Salt Dome Plumes and Dissolution Features: Are They Related?*

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ABSTRACT

Salt domes, historically of interest in hydrocarbon production and salt mining, were later recognized for their value as reservoirs to store petroleum products, for energy stored as compressed air and possibly for hazardous wastes. One of the problems encountered when drilling into the salt stock, prior to the leaching of a cavity, is a loss of drilling fluids in the cavernous zones which overlie many salt domes. Of particular interest are cavernous zones at the salt-caprock interface where active dissolution of the salt by circulating groundwater is most likely to be occurring.

The salt-caprock interface zone may be characterized by a tight, a cavernous or a sandy (granular anhydrite) contact. The condition of the salt-caprock interface not only affects solution mining of cavities where lost circulation hinders drilling operations prior to penetrating the salt, but also may have implications to the long-term hydrologic stability or degree of ongoing dissolution of the dome for consideration in planning waste storage projects.

Dissolution cavities or residual anhydrite sand (previously embedded in the salt) at the salt-caprock interface and the presence of saline plumes in aquifers in contact with the salt have been used as evidence of dissolution. A positive correlation between dissolution features at the interface and the presence of saline plumes in surrounding aquifers could be useful in the prediction of drilling problems at the interface when planning salt dome utilization projects. Studies, based on limited data, have proven inconclusive thus far; additional field evidence may resolve this question. A better understanding of the relationships between dissolution features and saline plumes would also be helpful in hydrologic stability studies of waste storage projects.

INTRODUCTION

Salt domes and their associated caprock have traditionally been utilized as sources of numerous consumer and industrial products. In addition to its more common direct uses, salt is also used by the chemical industry to produce chlorine, caustic soda, soda ash and other products. Salt dome caprock has been mined for native sulfur as well as for calcite, anhydrite and gypsum. Also, hydrocarbon traps have been created around salt domes as a result of their upward movement through the strata (Hawkins and Jirik, 1966; Martinez, 1979).

Salt domes later began to be viewed not only as exploitable sources of various products but also as resources in themselves to provide storage space for liquified petroleum gas, natural gas, crude oil and chemical wastes. More recently salt domes have been studied for possible storage of off-peak electrical energy as compressed air and for long-term storage or disposal of radioactive wastes.

*Research Funded by Institute for Environmental Studies of Louisiana State University and Louisiana Geological Survey, Baton Rouge La., USA.

A primary concern in considering salt domes for long-term storage projects is to keep the waste isolated from the biosphere. Contamination is most likely to reach the biosphere via groundwater transport horizontally or to surface discharge areas. Although salt domes are generally considered to be impervious to groundwater flow, they are also susceptible to dissolution by circulating subsurface waters.

Dissolution is normally recognized only by such indirect evidence as the presence of saline plumes in aquifers surrounding salt domes and dissolution cavities or residual anhydrite sands (formerly embedded in the salt) at the salt-caprock interface. The chloride concentration in aquifers has been found to increase in the vicinity of many salt domes (Minor, 1925; Wesselman, 1971), and saline plumes, which would be expected to develop downstream of dissolving domes, have been mapped for some domes (Wesselman, 1971; Wesselman, 1972; Smith in Martinez *et al.*, 1975; Smith in Martinez *et al.*, 1977; Fogg *et al.* in Kreitler *et al.*, 1980).

The salt-caprock interface zone is usually characterized by any of three types of contact: a tight contact between the base of the cap and top of the salt, an anhydrite sand contact, and/or a cavernous or vuggy contact. Because the interface is most likely a zone of major salt dissolution, such characteristics as the presence of sand or cavities may indicate recent or ongoing dissolution of the salt stock. A permeable cavernous or granular contact would permit flowing water to dissolve salt and to transport it into surrounding aquifers. A tight salt-caprock contact, therefore, probably indicates that the top of the salt stock is not currently being dissolved at that particular location.

Cavernous zones at the salt-caprock interface commonly cause the loss of drilling fluids into the cavities when penetrated by the bit. This problem is not limited to the salt-caprock interface but occurs wherever cavernous or fractured zones exist throughout the caprock (Gray *et al.*, 1956; Chafin and Harvey, 1963; Harter, 1981; Rainey, 1981) and where the hydrostatic pressure exerted by the column of drilling mud exceeds the formation fluid pressure (Chaney, 1949). The relatively low hydrostatic head and large volume or extensive interconnection of these cavernous zones have allowed several million barrels of drilling fluid and water to be pumped into the caprock of a single dome without appreciably increasing the hydrostatic head in the zone (Judson and Stamey, 1933). Because the remaining caprock is often drilled without returns following lost circulation problems, the nature of the salt-caprock interface may not be readily determined in many wells (Rainey, 1981; Van Fossan, 1982).

In the absence of drill-holes into the salt dome itself the presence of saline plumes has been used as evidence of dissolution. A critical test of this relationship would be establishing a positive correlation between dissolution features at the salt-caprock interface and the presence of saline plumes in aquifers in contact with the domes. Not only would this establish the usefulness of saline plumes for identifying ongoing dissolution, but it may also provide a technique for predicting drilling problems in particular domes. Furthermore, a better understanding may be developed about the nature of long-term salt dome stability for hazardous waste storage by examining relationships among characteristics which are assumed to indicate dissolution.

LOUISIANA SALT DOMES

Vacherie Dome, Bienville and Webster Parishes

The salt-caprock interface near the center of Vacherie dome, as seen in a core (DOE-V), is a distinct, well-cemented contact (Nance *et al.*, 1979; Nance and Stirling in Martinez *et al.*, 1979). In contrast, a well (V-7) located about 1 km west of this corehole, went through a 3-to-5-foot zone (0.91 to 1.52 m) of rapid drilling at 797 feet (242.9 m) just before hitting salt. Although the precise nature of this zone is not known, unconsolidated sediments, assumed to be anhydrite grains, are indicated (Smith in Martinez *et al.*, 1977). Because the caliper log shows a borehole size larger than the bit diameter in this zone, the increased drilling rate could have been due to the presence of a cavity or a washed-out zone, possibly due to the dissolution of salt by drilling fluids, however. No loss of drilling fluid circulation was reported at the interface in either well.

Well V-7 was screened in the salt-caprock interface zone from 796 to 806 feet (242.6 to 245.7 m). The well produced only 300 gallons of brine after three days of intermittent pumping, and swabbing failed to improve the yield. A maximum chloride concentration of 180,000 ppm was measured on the first day of sampling. A limited extent of interconnection of the porous zone to other water-bearing zones may have been the reason for the small volume of water produced (Kumar, 1982). However, the low yield of the well could also have been due to improper completion of the well, low permeability in the completed zone or reduced permeability caused by the accumulation of oil also produced during sampling (Smith in Martinez *et al.*, 1977).

An analysis of the geohydrology around Vacherie dome using electrical logs indicates that a weak salinity anomaly exists in the Wilcox sand east of the dome. The maximum dissolved solids concentration in this anomaly was estimated to be 4,000 ppm using electrical log resistivity readings (Smith in Martinez *et al.*, 1977). The deeper Nacatoch and Brownstown sands, from 1,700 to 2,000 feet (518.2 to 609.6 m) and from 2,200 to 2,700 feet (670.6 to 823.0 m), respectively, below land surface, were analyzed using the SP curve because sufficient data on porosity or formation factors needed to relate resistivity to salinity were unavailable. These deeper aquifers appear to have salinity anomalies east of the dome also (Kumar and Hoda in Martinez *et al.*, 1978).

Higher hydraulic heads in the caprock wells than in the Wilcox aquifer wells indicate that flow is probably into the Wilcox from the caprock (Smith in Martinez *et al.*, 1977). Also, integrated data on the isotopic composition and chemistry of the water and the direction of flow relative to the salinity anomaly suggest that the salinity originates from the dissolution of the salt stock by fresh water flowing southward or eastward; however, no definite conclusion has been made due to insufficient data (Kumar in Martinez *et al.*, 1979).

The absence of dissolution features at the salt-caprock interface in the cored well suggests that the salt is not currently being dissolved in the vicinity of the well. The saline plume, if indeed it is a plume, may be relict marine brine washed by meteoric water away from the uplifted sediments around the dome (Kumar and Hoda in Martinez *et al.*, 1978). Another possibility is that the saline water travelled upward from deeper saline aquifers along faults (Smith in Martinez *et al.*, 1976). The salinity could also be due to dissolution in an area on the dome other than that which was tested or from dissolution that occurred in the recent geologic past.

Winnfield Dome, Winn Parish

Much of the information available for Winnfield dome comes from the caprock and salt mining operations begun there in the 1930s. The salt-caprock interface was exposed during the sinking of a mine shaft by the Carey Salt Company. Anhydrite sand was associated with a flow of water and gas in the northwest section of the shaft at the salt-anhydrite contact. The interconnection between the interface and the caprock exposed at the surface was evidenced by the appearance of grout in the quarry one quarter of a mile (0.4 km) from the shaft where grout was applied to stop the flow of water. The initial flow from another leak in 1937 was a nearly saturated brine that shortly became almost fresh. This also suggests an interconnection of the salt-caprock interface to surface or subsurface fresh water sources (Taylor, 1938; Belchic, 1960; Kumar, 1981).

Salinity estimates based on the SP curve indicate anomalously high NaCl concentrations near the salt stock in mid-Wilcox sands. This high salinity decreases in concentration over a greater distance north of the dome than it does to the southeast. The Wilcox group sands are in contact with the caprock or salt and are estimated to be 40% to 70% sand near the dome (Smith in Martinez *et al.*, 1975). Therefore, the Wilcox could very well supply the circulating water to dissolve the salt and transport it away from the dome. The highly transmissive Sparta sand is probably also in contact with the caprock and could be a source of meteoric water to the caprock (Kumar, 1981).

The presence of anhydrite sand and flowing water at the salt-caprock interface, along with an estimated salinity anomaly in the Wilcox aquifer adjacent to the dome, indicate that salt is currently being dissolved at Winnfield. Kumar (1981) concluded that the salt-caprock contact is water-filled and cavernous.

Rayburn's Dome, Bienville Parish

The indurated caprock at Rayburn's dome is separated from the salt by a cavernous contact in the vicinity of the corehole (DOE-R) drilled as part of the nuclear waste isolation study conducted by the Institute for Environmental Studies of Louisiana State University. The salt-caprock interface is indicated by 1.6 feet (0.49 m) of missing core above the top of salt at a depth of 138 feet (42.1 m). This zone correlated with a loss of circulation during the drilling of the corehole (Nance and Wilcox, 1979; Nance and Stirling in Martinez *et al.*, 1979); 150 barrels of mud were lost at this point. The presence of a cavity at the salt-caprock interface is also indicated by the bit having dropped 8 inches (0.20 m), presumably into a void, at the time circulation was lost (Hawkins, 1978).

Even though Rayburn's dome extends above the base of fresh water in the local aquifers (Anderson *et al.*, 1973), no salinity anomalies were found in the Wilcox or Sparta aquifers near the dome, based on electrical log resistivity readings. It is possible that the Midway clays, which appear to lie between the dome and the Wilcox aquifer, serve as a barrier to active salt dissolution by hydrologically isolating the salt stock from the aquifers. Another possibility is that salt water resulting from dissolution is flushed away from the dome by meteoric water recharging the uplifted Wilcox around the dome (Smith in Martinez *et al.*, 1975). Because water level measurements indicate that the subsurface flow is southward in the vicinity of the dome (Kumar and Hoda in Martinez *et al.*, 1978), and the wells from which salinity estimates were made were not located directly south of the dome, they may have been too far to the east or west to detect any plume that may exist. Finally, Quaternary studies of Rayburn's dome indicate that the caprock forms a ridge around the periphery of the dome. Very saline water is found in wells drilled within the borders of this bowl-shaped structure, possibly indicating that brine from dissolution of the salt has been trapped and has not been transported away from the dome in a plume (Kolb, 1982; Kolb and Holmes, 1982).

The presence of a cavity in the core at the salt-caprock interface and saline groundwater over the dome suggest ongoing dissolution of the salt stock, but no saline plume has been found to date in the aquifers surrounding the dome. The thin caprock may indicate that it has been subjected to subaerial erosion in the recent geologic past (Kolb and Holmes, 1982), during which time the brine from dissolution could have been discharged at the surface. The more recently dissolved salt may be trapped in the sediments above the bowl-shaped caprock, as described above.

Napoleonville Dome, Assumption Parish

Information on the caprock at Napoleonville is sparse, but a U.S. Strategic Petroleum Reserve (1977) study reports that the caprock consists of 105 feet (32 m) of calcite, 114 feet (34.7 m) of gypsum, within which a 25 foot (7.6 m) layer of shale is commonly encountered, and as much as 29 feet (8.8 m) of anhydrite. One well encountered 304 feet (92.7 m) of caprock overlying the top of salt at 724 feet (220.7 m); circulation of drilling fluids was lost in a cavernous zone at 655 feet (199.6 m). Of 15 wells drilled into the salt by one company, only the northernmost one did not have problems with lost returns. This well drilled directly into salt from the caprock without encountering a cavity (source withheld upon request).

Analysis of electrical log resistivity readings (Figure 1)

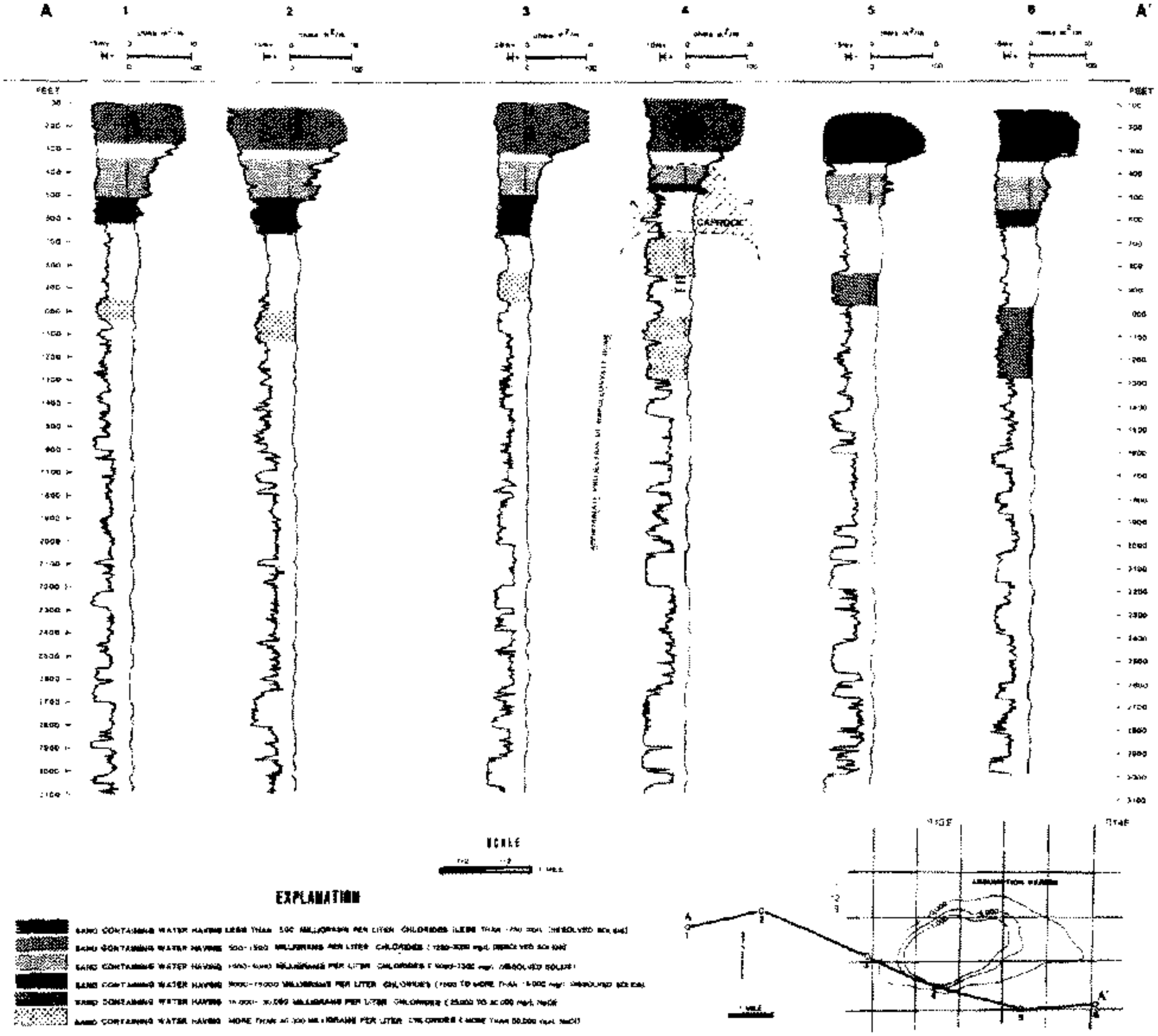


Figure 1. Geohydrologic cross section of Napoleonville dome (Wouch, 1982). (Salt contour map modified from Stipe, 1960)

indicates that a saline plume may exist to the west and southwest of Napoleonville dome in the upper unit of the Plaquemine aquifer. The brackish lower unit of this aquifer appears to be slightly more saline to the east or southeast of the dome. The next deeper aquifer was analyzed using the SP curve from electrical logs because resistivity-salinity relationships could not be determined for the deeper, more saline aquifers with the available data. This aquifer is apparently most saline adjacent to the dome; however, no plume is detectable in this aquifer from the wells analyzed in the surrounding area (Wouch, 1982).

Water level data is scarce for the Napoleonville area, but the net direction of subsurface flow is probably to the south or southwest, very likely more to the southwest, toward the Atchafalaya Basin (Dial, 1982). Approximately 15 miles to the north, and closer to the Mississippi River, groundwater flows either toward the river or away, depending on the river stage (Whiteman, 1972). Although the Mississippi River does not influence the flow direction in the vicinity of Napoleonville dome to any great extent today, the various courses taken by the river in the recent geologic past (Kolb and Van Lopik, 1966) may have caused a more westerly flow in the upper aquifer to allow a plume to develop west of the dome. Two wells, one to the southwest and one to the south, indicate higher salinities than those to the north or east, however, which suggests the presence of a plume, although well control is limited here. The slight easterly plume in the brackish aquifer may have resulted from salt dissolution during a period when subsurface flow was more to the east, and the salinity may not as yet have been dispersed in another direction (Wouch, 1982). The course changes taken by the Mississippi and its distributaries in the past (Howe *et al.*, 1938; Kolb and Van Lopik, 1966) may have caused the direction of subsurface flow to change many times in the vicinity of Napoleonville dome.

The presence of dissolution features at the salt-caprock interface and of an apparent saline plume in the freshwater aquifer indicate that Napoleonville dome is currently being dissolved or has been in the recent geologic past. As with all saline plumes determined using electrical logs, however, actual water quality testing is recommended to verify the log data.

MISSISSIPPI SALT DOMES

Tatum Dome, Lamar County

Tatum dome has been explored fairly extensively as a consequence of its history as a test site for two nuclear detonations, Salmon (which formed the cavity used in subsequent tests) in 1964 and Sterling in 1966, as well as for two nonnuclear gas explosions in 1969 and 1970 (Fenske and Humphrey, 1980). Test holes have been drilled into and around Tatum dome as part of a preliminary study and post-detonation monitoring program.

The caprock, which is more than 600 feet (182.9 m) thick near the center of the dome, consists of a cavernous and probably fractured calcite zone, a thin [2 feet (0.61 m) or less] gypsum band, if present at all, and 450 to 470 feet (137.2 to 143.3 m) of generally massive anhydrite (Chafin and Harvey, 1963; Summers, 1968; Fenske and Humphrey, 1980). The salt-caprock interface zone appears to be similar in at least 3 wells described in the "Dribble" reports and in the core examined by Wouch (1982). The partially indurated anhydrite sand at the contact has a sugary texture, is porous and is salty to the taste. The contact of the granular anhydrite with the salt is sharp in Wells WP-4 (Eargle, 1962b) and WP-1 (Eargle, 1962a), but calcareous and brecciated in Well E-7 (Armstrong *et al.*, 1961). The salt-anhydrite contact at Station 1A is tight, however, and water levels in the caprock observation wells did not fluctuate when the contact zone was penetrated (Taylor, 1966). Figures 2a and 2b show the locations of these wells.

Lost circulation was a problem in 22 of the 30 wells drilled through the caprock. Drilling fluid returns were lost in 12 places within the anhydrite or gypsum and in 23 places within the calcite. Although most of the lost circulation zones in different wells could not be correlated across the caprock, the anhydrite-calcite contact and, in at least 3 wells, a zone ranging from 36 to 45 feet (11.0 to 13.7 m) above the salt-anhydrite contact caused problems.

The entire caprock is extremely variable in hydrologic characteristics. Chafin and Harvey (1963, p. 7) state that "there is no conclusive evidence that may be used to divide Tatum Dome into sections wherein a well being drilled might be expected to penetrate the caprock and have a lesser or greater degree of lost circulation; nor can it be said that a zone of lost circulation will be encountered in the upper or lower part of either the calcite caprock or the anhydrite." However, most of the "Dribble" reports describe the salt-anhydrite contact as being "porous."

The caprock water at Tatum is relatively fresh and hard, basically a combined calcium sulfate-sodium bicarbonate type (Chafin and Harvey, 1963). Fenske and Humphrey (1980) report saline (more than 5,000 mg/L of salt) to fresh (less than 1,000 mg/L of salt) water being produced from fractures and cavities in the calcite and anhydrite. The caprock also appears to be hydrologically connected with aquifers 3 and 4 (Harvey and Chafin, 1972; Anderson *et al.*, 1973; Fenske and Humphrey, 1980). Water level and chemical quality data indicate that water actually moves from Aquifer 4 on the flank of the dome through the calcite caprock and into the overlying Miocene formations (Chafin and Harvey, 1963).

Aquifers 1, 2, 3 and 4 contain fresh water in the vicinity of Tatum dome (Summers, 1968; Harvey and Chafin, 1972); however, Fenske and Humphrey (1980) label Aquifer 4 as brackish. Aquifer 5 is saline, having 18,600 ppm on the northeast side of the dome and 31,100 ppm TDS on the southwest side of the dome, although it should be noted that brine has been injected into this aquifer near Baxterville, less than 5 miles (8.05 km) southwest of the dome. Aquifer 4 has similar water qualities on both the northeast and southwest sides of the dome (Harvey and Chafin, 1972). No saline plume has been found in any of the freshwater aquifers in the vicinity of Tatum dome (Smith in Martinez *et al.*, 1976). Plumes would be expected to the south-southwest of the dome because that is the pre-anthropogenic direction of water flow for the deeper aquifers. Aquifers 1 through 3 now flow in an easterly direction as a result of pumping in the area (Fenske and Humphrey, 1980).

The presence of anhydrite sand at the salt-caprock interface and dissolution cavities at or near the interface suggest that the Tatum salt stock is being dissolved by circulating subsurface waters. The absence of a saline plume in the vicinity of Tatum dome may indicate that the dense brine has moved downward into the deeper saline aquifers (Smith in Martinez *et al.*, 1976), although it should be noted that Chafin and Harvey (1963) concluded that the flow was from Aquifer 4 upward through the caprock and into overlying strata. Also, the low salinity of caprock waters (Chafin and Harvey, 1963; Harvey

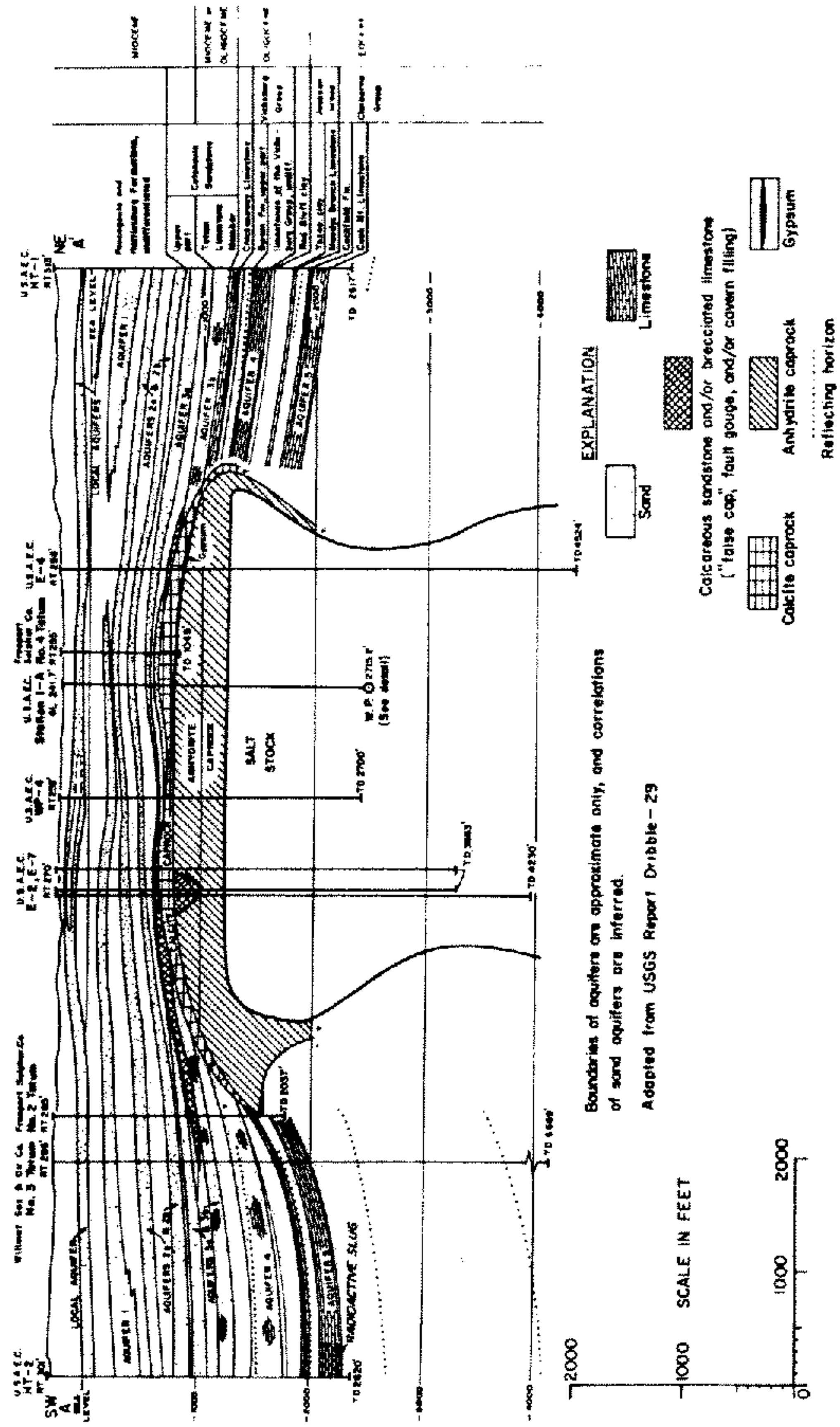
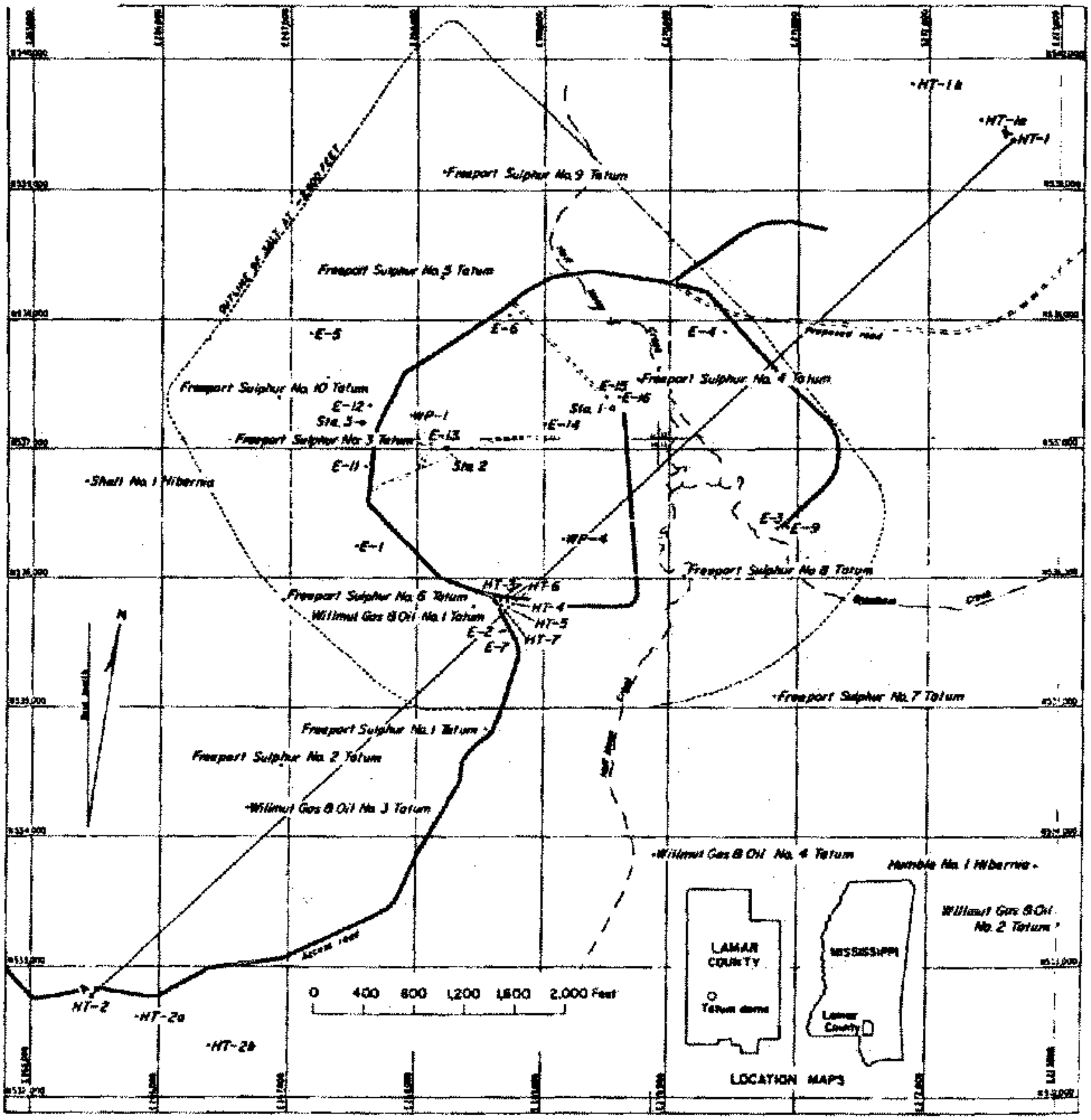


Figure 2a. Geohydrologic cross section of Tatum dome (from U.S. Department of Energy, 1978).



(From Eargle, 1971)
Note: Sta. 1-A, ground zero for the Salmon event, is 30 feet north of Sta. 1.
Figure 2b. Location map for Section A-A′ (Figure 2a), Tatum dome (Anderson *et al.*, 1973).

and Chafin, 1972) may indicate either rapid flushing of the brine from dissolution of the salt or that the salt is not presently being dissolved and any dissolved NaCl has been effectively dispersed. Whatever the reason, dissolution features at the salt-caprock interface and loss of drilling fluids into cavernous zones could not have been predicted by a geohydrologic reconnaissance of the Tatum dome area, which failed to detect a saline plume if one is indeed present.

Richton Dome, Perry County

The crystalline anhydrite caprock at Richton dome grades into 5 to 8 feet (1.5 to 2.4 m) of unconsolidated anhydrite sand immediately above the salt in the U.S. Department of Energy test well, DOE Masonite MRIG-9. This sand proved to be a poor aquifer when tested and caused no problems with lost circulation of drilling muds (LETCo, 1980b; Jackson, A., 1981; Deyling, 1982). Other wells at Richton which penetrated the salt also encountered a "porous" contact with the caprock (Stover, 1982); L. E. Ridgway No. B-8 encountered 7 feet (2.1 m) of granular anhydrite before penetrating salt at 758 feet (231 m) (Samuelson, 1982). Figures 3a and 3b show the locations of these wells.

Caprock waters were found to be slightly saline, being about 11,000 mg/L TDS, but the specific conductance decreased during testing, indicating possible hydraulic connection to the less saline aquifer that overlies the caprock. The permeability of the caprock appears to increase upward, and water movement in the upper portions of the caprock is through fractures, joints and solution channels (LETCo, 1980b).

Although the base of fresh water is shallower in the vicinity of Richton dome than in surrounding areas, this may be due more to structural uplift of saltwater-bearing strata and the trapping of saline water above clay layers than to ongoing dissolution of the salt stock (LETCo, 1980b; Deyling, 1982). The subsurface flow is believed to be southerly (Gandl and Spiers, 1980), but there is also an upward component to the flow which is weaker than the southerly component (LETCo, 1980b). The base of fresh water appears to be higher in the down dip sections south of the dome than elsewhere in Perry County, which could be due to dissolution of the salt stock, but could also be due to incomplete flushing of saline water originally in the aquifers or to upwellings from deeper saline aquifers (Spiers and Gandl, 1980).

The upward component of flow may be responsible for slightly saline waters found in water wells west and northwest of the town of Richton over the shallowest part of the dome. Chloride concentrations from wells in the town of Richton are more than 100 mg/L higher than the average for Miocene aquifers in the area. Also, wells south of Richton dome near Beaumont and New Augusta show chloride concentrations more than 60 mg/L above the average (Spiers and Gandl, 1980). Whether the source of these anomalies is dissolution of the salt stock or upward movement of waters from deeper saline aquifers has not been determined.

The evidence supporting dissolution at Richton dome is weak. The saline anomalies found in aquifers adjacent to Richton dome cannot be conclusively linked to the dissolution of the salt stock (Deyling, 1982; Stover, 1982). The anomalous salinities may be due to the failure of the slow-moving groundwater in this area to flush out relict brines (ONWI, 1982). It is, in fact, questionable to refer to the anomaly as a "saline plume" because of insufficient evidence. Therefore, the presence of anhydrite sand at the salt-caprock interface cannot be correlated with a plume as evidence of salt dissolution at Richton dome.

TEXAS SALT DOMES

Barber's Hill Dome, Chambers County

The unpredictable occurrence of lost circulation during salt dome caprock drilling operations is exemplified by the problems encountered on six different wells at Barber's Hill dome. Two wells had lost circulation problems at the top of the caprock; one of these was drilled dry after returns were lost, and, therefore, no further information is available from that well on lost circulation. One well lost returns in a "rock zone" between the calcite and anhydrite caprock zones. Two wells lost returns both on top of the caprock and at the salt-caprock interface, and another experienced no loss of circulation at all (Van Fossan, 1982).

The presence of small cavities at the salt-caprock contact was reported by Judson and Stamey (1933). Chatter on the bit as the salt-caprock interface was drilled indicates that the interface is not sandy but is probably at least partially indurated and cavernous (Van Fossan, 1982).

Water quality measurements and electrical logs indicate the existence of a salinity anomaly in the Chicot and Evangeline aquifers at least within a mile of the dome (Wesselman, 1971), as shown in Figure 4. The salt core is intrusive and has pierced the surrounding formation; therefore, interconnection of the freshwater aquifers with the caprock or salt is likely. Crystals of sulfur, pyrite and calcite deposited in porous sections of the caprock are rounded at the edges, indicating contact with circulating waters (Bevier, 1925). Higher sulfate and sulfide concentrations in aquifers in the vicinity of Barber's Hill also suggest that water is circulating through the caprock (Henniger, 1925; Wesselman, 1971), which is composed largely of calcium sulfate and usually contains other forms of sulfur within its structure.

The presence of a saline plume and dissolution features at Barber's Hill suggest ongoing dissolution of the salt stock. Another indication of recent or ongoing dissolution is that anhydrite sand with a maximum thickness of 25 feet (7.62 m) was found beneath the overhang along the flanks of the dome (Judson *et al.*, 1932).

Oakwood Dome, Leon and Freestone Counties

The caprock (Renick, 1928) and salt at Oakwood dome are apparently in contact with the freshwater Wilcox aquifer (LETCo, 1980a; Fogg *et al.* in Kreitler *et al.*, 1980). However, the salinity anomalies found in the Wilcox occur in a thin, muddy sand layer near the base of the formation. These saline shaly sands have low hydraulic con-

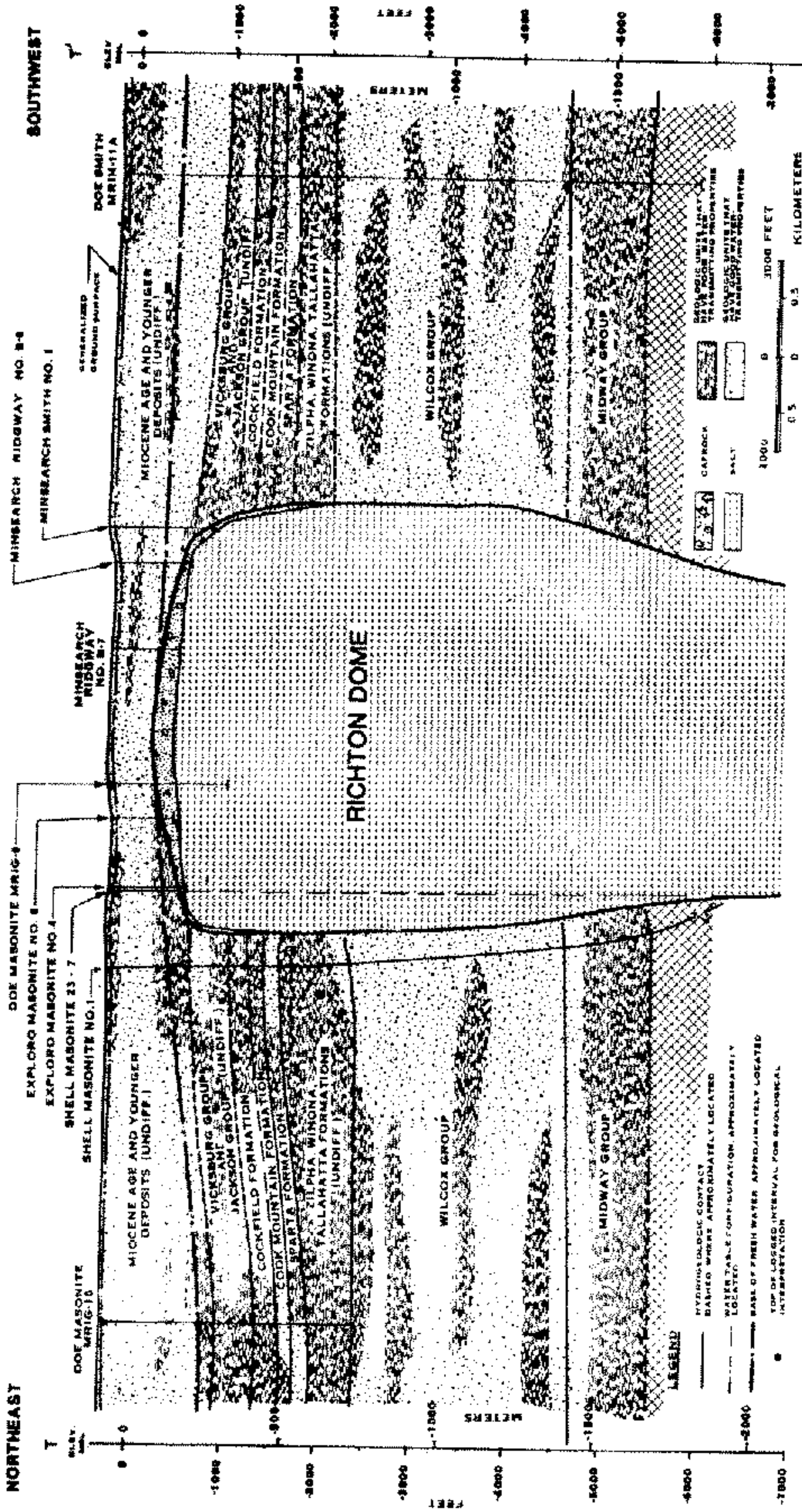


Figure 3a. Geohydrologic cross section of Richton dome (from LETCo, 1980b).

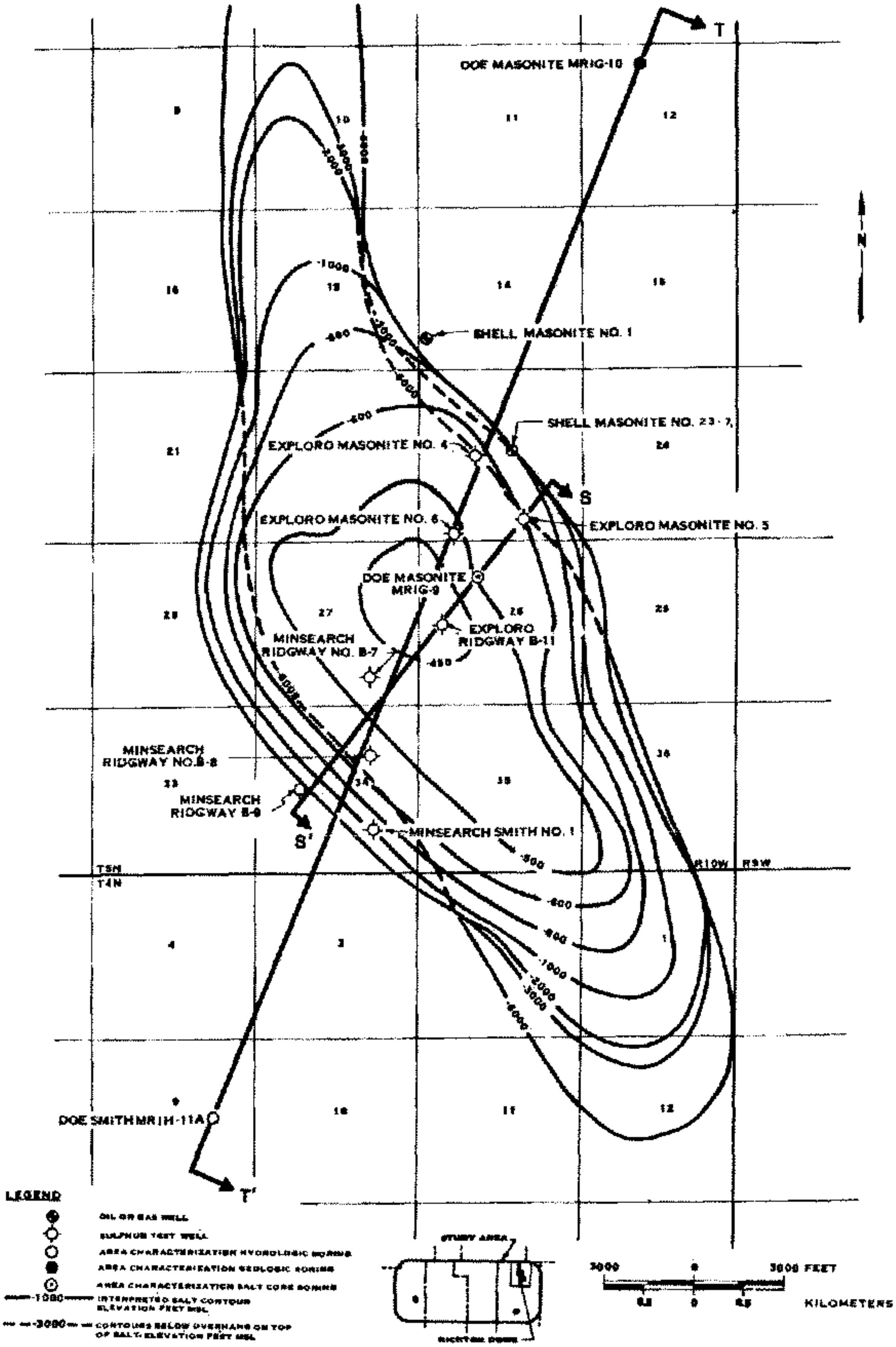


Figure 3b. Location map for section T-T′ (Figure 3a), Richton dome (from LETCo, 1980b).

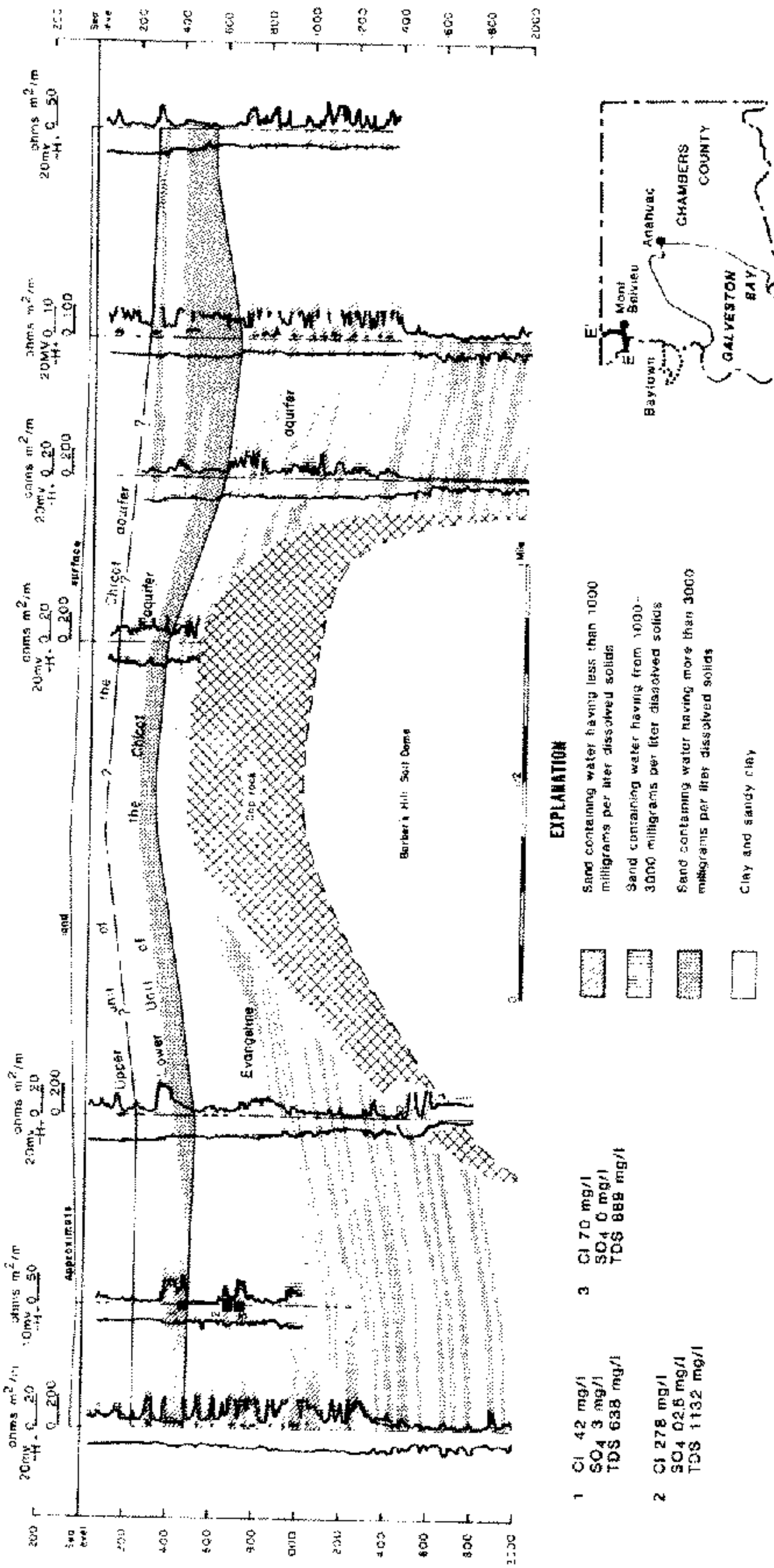


Figure 4. Geohydrologic cross section of Barber's Hill dome (modified from Wesselman, 1971).

ductivities and are separated from the clean sands above by 100 to 300 feet (30 to 90 m) of impervious sediments. The elongate plume (2,000 to 4,000 ppm dissolved solids) extends to the northeast, but the regional groundwater flow to the southeast is perpendicular to the direction of the plume's elongation. Therefore, the salinity anomalies probably do not represent significant ongoing dissolution of the salt stock (Fogg *et al.* in Kreitler *et al.*, 1980).

Fogg *et al.* (1980) suggested three possibilities for the absence of a well-developed plume that can be linked to ongoing dissolution of the salt stock: (1) the caprock may act as a barrier to circulating water which would dissolve and transport the salt, (2) there may be a decrease in permeability near the dome and (3) there may be rapid flushing of saline water by fresh water recharge. Jackson (1982) suggested possible upwellings from deeper saline formations rather than salt dissolution as the source of brine near Oakwood dome.

There is a sharp, cavity-free contact at the salt-caprock interface (LETCo., 1980a; Dix and Jackson, 1982), which probably indicates the lack of active dissolution at least in the vicinity tested. The absence of cavities at the interface may also indicate that the salt is simply rising faster than it is being dissolved. The pressure applied by the rising salt stock, which apparently caused the accretion of anhydrite grains onto the base of the caprock (Jackson, M. P. A., 1981), may also have reduced the permeability of the caprock near the salt contact. The caprock, therefore, may protect the salt from dissolution by circulating waters in the Wilcox. The saline plume near the basal Wilcox may actually be a relict from dissolution in the geologic past when the subsurface flow direction was different than it is today. However, increased salinity near the up dip flanks of the dome (Fogg *et al.* in Kreitler *et al.*, 1980) may indicate very recent salt dissolution that has not yet been dispersed and transported far from the dome.

Palestine Dome, Anderson County

Early accounts of salt mining activities at Palestine dome refer to a sand layer, presumably of residual anhydrite grains, between the consolidated caprock and the salt. Wells were drilled into the caprock, where casing was set, and then through sand into the salt (Hopkins, 1918). This sand is alluded to as a "salt sand" in a driller's log and had sufficient permeability and flow to be a source of water for solution mining of the salt (Powers, 1926).

No saline plumes have been found to date in the aquifers surrounding Palestine dome, although surface salines have been reported which may reflect significant dissolution of the salt (Smith in Martinez *et al.*, 1976). A study by the Bureau of Economic Geology of the University of Texas at Austin concluded that Palestine dome is currently undergoing dissolution, possibly aggravated by solution cavities which remain from abandoned brine wells. Collapse features continue to develop over this dome, most of which contain fresh water, but some are saline, suggesting possible interconnections to caprock brines (Fogg and Kreitler in Kreitler *et al.*, 1980). Uplifted formations around the dome may also be a source of saline waters in surface salines and sinkholes.

The apparent isolation of the salt dome from the Wilcox aquifer by shale beds and the absence of a saline plume (Smith in Martinez *et al.*, 1976) suggest that Palestine dome is not being dissolved by circulating groundwater. The presence of sand at the salt-caprock interface and the active formation of collapse features over the dome offer evidence to the contrary. However, the collapse features appear to be due to poor solution mining practices and may not be caused by naturally occurring ongoing dissolution. The cavities created by solution mining may not necessarily be enlarging, but recent collapses may simply be due to old caverns failing under newly-applied stresses, such as the reported (Fogg and Kreitler in Kreitler *et al.*, 1980) sinkhole that formed minutes after an automobile rode over the site.

The sand at the salt-caprock interface was used to produce water for brining activities. Therefore, it is assumed that lost circulation was not a problem here, possibly indicating an absence of natural dissolution cavities at the interface. Because flowing water is present at the interface, however, it seems likely that some dissolution is occurring.

The evidence available for Palestine dome does not support a correlation between the presence of dissolution features at the salt-caprock interface and saline plumes. However the dissolved salt may be transported to the surface rather than laterally. That water is abundant at the salt-caprock interface is evident from early solution mining records, but the question of dissolution of the salt and its transport from the interface should be examined further.

Grand Saline Dome, Van Zandt County

Some wells drilled into the salt at Grand Saline dome penetrated a zone of sand and gravel, presumably of residual anhydrite, at the salt-caprock interface. This sand yielded water of 150,000 ppm salinity in sufficient quantities to provide water for some solution mining wells 100 to 200 feet (30.5 to 61 m) into the salt; water had to be pumped into other wells (Powers and Hopkins, 1923). Wells drilled after the original ones, however, found cavities on top of the salt. Although the wells did not seem to be interconnected, it is possible that the cavities resulted from earlier solution mining activities (Powers, 1926).

The fact that the sand at the salt-caprock interface provided a permanent water supply to some brine wells

(Powers, 1926) indicates that there is interconnection with local aquifers or surface waters. The high salinity concentration of the water at the interface probably indicates that dissolution is occurring where this circulating water is in contact with the salt. Surface salines in the vicinity of the dome (White, 1973), although not definitely attributable to dissolution of the salt dome (Smith in Martinez *et al.*, 1976), supports the evidence of dissolution found at the salt-caprock interface zone.

Despite the evidence of dissolution at the salt-caprock contact, no saline plume has been found in the Wilcox aquifer surrounding the dome (electrical logs used to determine dissolved solids). However, water-level contours indicate that subsurface flow is eastward, and well control is lacking east of the dome where the plume would most likely be located (Smith in Martinez *et al.*, 1976). That a plume may exist east of the dome is indicated by an artesian well 450 feet (137.2 m) deep and less than 1 mile (1.61 km) northeast of the salt marsh over the dome which yielded saline water. Two shallower wells, 312 and 324 feet (95.1 and 98.8 km) deep, roughly 1/8 mile (0.20 km) southwest of the salty well yielded fresh water, however (Powers and Hopkins, 1923).

The top of Grand Saline dome is apparently being dissolved by groundwater (Smith in Martinez *et al.*, 1976). The dissolved salt is either being discharged at the surface or is concentrated in a plume in a direction where there is insufficient data to detect it. Dissolution features at the interface do not appear to be severe enough to cause lost returns, based on the reported use of the sand as a source of water and the apparent lack of interconnection of the cavities.

Moss Bluff Dome, Liberty County

The characteristics of the salt-caprock interface at Moss Bluff dome vary over the surface of the contact. Unconsolidated sands and cavities are found as well as tight contacts. The northeast section of the dome is characterized by a cavernous interface which caused lost circulation problems when penetrated. A tight contact between the salt and caprock apparently predominates over the eastern part of Moss Bluff. Sandy shale is found below the calcite and sometimes encased within the gypsum on the south and southwest part of the dome. Because the shale layer is shaped like a wedge, it is speculated that the shale migrated in from the flank of the dome, possibly during a period of rapid salt dissolution (Samuelson, 1982).

Electrical log and water quality data indicate that salinity increases in the aquifers near Moss Bluff dome. Salinity contour maps suggest the presence of a plume extending northwest and possibly south to southeast from the dome. This salinity trend appears related to the direction of groundwater flow near the dome. Although water presently flows toward the west or northwest in the southern part of Liberty County, the direction of flow prior to man's interference was southeasterly (Anders *et al.*, 1968; Wesselman, 1971).

SUMMARY AND CONCLUSIONS

The salt-caprock interface characteristics in relation to the presence of saline plumes in aquifers adjacent to the 11 domes studied are summarized in Table 1. Saline plumes were found at Winnfield and Napoleonville domes in Louisiana, and at Barber's Hill and Moss Bluff domes in Texas. Salinity anomalies, which may or may not be related to dissolution plumes, exist at Vacherie dome in Louisiana, Richton dome in Mississippi and Oakwood dome in Texas. No plume was found at Rayburn's dome in Louisiana, Tatum dome in Mississippi or at Palestine and Grand Saline domes in Texas. Lost circulation was found to be a problem in the cavernous interface zones of Rayburn's, Napoleonville, Tatum, Barber's Hill and Moss Bluff domes. Three of the 11 domes studied, Napoleonville, Barber's Hill and Moss Bluff, had both cavernous contacts and saline plumes. Moss Bluff dome, however, has a tight contact over at least the eastern section of the salt-caprock interface. Winnfield dome has a sandy contact and a saline plume. Vacherie and Oakwood domes have tight salt-caprock contacts but also have anomalous salinities in adjacent aquifers. Rayburn's and Tatum domes have no saline plumes as yet detected, but lost circulation is a problem at the salt-caprock interface. Palestine and Grand Saline domes, at least when mining originally began, had sandy interfaces without lost circulation problems, and no saline plumes have been found in the surrounding aquifers.

The data presented on the domes studied indicate that the presence of saline plumes in aquifers surrounding a particular salt dome is not a reliable basis for predicting the occurrence of lost circulation problems at the salt-caprock interface. This does not, however, invalidate the relationship between dissolution features at the salt-caprock interface and the presence of saline plumes in adjacent aquifers. The absence of a saline plume may actually indicate a failure to detect a plume because of an insufficient number of or poorly located wells in relation to the plume axis.

The nature of the salt-caprock interface as deduced from limited borehole data may also be incorrectly assessed. If caprock is truly supported over a salt stock by a series of columns and arches, as suggested by O'Donnell (1935), a cavernous interface may appear to have a tight contact if the only data available comes from wells that happen to be drilled through one or more of the columns. This may have been the case at Napoleonville and Tatum domes, where at least one well penetrated a tight contact

TABLE I

Summary of Interface Characteristics in Relation to Presence of Saline Plumes

Dome	Interface characteristics	Lost circulation at interface	Saline plume*	Comments
Louisiana				
Vacherie	Sharp, tightly cemented[1,2] Sand reported in well—not preserved in cores[6]	No[3]	Possible[4,5]	Salinity determined from electrical log resistivity—maximum concentration of 4,000 ppm dissolved solids.[4]
Winnfield	Sand[7,8] Assumed cavernous[10]	?	Yes[9]	Plume determined from SP curve.[9]
Rayburn's	Cavernous[1,3,11]	Yes[1,3]	No[5,9,12,13]	Dissolved solids determined from electrical log resistivity.[9]
Napoleonville	Cavernous[14]	Yes[14]	Yes[15]	Plume determined from electrical log resistivity.
Mississippi				
Tatum	Sand[16,17] Cavernous[18]	Yes[18]	No[19]	Note: Dipping of fresh aquifers into saline aquifers may mask saline plume.[20]
Richton	Sand[20,21,22,23]	No[22,24]	Possible[25]	Salinity anomalies exist but insufficient data to label as a plume.[20]
Texas				
Barber's Hill	Cavernous[26,27]	Yes[27]	Yes[28]	Physical water quality measurements and electrical logs used to determine plume.[29]
Oakwood	Sharp, tight contact[21,30]	No (assumed)	Possible[31]	Plume does not appear to indicate significant ongoing dissolution of the salt[31,32], which is in contact with freshwater Wilcox sands.[21,31] Physical water quality measurements and electrical logs used to determine plume.[31]
Palestine	Sand[33,34]	No (assumed from description of solution mining[34])	No[19]	Dissolved solids determinind from electrical log resistivity.[19]
Grand Saline	Sand[34,35] Cavernous[34]	No (assumed from description of solution mining[34,35])	No[19]	Dissolved solids determined from electrical log resistivity. Insufficient data to east of dome where plume would be expected.[19]
Moss Bluff	Cavernous[23] Tight contact[23]	Yes[23] No[23]	Yes[28,36]	Plume suggested from salinity contour maps.[28,36] Water quality from measurements and as determined from electrical logs.[28,36]

1. Nance and Stirling in Martinez *et al.*, 1979
2. Nance, Rovik and Wilcox, 1979
3. Hawkins, 1978
4. Smith in Martinez *et al.*, 1977
5. Kumar in Martinez *et al.*, 1979
6. Rovik in Martinez *et al.*, 1978
7. Huner, 1939
8. Belchic, 1960
9. Smith in Martinez *et al.*, 1975
10. Kumar, 1981
11. Nance and Wilcox, 1979
12. Smith, Barlow and Hoda in Martinez *et al.*, 1977
13. Kumar and Hoda in Martinez *et al.*, 1978
14. Source withheld upon request
15. Wouch, 1982
16. Eargle, 1962a
17. Eargle, 1962b
18. Chafin and Harvey, 1963
19. Smith in Martinez *et al.*, 1976
20. Stover, 1982
21. LETCo, 1980
22. Deyling, 1982
23. Samuelson, 1982
24. Jackson, A., 1981
25. Spiers and Gandl, 1980
26. Judson and Stamey, 1933
27. Van Fossan, 1982
28. Wesselman, 1971
29. Wesselman, 1982
30. Dix and Jackson, 1982
31. Fogg *et al.* in Kreitler *et al.*, 1980
32. Fogg in Kreitler *et al.*, 1980
33. Hopkins, 1918
34. Powers, 1926
35. Powers and Hopkins, 1923
36. Anders *et al.*, 1968

*Because of incomplete data in most cases, the presence or absence of a plume should be considered only as a best estimate based on the available data.

on each dome while others encountered cavernous contacts.

The difficulty in predicting interface characteristics is further illustrated by Moss Bluff dome, which has a tight contact over its eastern section and a cavernous contact over its northeastern section, according to the available records (Samuelson, 1982). The saline plume at Moss Bluff may be useful in predicting that a cavernous interface exists somewhere on the dome, but the engineering applications of such information would be limited due to the inability to predict the location or the uniformity of interface characteristics over the surface of the dome.

The findings presented here underscore the value to hydrologic stability studies of salt domes for long-term waste isolation projects of as much information as is possible regarding the salt-caprock interface characteristics along with the salinity patterns in aquifers surrounding the target domes. The presence of a plume may not necessarily indicate ongoing dissolution of the salt stock. The plumes may be relicts of past periods of dissolution that have not been flushed or completely dispersed. Another possibility is that the plumes are related to dissolved solids being transported from upturned saline aquifers around salt domes into the freshwater aquifers. Saline waters may also travel upward along faults common in the strata around piercement-type salt domes (Timm and Maricelli, 1953). Finally, the salinity in some sands has been found to be related to the compaction of adjacent shales (Timm and Maricelli, 1953; Davis and DeWiest, 1966). Although this may not be a major source of salinity, the compaction of shales by the upward-moving salt stock may contribute in some cases to salinity anomalies around salt domes. When long-term hydrologic stability is a factor in planning salt dome utilization projects, however, it may be prudent to be safe and to assume that the salinity is due to dissolution unless other information is available.

The nature of the salt-caprock interface is probably related as much to the tectonic stability of the salt stock as it is to its rate of dissolution. If the salt is rising more rapidly than it is being dissolved over its entirety or locally, no dissolution features may be apparent at the interface in any given well, but a saline plume resulting from the dissolution could be present in the surrounding aquifers. Also, the absence of a saline plume may indicate an upward or downward, rather than a lateral, path followed by the dissolved salt. Therefore, the use of saline plumes or dissolution features alone for determining the hydrologic stability of salt domes probably is insufficient in most cases (Wouch, 1982).

More research also is needed to clarify the relationships between geophysical well logs and water quality determination. Salinity estimates from electrical logs are tentative, especially with the data generally available for freshwater zones, and any "plumes" determined using only log data should be examined with this in mind (Wouch, 1982). Physical water sampling should precede the selection of any salt dome for long-term waste isolation based on well log inferences of salinity patterns around the dome. The water samples may also be helpful in determining the source of the salinity, perhaps by measuring the Cl/Mg (equivalents per million) ratio as described by Parker (1969), by comparing isotopic ratios as described by Knauth *et al.* (1980) or by some other method.

The complex interrelationships between the dissolution of salt, the characteristics of the salt-caprock interface and the geohydrologic conditions around a salt dome cannot be defined in one general statement. Each dome must be studied individually and in detail before conclusions can be drawn concerning the prediction of lost circulation at the salt-caprock interface or the long-term geohydrologic stability of any particular salt dome.

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