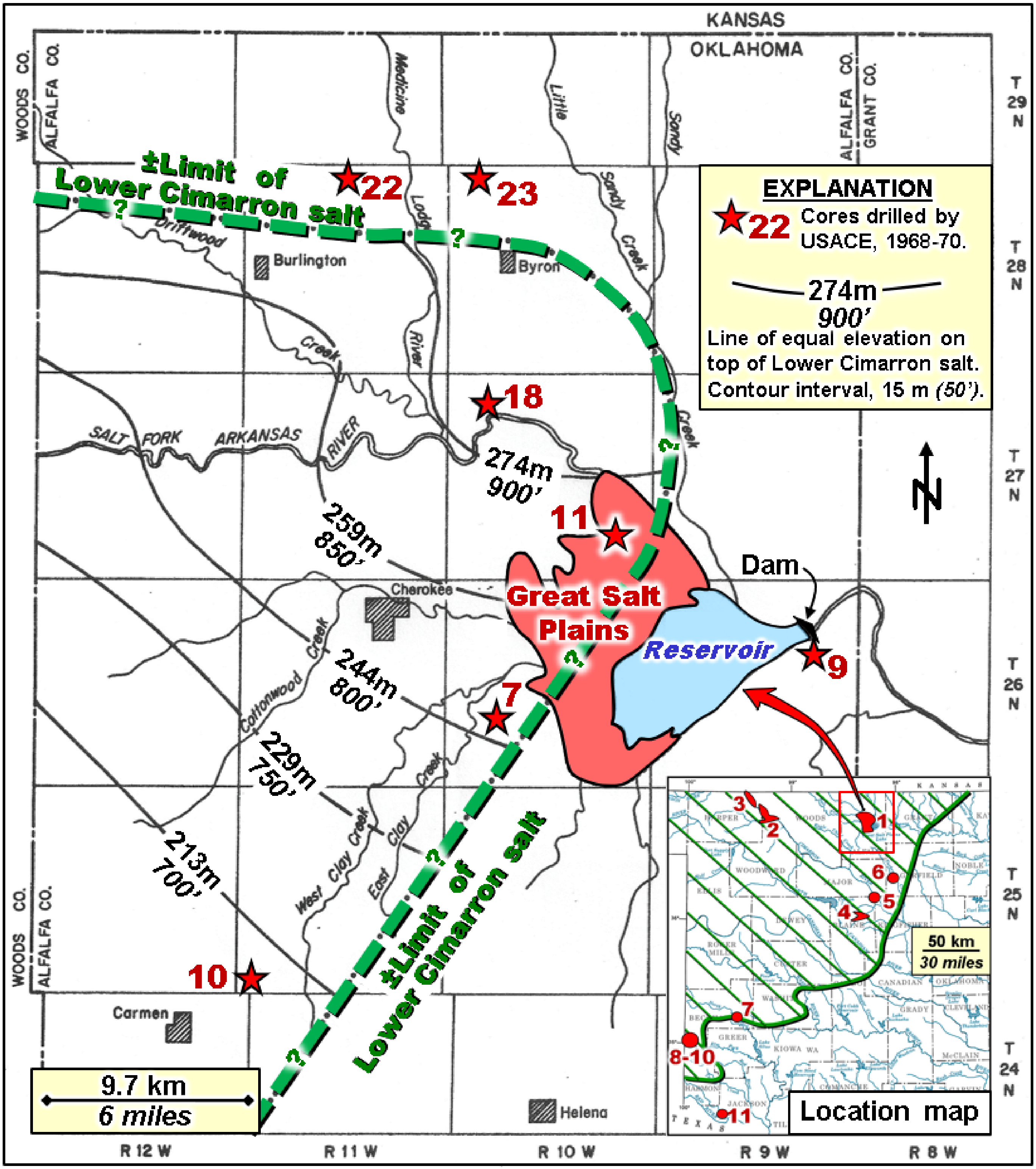


Figure 10. Map showing distribution and elevation of top of Lower Cimarron salt at Great Salt Plains, Alfalfa County. Based on 7 cores drilled by US Army Corps of Engineers (USACE) through salt or equivalent non-salt strata, and geophysical logs of nearly 50 oil and gas boreholes. Modified from Johnson (2019c).

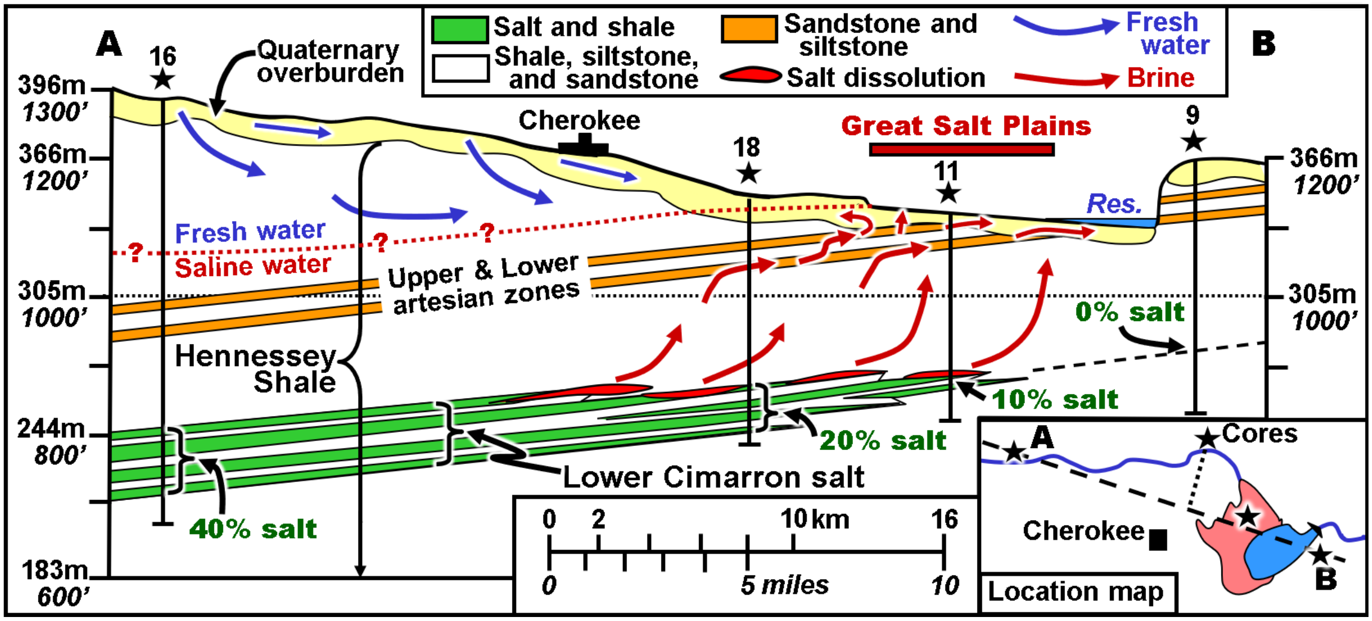


Figure 11. Generalized geologic cross section showing salt and other Permian bedrock units near Great Salt Plains, as well as probable salt-dissolution zones and ground-water-flow patterns. Based primarily upon four cores (16, 18, 11, and 9) drilled in 1968-70 by USACE. Also shown is the percent of salt within the Lower Cimarron salt in each core. Modified from Johnson (2013a).

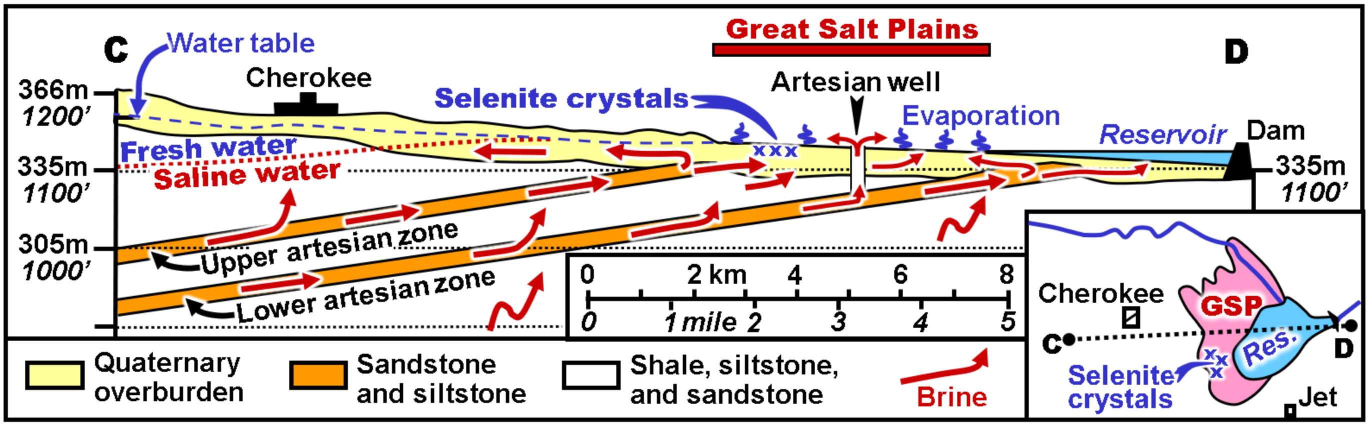
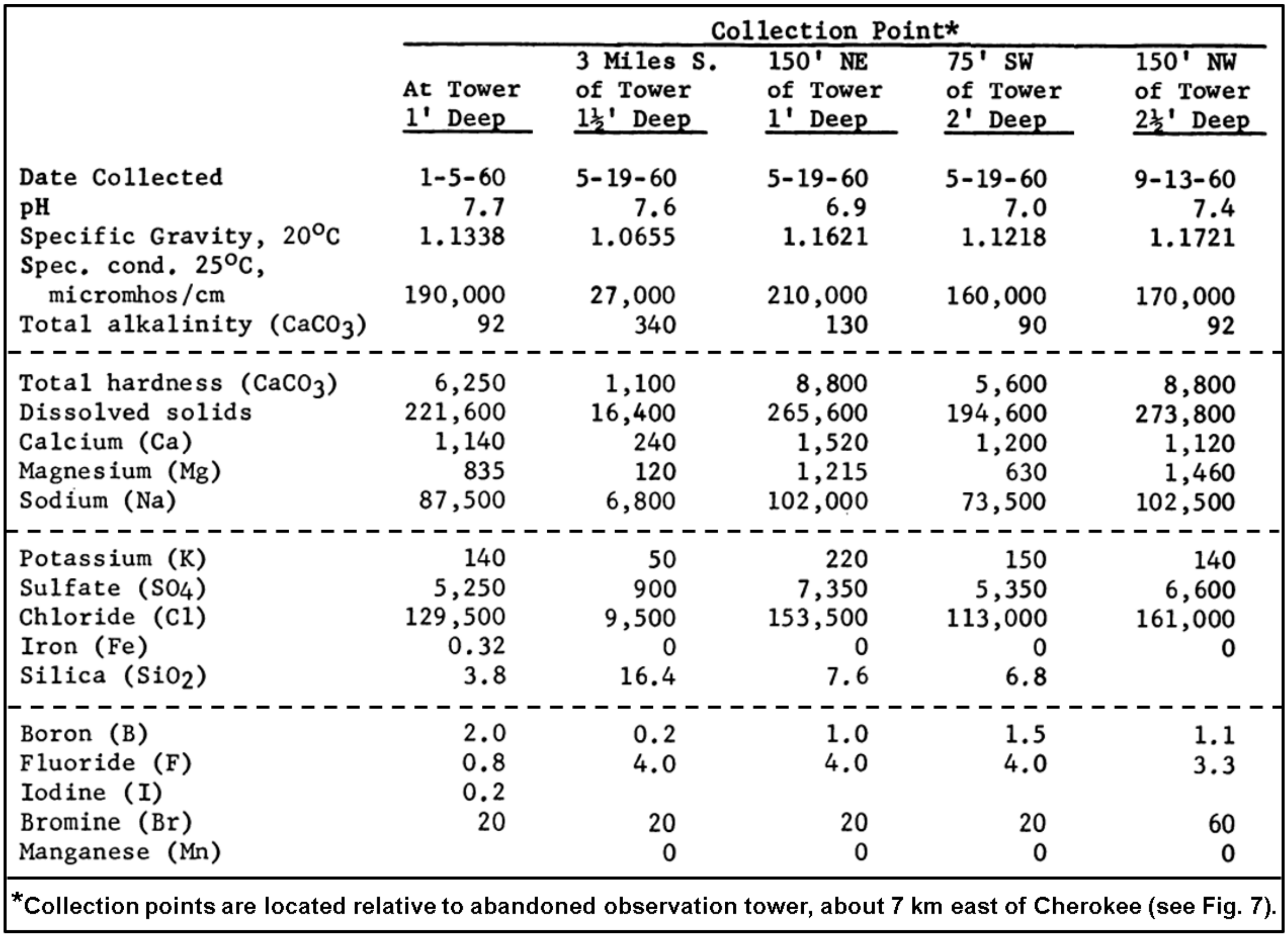


Figure 12. Generalized geologic cross section showing brine movement near Great Salt Plains (modified from Johnson, 1972, 2013a).

upper part of the salt has already been dissolved at this site). Salt in these cores is commonly smoky and faintly gray or red brown in color: it contains disseminated or mixed masses of gray or red-brown shale or siltstone. The salt is also associated with irregular masses and vein-like stringers or layers of anhydrite and shale.

Away from the salt flats, the depth to the top of the salt in oil and gas wells ranges from about 70 to 120 m in the north, near the Byron-Burlington area, and increases to the south to about 150 in the southwest corner of T. 26 N., R. 11 W., and to 208 m just northeast of Carmen (Fig. 10, core #10). This increase in depth results from the gentle southwest dip of the salt beds (about 3 m/km, or 0.15°) and the general increase in topographic elevation to the southwest, away from Salt Fork Arkansas River and Great Salt Plains.

The Lower Cimarron salt in Alfalfa County was deposited near the eastern edge of a shallow inland sea that extended westward across most of western Oklahoma and the Texas Panhandle (Jordan and Vosburg, 1963; Johnson, 1976). Beds of massive rock salt deposited in the west (core #16, and farther west) grade eastward into shaley salt and salty shale near the limits of evaporite deposition, and finally into shales and siltstones that lack



	Collection Point*				
	At Tower 1' Deep	3 Miles S. of Tower 1½' Deep	150' NE of Tower 1' Deep	75' SW of Tower 2' Deep	150' NW of Tower 2½' Deep
Date Collected	1-5-60	5-19-60	5-19-60	5-19-60	9-13-60
pH	7.7	7.6	6.9	7.0	7.4
Specific Gravity, 20°C	1.1338	1.0655	1.1621	1.1218	1.1721
Spec. cond. 25°C, micromhos/cm	190,000	27,000	210,000	160,000	170,000
Total alkalinity ($CaCO_3$)	92	340	130	90	92
Total hardness ($CaCO_3$)	6,250	1,100	8,800	5,600	8,800
Dissolved solids	221,600	16,400	265,600	194,600	273,800
Calcium (Ca)	1,140	240	1,520	1,200	1,120
Magnesium (Mg)	835	120	1,215	630	1,460
Sodium (Na)	87,500	6,800	102,000	73,500	102,500
Potassium (K)	140	50	220	150	140
Sulfate (SO_4)	5,250	900	7,350	5,350	6,600
Chloride (Cl)	129,500	9,500	153,500	113,000	161,000
Iron (Fe)	0.32	0	0	0	0
Silica (SiO_2)	3.8	16.4	7.6	6.8	
Boron (B)	2.0	0.2	1.0	1.5	1.1
Fluoride (F)	0.8	4.0	4.0	4.0	3.3
Iodine (I)	0.2				
Bromine (Br)	20	20	20	20	60
Manganese (Mn)		0	0	0	0

***Collection points are located relative to abandoned observation tower, about 7 km east of Cherokee (see Fig. 7).**

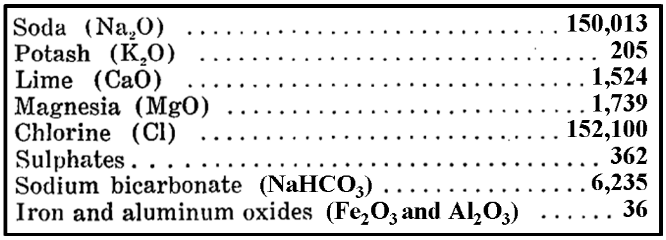
Table 3. Analyses of natural brines from Great Salt Plains in mg/l, except pH (unless otherwise indicated). From US Department of Health (1964).

salt (core #9). The present-day eastern and northern limits of this salt in Alfalfa County are probably fairly close to the original depositional limits, but these have been modified, at least somewhat, by salt dissolution. Dissolution is probably occurring along the eastern limit of the salt in Ts. 26–28 N., and along the northern limit of the salt in Rs. 10–12 W. (Fig. 10): it is most likely occurring in the upper part of the salt unit at scattered locations in Ts. 26–27 N., Rs. 10–11 W., where the salt is in contact with circulating groundwater, and the resultant brine is being emitted at Great Salt Plains through two artesian zones (the upper and lower artesian zones) (Figs. 11, 12).

The only other salt unit in Alfalfa County is the deep Hutchinson Salt Member at the top of the Wellington Formation (Fig. 9): it consists of 122 to 137 m of salt interbedded with anhydrite and shale, with salt making up about 40 to 50% of the unit. The top of the Hutchinson Salt is about 365 m deep in the vicinity of Great Salt Plains (Plate 3 in Johnson, 1976), and is too deep to be a source of the brine in this area.

Brine Emissions

Three sets of analyses of brines emitted at Great Salt Plains have been reported (Tables 2–4). There are no "salt springs" on the salt flats or nearby, so all samples for these analyses were obtained by digging holes 30 to 75 cm deep in the unconsolidated Quaternary sediments, and sampling the water that filled the holes. Of the sev-



Soda (Na_2O)	150,013
Potash (K_2O)	205
Lime (CaO)	1,524
Magnesia (MgO)	1,739
Chlorine (Cl)	152,100
Sulphates	362
Sodium bicarbonate ($NaHCO_3$)	6,235
Iron and aluminum oxides (Fe_2O_3 and Al_2O_3)	36

Table 4. Analysis of natural brine from Great Salt Plains, in parts per million. From Snider (1913).

en analyses in Tables 2–4, six of them are high-salinity brines with the following concentrations: chloride ranges from 113,000 to 161,000 ppm, and averages about 137,000 ppm; and salt ranges from 185,000 to 263,000 ppm, and averages about 228,000 ppm.

In addition, Slaughter and Cody (1989) collected similar groundwater samples from 63 uniformly spaced holes dug to depths of 0.5 to 1.2 m below the surface of the salt flats during summer and winter seasons. Their data showed slightly lower chloride averages in the south part of the salt plains (132,000 ppm in Summer, and 123,000 ppm in Winter), and somewhat higher averages in the central and north parts of the salt plains (142,000 to 155,000 ppm in Summer, and 146,000 to 160,000 ppm in Winter).

Two artesian zones in the Hennessey Shale subcrop at the base of Quaternary overburden in the vicinity of Great Salt Plains and the much smaller salt plain at Sucker Flat, about 6 km to the north (Figs. 11–13). The few test holes drilled south and north of the salt plains area did not yield much brine, so the brine-emission problem appears to be confined to Great Salt Plains and Sucker Flat, and areas close to them (Fig. 13). The two artesian zones that contain brine are siltstone and sandstone beds that are 6 to 30 m below the salt flats (Fig. 12): these beds were cored by the USACE, and they typically contain many vugs, pits, and salt casts that indicate the prior existence of salt. Although salt has not been recovered or observed in these strata, these vugs and other cavities indicate that they may have contained scattered crystals of salt at one time.

Daily emission of salt from Great Salt Plains is estimated to be 1,400 to 2,000 short tons of chloride, or 2,310 to 3,300 short tons of salt (Table 1). This is the greatest amount of salt that issues from any salt plain in Oklahoma.

The origin of brine at Great Salt Plains apparently results from the following: 1) fresh meteoric water seeps into the ground at unknown locations north, northwest, west, and/or southwest of the salt plains; 2) the water moves down vertically and laterally through porous sandstones and fractures in Permian bedrock; 3) it then dissolves salt from salt beds or salty strata; and 4) the resultant brine eventually rises to the surface beneath the salt plain (as shown generally in Fig. 6). The most probable salt beds now being dissolved are thin layers, veins, nodules, and disseminated crystals of salt in the Lower Cimarron salt that are beneath and just west of the salt

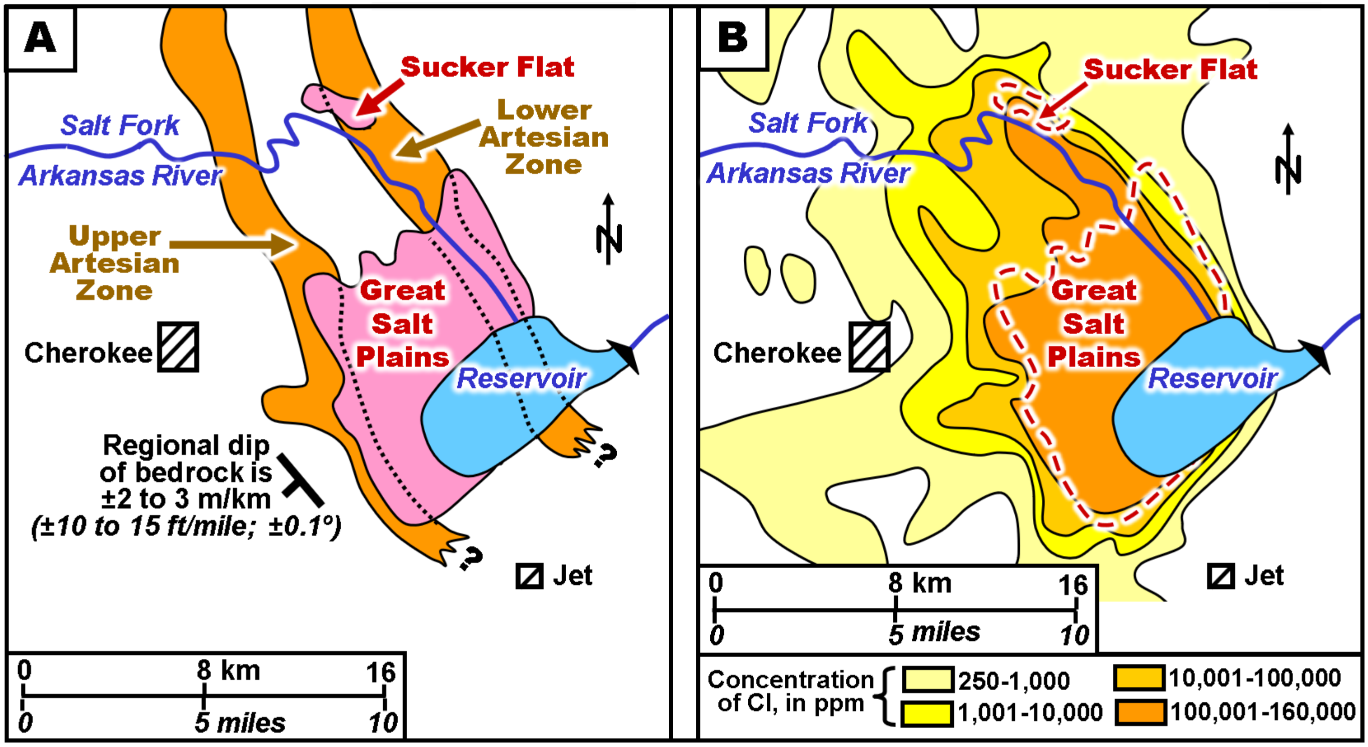


Figure 13. Maps of Great Salt Plains area showing subcrop of artesian aquifers and concentration of chlorides; based on borehole data from USACE (modified from Johnson, 2013a). A) Subcrop of Permian bedrock artesian zones at base of Quaternary overburden. B) Chloride concentration of groundwater at top of Permian bedrock (base of overburden).

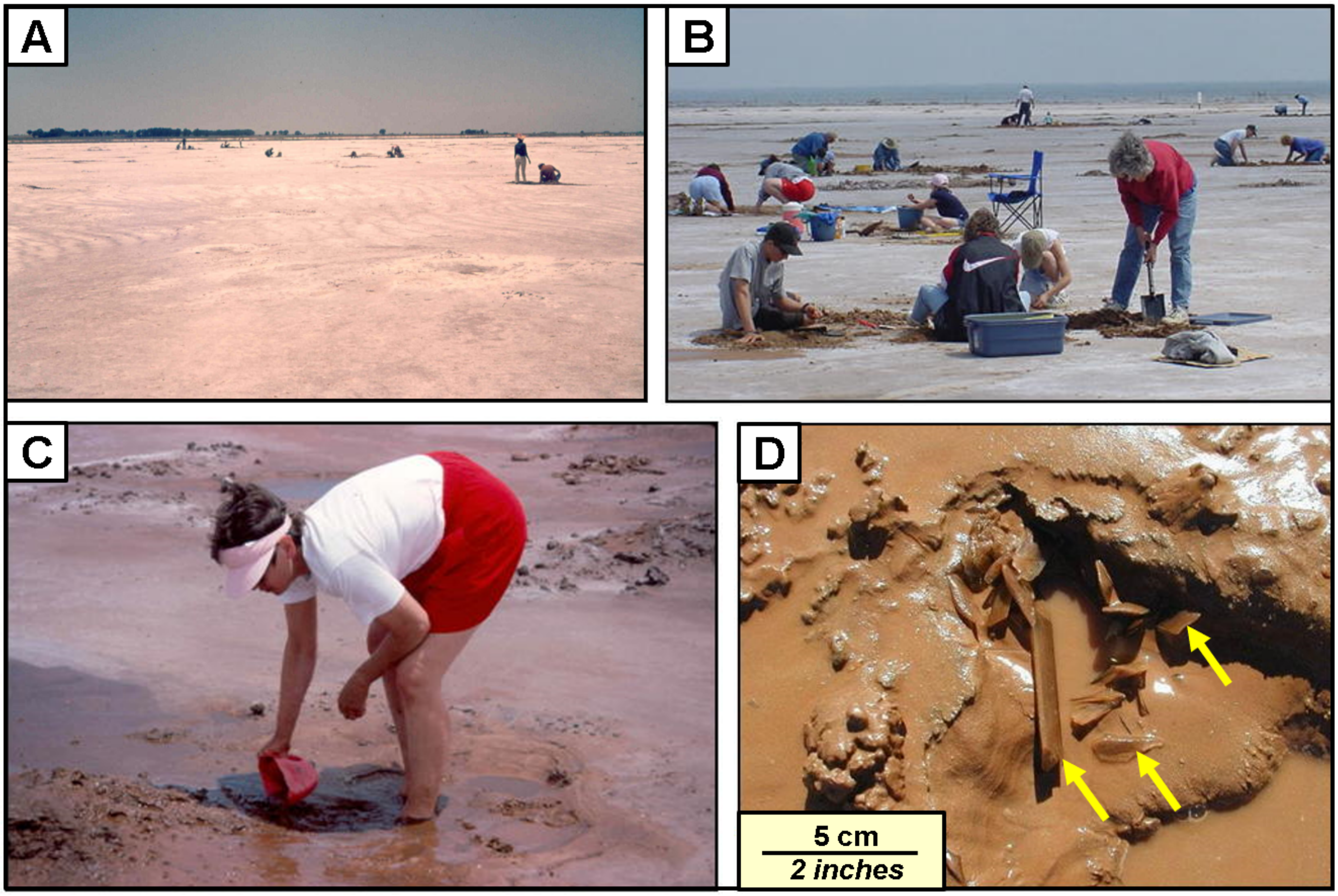


Figure 14. Collecting hourglass-selenite crystals on Great Salt Plains (from Johnson, 2013a). A) View of salt plains digging area. B) Families and groups digging for crystals on salt plains. C) Claren Kidd, retired geology librarian at The University of Oklahoma, digging for crystals. D) Selenite crystals (arrows) are exposed just several centimeters below the surface of the salt plain.

plains (Fig. 11).

Brine is present in the bedrock under a hydrostatic head that causes it to rise above ground level as artesian flow in boreholes. It moves laterally and upward through aquifers and fractures in the bedrock and is discharged, mainly from the upper and lower artesian zones, into the bottom of overlying Quaternary sediments (Fig. 12). Salt is then precipitated on the salt flats (Fig. 8) as water (H_2O) is evaporated from brine drawn to the surface by capillary action.

The upper and lower artesian zones are sandstone/siltstone units, each being up to 9 m thick, that are interbedded with shales of the Hennessey Formation in a sequence that is about 25 m thick (US Army Corps of Engineers, 1971) (Fig. 12). Brine movement is largely restricted to these two zones, wherein the sandstones and siltstones are generally friable and contain many vugs, pits, fractures, and salt casts. Beds of sandstone and siltstone in the two aquifers are not sheet-like, continuous layers, but generally are lenticular: individual lenses are not easily correlated from borehole to borehole. Therefore, these aquifers are two zones in which high-salinity brines are preferentially carried, under artesian pressure, to the base of Quaternary deposits that cover the salt plains.

Cores drilled by the USACE established that the two artesian zones subcrop at the base of Quaternary overburden in the vicinity of Great Salt Plains and the much smaller Sucker Flat (Fig. 13A). High-salinity brine in these bedrock aquifers has a chloride content normally ranging from about 90,000 to 150,000 ppm, although locally it is up to 160,000 ppm (Fig. 13B). The other chief constituents of brine in the bedrock at Great Salt Plains are calcium, magnesium, and sulfate (table 3). Johnson (1972) reported similar results at Great Salt Plains for calcium (±1,500 ppm), magnesium (±1,000 ppm), and sulfate (±7,000 ppm). At these concentrations, the brine is fully saturated with respect to both sodium chloride and calcium sulfate, and thus evaporation of the brine and further concentration leads to precipitation of halite (NaCl), and also of gypsum ($CaSO_4•2H_2O$) as hourglass-selenite crystals (described below).

Although lateral movement of brine through artesian zones appears to be the dominant movement, vertical migration of brine also occurs through fractures, joints, and fissures in the rock. There is enough interconnection between the two artesian zones that the entire 25 m of strata could be regarded as a single aquifer system with two zones of much higher permeability. Fractures, joints, and fissures in the aquifer, and in the underlying and overlying bedrock, result at least in part from settling and collapse due to partial dissolution of underlying salt beds.

In pre-historic through early-Statehood days, salt was collected from Great Salt Plains by Native Americans and early European settlers, but no commercial production of salt has been recorded. The area is now a National Wildlife Refuge, and thus is not open to commercial development of salt resources.

Hourglass-Selenite Crystals

Note: this section is liberally taken from Johnson (1972, 2013a, 2019c). Brine entering Great Salt Plains is fully saturated with respect to both sodium chloride and calcium sulfate. Once the brine enters the Quaternary sediments, it is further concentrated by evaporation at the land surface. Brine rises to the water table, several centimeters or more below the surface, and capillary action draws it up to the land surface where it is evaporated. Salt is precipitated as a crust (locally up to 5 cm thick, after long hot and dry spells) on the surface of the salt flats, and gypsum is precipitated as hourglass-selenite crystals just below the surface, where the brine is saturated with respect to calcium sulfate. The evaporation rate here is extremely high: the average annual precipitation is only about 76 cm (H.L. Johnson, 2008), and the average rate of freshwater evaporation is about 203 cm (Davis, 1968).

Hourglass-selenite crystals are unique to the Great Salt Plains (Figs. 14, 15), and they were designated as the "official Oklahoma State Crystal" in 2005. The interior of each crystal contains a ghostlike, hourglass form consisting of red-brown sand, silt, and/or clay particles incorporated within the crystal as it grows (Fig. 15). The red-brown color is due to the presence of iron oxides that coat the particles enclosed in the crystal. As the crystal grows, the loose particles are enveloped or enclosed only at the ends of the crystal, at the (110) crystal faces, whereas particles adjacent to the sides of the crystal, the (111) faces, are merely pushed aside (Fig. 15B): crystal faces were identified by Merritt (1935).

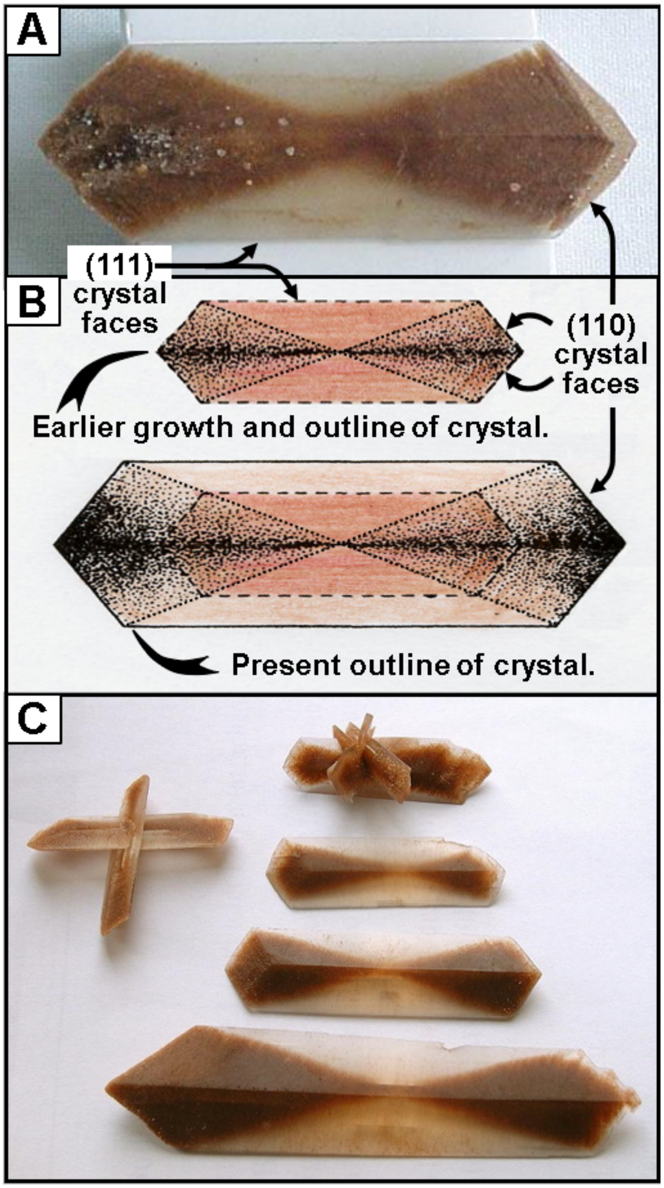


Figure 15. Hourglass-selenite crystals collected at Great Salt Plains (Johnson, 2013a). A) Crystal, 8 cm long, that grew in sand and silt. B) Drawings of crystal, showing two stages of growth. C) Three crystals that grew in clay (bottom samples), and two examples of twin crystals (at top and left).

The reason for this hourglass pattern is not certain, but it appears that the bond between molecules forming the smooth (111) faces on the sides of the crystal is so strong that each new layer of molecules that is added forces foreign particles away from the crystal. On the other hand, the bond between molecules forming the (110) faces at the ends of the crystal is not strong enough to push foreign

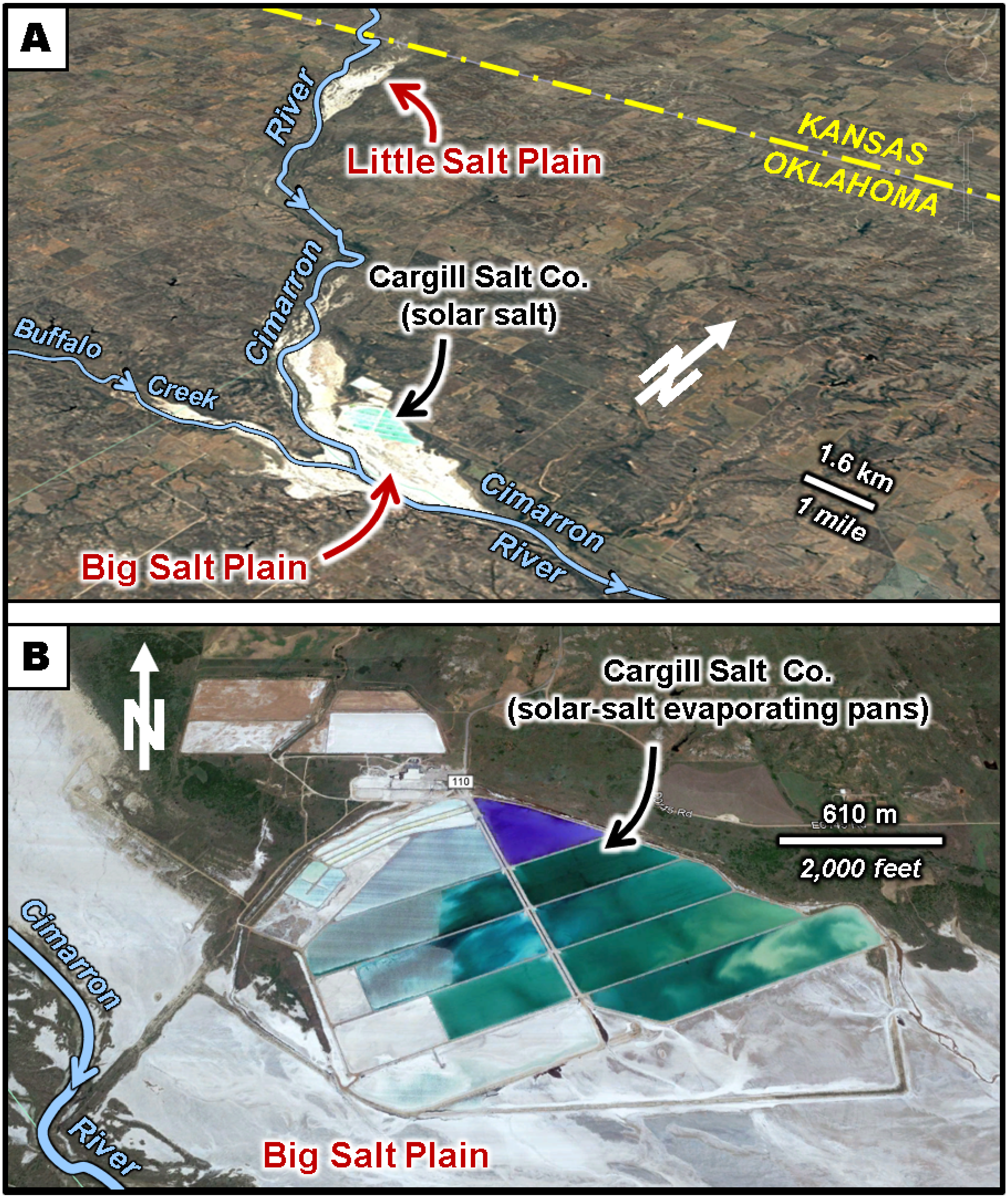


Figure 16. Aerial views of Big and Little Salt Plains on Cimarron River in northwest Oklahoma. A) Oblique Google Earth photo (dated December, 2006) of Big Salt Plain, Little Salt Plain, and Cargill Salt Co. solar-salt plant. B) Vertical Google Earth photo (dated June, 2017) shows that Cargill Salt Co. has about 200 hectares (500 acres) of evaporating pans on Big Salt Plain. Modified from Johnson (2019b).

matter aside, and therefore new layers on the ends of the crystal envelop the red-brown sand, silt, and clay particles.

Crystals form just below the surface of the salt flats, seldom more than 60 cm deep. Selenite occurs as individual crystals up to 18 cm long, and clusters of intergrown crystals have weighed as much as 17 kg. Crystals have also enclosed sticks, rocks, bones, and cockleburs that are part of the host sediment.

A study of the shapes and growth rates of these crystals was conducted by members of the Enid Gem and Mineral Society from May 1966 to May 1969 (Vickers, 1969). Pre-measured crystals they "planted" grew as much as 26% within a year, under favorable climatic conditions (cool, wet springs and hot, dry summers). Also, they found that the quality of crystals depends in part on the host sediment, with the clearest crystals forming in clay and the more-cloudy ones forming in sand and silt. Several studies related to selenite-crystal growth and/or brine chemistry were done by Merritt (1935), Davis (1968), Vickers (1969), Slaughter and Cody (1989), and Evans (2017).

Digging for crystals in the best collecting area on the salt flats is regulated by the Great Salt Plains National Wildlife Refuge (GSPNWR). To allow for new crystal growth, a new area is opened for digging and collecting each year (on a rotating basis) from April 1 through October 15. Only two areas on the salt plains are open to public access (Fig. 7): the crystal-collecting area in the south, and bird watching is permitted from the Sandpiper Trail Observation Platform on the north.

To dig for crystals (Fig. 14), the following is recommended by the GSPNWR. Dig a hole about 60 cm wide and 30 to 60 cm deep, and allow it to fill with water that seeps in from below (you may need to bring your own water to have a sufficient supply). Splash water against the sides of the hole and gently wash the soil away from crystals until they are free. At first, crystals are fragile and must be gently placed where the sun and wind can dry them. When dry, they are quite hard and can be handled with normal care. A fine YouTube video shows how to dig for crystals: http://www.youtube.com/watch?v=5qYDZ3ehNz8

Great Salt Plains also has historical significance. According to the GSPNWR website, an Osage Indian, Sans Orielle, guided Major George C. Sibley (the Indian Agent from Fort Osage, Missouri) and his party to Great Salt Plains in 1811. They are thought to have been the first white men to see the salt plains. From that time on, settlers made trips to the site to collect salt, just as Native Americans had for centuries before. And during World War II, Great Salt Plains was used as a practice-bombing range, and a small area was used for disposal of World War II chemical-warfare-training kits. Discovery of these kits, which contained diluted mustard, lewisite, chloropicrin, and undiluted phosgene gases and liquids, led to closure of the crystal-digging area in 2007 and 2008. After a thorough search of the area by the USACE, the crystal-digging area was cleared in 2009, although warnings are posted to advise the public of potential hazards

Big Salt Plain and Little Salt Plain

Big Salt Plain and Little Salt Plain (Fig. 3, sites 2 and 3, respectively) are the largest area of salt plains on the Cimarron River, and are the second- and third-largest salt plain, respectively, in Oklahoma (Great Salt Plains being the largest) (Figs. 16–18). The major part of Big Salt Plain is in Woods County, but it also occupies parts of Woodward and Harper Counties; Little Salt Plain is almost entirely in Woods County, with just a small portion being on the west side of Cimarron River in Harper County. The main part of Big Salt Plain covers about 17.7 km^2, and the main part of Little Salt Plain covers about 6.5 km^2. Although they are two separate emission areas, they are discussed together here because of their proximity and similar geology. In USACE studies, Big Salt Plain is referred to as "Area II" and Little Salt Plain is referred to as "Area III." The following description of the Big and Little Salt Plains is modified from an earlier report by Johnson (2019b).

High-salinity brine saturates the alluvium at both sites, with brine forming when groundwater dissolves Flowerpot salt at shallow depths beneath and adjacent to the river (Figs. 17, 18): brine then migrates, due to hydrostatic pressure, up from the bedrock into the base of the alluvium. The top of the Flowerpot salt ranges from 9 to 60 m below the surface of the salt plains. Dissolution of salt is more advanced beneath the river, and as a result the adjacent bedrock is partly collapsed and drapes (or dips) down toward the river. The USACE plans for protecting freshwater and controlling brines in this area involve: 1) constructing a dam to capture fresh Cimarron-River water just above Little Salt Plain (the dam to be located along the line of cross section A–B in Fig. 18); 2) constructing a canal to divert that freshwater around the two salt plains and back into Cimarron River below Big Salt Plain; and 3) allowing both salt plains to accumulate brine and salt, but remain separated from freshwater in

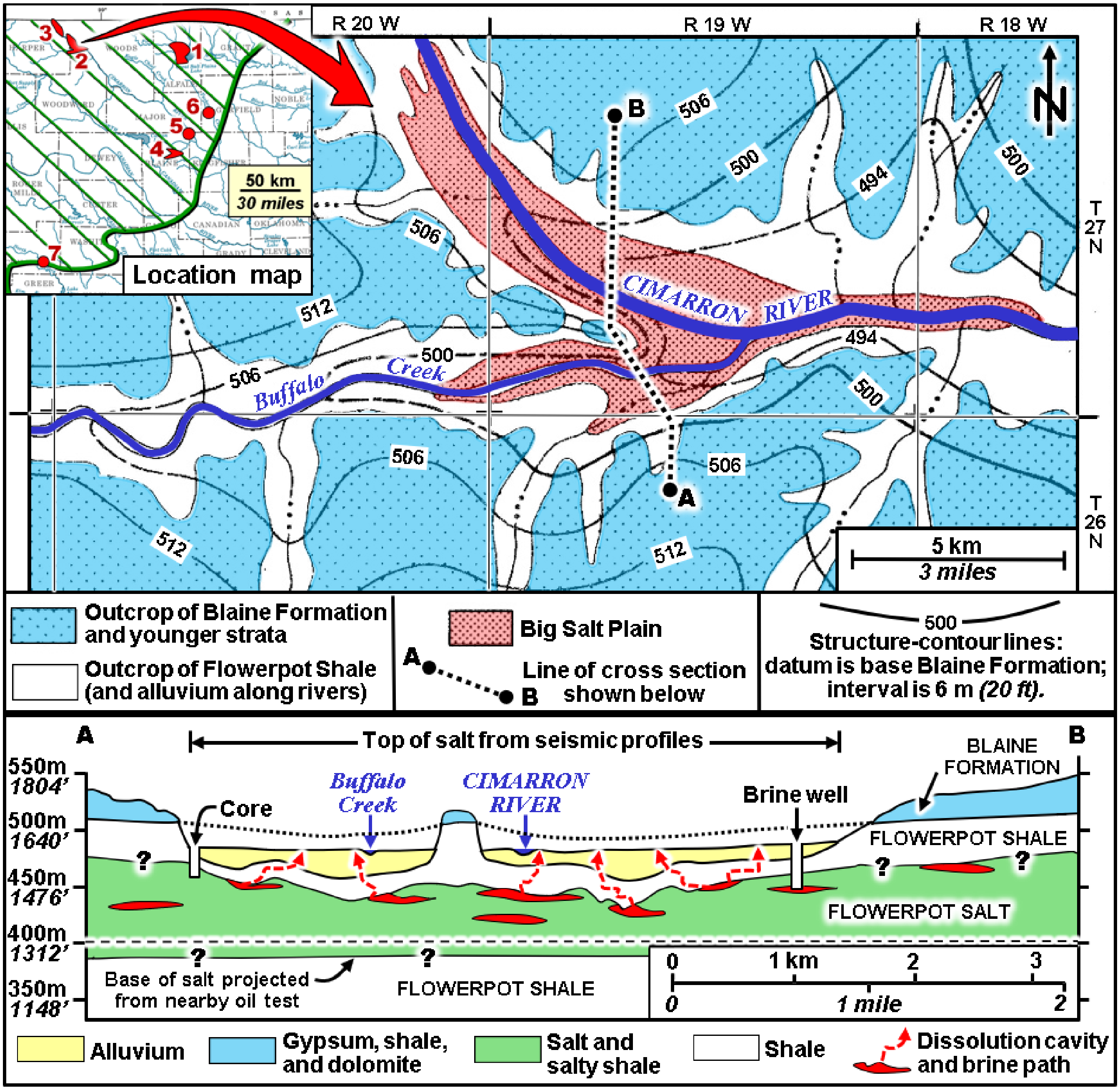


Figure 17. Map and cross section of Big Salt Plain in northwest Oklahoma. Geologic and structure-contour map (above) and cross section (below) show drape of Blaine Formation toward Cimarron River and Buffalo Creek owing to dissolution of upper parts of Flowerpot salt; based on data from USACE (modified from Johnson, 1981, 2019b, Plate 1). Locations of dissolution cavities and brine paths in cross section are hypothetical.

the Cimarron River.

Gould (1901) stated that Big Salt Plain is perhaps the most noted of the salt plains, from the standpoint of a historian. Coronado, the Spanish conquistador and explorer, probably was the first European to visit this place during his search for the Seven Cities of Cibola in 1540-42. Later, Native American reports about Big Salt Plain as a "salt mountain" became part of the justification used by Thomas Jefferson to acquire the Louisiana Territory from the French (Isern, 1980). Jefferson wrote of the natural resources of the yet-to-be-acquired Louisiana Territory, including a salt mountain which, reportedly, was "one hundred and eighty miles long, and forty-five in width, composed of solid rock salt, without any trees, or even any shrubs on it." Isern (1980) states that Native Americans probably referred to the salt plain as their "salt mountain" because it was at the base of a "mountain" (the local 35-m-high cliffs capped by gypsum) where they gathered their salt. Obviously, the reports that reached Jefferson were a great overstatement of the facts, and his detractors subsequently referred to this feature as "Jefferson's salt mountain."

Surface Geology

Principal outcropping rock units around the two salt plains are the Flowerpot Shale and the overlying Blaine Formation (Figs. 17, 18). Large-scale, detailed geologic maps of both salt plains are given in Johnson (2019b, Plates 1 and 2 therein). The Flowerpot consists chiefly of red-brown shale, with many thin beds of gray shale, brown siltstone, and gypsum or gypsum nodules. The formation is about 90 m thick (Fay, 1965, reports 85 to 130 m in outcrops of eastern Woods County), but the contact with the underlying Cedar Hills Member of the Hennessey Formation is not exposed in the study area, nor has it been cored in the vicinity of either salt plain. The upper part of the formation is well-exposed in bluffs along Cimarron River adjacent to both salt plains, and as much as 30 m of the formation can be examined at Big Salt Plain, just below the confluence of Cimarron River and Buffalo Creek. Farther northwest, near Little Salt Plain, the top 20 m of the Flowerpot is exposed north of US Highway 64 bridge, but only the top 6 m is exposed near the Oklahoma–Kansas border. Where shales of this formation are interbedded with salt (back from the outcrop, and beneath the salt plains), the salt-bearing unit is called the Flowerpot salt (Figs. 17, 18, cross sections).

The overlying Blaine Formation is 25 to 30 m thick and consists of white gypsum interbedded with red-brown shale and thin layers of green-gray shale and dolomite. The Blaine has three main gypsum beds, each 3 to 8 m thick, with the most conspicuous being the 8-m-thick

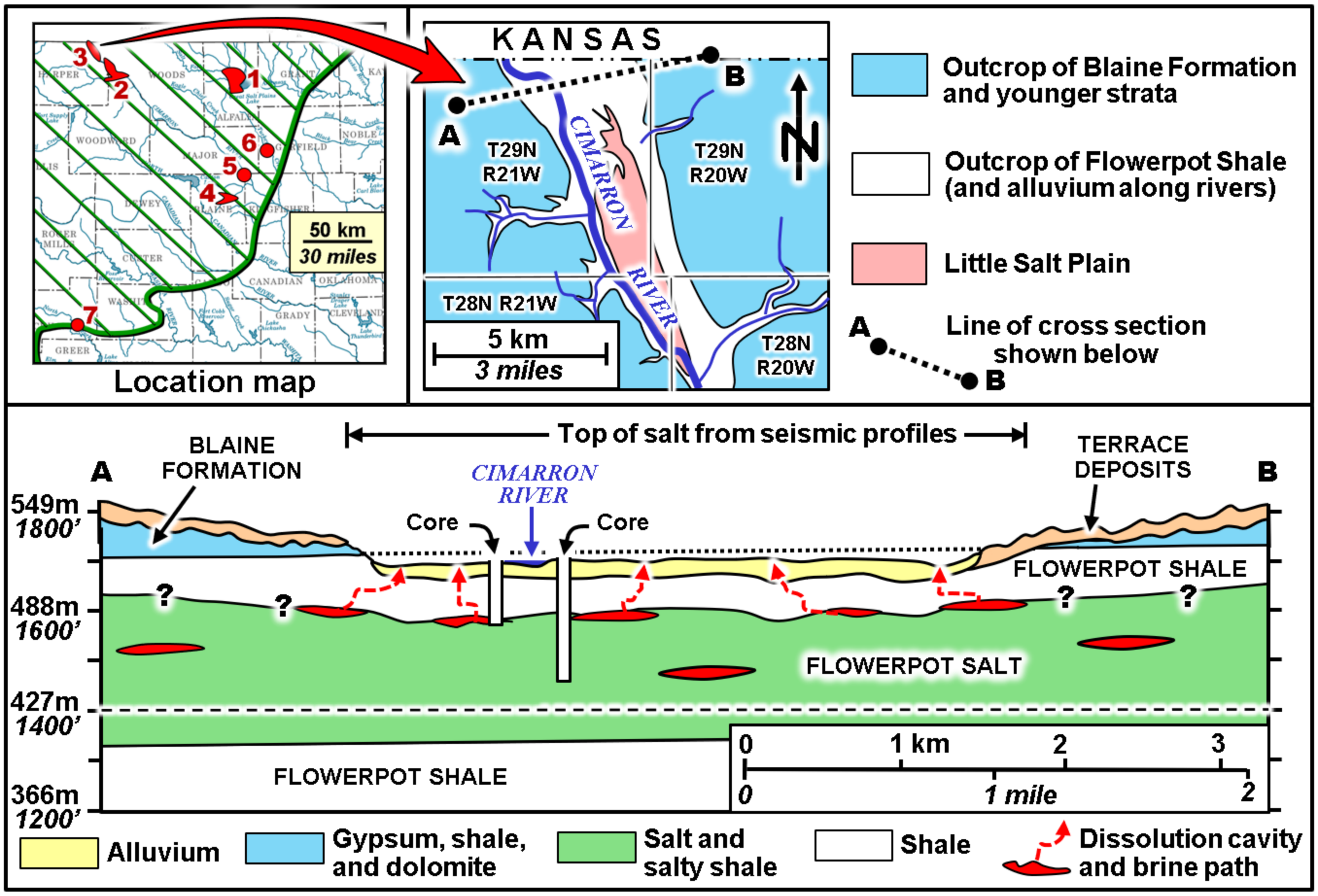


Figure 18. Map and cross section of Little Salt Plain in northwest Oklahoma. Geologic map (above) and cross section (below) show dissolution of upper parts of Flowerpot salt beneath Cimarron River; based upon data from USACE (modified from Johnson, 2019b, plate 2). Locations of dissolution cavities and brine paths on cross section are hypothetical. Cross section is along proposed alignment of a freshwater dam, just upstream of salt plain.

Medicine Lodge Gypsum Bed at the base. Individual gypsum beds of the Blaine are abnormally thin at a number of places, and locally one or more of the gypsum beds is completely missing: this results from the gypsum bed(s) having been locally dissolved, most likely during the Late Cenozoic Era. In many places, a brown silty or clayey sediment was deposited in Quaternary time to fill original caverns and void spaces that resulted from dissolution of the gypsum. The Medicine Lodge Gypsum Bed is the best marker bed for structural mapping in the area (Fig. 17).

Overlying the Blaine Formation are several other formations locally seen in outcrops. The Dog Creek Shale, immediately above the Blaine, is 12 to 15 m of mostly red-brown shale, and above the Dog Creek are orange-brown sandstones of the Marlow Formation (the lower part of the Whitehorse Group).

Quaternary terrace deposits consist chiefly of sand and gravel deposited along the former courses of Cimarron River and Buffalo Creek. Typically, they are well above Cimarron River on the south side of the salt plains, but they extend down to, and are in contact with, alluvial deposits on the north side of the river. Terrace deposits range from 1 to 15 m thick.

The youngest sediments in the area are Quaternary sand, silt, clay, and gravel that comprise alluvium along flood plains of Cimarron River, Buffalo Creek, and their principal tributaries. These youngest sediments are typically 3 to 20 m thick on Cimarron River, and are 6 to 18 m thick on Buffalo Creek. Detailed information concerning thickness of the alluvium was available from boreholes drilled by the USACE, and from seismic profiles made by Geo Prospectors, Inc. (Figs. 17, 18).

Outcropping rocks throughout the area are essentially flat-lying, except for the gentle dip (4 to 8 m/km, or 0.2º to 0.4º) towards Cimarron River and Buffalo Creek at Big Salt Plain: the Blaine Formation, and the upper part of the Flowerpot Shale, form a definite synclinal structure along the two principal rivers in the area (Fig. 17). This dip of the rocks towards the rivers results from dissolution of salt in the upper part of the Flowerpot salt; dissolution is more advanced directly beneath Cimarron River and Buffalo Creek, and thus the amount of collapse and drape of overlying rocks is greatest in these areas.

Outcropping Permian strata on both sides of Cimarron River are disturbed locally as a result of dissolution of Flowerpot salt. One area that is highly chaotic is in sections 3, 4, and 10, T. 28 N., R. 21 W., just west of Little Salt Plain (Plate 2 in Johnson, 2019b). In this area, the logs of two oil wells show there is a difference in elevation of 11m at the base of the Blaine within a distance of about 3 km, and outcropping rocks between these two wells are chaotic blocks that dip 20º to 30º in various directions, as a result of being dropped into underlying dissolution cavities. Similar dissolution-and-collapse features near Big Salt Plain are in sec 21, T. 27 N., R. 19 W., in sec. 4, T. 26 N., R. 19 W., in sec. 22, T. 27 N., R. 21 W., and several other places where the base of the Blaine has been dropped more than 3 or 6 m (Plate 1 in Johnson, 2019b).

Subsurface Salt Deposits

Flowerpot salt is at shallow depths beneath Big Salt Plain, Little Salt Plain, and adjacent areas (Figs. 17, 18), and the total thickness of Flowerpot salt here is about 45 to 55 m (Plate 6 in Johnson, 1976). It consists of red-brown shale interbedded with transparent to translucent layers, crystals, and veins of salt. Commonly, the salt is reddish in color, due to shale impurities, and in many layers it is intimately intermixed with shale. Stratigraphic zones containing salt are typically 1 to 3 m thick (based upon core holes drilled in 1960–1961 by the USACE), and salt appears to comprise about half of the entire Flowerpot salt unit. The full thickness of the salt unit has not been cored, but as much as 18 m of salt and interbedded shale were cored by the USACE in the lower half of the 36-m-deep hole no. II–20, drilled in sec. 21, T. 27 N., R. 19 W.

The top of the Flowerpot salt is commonly about 30 m below the top of the Flowerpot Shale near these salt plains, but the upper surface is irregular as a result of dissolution of the salt by groundwater; this irregularity is well displayed in the seismic profiles (Figs. 17, 18). Groundwater dissolves the salt principally from the upper part of the unit beneath Cimarron River and Buffalo Creek. In some boreholes there is a solution cavity, or a "zone of lost circulation," at the top of the salt unit: this probably represents the zone in which dissolution is now most active, and/or the zone that is transmitting high-salinity brine away from the salt beds. The top of the Flowerpot salt is only 15 to 30 m below the top of the formation several kilometers from Cimarron River at Little Salt Plain, such as in two oil-well tests drilled in secs. 4 and 10, T. 28 N., R. 21 W.

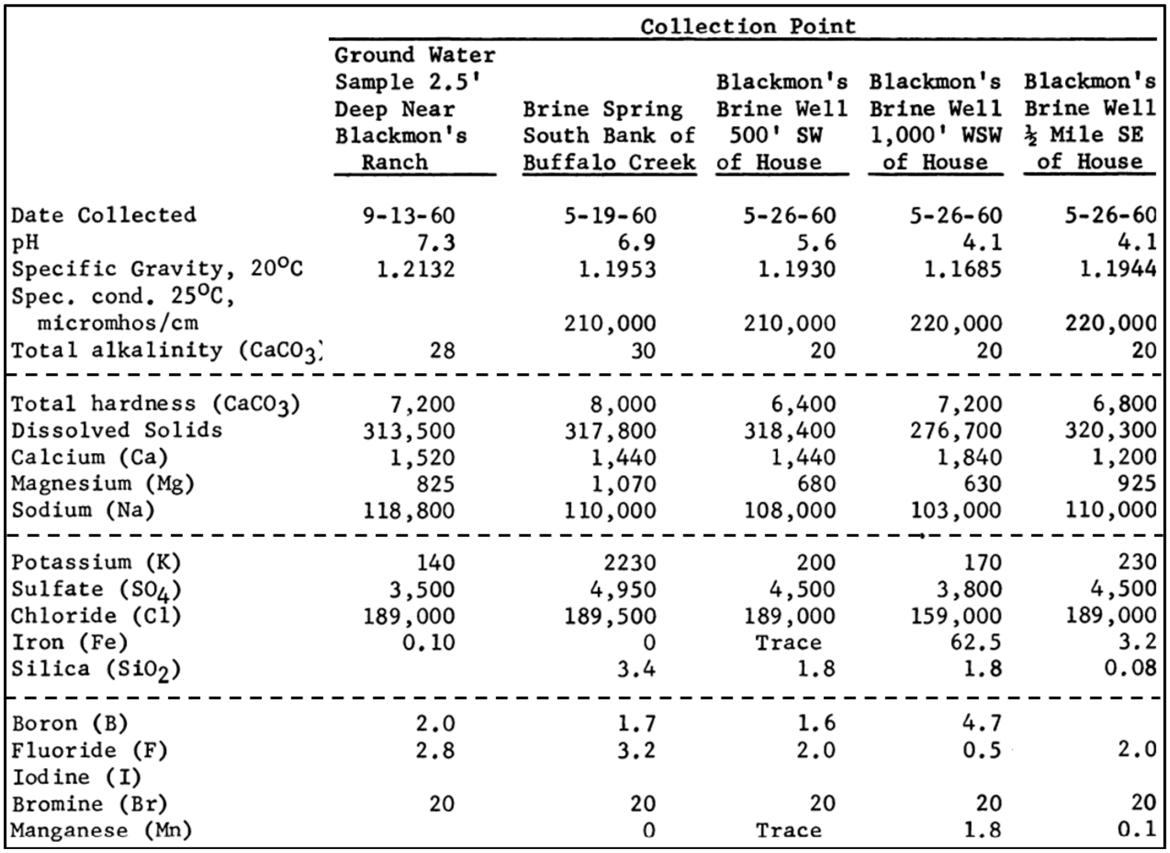
The depth to the top of salt beds beneath Big Salt Plain is generally 15 to 30 m, and beneath Little Salt Plain it is 30 to 38 m. The salt is shallowest at Big Salt Plain in sec. 21, T. 27 N., R. 19 W., where it was encountered only 9 m below the surface in the USACE hole no. II–50. The top of the salt is at slightly greater depths to the northwest and west of that location, but it drops off to a considerable depth (about 55 m below the surface) eastward along the east line of sec. 21 (Ward, 1961b; Johnson, 1981).

Further evidence suggesting dissolution of Flowerpot salt near Big Salt Plain is the "Freedom Gas Blowout," as described by Preston (1980a, b) and Johnson (2003). In 1980, natural gas erupted from alluvium in the Cimarron River floodplain about 3 km east of Big Salt Plain and created a 6-m-wide crater from which mud was ejected to a height of 20 m. Other nearby craters were up to 9 m wide and 3.2 m deep. An estimated 20 million cubic feet (about 566 million liters) of gas was emitted daily from the larger vents. Johnson (2003) summarized that apparently a mechanical failure in a deep gas well, drilled 16 km to the southwest, allowed high-pressure natural gas to enter a "lost-circulation zone" (an open, probably cavernous or karstic zone) at a depth of 54 m in the well—a well depth that is within the Flowerpot salt. The data suggest the following (Johnson, 2003): 1) high-pressure gas from the well entered dissolution cavities in the Flowerpot salt; 2) the gas then migrated laterally 16 km to the northeast through dissolution cavities in the Flowerpot salt; and 3) then reached the land surface through fractured Flowerpot shale that underlies Cimarron River alluvium just east of Big Salt Plain.

Other salt units are also present beneath Big Salt Plain and Little Salt Plain (Jordan and Vosburg, 1963; Johnson 1976), but they are too deep to be making any contribution here to the flow of brine at the surface. Salty shale is present in the Upper Cimarron salt at a depth of 150 m below both salt plains, and massive beds of salt in the Lower Cimarron salt are present about 240 to 275 m below the salt plains. In addition, thick salts in the Hutchinson Salt are at least 520 m below both salt plains.

Brine Emissions and Salt Production

Three sets of analyses of brines emitted at Big Salt Plain have been reported (Tables 2, 5, 6), and two sets of analyses have been reported for Little Salt Plain (Tables 2, 7). Seven brine samples at Big Salt Plain, collected from a combination of wells, springs, and holes dug on the salt flat, have the following concentrations:



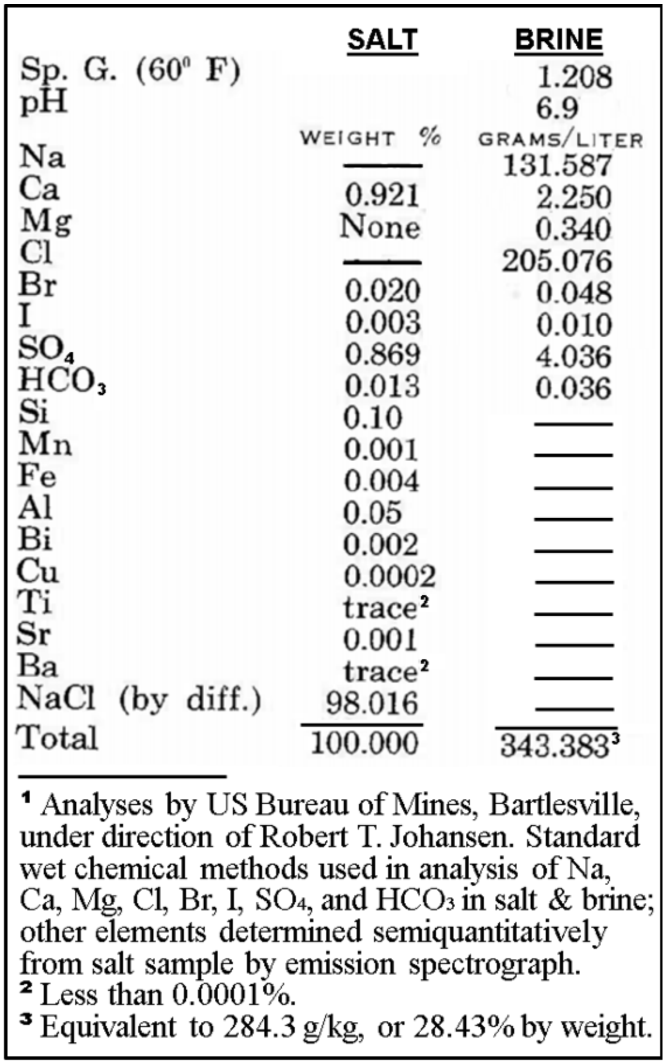
	Collection Point				
	Ground Water Sample 2.5' Deep Near Blackmon's Ranch	Brine Spring South Bank of Buffalo Creek	Blackmon's Brine Well 500' SW of House	Blackmon's Brine Well 1,000' WSW of House	Blackmon's Brine Well ½ Mile SE of House
Date Collected	9-13-60	5-19-60	5-26-60	5-26-60	5-26-60
pH	7.3	6.9	5.6	4.1	4.1
Specific Gravity, 20°C	1.2132	1.1953	1.1930	1.1685	1.1944
Spec. cond. 25°C, micromhos/cm		210,000	210,000	220,000	220,000
Total alkalinity ($CaCO_3$)	28	30	20	20	20
Total hardness ($CaCO_3$)	7,200	8,000	6,400	7,200	6,800
Dissolved Solids	313,500	317,800	318,400	276,700	320,300
Calcium (Ca)	1,520	1,440	1,440	1,840	1,200
Magnesium (Mg)	825	1,070	680	630	925
Sodium (Na)	118,800	110,000	108,000	103,000	110,000
Potassium (K)	140	2230	200	170	230
Sulfate (SO_4)	3,500	4,950	4,500	3,800	4,500
Chloride (Cl)	189,000	189,500	189,000	159,000	189,000
Iron (Fe)	0.10	0	Trace	62.5	3.2
Silica (SiO_2)		3.4	1.8	1.8	0.08
Boron (B)	2.0	1.7	1.6	4.7	
Fluoride (F)	2.8	3.2	2.0	0.5	2.0
Iodine (I)					
Bromine (Br)	20	20	20	20	20
Manganese (Mn)		0	Trace	1.8	0.1

Table 5. Analyses of natural brines from Big Salt Plain in mg/l, except pH (unless otherwise indicated). From US Department of Health (1964).

chloride ranges from 156,000 to 205, 076 ppm, and averages about 182,286 ppm; and salt ranges from 262,000 to 336,663 ppm, and averages about 294,000 ppm. Three samples at Little Salt Plain, collected from brine seeps and a hole dug less than 90 cm deep, have the following concentrations: chloride ranges from 61,000 to 194,000 ppm, and averages about 137,667 ppm; and salt ranges from 103,500 to 319,000 ppm, and averages about 229,500 ppm.

Clearly, brine is forming in the shallow subsurface by dissolution of salt beds in the Flowerpot salt, and it is coming to the surface through alluvial deposits in Cimarron River and Buffalo Creek (Figs. 17, 18). The brine is saturated with respect to sodium chloride: a sample from one brine well of Blackmon Salt Co. (now Cargill Salt Co., see Fig. 19) on Big Salt Plain contained up to 205,076 ppm of chloride (Table 6). Ward (1963a) reports that a spring at the base of bluffs on the south side of Big Salt Plain had a concentration of 156,000 ppm chloride, and that a seep on Little Salt Plain had a concentration of 162,000 ppm. An artesian brine well on the south side of the Buffalo Creek portion of Big Salt Plain (USACE hole no. II–31, in sec. 33, T. 27 N., R. 19 W.) had salt encrusted over the surface pipe, because salt is precipitated here from saturated brine immediately upon coming to the surface.

Estimates of the daily salt emissions from the salt plains are (Table 1): Big Salt Plain, 1,600 to 2,950 short tons of chloride, or 2,600 to 4,870 short tons of salt; Little Salt Plain, 100 to 600 tons of chloride, or 160 to 990 short tons of salt. From these data, it appears that Big Salt Plain is the largest contributor of salt to the waterways of Oklahoma.



	SALT	BRINE
Sp. G. (60° F)		1.208
pH		6.9
	WEIGHT %	GRAMS/LITER
Na	——	131.587
Ca	0.921	2.250
Mg	None	0.340
Cl	——	205.076
Br	0.020	0.048
I	0.003	0.010
SO_4	0.869	4.036
HCO_3	0.013	0.036
Si	0.10	——
Mn	0.001	——
Fe	0.004	——
Al	0.05	——
Bi	0.002	——
Cu	0.0002	——
Ti	trace[2]	——
Sr	0.001	——
Ba	trace[2]	——
NaCl (by diff.)	98.016	——
Total	100.000	343.383[3]

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[1] Analyses by US Bureau of Mines, Bartlesville, under direction of Robert T. Johansen. Standard wet chemical methods used in analysis of Na, Ca, Mg, Cl, Br, I, SO_4, and HCO_3 in salt & brine; other elements determined semiquantitatively from salt sample by emission spectrograph.

[2] Less than 0.0001%.

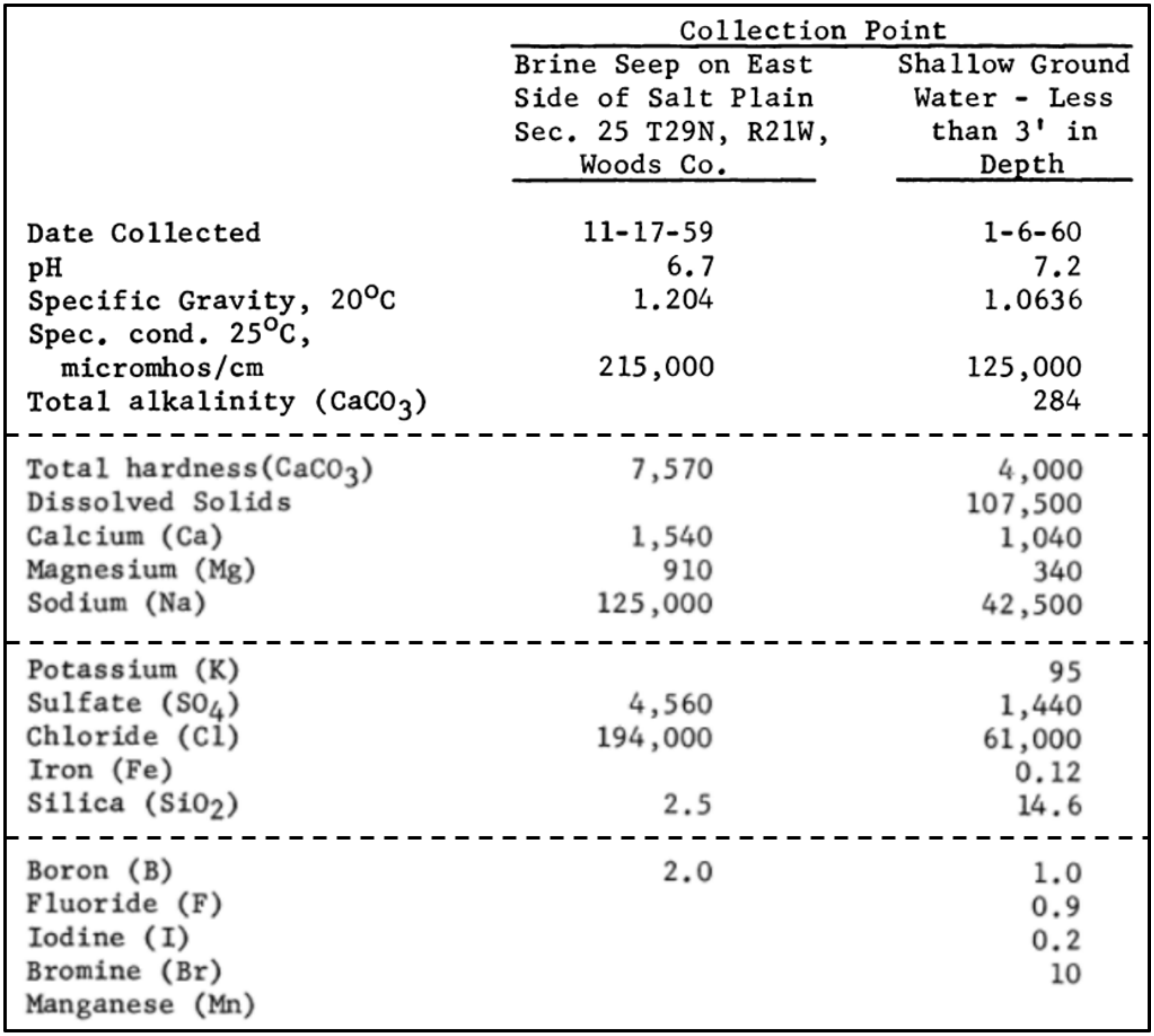
[3] Equivalent to 284.3 g/kg, or 28.43% by weight.

Table 6. Analyses of solar salt and natural brine from Blackmon Salt Co. at Big Salt Plain[1]. Samples obtained August 22, 1969. From Johnson (1970).

Brine is present in bedrock under a hydrostatic head that causes it to rise above ground level in artesian flow. This is seen both in Blackmon's original wells and in the artesian well on the south side of Buffalo Creek. With this hydrostatic head, brine is forced into the base or the sides of the alluvial deposits and is then forced upwards to the surface of the alluvium. At the surface, water (H_2O) is evaporated from the brine, and salt is precipitated as a crust on the salt plain. Ward (1963a) noted that tritium from a spring flowing from Flowerpot Shale on the south side of Big Salt Plain indicated an age of the water of less than 20 years, and that it had probably not migrated very far from where the original freshwater entered the ground.

Some of the brine flows in subsurface through dissolution cavities at and near the upper surface of the Flowerpot salt. Much of the brine probably is entering the base of alluvium through bedrock joints and fractures formed, in part, by collapse of overlying Flowerpot strata when salt is dissolved. Some brine may also be entering alluvium through thin aquifers in the Flowerpot Shale.

In general, water wells drilled on the north and east side of Cimarron River are in terrace deposits: they provide fairly good- to good-quality freshwater, and often they are flowing wells. Groundwater here results from precipitation falling on the terrace deposits. Wells drilled on the west and south side of the river (particularly north of US Highway 64, which crosses Cimarron River between the two salt plains) can obtain small yields of freshwater from the terrace deposits, but when drilled into bedrock they typically encounter salty water derived by dissolving the Flowerpot salt. The difference in groundwater



	Collection Point	
	Brine Seep on East Side of Salt Plain Sec. 25 T29N, R21W, Woods Co.	Shallow Ground Water - Less than 3' in Depth
Date Collected	11-17-59	1-6-60
pH	6.7	7.2
Specific Gravity, 20°C	1.204	1.0636
Spec. cond. 25°C, micromhos/cm	215,000	125,000
Total alkalinity ($CaCO_3$)		284
Total hardness($CaCO_3$)	7,570	4,000
Dissolved Solids		107,500
Calcium (Ca)	1,540	1,040
Magnesium (Mg)	910	340
Sodium (Na)	125,000	42,500
Potassium (K)		95
Sulfate (SO_4)	4,560	1,440
Chloride (Cl)	194,000	61,000
Iron (Fe)		0.12
Silica (SiO_2)	2.5	14.6
Boron (B)	2.0	1.0
Fluoride (F)		0.9
Iodine (I)		0.2
Bromine (Br)		10
Manganese (Mn)		

Table 7. Analyses of natural brines from Little Salt Plain in mg/l, except pH (unless otherwise indicated). From US Department of Health (1964).

quality between the northeast (terrace deposits) and southwest (bedrock) sides of Cimarron River is seen at many places farther downstream, such as in the Okeene Salt Plain area.

Alluvium near, and downstream from, the salt plains is undoubtedly saturated with high-salinity brine. Adjacent to Little Salt Plain, a water well drilled in 15 m of alluvium in NW¼ sec. 6, T. 28 N., R. 20 W., yielded water with about 60,000 ppm chloride, at a rate of more than 375 liters per minute (the well supplied drilling water for a nearby oil test).

Salt has been harvested from Big Salt Plain since before Oklahoma Statehood (before 1907). Gould (1901) noted the presence of a dozen or more trails radiating out from the salt flats as evidence that this place had been used for a long time as a source of salt for Native Americans and for the various forts and early settlements in the region. Commercial solar evaporation of brine to recover salt began when the Blackmon Salt Co. established and carried out a small salt business starting in the 1920s (Johnson, 1970). Brine used by Blackmon Salt Co. was saturated with respect to salt: it had a specific gravity of 1.208 and the Na+Cl content was about 337 g/liter (about 337,000 ppm) (Table 6). Na+Cl were about 98.1% of dissolved solids in that brine, and $Ca+SO_4$ made up about 1.8% of dissolved solids.

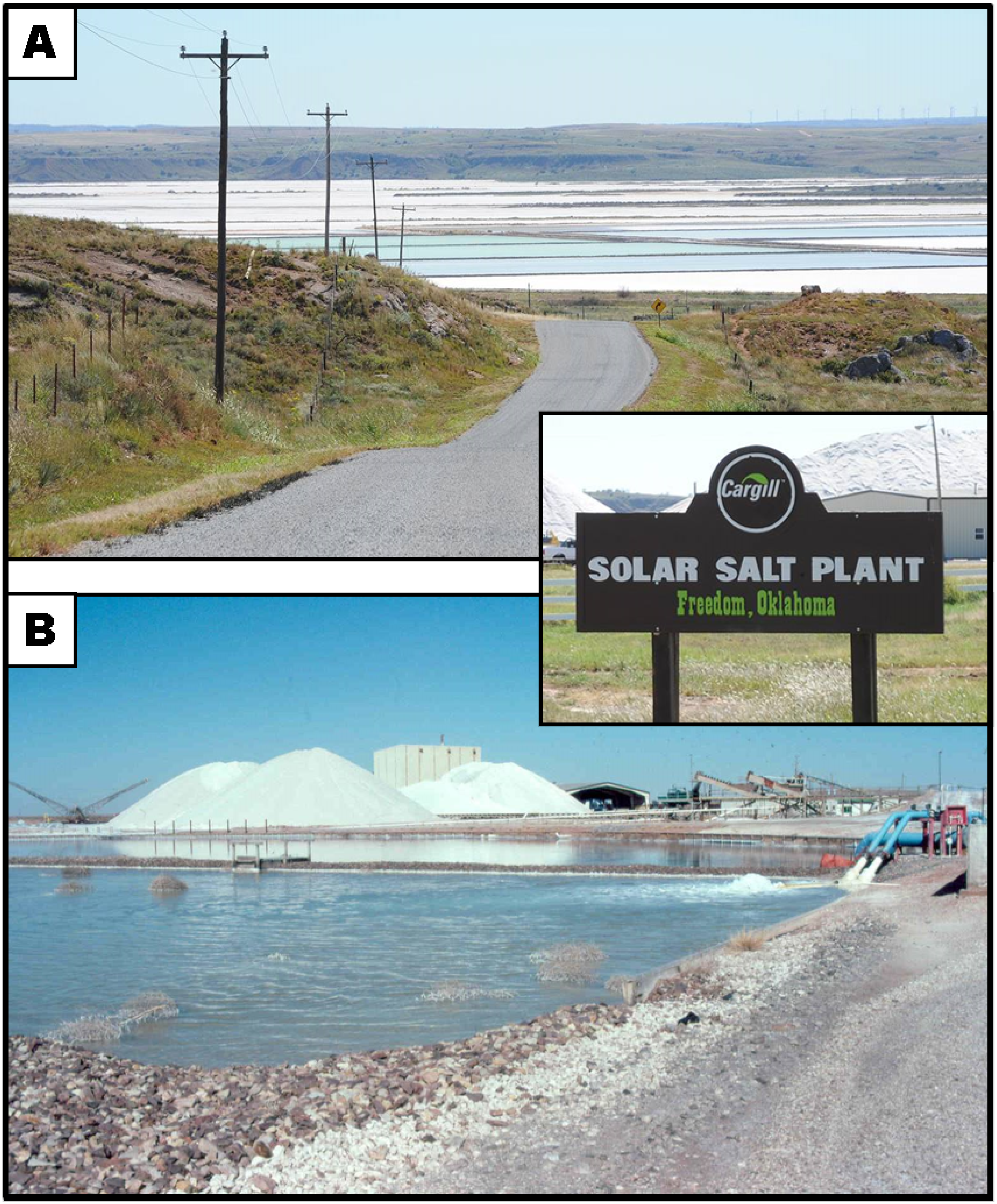


Figure 19. Views of Cargill Salt Co. solar-salt plant at Big Salt Plain on Cimarron River. A) Approaching Cargill Salt Co. evaporating pans from the north. B) View of brine pouring (on right) into one of the evaporation pans, and in the background are large piles of high-purity solar salt that has been harvested and is ready for market. From Johnson (2019b).

In 1984, Cargill Inc. acquired the Blackmon lands and constructed about 200 hectares of solar ponds that could produce about 150,000 to 200,000 short tons of salt annually (Figs. 16, 19). Joachims (1999) describes Cargill's operation thus: 1) saturated brine is pumped to the surface from cavities in the Flowerpot salt beneath the salt plain; 2) the brine is placed in about 200 hectares of earthen pans, surrounded by earthen embankments; 3) evaporation of H_2O from the brine is enhanced by lots of summer sunshine and strong winds, and thus salt is precipitated on the floor of the earthen pans; and 4) high-purity salt (99.5 to 99.8% NaCl) is harvested from the earthen pans in the fall of the year, and is marketed for water-softening, industrial, and agricultural (livestock feed) uses, as well as for de-icing of roads in the winter.

There is no record of any historic or present commercial production of salt at Little Salt Plain, although it is likely that at least some salt was harvested by Native Americans and early settlers.

Salt Creek Canyon Salt Plain

Salt Creek Canyon is one of the two known salt-emission areas in Blaine County (Fig. 3, site 4). Outcropping rocks in the area are the Permian Flowerpot Shale, Blaine Formation, and Dog Creek Shale, with brine coming from siltstone and sandstone beds in the Chickasha Tongue of the Flowerpot Shale exposed in the canyon floor (Figs. 20–22). Brine apparently forms by dissolution of salt beds in the Upper Cimarron salt, which is about 80 m below the canyon floor (Fig. 20). Brine then migrates laterally and upward through fractures and joints, and laterally through siltstone and sandstone beds, until it reaches the surface in Salt Creek Canyon (Fig. 21, 22).

It appears as if almost all of the chloride load entering Salt Creek is being emitted within the confines of the canyon itself. Therefore, to keep this brine from entering Salt Fork Arkansas River it seems best to attempt trapping and retaining the brine at the mouth of the canyon. Salt Creek Canyon Salt Plain is the fourth-largest salt plain in Oklahoma. The area of the salt plain within the canyon itself is about 25 hectares, but an additional 200 hectares of alluvium is occasionally encrusted with salt for a distance of about 5.5 km farther downstream to the east. In USACE studies, Salt Creek Canyon is referred to as "Area IV." The following description of Salt Creek Canyon Salt Plain is modified from an earlier report by Johnson (2019b).

Surface geology

A clear understanding of the Flowerpot, Blaine, and Dog Creek strata in the area is provided in the Southard core (Appendix A), drilled by the USACE about 0.5 km west of the SE corner sec. 21, T. 18 N., R. 12 W., about 2.5 km west of the salt plain (Fig. 21). Rock units of principal importance are the Flowerpot Shale and the Chickasha Tongue, which is considered part of the Flowerpot Shale (Fay and others, 1962). The Flowerpot here consists mainly of red-brown shale, with some thin layers of gray shale, gypsum nodules, siltstone, and sandstone. The formation is about 140 m thick in the area, but only the top 40 to 45 m are exposed in canyon walls adjacent to the salt plains. Older Flowerpot strata are exposed farther east along Salt Creek. Although the Southard core drilled through the top 16 m of the Flowerpot, it did not reach deep enough to penetrate any of the Chickasha Tongue.

The floor of Salt Creek Canyon consists mostly of interbedded siltstone, sandstone, and mudstone layers of the Chickasha Tongue, which has large-scale cross beds that dip generally to the west: cross beds represent the foreset beds of a deltaic sequence (the land area at that time lay to the east). Cross-bedded deltaic sands are red brown and green gray, and they contrast with overlying layers of orange-brown and red-brown shale and mudstone in the Flowerpot Shale. Deltaic strata exposed in the floor of the canyon are the youngest deposits of the Chickasha Tongue in this area, and they probably are equivalent to unit Pf-4, as described by Fay and others (1962). The base of the deltaic sequence is not exposed in the canyon area, but the full thickness of the Chickasha Tongue is probably about 35 m.

Overlying the Flowerpot Shale are interbeds of thick gypsums and shales in the Blaine Formation. Resistant gypsum beds cap high escarpments in the area, and the thicker gypsums are being mined by US Gypsum Co. to the north of Salt Creek Canyon (Fig. 22A). The Blaine Formation is 24 to 27 m thick in the area, and individual gypsum/anhydrite beds are 2 to 5 m thick. At the base of the Blaine is the Medicine Lodge Gypsum Bed, which is 2 m thick. Structure mapping on the base of the Blaine Formation (Plate 3 in Johnson, 2019b) shows that outcropping rocks dip to the southwest at a rate of about 4 m/km (about 0.2º), and that there is no evidence of faults or folds.

Overlying the Blaine Formation is the Dog Creek Shale, which comprises 15 to 30 m of red-brown shale. The formation also contains several thin beds of siltstone and dolomite. At all places near Salt Creek Canyon, the

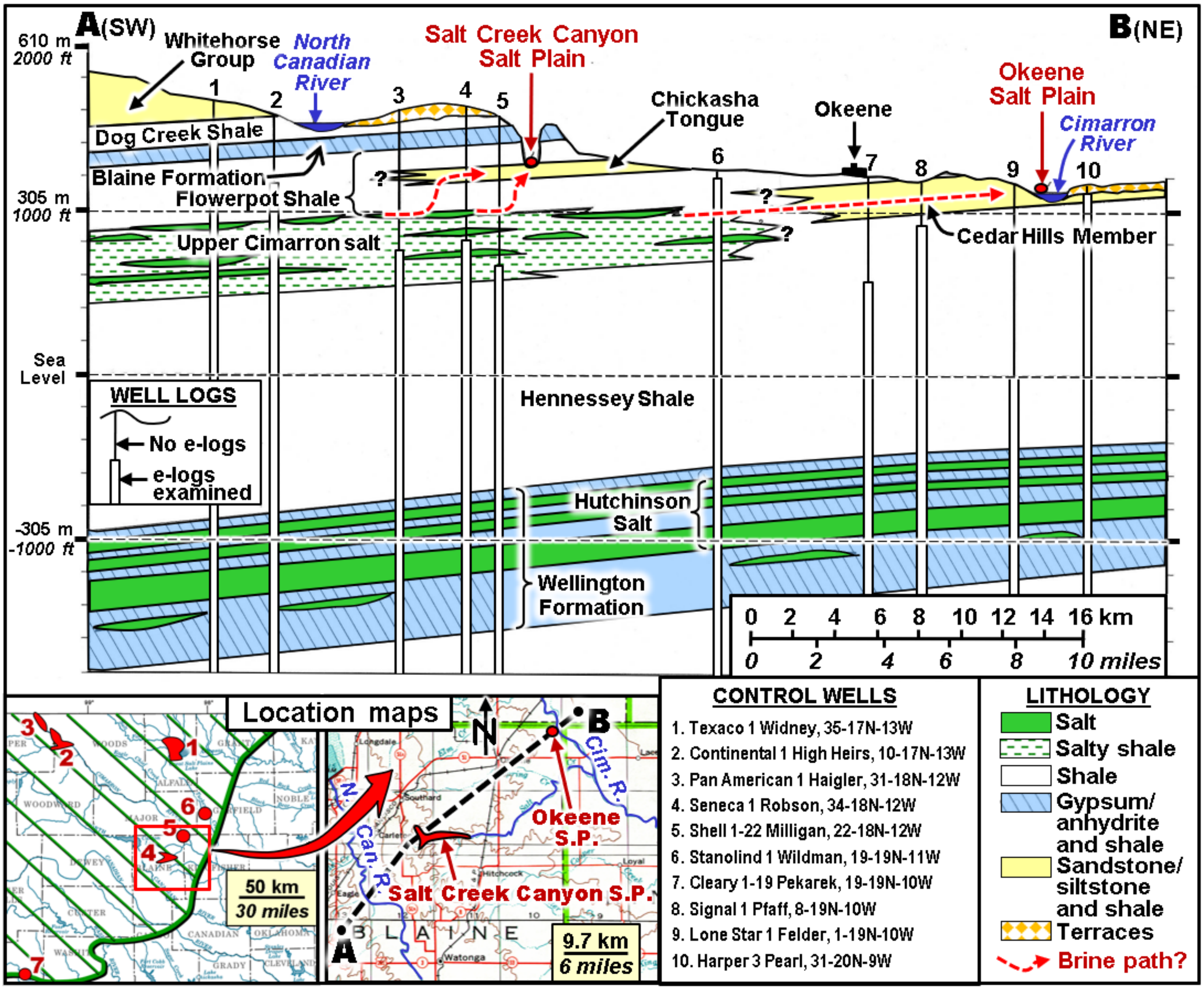


Figure 20. Cross section showing subsurface geology related to Salt Creek Canyon and Okeene Salt Plains in Blaine County, northwest Oklahoma (modified from Johnson, 2019b). Brine apparently forms by dissolution of salt layers in Upper Cimarron salt, and reaches the surface through siltstone and sandstone aquifers in the Chickasha Tongue of the Flowerpot Shale and the Cedar Hills Member of the Hennessey Shale.

top of the formation is eroded and is overlain by Quaternary terrace deposits.

Terrace deposits consist mostly of sand and gravel deposited along former courses of North Canadian River: they are as much as 18 m thick. Their high permeability makes them an excellent medium for trapping precipitation and allowing it to percolate down into the groundwater system.

Quaternary alluvium is present along Salt Creek below the mouth of Salt Creek Canyon. It is commonly about 1 m thick just east of the canyon, in sec. 24, T. 18 N., R. 12 W. Alluvium is 2 to 4 m thick about 5 km farther downstream from the canyon, along the USACE Survey-Report axis (based upon boreholes drilled by the USACE in 1962 along the proposed axis). Within Salt Creek Canyon, bedrock is exposed in the creek bottom at most places, or it is covered by no more than 0.3 to 0.6 m of alluvium.

Minor amounts of salt occur in the Blaine Formation in the Southard core (Appendix A): scattered small crystals and veins of salt make up 1 to 2% (or less) of some of the gypsum/anhydrite layers, and all the shales and siltstones of the Blaine have a taste of salt. There is no evidence of similar, minor amounts of salt either in the overlying Dog Creek Shale or in the upper part of the Flowerpot Shale in the Southard core; drilling of the Southard core ceased at a depth of 90.1 m, after penetrating only 16 m of the Flowerpot.

Subsurface Salt Deposits

The most probable source of brine in this area is subsurface dissolution of salt in the Upper Cimarron salt unit. Brine then probably moves upward and laterally through fractured and jointed strata and aquifers above the salt, and finally reaches the surface in permeable beds of the Chickasha Tongue (Figs. 20, 21). Although data on the shallow subsurface beneath Salt Creek Canyon are meager, salty shale and salt beds of the Upper Cimarron salt appear to be about 120 m thick, and the top of the unit is about 80 m below the canyon floor. Several km west of Salt Creek Canyon, where ground level is much higher, the top of the salt is about 180 m deep. Dissolution of this salt undoubtedly is taking place beneath or just west of the canyon, where salt is in this range of 80 to 180 m below the surface.

The Upper Cimarron salt is the only salt-bearing unit present here in the shallow subsurface. The nearest Flowerpot salt, which is stratigraphically equivalent to rocks

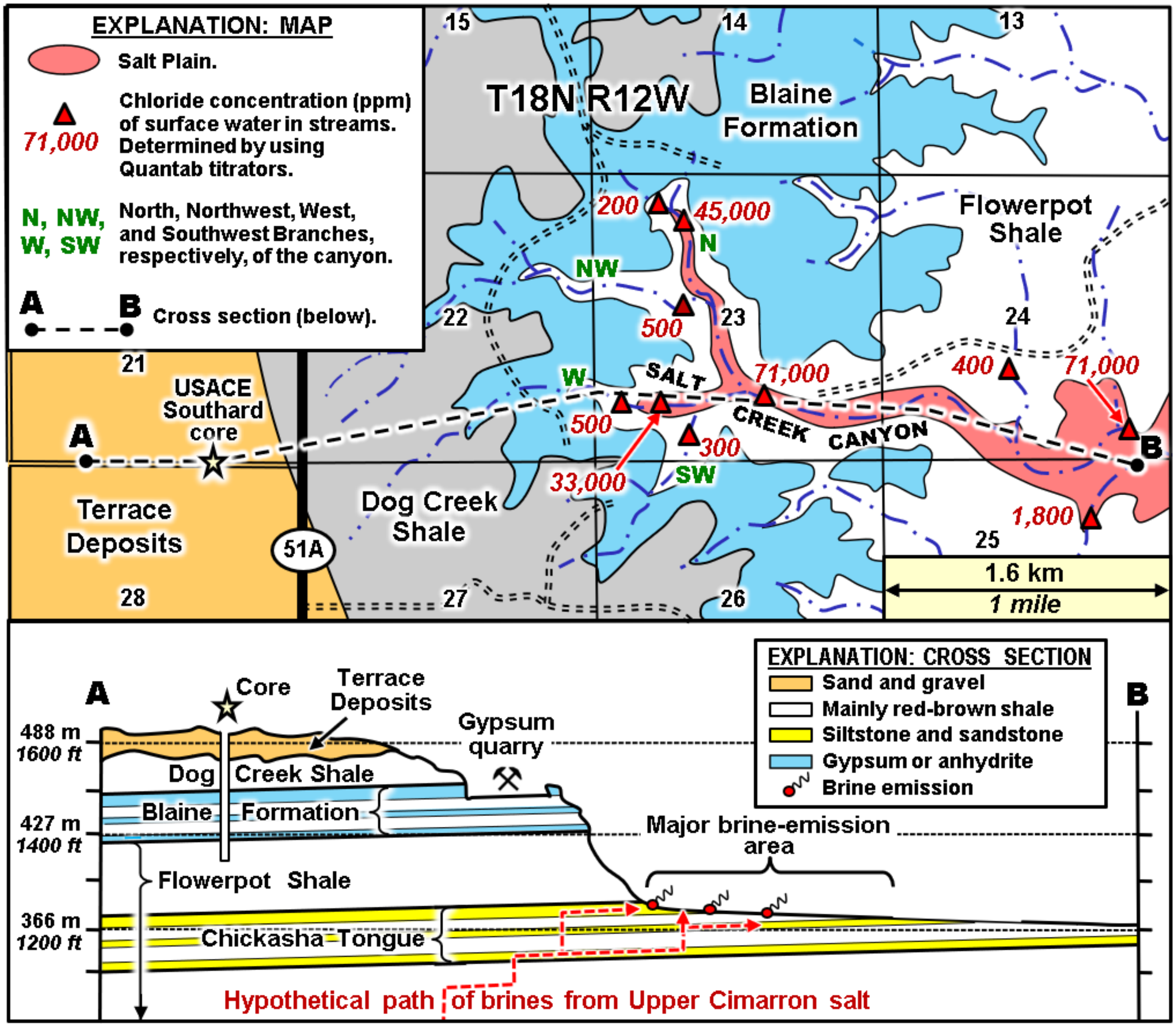
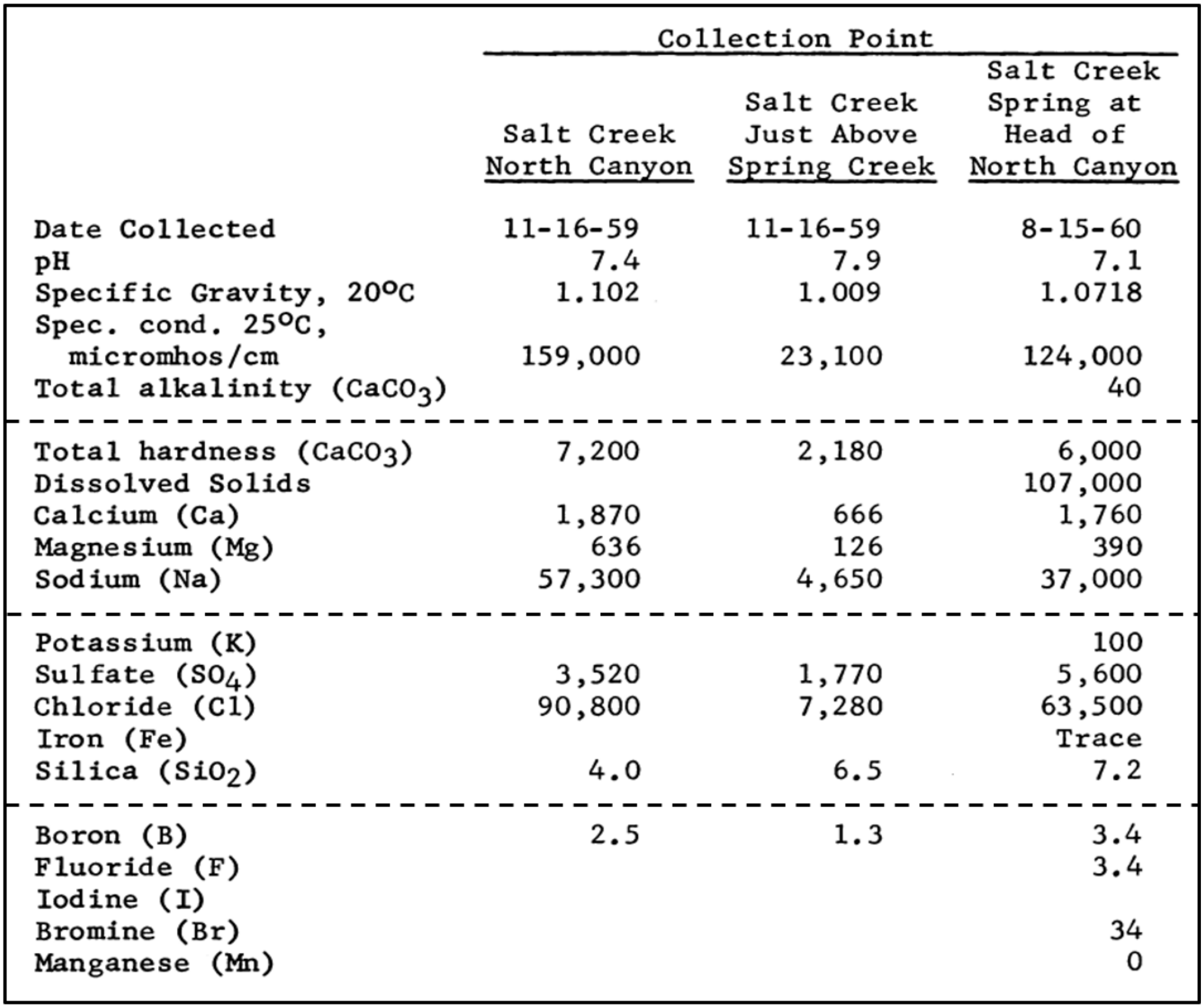
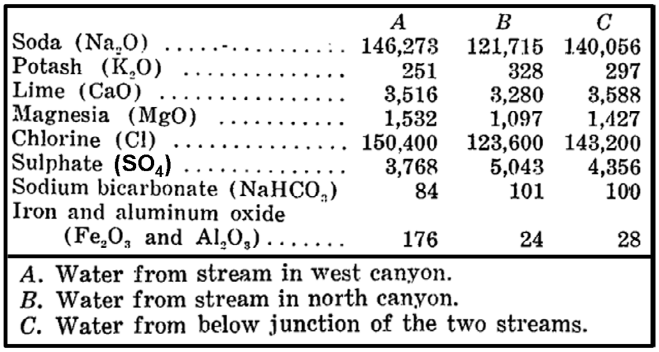


Figure 21. Geologic map and cross section of Salt Creek Canyon Salt Plain area in Blaine County, northwest Oklahoma, showing chloride concentration of surface waters on and near salt plain (modified from Johnson, 2019b, Plate 3). Permian rocks dip to southwest at about 4 m/km (20 ft/mile), about 0.2 degree.



	Collection Point		
	Salt Creek North Canyon	Salt Creek Just Above Spring Creek	Salt Creek Spring at Head of North Canyon
Date Collected	11-16-59	11-16-59	8-15-60
pH	7.4	7.9	7.1
Specific Gravity, 20°C	1.102	1.009	1.0718
Spec. cond. 25°C, micromhos/cm	159,000	23,100	124,000
Total alkalinity ($CaCO_3$)			40
Total hardness ($CaCO_3$)	7,200	2,180	6,000
Dissolved Solids			107,000
Calcium (Ca)	1,870	666	1,760
Magnesium (Mg)	636	126	390
Sodium (Na)	57,300	4,650	37,000
Potassium (K)			100
Sulfate (SO_4)	3,520	1,770	5,600
Chloride (Cl)	90,800	7,280	63,500
Iron (Fe)			Trace
Silica (SiO_2)	4.0	6.5	7.2
Boron (B)	2.5	1.3	3.4
Fluoride (F)			3.4
Iodine (I)			
Bromine (Br)			34
Manganese (Mn)			0

Table 8. Analyses of natural brines from Salt Creek Canyon Salt Plain in mg/l, except pH (unless otherwise indicated). From US Department of Health (1964).



	A	*B*	*C*
Soda (Na_2O)	146,273	121,715	140,056
Potash (K_2O)	251	328	297
Lime (CaO)	3,516	3,280	3,588
Magnesia (MgO)	1,532	1,097	1,427
Chlorine (Cl)	150,400	123,600	143,200
Sulphate (SO_4)	3,768	5,043	4,356
Sodium bicarbonate ($NaHCO_3$)	84	101	100
Iron and aluminum oxide (Fe_2O_3 and Al_2O_3)	176	24	28

A. Water from stream in west canyon.
B. Water from stream in north canyon.
C. Water from below junction of the two streams.

Table 9. Analyses of natural brines from Salt Creek Canyon Salt Plain, in parts per million. From Snider (1913).

cropping out in Salt Creek Canyon, is about 50 km west and southwest of the area (Plate 6 in Johnson, 1976); and the Wellington Formation evaporites are about 600 m below the surface at Salt Creek Canyon (Fig. 20). Therefore, neither the Flowerpot salt or the Hutchinson Salt can be making any contribution to brine emissions in this area.

Upper Cimarron salt has not been cored here, and thus it is impossible to give an accurate description of the unit. However, it probably consists mostly of red-brown salty shale, with some layers of rock salt. Salt probably makes up only about 10 to 25% of the unit, and the remainder is almost entirely shale.

Brine Emissions and Salt Production

Three sets of analyses of brines collected at Salt Creek Canyon have been reported (Tables 2, 8, 9). A total of seven samples were collected from springs or streams in, or just below, Salt Creek Canyon. Based on their salinities, the samples fall into two groups: group one includes four brines of moderate salinity (Tables 2, 8), and group 2 includes three high-salinity brines (Table 9). In group one, chloride ranges from 7,280 to 90,800 ppm, and averages 61,045 ppm; salt ranges from 11,930 to 148,100 ppm, and averages 114,069 ppm. In group two, chloride ranges from 123,600 to 150,400 ppm, and averages 139,067 ppm; salt (assuming salt is 1.65 x Cl concentration) ranges from 203,940 to 254,100 ppm, and averages 231,440 ppm.

Emission of brine appears to be restricted to the bottom of Salt Creek Canyon in sec. 23, T. 18 N., R. 12 W. (Figs. 21, 22). Bedrock from which brine is emerging in all parts of the canyon is interbedded siltstone, sandstone, and mudstone of the Chickasha Tongue. Brine is mostly emerging from joints or fractures in the bedrock; one set of joints strikes east-west, and the other set of joints strikes N 35º E. There are four branches that feed water into Salt Creek Canyon: they are labeled as North, Northwest, West, and Southwest Branches of the canyons (Fig. 21). The flow of water in the uppermost reaches of all branches is relatively fresh, ranging from 200 to 500 ppm chloride (Fig. 21).

High-salinity brine is introduced only in the North and West Branches, where it was 45,000 and 33,000 ppm chloride, respectively, on one day of measurements (Plate 3 in Johnson, 2019b). Where the North and West Branches converge in SE¼ sec. 23, the water is 71,000 ppm chloride, and it remains at 71,000 ppm chloride across the southern half of sec. 24 (Fig. 21). The concentration is then reduced farther to the east, in T. 18 N., R. 11W., to 22,000 ppm chloride in sec. 29, and to 7,800 ppm chloride in sec. 21, because of the influx of large amounts of fairly fresh water from Ruby Mill Canyon, Bitter Creek, and other smaller tributaries (Plate 3 in Johnson, 2019b). Ward (1963a) reported that water in Salt Creek, below the salt springs (location not given), was 82,000 ppm chloride.

Principal tributaries entering Salt Creek downstream from the mouth of the canyon have a relatively low chloride content (Plate 3 in Johnson, 2019b). The largest stream is Bitter Creek (in sec. 28, T. 18 N., R. 11 W.), with 840 ppm chloride, and the other principal flow comes from the creek in Ruby Canyon, with 1,800 ppm chloride (sec. 25, T. 18 N., R. 12 W., in Fig. 21). Other tributaries entering Salt Creek contribute less water and range from 400 to 1,000 ppm chloride.

Daily emissions of salt from the Salt Creek Canyon Salt Plains are estimated to be 100 to 220 short tons of chloride, or 160 to 360 short tons of salt (Table 1).

Several outcrops along the banks of Salt Creek (downstream from the canyon), and along tributaries to Salt Creek, have encrustations of a white mineral. At many places this mineral does not have the taste of salt, but instead is somewhat bitter and may be a sodium-sulfate mineral (thenardite?) resulting from evaporation of mineralized water present in some of the siltstone beds in the area.

There is no production of salt here at this time, but Gould (1905, 1910) considered the area to have potential. He stated that a number of primitive salt-producing operations had been located at the edge of the plain at times in the past (pre-1905). Gould reported that operations here involved digging a well in the sand of the salt plain, and pumping the water, by hand, into vats for evaporation by boiling the brine. Fuel, gathered from nearby canyons, was chiefly cedar and oak trees. He reported that three buckets of brine would produce one bucket of salt upon evaporation, and that the capacity of one of the operations was reported to be 500 to 2,000 pounds (227 to 907 kg) per day. Salt was then hauled to local sites in wagons, and demand had exceeded supply for a number of years.

Gould (1905, 1910) also reported that one company, the Oklahoma Salt Company, was set up at the nearby (now abandoned) town of Ferguson, located about 1 km south of the east end of the salt plain in sec. 28, T. 18 N., R. 11 W. The plant had a capacity of processing 450 barrels of brine per day, with the brine being conveyed in iron pipes from wells drilled about 3 km away on the salt plain. Solar-evaporation pans at Ferguson were made of cement: their dimensions were about 3.7 by 15 m, and they were about 50 cm deep. This plant only operated for a few months, when it was purchased by a salt trust, and then shut down and dismantled (Gould, 1910).

Okeene Salt Plain

A newly recognized salt plain was described by John Dunlap as a result of his study of chloride emissions on Cimarron River between Okeene and Orienta (Dunlap, 1975). This salt plain was referred to as the "Okeene Salt Plain" by Johnson (2019b). The main part of the salt plain is in the northeast corner of Blaine County (Fig. 3, site 5), in secs. 1 and 2, T. 19 N., R. 10 W. (Fig. 23): the combined area of the two salt flats shown on Figure 23 is about 7 hectares. Apparently, brine is also entering

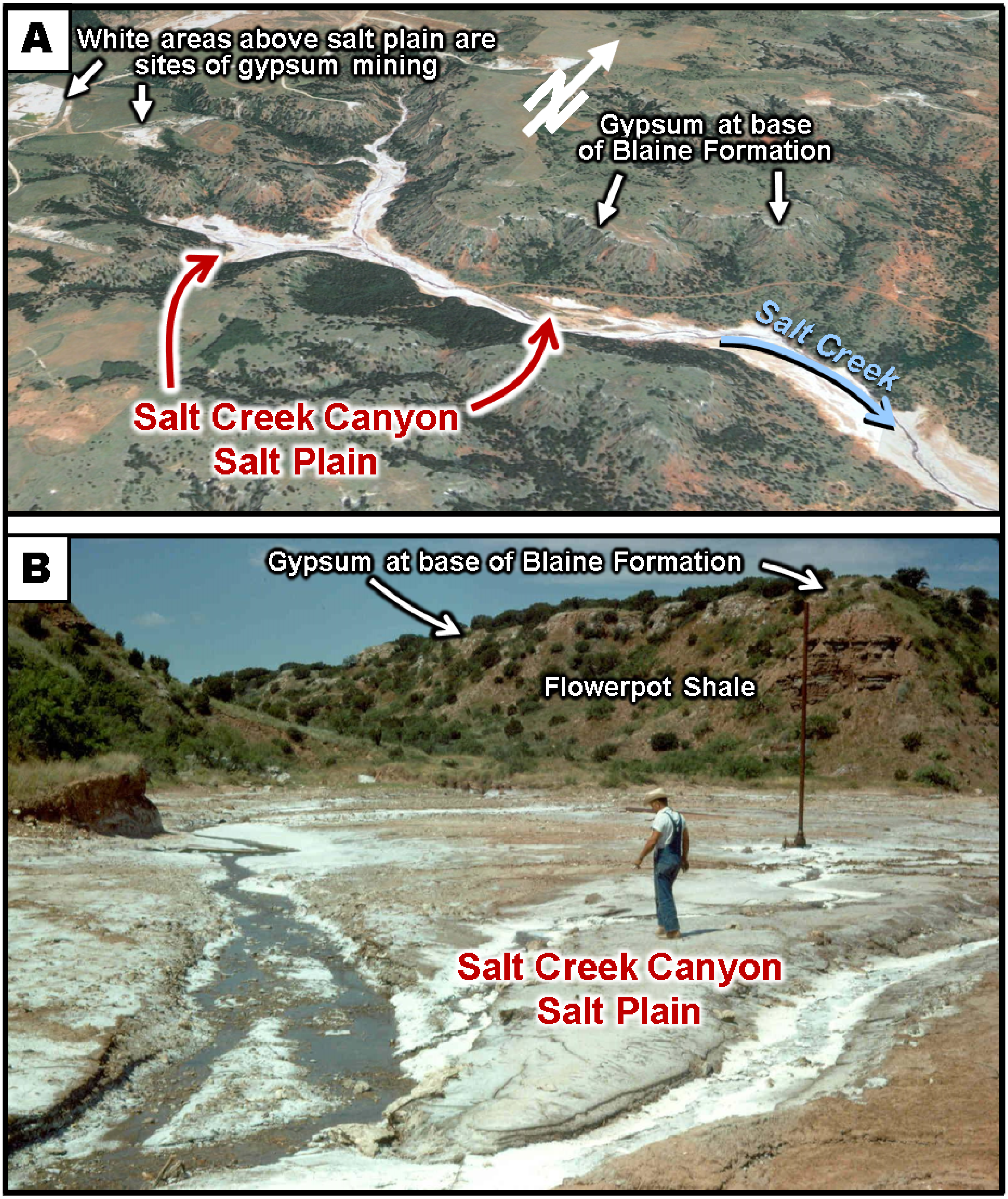


Figure 22. Views of Salt Creek Canyon Salt Plain in Blaine County, northwest Oklahoma (from Johnson, 2019b). A) Oblique Google Earth photo (dated October, 2006) of Salt Creek Canyon showing salt crust on the canyon floor and farther downstream. B) Ground view (looking west) of Salt Creek Canyon at confluence of streams merging from north and west canyons.

the Cimarron River for about 7 km upstream and downstream from the salt plain. Mr. Dunlap discovered, by talking with residents of the area, that the salt plain had once been more conspicuous and well developed, until a flood in the 1920s caused the river to shift its position and cut through the middle of the salt plain. Since then, it has been more difficult to recognize the area as a salt plain, probably because of repeated flush-outs by fresher water in the Cimarron River. The following description of Okeene Salt Plain is modified from an earlier report by Johnson (2019b).

Surface Geology

The principal outcropping rock unit in the area is the Cedar Hills Member, at the top of the Hennessey Shale. It consists of red-brown shale interbedded with light-gray and red-brown siltstone beds that commonly are 0.3 to 2 m thick. Total thickness of the Cedar Hills Member is about 60 m, but only the top 30 m is exposed within the map area. The Cedar Hills dips gently to the southwest at about 4 m/km (about 0.2º), based upon regional mapping of the underlying Wellington evaporites (Plate III in Jordan and Vosburg, 1963), and it grades laterally into part of the Upper Cimarron salt in subsurface southwest of

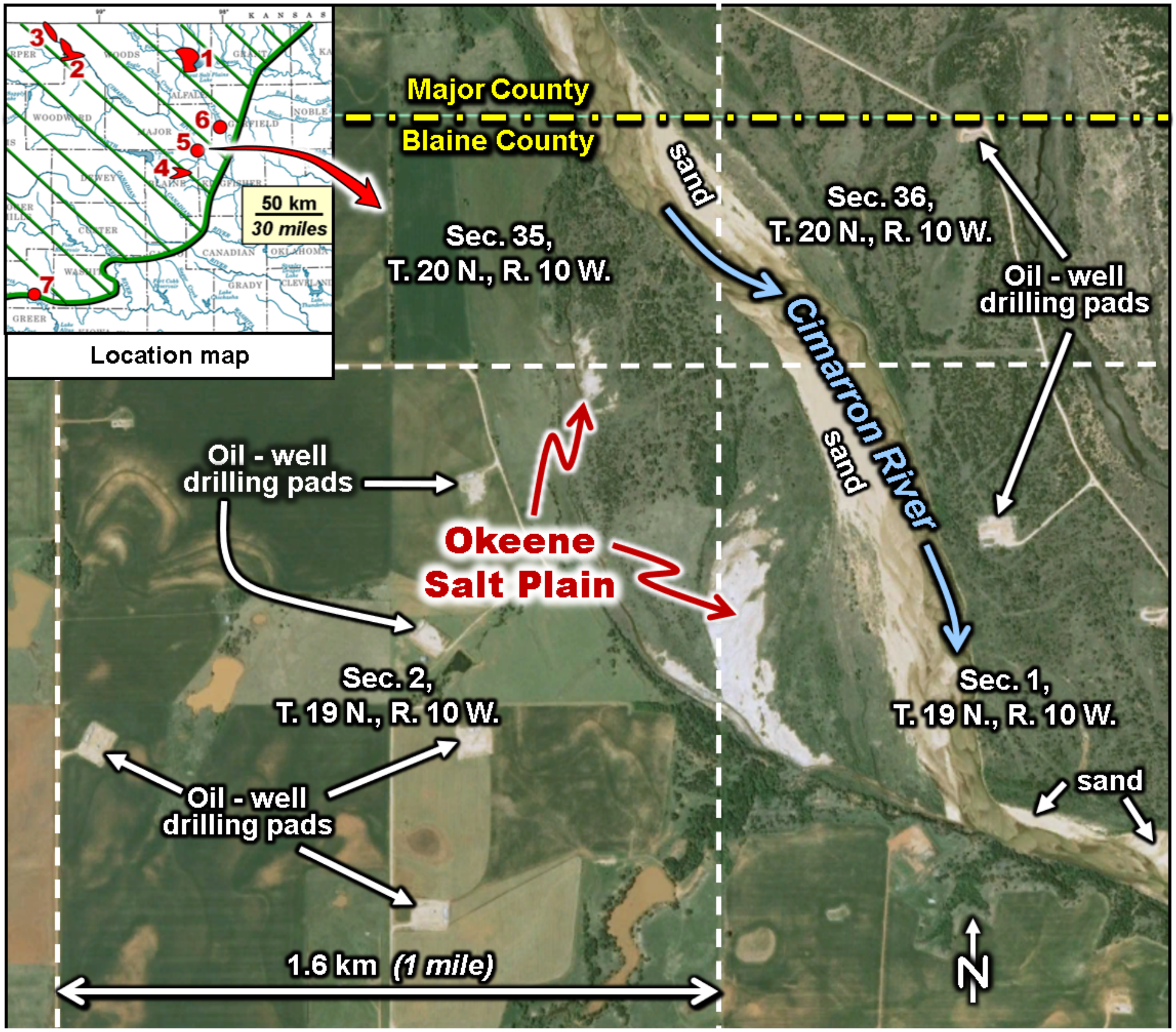


Figure 23. Aerial photo showing Okeene Salt Plain developed on Cimarron River alluvium in Blaine County, northwest Oklahoma (from Johnson, 2019b). Photo from Google Earth, dated September, 2010.

Okeene (Fig. 20). The lower part of the overlying Flowerpot Shale is also exposed in the study area, several kilometers southwest of the salt plain. No cores are known to have been drilled in the vicinity of the Okeene Salt Plain.

Alluvium in this area consists of sand, silt, clay, and gravel deposited by Cimarron River; it is as much as 12 m thick, based upon water-well information. Cimarron River alluvium rests upon shales and siltstones of the Cedar Hills Member in most of the study area, and elsewhere it is also in contact with terrace deposits. The terraces consist mostly of sand and gravel deposited along the former courses of Cimarron River. Terraces are generally 12 to 24 m thick and are continuous on the northeast side of the river, whereas southwest of the river they typically are much thinner and are scattered.

Subsurface Salt Deposits

Salt beds believed to be responsible for brine emission at and near Okeene Salt Plain are in the Upper Cimarron salt. This salt unit is present in shallow subsurface southwest of the salt plains (Fig. 20): Jordan and Vosburg (1963, Plate III therein) show that the nearest Upper Cimarron salt is about 15 km to the west. There are no cores of the Upper Cimarron salt there, and there is no detailed description of it any place in the study area. The Upper Cimarron salt probably is mostly salty shale with some interbeds of salt, based upon examination of geophysical logs of the unit in the region.

Thick salt beds in the Hutchinson Salt are nearly 500 m below the surface at the salt plains (Fig. 20), and thus are so deep that they clearly make no contribution to the flow of brine at the surface.

Brine Emissions

Brine coming to the surface in the Okeene Salt Plain area is seeping into alluvium from the bedrock, and is probably under hydrostatic pressure in the bedrock. Aquifers carrying brine to the base of alluvium are siltstone beds of the Cedar Hills Member of the Hennessey Formation, and they are laterally equivalent to the Upper Cimarron salt farther to the southwest (Fig. 20). Apparently, groundwater southwest of the river circulates down, where it dissolves the salt and becomes brine; the brine then moves up dip, and perhaps upward across fractures and joints, to emerge at the base of the alluvium. No brine was seen coming directly out of bedrock in this area.

Water-well drillers in the area (Wade and Charles Ewbank of Ewbank Drilling, Co., Fairview, OK) reported encountering brine at depths ranging from 20 m to as much as 90 m southwest of the river in the Orienta-Fairview-Isabella-Okeene region. Typically, the brine is 60 to 90 m below the surface in the west, and it is at successively shallower depths to the east, toward Cimarron River. Just west of Cimarron River, the brine is about 30 m below the surface. Wade and Charles Ewbank say that at some places they recover saltwater, and at other places they encounter a “zone of lost circulation,” which they assume is saltwater. This zone of lost circulation may be a highly porous bed in the Cedar Hills Member that is carrying brine to the east, or a zone of salt dissolution in the Upper Cimarron salt. There may be several aquifers carrying brine eastward to the surface; in this way, it is similar to movement of brine through aquifers at Great Salt Plains in Alfalfa County, as described above.

Dunlap (1975) measured the contribution of chloride to Cimarron River along a 13-km-long stretch of the river, which included Okeene Salt Plain: measurements extended from 6 km above the salt plain to the State Highway 51 bridge, located 7 km below the salt plain. Measurements made by him on a single day, or on consecutive days, along this part of the river showed the following increases in total chloride load: 1) on May 22-23, 1974, the load increased from 878 tpd (short tons per day) to 1,447 tpd (an increase of +569 tpd) from km-13 (13 km above the Highway 51 bridge) down to the bridge; 2) on August 1, 1974, the load increased from 49 tpd to 180 tpd (+131 tpd) from km-11 to km-2; and 3) on January 1, 1975, the load increased from 4,159 tpd to 6,234 tpd (+2,075 tpd) from km-11 to the bridge. Dunlap’s work clearly shows a major influx of brine in the 13-km stretch upstream from Highway 51 bridge. During these three measuring periods, the daily increase in chloride ranged from 131 to 2,075 short tons, and averaged 925 short tons (Table 1); these data indicate that the daily increase of salt ranged from 215 to 3,420 short tons, and averaged 1,525 short tons (chloride x 1.65 = salt).

Dunlap (1975) concluded that there was no significant influx of brine upstream from km-13; that is, from km-13 up to the US Highway 60 bridge at Orienta, a distance of about 30 km. Inasmuch as the Na/Cl ratio of Cimarron River water during these measurements was commonly 0.62 to 0.66, Dunlap properly concluded that this influx results from emission of natural brine formed by dissolution of salt, and not from oil-field brines (see section below on “Distinguishing salt-dissolution brines from oil-field brines”). It is certainly possible that more brine is entering Cimarron River downstream from Highway 51 bridge.

Water wells drilled into thick terrace deposits northeast of the river encountered freshwater in almost all cases. It is clear that groundwater in these terrace deposits results from precipitation on the northeast side of the river, and there is little or no seepage of brine from bedrock into these terraces. However, influx of natural saltwater into terrace deposits farther downstream near Dover is reported by the Oklahoma Water Resources Board (1975), but the source of these brines is unknown.

There is no record of historic or present production of salt from Okeene Salt Plain.

Drummond Flats Salt Plain

Drummond Flats Salt Plain, located about 16 km southwest of Enid in southwest Garfield County (Figs. 3, 24), is the most difficult salt plain in Oklahoma to describe for the following reasons: 1) it does not have conspicuous salt encrustations (salt flats) that are common at the other salt plains; 2) although it covers a large area, it has one of the smallest salt emissions of all the salt plains; 3) there are fewer published data available for this salt plain than for most of the others; 4) the subsurface source of the salt/brine is uncertain; 5) there are few chemical data available for the brines in the area; and 6) apparently these brines have the lowest salinity of any of the salt plains.

The main part of the Drummond Flats Salt Plain is within the Drummond Flats Wildlife Management Area (DFWMA) (Fig. 24), although some saline ground extends beyond its boundaries. Access to the DFWMA is limited, and is administered by the Oklahoma Department of Wildlife Conservation. Several public county roads do cross the area, but leaving these roads for examination of the land or water within the DFWMA requires a hunting/fishing license, a permit, or approval from the Wildlife Department. A number of birds and mammals use the area permanently or during migrations, and the main hunting season for this wildlife area is from October 1 through the end of February.

Surface Geology

Bedrock beneath Drummond Flats Salt Plain is the Permian Hennessey Formation, which consists of orange-brown to red-brown silty shale and siltstone (Stanley and others, 2002). The Hennessey dips gently to the southwest at about 3 m/km (about 0.15°), based upon regional structure mapping of the underlying Wellington evaporites (Plate III in Jordan and Vosburg, 1963). No cores of near-surface rocks are known to have been drilled in the vicinity of the salt plain.

Surficial material covering the bedrock is mapped as alluvium by Stanley and others (2002), and is described as unconsolidated sand, silt, clay, and gravel. Barclay (1952) characterized these sediments as lacustrine deposits that fill a depression formed by collapse of near-surface rocks due to dissolution of soluble layers in the underlying bedrock (he presumed the soluble layers to be salt, gypsum, or calcium carbonate). The depression was then filled by a combination of lacustrine deposits, slope wash, and sediment deposited by Turkey Creek during floods. The collapse and the resulting lacustrine/alluvial sediments created a large, flat, roughly oval surface area about 10 km long (north-south) and 5 km wide (east-west), most of which is within the DFWMA (Barclay, 1952).

Some of the Drummond, Miller, and Reinach soils, which are present in most of the DFWMA (Fig. 24B), are described as being saline, or containing soluble salts (Swafford, 1967): presumably he is referring to the presence of halite (NaCl). Some of these soils, or soil subtypes, are sufficiently saline that they cannot support crops. In particular, the "Miller-Slickspots complex" and the "Reinach-Slickspots complex" are characterized as being high in soluble salt and with a thin platy crust. Undoubtedly, these soils are saline due to salt-water brines rising from the underlying bedrock.

Subsurface Salt Deposits

Identity of salt beds that are the source of brines at Drummond Flats is uncertain. Bedrock in the area is the Hennessey Formation, and the Hennessey is equivalent to the Lower and Upper Cimarron salts farther west. However, the mapped eastern limit of each of these salt units is about 30 km to the west or northwest (Plate III, Map D, in Jordan and Vosburg, 1962; Plates 4 and 5 in Johnson, 1976). It is possible (and probably likely) that some outlying salt or salty shale in the Cimarron salts extends east of those limits to, or almost to, the Drummond Flats area, and is being dissolved to produce the brine emitted at Drummond Flats.

Specifically, the most likely salt source for brines in the area is the Upper Cimarron salt. Based upon subsurface studies farther west, and projecting the stratigraphic position of the Upper Cimarron salt into well logs at Drummond Flats, strata equivalent to this salt are about 30 to 90 m deep beneath the Flats, whereas strata equivalent to the Lower Cimarron salt are about 180 to 210 m deep beneath the Flats. It is possible that salt or salty strata equivalent to the Upper Cimarron salt were deposited

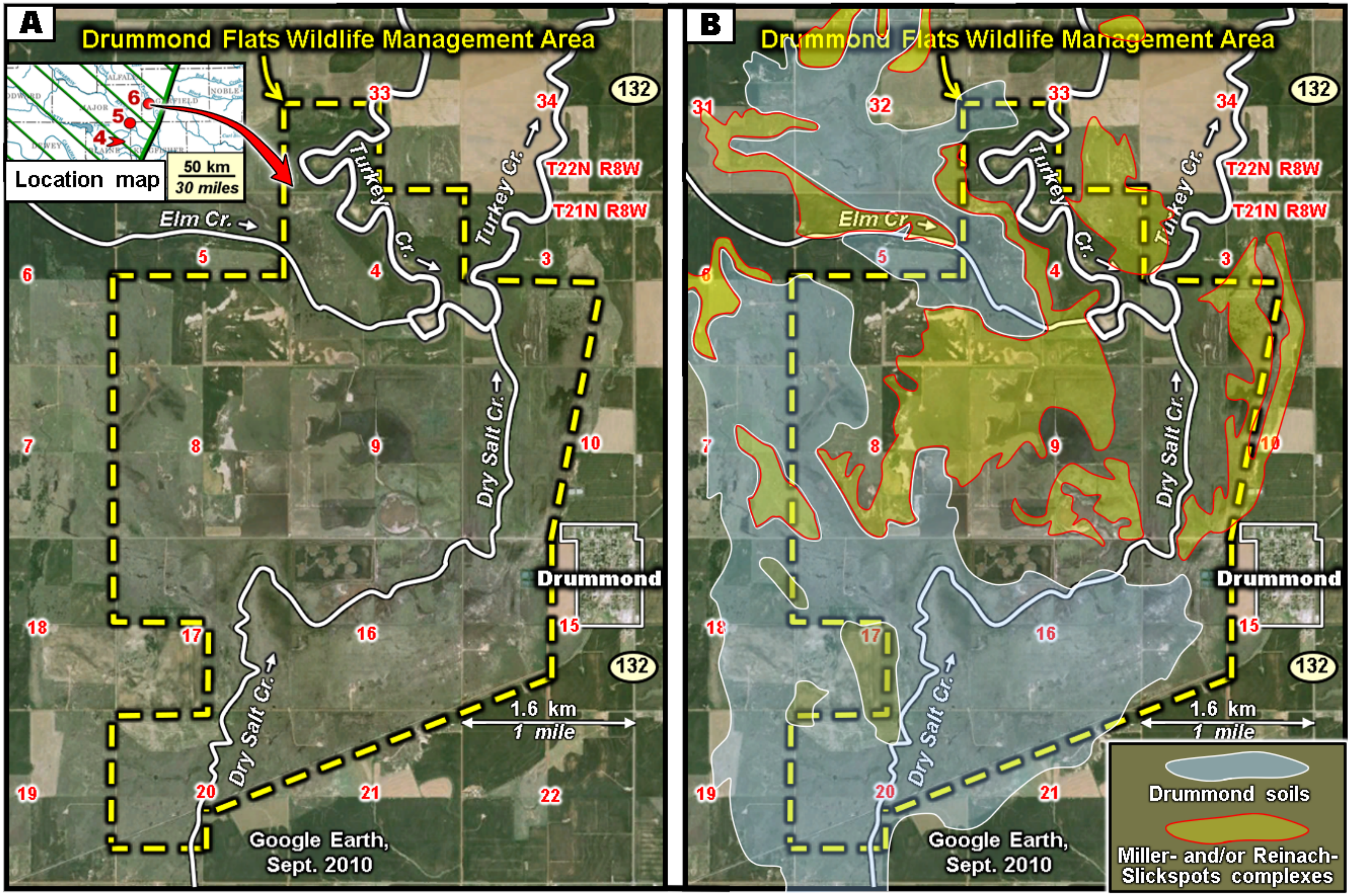


Figure 24. A) Aerial photo of Drummond Flats Wildlife Management Area in Garfield County, northwest Oklahoma. B) Same aerial photo on which is superposed the distribution of salty or saline soils, as described by Swafford (1967).

some 30 km east of its previously mapped eastern limit, and, being at a fairly shallow depth, it is now being dissolved to form brine that is seeping into the local soils. The only other salt unit in the area is the Hutchinson Salt Member at, or near, the top of the Wellington Formation (Fig. 9). The top of the Wellington is about 450 m deep at Drummond Flats, and is too deep to be a likely source of the surface brines.

Brine Emissions

Brine emissions in the Drummond Flats area are due to saltwater rising from the bedrock, entering the soils, and capillary action apparently bringing the brine to, or near, the land surface. Saltwater is reported at a depth of less than 1.5 m beneath much of the central portion of the DFWMA, and Dry Salt Creek alluvium occasionally contains a slight salt crust during dry weather (Ward, 1963a; US Department of Health, 1964). Salinity of the brines is not as high as at most other salt plains, and a salt crust rarely forms when the brine reaches the land surface: at other salt plains the brine is nearly saturated, so a salt crust forms quickly, with only minor evaporation. Although salt crusts are rare here, brine does enter the soils and then seeps into Turkey Creek and its tributaries, Elm Creek and Dry Salt Creek.

Evidence of brine entering the soils is found in the soil survey of Garfield County (Swafford, 1967): in particular, the three soils that are saline, or that contain soluble salts, are the Drummond soils, the Miller-Slickspots complex, and the Reinach-Slickspots complex. For Drummond soils, Swafford (1967) states: “Practically all their acreage is in native grasses or has been reseeded to salt-tolerant grasses. Salts injurious to most cultivated crops may be on the surface or throughout the profile.” For Miller-Slickspots complex soils, Swafford states: “The slickspots part [of the Miller clay soil] has a thin, light-colored surface layer over a massive, very slowly permeable clay that is high in salts. A crust forms because salinity causes breakdown of soil structure, and the soil particles then run together….A crust forms on the slickspots that limits intake of moisture.” For the Reinach-Slickspots complex, Swafford states: “These spots range from 6 to 50 feet [2 to 15 m] in diameter. The surface layer of the slickspots is light colored, high in soluble salt, and has a thin platy crust….In some locations, however, slight to moderate concentrations of salt crystals can be seen through the layers of this complex.” Presumably, Swafford’s description of salt or saline nature of these soils refers to halite (NaCl).

Distribution of these three saline soils covers more than half of the DFWMA (Fig. 24B). Swafford (1967) estimates the acreage of each soil in Garfield County as follows: Drummond soils, 1,540 hectares; Miller-Slickspots complex, 955 hectares; and Reinach-Slickspots complex, 669 hectares. The total of all three soils is 3,164 hectares, and the total acreage of the DFWMA is 1,884 hectares. These three soils are predominantly in and around DFWMA, and nearby parts of southwest Garfield County.

The only chemical data for the area result from the US Geological Survey (USGS) collecting water samples intermittently from 1951 to 1959 from Turkey Creek below Drummond Flats: the chlorides in Turkey Creek during that period ranged from a few ppm to 2,790 ppm (Ward, 1963a; US Department of Health, 1964). Ward (1963a) further reported that where Turkey Creek enters the Drummond Flats it has 77 ppm chlorides, and where it leaves the Flats it has 570 ppm chlorides. The chloride load, based on intermittent measurements from 1951 to 1959 by the USGS, averaged about 50 short tons per day, and the salt load averaged about 83 short tons per day (Table 1).

There is no record of any historic or present production of salt at Drummond Flats Salt Plain.

Boggy Creek Salt Plain

Boggy Creek Salt Plain is a relatively small salt plain located about 5 km south of the town of Carter, in Beckham County (Fig. 3, site 7), and it occupies parts of secs. 10, 11, 14, and 15, T. 8 N., R. 22 W. (Fig. 25). The brine springs are at and near the base of the Blaine Formation, and may also emit from the upper part of the Flowerpot Shale. A number of brine springs also bubble up from the surface of the salt plain. The amount of brine emitted is small, and it flows only about 0.6 km to North Fork Red River. The source of brine is dissolution of the Flowerpot salt, which is present in subsurface just to the north, in the Anadarko Basin. A brief description of the area is given by Gould (1905), while more-extensive discussions are by Ward (1963a) and US Department of Health (1964). The actual area of salt encrustation is about 6 hectares.

Surface Geology

Outcropping rocks in Boggy Creek are the Flowerpot Shale and overlying Blaine Formation (Fig. 25). The Flowerpot Shale is about 45 m thick in the area, whereas thickness of the Elm Fork Member, the lower half of the Blaine Formation, is about 34 m; the Haystack Gypsum

Bed, at the base of the Elm fork Member, is about 7.5 m thick (Scott and Ham, 1957). It is from the Haystack bed that most of the brine is emitted. Quaternary alluvial sand, silt, and clay associated with Boggy Creek mantle the Flowerpot Shale in much of the area.

A nearby core, the Carter core (Appendix C), recovered the entire 45 m of the Blaine Formation, and only 1 m of the uppermost Flowerpot Shale. The Carter core was drilled in the northeast corner of sec. 18, T. 8 N., R. 21 W., 5 km due east of Boggy Creek Salt Plain. Although no salt was recovered in this core, all the rock in the core had a salty taste from a depth of 26 m to the total depth of 59 m.

Boggy Creek Salt Plain is located about 1 to 2 km south of the fault–flexure zone that separates the Wichita Uplift from the Anadarko Basin. Permian strata at the salt plain

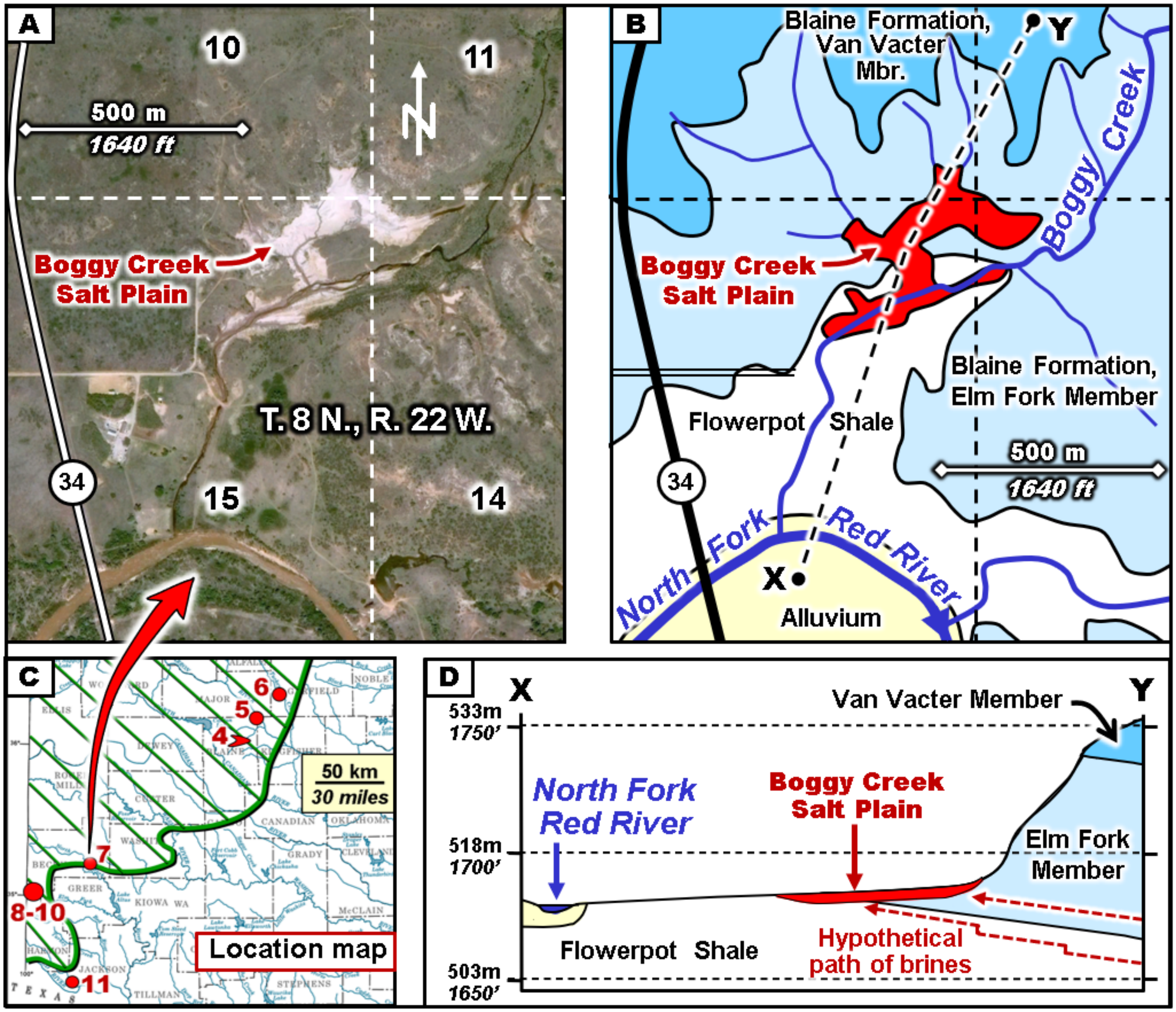


Figure 25. Aerial photo, geologic map, and cross section of Boggy Creek Salt Plain in Beckham County, southwest Oklahoma. A) Aerial photo from Google Earth (September, 2010); B) geologic map from Scott and Ham (1957); C) location map; D) cross section is interpreted from geologic and topographic maps. Brine, derived by dissolution of Flowerpot salt in deeper subsurface farther north, apparently flows through fissures and fractures in the Flowerpot Shale and cavities in the Haystack Gypsum, which is at the base of the Elm Fork Member of the Blaine Formation. True dip here is about 23 m/km (about 120 ft/mile), or about 1 degree, to the north.

dip to the NNE, towards the Anadarko Basin, at a rate of about 30 m/km (about 1.5º).

Subsurface Salt Deposits

The source of brine at Boggy Creek is dissolution of the Flowerpot salt, which is present in subsurface just 1or 2 km to the north where the salt is about 12 m thick and at a depth of about 38 m (Plate III in Jordan and Vosburg, 1963). A bit farther north, deeper in the Anadarko Basin, those authors show the Flowerpot salt is about 30 m thick and at depths of 270 to 335 m. The Flowerpot salt is not of high purity and massive, but instead consists of a number of impure salt layers interbedded with salty shale. No cores of the salt are available in this area, but elsewhere, near the Salton Salt Plain (Chaney core in northern Harmon County, Appendix B), it is mainly colorless, with many impurities of green-gray and red-brown shale and with scattered layers and crystals of gypsum within the salt layers; individual salt beds there are 15 to 91 cm thick, and red-brown and green-gray shale interbeds are 9 to 219 cm thick.

Brine Emissions and Salt Production

Dissolution of Flowerpot salt in subsurface just to the north produces brine that seeps to the surface at and near the base of the Haystack Gypsum Bed of the Blaine Formation, and also from the upper part of the Flowerpot Shale (Fig. 25). Some of the surface springs flow directly from the Permian bedrock, and some of the springs bubble up from alluvium on the salt plain's surface (Gould, 1905; US Department of Health, 1964). Gould (1905) observed a total of 20 or more springs at the site, and US Department of Health (1964) noted that around some of the springs the salt crust attains a thickness of about 7.5 to 10 cm.

According to US Department of Health (1964), salinity of the water from one of the larger springs was 64,000 ppm chloride (105,600 ppm salt), although near where Boggy Creek enters North Fork Red River, the creek water was diluted to only 1,650 ppm chloride: some of the nearby springs away from the salt plain emit water of relatively good quality.

It is estimated that the daily yield of Boggy Creek Salt Plain is about 20 short tons of chloride, or about 33 short tons of salt (Table 1).

Gould (1905) reported that salt had been manufactured from the brine at Boggy Creek for many years; he noted that the brine contained a lot of dissolved gypsum, but not enough to make it unfit for use in making and using salt. Apparently, production ceased not too long after Gould's visit, and there is no production of salt here at this time.

Salton (Chaney), Robinson, and Kiser Salt Plains

Elm Fork Red River contains three principal brine-emission areas in northern Harmon County (Fig. 3, sites 8–10), and the brine is emitted near the mouths of three canyons: Salton (also called "Chaney"), Robinson, and Kiser Canyons, on the south side of Elm Fork (Figs. 26, 27, 28). Each of the three salt plains has an area of between 1 and 4 hectares.

Descriptions of these salt plains are given in Ward (1962, 1963a, b) and US Department of Health (1964). A brief review of the general geology, brine composition, and potential for solar evaporation of the brine to produce commercial salt at these salt plains is also given by Johnson and Denison (1973); they note that brine is produced from dissolution cavities in salt at depths of 9 to 12 m, and include a generalized cross section through the Salton Salt Plain showing the inferred subsurface distribution of salt and its relation to the brine springs and salt plains (Fig. 26). In shallow subsurface, and especially farther south in the Hollis Basin, the upper part of the Flowerpot contains beds of impure salt that are mixed with varying amounts of clay or shale. Additional descriptions of these salt plains were published by Johnson (1981, 2019a). There has been intermittent commercial use of these brines. In USACE studies, the salt plains on Elm Fork Red River are referred to as "Area VI."

Surface Geology

Outcropping rocks at the three salt plains are the Flowerpot Shale and overlying Blaine Formation (Figs. 26, 28). All the brine is being emitted from the Flowerpot, which is mainly red-brown shale with thin interbeds of gray shale, siltstone, and gypsum. The formation is at least 60 m thick in the area, but it's base is indistinguishable from the underlying Hennessey Shale (Johnson, 1967). The upper part of the Flowerpot is well-exposed in bluffs along the south side of Elm Fork (Fig. 27), and about 20 m of the formation can be examined along State Highway 30, just east of Kiser Salt Plain (Edwards, 1958). In addition, the Chaney core (Appendix B), drilled about 2 km SSW of the Salton Salt Plain, provides excellent information on the Flowerpot and Blaine Formations in the area.

Two gypsum beds in the upper part of the Flowerpot are well-exposed in the bluffs, and also in the Highway-30 roadcuts. In these roadcuts, the Kiser Gypsum Bed, lo-

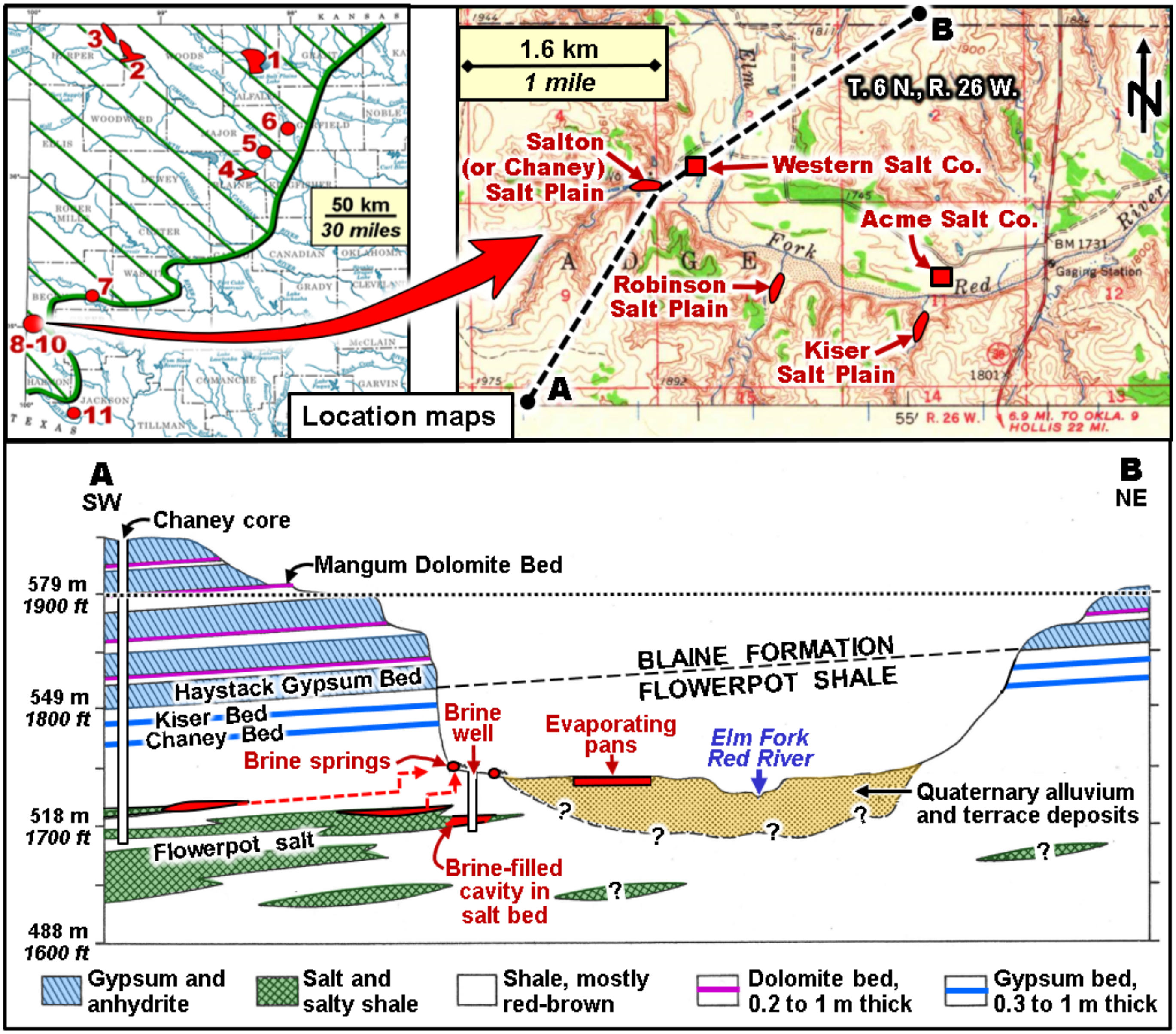


Figure 26. Location maps and cross section showing geology of salt plains on Elm Fork Red River in Harmon County, southwestern Oklahoma (modified from Johnson and Denison, 1973). Flowerpot salt is dissolved to produce brine springs at the Salton (or Chaney), Robinson, and Kiser Salt Plains. In 1973, two companies (Western Salt Co. and Acme Salt Co.) were producing salt in solar-evaporation pans on the alluvial plain of Elm Fork Red River.

cated about 4.5 m below the top of the formation, is 0.6 m of greenish-white, shaley gypsum: another 4 m lower in the Flowerpot is the Chaney Gypsum Bed, which is 0.9 m of white, fine-crystalline, massive gypsum. The Chaney Bed is the most conspicuous marker bed in the upper Flowerpot in the area. In the Chaney core, the Kiser Bed is 2.1 m below the Blaine Formation, and the Chaney Bed is 7.7 m below the Blaine (Appendix B).

Overlying the Flowerpot is the Blaine Formation, which consists of white gypsum beds alternating with layers of red-brown shale and thin layers of green-gray shale and dolomite. The Blaine here is about 50 to 55 m thick and comprises nine main gypsum beds, each 2 to 6 m thick, and most of them are underlain by dolomite beds 0.2 to 0.9 m thick. Thickness of the various gypsum beds is a bit variable inasmuch as each of them is at least somewhat dissolved, locally, and karst features are conspicuous just south of each of the salt plains. The gypsum at the base of the Blaine is the Haystack Gypsum Bed, which is about 6 m thick and, in the Chaney core, contains about 1.3 m of dolomite in the middle of the gypsum.

The Dog Creek Shale overlies the Blaine Formation,

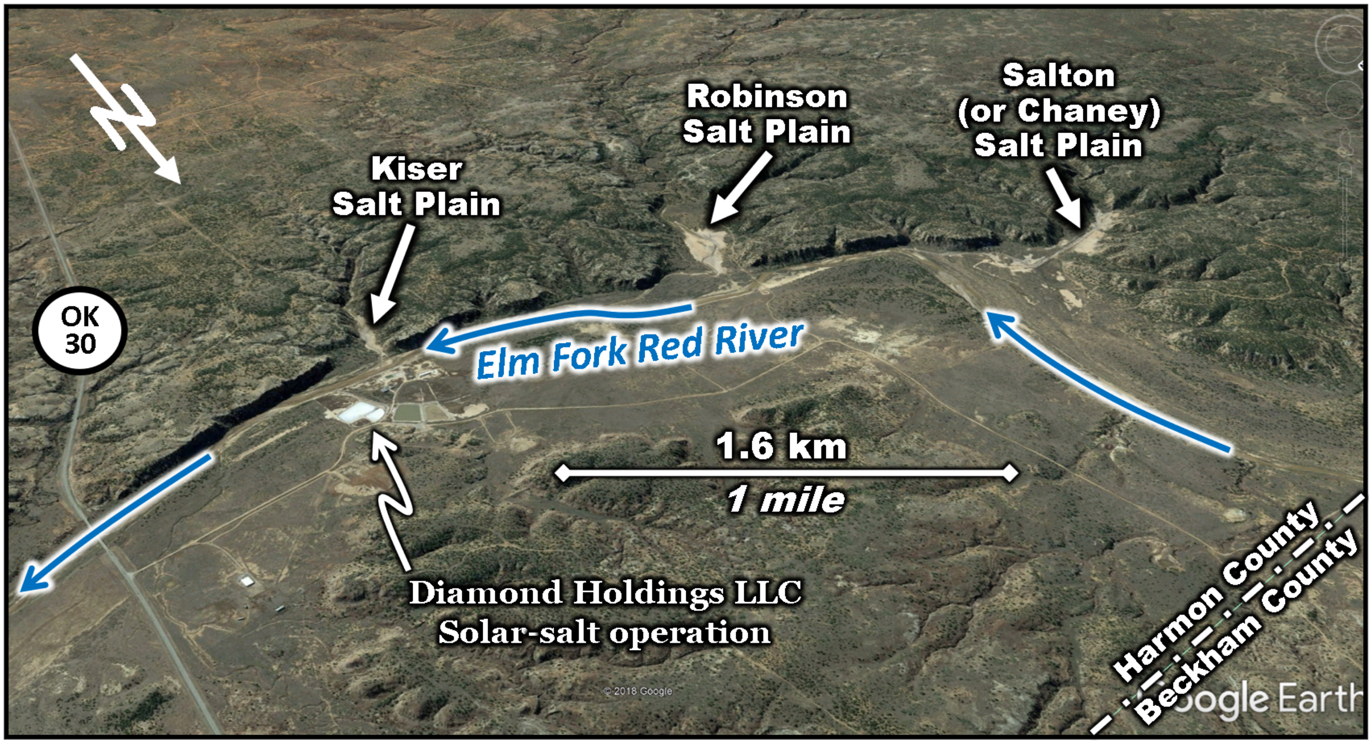


Figure 27. Oblique aerial view of three salt plains on Elm Fork Red River in Harmon County, southwestern Oklahoma (modified from Johnson, 2019a). Aerial photo from Google Earth (dated November, 2014), looking to southwest.

and in outcrops it consists of about 30 m of red-brown shale, with two beds of gypsum in the lower part of the formation. And above the Dog Creek Shale is the Whitehorse Group, comprising unconsolidated (or loosely cemented) orange-brown to red-brown sandstone and siltstone.

Quaternary sand, silt, clay, and gravel are the youngest sediments at and near the salt plains. They comprise alluvium along the flood plains of Elm Fork Red River and the floor of the three canyons containing the salt plains. The thickness of these alluvial deposits is unknown, but may be up to 15 m thick in Elm Fork, and probably no more than 1 or 2 m thick in the canyons.

Permian strata in the area dip gently to the south at about 20 to 30 m/km (a little over 1°). This is due to strata dipping from the Wichita Uplift (on the north) toward the Hollis Basin (to the south) (Johnson, 2019d).

Subsurface Salt Deposits

Brine has been encountered in solution cavities within salt beds at depths of 9 to 12 m beneath Salton and Kiser Salt Plains: Ward (1962) noted that test-hole 7 encountered salt 9 m beneath Salton Salt Plain. Additional subsurface data are available for local salt deposits because of the Chaney core (Appendix B) and a petroleum test, the Ran Ricks, Jr., Avery A #8, drilled about 10 km south of the salt plains (Figs. 28, 29). The Chaney core recovered about 37 m of the middle and lower Blaine Formation, underlain first by almost 25 m of Flowerpot Shale (from which salt has undoubtedly been dissolved), and then the top 6.7 m of the remaining Flowerpot salt. The Avery well penetrated the entire Flowerpot salt, and recorded these strata on a series of geophysical logs.

In the Avery well, the Flowerpot salt is 53 m thick, and essentially it extends up to the base of the Blaine Formation (Fig. 29). In the geophysical logs of this well, individual salt beds are 0.6 to 3 m thick, and shale interbeds are 0.6 to 5.2 m thick. The cumulative thickness of salt beds in the Flowerpot salt is about 15 m, and thus salt beds make up about 28% of the Flowerpot salt in the well. Salt beds probably are not high-purity salt, but are more likely to be impure salt layers, similar to those described (below) in the Chaney core.

In the Chaney core, located just 2 km SSW of the Salton (Chaney) Salt Plain, the Flowerpot salt is mainly colorless, but it contains many impurities of green-gray and red-brown shale, along with scattered layers and crystals of gypsum within the salt layers (Appendix B). Individual salt beds are 15 to 91 cm thick, and the red-brown and green-gray shale interbeds are 9 to 219 cm thick. Although the top of the Flowerpot salt (at a depth of 62 m) is 24.6 m below the top of the Flowerpot Shale,

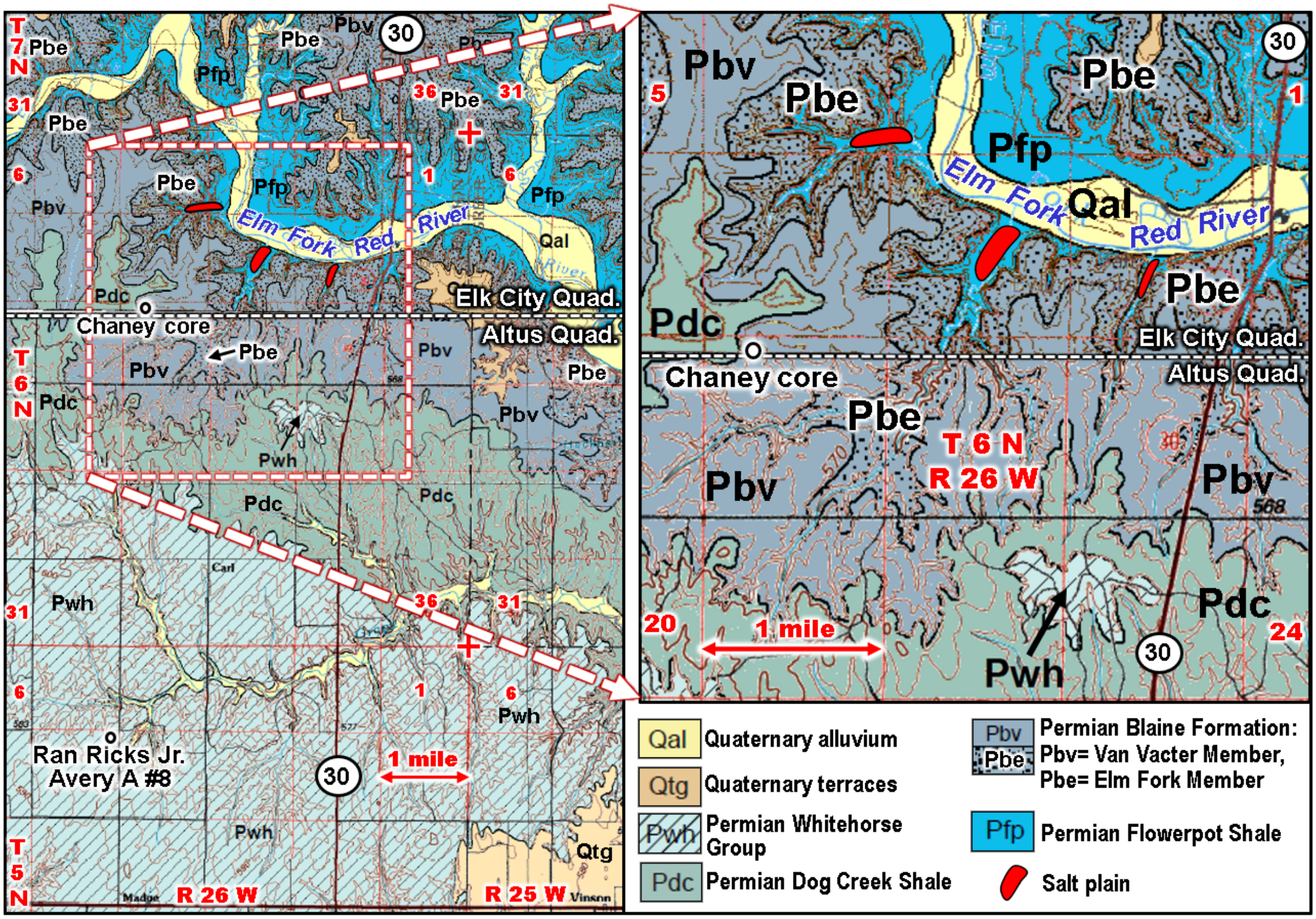


Figure 28. Geologic map of salt-plains area on Elm Fork Red River in northern Harmon County, Oklahoma. Consists of two geologic maps spliced together: north part is from Elk City Quadrangle (Johnson and others, 2003); south part is from Altus Quadrangle (Stanley and Miller, 2004). Also shown are locations of the Chaney core and the Ran Ricks Jr., Avery A #8 petroleum test.

the overlying 12.5 m of the Flowerpot Shale has a salty taste. Clearly, there originally were salt beds in the upper part of the Flowerpot Shale, as can be seen in the Avery well, but they have been dissolved in the Chaney core and in outcrops around the salt plains.

Brine Emissions and Salt Production

Three sets of analyses have been reported for the brines emitted from the salt plains on Elm Fork Red River (Tables 2, 10, 11). A total of six samples were collected from the three salt plains: two samples were collected in Salton Canyon, one sample in Robinson Canyon, and three samples in Kiser Canyon. Four of the samples were tested for chloride: the range is 184,000 to 190,000 ppm, and the average is 186,000 ppm. Six of the samples were tested for salt (Na+Cl): the range is 296,500 to 333,643 ppm, and the average is 310,931 ppm. These are the second highest reported values for chloride and for salt at all of the salt plains in western Oklahoma: they are exceeded only by one analysis of brine at Big Salt Plain (Table 6).

Natural salt springs are emitted from Flowerpot strata into alluvial sand and silt that covers the floors of each of the canyons, and a few springs are flowing from the Flowerpot Shale near the base of the canyon walls. Brine is most likely moving through joints and fractures in the shale, and through mildly permeable zones (siltstones?) within the Flowerpot (similar to Fig. 6). Inasmuch as wells drilled in the canyon floors have penetrated solution cavities within the shallow salt beds, it is clear that brine is also flowing through these karst features. Brine in the cavities is under artesian conditions, with a piezometric surface up to several meters above the canyon floors in some places. Therefore, wells that penetrate these cavities at depths of 9 to 12 m are able to produce high-salinity brine from flowing wells, and the rate of production is about 300 to 400 l/min per well (Johnson

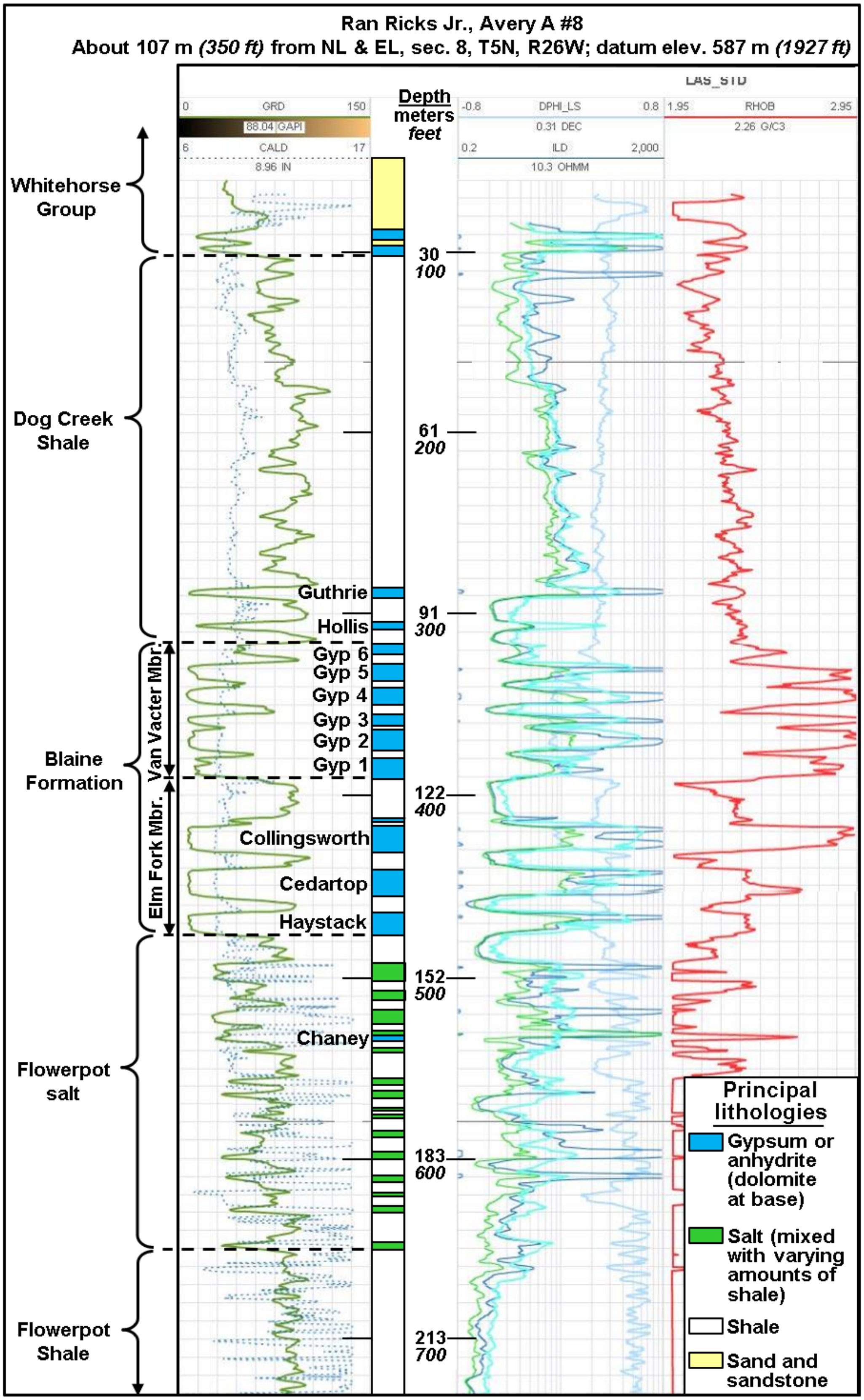
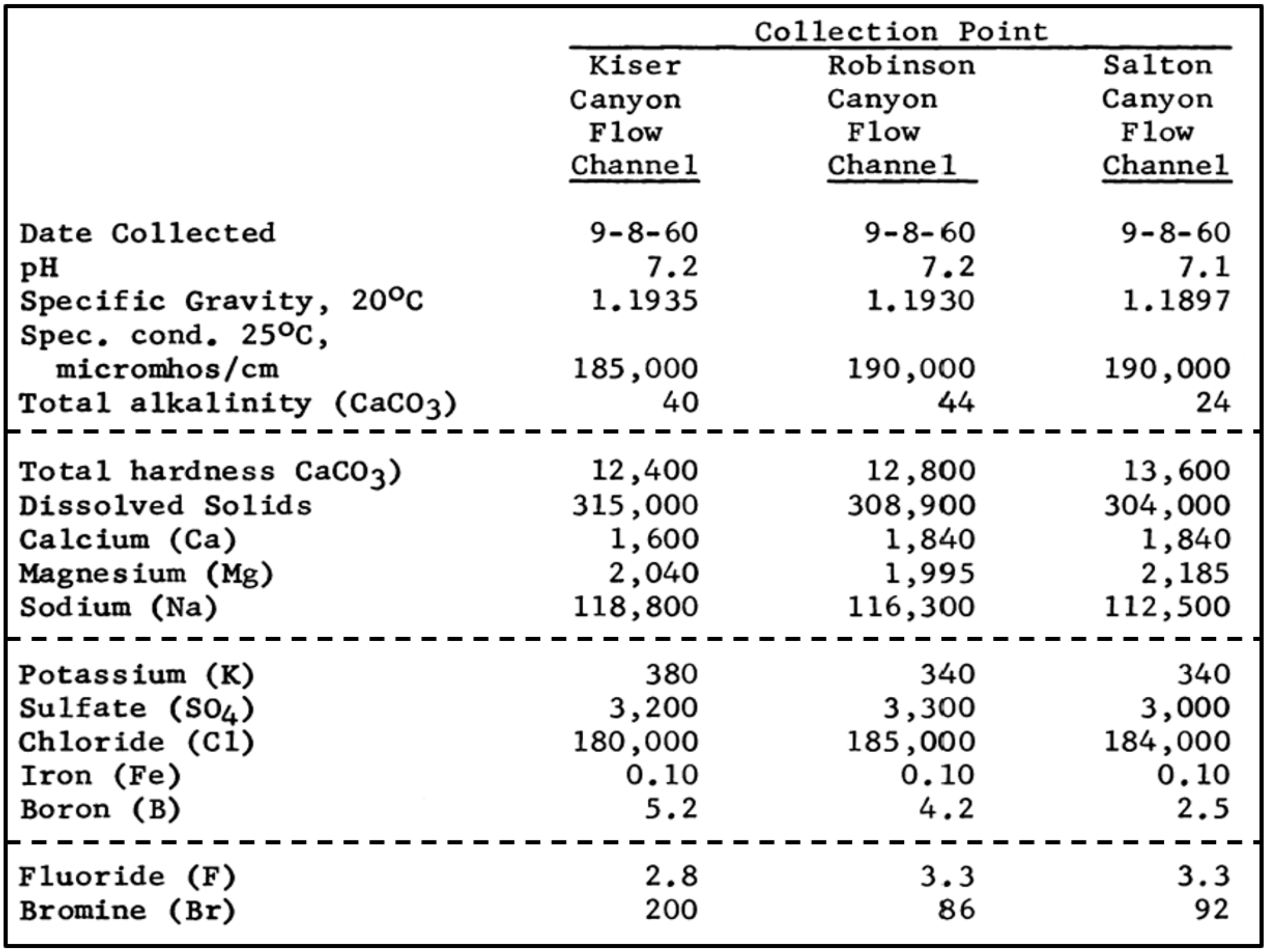


Figure 29. Geophysical logs and interpretive lithology of Ran Ricks Jr., Avery A #8 well, located in northern Harmon County, about 10 km south of salt plains on Elm Fork Red River. Appreciation is expressed to TGS, the Houston-based company with the largest online well-log database, for access to these geophysical logs.



	Collection Point		
	Kiser Canyon Flow Channel	Robinson Canyon Flow Channel	Salton Canyon Flow Channel
Date Collected	9-8-60	9-8-60	9-8-60
pH	7.2	7.2	7.1
Specific Gravity, 20°C	1.1935	1.1930	1.1897
Spec. cond. 25°C, micromhos/cm	185,000	190,000	190,000
Total alkalinity ($CaCO_3$)	40	44	24
Total hardness $CaCO_3$)	12,400	12,800	13,600
Dissolved Solids	315,000	308,900	304,000
Calcium (Ca)	1,600	1,840	1,840
Magnesium (Mg)	2,040	1,995	2,185
Sodium (Na)	118,800	116,300	112,500
Potassium (K)	380	340	340
Sulfate (SO_4)	3,200	3,300	3,000
Chloride (Cl)	180,000	185,000	184,000
Iron (Fe)	0.10	0.10	0.10
Boron (B)	5.2	4.2	2.5
Fluoride (F)	2.8	3.3	3.3
Bromine (Br)	200	86	92

Table 10. Analyses of natural brines from Kiser, Robinson, and Salton (Chaney) Salt Plains in mg/l, except pH (unless otherwise indicated). From US Department of Health (1964).

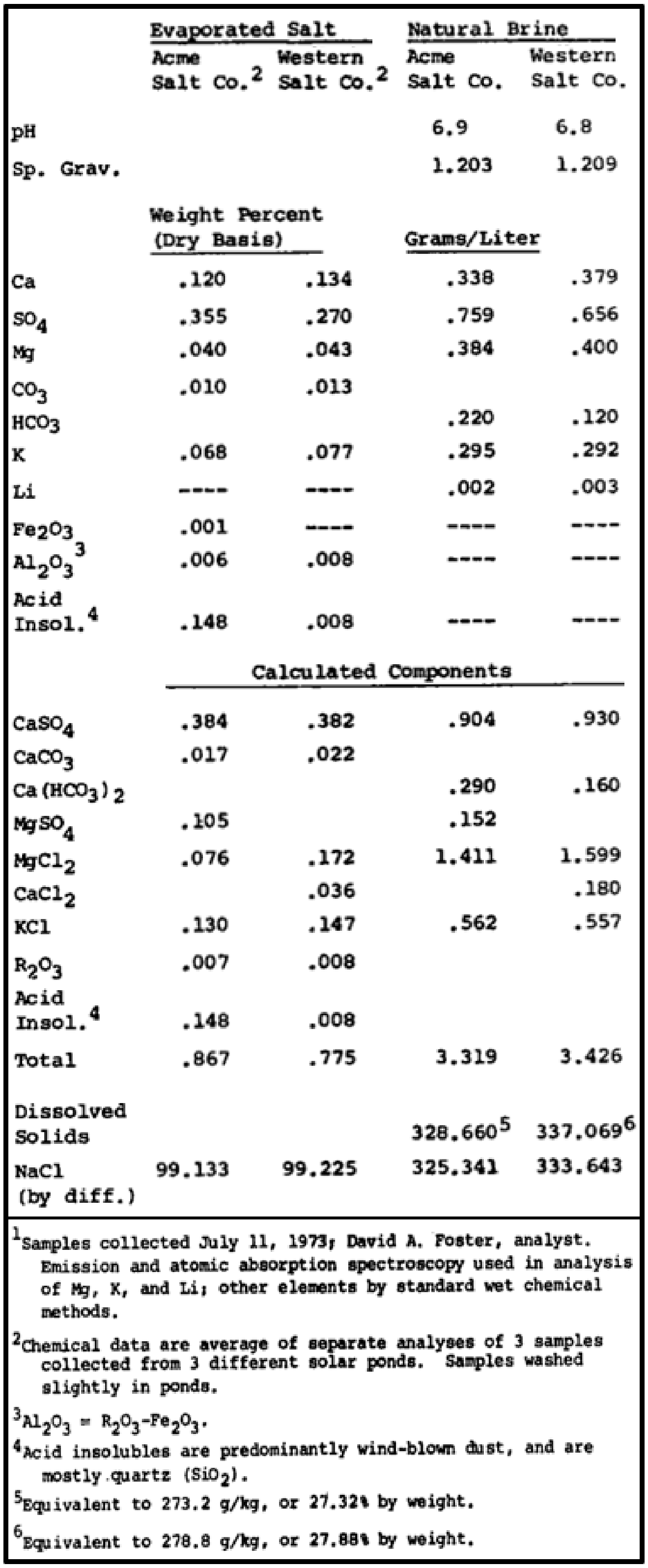
and Denison, 1973).

Salinity of brines from wells drilled in Salton and Kiser Salt Plains were reported by Johnson and Denison (1973) (Table 11). Both brines were saturated with respect to salt, and they contained 325 and 333 g/l NaCl: this represents almost 99% of the dissolved solids in the brine. Solar salts produced from these brines were 99.1 and 99.2% NaCl. Brine analyzed by Ward (1963a) showed that the springs had a chloride content that ranged up to 190,000 ppm (Table 2).

Although the amount of salt emitted from the salt plains varies, it is estimated that daily emissions from all three salt plains combined are about 250 to 300 tons of chloride, or 410 to 490 short tons of salt (Table 1).

Groundwater that dissolves the salt and emerges as brine travels a relatively short distance. Tritium analysis of brine from a spring in Salton Canyon suggests that the age of the water is less than 20 years (Ward, 1963a). Ward reasons that if the water had traveled a great distance before reaching Salton Canyon, its age would be greater than that shown by the tritium. The abundant karst features in the outcropping Blaine Formation to the south and southwest of Salton Canyon provide ample pathways for precipitation to enter the groundwater system locally and migrate down to the Flowerpot salt. Outcrops of the karstic Blaine Formation extend about 5 km to the south of Salton Canyon (Fig. 28), and thus the flow path for this salt-dissolving system is probably no more than about 5 km. Ward (1963b) presented a map of the area south of Elm Fork Red River showing that the piezometric surface dips at rates of 10 to 25 m/km (0.5° to 1.3°) to the north and northeast, towards the river and the salt plains.

Salt and brine have been produced commercially from one or more of these salt plains for a long time. Gould (1905, 1910) stated that a local salt-manufacturing industry had flourished for 20 years, and that in some years



	Evaporated Salt		Natural Brine	
	Acme Salt Co.[2]	Western Salt Co.[2]	Acme Salt Co.	Western Salt Co.
pH			6.9	6.8
Sp. Grav.			1.203	1.209
	Weight Percent (Dry Basis)		Grams/Liter	
Ca	.120	.134	.338	.379
SO_4	.355	.270	.759	.656
Mg	.040	.043	.384	.400
CO_3	.010	.013		
HCO_3			.220	.120
K	.068	.077	.295	.292
Li	----	----	.002	.003
Fe_2O_3	.001	----	----	----
Al_2O_3[3]	.006	.008	----	----
Acid Insol.[4]	.148	.008	----	----
	Calculated Components			
$CaSO_4$	.384	.382	.904	.930
$CaCO_3$	.017	.022		
$Ca(HCO_3)_2$			.290	.160
$MgSO_4$	.105		.152	
$MgCl_2$	.076	.172	1.411	1.599
$CaCl_2$		.036		.180
KCl	.130	.147	.562	.557
R_2O_3	.007	.008		
Acid Insol.[4]	.148	.008		
Total	.867	.775	3.319	3.426
Dissolved Solids			328.660[5]	337.069[6]
NaCl (by diff.)	99.133	99.225	325.341	333.643

[1] Samples collected July 11, 1973; David A. Foster, analyst. Emission and atomic absorption spectroscopy used in analysis of Mg, K, and Li; other elements by standard wet chemical methods.

[2] Chemical data are average of separate analyses of 3 samples collected from 3 different solar ponds. Samples washed slightly in ponds.

[3] $Al_2O_3 = R_2O_3 - Fe_2O_3$.

[4] Acid insolubles are predominantly wind-blown dust, and are mostly quartz (SiO_2).

[5] Equivalent to 273.2 g/kg, or 27.32% by weight.

[6] Equivalent to 278.8 g/kg, or 27.88% by weight.

Table 11. Analyses of solar salt and natural brines from Kiser (Acme Salt Co.) and Salton (Western Salt Co.) Salt Plains. From Johnson and Denison (1973).

as much as 300 short tons of salt had been produced at Salton and at Kiser Salt Plain. Inasmuch as early production led to depletion of the local timber supply (wood was used as fuel to boil brine and precipitate the salt), the operators by then were largely using solar evaporation of brine in earthen pans. Snider (1913) noted that salt had been produced for several years before his visit also.

US Department of Health (1964) reported that at that time (about 1964) the Salton Salt Co. was producing solar salt from Salton Canyon. The company had a production area of about 3.7 hectares, and production capacity was about 15,000 short tons of salt per year. The brine had a chloride content of about 190,000 ppm, and yielded about 3 pounds of salt per gallon of brine (about 0.36 kg of salt per liter of brine).

Production of salt continued for many years, and Johnson and Denison (1973) reported that two companies had constructed large evaporating pans to produce high-quality solar salt (Table 11). Western Salt Co. was then working brine from Salton Canyon, and Acme Salt Co. was using brine from Kiser Canyon; each company had set up about 2.4 hectares of evaporating pans on the Elm Fork alluvial plain, outside of the canyons, and each company had the potential of producing about 6,000 short tons of salt per year. In addition to producing solar salt, the companies also sold brine to the petroleum industry to be used in salt-based drilling fluids for wells penetrating salt beds in the nearby Anadarko and Hollis Basins. At present, Diamond Holdings LLC is operating a solar-salt operation using brine from Kiser Canyon, but has reported only limited salt production over the past several years.

Sandy Creek Salt Plain

Sandy Creek Salt Plain, previously referred to as “Lebos Creek Salt Plain,” is a relatively small brine-emission area about 6 km south of the town of Eldorado, in Jackson County (Fig. 3, site 11). Salt emissions here are from the Blaine Formation and are described briefly by Ward (1963a) and US Department of Health (1964). Although groundwater seepage occurs along the lower 16 to 19 km of Sandy Creek, before it enters Prairie Dog Town Fork Red River, the main visible area of brine seepage is from several small sites in secs. 5 and 6, T. 2 S., R. 23 W. (US. Department of Health, 1964) (Fig. 30). The combined area of the four small salt flats shown on Figure 30 is about 1.6 hectares. Snider (1913) also mentions another small salt plain about 1.5 km north of the one in section 6, but it does not show up clearly in any of the Google Earth

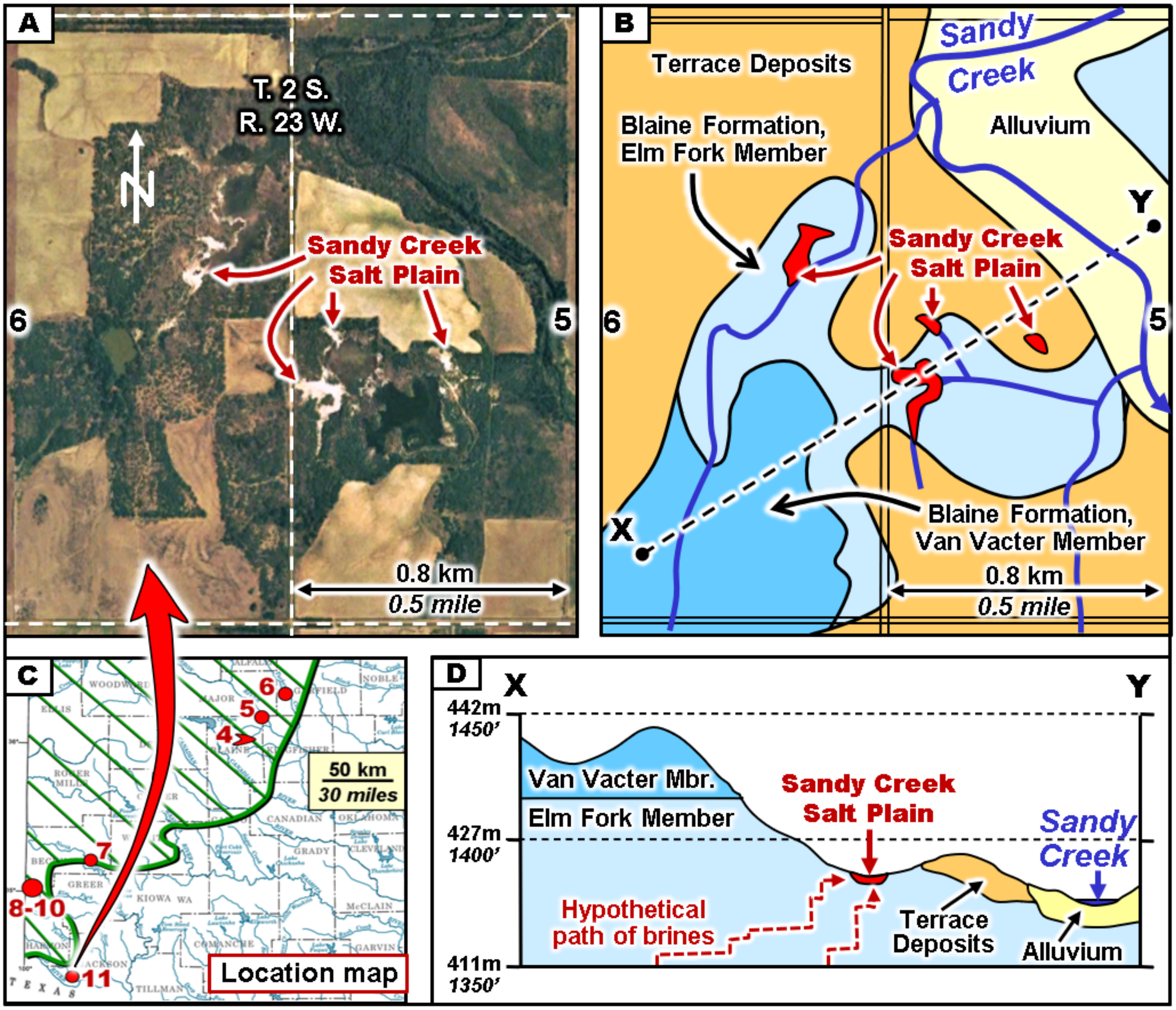


Figure 30. Aerial photo, geologic map, and cross section of Sandy Creek Salt Plain in Jackson County, southwestern Oklahoma. A) Aerial photo from Google Earth (October, 2005); B) geologic map from unpublished map of southwestern Oklahoma; C) location map; D) cross section interpreted from geologic and topographic maps. Brine, derived by dissolution of Flowerpot salt in deeper subsurface farther to the north or northwest, probably comes to the surface through cavities in gypsum and/or dolomite beds of the Elm Fork Member of the Blaine Formation. Strata are essentially horizontal.

photos of the area and is not included in this discussion. The source of the brine for the salt plain is dissolution of Flowerpot salt, which is present to the north and northwest in the Hollis Basin.

Surface Geology

Bedrock in the area is the Blaine Formation, and brine is seeping from the upper part of the Elm Fork Member—specifically, the Collingsworth Gypsum Bed, or the shale that immediately overlies the Collingsworth. Much of the area is mantled with Quaternary terrace deposits, and thus details of the local geology are somewhat obscure. Based upon borehole data from the area, the Collingsworth Gypsum is about 5 m thick, and the overlying shale is about 12 m thick. Above this shale is the Mangum Dolomite Bed, at the base of the Van Vacter Member of the Blaine Formation. Below the Collingsworth Bed are two gypsums, the Cedartop and Haystack Gypsum Beds (in descending order), and then the top of the Flowerpot Shale, which is about 20 m below the salt plain. The

Blaine Formation here is essentially flat lying, and there are no known faults, flexures, or dissolution-collapse features (Johnson, 2019d).

Subsurface Salt Deposits

The only salt present in the Hollis Basin, which embraces the Sandy Creek Salt Plain, is the Flowerpot salt. This salt unit is known to be nearly 25 to almost 50 m thick about 40 km NNW of the salt plain (Plate 6 in Johnson, 1976), and is 53 m thick a bit farther north, in northern Harmon County (Fig. 29). It is likely that there are residual patches or masses of this salt farther to the south-southeast of known occurrences, and these patches/masses are now being dissolved to supply brine to Sandy Creek Salt Plain. Although Ward (1963a) reports "salt" in two wells at depths of 30 and 45 m below the surface in the north part of T. 1 N., R., 24 W., about 20 km north of the salt plain (Plate 3 in Ward, 1963a), strata at these depths in that area are in the Blaine Formation. I have examined numerous cores and logs of wells drilled in the Blaine Formation in the Hollis Basin, and never saw salt, or reference to beds of salt in driller's logs, in any of the Blaine strata (Johnson, 2019d, cross sections B–B' and C–C'): therefore, it is unlikely that the Blaine contains salt in these wells, and it probably was saltwater (that may have evaporated to salt crystals upon reaching the surface?).

Saltwater is present in subsurface, based on wells drilled in the vicinity of Sandy Creek Salt Plain (Ward, 1963a). One well, located 1.6 km west of the salt plain, encountered saltwater at a depth of 26 m, and another well, about 3 km southwest of the salt plain, found saltwater at a depth of 36 m. Ward also reported that several other wells in the area encountered salt or saltwater at depths of less than 60 m below the land surface.

Brine Emissions

Undoubtedly, saltwater in the nearby wells, mentioned above, was derived by dissolution of the Flowerpot salt farther to the north and northwest, and is part of the same system that is causing brine to be emitted at Sandy Creek Salt Plain. At the salt plain, Ward (1963a) reports: "No springs have been observed, but during periods of dry weather a thin crust of salt and gypsum forms on sand bars and on the sandy alluvium along both sides of the creek. Some saltwater apparently seeps directly from bedrock into the alluvium and does not appear at the surface before it enters the creek." The main evidence of salt crusts now is near the two small tributaries on the west side of Sandy Creek, which are flanked by thin crusts of salt (Fig. 30).

Ward (1963a) noted that brine flowing from the salt plain in the NE¼ of section 6 (Fig. 30) contained 10,500 ppm chloride: the surface flow was then only a trickle, and he thought the brine was concentrated by evaporation. Snider (1913) noted that the water at the salt plain is not saturated: he observed minnows swimming in the small streams, almost up to the salt springs. He also noted that the water has a strong taste, but is bitter rather than salty: his analyses (not presented in his report) showed that the water contains much more sodium sulfate than sodium chloride. The high amount of sulfate probably results from the brine passing through, and dissolving, some of the gypsum beds of the Blaine Formation as it moves from the Flowerpot salt, through the Blaine Formation, to the land surface.

Daily brine emissions at Sandy Creek Salt Plain contain an estimated 80 short tons of chloride, or 132 short tons of salt (Table 1).

There is no record of any historic or present production of salt at Sandy Creek Salt Plain.

DISTINGUISHING SALT-DISSOLUTION BRINES FROM OIL-FIELD BRINES

Although natural salt-dissolution brines are emitted at Oklahoma's 11 salt plains, another source of brines that occasionally come to, or near, the land surface are oil-field brines originally present in the deep subsurface. These brines were incorporated or trapped in oil- or gas-producing formations at the time of their deposition, millions of years ago, or may have migrated into the producing formation from other nearby rock units in subsurface: these brines are also referred to as "formation water." Similar brines can also be present as connate waters that are in, or seep from, deep or shallow formations not associated with petroleum occurrences or production.

Although oil-field brines normally are deep underground, they can rise up to, or near, the land surface when they are co-produced with oil or gas. For each barrel of oil produced in Oklahoma from 2014 to 2018, wells also generally produced 5 to 10 barrels of brine: a brine-to-oil ratio of 5:1 to 10:1 (personal communication from Kyle E. Murray, 2021). It is also possible for such brines to rise to, or near, the surface in poorly completed or abandoned wells.

Collins (1971) described a number of petroleum-related activities that could bring oil-field brines to, or near, the land surface. In addition to accidental spills, brine can escape from corroded pipe or leaky pipe connections, or from wells that are unplugged or improperly plugged. Wells can also be improperly cased or cemented at or near the surface, and it is possible that pipelines or storage tanks can corrode and develop leaks. Disposal of oil-field brines can also be a problem if there are leaks in pumps or in a brine-disposal well, and brine can leak from surface containment ponds that overflow or are poorly constructed. Any of these problems can cause oil-field brine, or other saline water, to enter soils or streams at the land surface, or enter aquifers in the shallow subsurface.

The dissolved salts of oil-field brines generally range from about 5,000 to more than 200,000 ppm. Such salinities can be almost as high as those of some salt-dissolution brines, but the details of their chemistry are different, and thus they can be differentiated from salt-dissolution brines. The chief means of differentiating between the two types of brine is comparing their sodium-chloride and calcium-sulfate ratios (Na/Cl and Ca/SO_4 ratios), by their weight or mass (generally expressed in ppm, or mg/l). These four ions, Na, Cl, Ca, and SO_4, are especially useful, as they are commonly tested for in all water analyses. Oklahoma's salt-dissolution brines result from dissolution of Permian rock salt (i.e., halite, NaCl) that is intimately associated with gypsum and anhydrite ($CaSO_4 \cdot 2H_2O$ and $CaSO_4$), whereas Oklahoma's oil-field brines typically come from formations containing little or no rock salt, gypsum, or anhydrite. Among the other ionic ratios that have been used to distinguish salt-dissolution brines from oil-field brines are the bromide-chloride and iodide-chloride ratios (Br/Cl and I/Cl ratios).

Sodium-Chloride Ratio (Na/Cl)

Pure salt has a sodium-chloride ratio (Na/Cl ratio) of 0.648, and a solution of salt dissolved in pure water would have that same Na/Cl ratio. Leonard and Ward (1962) and Ward (1963a) used this ratio to show whether a particular brine sample was derived from the dissolution of salt, or if it was an oil-field brine—which consistently have Na/Cl ratios of less than 0.60. They concluded that it would be possible to distinguish between a salt-dissolution brine and an oil-field brine by determining the Na/Cl ratio of the suspect brine.

In their original work, Leonard and Ward (1962) and Ward (1963a) plotted the Na/Cl ratios of 13 salt-dissolution brines and 29 oil-field brines (Fig. 31). They found that the Na/Cl ratio for the salt-dissolution brines was between 0.62 and 0.66 for all their samples, and the mean was about 0.64, regardless of the amount of chloride present. This indicated that a nearly pure salt (Na/Cl ratio of 0.648) was the source of these brines.

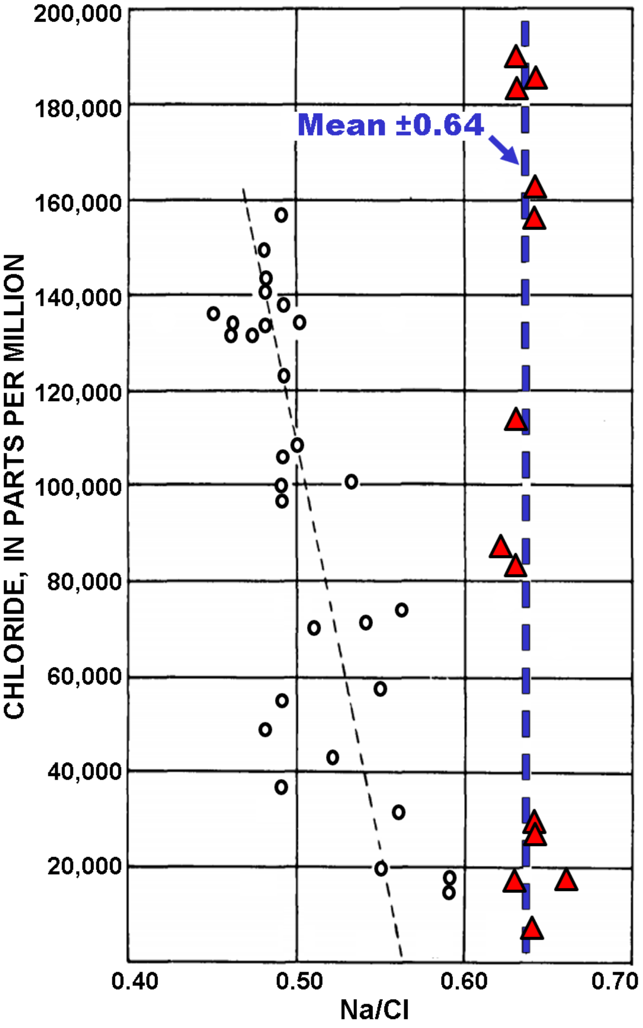


Figure 31. Comparison of Na/Cl ratios for: 1) natural salt-dissolution brines (13 red triangles), derived by dissolving Permian salt deposits in western Oklahoma and southwestern Kansas; and 2) oil-field brines (29 black circles). Modified from Leonard and Ward (1962) and Ward (1963a). Dashed blue line is the mean of salt-dissolution data; black line is the trendline of plotted oil-field data.

Twenty-nine oil-field brines plotted by Leonard and Ward (1962) and Ward (1963a) all had Na/Cl ratios between 0.45 and 0.59, and averaged about 0.50 (Fig. 31): the ratio decreased as the chloride content increased. They concluded that the oil-field brines contained excessive chloride ions due to the presence of other compounds of chloride (i.e., calcium- or magnesium-chloride) that are not present in either salt deposits or the brines resulting from dissolution of salt.

As a further assessment of the utility of the Na/Cl ratio in differentiating the source of brines, the Na/Cl ratios were calculated (Table 12) and plotted (Fig. 32) for 28 of the 29 salt-dissolution brines shown on Tables 1–10 in the current report: data from Table 11 were not included, inasmuch as they do not include specific analyses for sodium or chloride. Plotted data (Fig. 32) show the following: 19 of the 28 Na/Cl ratios are between 0.60 and 0.70; four ratios are between 0.571 and 0.583; five are between 0.716 and 0.730; and the mean for all 28 ratios is 0.649 (virtually the same as pure salt).

The results plotted in Figure 32 agree fairly well with the plot in Figure 31, although Figure 32 does show a greater range of values; 0.571 to 0.730 in Figure 32, but only 0.62 to 0.66 in Figure 31. Why there is a greater

Brine source (salt formation)	Table in text	Na	Cl	Na/Cl ratio
Flowerpot	2	100,000	156,000	0.641
Flowerpot	2	104,000	162,000	0.642
Flowerpot	2	120,000	190,000	0.632
Flowerpot	5	118,800	189,000	0.629
Flowerpot	5	110,000	189,500	0.580
Flowerpot	5	108,000	189,000	0.571
Flowerpot	5	103,000	159,000	0.648
Flowerpot	5	110,000	189,000	0.582
Flowerpot	6	131,587	205,076	0.642
Flowerpot	7	125,000	194,000	0.644
Flowerpot	7	42,500	61,000	0.697
Flowerpot	10	118,800	180,000	0.660
Flowerpot	10	116,300	185,000	0.629
Flowerpot	10	112,500	184,000	0.611
Upper Cimarron	2	52,100	82,600	0.631
Upper Cimarron	8	57,300	90,800	0.631
Upper Cimarron	8	4,650	7,280	0.639
Upper Cimarron	8	37,000	63,500	0.583
Upper Cimarron	9	108,242	150,400	0.720
Upper Cimarron	9	90,069	123,600	0.729
Upper Cimarron	9	103,641	143,200	0.724
Lower Cimarron	2	71,300	114,000	0.625
Lower Cimarron	3	87,500	129,500	0.676
Lower Cimarron	3	6,800	9,500	0.716
Lower Cimarron	3	102,000	153,500	0.664
Lower Cimarron	3	73,500	113,000	0.650
Lower Cimarron	3	102,500	161,000	0.637
Lower Cimarron	4	111,010	152,100	0.730

Table 12. Calculation of Na/Cl ratios for 28 salt-derived brines in western Oklahoma. Data are based on all sodium and chloride analyses on Tables 1-10 in this report; in Table 11, sodium and chloride were not determined separately. Na/Cl ratios are plotted in Figure 32.

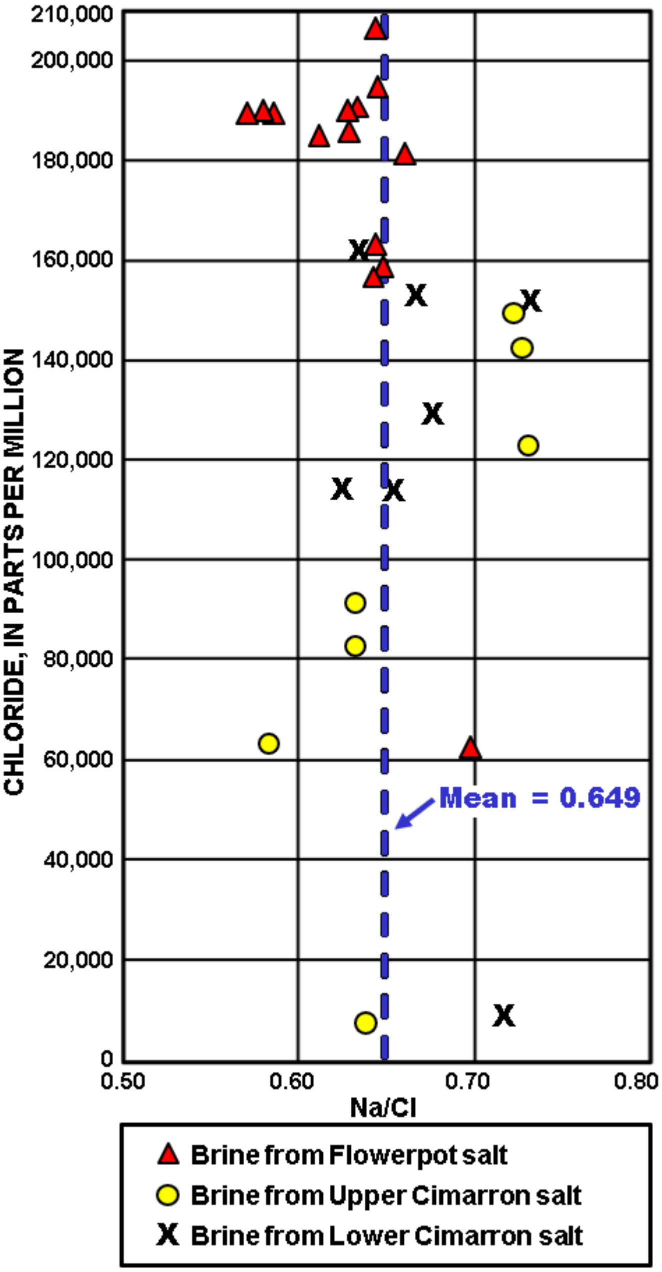


Figure 32. Plot of Na/Cl ratios for 28 brines derived by dissolving Permian salt deposits in western Oklahoma. Source of brine is shown by different symbols. Dashed blue line is the calculated mean of plotted data. Data are based on all sodium and chloride analyses on Tables 1-10 in this report; in Table 11, sodium and chloride were not determined separately. Calculation of Na/Cl ratios shown in Table 12.

range of values in Figure 32 is uncertain, but it's clear that even these data indicate that most Na/Cl values are over 0.60, and thus are above the probable range of Na/Cl values of oil-field brines. The four brines with ratios below 0.60 (Table 12) were all taken directly from brine springs or brine wells on salt flats, so there is no question about their salt-dissolution sources: also, the Ca/SO_4 ratios of these four samples supports their salt-dissolution sources (see Ca/SO_4 discussion, below).

Na/Cl data (Table 12), and the plot of those data (Fig. 32), show which salt produced each brine sample. The 14 brine samples from the Flowerpot salt include the most saline of the brines, and in most cases have a Na/Cl ratio that is lower than the mean (0.649): twelve of the brines derived from the Flowerpot salt have Na/Cl ratios between 0.571 and 0.648; the other two have ratios of 0.660 and 0.697. The seven brines derived from the Upper Cimarron salt have a wide range of salinity, and their Na/Cl ratios are somewhat equally divided above and below the mean: four samples have ratios between 0.583 and 0.639, and the other three samples have ratios between 0.720 and 0.729. The seven brines derived from the Lower Cimarron salt have the highest average Na/Cl ratio of the three groups of brines: two have ratios of 0.625 and 0.637, below the mean, and the remaining five samples are above the mean with ratios between 0.650 and 0.730. In summary, brines from the Flowerpot salt are mostly below the mean, whereas brines from the Upper Cimarron salt are somewhat equally below and above the mean, and brines from the Lower Cimarron salt are mostly above the mean.

In summary, if a brine is encountered at or near the surface, and its source is unknown, the Na/Cl ratio of that brine and of oil-field brines in the vicinity should be determined to see if the suspect brine matches an oil-field brine (generally in the range of 0.45 to 0.59), or a salt-dissolution brine (typically 0.60 to 0.70).

Calcium-Sulfate Ratio (Ca/SO_4)

Another important criterion in distinguishing oil-field brines from those resulting from dissolution of Permian salts is the calcium-sulfate ratio (Ca/SO_4 ratio) of the brine. Permian salt deposits in Oklahoma are all associated with gypsum and/or anhydrite in subsurface, and both these minerals consist of calcium sulfate: gypsum is $CaSO_4 \cdot 2H_2O$, and anhydrite is $CaSO_4$. The ratio of calcium to sulfate in both of these minerals is about 0.42 (40÷96~0.42 [actually 0.4167]).

The Ca/SO_4 ratios (Table 13) were calculated for all 29 salt-dissolution brines shown on Tables 1–11 in the current report, and the data for 28 of those brines were plotted (Fig. 33): the Ca/SO_4 ratio for the brine in Table 4 is anomalous and inexplicably high (2.99), and is excluded from the plot and the characterization of Ca/SO_4 ratios (however, note that the Na/Cl ratio of this brine is 0.730, so clearly this sample is derived by dissolution of salt). The other 28 analyses of brines formed by dissolution of salt beds (with associated gypsum/anhydrite) have Ca/SO_4 ratios of between 0.17 and 0.72, and the average Ca/SO_4 ratio of these analyses is 0.4175—almost

Brine source (salt formation)	Table in text	Ca	SO_4	Ca/SO_4 ratio
Flowerpot	2	1,120	3,750	0.30
Flowerpot	2	1,280	3,800	0.34
Flowerpot	2	1,480	3,720	0.40
Flowerpot	5	1,520	3,500	0.43
Flowerpot	5	1,440	4,950	0.29
Flowerpot	5	1,440	4,500	0.32
Flowerpot	5	1,840	3,800	0.48
Flowerpot	5	1,200	4,500	0.27
Flowerpot	6	2,250	4,036	0.56
Flowerpot	7	1,540	4,560	0.34
Flowerpot	7	1,040	1,440	0.72
Flowerpot	10	1,600	3,200	0.50
Flowerpot	10	1,840	3,300	0.56
Flowerpot	10	1,840	3,000	0.61
Flowerpot	11	338	759	0.45
Flowerpot	11	379	656	0.58
Upper Cimarron	2	1,700	3,200	0.53
Upper Cimarron	8	1,870	3,520	0.53
Upper Cimarron	8	666	1,770	0.38
Upper Cimarron	8	1,760	5,600	0.31
Upper Cimarron	9	2,496	3,768	0.66
Upper Cimarron	9	2,329	5,043	0.46
Upper Cimarron	9	2,547	4,356	0.58
Lower Cimarron	3	1,140	5,250	0.22
Lower Cimarron	3	240	900	0.27
Lower Cimarron	3	1,520	7,350	0.21
Lower Cimarron	3	1.200	5,350	0.22
Lower Cimarron	3	1,120	6,600	0.17
Lower Cimarron	4	1,082	362	2.99

Table 13. Calculation of Ca/SO_4 ratios for 29 salt-derived brines in western Oklahoma. Data are based on all calcium and sulfate analyses on Tables 1–11 in this report. Note that on Table 4, the Ca/SO_4 ratio of brine from the Lower Cimarron salt is anomalously high (2.99). Ca/SO_4 ratios are plotted in Figure 33.

identical to the actual Ca/SO_4 ratio in gypsum and anhydrite (0.4167).

Noticeable patterns in the plotted data (Fig. 33) are: 1) there is an increase in the Ca/SO_4 ratio with an increase in Ca content (note trendline); 2) Ca/SO_4 ratios for the Lower Cimarron salt brines (all collected near the surface of Great Salt Plains [Table 3]) are lower than for either of the other brines, meaning that there is a higher percent of SO_4, compared to the Ca content, in these brines than in the others; 3) although there are some anomalous ratios, the trendline of Ca/SO_4 ratios for each of the brines plots reasonably close to the overall trendline; and 4), most importantly, that all the brines (except the one sample in Table 4) have exceptionally low Ca/SO_4 ratios, when compared to those of oil-field brines (described below).

A cursory examination of the Ca/SO_4 ratios of oil-field brines in Oklahoma shows a marked difference, when compared to salt-dissolution brines. To approximate the Ca/SO_4 ratio of oil-field brines, 19 brine analyses from the west half of Oklahoma were randomly selected, out of the 923 State-wide oil-field brines analyzed by Wright and others (1957). The selected analyses are of brines co-produced from a variety of formations, including: granite wash, Hoxbar (several zones), Layton sand, Bartlesville sand, Mississippi lime, Oswego lime, Hunton lime, Wilcox sand, Simpson lime, and Arbuckle lime. The Ca/SO_4 ratio of these 19 brines ranged from 3.2 to 251, and averaged 52; most of the values were between 20 and 80, clearly well above the average Ca/SO_4 value for salt-dissolution brines (~0.42).

Therefore, if a brine is encountered at or near the surface, and its source is unknown, the Ca/SO_4 ratio of that brine and of oil-field brines in the vicinity should be determined to see if the suspect brine matches an oil-field brine (generally in the range of 20 to 80), or a salt-dissolution brine (generally 0.17 to 0.72).

Bromide-Chloride and Iodide-Chloride Ratios (Br/Cl and I/Cl)

Richter and Kreitler (1986) analyzed and characterized salt springs and shallow-subsurface brines from Permian salts in north-central Texas and in northern Harmon County, Oklahoma (the salt plains on Elm Fork Red River). Later, Richter and Kreitler (1991) concluded the following: 1) salt-dissolution brines had Br/Cl ratios less than 0.0004 (<4 x 10^{-4}) and I/Cl ratios of less than 0.00001 (<1 x 10^{-5}); whereas 2) oil-field brines had Br/Cl

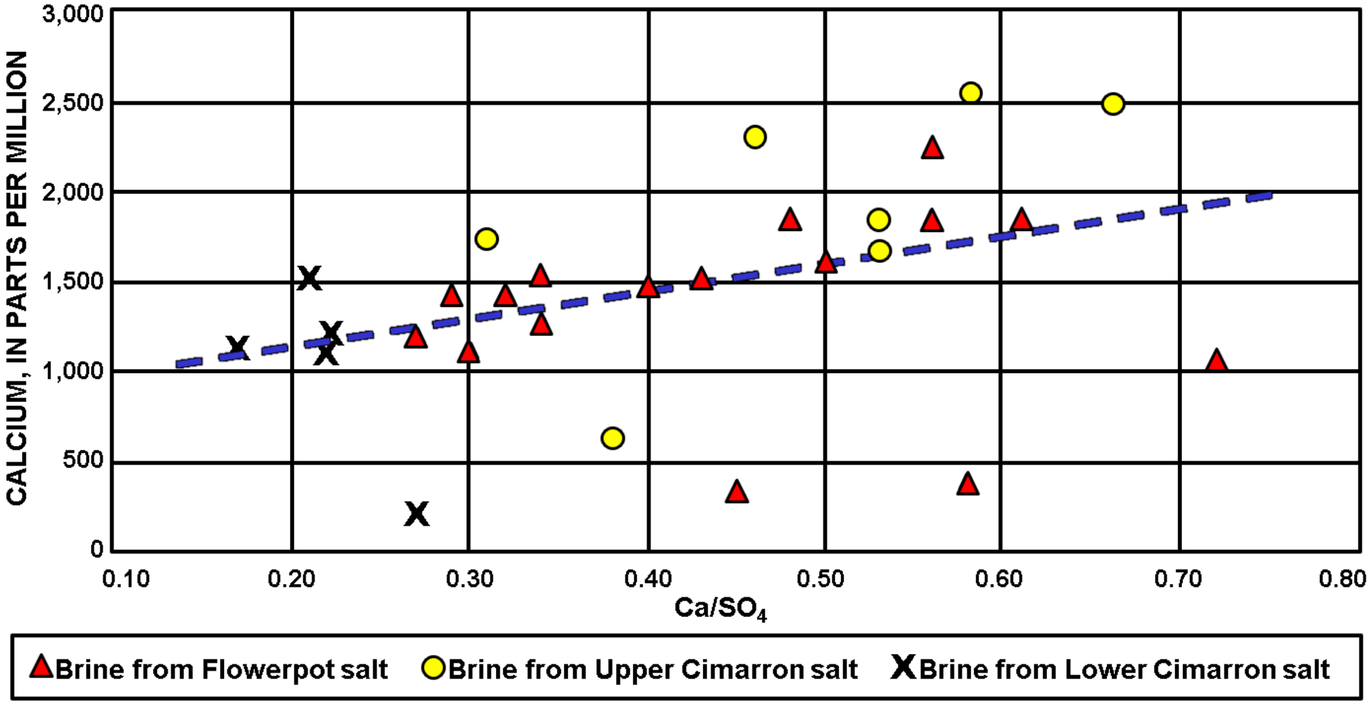


Figure 33. Plot of Ca/SO_4 ratios for 28 brines derived by dissolving Permian salt deposits in western Oklahoma. Source of brine is shown by different symbols. Dashed blue line is the trendline using Excel. Data are based on all calcium and sulfate analyses on Tables 1-11 in this report, except Table 4 where brine from the Lower Cimarron salt has an anomalously high Ca/SO_4 ratio (2.99). Calculation of Ca/SO_4 ratios shown in Table 13.

ratios greater than 0.0025 (>25 x 10^{-4}) and I/Cl ratios of greater than 0.00002 (>2 x 10^{-5}). Bromide and/or iodide concentrations of salt-dissolution brines are shown on only six of the tables in the current report (Tables 3, 5, 6, 7, 8, and 10). Thus, the Br/Cl- and I/Cl-ratio data available for the Oklahoma salt-dissolution brines are not as comprehensive as the Na/Cl and Ca/SO_4 data described above, but those data are discussed below.

Br/Cl data are available for 13 salt-dissolution samples in this report (Tables 3, 5, 6, 7, 8, and 10). The Br/Cl ratios for these samples range from 0.00011 to 0.00210, and average 0.00041. Although most of the samples have Br/Cl ratios well below 0.0004, two samples are quite high: on Table 3, the sample 2 ratio is 0.00210, and on Table 10, the sample 1 ratio is 0.00111, so both of them are well above the Br/Cl ratios for salt-dissolution brines. However, these two samples have Na/Cl ratios of 0.716 and 0.660, respectively, and the Ca/SO_4 ratios of 0.27 and 0.50, respectively: these data clearly indicate they are salt-dissolution brines. The eleven remaining samples are in the range of 0.00011 to 0.00054. Therefore, all 13 samples have Br/Cl ratios lower than the >0.0025 ratio that characterizes oil-field brines.

I/Cl data are available for only three salt-dissolution samples in this report (Tables 3, 6, and 7). The I/Cl ratios for these samples are: 0.0000015 (Table 3, sample 2), 0.0000487 (Table 6), and 0.0000032 (Table 7, sample 2), and the three samples average 0.0000178. The I/Cl ratios for samples on Tables 3 and 7 are clearly in the range of salt-dissolution brines (<0.00001), but for the sample on Table 6 the ratio suggests that it is an oil-field brine (>0.00002). However, both the Na/Cl ratio (0.642) and Ca/SO_4 ratio (0.56) for the Table-6 sample clearly indicate that it is a salt-dissolution brine.

Mixing of Oil-Field Brine with Salt-Dissolution Brine?

It is certainly possible for oil-field brine to mix with salt-dissolution brine and come to the surface at, or in the vicinity of, one or more of the eleven natural salt plains in western Oklahoma, but there is no obvious case where this is happening. Such an occurrence might be difficult to identify, unless the amount of oil-field brine was significant. If that were to happen, the Na/Cl ratio of the mixed brine should be reduced, and the Ca/SO_4 ratio should increase sharply. The Ca/SO_4 ratio should be most telling in that case, inasmuch as oil-field brines have such a high Ca/SO_4 ratio in comparison to salt-dissolution brines: most of the oil-field brines examined for this report have ratios of 20 to 80, whereas salt-dissolution brines typically have ratios between 0.20 and 0.70 (Table 13). Therefore, even a moderate addition of oil-field brine to a salt-dissolution brine should result in a significant increase in the Ca/SO_4 ratio.

The various salt plains of Oklahoma have been known since before Statehood (before 1907), and there is no evidence so far to indicate that brines coming to the surface at any of these sites contain any oil-field brine. However, specific studies have not been carried out to date on the possible mixing of oil-field and salt-dissolution brines at Oklahoma's salt plains. Additional sampling and analysis of salt-dissolution and oil-field brines in western Oklahoma, along with a full discussion on this topic, are beyond the scope of this report, but they are fields of study that warrant future research.

SUMMARY AND CONCLUSIONS

Permian salt beds are being dissolved at shallow depths in western Oklahoma, and the resultant brine is coming to the land surface at 11 locations to form salt plains or salt flats in the Arkansas and Red River watersheds. Fresh groundwater is dissolving the salt beds at depths of 9 m to about 200 m below the surface, and the resulting brine is then discharged at the surface. The brine evaporates and salt is precipitated to form a salt crust that typically is about 0.5 to 3 cm thick, but can be as much as 15 cm thick. As a result of rainfall or flooding events, the salt plains are then partly flushed of their salt: as a result, parts of the Arkansas and Red River systems are naturally contaminated with salt.

The six salt plains in the Arkansas River watershed (which includes the Cimarron River) are: Great Salt Plains, Big Salt Plain, Little Salt Plain, Salt Creek Canyon Salt Plain, Okeene Salt Plain, and Drummond Flats Salt Plain. The other five, in the Red River watershed, are: Boggy Creek Salt Plain, Salton (Chaney) Salt Plain, Robinson Salt Plain, Kiser Salt Plain, and Sandy Creek Salt Plain. Great Salt Plains, the largest salt plain, covers about 65 km^2 (originally about 101 km^2), whereas the Salton, Robinson, Kiser, and Sandy Creek Salt Plains are the smallest, with each of them covering between 1 to 4 hectares. Salt plains that produce the most salt are Big Salt Plain (2,600 to 4,870 short tons per day) and Great

Salt Plains (2,310 to 3,300 tons of salt per day).

Most of the salt plains emit high-salinity brines, with chloride concentrations of 150,000 to 205,000 ppm and salt concentrations of 255,000 to 337,000 ppm. Some brines are so highly concentrated that salt is precipitated on the salt flat almost immediately after brine reaches the surface. Native Americans and early European settlers harvested salt from the Oklahoma salt plains before 1900 AD, and since then commercial salt has also been produced at Big Salt Plain, Salt Creek Canyon Salt Plain, Boggy Creek Salt Plain, Salton Salt Plain, and Kiser Salt Plain.

Oil-field brines or briny formation waters occasionally contaminate freshwater sources, and it is important to distinguish between these brines and salt-dissolution brines. This can be done by examining the sodium-chloride and calcium-sulfate ratios (Na/Cl and Ca/SO_4 ratios) of a suspect brine. Pure salt has a Na/Cl ratio of 0.648, and salt-dissolution brines of western Oklahoma in this report have Na/Cl ratios that mostly range from 0.60 to 0.70, and average 0.649. On the other hand, selected oil-field brines from western Oklahoma have Na/Cl ratios between 0.45 and 0.59, and average about 0.50. Gypsum and anhydrite, each with a Ca/SO_4 ratio of 0.4167, are associated with all the salt beds in western Oklahoma. Salt-dissolution brines described in this report have Ca/SO_4 ratios between 0.17 and 0.72, and average 0.4175 (although for one brine the ratio is 2.99). This contrasts with selected Oklahoma oil-field brines, which have Ca/SO_4 ratios that range from 3.2 to 251 and average 52; most of the values are between 20 and 80. Therefore, by measuring the Na/Cl and Ca/SO_4 ratios of a particular brine, it should be possible to determine if it is a salt-dissolution brine or an oil-field brine. Other ionic ratios that have been used to distinguish between these brines are bromide-chloride and iodide-chloride ratios (Br/Cl and I/Cl ratios), and data in this report support the using of these ratios.

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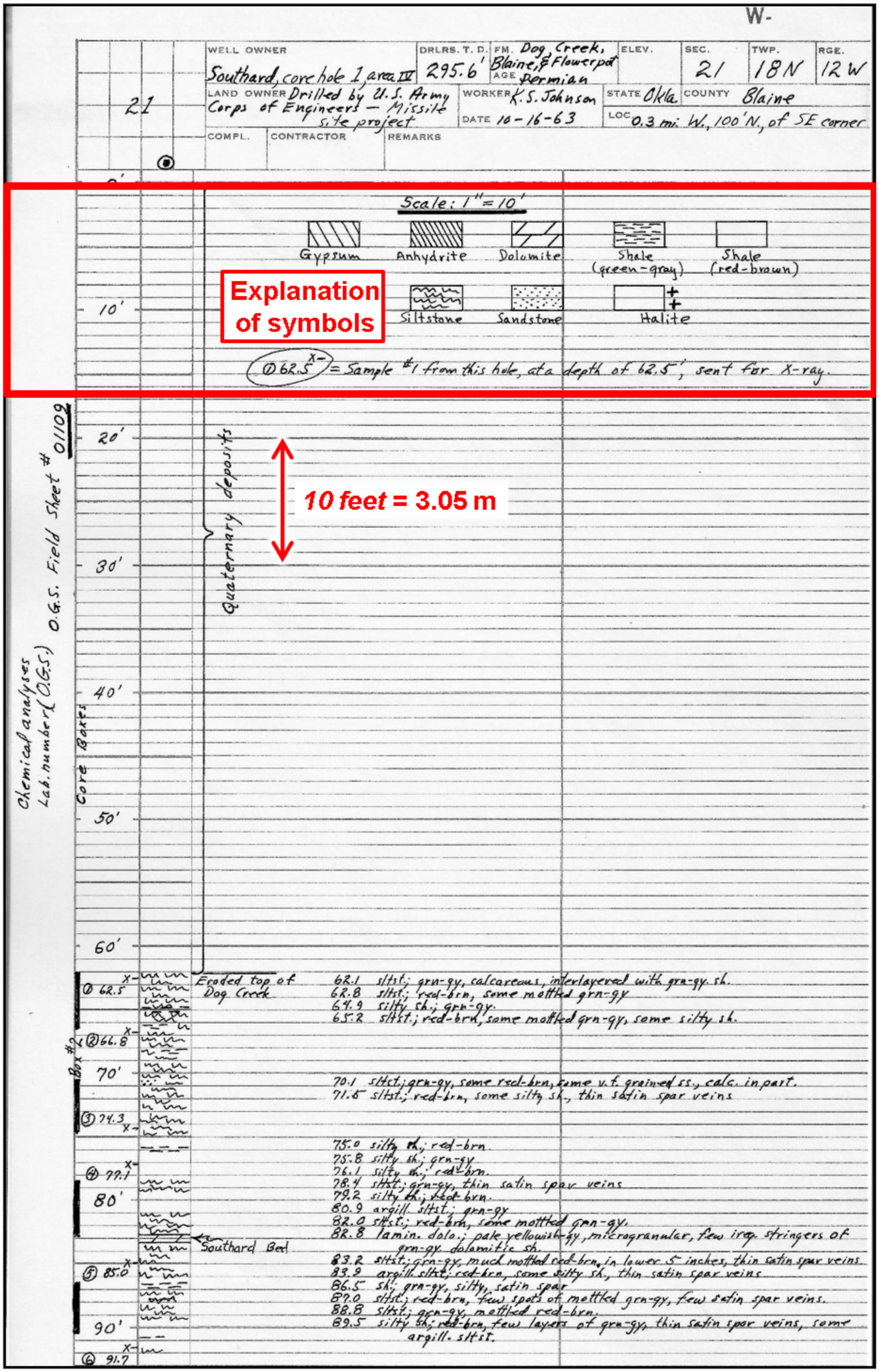


WELL OWNER Southard, core hole 1, area IV
DRLRS. T. D. 295.6'
FM. Dog Creek, Blaine, & Flowerpot
AGE Permian
ELEV.
SEC. 21
TWP. 18N
RGE. 12 W
LAND OWNER Drilled by U.S. Army Corps of Engineers — Missile site project
WORKER K. S. Johnson
DATE 10-16-63
STATE Okla.
COUNTY Blaine
LOC 0.3 mi. W., 100' N., of SE corner
COMPL.
CONTRACTOR
REMARKS

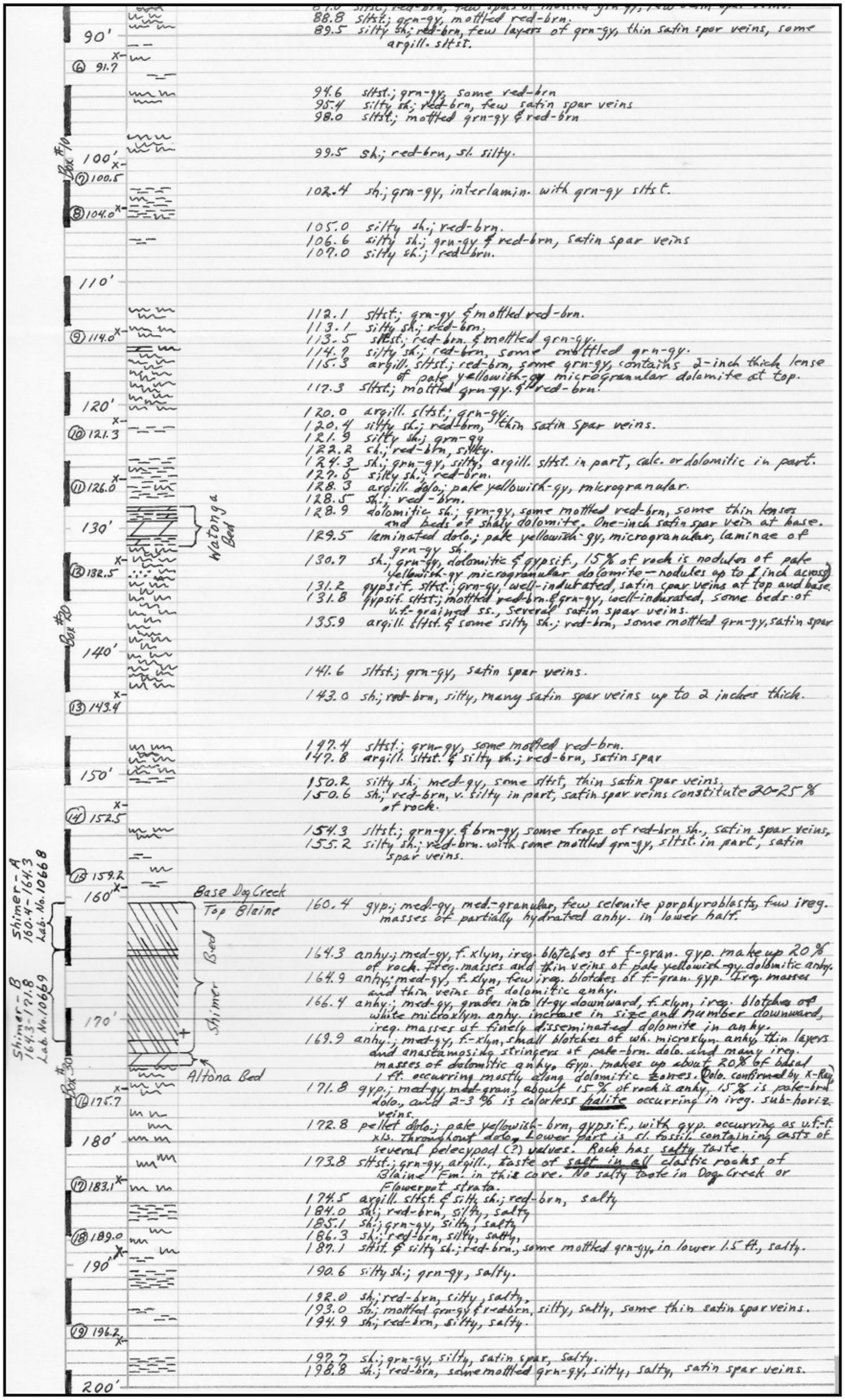
Explanation of symbols

① 62.5 X– = Sample #1 from this hole, at a depth of 62.5', sent for X-ray.

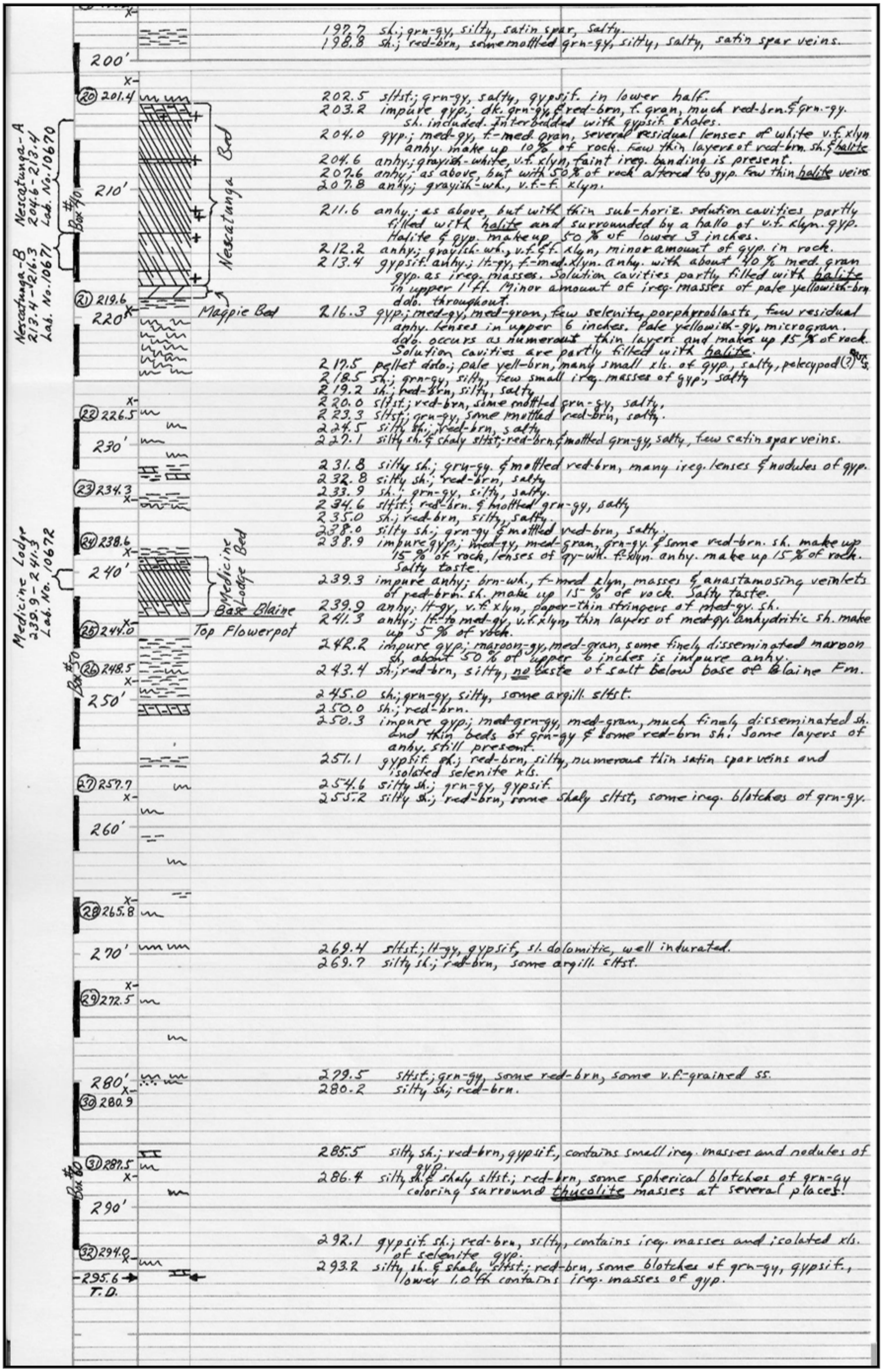
10 feet = 3.05 m

62.1 sltst.; grn-gy, calcareous, interlayered with grn-gy. sh.
62.8 sltst.; red-brn, some mottled grn-gy
64.9 silty sh.; grn-gy.
65.2 sltst.; red-brn, some mottled grn-gy, some silty sh.
70.1 sltst.; grn-gy, some red-brn, some v.f. grained ss., calc. in part.
71.5 sltst.; red-brn, some silty sh., thin satin spar veins
75.0 silty sh.; red-brn.
75.8 silty sh.; grn-gy
76.1 silty sh.; red-brn.
78.4 sltst.; grn-gy, thin satin spar veins
79.2 silty sh.; red-brn.
80.9 argill. sltst.; grn-gy
82.0 sltst.; red-brn, some mottled grn-gy.
82.8 lamin. dolo.; pale yellowish-gy, microgranular, few irreg. stringers of grn-gy. dolomitic sh.
83.2 sltst.; grn-gy, much mottled red-brn. in lower 5 inches, thin satin spar veins.
83.9 argill. sltst.; red-brn, some silty sh., thin satin spar veins
86.5 sh.; grn-gy, silty, satin spar
87.0 sltst.; red-brn, few spots of mottled grn-gy, few satin spar veins.
88.8 sltst.; grn-gy, mottled red-brn.
89.5 silty sh.; red-brn, few layers of grn-gy, thin satin spar veins, some argill. sltst.

APPENDIX A: SOUTHARD CORE (CONTINUED)



88.8 sltst.; grn-gy, mottled red-brn.
89.5 silty sh.; red-brn, few layers of grn-gy, thin satin spar veins, some argill. sltst.
94.6 sltst.; grn-gy, some red-brn
95.4 silty sh.; red-brn, few satin spar veins
98.0 sltst.; mottled grn-gy & red-brn
99.5 sh.; red-brn, sl. silty.
102.4 sh.; grn-gy, interlamin. with grn-gy sltst.
105.0 silty sh.; red-brn.
106.6 silty sh.; grn-gy & red-brn, satin spar veins
107.0 silty sh.; red-brn.
112.1 sltst.; grn-gy & mottled red-brn.
113.1 silty sh.; red-brn.
113.5 sltst.; red-brn. & mottled grn-gy.
114.7 silty sh.; red-brn, some mottled grn-gy.
115.3 argill. sltst.; red-brn, some grn-gy, contains 2-inch thick lense of pale yellowish-gy microgranular dolomite at top.
117.3 sltst.; mottled grn-gy. & red-brn.
120.0 argill. sltst.; grn-gy.
120.4 silty sh.; red-brn, thin satin spar veins.
121.9 silty sh.; grn-gy
122.2 sh.; red-brn, silty.
124.3 sh.; grn-gy, silty, argill. sltst. in part, calc. or dolomitic in part.
127.5 silty sh.; red-brn.
128.3 argill. dolo.; pale yellowish-gy, microgranular.
128.5 sh.; red-brn.
128.9 dolomitic sh.; grn-gy, some mottled red-brn, some thin lenses and beds of shaly dolomite. One-inch satin spar vein at base.
129.5 laminated dolo.; pale yellowish-gy, microgranular, laminae of grn-gy sh.
130.7 sh.; grn-gy, dolomitic & gypsif., 15% of rock is nodules of pale yellowish-gy microgranular dolomite—nodules up to 1 inch across)
131.2 gypsif. sltst.; grn-gy, well-indurated, satin spar veins at top and base.
131.8 gypsif. sltst.; mottled red-brn. & grn-gy, well-indurated, some beds of v.f.-grained ss., several satin spar veins.
135.9 argill. sltst. & some silty sh.; red-brn, some mottled grn-gy, satin spar
141.6 sltst.; grn-gy, satin spar veins.
143.0 sh.; red-brn, silty, many satin spar veins up to 2 inches thick.
147.4 sltst.; grn-gy, some mottled red-brn.
147.8 argill. sltst. & silty sh.; red-brn, satin spar
150.2 silty sh.; med-gy, some sltst, thin satin spar veins.
150.6 sh.; red-brn, v. silty in part, satin spar veins constitute 20-25% of rock.
154.3 sltst.; grn-gy. & brn-gy, some frags. of red-brn sh., satin spar veins,
155.2 silty sh.; red-brn. with some mottled grn-gy, sltst. in part, satin spar veins.
160.4 gyp.; med-gy, med.-granular, few selenite porphyroblasts, few ireg. masses of partially hydrated anhy. in lower half.
164.3 anhy.; med-gy, f. xlyn, ireg. blotches of f-gran. gyp. make up 20% of rock. Ireg. masses and thin veins of pale yellowish-gy. dolomitic anhy.
164.9 anhy.; med-gy, f. xlyn, few ireg. blotches of f-gran. gyp. Ireg. masses and thin veins of dolomitic anhy.
166.4 anhy.; med-gy, grades into lt-gy downward, f. xlyn, ireg. blotches of white microxlyn. anhy. increase in size and number downward, ireg. masses of finely disseminated dolomite in anhy.
169.9 anhy.; med-gy, f.-xlyn, small blotches of wh. microxlyn. anhy, thin layers and anastamosing stringers of pale-brn. dolo. and many ireg. masses of dolomitic anhy. Gyp. makes up about 20% of basal 1 ft. occurring mostly along dolomitic zones. (Dolo. confirmed by X-Ray)
171.8 gyp.; med-gy, med-gran., about 15% of rock is anhy, 15% is pale-brn dolo., and 2-3% is colorless halite occurring in ireg. sub-horiz. veins.
172.8 pellet dolo.; pale yellowish-brn, gypsif., with gyp. occurring as v.f.-f. xls. throughout dolo. Lower part is sl. fossil. containing casts of several pelecypod (?) valves. Rock has salty taste.
173.8 sltst.; grn-gy, argill., taste of salt in all clastic rocks of Blaine Fm. in this core. No salty taste in Dog Creek or Flowerpot strata.
174.5 argill. sltst. & silty sh.; red-brn, salty
184.0 sh.; red-brn, silty, salty
185.1 sh.; grn-gy, silty, salty
186.3 sh.; red-brn, silty, salty,
187.1 sltst. & silty sh.; red-brn., some mottled grn-gy, in lower 1.5 ft., salty.
190.6 silty sh.; grn-gy, salty.
192.0 sh.; red-brn, silty, salty,
193.0 sh.; mottled grn-gy & red-brn, silty, salty, some thin satin spar veins.
194.9 sh.; red-brn, silty, salty.
197.7 sh.; grn-gy, silty, satin spar, salty.
198.8 sh.; red-brn, some mottled grn-gy, silty, salty, satin spar veins.



197.7 sh.; grn-gy, silty, satin spar, salty.
198.8 sh.; red-brn, some mottled grn-gy, silty, salty, satin spar veins.

202.5 sltst.; grn-gy, salty, gypsif. in lower half.
203.2 impure gyp.; dk. grn-gy & red-brn, f. gran, much red-brn. & grn.-gy. sh. included. Interbedded with gypsif. shales.
204.0 gyp.; med-gy, f-med. gran, several residual lenses of white v.f. xlyn anhy. make up 10% of rock. Few thin layers of red-brn. sh. & halite
204.6 anhy.; grayish-white, v.f. xlyn, faint irreg. banding is present.
207.6 anhy.; as above, but with 50% of rock altered to gyp. Few thin halite veins
207.8 anhy.; grayish-wh., v.f.-f. xlyn.

211.6 anhy.; as above, but with thin sub-horiz. solution cavities partly filled with halite and surrounded by a hallo of v.f. xlyn. gyp. Halite & gyp. makeup 50% of lower 3 inches.
212.2 anhy.; grayish-wh., v.f. & f. xlyn, minor amount of gyp. in rock.
213.4 gypsif. anhy.; lt-gy, f-med. xlyn. anhy. with about 40% med. gran gyp. as irreg. masses. Solution cavities partly filled with halite in upper 1 ft. Minor amount of irreg. masses of pale yellowish-brn dolo. throughout.
216.3 gyp.; med-gy, med-gran, few selenite porphyroblasts, few residual anhy. lenses in upper 6 inches. Pale yellowish-gy, microgran. dolo. occurs as numerous thin layers and makes up 15% of rock. Solution cavities are partly filled with halite.
217.5 pellet dolo.; pale yell-brn, many small xls. of gyp., salty, pelecypod(?) qtz's.
218.5 sh.; grn-gy, silty, few small irreg. masses of gyp., salty
219.2 sh.; red-brn, silty, salty
220.0 sltst.; red-brn, some mottled grn-gy, salty,
223.3 sltst.; grn-gy, some mottled red-brn, salty.
224.5 silty sh.; red-brn, salty
227.1 silty sh. & shaly sltst; red-brn. & mottled grn-gy, salty, few satin spar veins.

231.8 silty sh.; grn-gy. & mottled red-brn, many irreg. lenses & nodules of gyp.
232.8 silty sh.; red-brn, salty
233.9 sh.; grn-gy, silty, salty.
234.6 sltst.; red-brn. & mottled grn-gy, salty
235.0 sh.; red-brn, silty, salty.
238.0 silty sh.; grn-gy & mottled red-brn, salty.
238.9 impure gyp.; med-gy, med-gran, grn-gy. & some red-brn. sh. make up 15% of rock, lenses of gy-wh. f. xlyn. anhy. make up 15% of rock. Salty taste.
239.3 impure anhy; brn-wh., f-med xlyn, masses & anastamosing veinlets of red-brn. sh. make up 15% of rock. Salty taste.
239.9 anhy; lt-gy, v.f. xlyn, paper-thin stringers of med-gy. sh.
241.3 anhy.; lt. to med-gy, v.f. xlyn, thin layers of med-gy. anhydritic sh. make up 5% of rock.
242.2 impure gyp.; maroon-gy, med-gran, some finely disseminated maroon sh, about 50% of upper 6 inches is impure anhy.
243.4 sh.; red-brn, silty, <u>no</u> taste of salt below base of Blaine Fm.

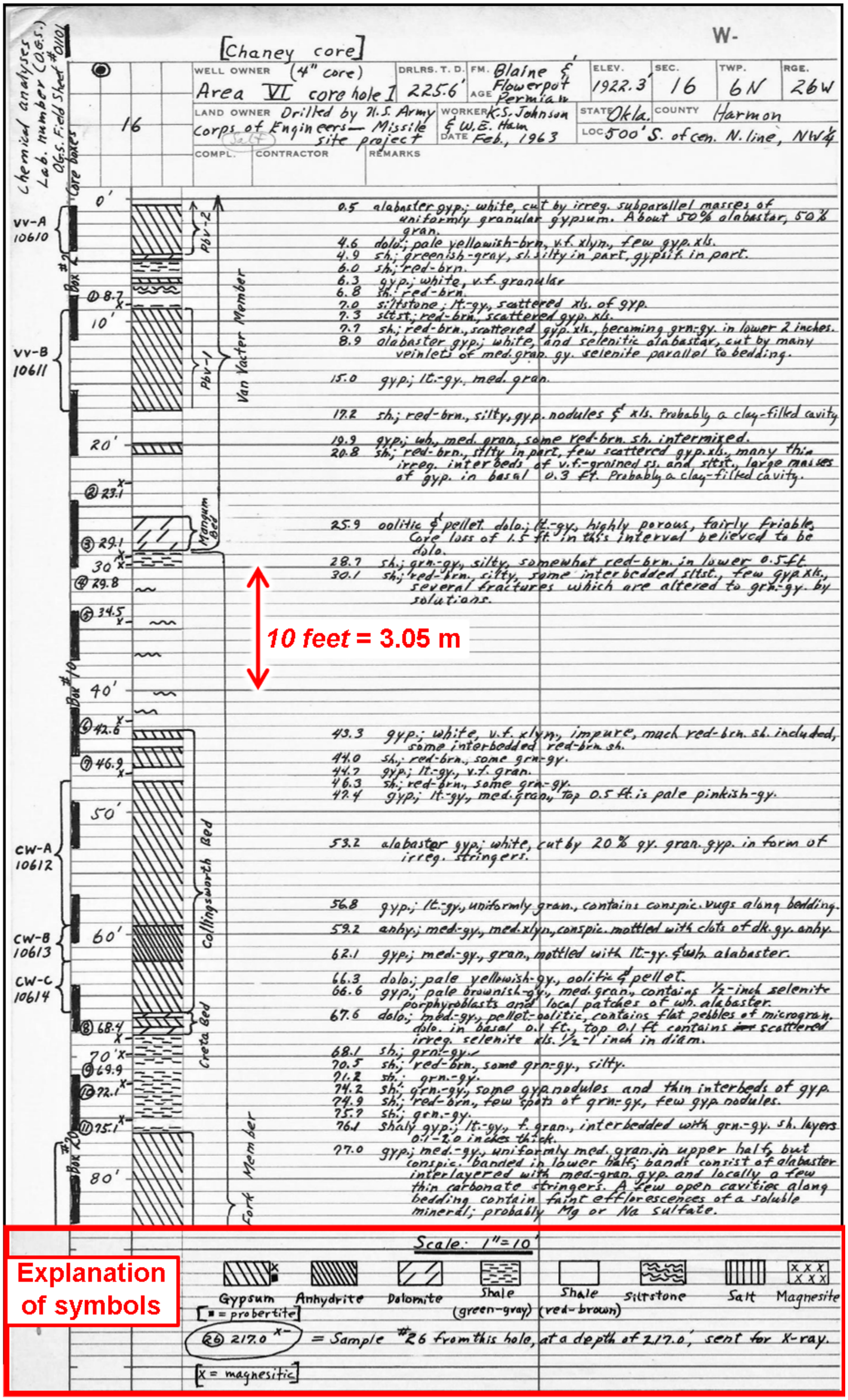
245.0 sh.; grn-gy, silty, some argill. sltst.
250.0 sh.; red-brn.
250.3 impure gyp.; med-grn-gy, med-gran, much finely disseminated sh. and thin beds of grn-gy & some red-brn sh. Some layers of anhy. still present.
251.1 gypsif. sh.; red-brn, silty, numerous thin satin spar veins and isolated selenite xls.
254.6 silty sh.; grn-gy, gypsif.
255.2 silty sh.; red-brn, some shaly sltst, some irreg. blotches of grn-gy.

269.4 sltst.; lt-gy, gypsif, sl. dolomitic, well indurated.
269.7 silty sh.; red-brn, some argill. sltst.

279.5 sltst.; grn-gy, some red-brn, some v.f.-grained ss.
280.2 silty sh.; red-brn.

285.5 silty sh.; red-brn, gypsif., contains small irreg. masses and nodules of gyp.
286.4 silty sh. & shaly sltst.; red-brn, some spherical blotches of grn-gy coloring surround thucolite masses at several places!

292.1 gypsif. sh.; red-brn, silty, contains irreg. masses and isolated xls. of selenite gyp.
293.2 silty sh. & shaly sltst.; red-brn, some blotches of grn-gy, gypsif., lower 1.0 ft. contains irreg. masses of gyp.



W-

[Chaney core]

WELL OWNER (4" core) Area VI core hole I	DRLRS. T. D. 225.6'	FM. Blaine & Flowerpot AGE Permian	ELEV. 1922.3'
SEC. 16	TWP. 6N	RGE. 26W	
LAND OWNER Drilled by U.S. Army Corps of Engineers— Missile site project	WORKER K.S. Johnson & W.E. Ham DATE Feb., 1963	STATE Okla.	COUNTY Harmon
LOC. 500' S. of cen. N. line, NW¼			
COMPL.	CONTRACTOR	REMARKS	

0.5	alabaster gyp.; white, cut by irreg. subparallel masses of uniformly granular gypsum. About 50% alabaster, 50% gran.
4.6	dolo.; pale yellowish-brn., v.f. xlyn., few gyp. xls.
4.9	sh.; greenish-gray, sl. silty in part, gypsif. in part.
6.0	sh.; red-brn.
6.3	gyp.; white, v.f. granular
6.8	sh.; red-brn.
7.0	siltstone; lt.-gy., scattered xls. of gyp.
7.3	sltst.; red-brn., scattered gyp. xls.
7.7	sh.; red-brn., scattered gyp. xls., becoming grn.-gy. in lower 2 inches.
8.9	alabaster gyp.; white, and selenitic alabaster, cut by many veinlets of med.-gran. gy. selenite parallel to bedding.
15.0	gyp.; lt.-gy., med. gran.
17.2	sh.; red-brn., silty, gyp. nodules & xls. Probably a clay-filled cavity
19.9	gyp.; wh., med. gran., some red-brn. sh. intermixed.
20.8	sh.; red-brn., silty in part, few scattered gyp. xls., many thin irreg. interbeds of v.f.-grained ss. and sltst., large masses of gyp. in basal 0.3 ft. Probably a clay-filled cavity.
25.9	oolitic & pellet dolo.; lt.-gy., highly porous, fairly friable. Core loss of 1.5 ft. in this interval believed to be dolo.
28.7	sh.; grn.-gy., silty, somewhat red-brn. in lower 0.5 ft.
30.1	sh.; red-brn., silty, some interbedded sltst., few gyp. xls., several fractures which are altered to grn.-gy. by solutions.
43.3	gyp.; white, v.f. xlyn., impure, much red-brn. sh. included, some interbedded red-brn. sh.
44.0	sh.; red-brn., some grn.-gy.
44.7	gyp.; lt.-gy., v.f. gran.
46.3	sh.; red-brn., some grn.-gy.
47.4	gyp.; lt.-gy., med. gran., Top 0.5 ft. is pale pinkish-gy.
53.2	alabaster gyp.; white, cut by 20% gy. gran. gyp. in form of irreg. stringers.
56.8	gyp.; lt.-gy., uniformly gran., contains conspic. vugs along bedding.
59.2	anhy.; med.-gy., med. xlyn., conspic. mottled with clots of dk. gy. anhy.
62.1	gyp.; med.-gy., gran., mottled with lt.-gy. & wh. alabaster.
66.3	dolo.; pale yellowish-gy., oolitic & pellet.
66.6	gyp.; pale brownish-gy., med. gran., contains ½-inch selenite porphyroblasts and local patches of wh. alabaster.
67.6	dolo.; med.-gy., pellet-oolitic, contains flat pebbles of microgran. dolo. in basal 0.1 ft., top 0.1 ft contains ~~[illegible]~~ scattered irreg. selenite xls. ½-1 inch in diam.
68.1	sh.; grn.-gy.
70.5	sh.; red-brn., some grn.-gy., silty.
71.2	sh.; grn.-gy.
74.2	sh.; grn.-gy., some gyp. nodules and thin interbeds of gyp.
74.9	sh.; red-brn., few spots of grn.-gy., few gyp. nodules.
75.7	sh.; grn.-gy.
76.1	shaly gyp.; lt.-gy., f. gran., interbedded with grn.-gy. sh. layers 0.1-2.0 inches thick.
77.0	gyp.; med.-gy., uniformly med. gran. in upper half, but conspic. banded in lower half; bands consist of alabaster interlayered with med.-gran. gyp. and locally a few thin carbonate stringers. A few open cavities along bedding contain faint efflorescences of a soluble mineral; probably Mg or Na sulfate.

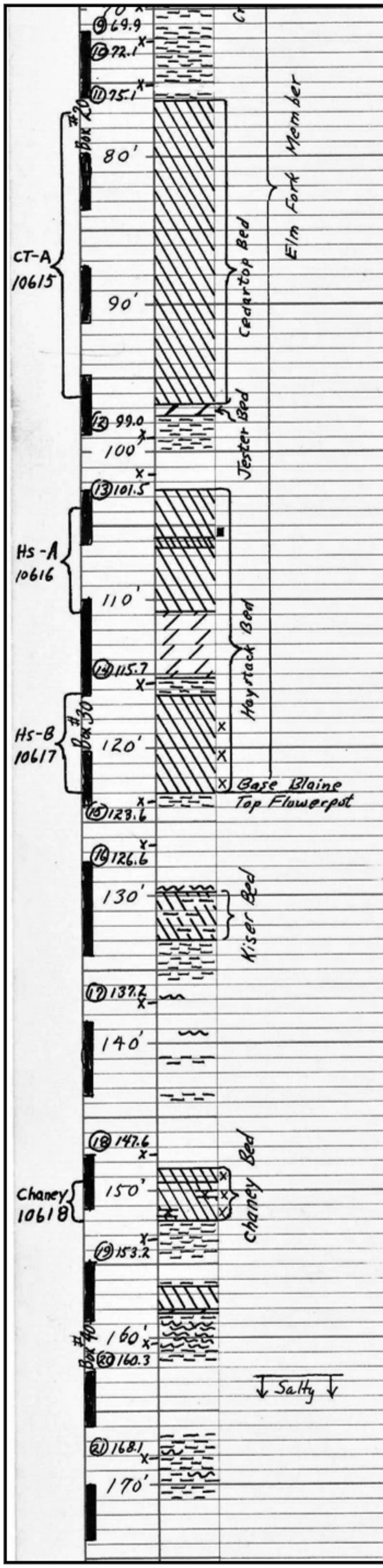
Scale: 1" = 10'

▨	▨	▱	▤	☐	≋	▥	⊠
Gypsum	Anhydrite	Dolomite	Shale (green-gray)	Shale (red-brown)	Siltstone	Salt	Magnesite

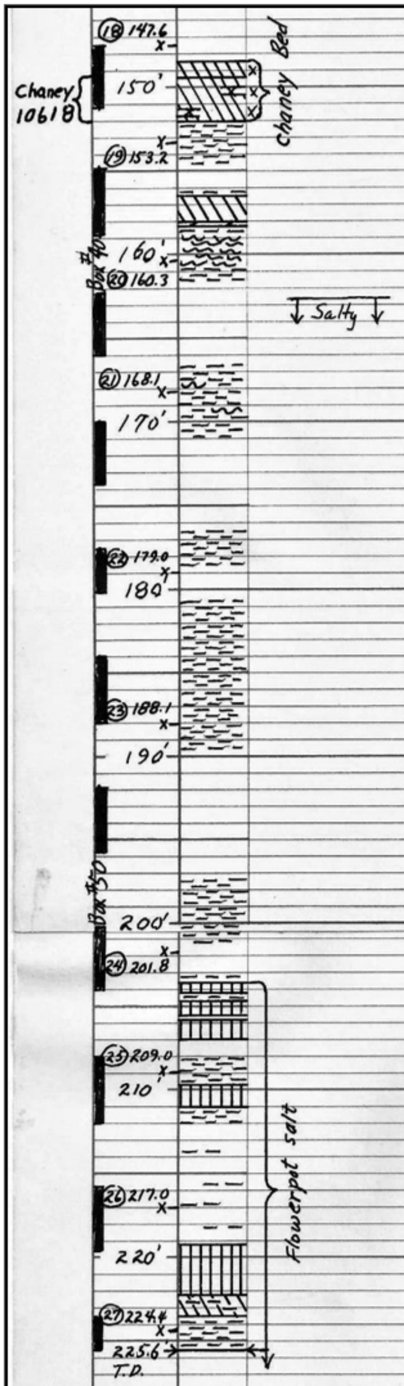
[■ = probertite]

㉖ 217.0 x— = Sample #26 from this hole, at a depth of 217.0', sent for X-ray.

[x = magnesitic]

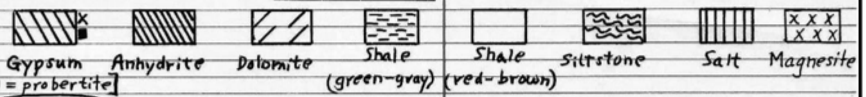


70.5	sh.; red-brn., some grn-gy., silty.
71.2	sh.; grn.-gy.
74.2	sh.; grn.-gy., some gyp. nodules and thin interbeds of gyp.
74.9	sh.; red-brn., few spots of grn-gy., few gyp nodules.
75.7	sh.; grn.-gy.
76.1	shaly gyp.; lt.-gy., f. gran., interbedded with grn.-gy. sh. layers 0.1-2.0 inches thick.
77.0	gyp.; med.-gy., uniformly med. gran. in upper half, but conspic. banded in lower half; bands consist of alabaster interlayered with med.-gran. gyp. and locally a few thin carbonate stringers. A few open cavities along bedding contain faint efflorescences of a soluble mineral; probably Mg or Na sulfate.
90.9	gyp.; mottled wh. alabaster & med.-gy. gran. gyp.
93.4	gyp.; pale pinkish-gy., med. gran., contains irreg. seams of dolo.
96.3	gyp.; pinkish-gy., gran., contains irreg. masses and veinlets of f. xlyn. yellowish-gy. dolo., in middle are clear selenite porphyroblasts up to 1 inch long.
96.8	lamin. dolo.; pale yellowish-gy., uniformly silt-sized xls., contains a few large selenite porphyroblasts and small knots of alabaster.
97.5	sh.; grn.-gy., sl. silty, scattered gyp. xls.
101.1	sh.; red-brn.; silty, few layers of lt.-med.-gy., scattered gyp. xls.
102.5	gyp.; wh. & pink, thinly interlayered with pale grn. sh.
103.7	gyp.; med.-gy., equigran., contains 0.7 ft. of thinly interlayered anhy. from 105.8-106.5. Probertite nodule, 1/8 inch in diam, found in gyp. 2 inches above anhy. Probertite identified by optical properties.
108.0	gyp.; med.-gy., med. gran., conspic. interlayered with lt.-gy. dolomitic gyp.
110.8	dolo.; pale cream-colored, microgran., sh. partings in basal 0.3 ft., a 1 inch layer of dolo.-chip breccia 1 ft. above base. Core loss of 2.4 ft. believed to be dolo.
115.2	sh.; grn.-gy., silty, few gyp. xls.
116.4	alabaster gyp.; white. Upper half contains numerous selenite porphyroblasts 1/2 in. in diam., numerous stringers of selenite gyp., and irreg. masses of yellowish-gy. dolo.
118.5	gyp.; even gran., conspic. interlayered with magnesitic alabaster, basal 1 in. is shaly and dk.-gy.
123.0	sh.; dk.-gy., silty, a siltstone in part.
123.9	sh.; red-brn., some lt.-gy., silty in part.
129.5	sltst.; lt.-gy., argill., few sh. partings, few gyp. xls.
129.8	shaly gyp.; wh., f. gran., much grn.-gy. sh., Reported core loss of 2.6 ft. in this interval.
133.0	sh.; grn.-gy., silty, some gyp. xls.
135.7	sh.; red-brn., some interbedded sltst., gyp. xls.
140.9	sh.; grn.-gy., sl. silty, few scattered gyp. xls.
141.4	sh.; red-brn., sl. silty.
143.5	sh.; grn.-gy.
143.9	sh.; red-brn, some grn.-gy., silty, thin layer of gyp. 2 ft. above base.
148.4	alabaster gyp.; lt.-gy., in form of irreg. knots and discontinuous layers separated by med. gran. gyp., minor amount of carbonate in form of thin stringers.
149.4	magnesitic gypsum; pale yellowish-gy, laminated in appearance due to intercalated (1/8-1 inch thick) magnesitic gyp. and gypsic magnesite. Magnesite identified by X-ray
152.0	sh.; grn.-gy., few near-vertical veins of satinspar.
154.5	sh.; red-brn., some grn.-gy., much satinspar
156.2	sh.; grn.-gy., silty.
156.4	gyp.; pale yellowish-gy., med.-gran., numerous irreg. selenite xls. 1/4-1 in. in diam.
157.8	gyp.; dk.-gy., f. gran.
158.0	dolo.; pale yellowish-gy., silt-sized grains, argill.
158.1	sh.; grn.-gy., some red-brn., silty.
158.8	sltst.; red-brn, some sh.
160.8	sh.; grn.-gy.
161.4	sh.; red-brn., some grn.-gy., silty, some selenite xls.
162.7	sh.; red-brn.; some grn.-gy., silty in part, thin veins of gyp., sl. taste of salt from here to bottom of hole.
166.7	sh.; grn.-gy., some sltst., some gyp. veins.
170.9	sh.; red-brn., few layers are grn.-gy., silty in part.



148.4	alabaster gyp.; lt.-gy., in form of irreg. knots and discontinuous layers separated by med. gran. gyp., minor amount of carbonate in form of thin stringers.
149.4	magnesitic gypsum; pale yellowish-gy., laminated in appearance due to intercalated (1/8–1 inch thick) magnesitic gyp. and gypsif. magnesite. Magnesite identified by X-ray
152.0	sh.; grn.-gy., few near-vertical veins of satinspar.
154.5	sh.; red-brn., some grn.-gy., much satinspar
156.2	sh.; grn.-gy., silty.
156.4	gyp.; pale yellowish-gy., med.-gran., numerous irreg. selenite xls. 1/4–1 in. in diam.
157.8	gyp.; dk-gy., f. gran.
158.0	dolo.; pale yellowish-gy., silt-sized grains, argill.
158.1	sh.; grn.-gy., some red-brn., silty.
158.8	sltst.; red-brn., some sh.
160.8	sh.; grn.-gy.
161.4	sh.; red-brn., some grn.-gy., silty, some selenite xls.
162.7	sh.; red-brn.; some grn.-gy., silty in part, thin veins of gyp., sl. taste of <u>salt</u> from here to bottom of hole.
166.7	sh.; grn.-gy., some sltst., some gyp. veins.
170.9	sh.; red-brn., few layers are grn.-gy., silty in part.
176.5	sh.; grn.-gy., some red-brn., veins & irreg. masses of gyp., silty in part.
178.5	sh.; red-brn., some grn.-gy., few xls. of gyp.
180.7	sh.; grn.-gy., has brn. hue in places, few gyp. veins, highly gypsif. in part.
189.8	sh.; red-brn., gyp. veins.
190.4	sh.; red-brn.; silty in part, gyp. veins, strong taste of <u>salt</u> and encrustations of fiberous salt xls. on outside of core from here to bottom of hole.
197.3	sh.; grn.-gy., brn. hue in part, silty in part, many veins and xls. of gyp. in top 1 ft.
201.3	sh.; red-brn., silty, few gyp. veins.
202.2	sh.; red-brn., nodules and xls. of gyp.
203.0	sh.; grn.-gy. in lower half, increase in red-brn. hue upwards, scattered nodules & veins of gyp.
203.7	rock salt; colorless, gyp. xls. & gray sh. impurities in upper part, several thin sh. & gyp. layers within salt.
204.2	sh.; grn.-gy.
204.7	rock salt; colorless, impurities are gyp. xls. & minor amounts of gy. sh.
205.5	sh.; red-brn. in lower part, grn.-gy. in upper part, reddish satinspar veins.
205.8	rock salt; colorless, grn.-gy. sh. and gyp. impurities in upper part, layers & inclusions of red-brn. sh. in lower part.
207.0	sh.; red-brn.; thick veins of red salt.
208.0	sh.; grn.-gy., veins of red salt.
209.7	rock salt; colorless, red-brn. sh. inclusions, 1/8 in. thick layer of shaly gyp. & gyp. xls. at base.
211.0	sh.; grn.-gy., gyp. xls., veins & a large inclusion of salt.
212.0	sh.; mottled red-brn. & grn.-gy., some veins & irreg. masses of colorless & red salt.
218.1	sh.; red-brn., some grn.-gy. in lower part, base marked by banded wh. gyp. with grn.-gy. sh. impurities.
219.2	rock salt; colorless, many grn.-gy. sh. impurities, thin sh. beds throughout.
222.2	gyp.; lt.-gy., impure, alternating with thin beds of gypsif. sh., compact. Many vugs, secondary deposits & veins of salt.
223.5	sh.; grn.-gy., several 1-in. thick veins of red salt, scattered gyp. veins & xls.

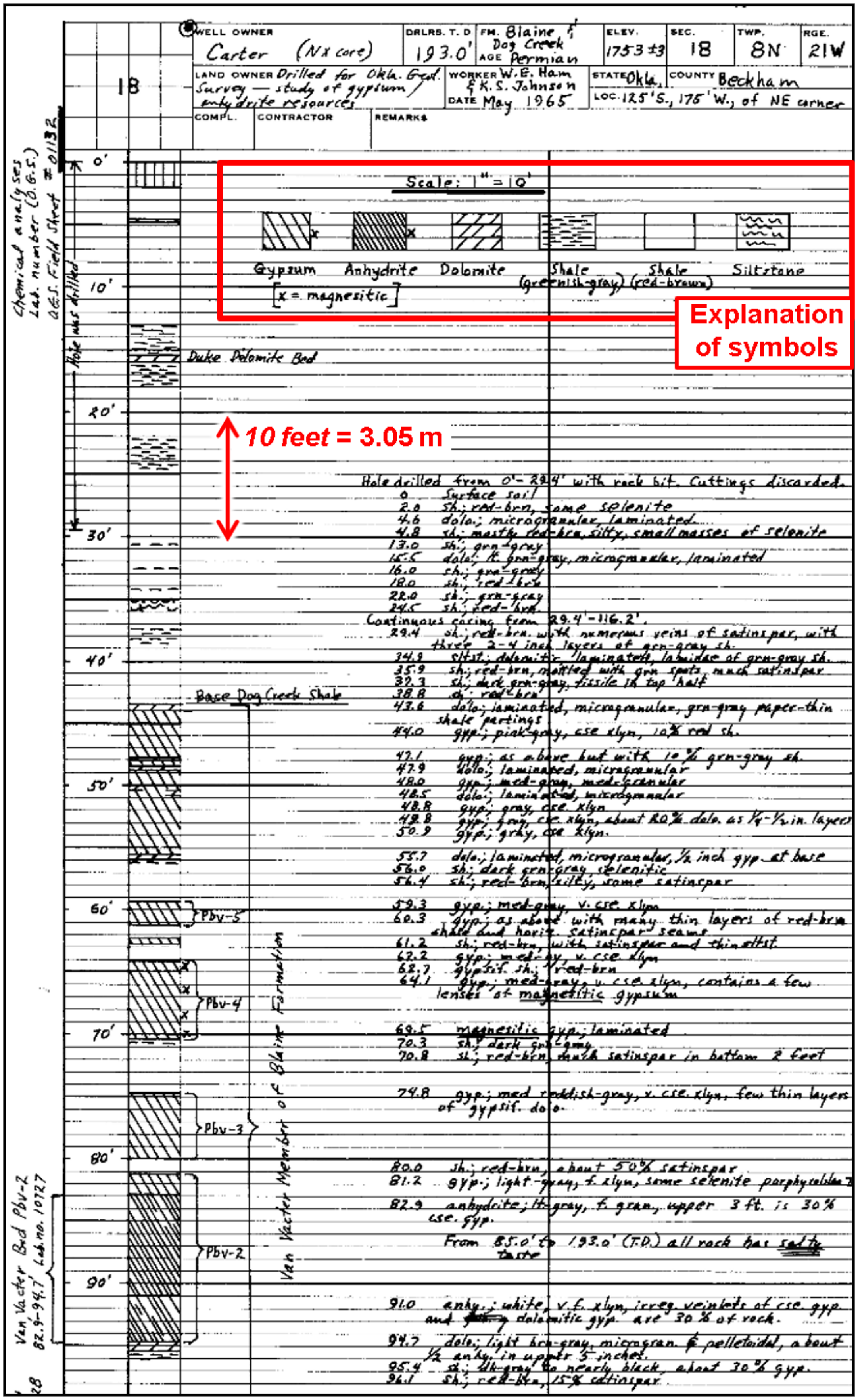
Scale: 1" = 10'



[■ = probertite]

㉖ 217.0 x– = Sample #26 from this hole, at a depth of 217.0', sent for X-ray.

[x = magnesitic]



WELL OWNER Carter (NX core)
DRLRS. T. D 193.0'
FM. Blaine & Dog Creek
AGE Permian
ELEV. 1753 ±3
SEC. 18
TWP. 8N
RGE. 21W
LAND OWNER Drilled for Okla. Geol. Survey — study of gypsum / anhydrite resources
WORKER W. E. Ham & K. S. Johnson
DATE May 1965
STATE Okla.
COUNTY Beckham
LOC. 125' S., 175' W., of NE corner
COMPL.
CONTRACTOR
REMARKS

Hole drilled from 0'- 29.4' with rock bit. Cuttings discarded.

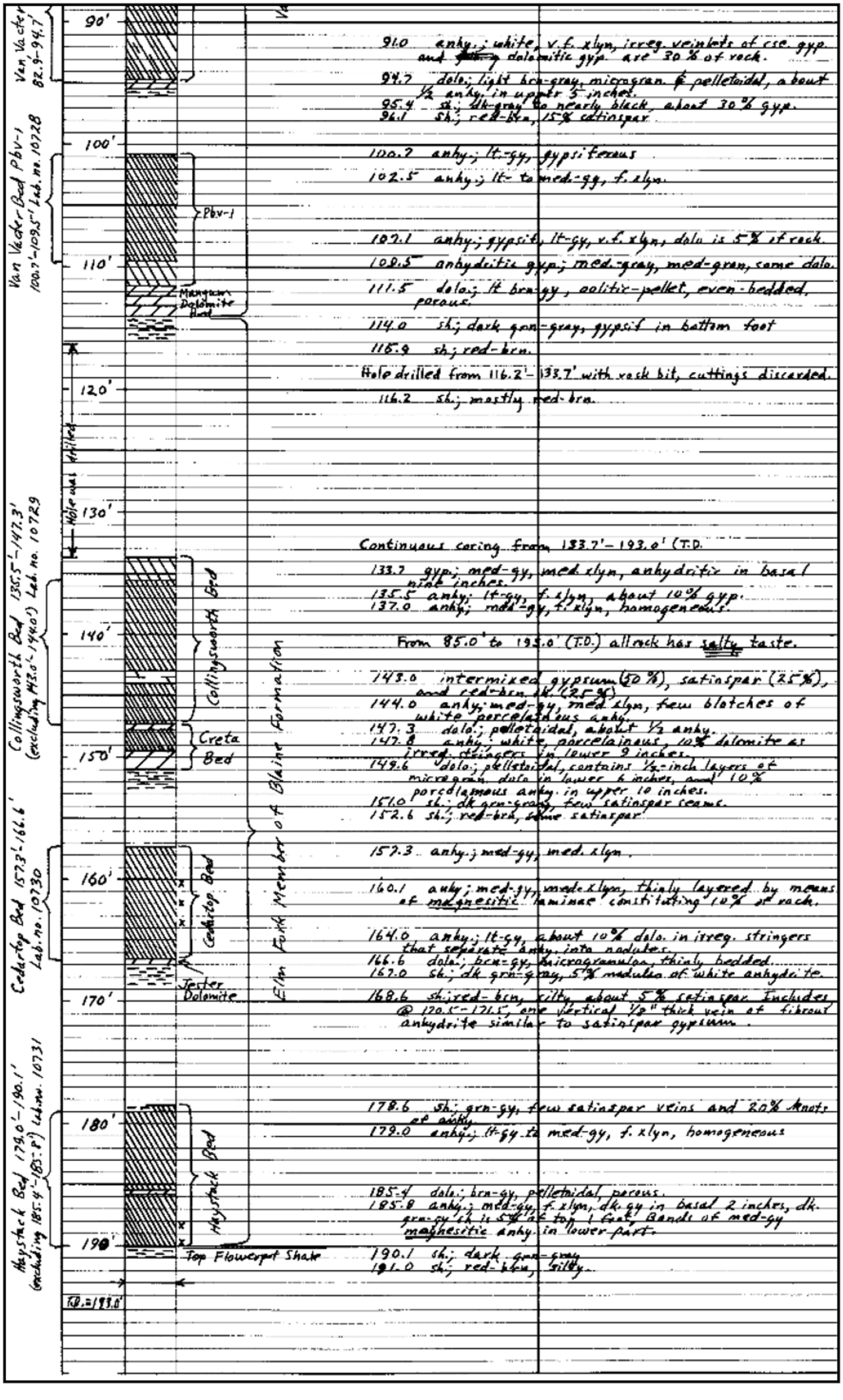
0	Surface soil
2.0	sh.; red-brn, some selenite
4.6	dolo.; microgranular, laminated
4.8	sh.; mostly red-brn, silty, small masses of selenite
13.0	sh.; grn-gray
15.5	dolo.; lt. grn-gray, microgranular, laminated
16.0	sh.; grn-gray
18.0	sh.; red-brn
22.0	sh.; grn-gray
24.5	sh.; red-brn.

Continuous coring from 29.4'-116.2'.

29.4	sh.; red-brn. with numerous veins of satinspar, with three 2-4 inch layers of grn-gray sh.
34.9	sltst.; dolomitic, laminated, laminae of grn-gray sh.
35.9	sh.; red-brn, mottled with grn spots, much satinspar
37.3	sh.; dark grn-gray, fissile in top half
38.8	sh.; red-brn
43.6	dolo.; laminated, microgranular, grn-gray paper-thin shale partings
44.0	gyp.; pink-gray, cse xlyn, 10% red sh.
47.1	gyp.; as above but with 10% grn-gray sh.
47.9	dolo.; laminated, microgranular
48.0	gyp.; med-gray, med-granular
48.5	dolo.; laminated, microgranular
48.8	gyp.; gray, cse. xlyn
49.8	gyp.; gray, cse. xlyn, about 20% dolo. as ¼-½ in. layers
50.9	gyp.; gray, cse xlyn.
55.7	dolo.; laminated, microgranular, ½ inch gyp. at base
56.0	sh.; dark grn-gray, selenitic
56.4	sh.; red-brn, silty, some satinspar
59.3	gyp.; med-gray, v. cse. xlyn
60.3	gyp.; as above with many thin layers of red-brn shale and horiz. satinspar seams
61.2	sh.; red-brn, with satinspar and thin sltst.
62.2	gyp.; med-gy, v. cse. xlyn
62.7	gypsif. sh.; red-brn
64.1	gyp.; med-gray, v. cse. xlyn, contains a few lenses of magnetitic gypsum
69.5	magnetitic gyp.; laminated
70.3	sh.; dark grn-gray
70.8	sh.; red-brn, much satinspar in bottom 2 feet
74.8	gyp.; med reddish-gray, v. cse. xlyn, few thin layers of gypsif. dolo.
80.0	sh.; red-brn, about 50% satinspar
81.2	gyp.; light-gray, f. xlyn, some selenite porphyrobla
82.9	anhydrite; lt. gray, f. gran, upper 3 ft. is 30% cse. gyp.

From 85.0' to 193.0' (T.D.) all rock has salty taste

91.0	anhy.; white, v.f. xlyn, irreg. veinlets of cse. gyp. and ~~[illegible]~~ dolomitic gyp. are 30% of rock.
94.7	dolo.; light brn-gray, microgran. & pelletoidal, about ½ anhy. in upper 5 inches.
95.4	sh.; dk-gray to nearly black, about 30% gyp.
96.1	sh.; red-brn, 15% satinspar



91.0 anhy.; white, v.f. xlyn, irreg. veinlets of cse. gyp. and dolomitic gyp. are 30% of rock.

94.7 dolo.; light brn-gray, microgran. & pelletoidal, about ½ anhy. in upper 5 inches.

95.4 sh.; dk-gray to nearly black, about 30% gyp.

96.1 sh.; red-brn, 15% satinspar.

100.7 anhy.; lt-gy, gypsiferous

102.5 anhy.; lt- to med-gy, f. xlyn.

107.1 anhy.; gypsif., lt-gy, v.f. xlyn, dolo is 5% of rock.

108.5 anhydritic gyp.; med-gray, med-gran, some dolo.

111.5 dolo.; lt brn-gy, oolitic-pellet, even-bedded, porous.

114.0 sh.; dark grn-gray, gypsif in bottom foot

115.9 sh.; red-brn.

Hole drilled from 116.2'-133.7' with rock bit, cuttings discarded.

116.2 sh.; mostly red-brn.

Continuous coring from 133.7'-193.0' (T.D.

133.7 gyp.; med-gy, med. xlyn, anhydritic in basal nine inches.

135.5 anhy.; lt-gy, f. xlyn, about 10% gyp.

137.0 anhy.; med-gy, f. xlyn, homogeneous.

From 85.0' to 193.0' (T.D.) all rock has salty taste.

143.0 intermixed gypsum (50%), satinspar (25%), and red-brn sh. (25%)

144.0 anhy.; med-gy, med. xlyn, few blotches of white porcelaneous anhy.

147.3 dolo.; pelletoidal, about ½ anhy.

147.8 anhy.; white, porcelaineous, 10% dolomite as irreg. stringers in lower 9 inches.

149.6 dolo.; pelletoidal, contains ½-inch layers of microgran. dolo in lower 6 inches, and 10% porcelaneous anhy. in upper 10 inches.

151.0 sh.; dk grn-gray, few satinspar seams.

152.6 sh.; red-brn, some satinspar

157.3 anhy.; med-gy, med. xlyn.

160.1 anhy.; med-gy, med. xlyn, thinly layered by means of magnesitic laminae constituting 10% of rock.

164.0 anhy.; lt-gy, about 10% dolo. in irreg. stringers that separate anhy. into nodules.

166.6 dolo.; brn-gy, microgranular, thinly bedded.

167.0 sh.; dk grn-gray, 5% nodules of white anhydrite.

168.6 sh.; red-brn, silty, about 5% satinspar. Includes @ 170.5'-171.5', one vertical ⅛" thick vein of fibrous anhydrite similar to satinspar gypsum.

178.6 sh.; grn-gy, few satinspar veins and 20% knots of anhy.

179.0 anhy.; lt-gy to med-gy, f. xlyn, homogeneous

185.4 dolo.; brn-gy, pelletoidal, porous.

185.8 anhy.; med-gy, f. xlyn, dk. gy in basal 2 inches, dk. grn-gy sh is 5% at top 1 foot, Bands of med-gy magnesitic anhy. in lower part.

190.1 sh.; dark grn-gray

191.0 sh.; red-brn, silty.