SALT CAVERN STUDIES — REGIONAL MAP OF SALT THICKNESS IN THE MIDLAND BASIN

FINAL CONTRACT REPORT

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CONTENTS

Figures

EXECUTIVE SUMMARY

Regional variation in the thickness of the major bedded salt-bearing interval of West Texas, the Salado Formation, provides a screening criterion for separating areas where the salt is heterogeneous, complex, and potentially less stable from areas where salt is more homogeneous. Areas of reduced and variable salt thickness and relatively shallow depths to the top of the salt are identified on the eastern shelf of the Midland Basin in Garza, Borden, Howard, Glasscock, and Reagan counties; along the Pecos River in Crockett, Upton, Crane, and Pecos Countries; and along the western edge of the Central Basin Platform in Ward and Winkler Counties. Reconnaissance data suggest that salt may be locally or regionally actively dissolving from these areas.

Salt thinning in areas where the top of salt is relatively deep (>1500 ft) is noted south of the Matador Arch in Cochran, Hockley, and Lubbock counties, and locally along the eastern edge of the Central Basin Platform in Gaines, Andrews, and Ector Counties. The thinning in these areas is tentatively interpreted as dominantly the result of deposition of thin salt or Permian salt dissolution. In all the areas of thinning, sedimentary patterns suggest that facies changes may also change the quality of the salt (salt purity, water content, bed thickness) over short distances.

In other areas within the Midland and Delaware Basins, salt thickness changes are gradual. However, the potential for local areas of salt dissolution not identified in this regional study, for example those that may be beneath saline lakes, to impact the suitability for salt in these areas as host strata for cavern development was not investigated in this regional study.

INTRODUCTION

Utilization of salt caverns in bedded salt for storage of product or disposal of wastes associated with oil and gas exploration and production activities is an attractive alternative to other storage and disposal options if there is assurance that products or wastes will remain isolated in the salt cavern. Both regulators and salt cavern developers and operators need access to information about bedded salt to assist them in site selection and evaluation.

Geologic factors that may influence the suitability of salt for facility development and long-term maintenance include (1) lateral and vertical variability in the thickness and purity of the salt beds, (2) composition, permeability, strength, and solubility of associated nonsalt beds, (3) lateral and vertical variability in the water content and crystal size of the salt, (4) composition, location, thickness, and permeability of associated units where casing and seals are set to isolate the salt interval from hydrologically active shallow units, (5) hydrogeologic settings that favor or preclude salt dissolution, and (6) potential for breaching of the salt or associated interbeds by dissolution.

PURPOSE

This project is a reconnaissance examination of bedded salt in a 28-county area of West Texas (fig. 1). Salt cavern disposal operations have been permitted or are pending in Andrews, Pecos, Yoakum, and Howard Counties (Railroad Commission of Texas, Richard Ginn, written communication). Numerous underground hydrocarbon storage facilities are sited in salt formations in this area (Railroad Commission of Texas, 1995). This reconnaissance examination is designed to document regional variation in salt thickness and to demonstrate the utility of geologic studies to provide basic information useful for siting and regulating salt caverns.

METHODS

The project was conducted in two phases. In the initial phase, geologic literature describing the distribution, thickness, and geologic stability of bedded salt in the study area and adjacent parts of the Permian Basin was reviewed and compiled. In the second phase, regional maps of salt were prepared. Goals were selected to accomplish mapping within the scope of the project. The Salado Formation (fig. 2) was selected as the unit to be mapped. The Salado Formation is

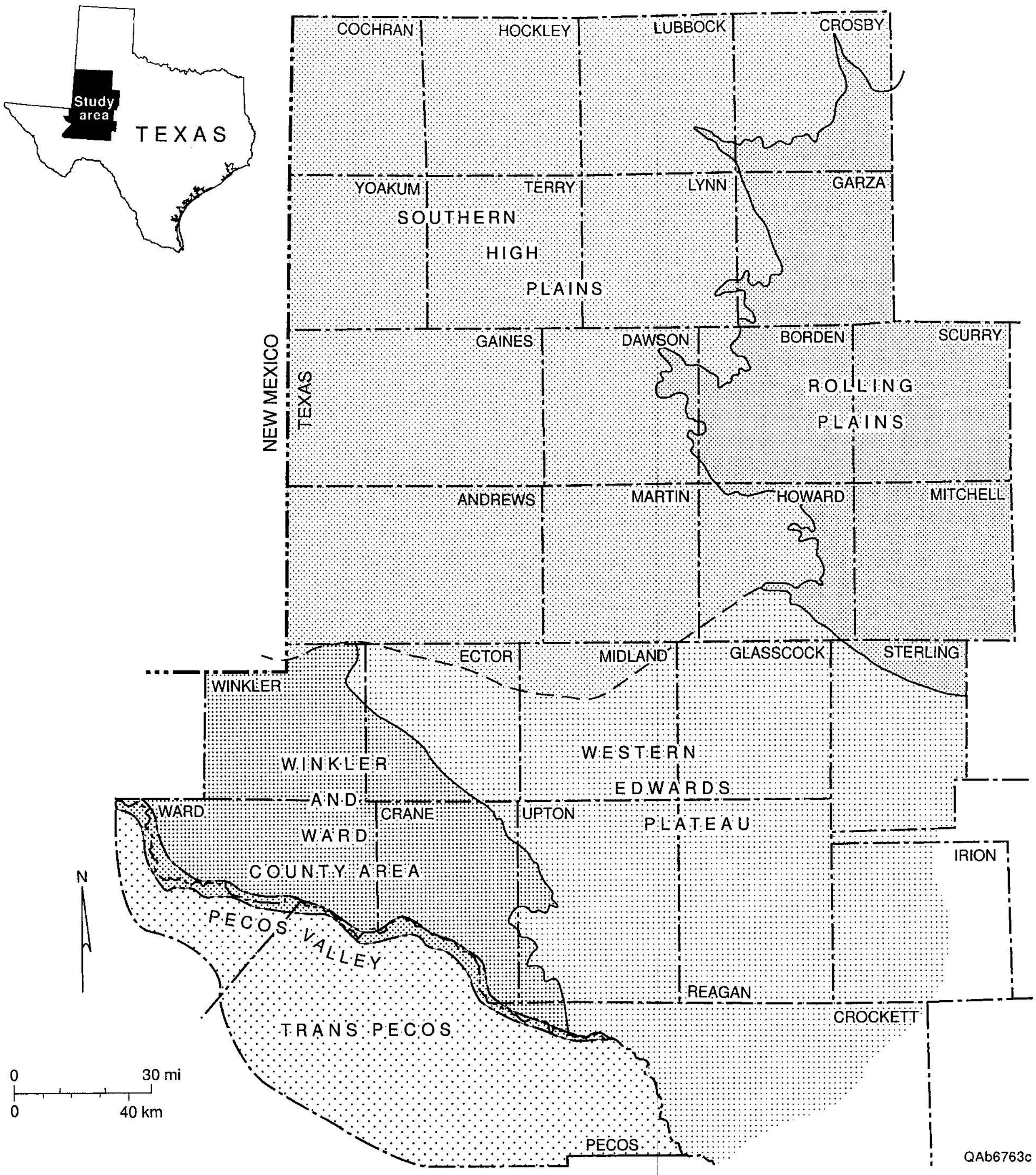

Figure 1. Location map showing study area and physiographic regions.

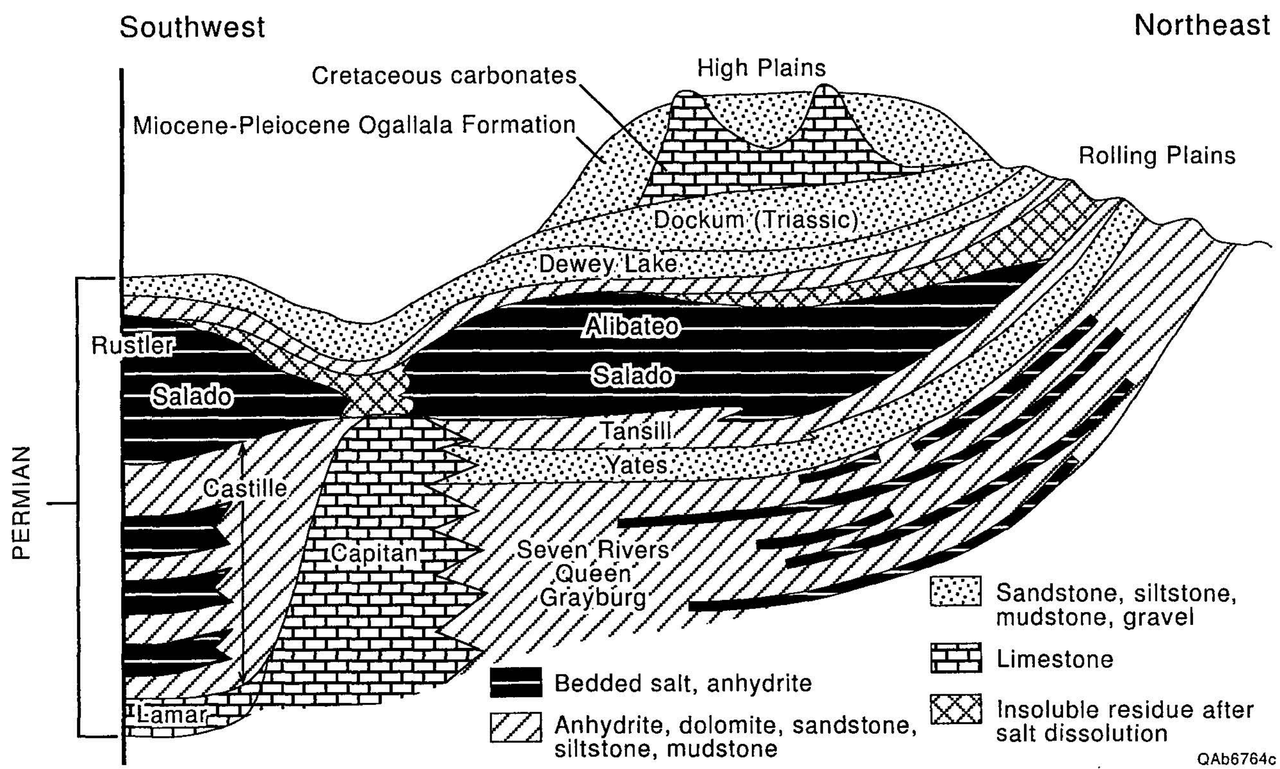

Figure 2. Schematic diagram showing relationships among stratigraphic units in the study area. Top of the Alibates Formation and equivalent top of upper Rustler anhydrite are the upper marker beds mapped in this study; top of Yates Formation and top of Lamar limestone are the lower marker beds.

the upper salt-bearing unit in the study area. Throughout much of the study area, the thickest and most extensive salts occur in this interval. Documents from the Railroad Commission of Texas (1995) indicate that the Salado Formation is the stratigraphic interval targeted for underground storage facilities in this area. However, when the extent of the Salado salt was mapped, some of the storage facilities lie east of the salt pinch-out. These facilities may be in the older salt bearing units, the Seven Rivers, Queen, and Grayburg Formations (fig. 2); therefore a reconnaissance map showing the extent of salt in these older units was also prepared.

About 500 wireline logs were selected and photocopied from log files at the Bureau of Economic Geology. An effort was made to distribute well locations through the study area with a few additional logs in areas where the literature search suggested that heterogeneity was expected. Previous experience suggested that the most useful logs for West Texas bedded salt mapping are gamma-ray–caliper–sonic combinations. If these were not available in the log files, neutron or resistivity logs were used. The log data base assembled is not exhaustive; many thousands more logs through the salt interval are available but could not be analyzed in the time available.

The stratigraphic interval selected for mapping was based on prominent, areally extensive markers that bound the salt. The upper marker bed is the top of the Alibates Formation in the Midland Basin and equivalent top of upper Rustler anhydrite in the Delaware Basin (fig. 2). The lower marker beds are the top of the Yates Formation in the Midland Basin and Central Basin Platform and top of the Lamar limestone in the Delaware Basin (fig. 2). Selection of these markers includes some regional nonsalt bed units within the mapped interval; however, using well-defined markers reduced stratigraphic ambiguity and allowed completion of mapping within the available time frame. Below the Salado Formation but within the mapped interval is the Tansill Formation, a relatively thin (typically 100-ft) carbonate, anhydrite, and sandstone unit. In the Delaware Basin, a thick interval of the Castile Formation, containing anhydrite, salt, organic shale, and carbonate, underlies the Salado Formation above the Lamar marker. Above the Salado salt are the relatively thin (average 100-ft) carbonate, anhydrite, and sandstone units of the

Alibates or Rustler Formation and variable amounts of insoluble residue left after salt dissolution.

Well location and datum elevation (kelly bushing or equivalent) were extracted from the log header and the well located on a blueline survey base (Midland Map Company, 1995). This paper map was scanned and registered on a digital county-line base (U.S. Geologic Survey 1: 250,000 base map). Some distortion of county shapes was noted on the paper base relative to the digital base, which limits the accuracy of the mapping at a fine scale. Well location and elevation data were checked by comparing the elevation of the top of the Yates to a detailed published structure map (Geomap, 1989), and logs with erroneous header data were discarded. Stratigraphic information was extracted from cross sections and stratigraphic studies (Adams, 1944; 1968; Herald, 1957; Humble Oil and Refining, 1960;1964a, 1964b; Tait and others; 1962; Feldman, 1962; Vertrees 1962-1963; Snider, 1966; McKee, Oriel and others, 1967; Mear 1968; Johnson, 1978; Presley, 1981; Matchus and Jones, 1984; Borns and Shaffer, 1985; McGookey and others, 1988; Hovorka, 1990). Stratigraphic units were marked on log photocopies and the datum and unit tops were entered into a spreadsheet and used to calculate unit thickness and structural elevation. These data were spotted on maps. Hand contouring was used to optimize interpretation of the regional data, using the published Yates structure map (Geomap, 1989) and surface geology (Barnes, 1992) to guide interpolation.

STRUCTURAL SETTING AND DEPOSITIONAL ENVIRONMENTS

The geometry, quality, and stability of salt depend on interactions among the character, thickness, and composition of the salt when it was deposited; postdepositional uplift and subsidence; and landscape development and resulting ground-water circulation patterns. Only a few studies have described the salt within the Midland Basin in detail. Extensive research on the salts in the adjacent Delaware and Palo Duro Basins, conducted during characterization of the salts in these areas as potential hosts for radioactive waste, can be readily applied to understanding the similar salt in the Midland Basin. A general overview, based on literature review, documenting how these variables control salt character is provided in the following section.

The depositional setting for salt in the Permian Basin was controlled by paleogeography. The Delaware Basin, at the western edge of the study area, was a structural and topographic basin that provided the inlet for marine water during most of the Permian (fig. 3). Sedimentary patterns show that by the Guadalupian, sedimentation had mostly leveled topography east of the Delaware Basin, so that the major structural elements such as the Central Basin Platform, Midland Basin, Northern Shelf, Matador Arch, Eastern Shelf, and Ozona Platform (fig. 3) were expressed only by subtle contrasts in subsidence rates (Adams, 1940; Feldman, 1962; Machus and Jones, 1984; Fracasso and Hovorka, 1986). The Sheffield and Hovey channels were topographic features that served as conduits for marine water to move onto the shelf. Salt precipitation began in the Midland Basin during the Guadalupian; salt occurs in the Grayburg, Queen, and Seven Rivers Formations (Price, 1991). The thickest salts are generally observed on the parts of the shelf away from the Delaware Basin toward the east and north. Carbonate accumulation rimming the Delaware Basin is known as the Capitan reef (King, 1942; Garber and others, 1989). Several cycles of sandstones, anhydrite, and halite of the Yates Formation were deposited across the platform during a sea-level lowstand; the corresponding deposits in the Delaware Basin are in the Bell Canyon Formation. The deposits of the following highstand, also composed of a number of cycles, are carbonate, anhydrite, halite, and sandstone of the Tansill Formation. The Lamar Limestone is the basinal equivalent (Garber and others, 1989).

During the Ochoan, evaporites began to precipitate in the Delaware Basin. The topographic depression was filled by the Castile Formation (Snider, 1966; Adams, 1944; Anderson and others, 1972). Deposition of thick salts in the Salado Formation followed. The Salado Formation, like preceding Permian units (Meissner, 1972; Hovorka, 1987), is highly cyclic on a meter scale throughout the Permian Basin (Dean and Anderson, 1978; Lowenstein and Hardie, 1985; Lowenstein, 1988; Hovorka, 1990; Holt and Powers, 1990). Cycles began with a flooding event, which typically precipitated anhydrite. Sediment aggradation caused restriction, limiting water

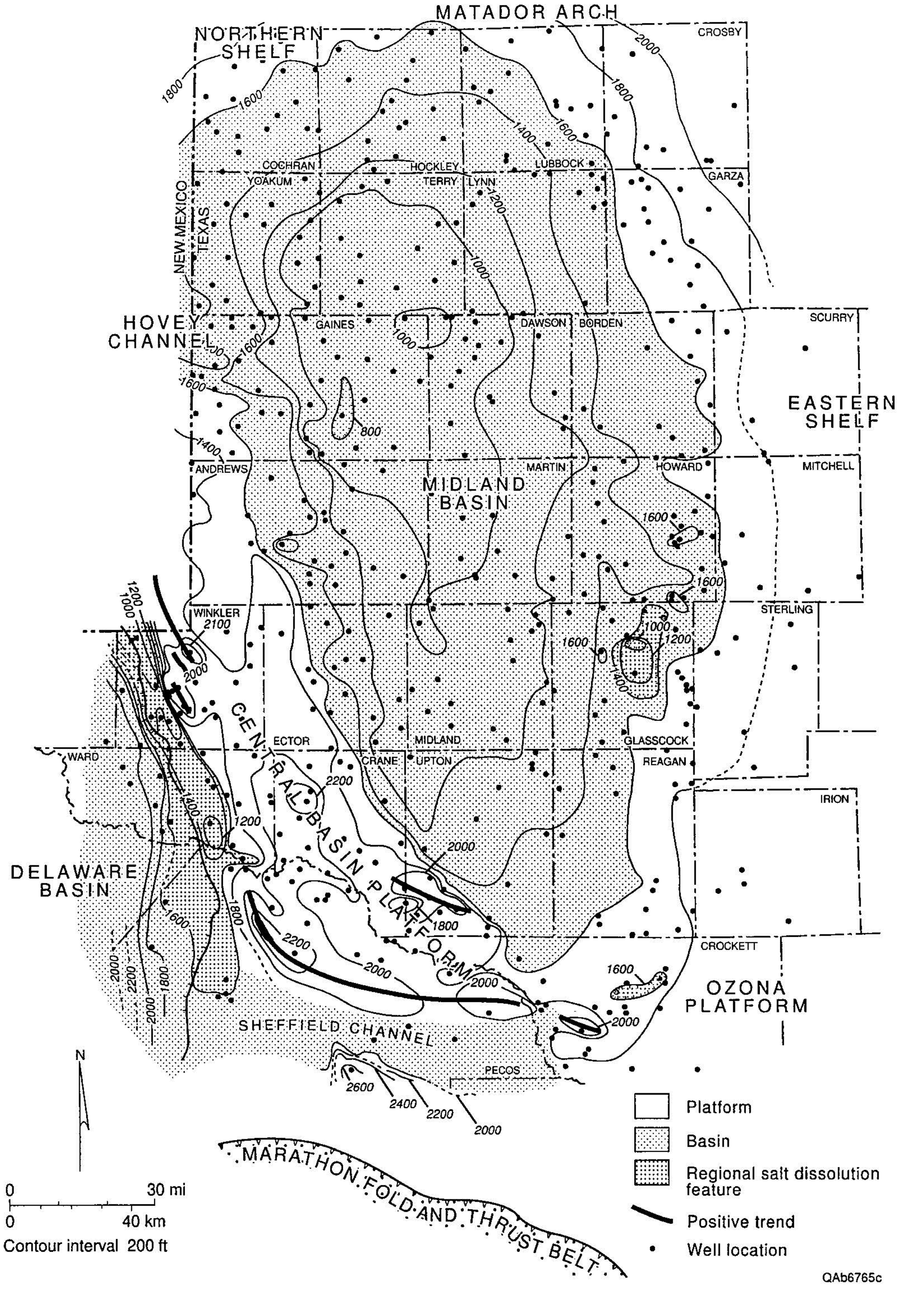

Figure 3. Structure on the top of Salado salt-bearing interval. Top Alibates Formation and equivalent top of upper Rustler anhydrite are used as markers. This map shows structural elements such as the Delaware Basin, Central Basin Platform, Sheffield and Hovey channels, Midland Basin, Northern Shelf; Matador Arch, Eastern shelf, and Ozona Platform. This marker bed overlies the Salado salt; therefore the prominent salt dissolution features can be identified in Winkler, Ward, and Glasscock counties.

movement and causing halite precipitation. In the Salado Formation, highly evaporated brines ponded on the saline flat altered previously deposited gypsum to polyhalite. Mud, silt, and sand deposited by eolian and arid-region fluvial processes are interbedded with the halite. Interbedding of anhydrite, polyhalite, halite, and fine-grained clastics on a centimeter scale reflects the variation in the depositional environment (Fracasso and Hovorka, 1986; Lowenstein, 1988; Hovorka, 1990; Hovorka, 1994). Facies within the salt depositional environment control variations in the amount, mineralogy, and distribution of impurities; in the crystals' size, shape, and interrelationship; and in the amount, distribution, and chemistry of included water. The facies are complex vertically and horizontally; however, analysis of the facies relationships can be used to map the characteristics of the salt (Kendall, 1992; Hovorka and others, 1993).

Salt deposition within the Permian Basin ended with a major transgression that deposited the Alibates Formation. This unit contains thin but extensive carbonate and anhydrite beds separated by a siltstone or sandstone (McGillis and Presley, 1981). Stratigraphic nomenclature and relationships are complex in the Delaware Basin (Powers and Holt, 1990). However, genetic equivalence and correlation of the upper Rustler anhydrite with the upper carbonate-anhydrite unit of the Alibates appears reasonable. Overlying the Alibates and the upper Rustler anhydrite are fine sandstones, siltstones and mudstones (Dewey Lake Formation or upper Rustler Formation) that represent the end of Permian deposition.

The post-Permian evolution of the area includes deposition of the Triassic Dockum Formation in fluvial and lacustrine environments (McGowen and others, 1979); erosion and truncation; deposition of Cretaceous sandstones and carbonates over most of the area; regional uplift and erosion during the Cenozoic; and deposition of gravels, sands, and finer grained clastics of the Miocene-Pliocene Ogallala Formation in fluvial and upland eolian settings (Seni, 1980; Gustavson, 1996). Other significant Cenozoic deposits include Pecos river gravels (Bachman, 1984) and surficial sand, terrace, and colluvial deposits (Barnes, 1992). Cenozoic uplift and tilting reactivated structural elements with the same sense of motion as they had during the Permian (McGookey, 1984), so that in the center of the Midland Basin the top of the Alibates is at 500 ft above sea level, while over the shelf and platform areas it lies at 1800 ft (fig. 3). In the Delaware Basin, Permian rocks dip gently toward the east; in the eastern shelf, Permian rocks dip gently toward the west.

Landscape development and resulting ground-water circulation patterns have modified the distribution of salt (fig. 1). In the eastern part of the study area, Cretaceous and Cenozoic deposits have been eroded and Permian rocks crop out at the surface (Barnes, 1992). Pecos incision has removed post-Permian rocks in the southern part of the study area. Across the Permian Basin, dissolution has occurred at several times in the past and continues today. Dissolution initially modified the geometry of the salt in the Permian depositional environment (Hovorka, 1994). These dissolution events combined with depositional processes to control salt bed thickness, purity, and continuity. Influx of marine water during short- or long-term sea level rise partly or completely dissolved previously deposited salt. Facies change as a result of this process may control the salt quality over the Central Basin Platform. Recrystallization, karstification, and salt dissolution also modify the salt during exposure as a result of sea level drop. These processes result in facies changes that effect salt across the platform but are dominant in updip settings (Nance, 1988, Hovorka and Granger, 1988). Correct interpretation of these Permian salt dissolution effects is needed to avoid overestimating the rates of modern salt dissolution.

Salt dissolution occurred during the Triassic and during the Cretaceous (Adams, 1940). The extent of salt dissolution during these times has only locally been determined because the effects of earlier and later dissolution are difficult to separate.

The major regional episode of salt dissolution occurred during Cenozoic uplift (Baker, 1977; Gustavson and others, 1980; Johnson, 1981; Boyd and Murphy, 1984; DeConto and Murphy, 1986; Goldstein and Collins, 1984; Gustavson, 1986; Johnson, 1989b). Like earlier dissolution episodes, Cenozoic dissolution was more pronounced over structural positive features than basins. In the Rolling Plains (Permian outcrop belt), Cenozoic dissolution has removed salt to depths of about 1000 ft below land surface. Beneath the Southern High Plains (Midland Basin area), where the Permian units are overlain by Triassic, Cretaceous, and Cenozoic strata, dissolution has removed less salt than in the Permian outcrop (Gustavson and others, 1980; McGookey and others, 1988). Cenozoic dissolution has also been documented along the Pecos Valley overlying the Central Basin Platform structurally positive feature (Adams, 1940) and above the Capitan reef trend in Winkler County (Bachman, 1984).

If hydrologic gradient exists, basinal brines that are undersaturated with respect to halite or fresh surface water can move along natural or man-made conduits and dissolve salt. This process is thought to have contributed to modern salt dissolution and collapse at the Wink Sink (Baumgardner and others, 1982; Johnson, 1987; 1989a), and modeling suggests that it might occur elsewhere in the Permian Basin (Anderson, 1981; Howard, 1987).

Depressions on the Southern High Plains surface that host large lakes have been interpreted as locations of focused salt dissolution (Reeves and Temple, 1986; Ateiga, 1990). The relationships between surface depressions and salt dissolution and the timing and process involved are complex and poorly understood. Not all lakes overlie areas of salt dissolution, and the timing and rates of dissolution appear to be variable.

Dissolution continues today throughout the Permian Basin. Ground-water chemistry and saline spring discharges provide evidence of current dissolution (Richter and Kreitler, 1986; Dutton, 1987; Paine and others, 1994; James and others, 1995). Collapse and subsidence features and rates can be identified using a variety of assumptions and dating techniques to determine the probable rates and processes of salt dissolution (Swenson, 1974; Gustavson and others, 1980; Gustavson and Simpkins 1989, Paine and others, 1994).

SALT THICKNESS

Salt thickness (fig. 4) was mapped in an interval from the top of the Alibates Formation and equivalent top of upper Rustler anhydrite to the top of the Yates Formation in the Midland Basin and Central Basin Platform and top of the Lamar limestone in the Delaware Basin (fig. 2). The thickest interval (2000 to 4000 ft) is in the Delaware Basin in the southwest part of the study area

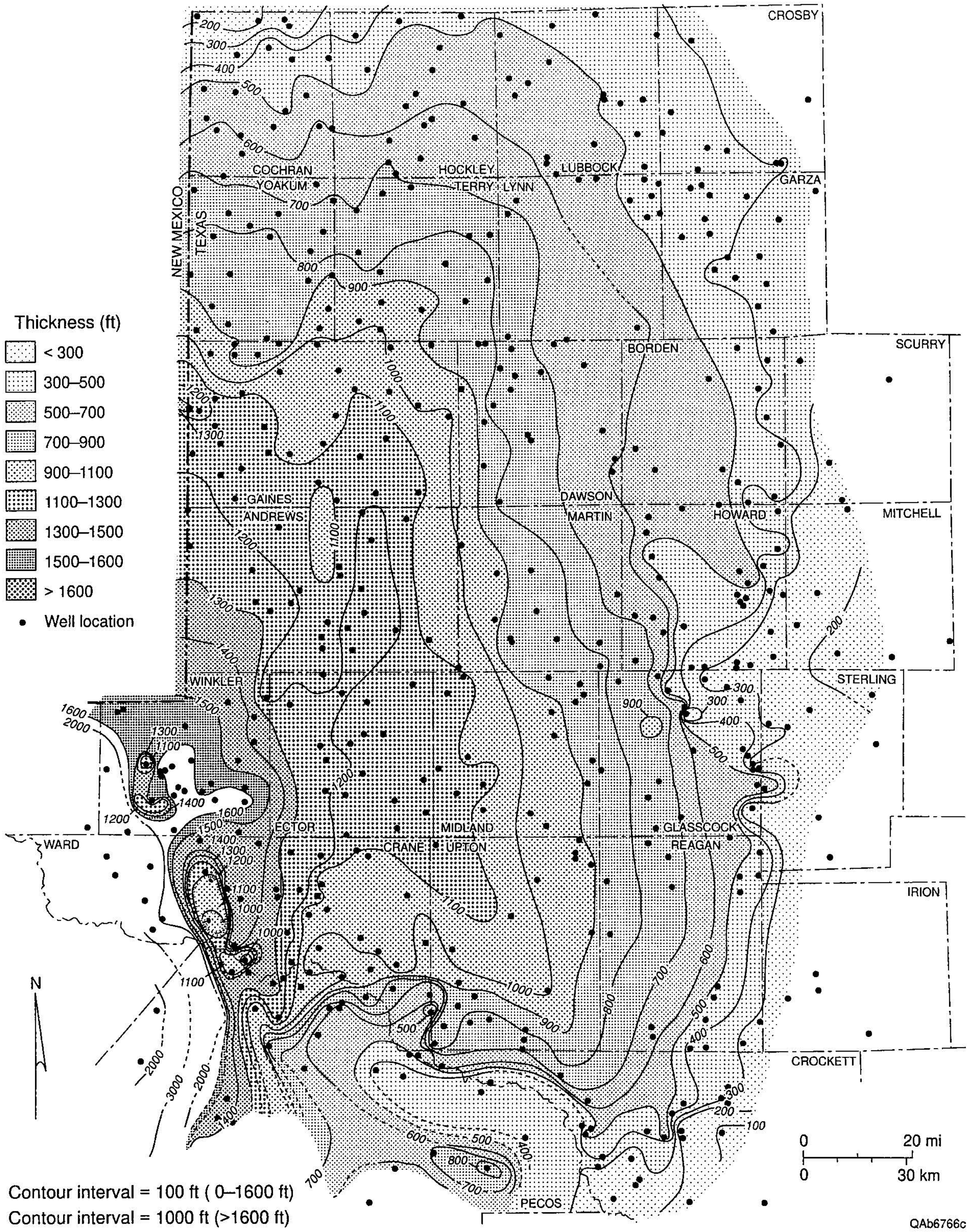

Figure 4. Thickness of interval containing Salado salt from the top of Alibates Formation and equivalent top of upper Rustler anhydrite to top of Yates Formation and top Lamar limestone. Percent salt in the interval varies from about 85 percent in thick intervals to 0 percent where salt has been dissolved in thin intervals.

(western Pecos, Ward, and Winkler counties). This is the margin of the very thick and extensive salt of the Delaware Basin. The lower half of this interval is made up of anhydrite of the Castile Formation; complex facies in the upper part of the Castile Formation precluded separating the Salado from the Castile Formation during this study. The Castile and Salado salt in this area has been examined in the Gulf Research PDB-03 core from southeastern Loving county just west of the study area (Hovorka, 1990). The salt-bearing interval thins rapidly over the Capitan reef margin (fig. 3). This thinning is because of dramatic thinning or pinch out of the Castile Formation as well as thinning of the Salado Formation (Girard, 1952; Bachman, 1984; Garber and others, 1989). On the platform that makes up the rest of the study area, a generally gradual eastward and northward thinning trend is noted. Examination of logs shows that throughout much of the study area, this interval contains abundant, thick, and extensive salt beds.

A number of variations superimposed on the regional pattern can be identified at the scale mapped (fig. 4). A thick salt interval (greater than 1200 ft) occurs in the western part of the Midland Basin (Ector, Midland, and Upton Counties); another thick interval fills the Hovey channel (western Gaines County). A pronounced thinning trend is noted on the edge of the Central Basin Platform, starting in Winkler and Ward County and extending eastward along the Central Basin Platform trend to eastern Pecos and western Crockett counties. This corresponds to thin, absent and dissolved salt along the Capitan reef trend (Girard, 1952; Baumgardner and others, 1982; Johnson, 1987; 1989a) and in the Yates field area (Adams, 1940; Wessel 1988, 1992a, 1992b). This trend also continues northward along the reef trend into New Mexico (Bachman, 1984).

Other areas of thinning over short distances are noted over structural features marking the Midland Basin margins. Thinning is noted in Crockett County over the Ozona Platform. Regional cross sections (Humble, 1960, 1964a; Vertrees, 1962-1963) show erosional truncation of the Permian beneath the Cretaceous in this area. Thinning of the interval to 300 or 200 ft corresponds to complete dissolution of the salt in the interval toward its truncated edge, leaving only the Tansill, Alibates, and insoluble residue after salt dissolution. The trend of thinning of the salt-bearing interval continues along the eastern shelf (Reagan, Glasscock, Howard, Bordon, Garza and Crosby counties). Depositional thinning, salt dissolution, and erosional truncation beneath the Cretaceous and toward outcrop are all factors in this thinning. Some areas of abrupt lateral thinning and complex geometries are noted in Glasscock and Howard counties, generally corresponding to a structurally high area (Humble, 1960; Vertrees, 1962-1963; Geomap, 1989). A general trend in salt thinning continues around the north of the Midland Basin along the Matador Arch and Northern Shelf structural and depositional positive elements. No areas of abrupt lateral thinning were noted in this area.

Several areas of more closely spaced contours are identified within the Midland Basin. In northern Gaines County, thinning of the salt bearing interval is noted north of the thick salt in the Hovey Channel. Another minor thinning trend corresponding to the eastern edge of the Central Basin Platform is noted across the central Gaines-Andrews county line.

DEPTH TO TOP OF SALT

A map showing the depth of the salt-bearing interval below the surface (fig. 5) was prepared as a simple way of separating the areas where active salt dissolution processes are probable (near surface settings) from areas where salt thinning may be relict from paleo-hydrologic conditions (deeply buried). Salt occurs near surface (fewer than 1000 ft) along the eastern edge of the study area and along the trend of the Central Basin Platform, especially in Crane and north central Pecos county (Yates oil field area). Salt is deeply buried by Triassic and Tertiary sediments along the Midland Basin, Northern Shelf, and Matador Arch structural elements. The age and significance of the prominent increase in depth to salts, which corresponds to the prominent salt thin (fig. 4) and depression in the top Alibates structure (fig. 3) in central Winkler and Ward Counties, requires further investigation. The relative importance of syndepositional, Mesozoic, and Cenozoic dissolution and whether dissolution is still active in this area is unresolved. Where Permian units crop out in the western Delaware Basin, burial to the top of the salt-bearing

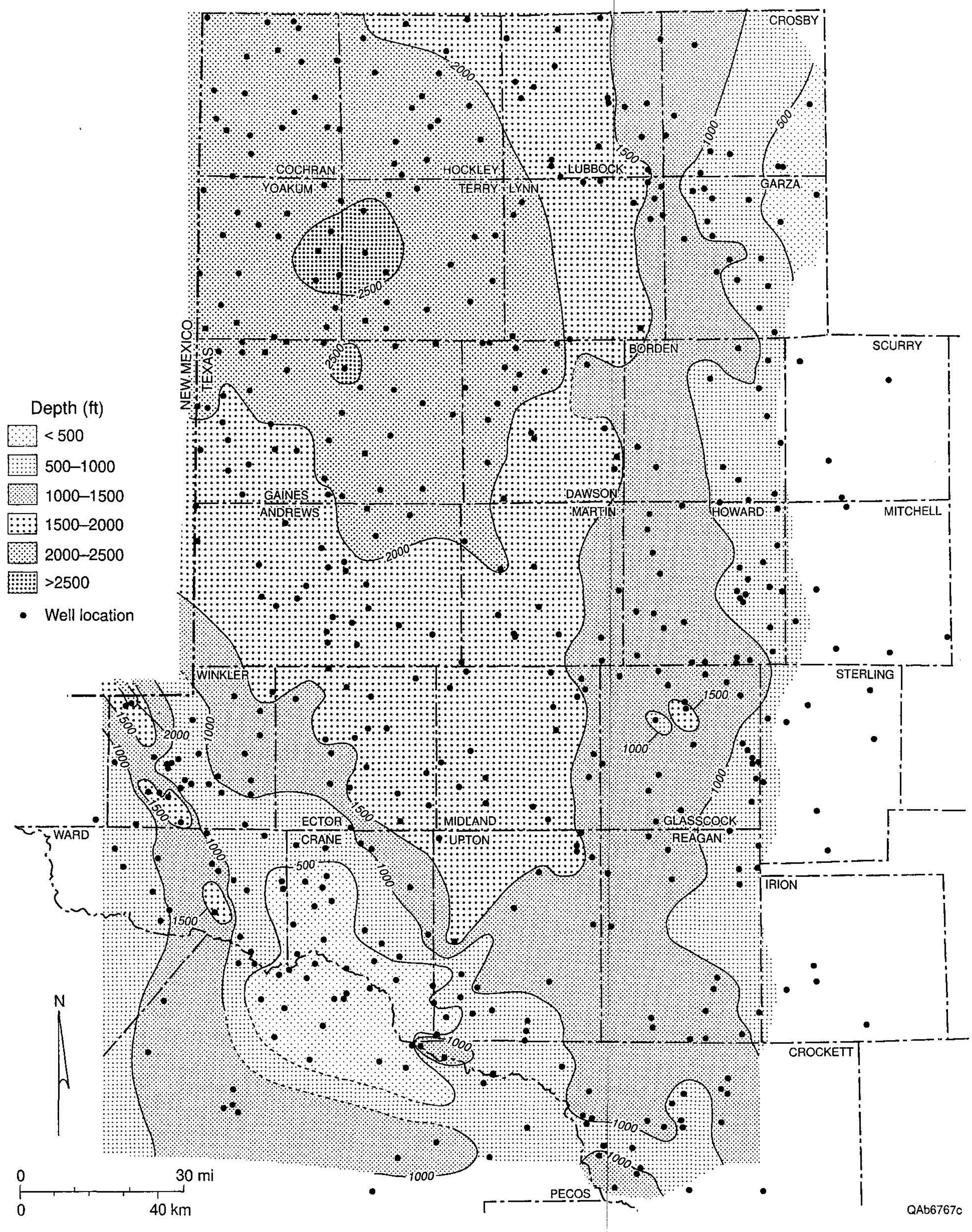

Figure 5. Depth to top of Salado salt-bearing interval from approximate land surface (log datum, typically kelly bushing) to top Alibates Formation and equivalent top of upper Rustler anhydrite.

interval is moderate, generally greater the 1000 feet but complicated by dissolution along the course of the modern and former Pecos River (Bachman, 1984).

DISTRIBUTION OF SALT IN THE SEVEN RIVERS, QUEEN, AND GRAYBURG FORMATIONS

During initial phases of this study, the interval containing the Salado salt was mapped because it is the uppermost and thickest salt over much of the study area. The distribution and geometry of salt in the underlying Seven Rivers, Queen, and Grayburg Formations are too complex to be mapped meaningfully on a single salt thickness map. Mapping salt pinch-outs into sandstone or anhydrite requires correlation of individual beds within the units and was beyond the scope of this study (for examples of this technique see Fracasso and Hovorka, 1986, and Hovorka, 1994). The location of salt cavern storage facilities (Railroad Commission of Texas, 1995) suggests that the Seven Rivers, Queen, and Grayburg salts are probably used for caverns in the eastern part of study area, notably in Scurry County where the Salado salts are thin or absent.

For this study, the general distribution of salt in the older units was mapped using available caliper logs and oil field stratigraphic descriptions (Feldman, 1962) as a guide to where further study is warranted (fig. 6). The Seven Rivers, Queen, and Grayburg contain marine-influenced facies over the Central Basin Platform, and salts are thin or absent. Salts are also thin or absent at the south end of the study area. North of the study area in the Palo Duro Basin, thick salts are found in the Seven Rivers Formation, but the Queen and Grayburg Formations are updip in the facies tract and are clastic dominated (Nance, 1988). Salt occurs in thick beds in the Seven Rivers, Queen, or Grayburg formations in the central, northern, and eastern part of the Midland Basin (fig. 6), and depositional setting and reconnaissance log examination suggest that salt beds thicken and become more numerous toward the north and east.

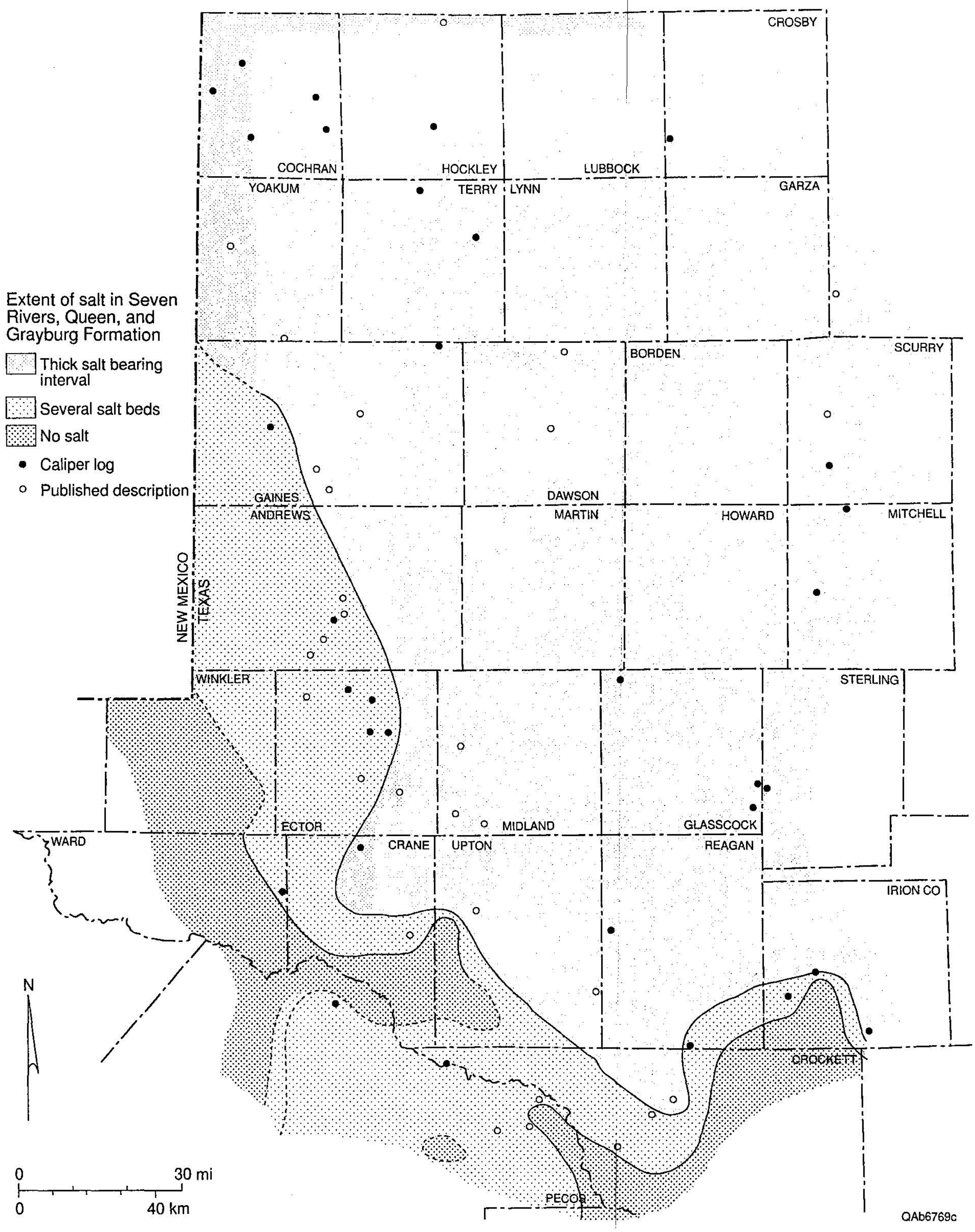

Figure 6. Extent of older salts in Seven Rivers, Queen, and Grayburg Formations. In many areas the salt in these intervals contains many mudstone, sandstone, and anhydrite interbeds; however, these formations comprise the major salt-bearing interval toward the east edge of the study area where the Salado is thin or absent because of dissolution.

AREAS OF SALT THINNING

Figure 7 synthesizes the results of comparison of salt thickness (fig. 4) to the physiographic setting (fig. 1), structure on top of the salt-bearing unit (fig. 3), and the depth to the top of the salt-bearing unit (fig. 5). Thin salt generally corresponds to positive structural elements. Inspection of facies relationships in the Midland Basin and comparison with relationships seen in detailed studies in adjacent areas indicate that the salt thinned toward the basin margins because of reduced accommodation during deposition. The general trend of thickening of the salt-bearing unit across the Central Basin Platform suggests that this area may have been subsiding and creating accommodation during Salado deposition; however, facies changes and strong modification by postdepositional salt dissolution have obscured relationships. The present day structure on the top of the Alibates Formation/Rustler anhydrite (fig. 3) follows the long-lived structural pattern of the basin, so that positive areas during deposition have been uplifted more strongly than basinal areas. Postdepositional (mostly Cenozoic) warping has therefore exposed thin marginal salt to more intense dissolution by placing it at higher elevations than basinal salts.

Modern landforms are overprinted on the structural elements. Areas where salt is present at shallow depth may influence landform development because salt has been dissolved, creating low areas, and overlying strata have collapsed, been brecciated, and are therefore easily eroded (Gustavson and others, 1982). The Pecos Valley generally overlies the salt thin on the south end of the Central Basin Platform. This relationship is similar to that localizing the Canadian River on the crest of the Amarillo Uplift because of dissolution of salt in that area (Gustavson, 1986). The Rolling Plains, where Permian rocks crop out at the surface, lie at lower elevations than the adjacent Edwards Plateau and Southern High Plains, indicating that the Permian rocks have been eroded more rapidly than the Cretaceous carbonates or the Ogallala Formation, which overlie preserved salt (Gustavson and Simpkins, 1989).

The prominent salt thin (fig. 4) and depression in the Alibates structure (fig. 3) in central Winkler and Ward Counties have been filled with post-salt dissolution sediments creating an increase in depth to salt in this area. Similar filled salt-dissolution features occur intermittently along the Capitan reef in New Mexico (Bachman, 1984) and have been interpreted as the result of salt dissolution related to the hydrology of the Capitan reef (Hiss, 1980), although the rates, timing, and processes of dissolution along this feature are not well constrained.

The areas of thin salt at shallow depth are identified as areas of probable recent and ongoing salt dissolution. On figure 7 these areas are highlighted; they include (1) the eastern shelf beneath the Rolling Plains, (2) the Ozona Platform beneath the western Edwards Plateau, and (3) the Central Basin Platform in the Pecos Valley area. The salt dissolution feature (4) along the Capitan reef trend in Ward and Winkler County is not related to a surface feature; however, the recent formation of the collapse feature at the Wink sink (Baumgardner and others, 1982; Johnson, 1987) on the eastern edge of the paleo-dissolution feature indicates that ongoing salt dissolution may be a risk in this area. A general thinning in the salt-bearing interval corresponding to the eastern edge of the Central Basin Platform in Crane and Ector Counties (5) occurs at shallow depths but has no surface expression; its cause and current status require additional work. Other areas of thin salt—the eastern edge of the Central Basin Platform (6), the north side of the Hovey Channel (7), the Matador Arch on the north edge of the Midland Basin (8)—are found at greater depth and have no surface expression; these may be entirely depositional or paleo-dissolution features.

Salt dissolution may occur in localized areas not identified on this regional study. Local areas where salt dissolution has occurred may be marked by geomorphic features. For example, some of the large saline lake basins on the Southern High Plains including some in the study area have been interpreted as having salt dissolution features beneath them (Reeves and Temple, 1986; Ateiga, 1990).

CONCLUSIONS

Geologic mapping is a fast and economical method for characterizing regional and local variability in the quality of salt. This study identifies regional trends in decreased salt thickness.

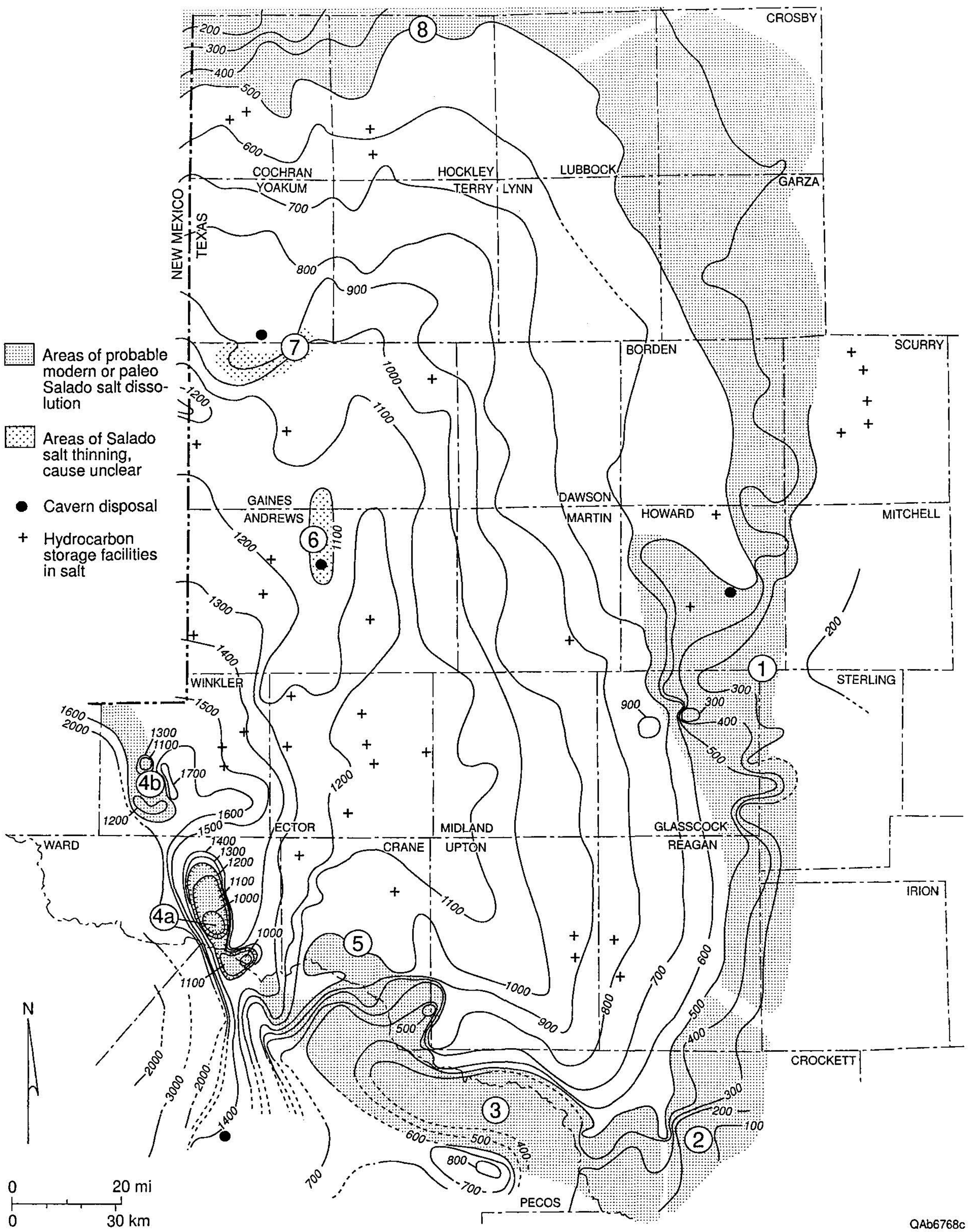

Figure 7. Interpreted areas where decreased salt thickness at shallow depths suggests potential for active salt dissolution. Other areas of thin salt are tentatively interpreted to reflect depositional variations in salt thickness. Numbers correspond to areas discussed in the text. Local areas of potential salt thinning such as beneath saline lakes or local collapse chimneys are not identified in this regional study.

Salt has been dissolved along the east margin of the basin, along the Pecos, and over the Capitan reef margin in Ward and Winkler counties. Depositional complexities in salt thickness are recognized in several areas, especially in areas of complex basin geometry such as Pecos County. Relationships among salt thickness, depositional trends, and structures are noted and can be used to further characterize salt.

FURTHER WORK

Additional work at a regional scale needed to complement the results of this study should include a map of percent salt. This would show the pinch-out of salt in areas of dissolution and variation in the quality of salt in stable areas. Hydrologic data for the Midland Basin documenting areas of highly saline ground water and high saline ground-water discharge complement geologic data by separating areas of current salt dissolution from areas of paleo dissolution. Areas where there are vertical hydrologic gradients across the salt may also be high risk because of the potential for boreholes to serve as conduits and allow salt dissolution, conduit, enlargement, contaminant movement or collapse, and loss of cavern integrity.

This study identified eight regions of complex salt geometry. Detailed studies of these areas could separate ancient from ongoing dissolution and refine mapping of areas having thin, complex, or rapidly dissolving salt.

Bedded salt is highly variable laterally and vertically and has different petrophysical and mechanical characteristics. Because the rheologic properties of salt are strongly dependent on water content, crystal size, and impurity distribution, a matrix of tests must be designed for each type of salt. Geologic data can extend the utility of costly geotechnical data by identifying areas where salt character is similar to the test sites.

REFERENCES

Adams, J. E., 1940, Structural development, Yates area, Texas, *in* DeFord and Lloyd, eds., West Texas-New Mexico symposium: Bulletin of the American Association of Petroleum Geologists, v. 24, no. 1, p. 134–142.

Adams, J. E., 1944, Upper Permian Ochoa Series of Delaware Basin, West Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 28, p. 1596–1625.

Adams, J. E., 1968, Permian salt deposits, West Texas and eastern New Mexico, saline deposits: Geological Society of America Special Paper 88, 407 p.

Anderson, R. Y., 1981, Deep-seated salt dissolution in the Delaware Basin, Texas and New Mexico, *in* Wells, S. G., Lamber, Wayne, Callender, J. F., eds., Environmental geology and hydrology in New Mexico: Special Publication - New Mexico Geological Society, v. 10, p. 133–145.

Anderson, R. Y., Dean, W. E., Kirkland, D. W., and Snider, H. I., 1972, Permian Castile varved evaporite sequence, West Texas and New Mexico: Geological Society of America Bulletin, v. 83, p. 59–86.

Ateiga, A. A., 1990, Geomorphic evidence of Permian salt dissolution, Hockley and Cochran Counties, Texas: Texas Tech University, Ph.D. dissertation, 129 p.

Bachman, G. O., 1984, Regional geology of Ochoan evaporites, northern part of Delaware Basin: New Mexico Bureau of Mines and Mineral Resources Circular 184, 22 p.

Baker, R. C., 1977, Hydrology of karst features in evaporite deposits of the Upper Permian in Texas., *in* Dilamarter, R. R., and Csallany, S. C., eds.: Hydrologic problems in karst regions, Western Kentucky University, Bowling Green, p. 333–339.

Barnes, V. E., project supervisor, 1992, Geologic map of Texas: The University of Texas at Austin, Bureau of Economic Geology, scale 1:500,000, 4 sheets.

Baumgardner, R. J., Jr., Hoadley, A. D., and Goldstein, A. G., 1982, Formation of the Wink Sink, a salt dissolution and collapse feature, Winkler County, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 114, 38 p.

Borns, D. J., and Shaffer, Sue-Ellen, 1985, Regional well-log correlation in the New Mexico portion of the Delaware Basin: Sandia Report SAND 83-1798, 73 p.

Boyd, S. D., and Murphy, P. J., 1984, Origin of Salado, Seven Rivers, and San Andres salt margins in Texas and New Mexico: Stone and Webster Engineering Corporation, Topical Report, ONWI/SUB/84 E512-05000-T27, 107 p.

Dean, W. E., and Anderson, R. Y., 1978, Salinity cycles: Evidence for subaqueous deposition of Castile Formation and lower part of Salado Formation, Delaware Basin, Texas and New Mexico, *in* Austin, G. S., compiler, Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas: New Mexico Bureau of Mines and Mineral Resources Circular 159, p. 15-20.

DeConto, R. T., and Murphy, P. J., 1986, Dissolution of the upper Seven Rivers and Salado salt in the interior Palo Duro Basin: Webster Engineering Corporation Contract Report, 177 p.

Dutton, A. R., 1987, Hydrogeologic and hydrochemical properties of salt-dissolution zones, Palo Duro Basin, Texas Panhandle — preliminary assessment: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 87-2, 32 p.

Feldman, M. L., Jr., chairman, 1962, Southwest-northeast cross section, Marathon region to Midland Basin: prepared by Stratigraphic Problems Committee of the West Texas Geological Society, 1 sheet.

Fracasso, M. A., and Hovorka, S. D., 1986, Cyclicity in the middle Permian San Andres Formation, Palo Duro Basin, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 156, 48 p.

Garber, R. A., Grover, G. A., and Harris, P. M., 1989, Geology of the Capitan shelf margin—subsurface data from the northern Delaware Basin, *in* Harris, P. M., and Grover, G. A., Subsurface and outcrop examination of the northern Capitan shelf margin, northern Delaware Basin: SEPM Core Workshop No. 13, p. 3–269.

Geomap, 1989, West Texas—Southeast New Mexico executive reference map.

Girard, R. M., 1952, The absence of Salado Salt, central Ward County, Texas: University of Texas, Austin, Master's thesis, 35 p.

Goldstein, A. G., and Collins, E. W., 1984, Deformation of Permian strata overlying a zone of salt dissolution and collapse in the Texas Panhandle: Geology, v. 12, p. 314–317.

Gustavson, T. C., 1986, Geomorphic development of the Canadian River valley, Texas Panhandle; an example of regional salt dissolution and subsidence: Geological Society of America Bulletin, v. 97, no. 4, p. 459–472.

Gustavson, T. C., 1996, Fluvial and eolian depositional systems, paleosols, and paleoclimate of the upper Cenozoic Ogallala and Blackwater Draw Formations, Southern High Plains, Texas and New Mexico: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 239, 62 p.

Gustavson, T. C., and Simpkins, W. W., 1989, Geomorphic processes and rates of retreat affecting the Caprock Escarpment, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 180, 49 p.

Gustavson, T. C., Finley, R. J., and McGillis, K. A., 1980, Regional dissolution of Permian salt in the Anadarko, Dalhart, and Palo Duro basins of the Texas Panhandle, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 106, 40 p.

Gustavson, T. C., Simpkins, W. W., Alhades, Alan, and Hoadley, Ann, 1982, Evaporite dissolution and development of karst features on the Rolling Plains of the Texas Panhandle: Earth Surface Processes and Landforms, v. 7, p. 545–563.

Herald, F. A., ed., 1957, Occurrence of oil and gas in West Texas, The University of Texas Publication 5716, 442 p.

Hiss, W. L., 1980, Movement of ground water in Permian Guadalupian aquifer systems, southeastern New Mexico and western Texas, *in* Dickerson, P. W., Hoffer, J. M., Callender, J. F., eds., Trans-Pecos region; southeastern New Mexico and West Texas: New Mexico Geological Society Guidebook 31, p. 289–294.

Holt, R. M., and Powers, D. W., 1990, Halite sequences within the late Permian Salado Formation in the vicinity of the Waste Isolation Pilot Plant, *in* Powers, Dennis, Rempe, Norman, Holt, Robert, and Beauheim, R. L., Geological and Hydrological studies of the evaporites in the northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP), New Mexico: Geological Society of America, 1990 Annual Meeting Field Trip No. 14 Guidebook, unpaginated.

Hovorka, S. D., 1987, Depositional environments of marine-dominated bedded halite, Permian San Andres Formation, Texas: Sedimentology, v. 34, p. 1029–1054.

Hovorka, S. D., 1990, Sedimentary processes controlling halite deposition, Permian Basin, Texas: The University of Texas at Austin, Ph.D. dissertation, 393 p.

Hovorka, S. D., 1994, Water-level controls on halite sedimentation: Permian cyclic evaporites of the Palo Duro Basin, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 214, 51 p.

Hovorka, S. D., and Granger, P. A., 1988, Surface to subsurface correlation of Permian evaporites—San Andres-Blaine-Flowerpot relationships, Texas Panhandle, *in* Morgan, W. A., and Babcock, J. A., eds., Permian rocks of the Midcontinent: Mid-Continent SEPM Special Publication 1, p. 137–159.

Hovorka, S. D., Knauth, L. P., Fisher, R. S., and Gao, Guoqui, 1993, Marine to non-marine facies transition in Permian evaporites of the Palo Duro Basin, Texas: Geological Society of America Bulletin, v. 105, 1119–1134.

Howard, K. S., 1987, Surficial manifestations of deep-seated Permian salt bed dissolution near Loco Hills, New Mexico: Texas Tech University, Master's thesis, p. 67.

Humble Oil and Refining Company, 1960, Paleozoic basin studies regional geologic cross section # 76: unpublished, one sheet.

Humble Oil and Refining Company, 1964a, Paleozoic basin studies regional geologic cross section # 75: unpublished, one sheet.

Humble Oil and Refining Company, 1964b, Paleozoic basin studies regional geologic cross section # 79: unpublished, one sheet.

James, W. P., Spongberg, M. E., Masciangliolі, P. A., 1995, Control of natural salt pollution in the Brazos River, Texas, *in* Cleveland, T. G., ed., Proceedings, Advances in the development and use of models in water resources: American Water Resources Association Technical Publication Series TPS, 95-3; p. 147–152.

Johnson, K. S., 1978, Stratigraphy and mineral resources of Guadalupian and Ochoan rocks in the Texas Panhandle and western Oklahoma, *in* Austin, G. S., compiler, Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas: New Mexico Bureau of Mines and Mineral Resources Circular 159, p. 57–62.

Johnson, K. S., 1981, Dissolution of salt on the east flank of the Permian Basin in the southwestern U.S.A., Back, William, Letolle, Rene, eds., Symposium on geochemistry of groundwater: Journal of Hydrology, v. 54, p. 1–3, 75–93.

Johnson, K. S., 1987, Development of the Wink Sink in West Texas due to salt dissolution and collapse, *in* Beck, B. F., Wilson, W. L., eds., Karst hydrogeology; engineering and environmental applications: Proceedings, Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, 2, p. 127–136.

Johnson, K. S, 1989a, Development of the Wink Sink in West Texas, U.S.A., due to salt dissolution and collapse: Environmental Geology and Water Sciences, v. 14, no. 2, p. 81–92.

Johnson, K. S., 1989b, Salt dissolution, interstratal karst, and ground subsidence in the northern part of the Texas Panhandle, *in* Beck, B. F., ed., Engineering and environmental impacts of sinkholes and karst: Proceedings of the third multidisciplinary conference, p. 115–121.

Kendall, A. C., 1992, Evaporites, *in* Walker, R. G., and James, N. P., Facies models, response to sea level change: Geological Association of Canada, St. Johns, Newfoundland, p. 375–409.

King, P. B., 1942, Permian of West Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 26, p. 535–763.

Lowenstein, T. K., and Hardie, L. A., 1985, Criteria for recognition of salt-pan evaporites: Sedimentology, v. 32, p. 627–644.

Lowenstein, T. K., 1988, Origin of depositional cycles in a Permian "saline giant": The Salado (McNutt zone) evaporites of New Mexico and Texas: Geological Society of America Bulletin, v. 100, p. 592–608.

Matchus, E. J., and Jones, T. S., co-chairman, 1984, East-west cross section through Permian Basin of West Texas: prepared by Stratigraphic Problems Committee of the West Texas Geological Society, 1 sheet.

McGillis, K. A., and Presley, M. W., 1981, Tansill, Salado, and Alibates Formations: Upper Permian evaporite/carbonate strata of the Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-8, 31 p.

McGookey, D. A., Gustavson, T. C., and Hoadley, A. D., 1988, Regional structural cross sections, Mid-Permian to Quaternary strata, Texas Panhandle and eastern New Mexico; distribution of evaporites and areas of evaporite dissolution and collapse: The University of Texas at Austin, Bureau of Economic Geology cross sections, 17 p.

McGookey, D. A., 1984, Cenozoic epeirogenic uplift of Palo Duro Basin, Texas, and its influence on structure, salt dissolution, and topography (abs.): American Association of Petroleum Geologists Bulletin, v. 68, p. 505.

McGowen, J. H., Granata, G. E., and Seni, S. J., 1979, Depositional framework of the lower Dockum Group (Triassic), Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations 97, 60 p.

McKee, E. D., Oriel, S. S., and others, 1967, Paleotectonic investigations of the Permian System of the United States: U.S. Geologic Survey Professional Paper 515, 271 p.

Mear, C. E., 1968, Upper Permian sediments in southeastern Permian Basin, Texas, *in* Saline deposits—International Conference Saline Deposits, Houston, Texas, 1962, Symposium: Geological Society of America, Special Paper, p. 349–358.

Meissner, F. F., 1972, Cyclic sedimentation in middle Permian strata of the Permian Basin, West Texas and New Mexico, *in* Elum, J. G., and Chuber, Stewart, eds., Cyclic sedimentation in the Permian Basin (2d ed.): West Texas Geological Society, p. 203–232.

Midland Map Company, 1995, Permian Basin regional base map, 2 sheets.

Nance, H. S., 1988, Interfingering of evaporites and red beds: an example from the Queen/Grayburg Formation, Texas: Sedimentary Geology, v. 56, p. 357–381.

Paine, J., Avakian, A., Gustavson, T. C., and Hovorka, S. D., 1994, Geophysical and geochemical delineation of sites of saline water inflow into the Canadian River, Texas and New Mexico: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 225, 73 p.

Powers, D. W., and Holt, R. M., 1990, Sedimentology of the Rustler Formation near the Waste Isolation Pilot Plant, *in* Powers, Dennis, Rempe, Norman, Holt, Robert, and Beauheim, R. L., Geological and hydrological studies of the evaporites in the northern Delaware Basin for the Waste Isolation Pilot Plant (WIPP), New Mexico: Geological Society of America 1990 Annual Meeting Field Trip No. 14 Guidebook, unpaginated.

Presley, M. W., 1981, Middle and upper Permian salt-bearing strata of the Texas Panhandle: lithologic and facies cross sections: The University of Texas at Austin, Bureau of Economic Geology cross sections.

Price, B. M., 1991, The mineralogy, fabric, geometry and depositional environment of the Seven Rivers and Queen evaporites (Guadalupian, Permian) in Crane, Ector and Upton Counties, Texas: Texas A&M University, Master's thesis, 84 p.

Railroad Commission of Texas, 1995, Underground hydrocarbon storage facilities in salt formations: unpublished data compilation, unpaginated.

Reeves, C. C., Jr., and Temple, J. M., 1986, Permian salt dissolution, alkaline lake basins, and nuclear-waste storage, Southern High Plains, Texas and New Mexico: Geology, v. 14, p. 939–942.

Richter, B. C., and Kreitler, C. W., 1986, Geochemistry of salt-spring and shallow subsurface brines in the rolling plains of Texas and southwestern Oklahoma, The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 155, 47 p.

Seni, S. J., 1980, Sand-body geometry and depositional systems, Ogallala Formation, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 105, 35 p.

Snider, H. I., 1966, Stratigraphy and associated tectonics of the upper Permian Castile-Salado-Rustler evaporite complex, Delaware Basin, West Texas: The University of New Mexico, Ph.D. dissertation, 196 p.

Swenson, F. A., 1974, Rates of salt solution in the Permian Basin: Journal of Research of the U.S. Geological Survey, v. 2, no. 2, p. 253–257.

Tait, D. B., Ahlen, J. L., Gordon, A., Scott, G. L., Motts, W. S., and Spitler, M. E., 1962, Artesia Group of New Mexico and West Texas: American Association of Petroleum Geologists Bulletin, v. 26, p. 504–517.

Vertrees, C. D., chairman, 1962-63, Cross section through Delaware and Val Verde Basins from Lea County, New Mexico to Edwards County, Texas: prepared by Stratigraphic Problems Committee of the West Texas Geological Society, 1 sheet.

Wessel, G. R., 1988, Shallow stratigraphy, structure, and salt-related features, Yates oil field area, Pecos and Crockett Counties, Texas: West Texas Geological Society Bulletin, v. 28, no. 4, p. 15.

Wessel, G. R., 1992a, Origin of surface structures at Yates Field; relation to deep structure, salt tectonics, and fluid migration: West Texas Geological Society Bulletin, v. 31; no. 6, p. 5–14.

Wessel, G. R., 1992b, Surface mapping and subsurface structure; application to the Permian Basin, West Texas: West Texas Geological Society Bulletin, v. 31, no. 7, p. 6.

Zaengle, J. F., and Lohmann, K. C., 1991, Structural controls on Ochoan salt dissolution and Delaware Mountain Group oil field permeability trends in the Delaware Basin, West Texas and Southeast New Mexico: American Association of Petroleum Geologists Bulletin, v. 75, no. 3, p. 699–700.