Oklahoma Geological Survey
Jeremy Boak, *Director*

Open-File Report 3-2019

Geologic studies, natural-brine emissions, and hourglass-selenite crystals at Great Salt Plains on Salt Fork Arkansas River, northwest Oklahoma

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Oklahoma Geological Survey Open-File Report Disclaimer

Preface

This report is updated from one that was originally prepared for the Tulsa District Office of the U.S. Army Corps of Engineers (USACE) in 1978 to characterize the geology at and near major natural salt plains in parts of the Arkansas River Chloride Control Project (ARCCP) area in northwestern Oklahoma. The ARCCP is designed to control natural chloride-brine emissions at major source areas in northwestern Oklahoma, and thus to improve water quality for municipal, industrial, and agricultural use downstream from the salt plains. Improvements that may help control brine emissions include construction of low-flow dams, pump stations, and diversion pipelines to impoundment facilities. The original 1978 report was titled: "Summary of geologic studies of major salt plains (Areas I, II, and III) of the Arkansas River Chloride Control Project, northwest Oklahoma and southern Kansas."

The current report looks specifically at one site in northwestern Oklahoma: Great Salt Plains (designated "Area I" by USACE), which is the largest salt plain in any part of Oklahoma or the ARCCP area. Great Salt Plains is located in Alfalfa County, just east of the town of Cherokee. Discussions of Big Salt Plain ("Area II") and Little Salt Plain ("Area III") are treated in Open-File Report 2–2019. http://www.ou.edu/content/dam/ogs/documents/data/OF2-2019.pdf

Although the original report is now dated, there is continued interest in reducing the flow of chloride brines in the Arkansas River and its tributaries. The original report had very limited distribution, and an electronic copy has not been available. Thus, in order to make the data more readily available to the geologic community, the Oklahoma Geological Survey is placing this updated version online as an Open-File Report.

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Purpose and scope of investigation

Permian-age salt deposits underlie a vast region extending across western Oklahoma and adjacent states, and many natural salt plains and salt springs exist along the east side of this region in the watersheds of Arkansas River and Red River (Fig. 1). Because of the large amount of salt (halite, NaCl) entering these two major water ways, the Tulsa District of the U.S. Army Corps of Engineers has been tasked to investigate and reduce this natural contamination and to improve water quality downstream from the salt plains. Efforts by the Corps are divided into studies of the Arkansas River Chloride Control Project and the Red River Chloride Control Project.

The purpose of my original report to the Corps of Engineers in 1978, and this current report, is to evaluate and summarize the surface and subsurface geologic features that bear upon natural emission of brine at Great Salt Plains (GSP) ("Area I," as designated by the Corps of Engineers), which is within the boundaries of the Arkansas River Chloride Control Project in northwest Oklahoma (Fig. 2). Field investigations were made of the surface geology at and near the salt flats of GSP, and this has been related to the subsurface distribution of salt and ways in which the brine reaches the land surface.

Field work and office studies for the original report to the Corps were carried out intermittently from 1968 through 1978; those data were then updated in 2018–19 for release of this report.

Rocks that crop out in the vicinity of GSP are reddish-brown shales, siltstones, and sandstones of the Hennessey Shale and the Nippewalla Group, which are Permian in age. The salt flats are underlain by the eastern limits of the Lower Cimarron salt unit, which is now being dissolved to provide brine that reaches GSP. The current study has led to a better understanding of the regional geologic framework in the vicinity of the salt flats, and demonstrates that brine is being produced by dissolution of salt beds beneath, and just west of, the salt plain, and that brine then migrates a short distance up to the land surface.

Methods of investigation

The original study entailed field work and office work: 1) field work included observation and characterization of rock units and overburden at and near GSP, and conferring with, and coordinating my efforts with, the geologic staff of the Corps of Engineers; and 2)

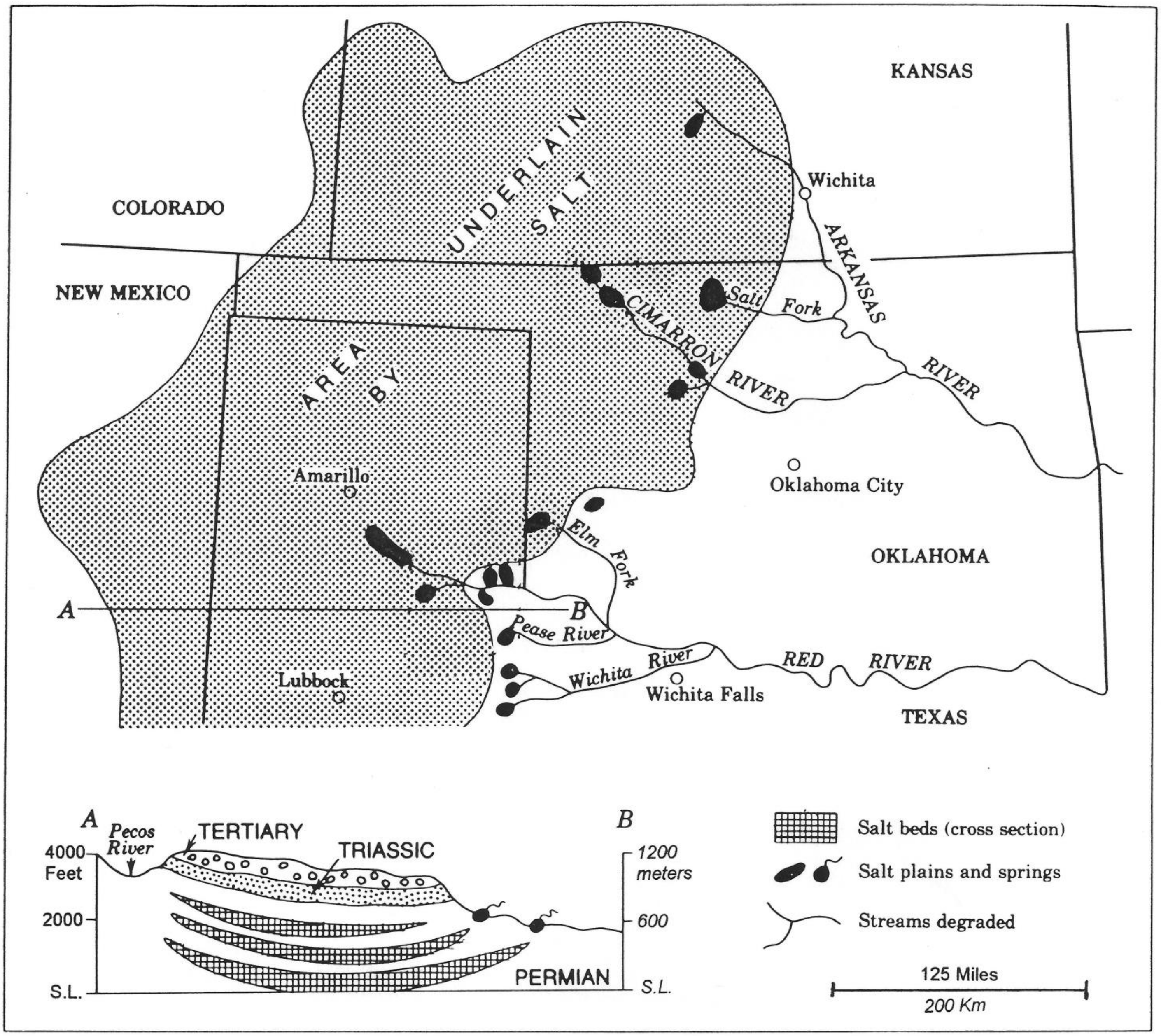

Figure 1. Map and schematic cross section showing distribution of Permian salts and salt plains in the Arkansas River and Red River watersheds of western Oklahoma and adjacent areas (Johnson, 1981).

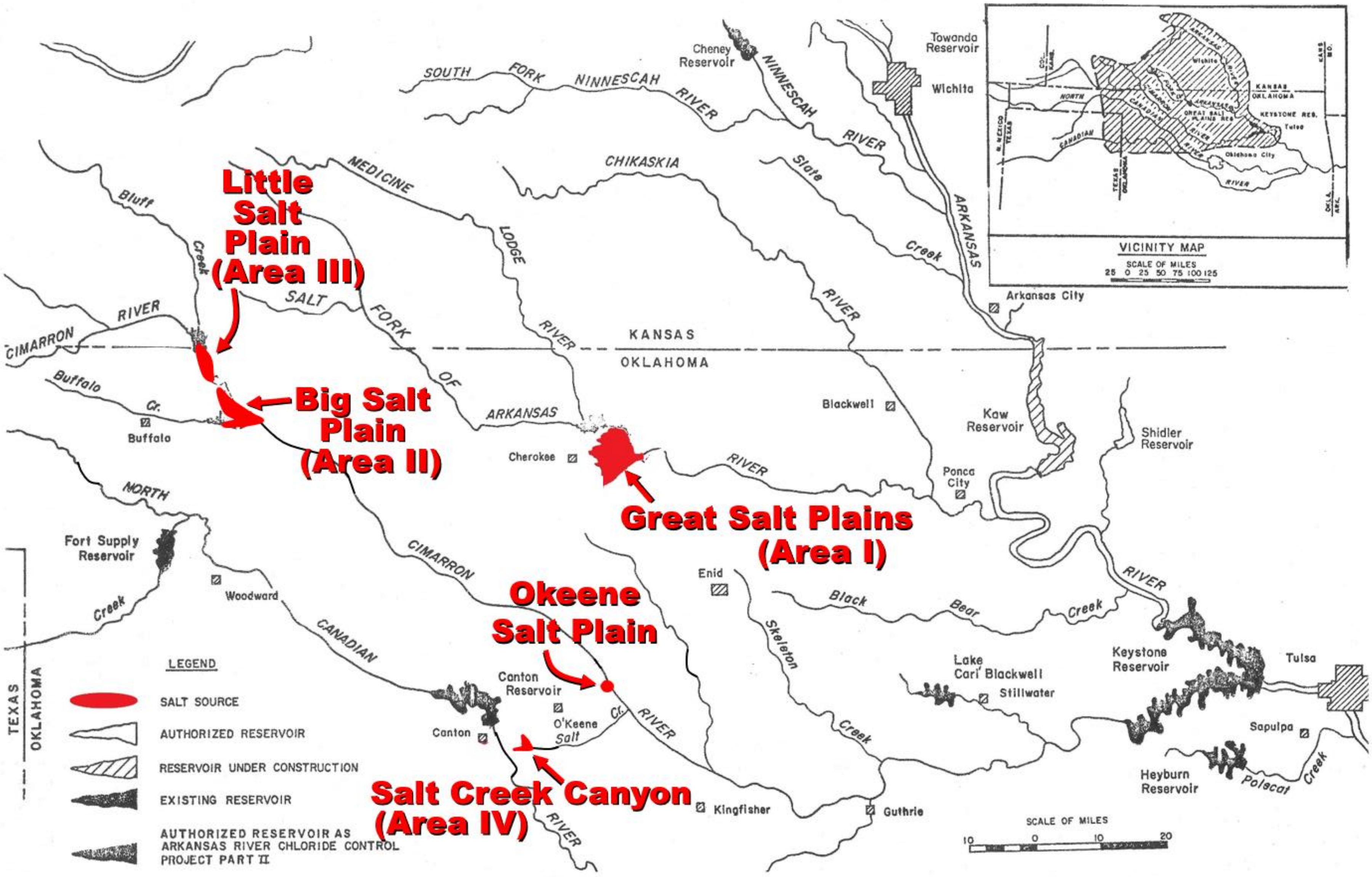

Figure 2. Location map showing brine-emission areas, reservoirs, and principal drainage of Arkansas and Cimarron Rivers in Oklahoma and Kansas.

office work consisted mainly of studying subsurface data from the Corps of Engineers and from petroleum test holes, and relating those data to the outcrop investigations. In addition, a continuing search of the literature (books, maps, articles, and reports) related to the study area was made, and references to new publication were forwarded to Corps personnel.

Several conferences with Corps personnel were held in the field and in the Tulsa District Office of the Corps of Engineers. These conferences had the multiple benefits of orienting new personnel to the on-going studies, of providing current data for project planning, and of keeping me informed of progress made by other investigators. It helped establish close liaison with Corps personnel and enabled me to provide continuing consultation of a variety of problems.

My original, unpublished report to the Corps in 1978 was entitled: “Summary of geologic studies of major salt plains (Areas I, II, and III) of the Arkansas River Chloride Control Project, northwest Oklahoma and southern Kansas.” This current report deals only with Great Salt Plains (Area I), whereas data on Big Salt Plain and Little Salt Plain (Areas II and III) have been released in another open-file report (Johnson, 2019b).

Acknowledgments

Much assistance and cooperation were provided by members of the Corps of Engineers during the course of this study. One or more field and/or office conferences were held with geologists Tom Gay, Gene Gilbert, Lawson Jackson, Wayne Wolfe, and Pete Smith, and with engineers Glenn Bayless and Bob James.

An earlier geologic report by Tom Gay and Gene Gilbert (U.S. Army Corps of Engineers, 1971) was extremely valuable in the study of GSP: it provided a foundation upon which to build my studies, and it fully summarized work done by the Corps in the area prior to 1971.

GENERAL GEOLOGIC SETTING

Outcropping rocks throughout the Arkansas River Chloride Control Project region are Permian in age, and all brine-emission sites are underlain by Permian sedimentary rocks. Therefore, the geology of Permian rocks in northwest Oklahoma and southern Kansas is a major key to understanding the salt deposits and brine emissions in the region. Bedrock at many places is overlain by a veneer of Quaternary alluvium (present-day river and stream deposits) and terrace deposits (remnants of earlier river deposits).

Great Salt Plains (GSP) is a flat, barren, featureless, salt-encrusted surface covering about 25 square miles in Alfalfa County, northwest Oklahoma (Figs. 3, 4). The salt flats consist of unconsolidated Quaternary deposits saturated with natural brine that is seeping up from underlying Permian salt-bearing strata. GSP is on the north shelf of the Anadarko Basin, a large east-west trending syncline extending across western Oklahoma and the Texas Panhandle. Outcropping Permian rocks in the area dip gently to the southwest into the basin at about 15 feet per mile (about 0.15 degrees). These outcropping Permian rocks consist mainly of reddish-brown shale, siltstone, and sandstone; they are interbedded with layers of salt-bearing strata in the subsurface beneath the salt plains, and are also interbedded with much salt in subsurface to the south and southwest, where salt layers are still preserved in deeper parts of the Anadarko Basin. Subsurface salt deposits beneath and near the salt flats are being dissolved to form brine that escapes at GSP.

Permian stratigraphy

Principal outcropping rock units studied for this report are the Hennessey Shale and Nippewalla Group of Permian age. Also of importance is the Lower Cimarron salt, which is the subsurface equivalent of part of the lower Hennessey Shale (Figs. 5, 6).

The Hennessey Shale and Nippewalla Group consist of reddish-brown shales interbedded with reddish-brown, orange-brown, and light-gray siltstone and sandstone. Total thickness of the Hennessey in northwest Oklahoma is about 700 feet. Mapping by Miller and Stanley (2003) regarded the Hennessey as being restricted to the area south and west of GSP, whereas roughly equivalent strata north and east of GSP were considered part of the Nippewalla Group (of Kansas nomenclature).

The Cimarron evaporites are a subsurface sequence of salt, shale, and gypsum/anhydrite that are equivalent to part of the Hennessey Shale (Fig. 5). Only the Lower Cimarron salt

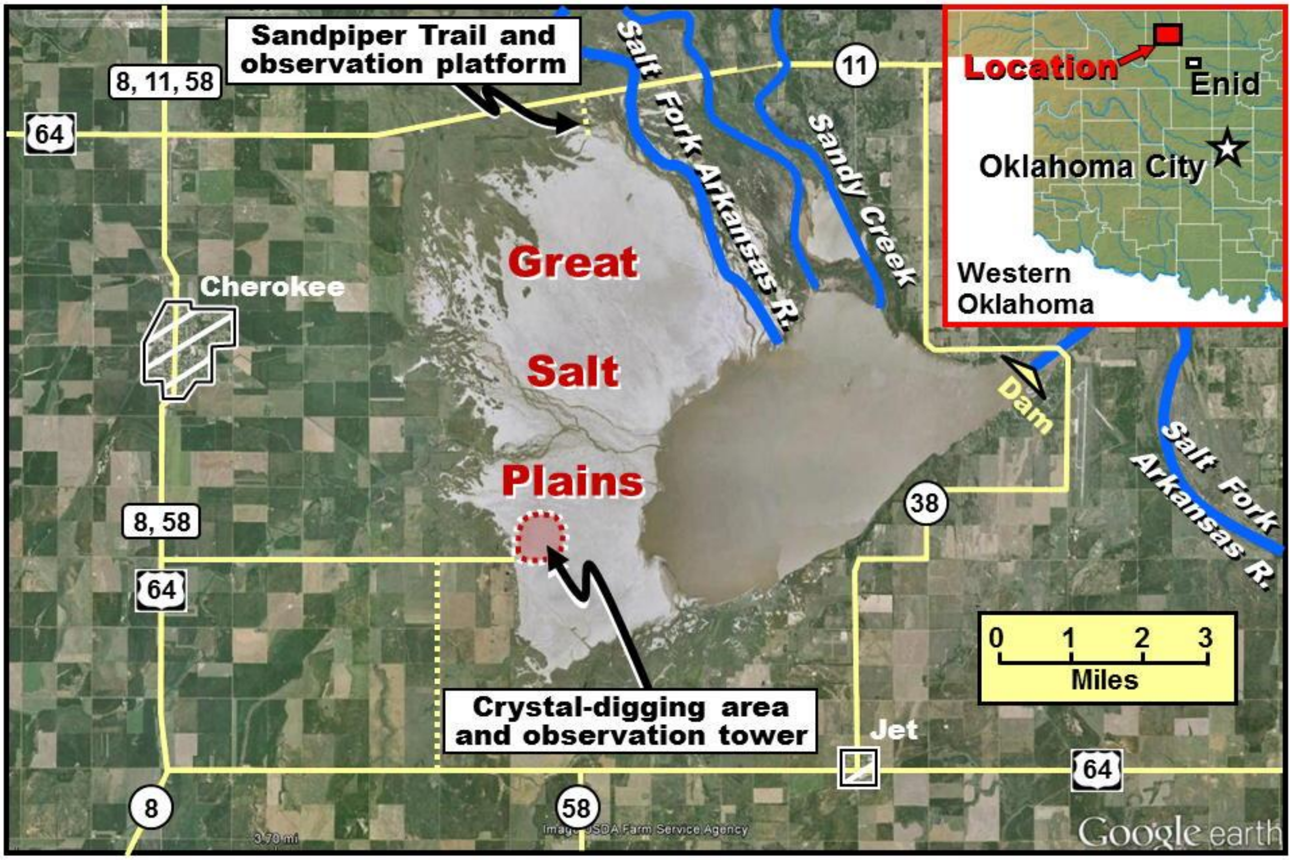

Figure 3. Location of Great Salt Plains in Alfalfa County, northwest Oklahoma (from Johnson, 2013a). Air photo from Google earth, dated September 2010.

Figure 4. View of salt flats on Great Salt Plains (courtesy Oklahoma Tourism Department).

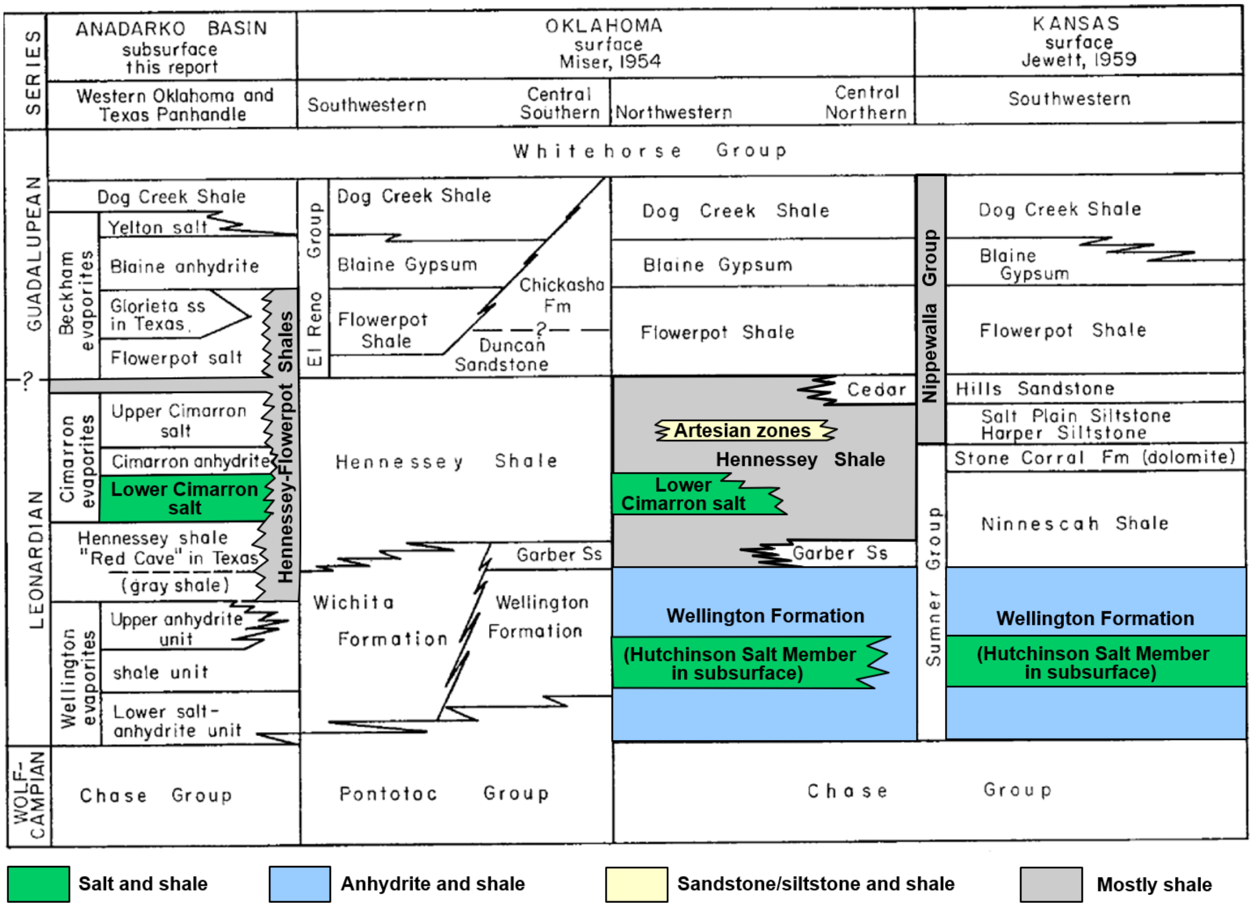

Figure 5. Stratigraphic nomenclature of Permian strata in outcrops and subsurface in northwest Oklahoma and nearby areas (Jordan and Vosburg, 1963). Rock units discussed in report shown in color.

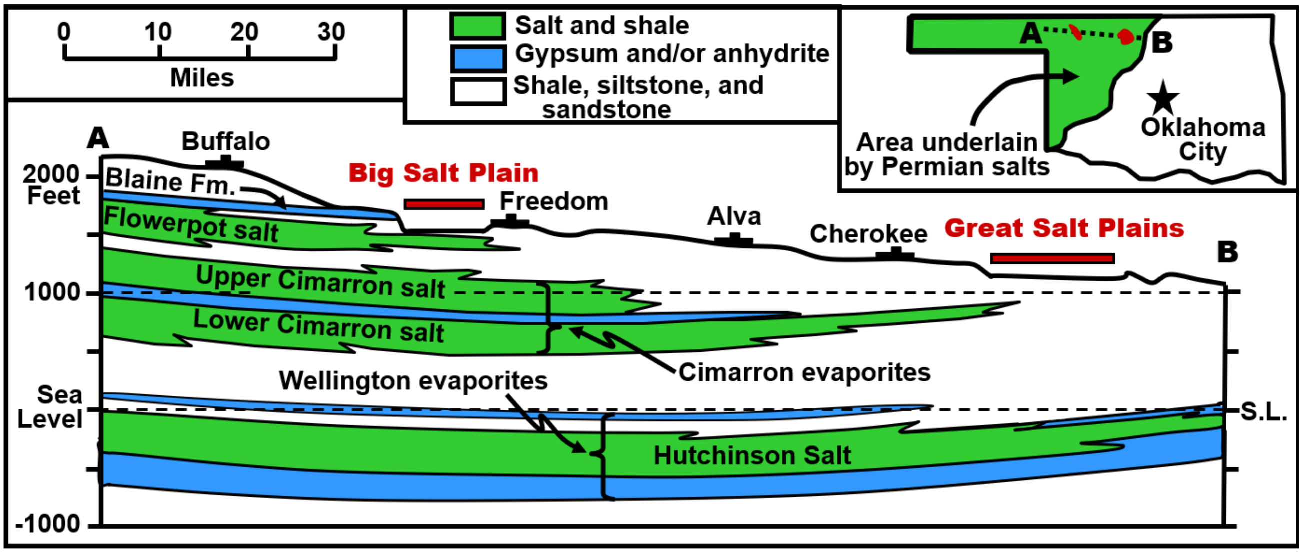

Figure 6. Generalized structural cross section of Permian strata in northwestern Oklahoma showing subsurface salt units and principal salt plains. Modified from Jordan and Vosburg (1963).

extends far enough to the east to reach GSP, and it is, in fact, the source of brines that reach the surface at GSP (Fig. 6).

Permian paleogeography

During the Permian Period, northwest Oklahoma and southern Kansas were located near the northeast end of a broad, shallow sea that covered much of southwestern United States (Fig. 7). Because of slow but continual sinking of the earth's crust beneath this inland sea, a thick sequence of redbeds and evaporites (salt, gypsum, and dolomite) was deposited north of the major reefs and other marine carbonates of the Permian Basin. Normal marine water entered the Permian Basin from the open ocean to the southwest, and after passing over the reefs it encountered the shallow sea (or shelf areas) where evaporation took place and evaporite rocks were deposited.

Permian shales, siltstones, and sandstones deposited in northwest Oklahoma were derived by erosion of land areas in eastern Oklahoma, eastern Kansas, and other areas farther to the east and northeast. Streams and rivers draining these land areas carried mud and other fine sediments into the shallow seas, where they were deposited as layers alternating with the salt, gypsum, and dolomite. Thus, fresh and brackish waters from the east mixed with marine and saline waters from the southwest: shales, siltstones, and sandstones were deposited from the former, whereas evaporites were deposited from the latter.

Deposition of salt

Deposition of the Lower Cimarron salt resulted from evaporation of sea water. The concentration of dissolved solids in the sea water was raised by this evaporation to the point where salt (halite, NaCl) was precipitated on the sea floor, or in the muds just below the sea floor. Salt beds in the Lower Cimarron salt do not have layers of gypsum, anhydrite, or dolomite associated with them in northwest Oklahoma. Thus, these salts do not represent a typical vertical sequence of evaporite deposition (which consists of dolomite beds, overlain by gypsum/anhydrite beds, overlain by salt beds). Far to the southwest, however, in the southern part of the Palo Duro Basin of Texas (and still farther south), dolomite and anhydrite beds make up a substantial thickness of Lower Clear Fork strata (Johnson, 1976, Plate 2; Presley, 1981), which are equivalent to the Lower Cimarron salts. It appears that a horizontal cycle of evaporite deposition took place during Lower Cimarron salt time: saline water was depleted of most of its dolomite and gypsum/anhydrite chemical constituents in the southern part of the Palo Duro

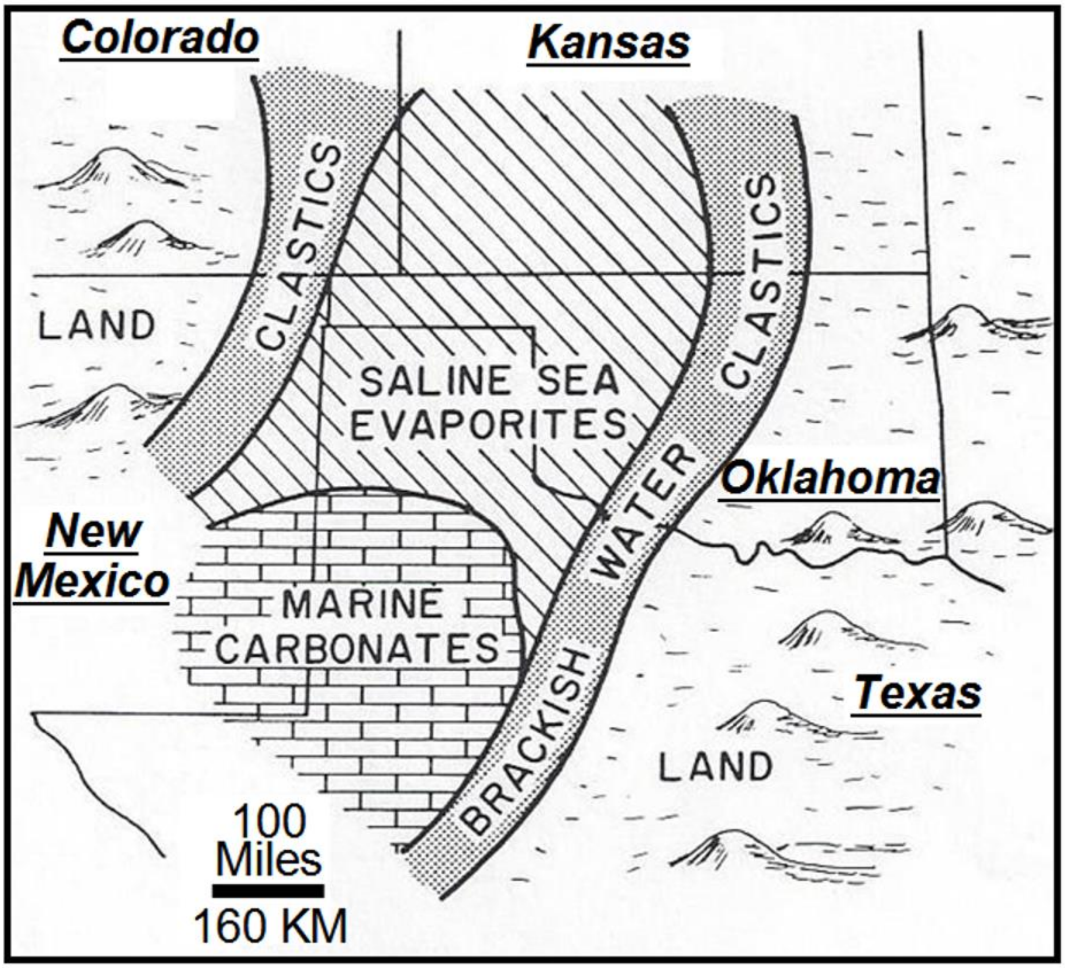

Figure 7. Paleogeography and principal facies of rocks deposited in the greater Permian Basin of southwestern United States during deposition of Cimarron evaporites.

Basin in Texas, and by the time it reached the Anadarko Basin and northwest Oklahoma, the water was saturated with NaCl (and it had much lesser amounts of $CaSO_4$ that could precipitate as gypsum or anhydrite).

Some of the Lower Cimarron salt in northwest Oklahoma occurs as discrete beds and layers of rock salt interbedded with layers of reddish-brown shale and salty shale; however, much of the salt unit is salty shale, which consists of isolated and/or intergrown crystals of halite, partially surrounded by red shale. These halite crystals probably developed and grew in the soft sediments just below the sea bottom shortly after deposition of the halite-encompassing mud or shale.

Subsurface distribution of salt

Salt is a highly soluble rock, more soluble than any other rock in the Permian sequence in this part of the State. Salt will be dissolved whether the water in contact with it is fresh or salty, as long as the water is not a brine already saturated with respect to salt (NaCl). Regional and detailed studies have shown that natural dissolution of bedded rock salt occurs at shallow depths at many places in western Oklahoma and adjacent areas on the east side of the greater Permian Basin (Johnson, 1976, 1981, 2013b, 2017, 2019a, 2019b; Gustavson and others, 1980; McGookey and others, 1988). Fresh ground water and brine can move laterally through aquifers, such as sandstone, or cavernous gypsum, dolomite, or salt, and these waters also can move vertically through sinkholes, fractures, and collapse features (Fig. 8).

Data on the subsurface distribution of salt in western Oklahoma and the Texas Panhandle were presented by Jordan and Vosburg (1963), Johnson (1976, 1981, 2013b, 2017), Johnson and Gonzales (1978), Gustavson and others (1980), Presley (1981), and McGookey and others (1988). Of special interest in northwest Oklahoma are maps showing distribution of the Flowerpot salt and the Lower Cimarron salt: a modified, and much-simplified version of these two maps made by Jordan and Vosburg (1963) is presented here (Fig. 9) to show the subsurface distribution of salt in comparison to known salt-emission sites.

GSP is located near the eastern limits of the Lower Cimarron salt (Figs. 6, 9), and it is the shallowest salt in the GSP area. Salty shale and salt beds of the Lower Cimarron salt are only about 230 to 300 feet below GSP, and are at depths of about 300 to 500 feet just northwest, west, and southwest of the salt plains. I believe that ground water is dissolving this salt, and the resulting brine moves upward and laterally until it comes to the surface at GSP.

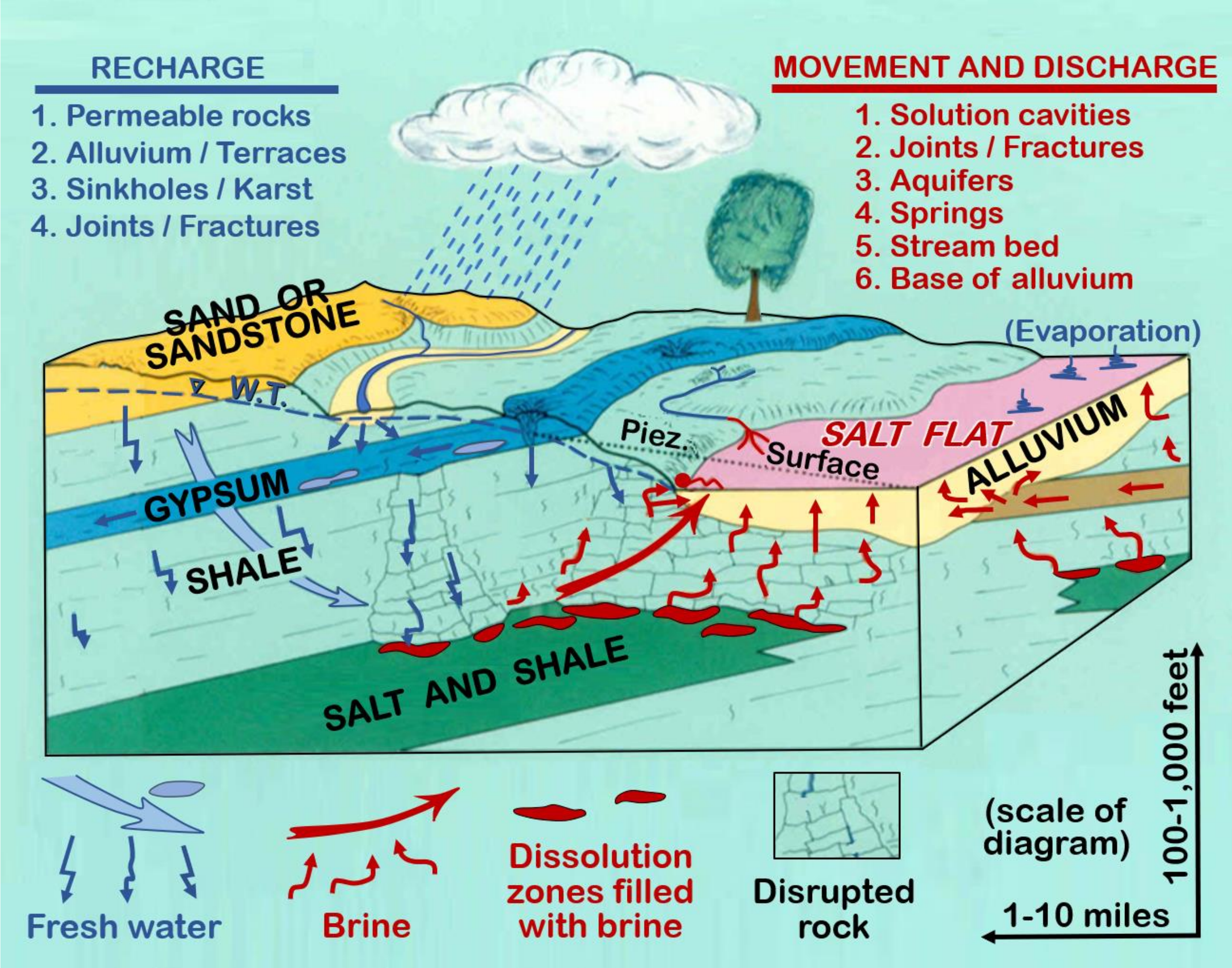

Figure 8. Schematic diagram showing circulation of fresh water and brine in areas of salt dissolution in northwestern Oklahoma (modified from Johnson, 1981).

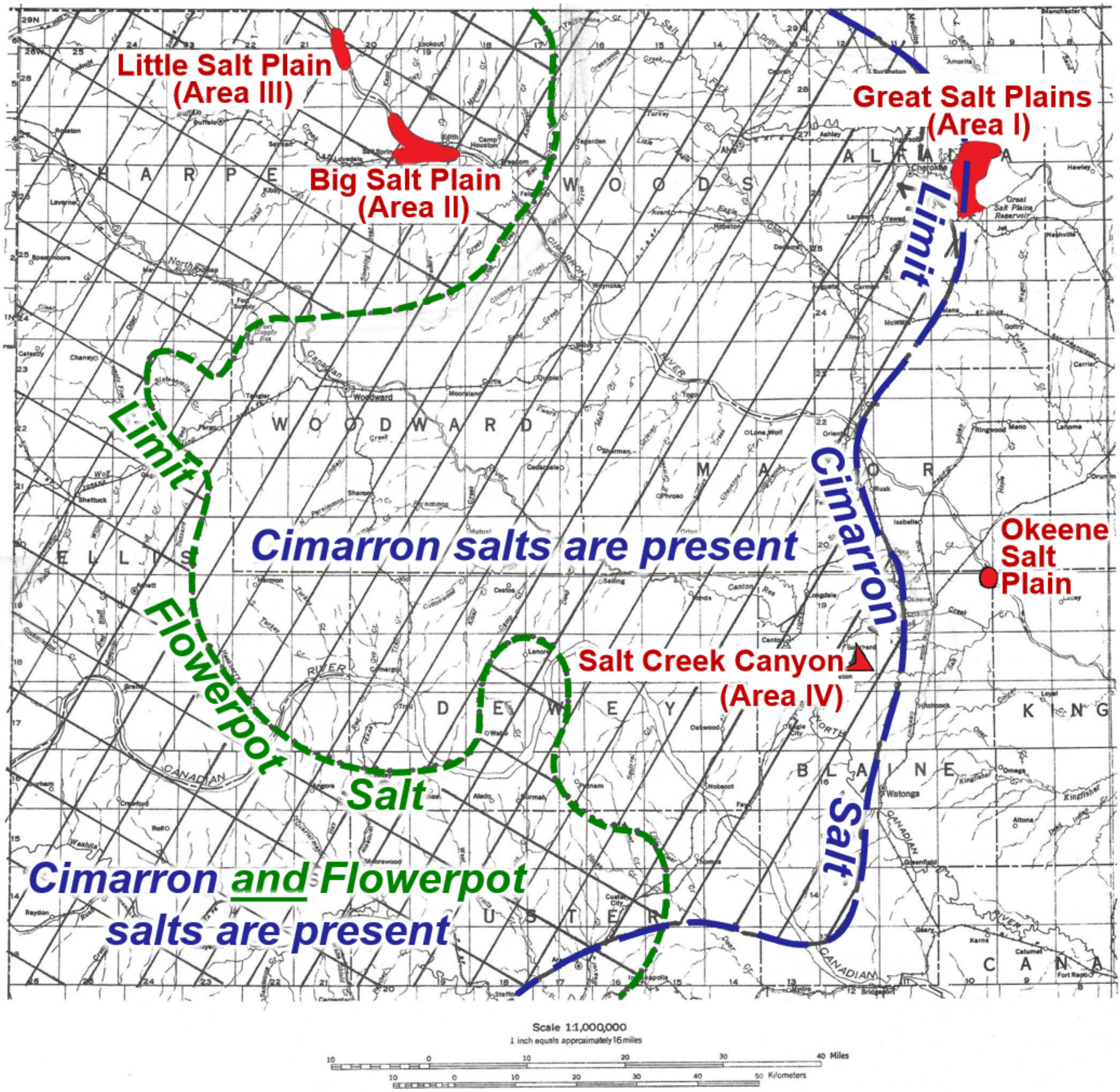

Figure 9. Distribution of Flowerpot and Cimarron salt units in the subsurface of northwestern Oklahoma, and limit of Lower Cimarron salt compared to Great Salt Plains. Modified from Jordan and Vosburg (1963, plate III).

Another major salt unit, the Lower Wellington salt and anhydrite unit of the Wellington evaporites, is present beneath all of northwest Oklahoma (Fig. 6). However, it is about 1,200 feet below the surface at GSP, and clearly does not contribute brine to these salt flats. This salt unit in the Wellington is equivalent to the Hutchinson Salt Member of the Wellington Formation in central and south-central Kansas.

GREAT SALT PLAINS (AREA I)

The 25 square miles of flat, salt-encrusted land makes GSP the largest salt plain in Oklahoma, or in any part of the Arkansas River system (Figs. 3, 4). A dam, completed in 1941, created the Great Salt Plains Reservoir (Fig. 3), and that lake now covers an additional 14 square miles of what was once part of the salt plain. Lake-water salinity varies from 2 to 15 grams of dissolved solids per kilogram of water, with the higher salinities occurring when heavy rains dissolve and wash the adjacent salt crust into the lake. Although the lake salinity varies, the amount of chlorides that flow from the reservoir into Salt Fork Arkansas River averages about 2,000 tons per day; that is second only to the average 4,600 tons of chloride emitted at Big and Little Salt Plains together.

The salt plains consist of loose Quaternary deposits saturated with high-salinity natural brine that is seeping up from underlying Permian rocks. Quaternary deposits consist of 10 to 25 feet 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 GSP have been discussed by Davis (1968), Johnson (1972, 2013a), Slaughter and Cody (1989), and Evans (2017).

The origin of the brine here appears to result from ground water dissolving the Lower Cimarron salt at moderate depths beneath, and just west of, the salt plains. Salt-water 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.

Surface geology

Bedrock formations cropping out in the vicinity of GSP 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 reddish-brown shales and siltstones, but also contain some layers of fine-grained sandstone and greenish-gray siltstone and shale.

Permian bedrock in the area dips gently to the southwest into the Anadarko Basin. The dip averages about 15 feet per mile (about 0.15 degrees) and ranges from 10 to 17 feet per mile. This agrees well with the structure of deeper beds: the base of the Wellington evaporites, at a depth of about 1,700 feet below the salt flats, dips about 20 feet per mile to the southwest (Jordan and Vosburg, 1963, Map B). There is no surface evidence of faults, or of erratic dips or undulating strata that might result from collapse of outcropping rocks due to underground dissolution of salt of other evaporites.

Most of the land surface 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 10 to 25 feet thick at GSP, but they are 10 to 50 feet thick north and west of the salt flats, and as much as 90 and 130 feet thick southeast and northeast, respectively, 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 halite that are locally up to two inches thick, especially after long hot and dry spells (Fig. 4).

Subsurface salt deposits

Rock salt (halite) is present in the Lower Cimarron salt in the shallow subsurface west of GSP, and also beneath the western part of the salt flats (Fig. 10). The total thickness of salt-bearing strata ranges from 80 to 120 feet in most parts of western Alfalfa County, but it decreases to only 15 feet in core #11 (all cores drilled by the Corps of Engineers from 1968 to 1970) beneath the salt flats, and is absent farther east (core #9) and in the northern part of the county (cores #22 and #23).

The Lower Cimarron salt sequence consists chiefly of reddish-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 farther west in core #16 (located in Woods County, in sec. 14, T. 27 N., R. 13 W.) as discrete layers of rock salt in beds 2 to 8 feet thick. In core #16, salt comprises an estimated 30 to 40% of an interval that is 96 feet thick (percentages and thickness of salt units in this and other cores are reported in U.S. Army Corps of Engineers, 1971). Data for other cores shown on Figure 10 include: core #10 contains 20 to 30 percent salt in an interval 54 feet thick; core #18 contains 20 to 30 percent salt in an interval 80 feet thick; core #7 contains 10 to 15 percent salt in an interval 52 feet thick; and core #11 contains 3 to 5 percent salt in an interval 15 feet thick. Depth to the top of salt beneath and near the salt flats was also reported by the Corps: core #18 = 232 feet; core #7 = 375 feet; and core #11 = 271 feet (note: depth to the top of salt in core #11 should be much less, but I presume the upper part of the salt has already been dissolved at this site). Halite in the 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

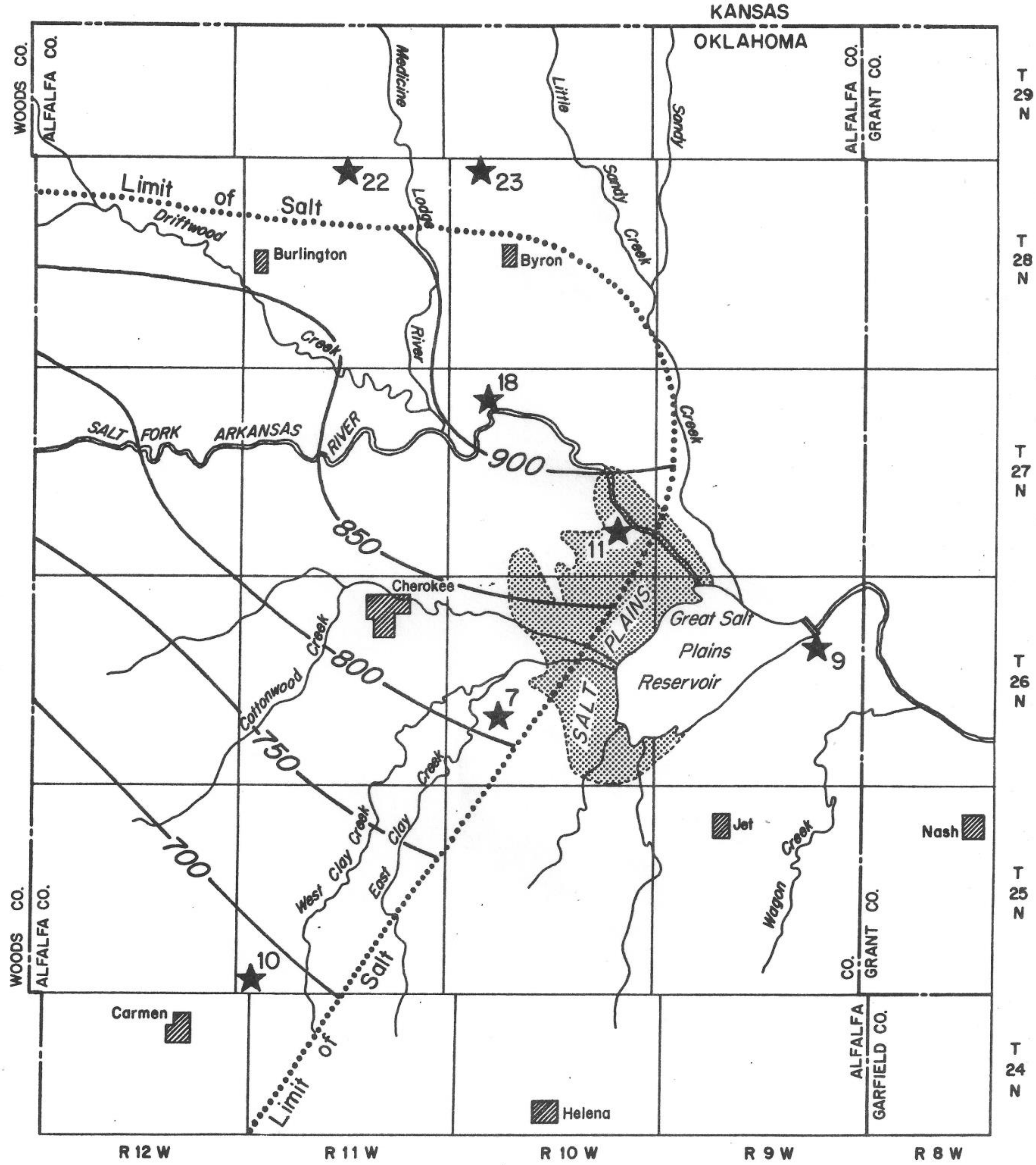

Figure 10. Map showing elevation on top of Lower Cimarron salt. Based upon 7 cores (stars) drilled through salt or equivalent strata, and upon interpretation of electric logs of nearly 50 oil and gas wells.

halite is also associated with irregular masses and vein-like stringers or layers of anhydrite and shale.

Depth to the top of the salt ranges from about 230 to 400 feet in the north, near the Byron-Burlington area, and increases southwestward to about 500 feet in the southwest corner of T. 26 N., R. 11 W., to 682 feet (in core #10), just northeast of Carmen. This increase in depth results from the gentle southwest dip of the salt beds (about 15 feet per mile) and the general increase in topographic elevation southwestward from Salt Fork Arkansas River and the GSP.

The Lower Cimarron salt in Alfalfa County was deposited at 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 salty shales near the limits of evaporite deposition, and finally into shales and siltstones that lack halite (core #9). I believe the present-day eastern and northern limits of this salt in Alfalfa County are 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 ground water, and the resultant brine is being emitted at GSP through two artesian zones (the upper and lower artesian zones) (Figs. 11, 12).

The only other significant salt unit in Alfalfa County is the deep Hutchinson Salt Member at the top of the Wellington Formation (Fig. 6): it consists or 400 to 450 feet of salt interbedded with anhydrite and shale, with halite making up about 40 to 50 percent of the unit. The top of the Hutchinson Salt is about 1,200 feet below ground level in the vicinity of GSP (Johnson, 1976).

Brine emission

Siltstone and sandstone beds that are 20 to 100 feet below the salt flats contain brine under artesian pressure (Fig. 12): these beds were cored by the Corps of Engineers, 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 halite at one time.

The origin of brine at GSP apparently results from the following: 1) fresh meteoric water seeps into the ground at unknown locations north, northwest, west, or southwest of the salt plains; 2) the water moves down vertically and laterally through porous sandstones and fractures

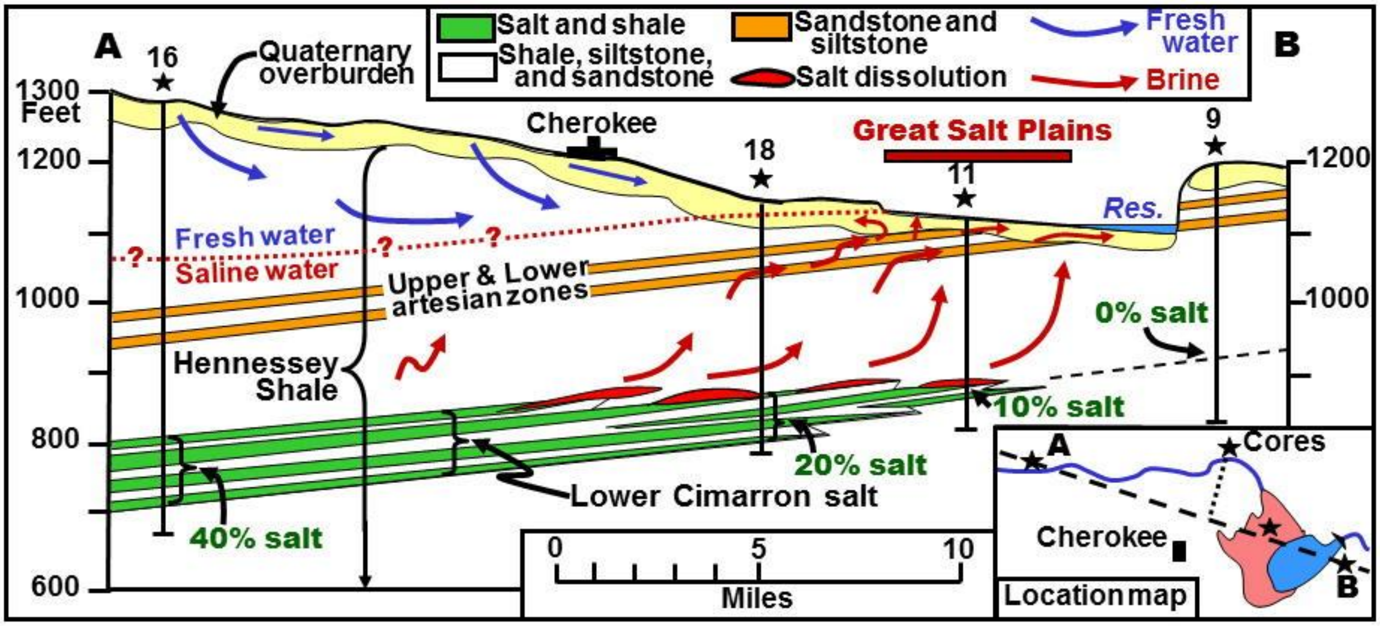

Figure 11. Generalized geologic cross section showing salt and other Permian bedrock units, as well as probable salt-dissolution zones and ground-waterflow patterns (from Johnson, 2013a). Based primarily upon four cores (16, 18, 11, and 9) drilled in 1960s by Corps of Engineers. Also shown is the percent of salt within the Lower Cimarron salt in each core.

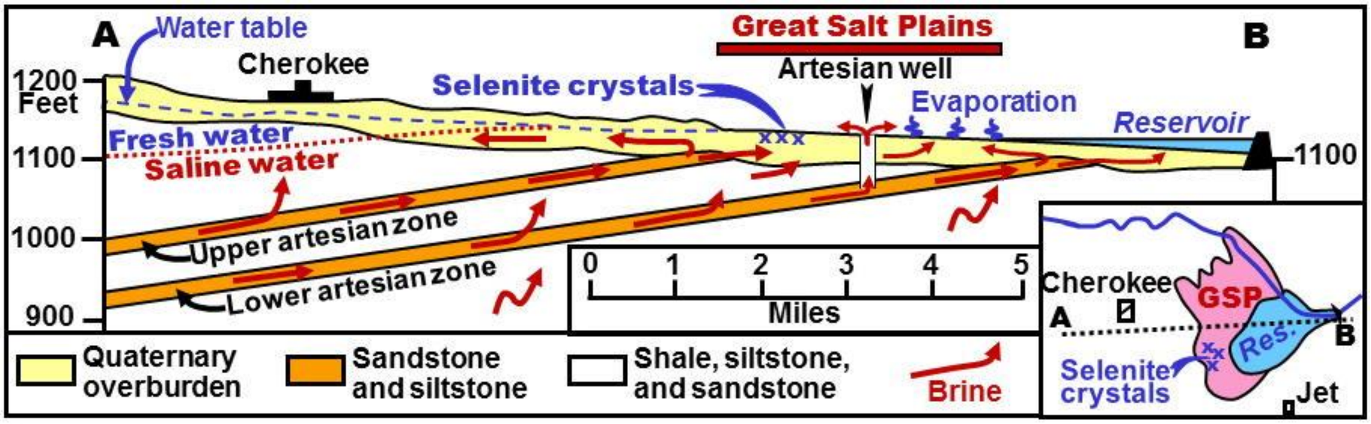

Figure 12. Generalized geologic cross section showing brine movement through upper and lower artesian zones in the vicinity of Great Salt Plains (from Johnson, 2013a).

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. The most probable sources of the salt are thin layers, veins, nodules, and disseminated crystals of halite in the Lower Cimarron salt (Fig. 11).

Brine is present in the bedrock under a hydrostatic head that causes it to rise above ground level at the salt flats in artesian flow. 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. 4) as water (H_2O) is evaporated from brine that is drawn to the surface by capillary action.

The upper and lower artesian zones are sandstone/siltstone units, each ranging from about 5 to 30 feet thick, that are interbedded with shales of the Hennessey Formation in a sequence that is about 80 feet thick (U.S. 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 are generally lenticular and 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 Corps of Engineers established that the two artesian zones subcrop at the base of Quaternary overburden in the vicinity of GSP and the much smaller Sucker Flat Salt Plain, about 4 miles to the north (Fig. 13). High-salinity natural brine in the bedrock aquifers has a *chloride* content normally ranging from about 90,000 to 150,000 parts per million (ppm), although locally it is up to 160,000 ppm (Fig. 14). *(Note: the sodium chloride content of this brine normally ranges from 150,000 to 250,000 ppm, or about 15 to 25% by weight. For comparison, sea water has a total salinity of only about 35,000 ppm, or about 3.5% by weight.)* The other chief constituents of brine in the bedrock at GSP are calcium (Ca, ±1,500 ppm), magnesium (Mg, ±1,000 ppm), and sulfate (SO_4, ±7,000 ppm) (Johnson, 1972). 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 both halite (NaCl) and also of gypsum ($CaSO_4 \cdot 2H_2O$) as hourglass-selenite crystals.

Although lateral movement of brine through artesian zones is the dominant movement, vertical migration of brine also occurs through fractures, joints, and fissures in the rock. I believe there is enough interconnection between the two artesian zones that we could consider

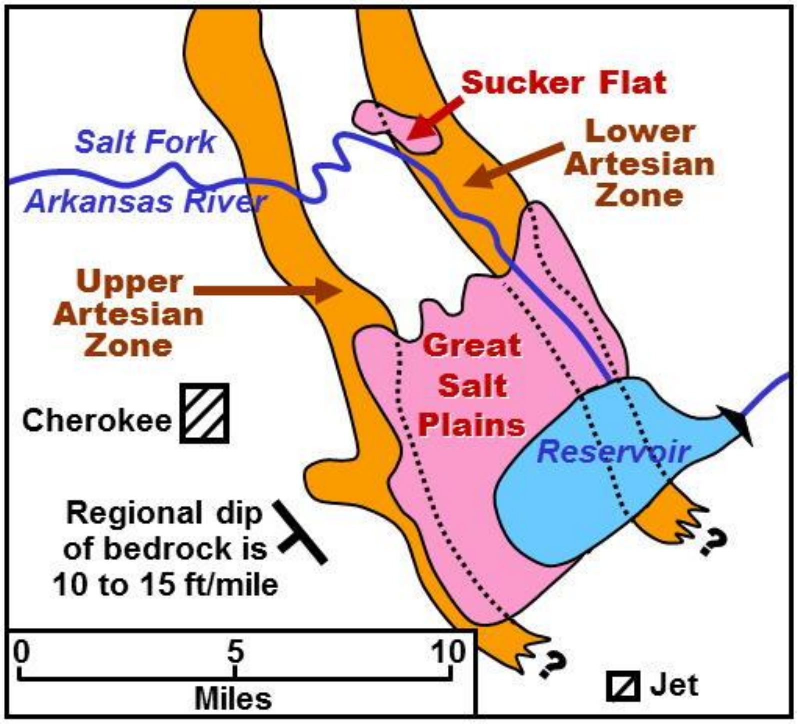

Figure 13. Subcrop of Permian bedrock artesian zones at base of Quaternary overburden (from Johnson, 2013a)—based upon borehole data from US Army Corps of Engineers (1971).

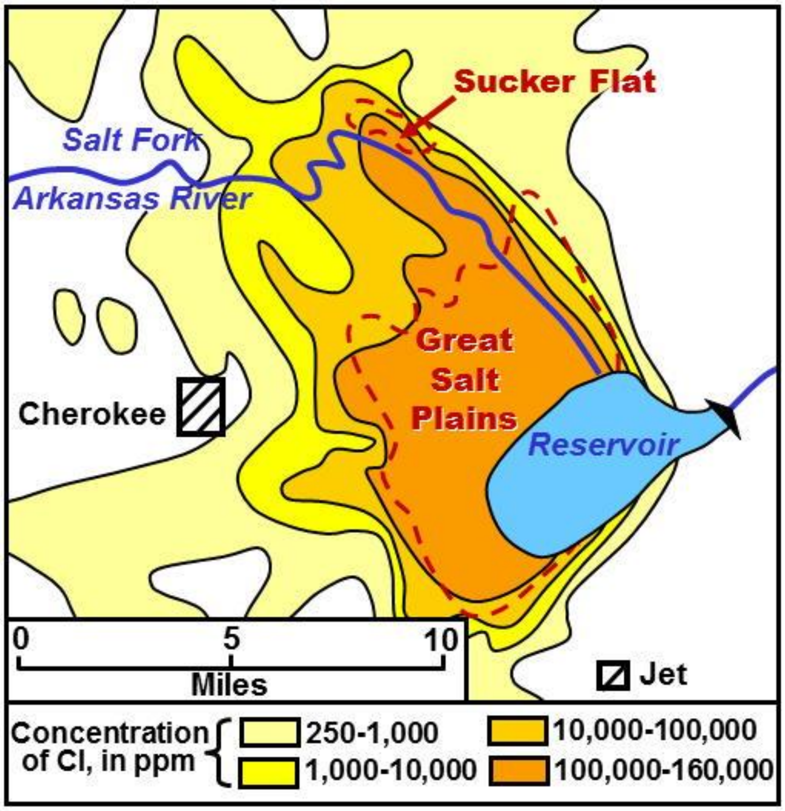

Figure 14. Chloride concentration of ground water at top of Permian bedrock, from Johnson (2013a)—based upon borehole data from US Army Corps of Engineers (1971). Note how higher chloride concentrations coincide with subcrop of upper and lower artesian zones.

the entire 80 feet of strata as a single aquifer system with the two zones of much higher permeability. Fractures, joints, and fissures in the aquifer and in overlying bedrock result at least in part from settling and collapse due to partial dissolution of underlying salt beds.

Hourglass-selenite crystals

Note: this section is liberally taken from Johnson (1972, 2013a). Brine entering GSP is fully saturated with respect to both sodium chloride (NaCl—halite, salt) and calcium sulfate ($CaSO_4 \cdot 2H_2O$—gypsum). Once the brine enters the Quaternary overburden, it is further concentrated by evaporation at the land surface. Brine rises to the water table, several inches or more below the surface, and capillary action draws it up to the land surface where it is evaporated. Halite is precipitated as a crust (locally up to two inches 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 26 inches, and the average rate of fresh-water evaporation is about 80 inches (Davis, 1968).

Hourglass-selenite crystals (Fig. 15) are unique to the GSP, and they were designated as the "official Oklahoma State Crystal" in 2005. The interior of each crystal contains a ghostlike, hour-glass form consisting of sand, silt, and/or clay particles incorporated within the crystal as it grows (Fig. 16). The reddish-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, the (110) crystal faces, whereas particles adjacent to the sides of the crystal are merely pushed aside (Fig. 16).

The reason for this hourglass pattern is not clear, but it appears that the bond between molecules forming the smooth faces on the sides of the crustal 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 is not strong enough to push foreign matter aside, and therefore new layers envelop the reddish-brown particles.

Crystals form just below the surface of GSP, seldom more than two feet deep. Selenite occurs as individual crystals up to seven inches long, and clusters of intergrown crystals have weighed as much as 38 pounds. Crystals can enclose sticks, rocks, bones, and cockleburs that are part of the host sediment.

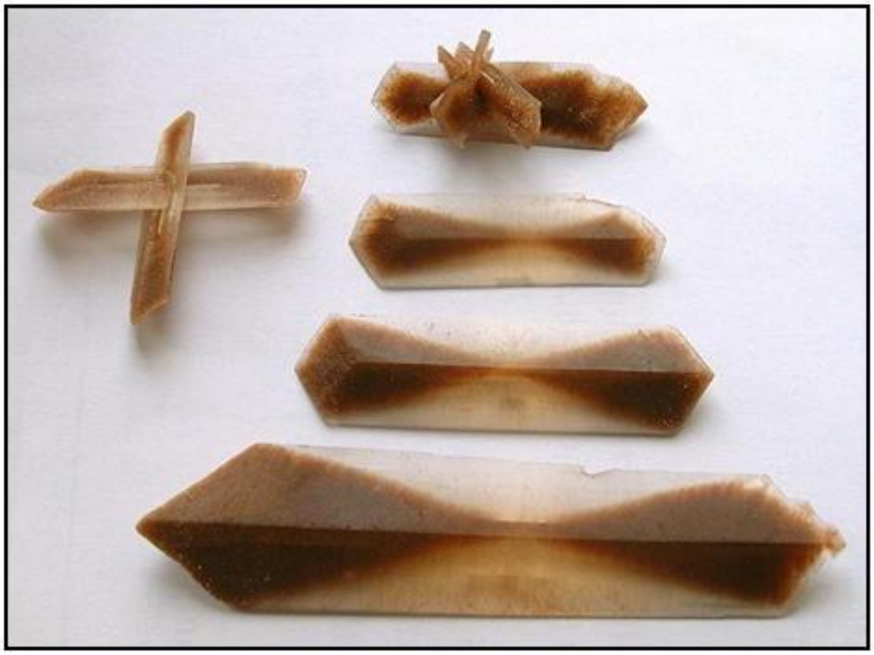

Figure 15. Samples of hourglass-selenite crystals that grew in clay, and (at top and left) two samples of twin crystals (from Johnson, 2013a).

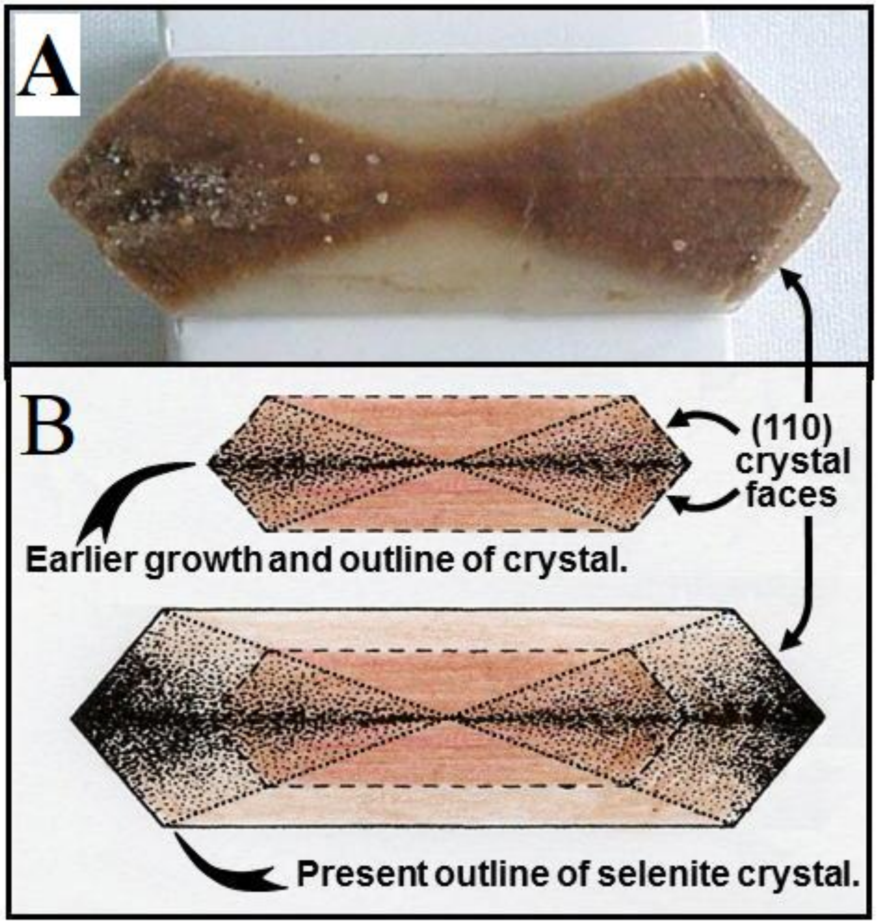

Figure 16. Top (**A**): hourglass-selenite crystal, three inches long, that grew in sand and silt. Bottom (**B**): drawing of hourglass-selenite crystal showing two stages of growth (from Johnson, 2013a).

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 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. The only access area for collecting crystals is shown on Figure 3 (in the south), and the Sandpiper Trail Observation Platform is accessible for bird watching from State Highway 11 (on the north).

To dig for crystals (Fig. 17), the following is recommended by the GSPNWR. Dig a hole about two feet wide and one to two feet 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

GSP 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 GSP 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 GSP to collect salt, just as Native Americans had done centuries earlier. And during World War II, GSP 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 Corps of Engineers, the crystal-digging area was cleared in 2009, although warnings are posted to advise the public of potential hazards.

Contact with GSPNWR is at:

Great Salt Plains National Wildlife Refuge
Rt. 1, Box 76
Jet, OK 73749
Phone: (580) 626-4794

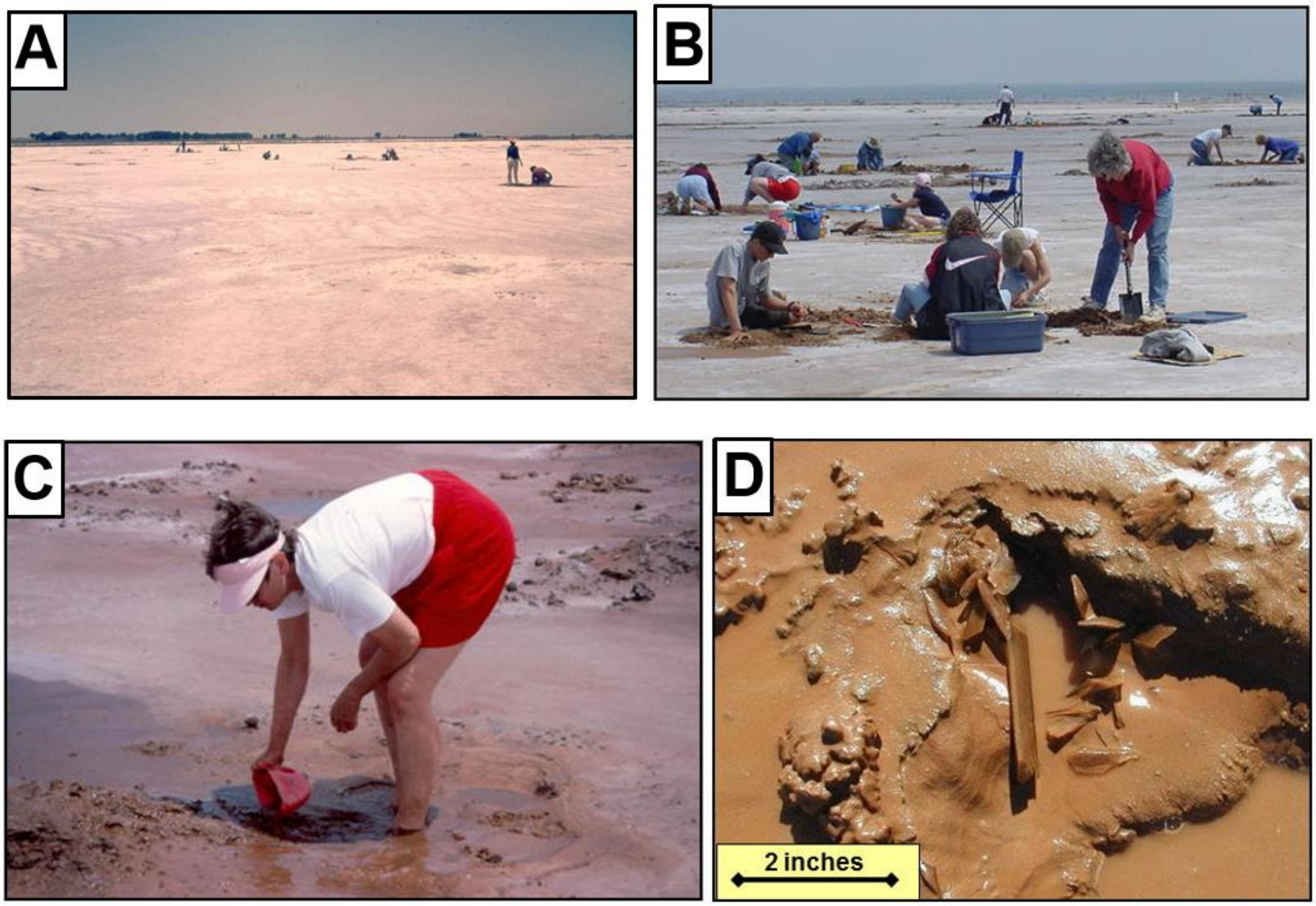

Figure 17. Collecting hourglass-selenite crystals on Great Salt Plains (from Johnson, 2013a).
A: view of salt plain. **B:** families and groups digging for crystals on salt plain.
C: Claren Kidd, retired geology librarian at The University of Oklahoma, digging for crystals.
D: selenite crystals are exposed just several inches below the surface of salt plain.

CONCLUSIONS

1. Working closely with Corps of Engineers geologists and engineers, and with other A-E contractors, helped establish the basic geologic framework for the region and detailed geology of the GSP area. Results of core drilling into bedrock were invaluable in all phases of geologic study, and such information is needed for any additional studies here, or similar studies in other problem areas.

2. Lower Cimarron salt is present in the subsurface beneath, and to the west and southwest of, GSP, and that salt is being dissolved to produce brine that migrates upward and reaches the salt flats.

3. The Wellington evaporites also contain an important salt unit (the Hutchinson Salt Member, of Kansas terminology), but it is about 1,200 feet below the salt plains and is not believed to be making any contribution to the GSP.

4. Salt deposits beneath GSP occur only as halite (NaCl); there is no evidence of potash or any other type of salt in the Lower Cimarron salt. There is, however, enough gypsum/anhydrite being dissolved from the Lower Cimarron salt (or other subsurface strata) to cause saturation of the brine with $CaSO_4$, and precipitation of hourglass-selenite crystals just below the surface in parts of GSP.

5. Some of the Lower Cimarron salt occurs as discrete beds and layers of rock salt interbedded with layers of reddish-brown shale and salty shale. However, much of the salt also occurs as isolated and/or intergrown crystals of halite, partially surrounded by reddish-brown shale.

6. Lower Cimarron salt is being dissolved at depths of about 233 to 500 feet beneath the surface of GSP and nearby areas.

7. Brine being emitted at GSP is formed by ground water dissolving the Lower Cimarron salt. The brine then migrates laterally and upward through interconnected aquifers and enters the base of Quaternary deposits comprising the salt flats. Joint systems and fractures (probably associated with solution and collapse of underlying salt deposits) are probably the principal means of vertical movement of brine. This process has been going on intermittently or continuously for a long time, probably tens of thousands of years, or perhaps even hundreds of thousands of years.

8. Evidence of subsurface dissolution of salt beneath and/or near GSP includes: 1) proximity of the salt flats to the eastern limit of Lower Cimarron salt; 2) the Lower Cimarron salt is fairly shallow in the area and can be reached by descending fresh, or unsaturated, meteoric waters; 3) brine reaching the surface is saturated (or nearly saturated) with NaCl, indicating contact of ground water with deposits of rock salt; and 4) the Na/Cl ratios of brine are typically about 0.64, which is to be expected when brine is derived by dissolving halite (NaCl).

9. Additional geologic and hydrologic studies are needed to fully understand the ground-water flow patterns that are bringing brines to the surface at GSP.

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