Chapter 12

Salt Domes in the Gulf Coast Aquifer

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Introduction

Salt domes are common geologic features within the Gulf Coast aquifer along the upper Texas Coast. The core of a salt dome forms a vertically elongate, cylindrical stock, consisting of 90 to 99 percent crystalline rock salt (halite). Cap rock composed of sulfate and carbonate minerals commonly overlies the crest of the salt stock and drapes down the uppermost flanks (Figure 12-1). Salt stock and cap rock are enclosed in sediments and sedimentary rocks of the Gulf Coast aquifer and deeper saline-water intervals. Salt-dome crests are generally one to three miles in diameter and buried at depths that range from land surface (essentially zero feet) to greater than 10,000 feet.

Shallow salt domes have the potential to increase groundwater salinities in the Gulf Coast aquifer in two ways: first by direct dissolution and transport of soluble dome minerals and second by providing pathways for groundwater mixing between shallow freshwater and deep saline-water aquifers. The salt domes of the Texas Gulf Coast have been thoroughly explored in the search for oil and gas, but the effects of shallow salt domes on groundwater quality have been less well studied. The purpose of this paper is to review the available literature on the salt domes of the Texas Gulf Coast and summarize our current understanding of salt dome hydrogeology.

Salt Dome Geology

Salt domes are geologic structures that grow and develop as sediments are being deposited around them (Seni and Jackson, 1984). The salt originally formed bedded evaporite deposits in the ancestral Gulf of Mexico during the Jurassic period. A thick (greater than 20,000 feet) sequence of sedimentary rocks now overlies the salt source layer (Figure 12-2). Salt, which is a low-density, ductile mineral, is gravitationally mobilized by sediment loading, forming a variety of upwelling structures, one of which is the cylindrical salt dome. The growth of salt structures, in turn, influences the structure and stratigraphy of surrounding sediments and sedimentary rocks. Uplift and upward drag occur against the salt stock and over its crest. Steeply dipping strata terminate against the salt stock, and shallower layers arch over the dome crest (Figure 12-2). The zone of uplift near the dome is surrounded by areas of subsidence and downwarping (Figure 12-2). Faults and fractures are also common features of salt dome growth.

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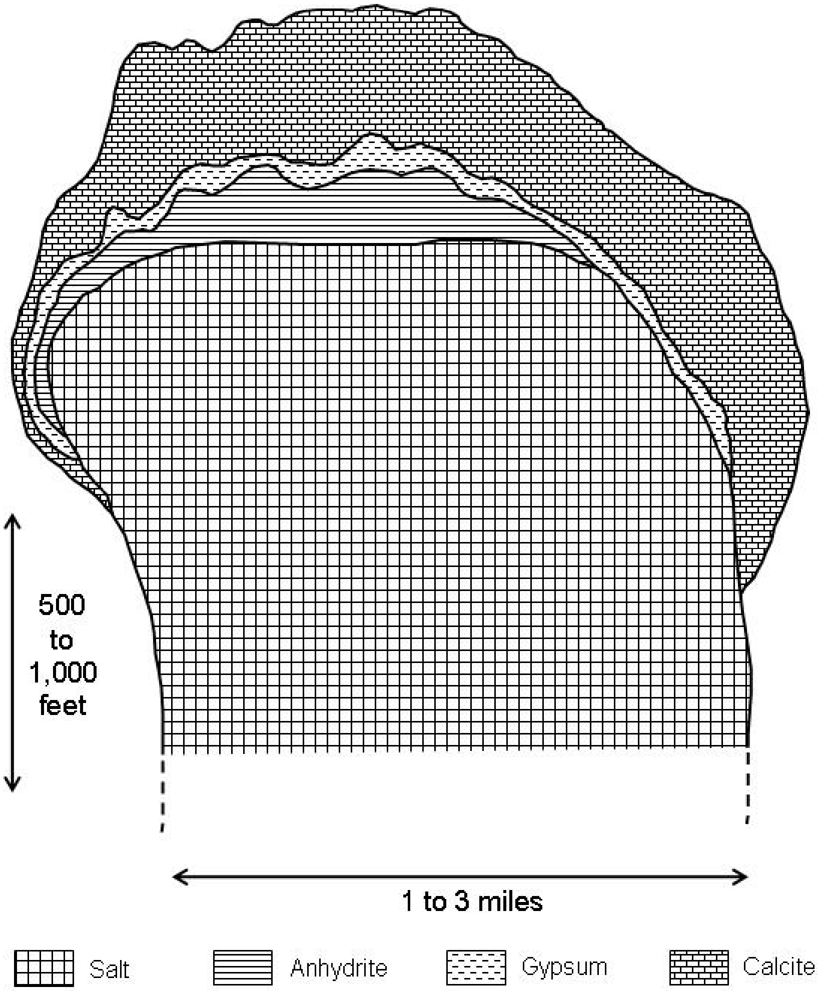


Figure 12-1. **Generalized cross section of a salt dome showing salt stock and cap rock mineralogical zones (modified from Halbouty, 1979).**

Salt dome growth also influences the topography of the overlying land surface. Positive topographic relief is linked to uplift, whereas subsidence of the topographic surface is linked to dissolution of the dome crest (Seni and Mullican, 1986; Mullican, 1988). Of the shallow domes along the upper Texas Gulf Coast, 63 percent have positive topographic relief over their crests (Seni and others, 1984d). Warping of the depositional surface, either on the coastal plain or in the shallow marine environment, influences sedimentation patterns. Muddy sediments tend to be deposited over dome crests, and sandy sediments tend to be deposited in surrounding downwarped areas.

Salt dome cap rock is composed mainly of anhydrite, gypsum, and calcite arranged in heterogeneous layers (Figure 12-1). Cap rock formation results from salt dissolution. Anhydrite (calcium sulfate), the main impurity in the salt stock, forms a residual accumulation at the dome crest. Other geochemical processes convert the anhydrite to gypsum (hydrous calcium sulfate),

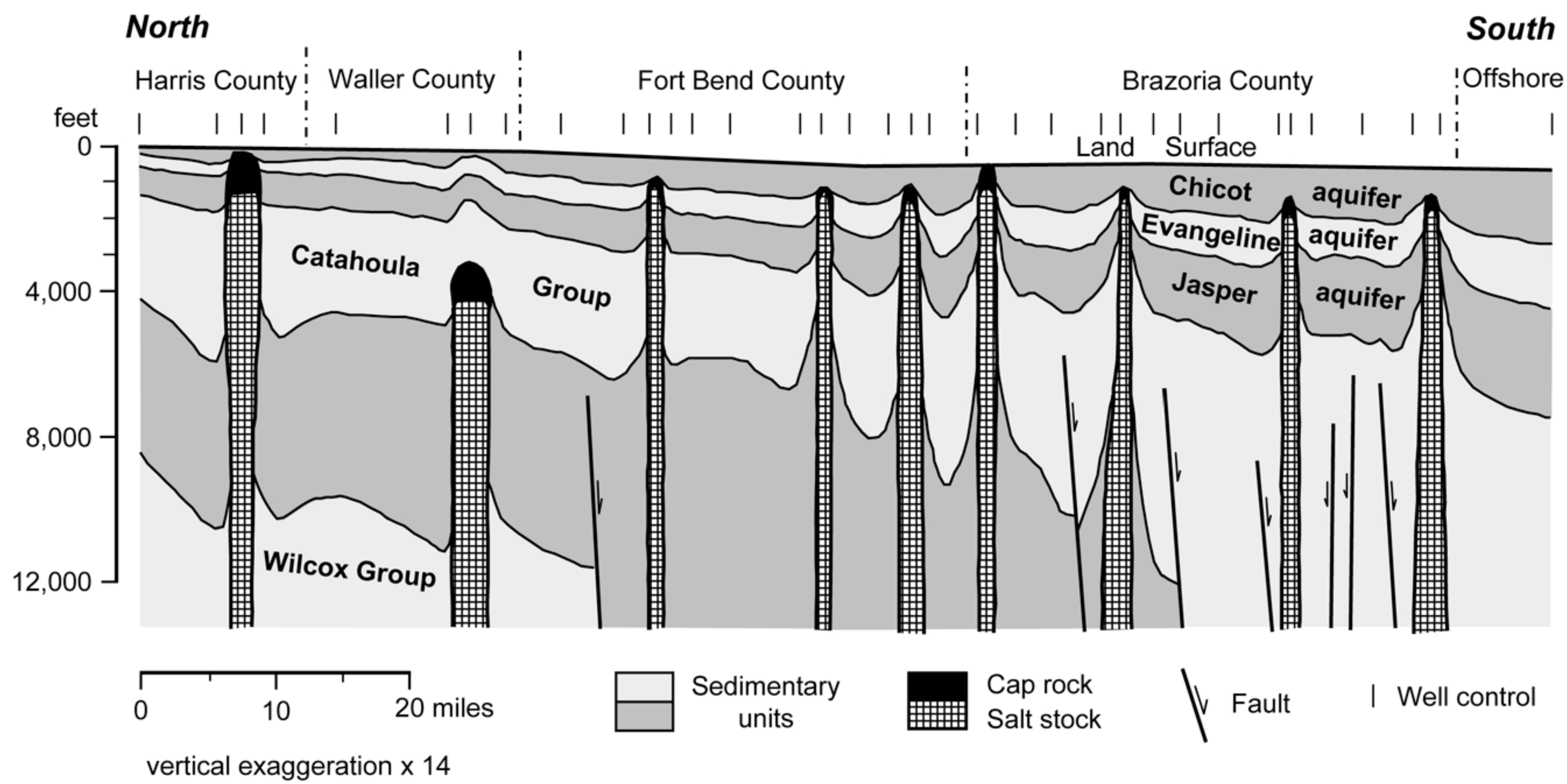


Figure 12-2. Regional dip-oriented cross section through the Gulf Coast Basin southwest of Houston intersecting a number of salt domes (modified from Hamlin, 1986). Line of section shown in Figure 12-3.

calcite (calcium carbonate), and to a lesser extent, native sulfur and metallic sulfides (Bodenlos, 1970; Kyle and Price, 1986). Cap rock layering is irregular and varies greatly from dome to dome. Structural deformation and fracturing are common, as are cavernous voids. Gulf Coast cap rocks range in thickness from 0 to 2,000 feet. Cap rocks are direct evidence for dissolution of salt by groundwater.

Most of the salt domes along the Gulf Coast of Texas occur in the northeast (Figure 12-3). The base of fresh to slightly saline water (less than 3,000 mg/L of total dissolved solids [TDS]) in the Gulf Coast aquifer varies but is generally less than 3,000 feet (Baker, 1979); therefore, shallow salt domes whose crests are less than 3,000 feet deep are the ones that could affect fresh groundwater quality. There are 3 shallow salt domes in South Texas southwest of Corpus Christi and 35 along the upper coast (Figure 12-3). Because there is a gap in depth distribution between shallow and deep salt domes, the maximum depth of shallow domes is only 1,500 feet. The average depth is 565 feet. Average cap rock thickness is 481 feet (Figure 12-4).

Natural Resources

Salt domes provide a variety of natural resources (Seni, 1986). Structural deformation and cap rock formation have created prolific petroleum reservoirs. Oil and gas are trapped in uplifted strata surrounding or overlying salt domes and in the cap rock itself. In addition to petroleum, salt from the salt stock and sulfur from the cap rock are the main commodities derived from Gulf Coast salt domes in Texas (Figure 12-5). Salt domes also provide space for storage and disposal (Seni and others, 1985). Solution-mined caverns in the salt stock have been created both for brine production and for storage of various petroleum products, most commonly liquid petroleum gas. The volume of some storage caverns exceeds ten million barrels. Crude oil for the Strategic Petroleum Reserve is stored in caverns at several Texas Gulf Coast salt domes. Cavernous zones in cap rocks have been used for brine disposal (Seni and others, 1984c), and the potential for disposal of chemical wastes in salt caverns has been evaluated (Seni and others, 1984a).

Resource development and production can create geologic and hydrologic instabilities around salt domes (Seni and others, 1985). Land-surface subsidence, sometimes involving catastrophic collapse and sinkhole formation, is common where large amounts of sulfur, salt, and/or petroleum have been extracted from the salt dome (Mullican, 1988). High-volume brine disposal elevates cap rock fluid pressures in shallow intervals laterally adjacent to freshwater sands, reversing pre-development hydraulic gradients and creating the potential for aquifer contamination (Hamlin and others, 1988). Petroleum storage caverns in the salt stock have failed and leaked product into surrounding freshwater sands (Seni and others, 1984b, 1985).

Hydrogeologic Units

A salt dome in the Gulf Coast aquifer forms a complex system of hydrogeologic units. The salt stock is a cylindrical vertical aquiclude. The cap rock rests on the salt stock like an inverted cup. Cap rocks are essentially karstic aquifers whose hydrodynamic properties are controlled by fracturing and dissolution. Irregularly distributed networks of vuggy to cavernous porosity are

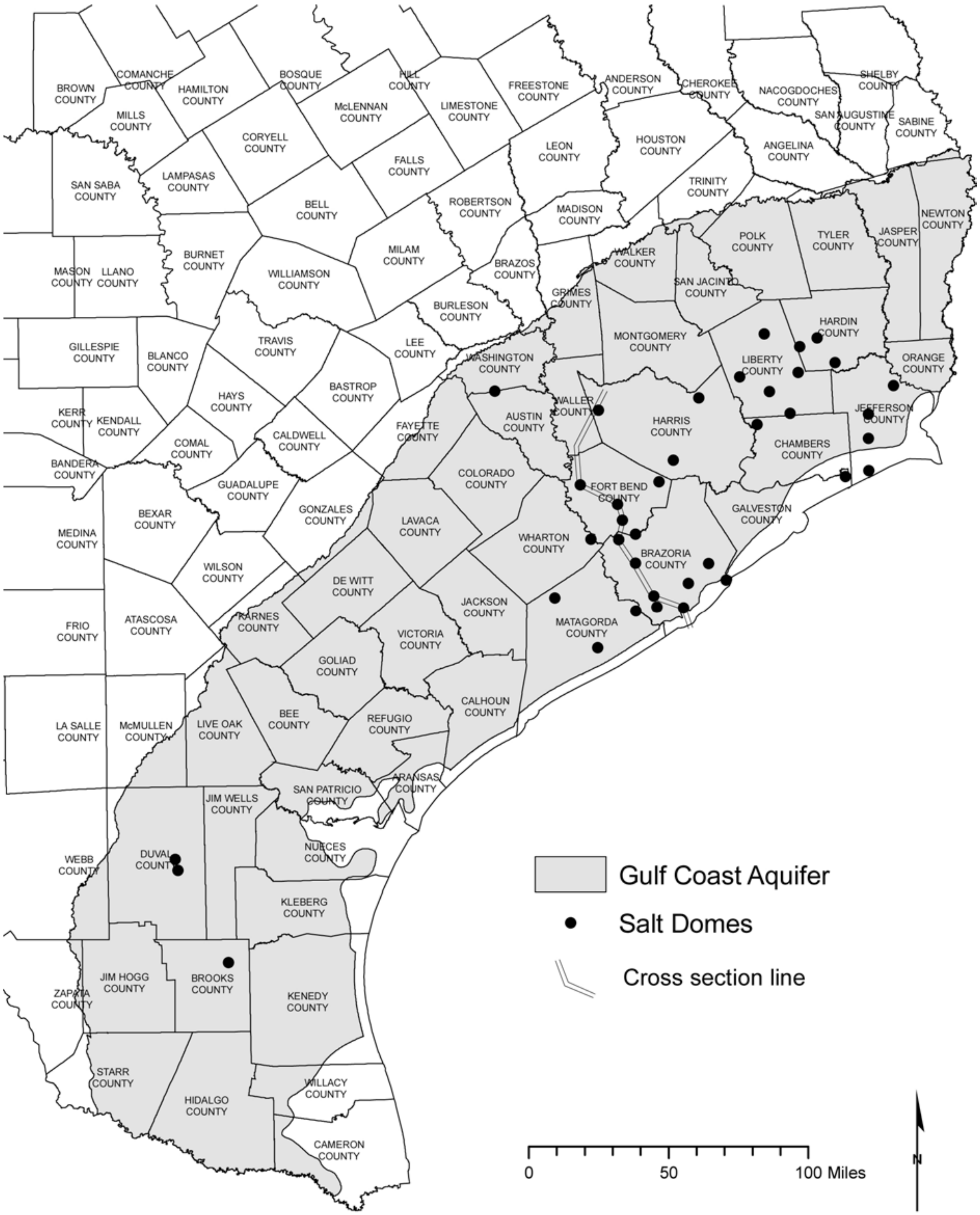
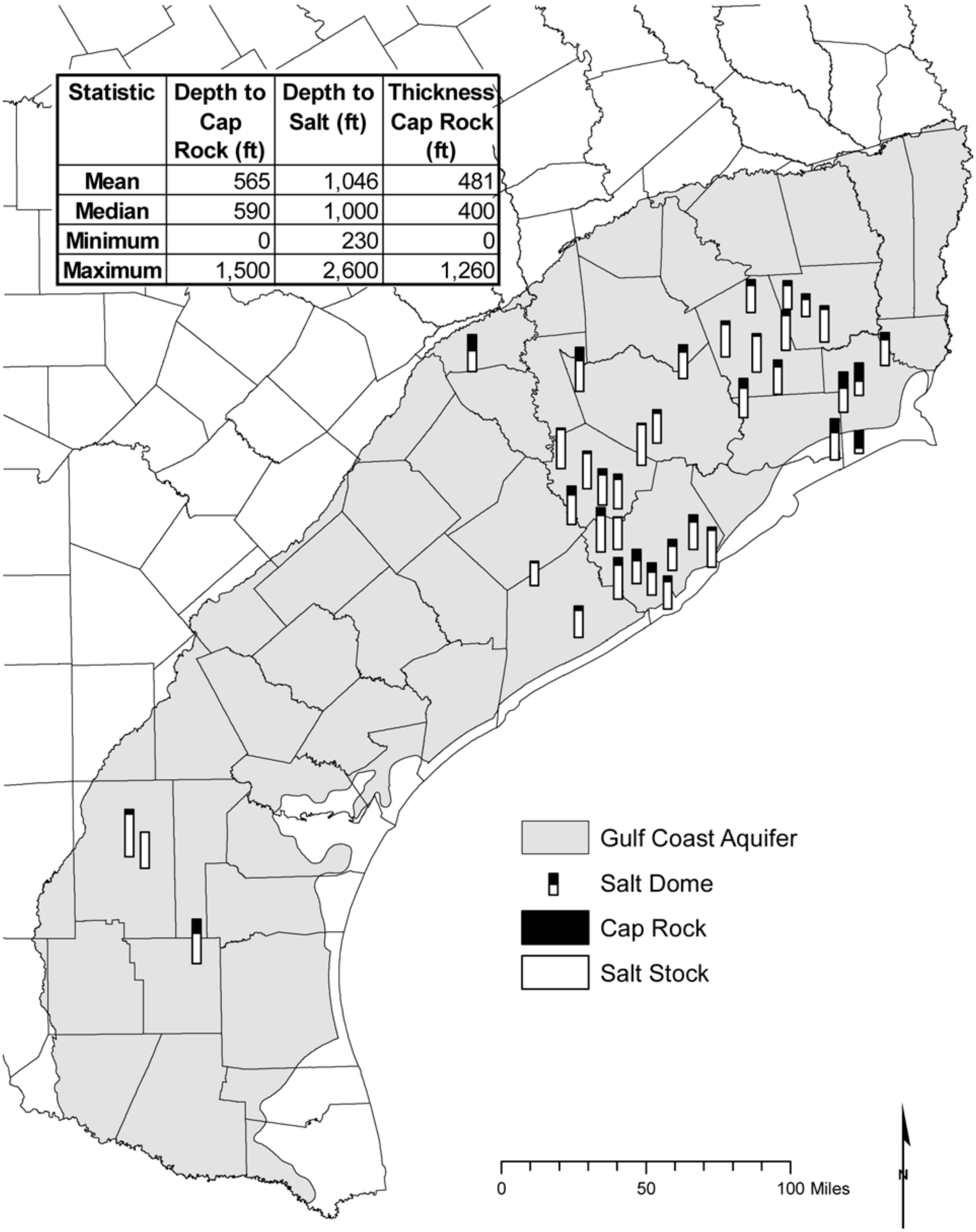


Figure 12-3. **Map of shallow salt domes in the Gulf Coast aquifer in Texas. Also showing line of cross section in Figure 12-2 (compiled from Seni and others, 1984b-d, 1985).**



Statistic	Depth to Cap Rock (ft)	Depth to Salt (ft)	Thickness Cap Rock (ft)
Mean	565	1,046	481
Median	590	1,000	400
Minimum	0	230	0
Maximum	1,500	2,600	1,260

Figure 12-4. **Map of shallow salt domes in the Gulf Coast aquifer showing relative depths and cap rock thicknesses. The salt domes are shown schematically extending above a datum at 3,000 feet below sea level. Depth and thickness statistics also shown (Compiled from Beckman and Williamson, 1990, and Seni and others, 1984b-d, 1985).**

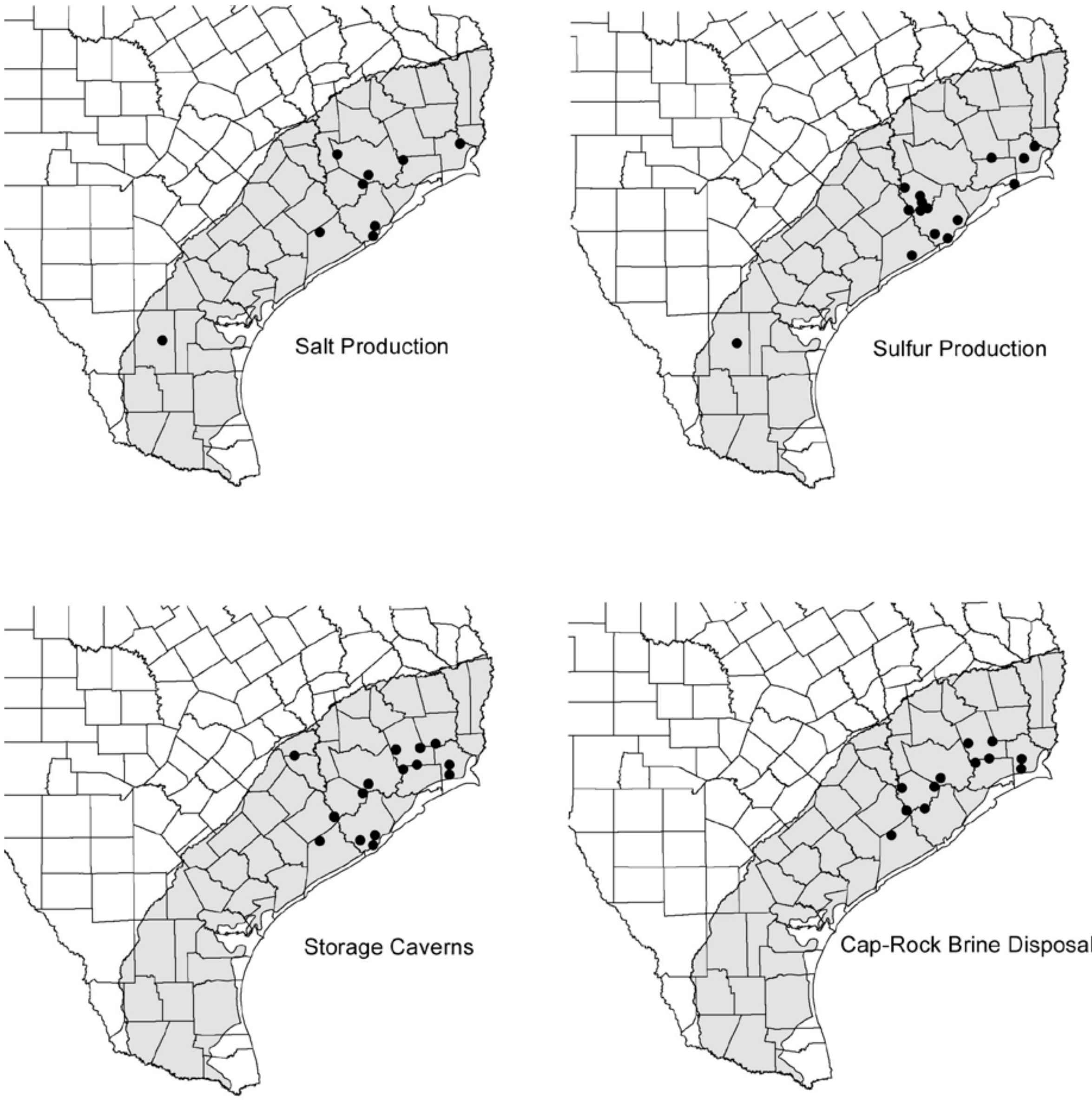


Figure 12-5. **Maps of shallow salt domes in the Gulf Coast aquifer showing natural resources. Petroleum resources (not shown) have been developed at most Gulf Coast salt domes (compiled from Seni and others, 1984b-d, 1985).**

common in cap rock. Drillers name these networks “lost-circulation zones” because of the difficulty of establishing drilling-fluid circulation in wells penetrating cavernous intervals. These are also the intervals favored for brine disposal because they readily accept high injection rates. However, cap rock also includes areas composed of dense calcite and anhydrite, which have low hydraulic conductivity.

The salt stock and cap rock are encased in interbedded sandy aquifers and muddy aquitards. In these interbedded sand and mud layers, hydraulic conductivity in the horizontal direction is typically many times greater than it is in the vertical direction. However, the potential for high vertical hydraulic conductivity exists within the zone of structural deformation around the salt dome. Gulf Coast salt domes contact freshwater sands in the Chicot, Evangeline, and Jasper aquifers, as well as saline-water sands in more deeply buried intervals (Figure 12-2).

Salt Domes and Groundwater Flow

The arrangement and physical properties of aquifers and aquitards in the salt dome environment delineate possible pathways for groundwater flow, but additional evidence is needed to document actual groundwater flow. Fluid-pressure gradients must be known to establish hydraulic driving forces for flow, and groundwater chemical compositions must be known to trace groundwater sources and mixing. Ideally, all available geologic and hydrologic data should be assembled in a conceptual model of the system that can then be translated into a numerical model of three-dimensional, density dependant groundwater flow around the salt dome. This section reviews the available hydrodynamic and hydrochemical evidence for groundwater flow around salt domes along the Texas Gulf Coast.

Evidence from Hydraulic Heads

In the salt-dome environment, groundwater flow is driven not only by hydraulic-head gradients but also by density gradients. The density gradients arise from the high thermal conductivity of salt and from groundwater salinity variations due to dissolution of the salt itself (Evans and others, 1991). Few studies have reported head and density distributions in the vicinity of Texas coastal salt domes. Work done in East Texas, where salt domes penetrate the Carrizo-Wilcox aquifer, suggests that dome-related uplift creates local recharge areas over some salt-dome crests, but in general regional flow patterns are not affected by the presence of salt domes (Fogg and others, 1983). Studies in Louisiana, where salt domes penetrate the Gulf Coast aquifer, document upward groundwater flow around deeper dome flanks but downward flow at shallower levels (Evans and others, 1991), although the focus of the Louisiana studies was the interval below the base of freshwater.

At Barbers Hill salt dome, which penetrates Evangeline and Chicot freshwater sands in Chambers County, head measurements and pumping tests were conducted in the cap rock aquifer, which is saturated with dense brine (Hamlin and others, 1988). Barbers Hill salt dome has a history of intense development, including oil production, salt-cavern storage, and cap rock brine disposal. Water-level data are available from cap rock disposal wells. When the effects of density variations were normalized, a hydraulic gradient directed radially outward and upward from the cap rock was revealed. The present magnitude and direction of this hydraulic gradient is attributable both to lowering of fluid pressures in the Chicot and the Evangeline aquifers by long-term pumping in the Houston area and to elevation of fluid pressures in the cap rock by high-volume brine disposal.

Controlled brine injection tests at Barbers Hill salt dome indicated that the cap rock is a single integrated aquifer with leaky vertical and lateral boundaries. Because of the arched shape of the cap rock (Figure 12-1), the vertical boundary corresponds to vertical and lateral contacts with freshwater sands, and the lateral boundary is the lower edge down the dome flanks that is in contact with deeper saline-water sands. Within the cap rock, water levels stabilized in observation wells during a long-term (29 days) brine injection test, showing that groundwater must be exiting the cap rock (Figure 12-6). During the brine injection test, however, water levels were not monitored in nearby Chicot and Evangeline water wells, so the exact destination of leaking cap rock brines was not documented.

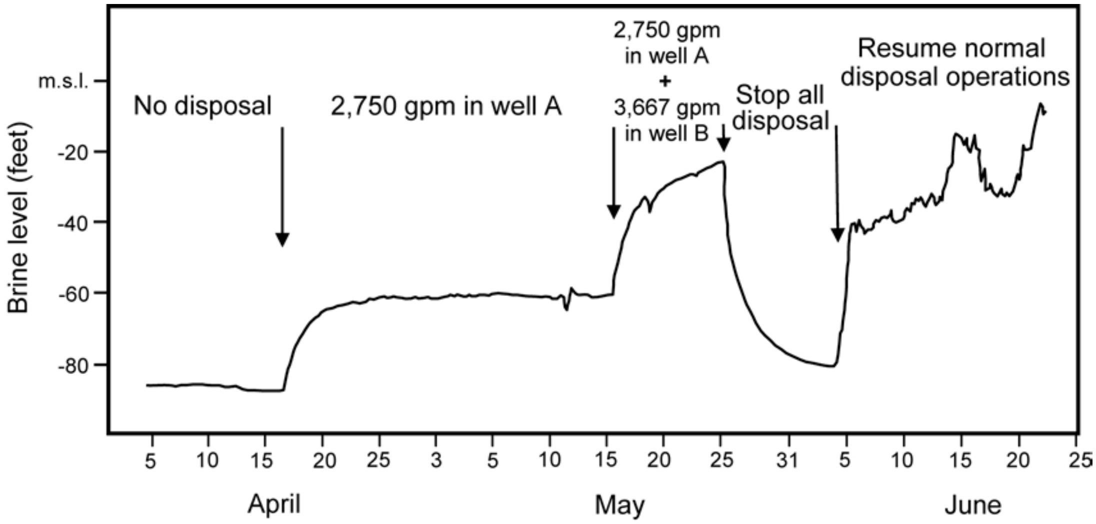


Figure 12-6. **Hydrograph of a long-term cap rock injection test at Barbers Hill salt dome showing brine-level changes in a cap rock observation well during controlled brine disposal in two other cap rock wells. Water levels in nearby Chicot and Evangeline wells are around 100 feet below sea level or similar to cap rock brine levels when no disposal is occurring (modified from Hamlin and others, 1988).**

Evidence from Groundwater Chemistry

Hydrochemical patterns in groundwater near salt domes provide information about flow of dome-related fluids into surrounding freshwater aquifers. The most commonly available data for measuring groundwater salinities in the near-dome environment are geophysical logs from oil and gas wells, because an empirical relationship can be established between groundwater salinity and electrical conductivity (Jones and Buford, 1951) and because most salt domes have been densely drilled in the quest for oil. Using geophysical logs, anomalously high salinities in shallow sands were documented near salt domes in Chambers, Fort Bend, and Jefferson counties (Wesselman, 1971, 1972).

At Barbers Hill salt dome, Hamlin and others (1988) used closely spaced well logs to map individual sand bodies and groundwater salinities near the dome, revealing a complicated pattern of vertical and lateral salinity variation (Figure 12-7). In one Chicot sand, a plume of high-salinity groundwater extends away from the salt dome in the direction of regional groundwater flow (Figure 12-8). Similar saline plumes extending away from salt domes in the direction of groundwater flow have been documented in the Carrizo-Wilcox aquifer in East Texas (Fogg and others, 1983) and in Germany (Klinge and others, 2002).

Chemical and isotopic analyses of groundwater are less abundantly available than are geophysical logs but can be used to reveal both fluid sources and flow patterns. Banga and others

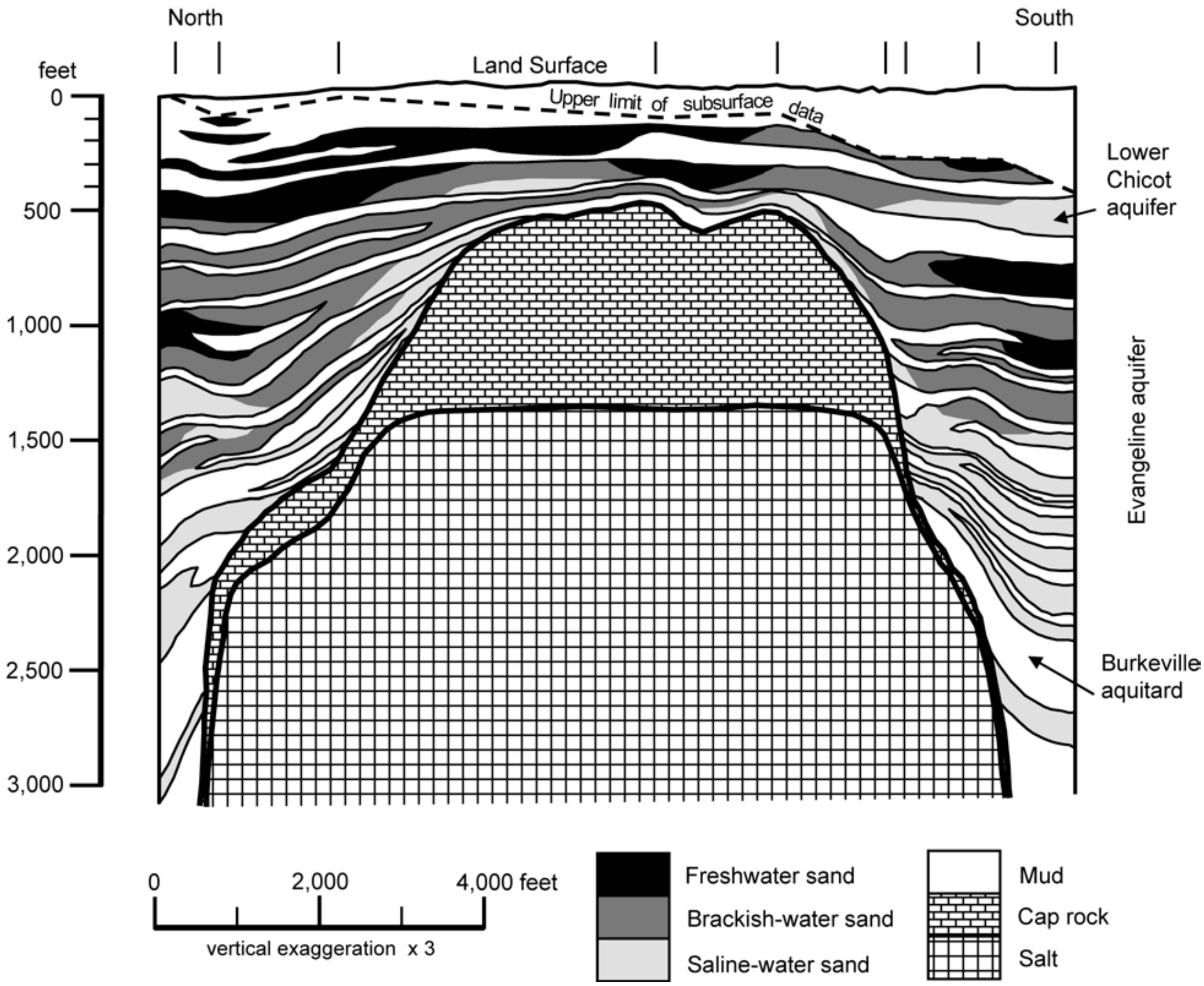


Figure 12-7. North-south cross section across Barbers Hill salt dome showing Chicot and Evangeline sands and groundwater salinities near and in contact with the cap rock. Groundwater salinities were interpreted from geophysical logs. Individual sand bodies were correlated and mapped using closely spaced geophysical and drillers logs. A map of salinity in the lower Chicot sand is shown in Figure 12-8 (modified from Hamlin and others, 1988).

(2002) used multi-element chemistry and isotopic tracers to document vertical flow patterns in deep sandstones (below freshwater) around South Liberty salt dome in Liberty County, showing that oil field brines near the salt dome are a mixture of shallow meteoric waters and deep formation waters. The presence of a meteoric component in deep brines indicates downward flow along the flanks of the salt dome. The implication of the South Liberty salt dome study is that shallow fresh groundwater flows across the top of the salt dome, dissolves salt, becomes increasingly dense, and then flows downward along the dome flanks driven by a density gradient.

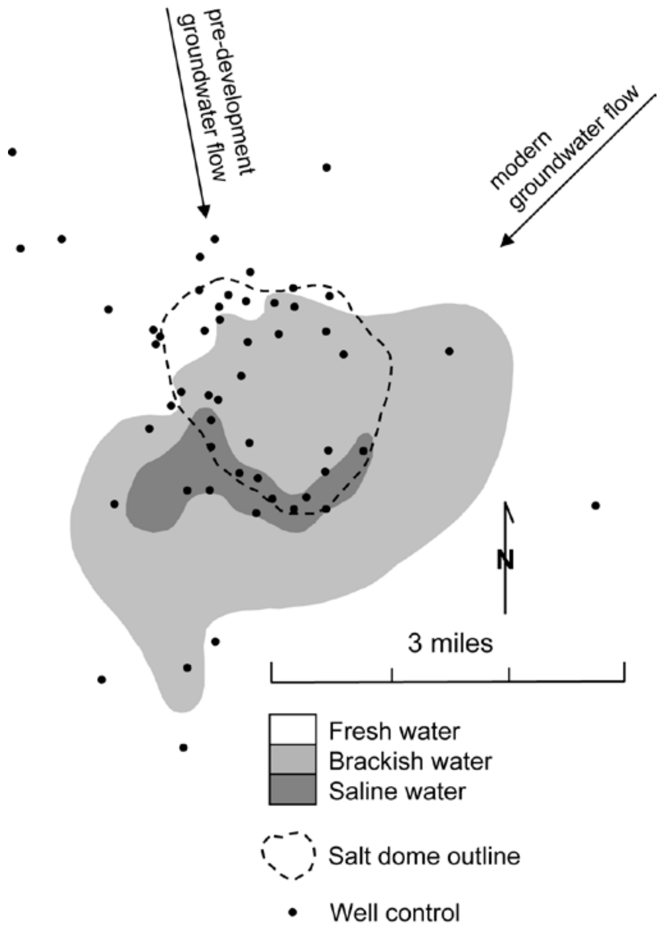


Figure 12-8. Map of groundwater salinity in a lower Chicot sand at Barbers Hill salt dome. Salinities were measured in water wells and calculated from geophysical logs. Anomalously high salinities on the southwest side of the dome outline a plume of saline water extending away from the salt dome in the down-flow direction (modified from Hamlin and others, 1988).

Evidence from Numerical Modeling

Numerical modeling of groundwater flow systems around salt domes has proved challenging owing to the complications of extreme salinity and density variations and complex boundary conditions (Konikow and others, 1997). Fogg and others (1983) modeled groundwater flow in the Carrizo-Wilcox aquifer around a salt dome but without explicitly including the dome itself or salinity variations. Their model helped identify recharge and discharge areas and flow paths in freshwater aquifer sands relative to the position of the salt dome, so that the movement of potential dome-related contaminants might be predicted. Their model also showed the importance of sand-body distribution and interconnection as controls on flow near salt domes. Hamlin and others (1988) modeled the cap rock aquifer at Barbers Hill salt dome, using the results of controlled brine injections tests, but did not include the surrounding Chicot and Evangeline sands or salinity/density variations. Nevertheless, their model accurately reproduced water-level measurements and demonstrated that the cap rock boundaries are leaking. Models of groundwater flow around Gulf Coast salt domes in Louisiana, which explicitly include both the salt dome and salinity/density variations, emphasize the importance of density-driven flow (Evans and others, 1991). The Louisiana models show that salt dissolved at the dome crest is carried down the dome flanks below the zone of freshwater.

Discussion

The evidence for dissolution of salt dome minerals in shallow groundwater is conclusive. Shallow salt domes extend well into the zone of freshwater and are surrounded laterally and vertically by Gulf Coast aquifer sands. As salt dissolves at the dome crest, an insoluble residue accumulates, forming the cap rock. Within the cap rock itself, chemical reactions occur that require the presence of low-temperature, low-salinity groundwaters (Kyle and Price, 1986). Geophysical logs have been used to identify high-salinity plumes within otherwise freshwater sands near several Gulf Coast salt domes and to map actual sand/dome contacts (Figure 12-7). Indeed, dissolution of salt domes by groundwater has been documented, and the amount of salt removed has been quantified (Seni and Jackson, 1984; Bruno and Hanor, 2003).

Although salt actively goes into solution at the crests of shallow salt domes, most of the high-salinity groundwater thus formed flows downward driven by density gradients. Recent studies document downward flow along salt-dome flanks and the control of faults and sand distribution on flow paths (Banga and others, 2002; Bruno and Hanor, 2003). Although upward flow occurs in deep zones below the base of freshwater (Evans and others, 1991), upward movement and mixing of dense saline groundwater from deep zones into the low-density freshwater zones appears unlikely.

Development of both fresh groundwater and salt-dome resources has increased the potential for contamination of shallow aquifers. In pre-development steady-state groundwater flow systems, salt-dome related contamination remained localized by high freshwater heads in surrounding sands and the tendency for high-density brines to flow downward. The combination of lowered heads in the Gulf Coast aquifer and increased heads in cap rocks has created hydraulic gradients directed outward from the salt dome toward adjacent freshwater sands. Resource extraction and leakage of stored petroleum product have further perturbed the natural system. Most of the available evidence for salt-dome-related contamination of the Gulf Coast aquifer is at least 20 years old. More recent hydraulic and hydrochemical data, including data collected periodically through time, are needed for proper risk analysis and for a more comprehensive understanding of groundwater flow near salt domes.

Acknowledgments

This review of salt dome hydrogeology is based primarily on research supported by the Texas Department of Water Resources and the Texas Water Commission during 1984 and 1985. Steven J. Seni, William F. Mullican, III, and I were the primary researchers. Since that time relatively little has been published on the effects of salt domes on Gulf Coast groundwater resources. Thanks to Steve and Bill for allowing me to mine their work for material for this paper, which I hope may generate renewed interest in the subject. Thanks also to Sarah Davidson for making the Gulf Coast aquifer conference and publication happen.

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