GW - 226

GENERAL CORRESPONDENCE

YEAR(S):

2002-1998

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November 12, 2002

RECEIVED
NOV 21 2002
Environmental Bureau
Oil Conservation Division

Mr Roger Anderson
Environmental Bureau Chief
New Mexico OCD
1220 S. ST. Francis Dr.
Santa Fe, NM
87507

Re: Class I Disposal Wells

Dear Roger,

I am still very interested in getting the disposal wells into salt caverns in Monument approved by OCD. It is my sincere belief that a Class I Disposal Well would be benefical to present and future industry in New Mexico.

I suspect that one of my problems has been my distance from the property. I am hoping to find a local company or individuals who can be more on top of this project.

In the past conditions have not justified the capital investment to permit, build and operate these wells and compete with surface disposal. Have there been any changes in OCD policy that might effect the permitting of these wells? If so, would you please send me any pretinent documents?

Sincerely,

Bill Quick

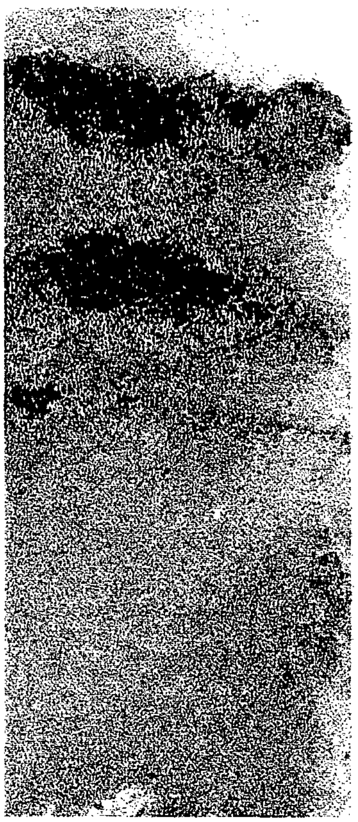
Bill Quick

Cc: Lori Wrotenbery

Characterization of Bedded Salt for Storage Caverns

Case Study from the Midland Basin

Susan D. Hovorka
Bureau of Economic Geology
The University of Texas at Austin



Evaluation of Salt: Geologic Processes

Case Studies

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BEG Environmental Research Page

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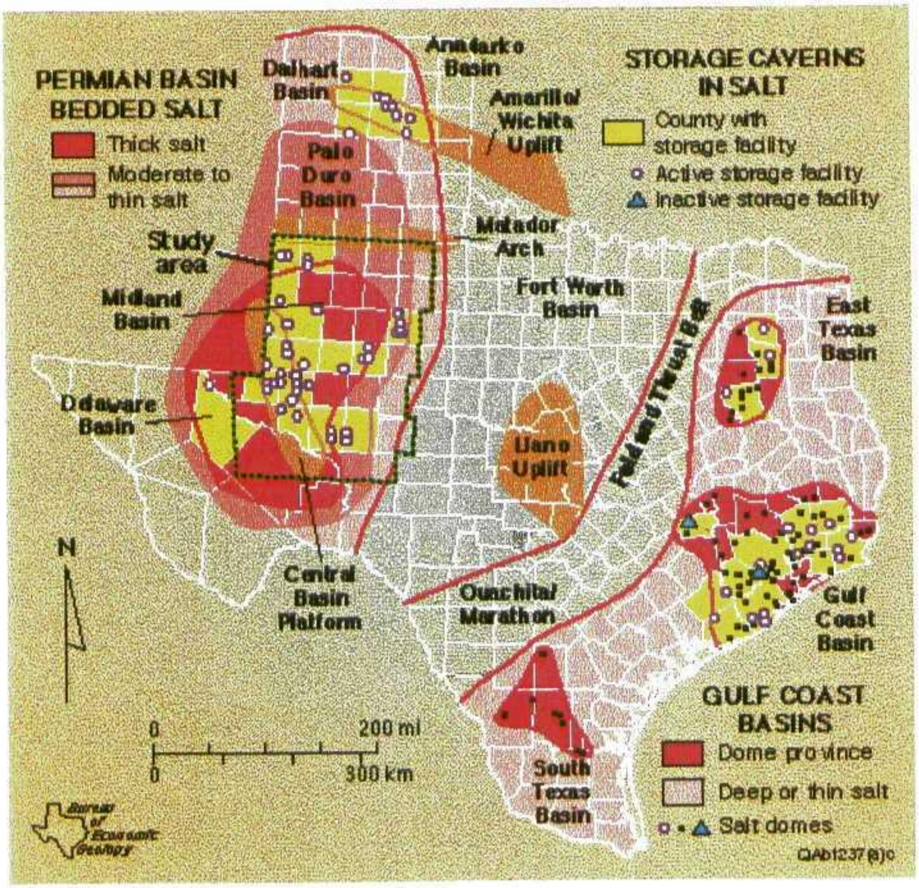
About Solution-Mined Caverns

Solution-mined caverns in salt are low-cost, large-volume storage facilities used for chemical feedstock. Caverns are also created when salt is dissolved to produce NaCl brine for drilling mud and other applications. Recently, solution-mined caverns have been used for disposal of oil-field wastes. Basic descriptive information on the geometry of salt is needed to site and regulate the development, use, and decommissioning of these facilities.



In Texas, 648 solution-mined caverns are currently licensed, with about 200 in bedded salt areas (Seni and others, 1995). Storage caverns are used by the chemical and petrochemical industry for storage of product and chemical feedstock. Exploration for sites for cavern development continues, with emphasis on locating suitable salt near facilities such as pipelines and industrial users. Other caverns have been created only to extract brine used by drilling and chemical industries. In addition, three salt caverns have been licensed for subsurface disposal of oil-production waste in the Midland Basin. Current regulation in Texas does not permit underground disposal of other types of industrial waste.

Salt is a unique host material for cavern development because its solubility in water permits low-cost, highly flexible, and rapid creation of caverns. Brine resulting from the mining can be sold as a product. Salt has very low permeability, making it an ideal medium for containment of stored materials. Preservation of soluble bedded salt over geologic time demonstrates the relatively inactive hydrologic setting, so that if material should leak from the cavern, transport away from the facility would generally be slow.

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Geology of salt

Geology of Salt

Salt is deposited as horizontal beds but, in some settings, deformation forms salt diapirs (Jackson, 1997). In Texas, the two main types of salt available to host caverns are piercement domes of the Gulf Coast and East Texas Basin and bedded salt in the Permian Basin of the Texas Panhandle. In this study, I describe the characteristics of bedded salt in the Midland Basin, one of the sub-basins of the Permian Basin (Index map of the Permian Basin, Texas-New Mexico, 99k).

The characteristics of bedded salt and domal salt are quite different. Typical Texas domal salt in the East Texas and Gulf Coast basins is derived from the Jurassic Louann Salt and is relatively pure and homogeneous. The lateral extent of domes is limited, however, and therefore the dome margins delimit the area useful for cavern development. Domal salt that has flowed upward to the surface has been dissolved where it is in contact with fresh water. Concentration of the impurities in salt produces cap rock at the top and, in some locations, sides of the domes. Cap rock may have low permeability and armor the dome against dissolution or, it may be permeable (Kreitler and Dutton, 1983). Structurally introduced anisotropy such as internal-boundary shear zones, foliation, bedding, mineralogy, moisture content, and grain-size variation may be features of concern in solution mining (Seni and others, 1995).

Bedded salt of the Permian Basin is much less pure than Texas dome salt. Permian salt is interbedded with limestone, dolomite, anhydrite, polyhalite (Na2MgK2(SO4) 4 ï H2O), and fine-grained siliciclastic red beds (mudstone, siltstone, and sandstone). The distribution of these low-solubility impurities is one of the limitations of engineering solution-mined caverns, and characterizing impurities is one major focus of our study. Salt beds are typically continuous over large areas, so that experience with solution mining in one property may be a good indicator of what to expect at a nearby site. However, salt beds thin, pinch out, or change facies laterally into other rock types; in this study I document the various types of lateral changes in bedded salt. Permian salt, like domal salt, has been dissolved where it has been in contact with fresh water. In the Permian Basin, concentration of impurities does not form a cap rock but, rather, forms a heterogeneous and mechanically weak insoluble residue. In this paper, I describe the geometries and criteria for identifying salt thinning as a result of dissolution.

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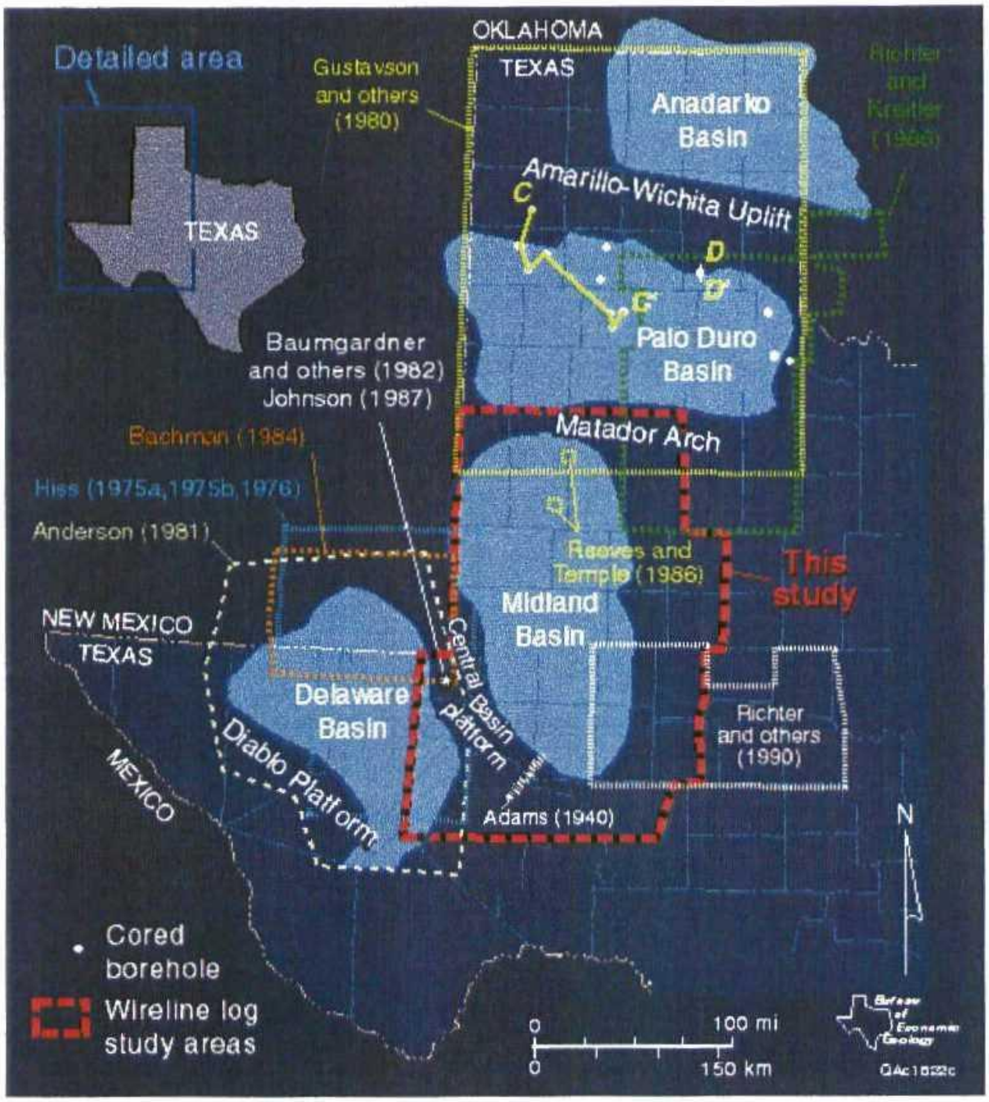
Purpose, scope, and methods of our study

Index Map of the Permian Basin



Regional data for interpreting the geometry of salt in the Midland Basin. Previous studies are cited in References.

Back to geology of salt
Back to Previous Work: Geologic Setting of Bedded Salt in the Permian Basin

Purpose, Scope, and Methods of Our Study

The purpose of this report is to present data specific to bedded salt that will be of interest to both industrial operators and to government regulators in the context of salt-cavern development. This information is intended to be both a regional description of bedded salt in the Midland Basin and a template for useful and geologically based description of salt in other basins worldwide. In particular, the objectives are to: (1) create and compile maps and cross sections documenting the regional extent, thickness, geometry, and quality of salt resources suitable for cavern development in the Midland Basin of Texas; and (2) identify some of the geologic factors and outline the methods for assessing variables that make specific sites more or less suitable for cavern development. To meet the second objective, I present conceptual models and interpretations that support and explain the descriptive data.

Some potential applications from this data set are to: (1) provide basic descriptive information such as stratigraphic nomenclature and log characteristics for describing existing or newly developed facilities; (2) match areas where storage or disposal facilities are needed with areas of salt of optimal characteristics in terms of thickness, depth, purity, and stability; (3) to provide context for comparing the history and performance of one solution-mined cavern with another; and (4) provide criteria useful for detailed site characterization of existing or newly developed facilities.

The data presented here builds upon a previous study (Hovorka, 1997) of gross salt thickness in the Midland Basin. The maps presented in this report supersede the reconnaissance results of that study. High-quality well location, increased well density, improved log interpretation, and integration with previous salt dissolution and hydrologic studies are the principal areas of improvement upon the previous study.

Methods

Map and cross-section compilation through the bedded salt section in the Midland Basin included a 31-county area (well and cross-section locations). Basic materials used in this study are 558 photocopied wireline logs from the Bureau of Economic Geology historic log library (appendix 1, downloadable PDF file). This data set was selected because (1) older logs more commonly include curves from the salt section, compared with modern log suites, that focus more on the subsalt-producing intervals, (2) it includes many wildcat wells and wells from productive fields and, therefore, provides regional coverage, and (3) it is available at no cost. Previous experience suggested that the most useful logs for West Texas bedded-salt mapping are gamma-ray, caliper, sonic combinations. If these log types were not available in the log files, neutron or resistivity logs were used. SP logs are of minimal use in salt. The log data base assembled is not exhaustive; thousands more logs through the salt interval are commercially available but were not incorporated because of the regional scope of the study. Denser well data were collected in areas where reconnaissance investigation (Hovorka, 1997) showed complex geometry.

We purchased API numbers from Petroleum Information/Dwights and georeferenced latitude/longitude locations from Tobin Data Graphics to improve well-spotting accuracy and to register the data on a 1:24,000-scale georeferenced U.S. Geological Survey (USGS) county base using ArcInfo1 Geographic Information System (GIS). The 90 wells for which the API number search was unsuccessful were located on a blueprint survey base (Midland Map Company, 1995) using survey information from the log header. The datum elevations (kelly bushing or equivalent) were extracted from the log header or from a 1:250,000-scale USGS topographic map. Well location and elevation data were checked by comparing the elevation of the top of the Yates to a published regional structure map (Geomap, 1986), and logs with erroneous header data were corrected or discarded. Stratigraphic units were marked on log photocopies and the datum and unit tops were entered into a spreadsheet (appendix 2, downloadable PDF file) and used to calculate unit thickness and structural elevation. These data were plotted on maps using ArcView GIS. Hand contouring was used to optimize interpretation of the regional data, using the published Yates structure map (Geomap, 1986), USGS 1:250,000-scale topographic maps, and surface geology (Barnes, 1992), in coordination with conceptual models to guide interpolation.

To supplement interpretation of this data, I have drawn on previous published and unpublished investigations elsewhere in the Permian Basin (index map of the Permian Basin, 99k). Salt cores collected by the U.S. Department of Energy (DOE) investigations of bedded salt in the Palo Duro Basin (Hovorka, 1994), cores collected by U.S. Army Corps of Engineers in an area of salt dissolution in the Hollis Basin (Hovorka and Granger, 1988), and the Gulf Research PDB-03 core from Loving County, Texas (Hovorka, 1989; 1990) are outside the Midland Basin study area but provide background information used to interpret the log response and geometric relationships seen in the Midland Basin. These cores are stored at the University of Texas Bureau of Economic Geology Core Research Center. Descriptions of salt geometry in the Delaware Basin used for this study include Adams (1944), Bachman (1984), Anderson and others (1972), and Snider (1966).

Areas in the Midland Basin were selected for case studies to document salt characteristics and hydrologic processes that are thought to affect the suitability of salt for hosting caverns, and detailed cross sections were prepared across these areas. We used a literature search to find information documenting the hydrologic setting and to identify areas of brine discharge.

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Previous work: geologic setting of the bedded salt in the Permian Basin

Previous Work: Geologic Setting of the Bedded Salt in the Permian Basin

The evolution of the Permian Basin is very well known because of the long and intense history of hydrocarbon exploration in the sub-salt section. The Permian Basin formed as an area of rapid Mississippian-Pennsylvanian subsidence in the foreland of the Ouachita Foldbelt. Complex faulting, creating platform or arch areas of slower subsidence, subdivided the Permian Basin. Subdivisions of significance to this report are, from southwest to northeast: the Delaware Basin, Central Basin Platform, Sheffield Channel, Midland Basin, Ozona Arch, and Matador Arch (map of structure on top of the Yates Formation, 66k).

The geometry, quality, and stability of salt depend on interactions among the depositional character, thickness, and composition of the salt; postdepositional uplift and subsidence; and landscape development and resulting ground-water circulation patterns. Few studies have described the salt within the Midland Basin. 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.

Permian basin filling began with Pennsylvanian marine shales, limestones, and arkoses (Cys and Gibson, 1988). By early to middle Permian (Leonardian), the north and east parts of the Permian Basin had been infilled with sediments. 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 (index map of the Permian Basin, Texas-New Mexico, 99k). 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 (map of structure on top of the Yates Formation, 66k) were expressed only by subtle contrasts in subsidence rates. This relationship is apparent in the continuity of strata across structural positive areas with only minor changes in thickness or composition (Adams, 1968; Feldman, 1962; Matchus and Jones, 1984; Fracasso and Hovorka, 1986). Connection with marine environments to the west therefore became poorer and saline brines began to form, first in the marginal parts of the Permian Basin and then, progressively, throughout the entire basin. Evaporite sediments, initially anhydrite and then halite, began to accumulate in the Palo Duro Basin during the Leonardian (Wichita and Clear Fork Groups and lower San Andres Formation).

Salt precipitation began in the Midland Basin during the Guadalupian; salt occurs in the Grayburg, Queen, and Seven Rivers Formations (details in next section). The thickest salts are generally observed on the parts of the shelf away from the Delaware Basin toward the east and north. The classic and extensively studied Capitan Reef is a strongly aggradational Guadalupian carbonate accumulation that rims the Delaware Basin (King, 1942; Garber and others, 1989; Bebout and Kerans, 1993). 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 at the top of the Bell Canyon Formation is the basinal equivalent to the Tansill (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 throughout the Permian Basin (Meissner, 1972; Fracasso and Hovorka, 1986; 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 that typically precipitated anhydrite. Sediment aggradation caused restriction, limiting water 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 crystal size, shape, and interrelationships; 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 most of 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). Although stratigraphic nomenclature and relationships are complex in the Delaware Basin (Powers and Holt, 1990), genetic equivalence and correlation of the upper Rustler carbonate-anhydrite unit (Magenta and Forty-Niner Members) 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 of the Dewey Lake Formation, or equivalent upper Rustler

Formation that were the final Permian deposits.

Basin evolution after evaporite deposition is significant for salt cavern siting because the salt geometry was modified by burial dissolution. Triassic deposition of lake-deposited mudstones and fluvial sandstones of the Dockum Formation occurred following subtle warping and reconfiguration of the basin to a large centripetally draining lake basin (McGowen and others, 1979). Inferred uplift along the margins may have permitted salt dissolution to begin at this time, although no dissolution features that unequivocally formed at this time have been identified. Complex sedimentation within the Dockum Group and later crosscutting episodes of salt dissolution have obscured the record of any dissolution that occurred at this time.

A long unconformity followed Dockum deposition and is represented by erosion and truncation preceding deposition of Cretaceous sandstones and carbonates over most of the area. Dissolution prior to Cretaceous deposition is reported in many parts of the Permian Basin (Adams, 1940; Gustavson and others, 1980; Wessel, 1992a). Regional uplift occurred during the Cenozoic, and gravel, sand, and finer grained clastics of the Miocene?Pliocene Ogallala Formation were deposited in fluvial and upland eolian settings (Seni, 1980; Gustavson, 1996). Other significant Cenozoic deposits include Pecos River gravel (Bachman, 1984) and surficial sand, terrace, and colluvial deposits (Barnes, 1992). The current structure of this region (generalized geologic map of the study area, 50k) is the result of post-Cretaceous uplift and tilting that reactivated structural elements with the same sense of motion as they had during the Permian (McGookey, 1984), so that beneath the Southern High Plains and in the center of the Midland Basin the top of the Alibates is at 500 ft above sea level, while over the Eastern Shelf of the Midland Basin at shallow depths beneath the Rolling Plains it has been elevated to 1,800 ft above sea level. The Permian has also been uplifted over the Central Platform where it lies beneath Triassic units in the Pecos Valley. In the Delaware Basin, Permian rocks dip gently toward the east; in the Eastern Shelf, Permian rocks dip gently toward the west. Cretaceous rocks are preserved only in the southeast part of the study area, and Permian, Triassic, and Cretaceous units have been partly covered by Cenozoic deposits. These units are now undergoing erosion to create the Caprock Escarpment that rims the Southern High Plains (generalized geologic map of the study area, 50k).

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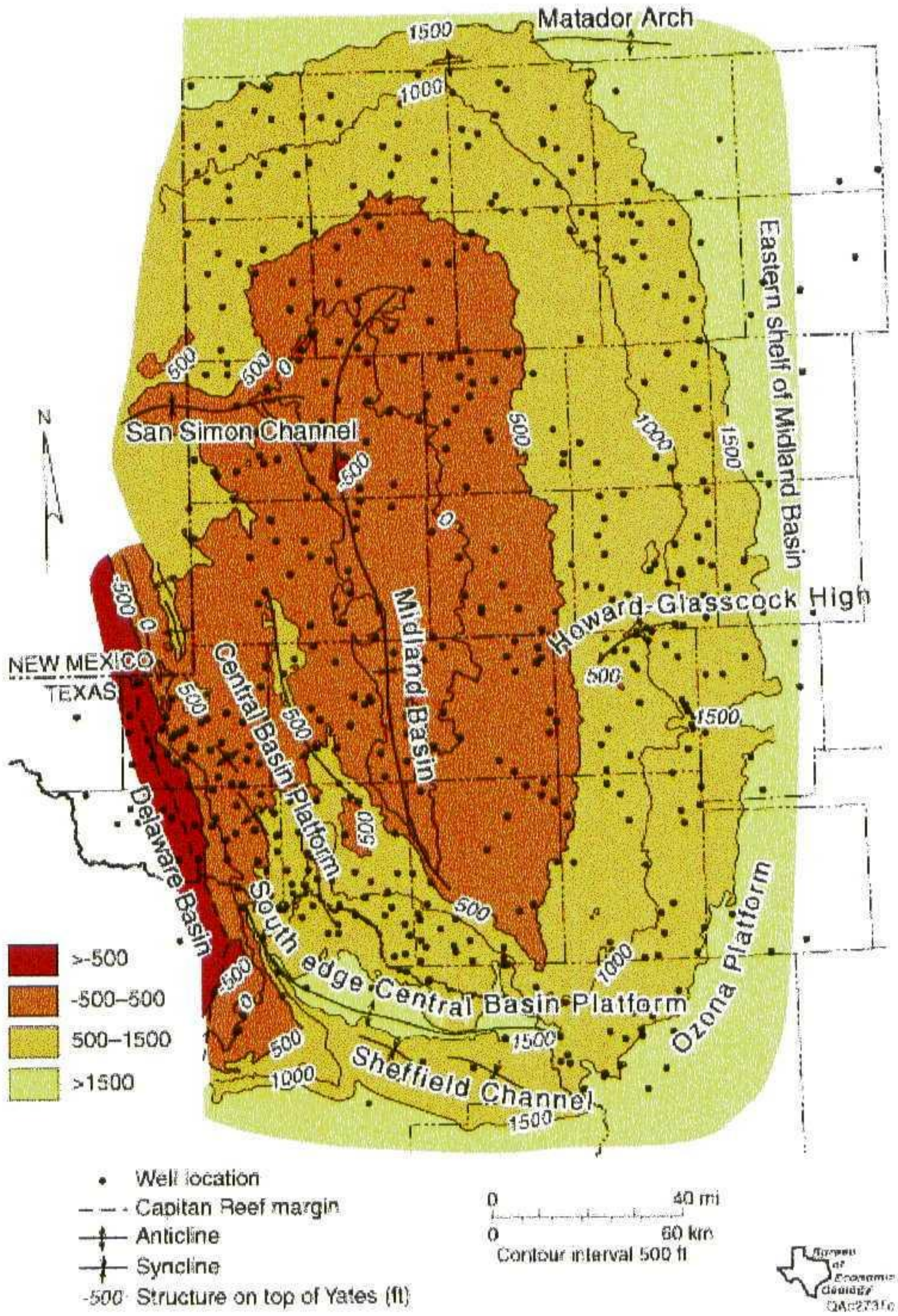
Stratigraphic units and type logs

Major Tectonic Elements of the Midland Basin Defined by Structure on Top of the Yates Formation



Tectonic elements that controlled depositional facies and salt dissolution in the Midland Basin. Structure contours on the top of Yates Formation modified from Geomap, 1986.

The structure on the top of the Yates Formation shows the sum of all the post-Guadalupian deformation in the study area, the net result of Permian subsidence, Mesozoic warping, and Cenozoic uplift. Facies in the Yates Formation siliciclastic red beds indicate that it was deposited over the entire area at near sea-level elevation, as controlled by the water table. The geometry of widespread anhydrite beds in the Salado Formation above the Yates support the concept that the Yates was deposited over a low-relief surface. However, in the Delaware Basin, the Bell Canyon was deposited on the basin floor. This surface may also have been fairly low relief but was at an elevation of as much as 1,000 ft below sea level at the end of the Guadalupian.

At present, in the structural center of the Midland Basin, the top of the Yates Formation, lies at 500 ft below sea level. East of the axis of Midland Basin, the top of the Yates Formation rises toward elevations of 2,000 ft above sea level in the Permian outcrop area on the Rolling Plains. Several areas of anomalous structure are noted within the Midland Basin: an isolated uplift in Reagan County; a closed depression in Midland County; and several uplifts and a depression at the Howard-Glasscock High. The top of the Yates also rises to 1,500 ft at the Matador Arch that defines the north edge of the Midland Basin. Elevation of the Yates Formation rises abruptly over the Central Basin Platform on the south and east edges of the Midland Basin, reaching 1,000 ft above sea level over the north part of the Central Basin Platform and 1,800 ft above sea level in the south edge of the Central Basin Platform. The complex pattern of uplifts that defines the structure of the Central Basin Platform and creates numerous structural traps is apparent even in the generalized regional view shown.

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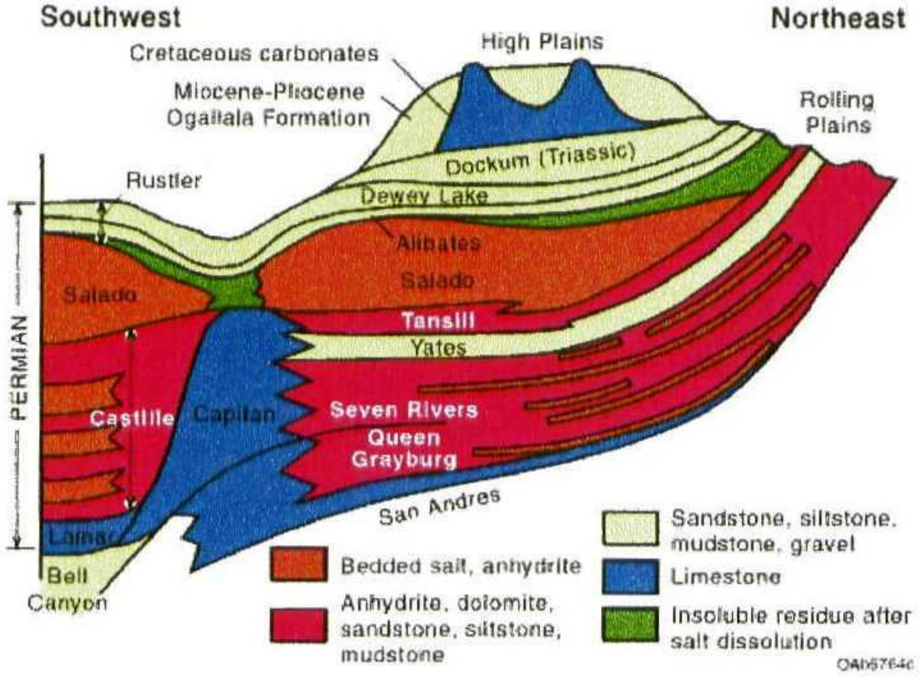
Above salt structure: Structure on top of the Alibates
Thickness of salt-bearing interval: Ochoan isopach
Salt quality: Net salt and percent salt

Stratigraphic Units and Type Logs

Midland Basin Stratigraphy



(Salt-bearing formation names link to detailed lithologic descriptions.)

Stratigraphic units selected for mapping in the Midland Basin were adapted 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 and others, 1967; Mear, 1968; Johnson, 1978; Presley, 1981; Matchus and Jones, 1984; Borns and Shaffer, 1985; McGookey and others, 1988; Hovorka, 1990). The Ochoan Dewey Lake, Alibates, and Salado Formations; and Guadalupian Tansill, Yates, and Seven Rivers Formations are readily identified in the Midland Basin and across the Central Basin Platform. Complex changes in the character and thickness of stratigraphic units reflecting the results of both facies changes and salt dissolution are noted near and across the west margin of the Central Basin Platform/east margin of the Delaware Basin. The Seven Rivers, Yates, and Tansill Formations are laterally equivalent to the Capitan Limestone Reef facies that forms the aggradational and progradational shelf margin of the Delaware Basin. Within the Delaware Basin, stratigraphic units are the Ochoan Rustler, Salado, and Castile Formations and the Guadalupian Bell Canyon Formations. Log analysis and preparation of cross sections, supplemented by core and outcrop descriptions, show the lithologies and facies relationships in each of these units.

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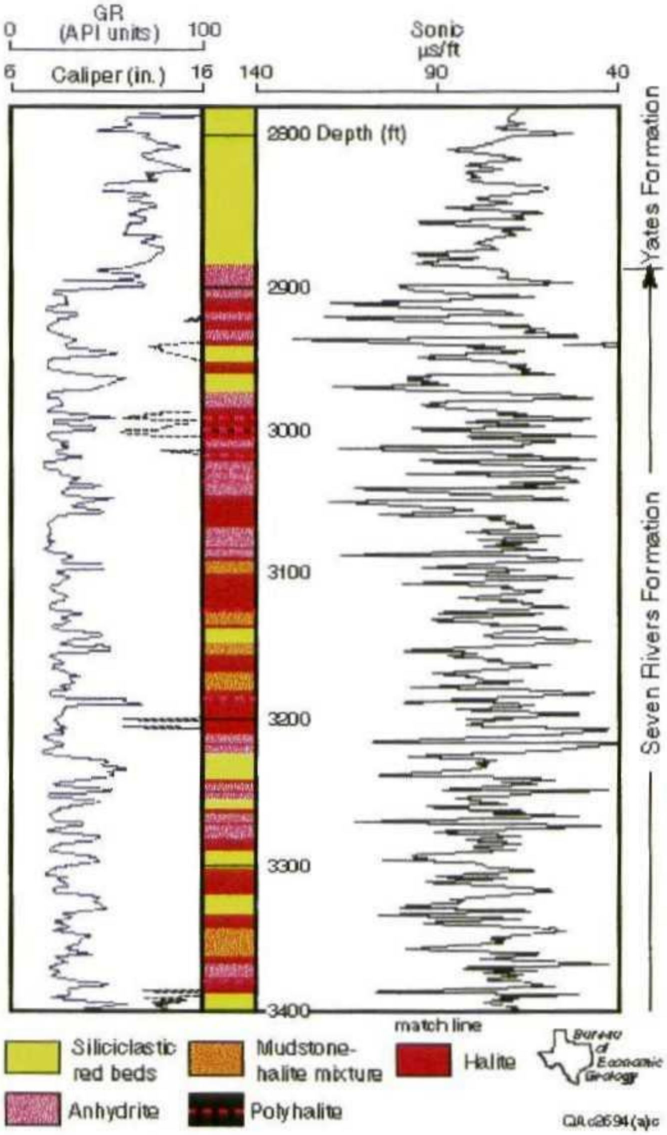
Seven Rivers and Yates Formations
Salado and Tansill Formations
Salado insoluble residue, Alibates and Dewey Lake Formations
Delaware Basin stratigraphy
Relationship between the Midland and Delaware Basin Units

Seven Rivers and Yates Formations



Type log through the Seven Rivers Formation. Cochran 14; Champlin Oil and Refining Company George E. Bensen No. 1, contains numerous salt beds in the Guadalupian section.

Yates Formation

The Yates Formation is a 100- to 175-ft-thick siliciclastic unit. The moderately high gamma-ray character, regional extent, and consistent thickness make this unit an optimum stratigraphic marker. Several anhydrite beds of subregional extent within the Yates provide additional log character. Very near the Capitan Reef margin, the Yates log character is obscured because it is laterally equivalent to back reef carbonate or to Capitan Reef facies. Interpretation of the depositional environment of the Yates is problematic from log character because sandstones and siltstones are accumulated in both marine and eolian flat environments. In the Palo Duro Basin north of the study area, cores through the Yates contain massive to disrupted (haloturbated) silt and very fine sandstone with illuviated clays, suggesting incipient soil formation interpreted as eolian flat facies accumulated as water level rose during a period of generally low sea level.

Seven Rivers Formation

The Seven Rivers Formation is composed of cyclically interbedded mudstones, salt, anhydrite, and dolomite. Several thick anhydrite beds at the top of the Seven Rivers Formation were the most extensive units in the section and were useful stratigraphic markers toward the basin margins. Regionally the amount of dolomite in the Seven Rivers Formation increases toward the Delaware Basin margin. In the New Mexico parts of the Delaware Basin Margin, the Seven Rivers is composed of shallow-water back-reef carbonate and is transitional into reef facies (Garber and others, 1989; Sarg, 1981). Log suites located for this study, however, were inadequate to correlate the lithologies. Halite is recognized on logs and in core descriptions over much of the study area, but clean salt beds are of limited thickness (<100 ft) and areal extent. The thickest Guadalupian net salt (100 to a maximum of 500 ft in several beds) identified is in the northernmost tier of counties in the study area (Cochran, Hockley, Lubbock, and Crosby) and in the Ector County in the depocenter of the Midland Basin. Because of the limited potential as a salt cavern resource and difficulty mapping significant units, detailed stratigraphic analysis of salt in the Seven Rivers Formation was not undertaken.

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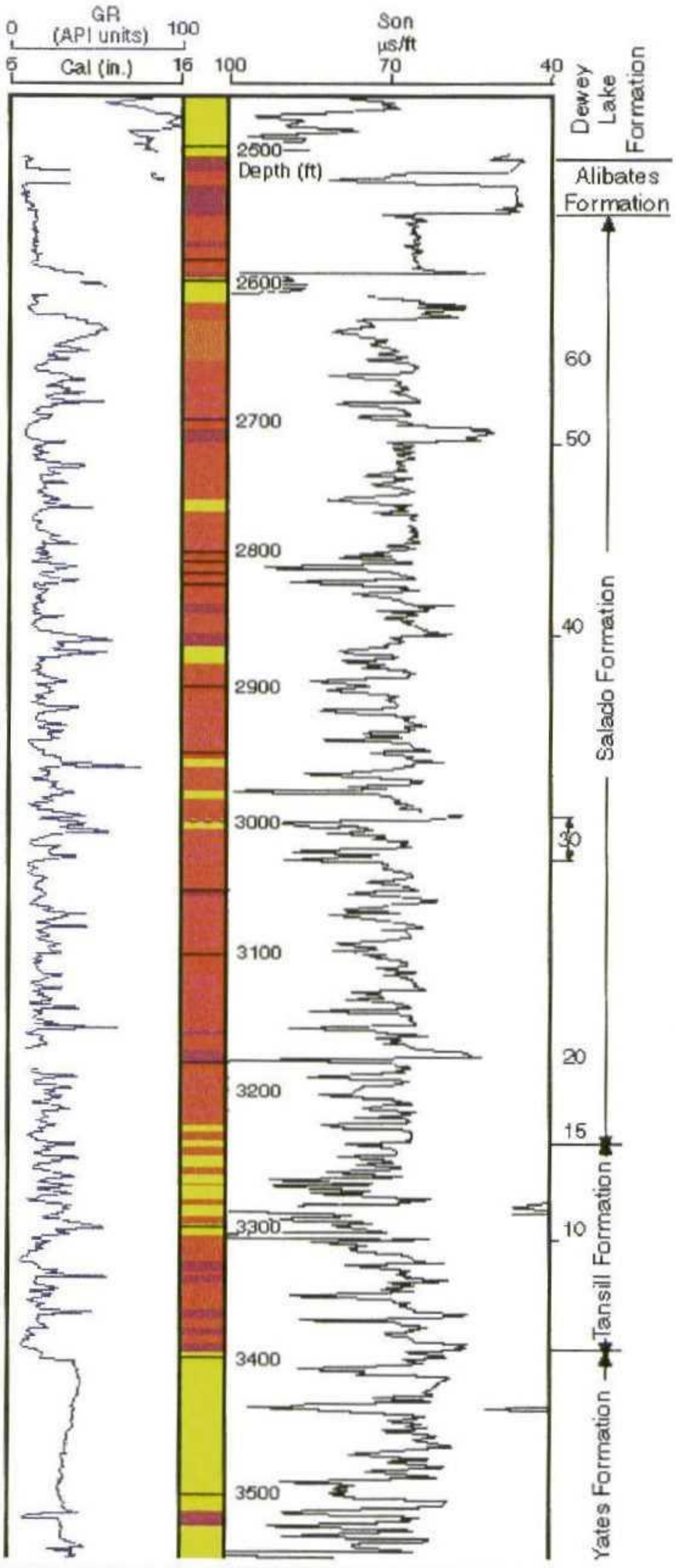
Salado and Tansill Formations

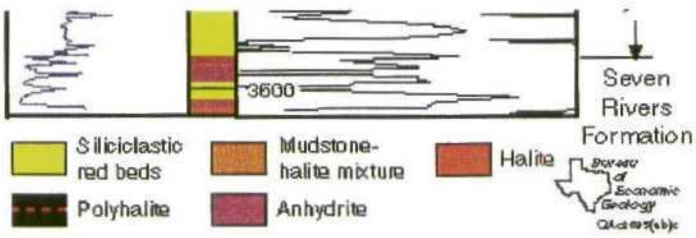
Salado and Tansill Formations



Type log though the Yates, Tansill, Salado, and Alibates Formations. Terry 16, Mobil Oil Corporation No. 1 Texas Tech University.

Salado Formation

The Salado Formation is the dominant halite-bearing unit of the Midland Basin and was mapped in detail for this study. Based on a model of salinity-controlled anhydrite-halite-mudstone depositional cycles (Hovorka, 1994), I used anhydrite beds as the major stratigraphic markers. Anhydrite represents the most-flooded, least-restricted conditions over the evaporite shelf where wind, storm, and seasonal circulation was adequate to maintain gypsum deposition.
Anhydrite beds are recognized by low response on gamma-ray logs, normal bore-hole diameter on caliper logs (in contrast, halite is commonly strongly embayed because it is dissolved in contact with undersaturated drilling mud), high count on neutron logs, high velocity on sonic logs, and high density log response. Anhydrite is typically fairly pure, although bed thickness limits log response from attaining the theoretical values for the thinner beds. Each anhydrite bed was flagged, correlated, and numbered. Regionally traceable beds were numbered 20, 30, 40, 50, and 60, and beds of more local extent were assigned intervening numbers (number 10 and 15 were used to subdivide Tansill stratigraphy, and 80 and 90 were used for anhydrite beds in the overlying Alibates Formation). Anhydrite bed 20 was identified across the entire study area and is distinctive because, in most areas, a thin insoluble residue of mudstone occurs at the base. Overlying anhydrite beds pinch out



toward the basin margins or are included in insoluble residue where intervening halite has been dissolved.

Anhydrite in the Salado Formation is commonly partly replaced in some intervals by polyhalite ($Na_2MgK_2(SO_4)_4$ ï H_2O). In core in the Palo Duro Basin and the Delaware Basin, polyhalite is observed to occur as needles and fine-grained masses that are typically red or pink because of thin iron-oxide coatings on polyhalite crystals. It is an early diagenetic replacement of gypsum as a result of interaction with pore water in the subaerial or shallow burial environment. The distribution of polyhalite is irregular on a fine scale, where it forms fabric-specific replacement textures and nodules, and on an intermediate scale, where it may replace only the floors of large polygons (Robert Holt, IT Corporation, 1990, personal communication), as well as on a regional scale. Although polyhalite is mined commercially as a potassium source in the Delaware Basin east of Carlsbad, New Mexico, no commercial uses are noted in the Midland Basin.

Polyhalite produces a strong gamma-ray-log response. Polyhalite has relatively low solubility in brine, so polyhalite beds are intervals of normal hole size on caliper logs, although thin beds within salt are commonly mechanically broken. Neutron-log response is variable because common admixture with anhydrite offsets the log response to the hydrous mineral. Polyhalite is admixed with mudstone in some settings, and these are also difficult to accurately separate.

Bedded halite is the most common lithology in the Salado Formation. In cores from adjacent basins (Lowenstein, 1988; Hovorka, 1990; 1994), bedded halite contains 5 to 15 percent anhydrite and mudstone as disseminated impurities and as millimeter- to centimeter-thick laminae. Log response and cycle structure suggests that halite in the Midland Basin probably has similar composition and fabric. Halite is identified in logs by a low gamma-ray response similar to anhydrite, oversized hole on caliper log, variable moderate-low neutron response, moderate and variable density and sonic log response, and high resistivity. In boreholes drilled with halite-saturated brine, halite beds produce little or no caliper log deviation.

Bedded halite is transitional into mudstone-halite mixtures and into mudstone. Mudstone in cores from the Palo Duro Basin (Hovorka, 1990; 1994) is composed of subequal mixtures of arkosic silt and illite-montmorillonite-dominated clays. Mudstone-halite mixtures or ìchaotic mud-saltî (Handford, 1982) are beds composed of poorly or nonbedded mixtures of euhedral or corroded halite crystals and mudstone matrix. Mudstone-halite mixtures are transitional into mudstone beds with minor inclusions of halite as euhedral or corroded halite crystals. Mudstone beds in turn are transitional by inclusion of less clay into siltstone and very fine sandstone. All these fine-grained clastics are collectively known as siliciclastic red beds.

Mudstone and mudstone-halite beds form during periods of prolonged exposure of the halite flat (Fracasso and Hovorka, 1986; Hovorka, 1994). Siliciclastics are transported onto the flat by sequential dust storm transport of fine materials, reworking by rainfall, and reworking by marine-derived saline-storm floodwater. Exposure and water-table drop cause formation of karst pits in halite, and these pits are filled with mudstone and mudstone and halite mixtures. The resulting distribution of mud is heterogeneous on a fine scale because pit fillings may be several feet thick adjacent to areas between pits where mudstone is thin or missing.

Log response to siliciclastic intervals is characterized by higher gamma-ray-log response than anhydrite and halite, and distinctly low neutron-log response because of high clay lattice and capillary water content. Sonic-log response is also generally low. Permeability of mudstones is generally considered to be very low because of high clay content; siltstone and sandstone porosity is typically occluded by halite cement, although investigation of the extent to which these generalities are true at a site scale may be needed. Borehole size as shown by caliper-log response in siliciclastic red-bed intervals is variable depending on drilling conditions and mud composition; in some boreholes, mudstones, and even siltstones and sandstones, are as strongly washed out as halite; in other boreholes, many siliciclastic beds form smaller borehole diameters than adjacent halite. Log suites were not adequate to consistently separate mudstone-halite mixtures from mudstone beds or mudstone beds from silty or sandy siliciclastic red beds.

Tansill Formation

The Tansill Formation is a highly cyclic and laterally heterogeneous unit about 100 ft thick. Toward the Delaware Basin, the Tansill Formation is dominated by anhydrite with or without dolomite and siliciclastic interbeds. In depositional updip environments toward the east and north margins of the Midland Basin, the Tansill Formation is composed of halite with abundant siliciclastic interbeds. In the middle of the Midland Basin, the basal part of the Tansill Formation is dominantly anhydrite or dolomite, siliciclastics with halite interbeds becoming more dominant upward. The log character of the Tansill is distinguished from the overlying Salado Formation because it contains more thin cycles and more abundant thin siliciclastic beds. Because of the cyclic nature of the sediments, however, no adequate stratigraphic marker was identified to regionally map the Tansill separately from the Salado Formation.

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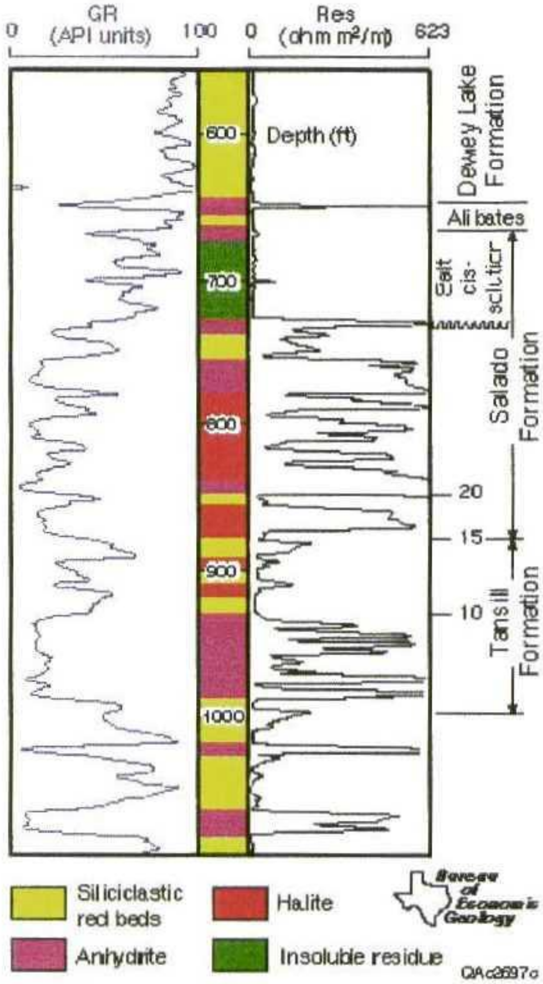
Salado insoluble residue, Alibates, and Dewey Lake Formations

Dewey Lake and Alibates Formations and Salado Insoluble Residue



Garza 13 John J. Eisner No. 1A Porter shows resistivity log response to dissolution.

Dewey Lake Formation

Overlying the Alibates is the Dewey Lake Formation, a 100- to 200-ft-thick siliciclastic red-bed sequence. This interval has moderately high, fairly uniform gamma-ray-log response. In the Palo Duro Basin, where this unit was examined in core, it is composed of siltstone and very fine sandstone deposited in pedogenically modified eolian-flat and cross-bedded wadi-channel environments.

Alibates Formation

The uppermost evaporite units in the Midland Basin are a pair of anhydrite beds of the Alibates Formation. These 10- to 50-ft-thick anhydrite beds and the siliciclastic interval that separates them forms a stratigraphic marker across most of the study area. Where this unit has been examined in core in the Palo Duro, the anhydrite beds are similar to other anhydrite beds in the section. They contain abundant pseudomorphs after bottom-grown gypsum, indicating that the unit formed in shallow, areally extensive brine pools. The pair of anhydrite beds of the Alibates are homogeneous and widespread over most of the basin. Complexities noted in this pattern include local thinning or absence of one or both anhydrite beds and change in log character, suggesting replacement of anhydrite by less dense, more porous, and more radioactive carbonate or chert. Thinning and compositional changes are common toward the north and east Midland Basin margins. More than two thick carbonate-anhydrite beds are common in the areas over and adjacent to the Capitan Reef, but the geometry of these units was not resolved in this study.

Where they have been examined in the Palo Duro Basin, diagenetic alteration in Alibates anhydrite beds has followed a more complex path than diagenesis of other anhydrite beds (Hovorka, 1992). In the Alibates, gypsum has been pseudomorphically replaced by dolomite, so that in places, the Alibates is a carbonate unit (McGillis and Presley, 1981). Locally in the Palo Duro Basin, the Alibates has been extensively replaced by chert. Silicification is a common diagenetic alteration of anhydrite but is very minor in other Permian anhydrite beds. In core from the Oldham nose structural positive on the northwest margin of the Palo Duro Basin, I observed cross-bedded, reworked, doubly-terminated quartz crystals with anhydrite inclusions in the upper Alibates dolomite bed. I have never observed halite overlying Alibates anhydrite beds, but brecciated, corroded, diagenetically altered anhydrite-siliciclastic contacts are areas where original halite may have been dissolved. This complex diagenesis is significant because it shows that Alibates deposition was preceded by an episode of reworking and silicification of older evaporites at least locally on the basin margins. Conforming to current stratigraphic nomenclature, this break is described as a sequence boundary. Additional alteration throughout the Alibates but not penetrating far into the underlying salt suggests that periods of alteration occurred before substantial warping of the Alibates, before or during Dewey Lake or Dockum deposition. These observations provide context in which to interpret heterogeneities observed within and beneath the Alibates in the Midland Basin.

Insoluble Residue

Above the halite-bearing part of the Salado Formation is an interval of insoluble residue. Insoluble residue thickness varies depending on the amount of salt dissolved and the impurity content of the salt. In cores from the Palo Duro and Delaware Basins, examination of the insoluble residue showed that this interval is composed of impurities in the salt, including anhydrite beds, mudstone beds, and impurities disseminated within the salt. Water sampling from this interval in the Palo Duro Basin (Dutton, 1987) showed that the insoluble residue contained brines that have dissolved evaporite but are not saturated with respect to halite. Anhydrite beds within insoluble residue are partly to completely altered to gypsum. The insoluble residue interval is commonly slightly to strongly brecciated containing horizontal fractures, small faults, high-angle fractures, abundant joints, or collapse breccia. Because the insoluble residue is commonly poorly understood and because it is a potential engineering challenge for caverns sited in the underlying salt interval, insoluble residues and the salt dissolution process are described in a following separate section.

Insoluble residue is recognized on logs by high gamma-ray-log response reflecting concentration of clayey and arkosic mudstone, low resistivity because of saline pore water in residue, which is more permeable than the underlying salt, and cycle skipping in sonic logs as a result of fracturing (Crane 5, W. H. Black No. 1 Shannon Estate, shows sonic-log response to fracturing and collapse). Comparison of insoluble residue intervals with adjacent logs where salt is preserved shows condensed thickness and concentration of anhydrite beds as intervening salt has been removed. Where anhydrite has been partly hydrated to gypsum, increased water content causes higher neutron count rates. As discussed in detail in a later section, salt dissolution in most areas is coincident with depositional changes in unit thickness and facies; this is one of the challenges in understanding these variations. As well as the common occurrence of insoluble residue at the top of the Salado, salt has also locally been dissolved from the base of the formation.

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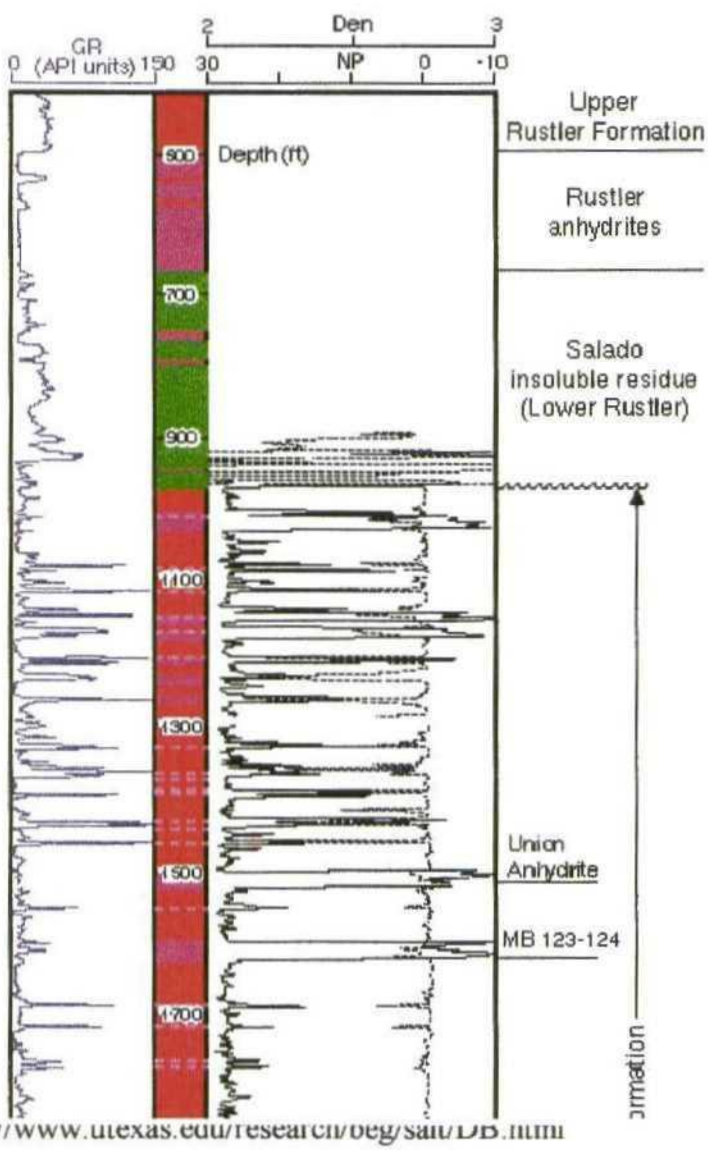
Delaware Basin Stratigraphy

Delaware Basin Stratigraphy

This brief discussion is for the purpose of setting the context for understanding the relationship of the Midland Basin salts to the Delaware Basin adjacent to the study area. More detailed descriptions are presented elsewhere (for example, Adams, 1944; Anderson and others, 1972; Snider, 1966; Lowenstein, 1988; and Hovorka, 1990). The upper Guadalupian section is composed of the Bell Canyon Formation, capped by the Lamar limestone, a finely laminated, organic-rich, silty limestone deposited prior to evaporite precipitation. The Bell Canyon Formation is the deep-water basinal equivalent of the Seven Rivers, Yates, and Tansill Formations on the Platform (Garber and others, 1989). Because of its high gamma-ray-log response and sharp contact with overlying Castile Anhydrite I, this contact serves as an excellent stratigraphic marker.



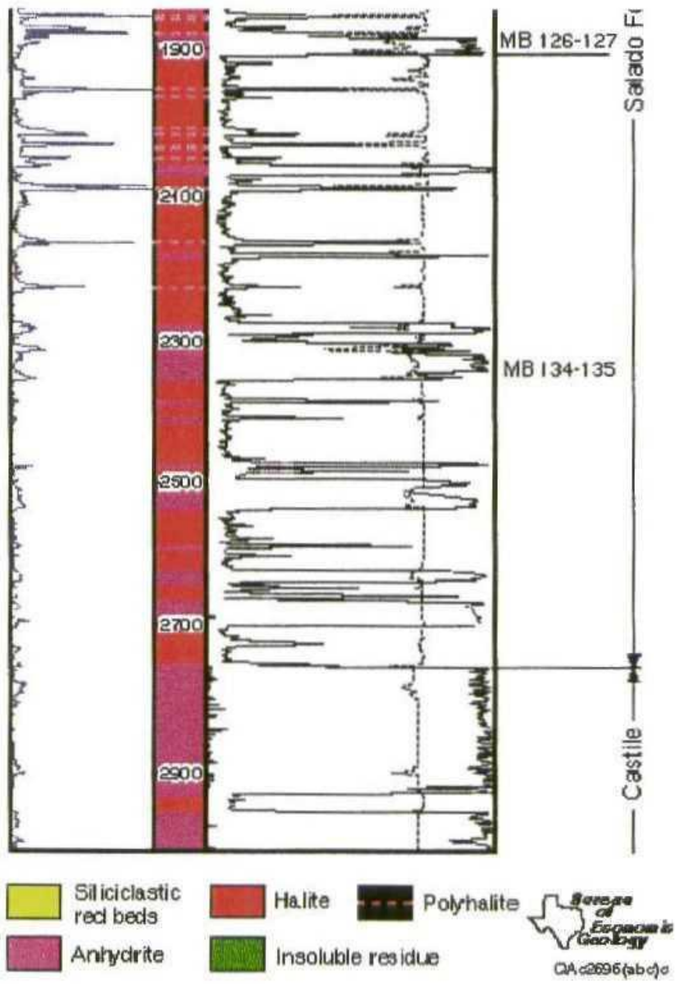
Gulf Research PDB-03 serves as a type log through the Delaware Basin section.

Rustler Formation

The two regionally traceable anhydrite-dolomite beds of the Rustler Formation are tentatively correlated with the two anhydrite-dolomite beds of the Alibates Formation, and the siliciclastics of the Dewey Lake with upper Rustler siliciclastics. In the Delaware Basin, insoluble residue is commonly included within the lower clastic unit of the Rustler Formation (Holt and Powers, 1987). Additional stratigraphic complexity observed elsewhere in the Rustler Formation (Holt and Powers, 1987) may be important for resolving the evolution of this part of the section but is outside the scope of this study.

Salado Formation

The Salado Formation in the Delaware Basin was examined in the Gulf Research PDB-03 core has a log response similar to the Salado



Formation of the Midland Basin. Cycles defined by anhydrite with or without polyhalite replacement define the base of cycles. Thick relatively pure halite (minor mud, polyhalite, and anhydrite) make up the upper part of cycles.

For this study, I used a unit tentatively correlated with the lower Salado MB 134 of Snider (1966) as a genetic break between the Salado and the Castile Formations. This unit was selected because, during my study of the PDB-03 core from Pinial Dome in Loving County, Texas, Salado MB 134 was observed to be an inflection point in the gradual upward-shallowing facies observed in the upper part of anhydrite IV and the lower Salado Formation. Above this marker, fabrics indicating shallow-water deposition and intermittent exposure are dominant in the halite as well as the anhydrite. A dolomite and magnesite bed within Salado MB 134 provided a moderately traceable gamma-ray-log kick, but, in some logs close to the Capitan Reef, the position of this anhydrite had to be estimated.

Castile Formation

The Castile Formation (only partly shown on this log) has been divided into four anhydrite units designated with Roman numerals (Snider, 1966), separated by laminated halite having dominantly recrystallized cumulate textures (Hovorka, 1990). Anhydrite beds I, II, and III, and their overlying halite units, can be traced widely over the Delaware Basin (Snider, 1966; Anderson and others, 1972), but near the Capitan Reef in the study area, the halite units pinch out or are laterally equivalent to anhydrite. Anhydrite bed

IV is a composite of multiple genetic units and, therefore, the stratigraphy and facies relationships are complex over much of the Delaware Basin as well as all of the study area (Hovorka, 1990); it is therefore difficult to identify and correlate a contact between the Castile and the Salado Formations.

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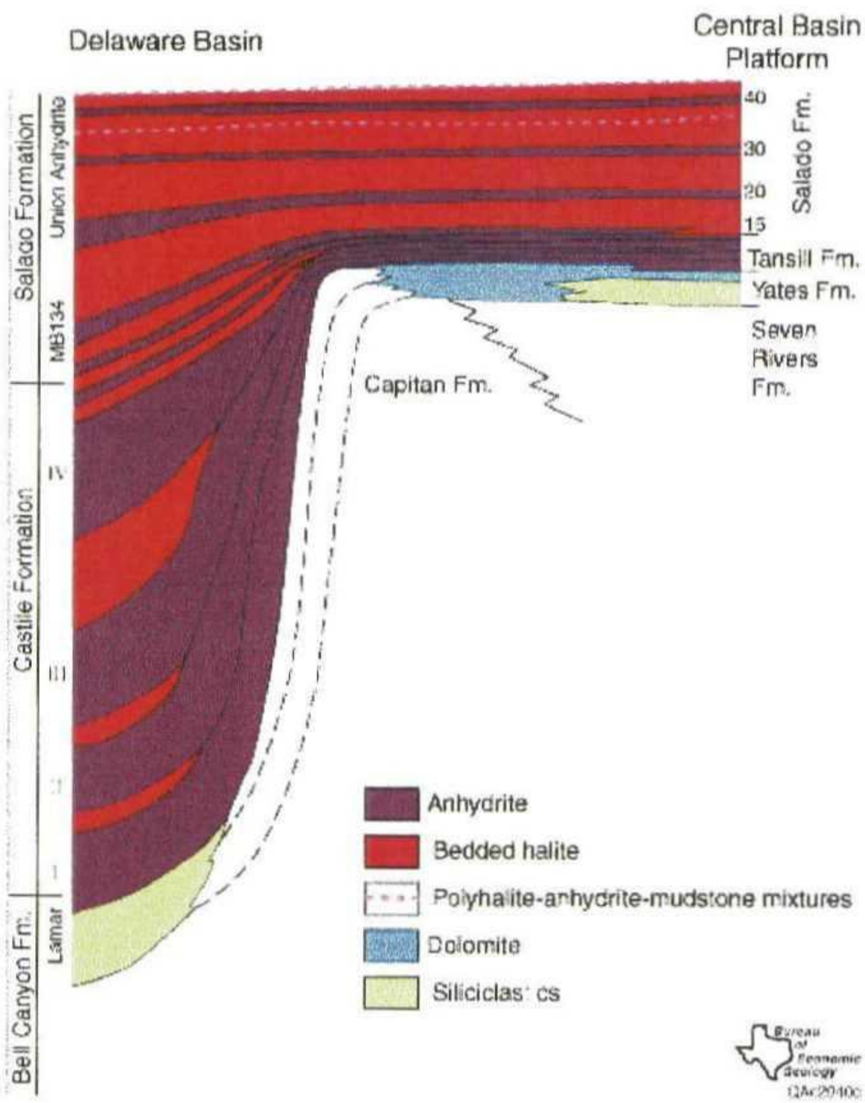
Relationship between Midland and Delaware Basin units

Relationship between Midland and Delaware Basin Units



The exact equivalence between the Delaware Basin units and the Central Basin Platform-Midland Basin units remains somewhat problematic. Time and facies relationships require that the units equivalent to the Castile on the shelf equivalent are thin or missing. The Castile evaporite in the basin was deposited very rapidly because of relatively high $CaSO_4$ concentrations in evaporite brine and accommodation in the deep basin.

I interpret that the most likely platform equivalent to the Castile Formation are the stacked high-frequency anhydrite cycles in the lower anhydritic part of the Tansill Formation. This interval (commonly called the Fletcher Anhydrite) in the Gulf PDB-04 core from the Capitan Reef in New Mexico is composed of anhydrite, minor carbonate, and red mudstone (Garber and others, 1989). I interpret the textures in this core as the product of repeated episodes of brine-pool deposition followed by diagenetic modification of brine-pool gypsum in a vadose-to-hypersaline ground-water environment. Bottom-grown textures have been intensely modified, red mud introduced during exposure episodes, and displacive gypsum sand crystals formed in a shallow ground-water environment. This correlation fits an interpretation of an alternately flooded and exposed shelf that accumulated condensed cycles at the same time the basin was rapidly filling with gypsum and halite.

If this correlation is accepted, then the shallow-water halite of the Salado Formation above MB134 in the Delaware Basin is then approximately correlated with the halite-siliciclastic cycles at the top of the Tansill and base of the Salado Formations of the Central Basin Platform and Midland Basin. Tentative correlations of groups of Salado polyhalite beds and individual anhydrite beds can then be made from the Delaware Basin into the Salado Formation on the Central Basin Platform.

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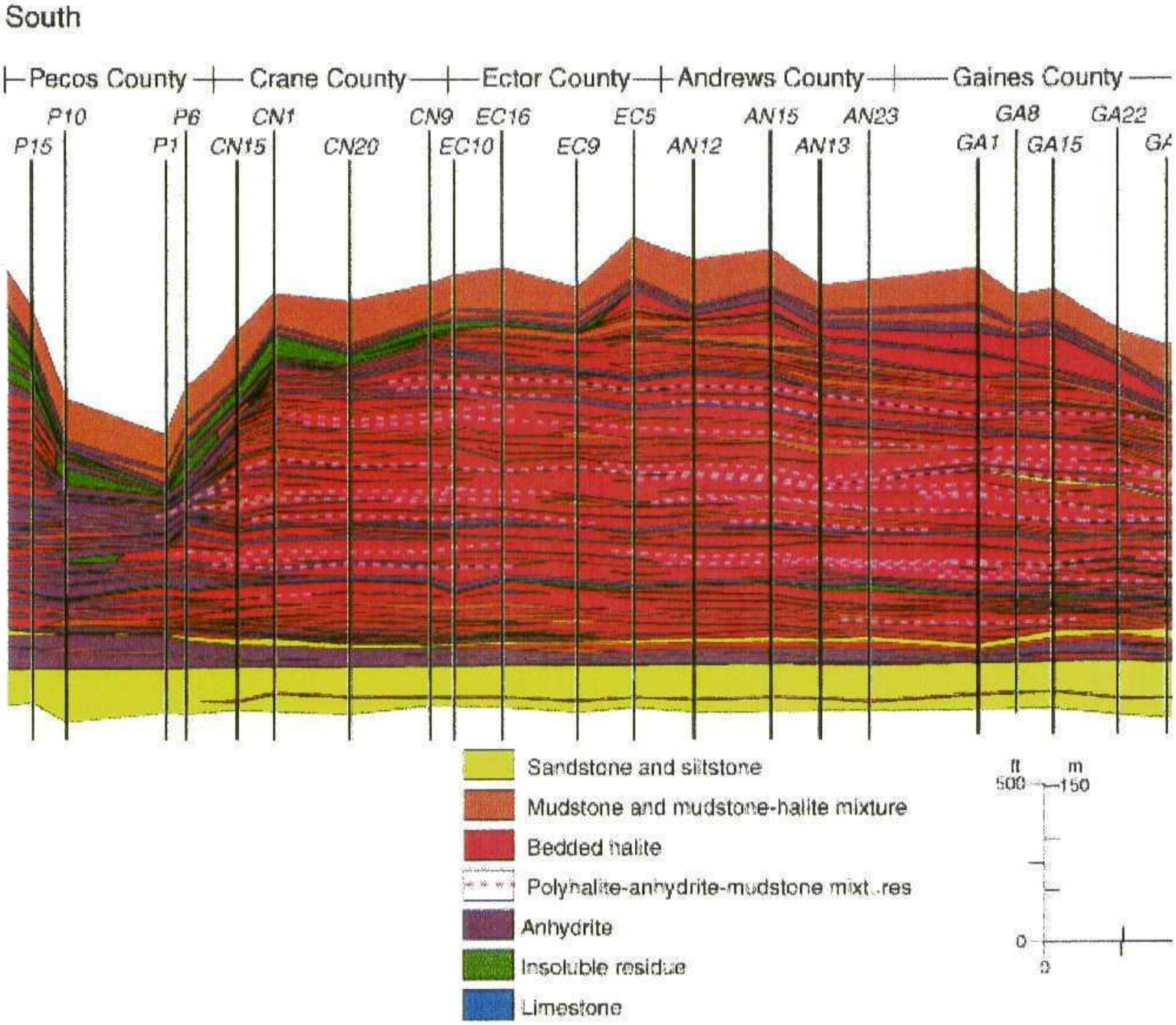
North-South Cross Section



Cross-section location shown on [index map]

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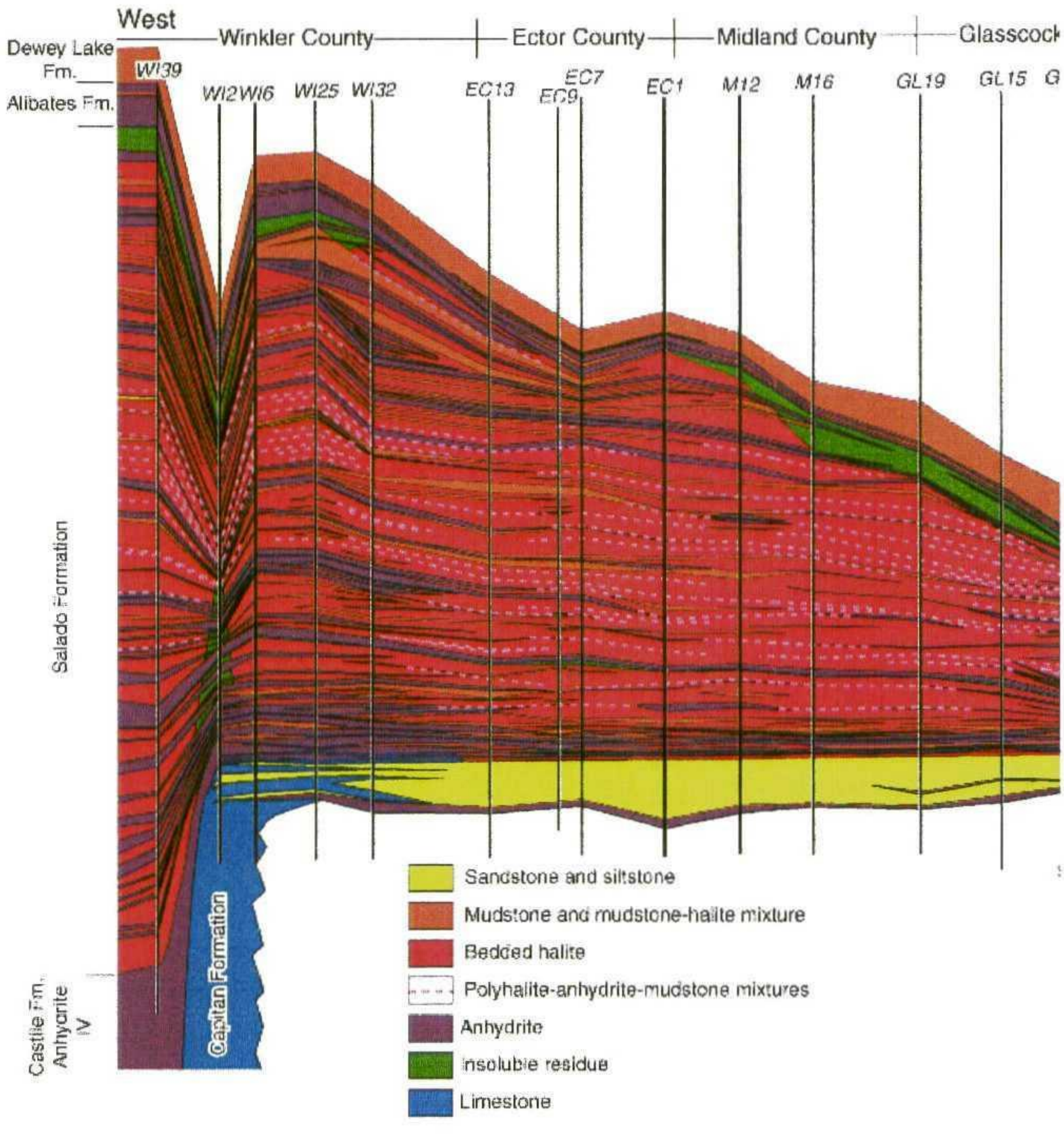
East-West Cross Section



Cross-section location shown on index map

Discussion of cross sections
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Discussion of Cross Sections

The basic genetic cycle style recognized in the Leonardian through Guadalupian of the Palo Duro Basin (Fracasso and Hovorka, 1986; Hovorka, 1994) and the Salado Formation of the Delaware Basin (Lowenstein, 1988; Hovorka, 1990) is also well displayed in the Midland Basin and provides the facies architecture needed to describe the thickness and continuity of salt beds and the distribution of impurities within them. Anhydrite beds formed during relative water-level rise form the bases of master cycles. Bundled between them are multiple intermediate cycles composed of halite, mudstone-halite, and mudstone.

Stacking of these master cycles produces a systematic regional thickening of halite from the north and east margins of the Midland Basin across the Central Basin Platform, toward the Delaware Basin. The conspicuous dissolution-induced variations in this trend over the Capitan Reef, Pecos River, and south Central Basin Platform area are discussed in following sections. Inspection of cycle patterns shows no major systematic change in salt quality with respect to salt purity, bed thickness, or spacing of anhydrite beds across the Midland Basin and Central Basin Platform. Anhydrite beds are gradually thicker and more numerous toward the Delaware Basin, but changes in anhydrite-bed thickness are specific to each master cycle, and no evidence for a consistent break is identified within the limits of the techniques used.

The 1,200-ft-thick lower part of the Tansill Formation contains three to five mapped cycles of anhydrite overlain by mudstone. Log character suggests that the mapped cycles are probably composites of more thin, anhydrite-dominated cycles. Cycles lack halite except in the north and east parts of the Midland Basin, indicating that although the shelf was frequently and extensively flooded, accommodation was limited and halite either did not accumulate or was dissolved during exposure at the end of each cycle. Anhydrite thickens and contains more dolomite toward the Delaware Basin and the Sheffield Channel. The upper Tansill contains three or four halite-siliciclastic cycles that thin toward the Delaware Basin and the Sheffield Channel.

The cycle pattern in Salado Formation in the Midland Basin is composed of six regionally traceable master cycles overlain by multiple complex cycles at the top. Master cycles are defined by a regionally traceable flooding event that deposited an anhydrite overlain by multiple halite-mudstone cycles. The lowest master cycle (50 to 150 ft thick) has a thin and discontinuous anhydrite or anhydrite-polyhalite bed (bed 15) at the base; the flooding event initiating this cycle was sufficient to end the upper Tansill cycles with abundant siliciclastic beds but only locally produced an anhydrite bed.

The next master cycle is about 175 ft thick and is defined by anhydrite bed 20 at the base. This anhydrite bed is one of the thickest (5 to 30 ft) and most distinctive beds in the Salado Formation. A persistent siliciclastic interval, interpreted as an insoluble residue at the cycle base, gives bed 20 a distinctive log character. It is commonly labeled Cowden anhydrite on published and marked logs, but the relationship of bed 20 in the Midland Basin to the named Salado anhydrite units of New Mexico has not been investigated in this study and, therefore, that nomenclature is not applied. Five or six traceable mudstone-halite cycles are present within this master cycle, and several locally traceable thin anhydrite beds are mapped within it. Polyhalite has replaced anhydrite in several of the mudstone-halite cycles in the Central Midland Basin.

Anhydrite bed 30 defines the base of the next 50- to 200-ft-thick master cycle. It shows more rapid lateral facies relationships than the underlying master cycle, including the occurrence of multiple and thicker anhydrite beds in the south part of the Midland Basin and greater changes in thickness across the Midland Basin. A maximum of nine polyhalite ± anhydrite-halite-mudstone cycles are found in the thick part of the master cycle. Polyhalite replacement increases westward across the Central Basin Platform, and this interval is correlated with an interval containing polyhalite beds in the Delaware Basin.

Anhydrite bed 40, which defines the base of the next 100- to 200-ft-thick master cycle, is discontinuous across the basin, and correlation of beds within this interval is therefore somewhat arbitrary. This interval contains abundant polyhalite beds that are correlated to an interval with abundant polyhalite beds in the Delaware Basin. Six to ten cycles are found in the master cycle. This bed is tentatively correlated with the Union anhydrite of the Delaware Basin (Snider, 1966).

Anhydrite bed 50 is continuous and well defined across the Central Basin Platform and Midland Basin and forms the base of the 75-ft-thick master cycle containing three to five halite-mudstone cycles. This master cycle remains fairly consistent in thickness over much of the area, forming a stratigraphic marker. The master cycle thins in the northernmost tier of counties of the study area and there, anhydrite bed 50 lies near the top of the Salado halite section. Polyhalite is minor in this interval.

Anhydrite bed 60 parallels bed 50 throughout its extent and pinches out toward the north edge of the Midland Basin. Above this bed, the cycle pattern breaks up, and interpretation of cycle correlation is unclear. The typical character of the anhydrite bed 60 to the base of the Alibates interval varies regionally across the study area. In the center of the Midland Basin (northwest Ector, east Andrews, east Gaines, and Midland Counties), this interval is 175 to 225 ft thick and contains two or three halite-mudstone cycles with thicker-than-average mudstone beds, overlain by several cycles with thin anhydrite beds and unusually thick (as much as 100 ft), relatively clean halite beds. In some areas halite directly underlies the lower Alibates anhydrite bed. Over the northern Central Basin Platform (west Andrews and most of Winkler County), the anhydrite bed 60 to base Alibates interval thickens, but much of it is composed of thick mudstone and mudstone-halite beds, as well as thicker anhydrite beds, than in the Midland Basin. Over the southern Central Basin Platform, this interval is thinner and dominated by mudstone and insoluble residue. In the north and east parts of the Midland Basin, the interval is thin and also composed of mudstone and insoluble residue. In the Delaware Basin, several hundred feet of fairly typical anhydrite-halite-mudstone cycles with minor polyhalite are correlated with this interval.

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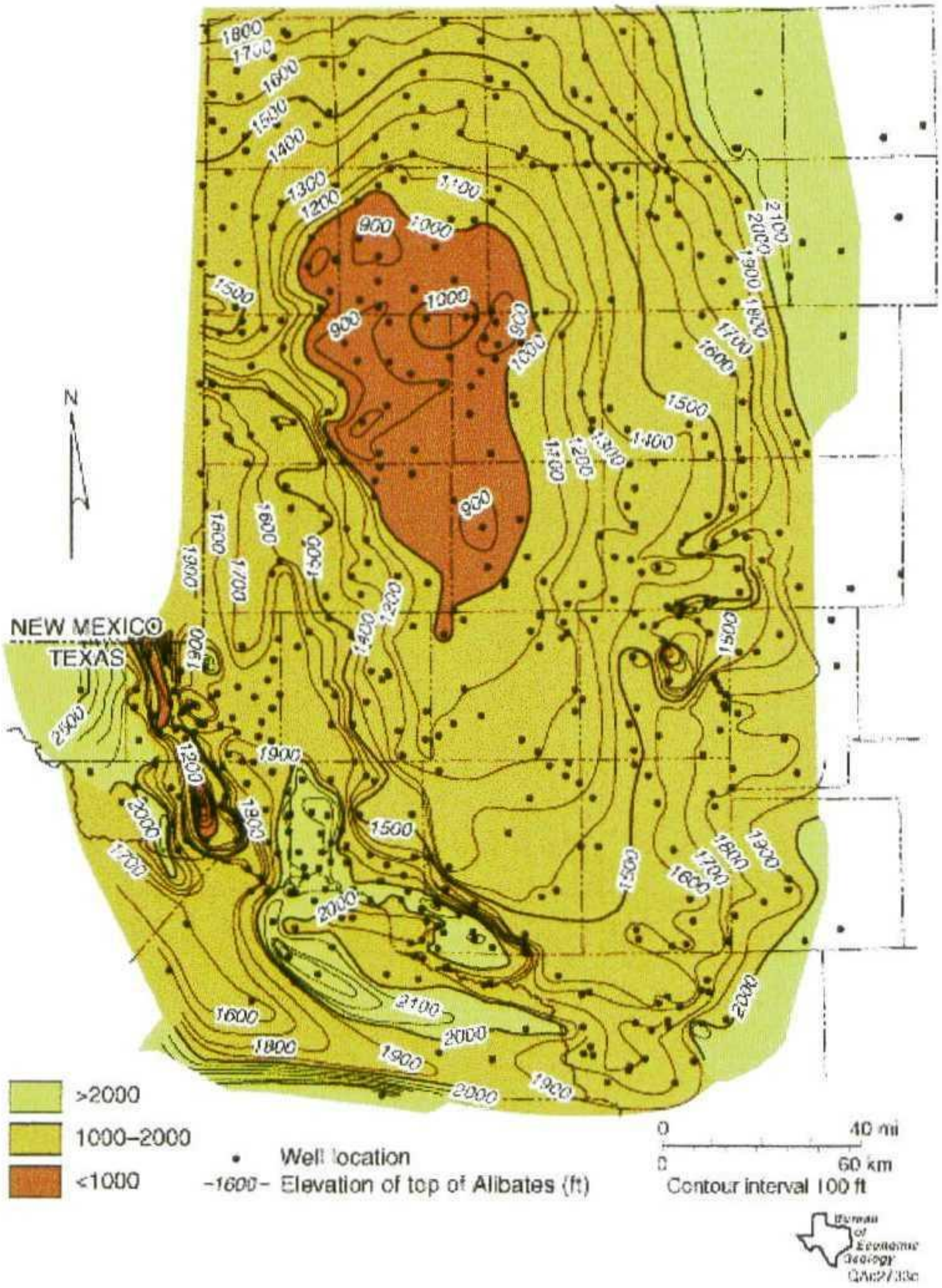
Isopach and structure maps

Structure above the Salt Section



Structure on the top of the Salado salt-bearing interval. Top Alibates Formation and equivalent top of upper Rustler anhydrite are used as markers. Prominent salt-dissolution features can be identified in Winkler, Ward, and Howard Counties.

Structure on top of the Alibates shows the effect that deposition and partial dissolution of bedded salt as well as postdepositional structural deformation had on the overlying stratigraphic marker. All of the major structural elements identified on the subsalt marker top Yates structure are also visible on the top Alibates structure, showing that the major components of the deformation postdate Alibates deposition. Many structural features, for example the east edge of the Central Basin Platform, are more subdued on the top Alibates structure than the top Yates structure, showing that some of the Yates deformation occurred during Salado deposition and created accommodation reflected in Ochoan thickness.

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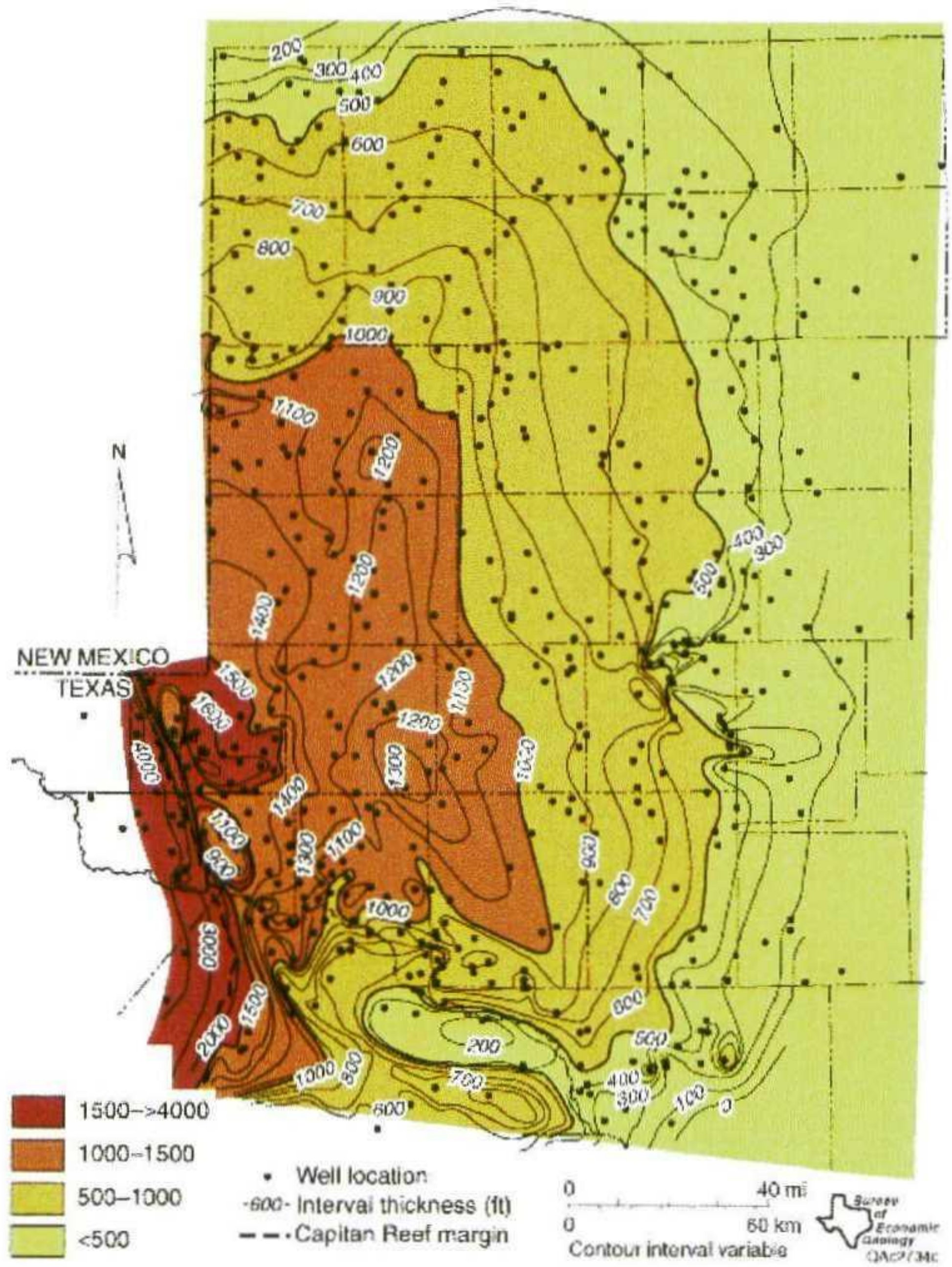
Depth to salt: Alibates-surface isopach
Thickness of salt-bearing interval: Ochoan isopach
Salt quality: Net salt and percent salt
Below salt structure: Structure on top of the Yates

Thickness of the Salt Section



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 of Lamar Limestone.

Synsedimentary effects influence the Alibates-Salado-Tansill isopach, which shows a general area of thick accumulation along the present structural axis of the Midland Basin. Comparison of the map view with cross sections shows that much of this thickening results from a combination of (1) regional thickening throughout the Salado from the north and east basin margins toward the west and (2) accumulation of thick Salado units at the top of the formation above bed 60.

The thickest interval in the Alibates-Salado-Tansill isopach (2,000 to 4,000 ft) is in the Delaware Basin in the southwest part of the study area (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. A thick Ochoan interval (>1,200 ft) also fills the San Simon channel (western Gaines County).

Comparing the salt thins to the top Alibates structure shows more depressions than the structural elements seen on the top Yates. One deep depression on top Alibates and thin in the isopach is found in central Winkler and Ward Counties. This corresponds to thin, absent, and dissolved salt along the Capitan Reef trend (Girard, 1952; Hiss, 1976; Baumgardner and others, 1982; Johnson, 1987; 1989a). Depressions are found along the Capitan Reef trend into New Mexico (Bachman, 1984; Hiss, 1976). Southward along a related trend is a large depression in the Alibates structure and corresponding thin in the Alibates-Salado-Tansill interval that lies above the south part of the Central Basin Platform in east Pecos and west Crockett Counties extending east to the Yates oil field area (Adams, 1940; Wessel, 1988a; 1988b; 1992a; 1992b).

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 Oil and Refining Company, 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, Borden, Garza, and Crosby Counties). Depositional thinning, salt dissolution, and erosional truncation beneath the Cretaceous and toward the 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 Oil and Refining Company, 1960; Vertrees, 1962; 1963; Geomap, 1986). Another area of salt thinning lies south of the Howard-Glasscock high. The thin area in the isopach is on the north side of a structural depression in both the top Yates and top Alibates structure, so that both the closed depression in the top Alibates is larger than in the top Yates because the interval thins along the northeast edge of the structural depression. 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 thinning were noted in this area.

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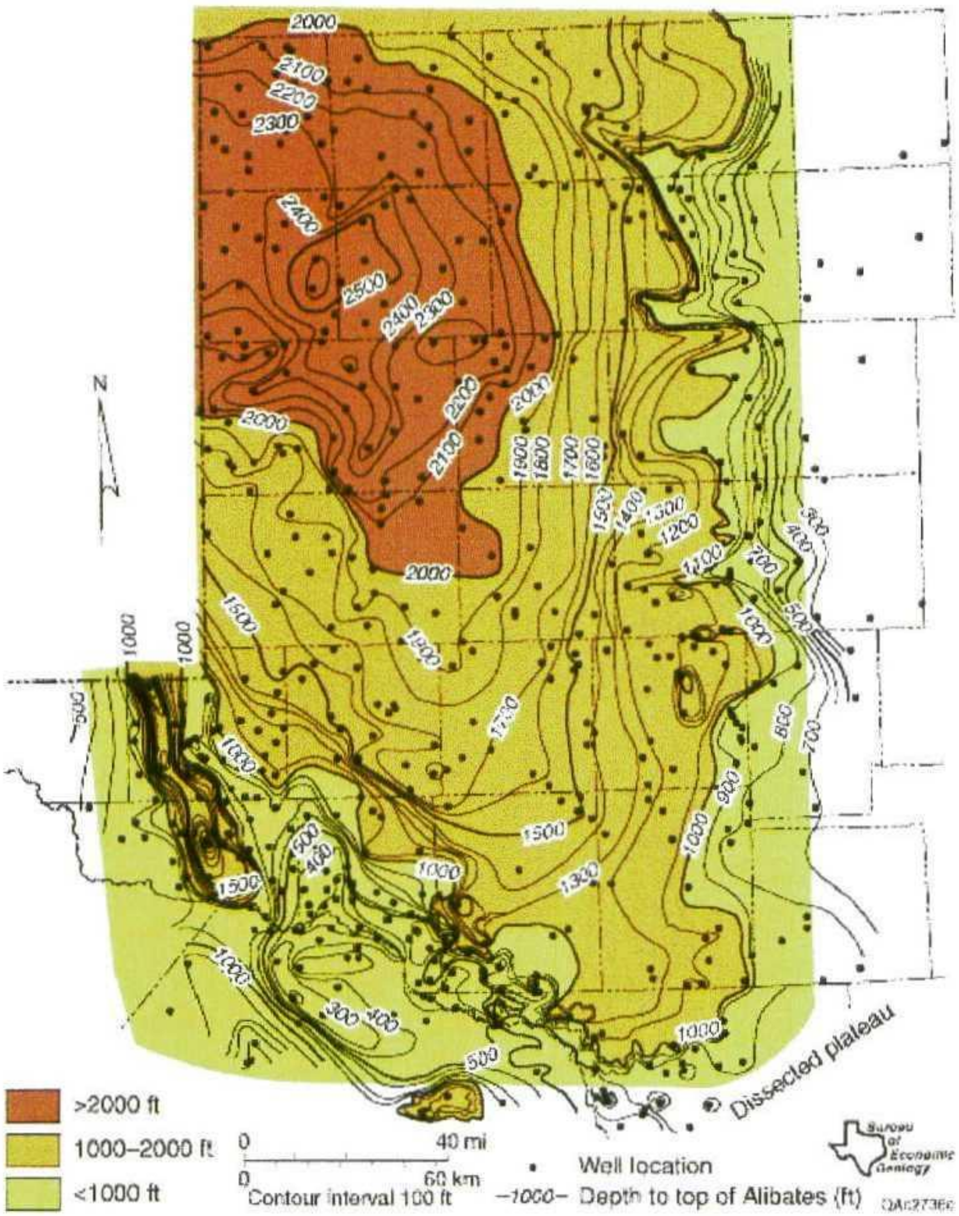
Depth to salt: Alibates-surface isopach
Above salt structure: Structure on top of the Alibates
Salt quality: Net salt and percent salt
Below salt structure: Structure on top of the Yates

Depth to Salt



Generalized depth to top of Salado salt-bearing interval from approximate land surface based on log datum and generalized 1:250,000-scale topographic maps to top Alibates Formation.

The depth of the Alibates below the surface 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 paleohydrologic conditions (deeply buried). Salt occurs near the surface (<1,000 ft deep) along the east edge of the study area and along the trend of the

Central Basin Platform, especially in Crane and north-central Pecos Counties (Yates oil field area). Salt is deeply buried by Triassic and Tertiary sediments along the Midland Basin, Northern Shelf, and Matador Arch structural elements. There is a prominent increase in depth to salt that corresponds to the prominent salt thin (Ochoan isopach) and depression in the top Alibates structure in central Winkler and Ward Counties. In the western Delaware Basin, burial to the top of the salt-bearing interval is moderate, generally >1,000 ft, but complicated by dissolution along the course of the modern and paleo Pecos River (Bachman, 1984).

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Thickness of salt-bearing interval: Ochoan isopach
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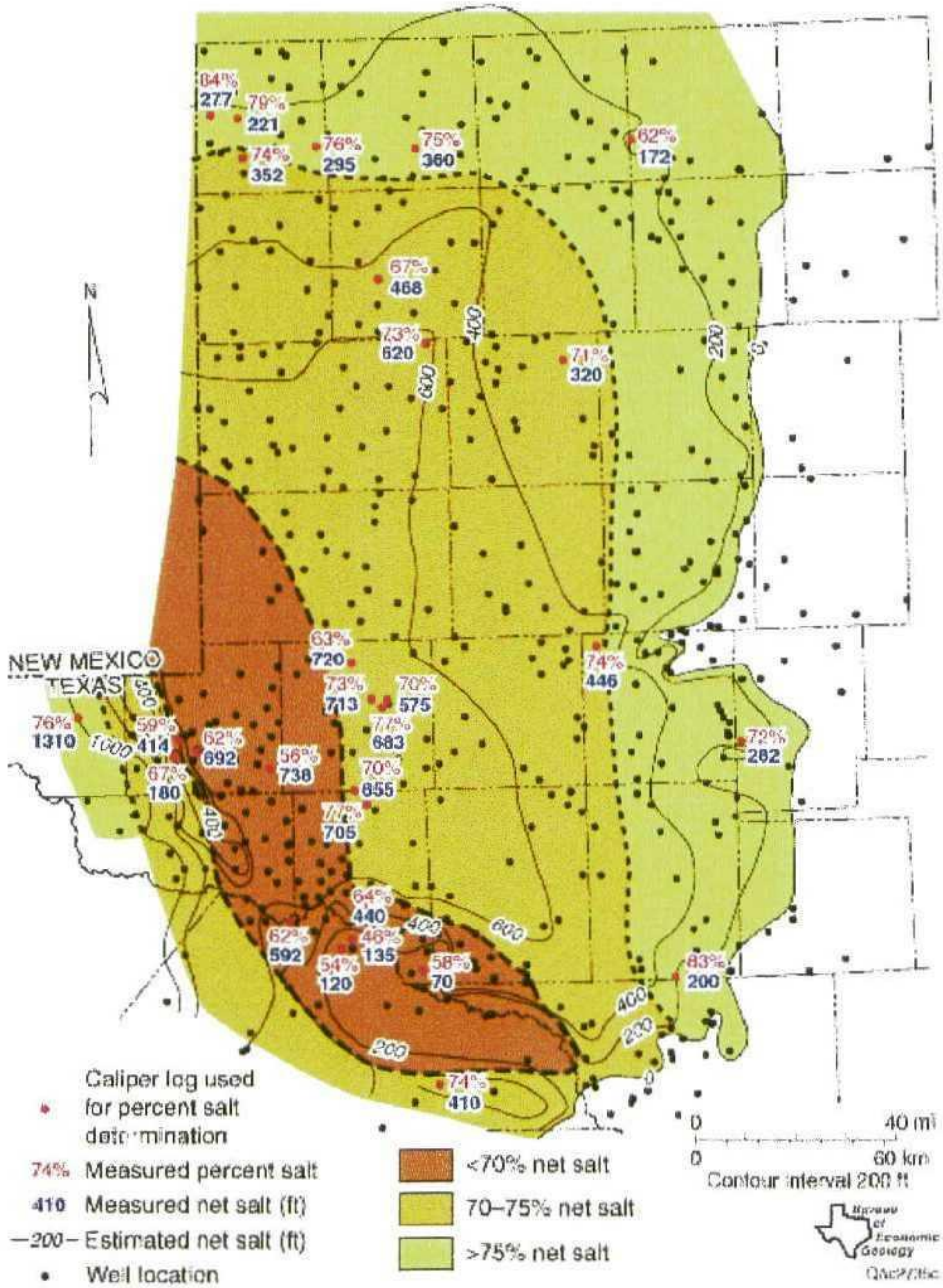
Salt Quality and Net Salt



Salado net salt and percent salt. Direct measurements of cumulative salt-bed thickness from wells with caliper logs in useful log suites are posted. Percent salt is calculated on the interval from top upper Tansill (marker 15) to the top of salt. Other thickness values are based on regional percent-salt average and the top salt to top Tansill interval thickness where it could be determined.

Log quality was sufficient to directly measure the amount of Salado salt in 55 logs in the study area (appendix 3 PDF file), generally because caliper-log response made it possible to reproducibly separate anhydrite from clean salt. Uncertainties remain in distinguishing mudstone-halite mixtures from mudstone in wells where the borehole has been enlarged in both lithologies. Additional measurement uncertainty is introduced by imprecise bed-thickness estimates in typical finely interbedded lithologies. Comparison of measurements from adjacent logs suggests that error of about 5 to 10 percent in measuring cumulative salt thickness is expected. In addition to measured salt thickness, thinned intervals of high gamma-ray-log response were interpreted as beds from which halite has been dissolved and used for defining the limits of salt. From measured salt thickness, the percent of salt from the salt-bearing intervals was calculated, and results ranged from 53 to 84 percent. The salt-bearing interval selected for this calculation was a minimum, from top salt to top upper Tansill clastic. This removes the insoluble material in the Alibates and above-salt insoluble residue and variable amounts of anhydrite and siliciclastic beds in the Tansill from the calculation. Typical values of percent salt were contoured, with the lowest percent salt (<70) over the Central Basin Platform and the highest percent salt (>75) toward the north and east updip edges of the Midland Basin. Inspection of the north-south and east-west cross sections suggests that thicker and more abundant anhydrite beds are the reason for increased impurities on the Central Basin Platform; in updip areas, decreased anhydrite bed abundance and thickness is partly but not wholly offset by increased abundance of siliciclastic beds.

The generalized percent salt in the salt-bearing interval was then used to estimate the salt thickness in logs from which salt beds could not be directly measured. The thickness from top salt to top Tansill siliciclastics was multiplied by the decimal percent salt mapped for the area and the estimated salt thickness calculated. In some logs top salt or top Tansill was difficult to pick and no value was posted. Resistivity logs are particularly useful in defining this interval because the salt section has low permeability and, therefore, has high resistivity, in contrast to the conductive saline-water-bearing insoluble residue and Tansill siliciclastics. The Alibates-Salado-Tansill isopach was used to guide the contouring of the net salt, and a large contour interval was used because of the measurement uncertainties.

The net salt map, like the Alibates-Salado-Tansill isopach, shows thick salt in the Midland Basin center. Even though the percent salt decreases slightly over the Central Basin Platform, the net salt continues to increase because the Salado thickness increases toward the Delaware Basin. In the Delaware Basin, the base of salt stratigraphically equivalent to the Salado Formation of the Midland Basin was approximated using the top of MB134, as the base of the Salado shows a moderate thickness increase. Salado thickness in the Delaware Basin is the result of increased accommodation in a dominantly shallow-water environment in a subsiding basin.

Toward the east margin of the Midland Basin, the net salt decreases fairly abruptly between 200 and 0 ft of salt, and this is where the depositional trend toward decreased interval thickness is overprinted by cross-cutting near-surface salt dissolution. A large zero-salt area is mapped over the south end of the Central Basin Platform and a small area is mapped over the Howard-Glasscock High. The depression over the Capitan Reef contains thin salt where it was intersected by wells, so in this area salt has not been completely removed.

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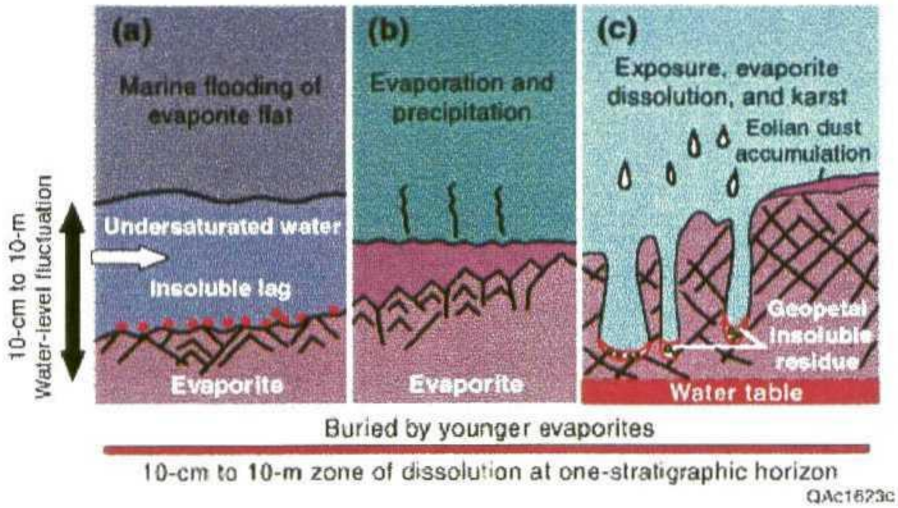
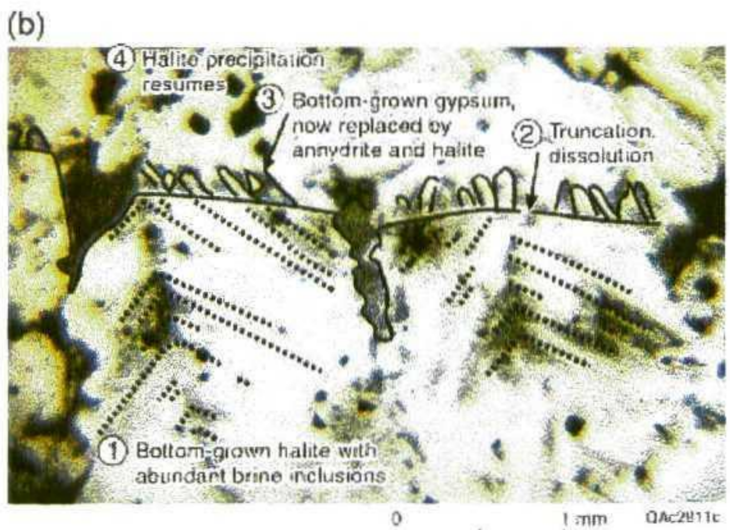
Outcrop geology: Generalized geologic map
Depth to salt: Alibates-surface isopach
Above salt structure: Structure on top of the Alibates
Thickness of salt-bearing interval: Ochoan isopach
Below salt structure: Structure on top of the Yates
Geologic processes in salt

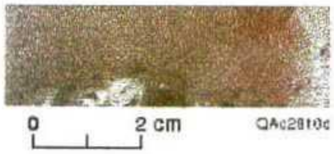
Deposition of Salt



Initial variations in thickness and quality of salt are introduced in the depositional environment. Sedimentary fabrics in halite (Hovorka, 1994) show that halite is typically deposited rapidly, producing large clear crystals. Impurities are introduced when environmental conditions shift, and halite deposition pauses. In shallow water, halite precipitates on the brine-pool floor as crusts of crystals that average a centimeter in height. When the brine pool is flooded by less highly evaporated marine water or by fresh rainwater, minor amounts of halite dissolve from the floor of the brine pool. Impurities within the halite accumulate as a lag on the brine-pool floor. If the floodwater is marine, a thin bed of gypsum commonly precipitates before halite precipitation resumes.



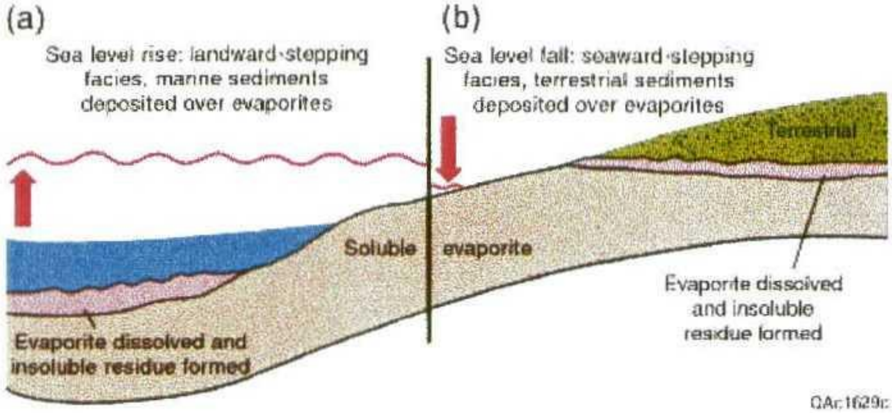
Halite on the brine-pool floor dissolved when the flat was flooded by marine water. (a) Truncated halite crystals contain



chevron-growth structures defined by fluid inclusions, accumulation of impurities forming dark bands in Gulf PDB 03 core, 2,398 ft below datum. (b) Photomicrograph showing dissolution of halite (note truncated growth bands defined by fluid inclusion), followed by precipitation of gypsum (now replaced pseudomorphically by anhydrite and halite) before halite precipitation resumed. DOE-Stone and Webster G. Friemel core, 2,522 ft below datum.

Deposition of Salt - continued

Base-of-Cycle Dissolution



Dissolution also occurs at the base of high-frequency cycles and at sequence boundaries. Influx of marine water during short- or long-term sea-level rise partly or completely dissolves the salt from the top of the previous cycle, and forms an insoluble residue at the base of the transgressive deposit (panel a).

Wavy-laminated base-of-cycle insoluble residue. This is one of the lowest Salado cycles in the Delaware Basin to exhibit base-of-cycle residue and indicates that sediment accumulation has shallowed that basin to the depth at which dissolution can occur. Gulf Research PDB-03 core, 2,360 ft below datum.

Insoluble residues are composed of disseminated impurities and mudstone and anhydrite interbeds from halite (Hovorka, 1994). As halite is dissolved from the top of the bed by undersaturated water, impurities accumulate first as a lag on the floor of the water body, and then as dissolution proceeds downward, as wavy-laminated impurities accreted to the bottom of the insoluble residue bed. Criteria for recognizing base of cycle dissolution are (1) a concentration of insoluble impurities at the base of a transgressive deposit and (2) distinctive accreted wavy-laminated texture. Under ideal circumstances, a relationship can be observed between the residue thickness and the amount and duration of freshening in the overlying cycle, so that thick residues are found downdip beneath thick carbonate beds, and thin residues are found updip beneath thin anhydrite beds (Hovorka, 1994). Dissolution of halite during transgression increases accommodation and bed thickness for the sediments deposited during transgression.

The mudstone bed at the base of Salado anhydrite 20 in the Midland Basin is tentatively identified as a base-of-cycle insoluble residue. Across the Central Basin Platform, base-of-cycle dissolution

during transgression is the probable mechanism for forming abundant, relatively thick anhydrite beds in the Salado Formation as seen in the north-south and east-west cross sections. Multiple episodes of base-of-cycle dissolution is the mechanism proposed for reducing the percent halite to <70 across the Central Basin Platform. This is an area where subsidence during Salado time created high accommodation as apparent in the isopach of the salt section.

Freshening of ground water at the base of a regressive depositional sequence can also result in dissolution of halite (panel b). A probable example of this process may be seen in the upper part of the Salado Formation above bed 60. Several episodes of accumulation of anhydrite beds and thick halite units along the structural axis of the Midland Basin are seen in the north-south and east-west cross sections. Salado facies equivalent to this interval along the north and east parts of the Midland Basin are thin mudstone beds or muddy insoluble residue. Marginal areas may have had salt dissolved while thick salt accumulated in the basin center. This interpretation is made uncertain by the probability that this interval has been attacked by undersaturated water at later times, during Alibates or Dockum deposition.

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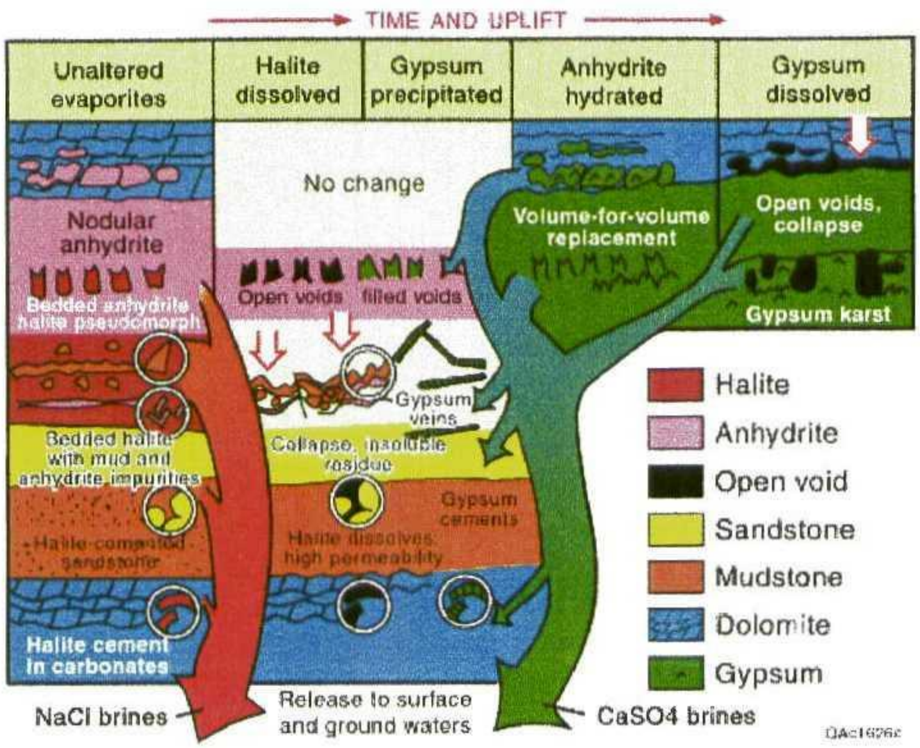
Burial dissolution

Post-Permian Salt Dissolution under Burial Conditions



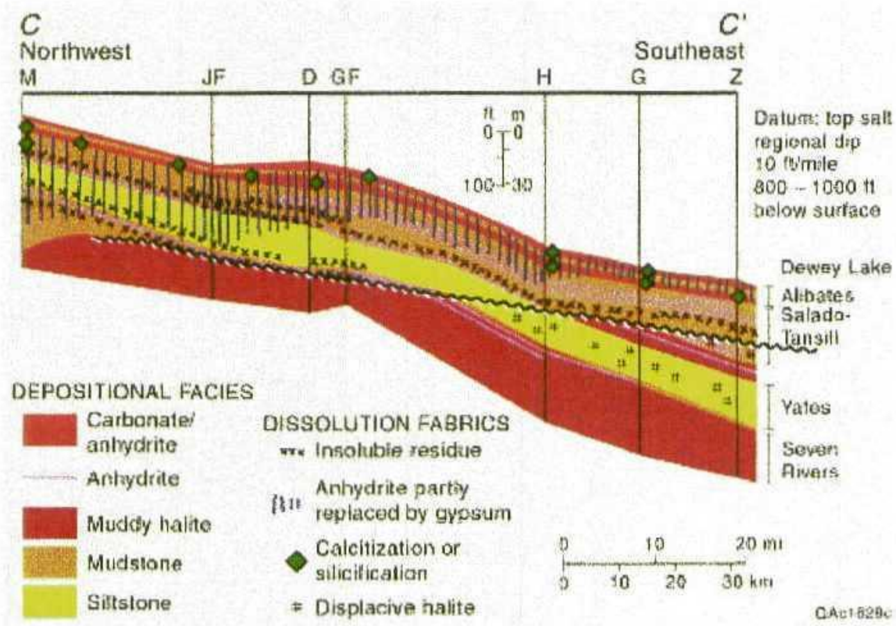
The processes and alteration of evaporites in the presence of undersaturated water. Unaltered evaporite is shown on the left, initial alteration in contact with undersaturated water in the middle, and intense alteration after prolonged contact with undersaturated water is shown on the right.

The processes involved in salt dissolution are phased depending on how long the evaporites have been in contact with invading undersaturated ground water. These phases were identified during examination of suites of cores across the Palo Duro and Hollis Basins (Hovorka and Granger, 1988). Initial alteration at the base of the salt-dissolution zone where undersaturated downward-moving water encounters halite is dominated by halite dissolution. Halite is removed from halite beds, forming beds of insoluble residue. Halite cements are also removed from other lithologies, increasing porosity and greatly enhancing permeability. This increase in porosity allows recognition of salt dissolution on resistivity logs.

In evaporite-residue sections that have been in contact with undersaturated brines for longer, gypsum alteration is important in creating textures. Anhydrite is hydrated to gypsum in undersaturated brines (Gustavson and others, 1994). Accompanying density change requires that volume-for-volume hydration of anhydrite to gypsum release large amounts of calcium sulfate to solution. Observed textures in core indicate that volume-for-volume hydration of anhydrite to gypsum is the dominant replacement mechanism, and show that gypsum cement is precipitated as fracture and void fillings. Sulfate is also removed in solution. This alteration is characteristic of the dissolution zone from several feet above the top of the uppermost salt to near land surface. Near land surface and in high-flow, high-transmissivity intervals, gypsum has been extensively dissolved, producing gypsum karst. The phased nature of evaporite dissolution is important for understanding log relationships observed in cross sections. Anhydrite and gypsum beds are commonly well preserved in areas where halite has been dissolved and can be traced through the dissolution zone to their depositional or erosional edge.

Regional low angle dissolution--passive let down

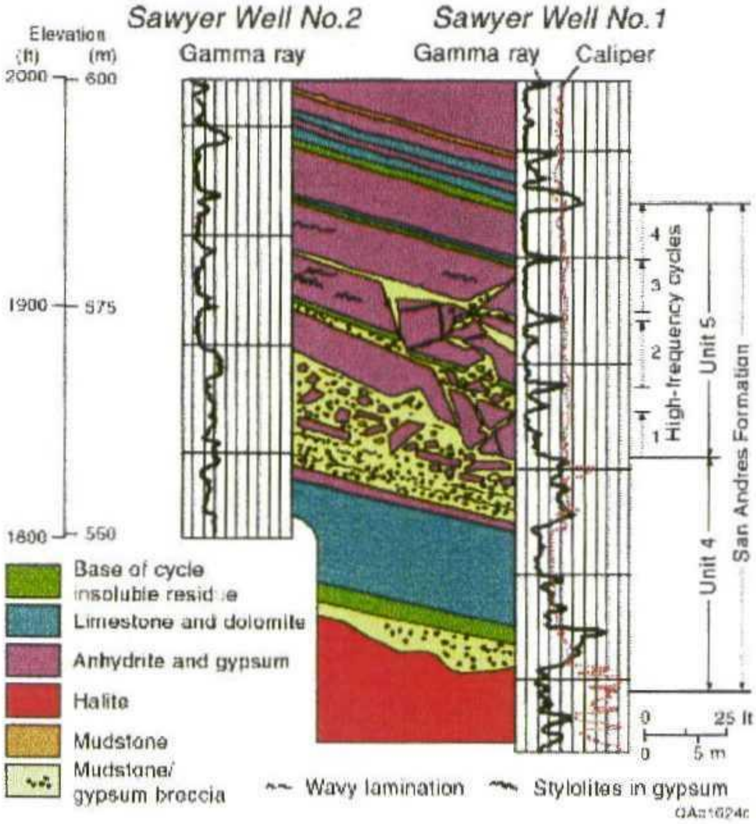
Commonly, undersaturated ground water moves downward at recharge areas, horizontally for long distances through aquifers, and upward at discharge points. Where salt has been dissolved in this kind of ground-water regime, the upper surface of the salt approximately parallels the flow lines and lies at a low angle to the land surface.



One example of this geometry is seen in the Palo Duro Basin, where the top of salt lies at 800 to 1,000 ft in depth and approximately parallels the low-relief Southern High Plains surface. The top of salt forms a low-relief surface paralleling the regional hydrologic gradient. Cross section based on data from Hovorka, Fisher, and Nance, 1988. Cross section location is shown on the general Permian Basin index map. This salt-dissolution surface regionally crosscuts stratigraphy, so that in the northwest, the Seven Rivers Formation is the uppermost salt-bearing unit and overlying salts have been slowly dissolved; down hydrologic gradient to the southeast Salado halite is partly preserved.

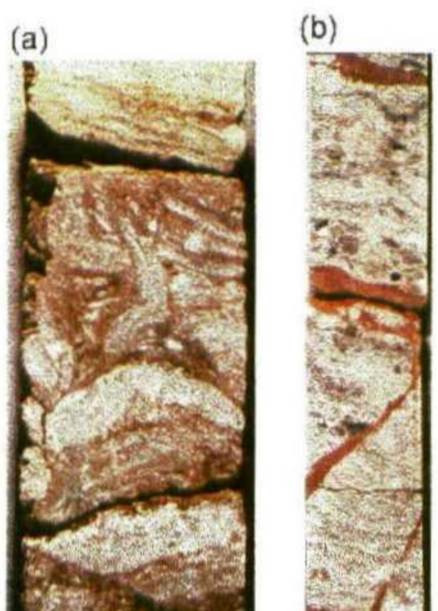
Post-Permian Salt Dissolution under Burial Conditions - continued

Focused Dissolution and Collapse



Detailed cross section between two closely spaced wells, in an area of complex salt dissolution. Location shown in general map of the Permian Basin.

In areas where hydrologic complexities are found, salt dissolution may be irregular and complex. Focused dissolution may remove salt from one small area and leave it intact in an adjacent area. In cross section focused dissolution and collapse results in steeper-than-regional dips and irregular unit thickness. Focused dissolution and irregular subsidence favors creation of abundant and potentially well-connected fracture systems (Goldstein and Collins, 1984; Collins and Luneau, 1986). Thicker intervals of permeable residue strata and more fracturing will focus flow and propagate further irregular dissolution patterns.



In the Palo Duro Basin, cored collapse breccia (a) from the floor of a small cavern, DOE Stone and Webster Sawyer core, 446 ft below datum. Strata overlying a large cavern collapse breccia have been fractured (b). These fabrics are interpreted as a result of formation and subsequent collapse of natural caverns in the salt in an area of complex salt dissolution over a structural positive in the Rolling Plains, an area of recognized salt-dissolution collapse (Baumgardner and others, 1982).

Hydrologic complexities with the potential to cause focused dissolution include enhanced permeability along faults and fractures or permeable strata and high hydrologic gradient related to topographic relief or to different hydrologic head in poorly connected aquifers. Although rigorous hydrologic analysis has not been undertaken for this study, the hydrologic regime in various parts of the study area is noted.

Several areas in the Midland Basin have characteristics that suggest past or ongoing focused dissolution. Complex structure on top salt corresponding to rapid lateral changes in salt thickness around the Howard-Glasscock positive, particularly in the closed structure contours on the Alibates on the south side of the positive and northeast of the graben, suggest that focused salt dissolution may have occurred in this area. Another area where salt dissolution appears to have removed salt is the south part of the Central Basin Platform. On the north side of this structure, closely spaced contours in the structure on top salt and salt thickness near the Pecos River suggest the potential for focused dissolution.

The best-documented area of focused dissolution in the study area is the Winkler and Ward County area over the Capitan Reef. Focused dissolution is thought to have contributed to modern salt dissolution and collapse at the Wink Sink (Baumgardner and others, 1982; Johnson, 1987; 1989a) in central Winkler County (see index map of the Permian Basin). Topographic maps of the Winkler County area note numerous sinkholes, although the unit being dissolved is not known. Several other salt-dissolution chimneys (Chimney C and San Simon Sink) that appear to be part of a trend of focused salt dissolution around the Capitan Reef crest in New Mexico have been described (Bachman, 1984). Over the Capitan Reef, detailed cycle correlations on the east-west cross section show that dissolution has occurred both from the bottom and from the top of the Salado Formation.

Dissolution at the base or intrastratally within the salt may occur elsewhere within the Midland Basin. During this study, I tentatively identified several areas on the east margin of the Midland Basin in the Permian outcrop belt where resistivity logs show highly conductive units in the base of the Salado, suggesting that dissolving water may have moved beneath the salt through the Yates and Tansill Formations. 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. Modeling suggests that subsalt dissolution might occur elsewhere in the Permian Basin (Anderson, 1981; Howard, 1987).

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Timing of salt dissolution

Timing of Salt Dissolution under Burial Conditions

Across the Permian Basin, dissolution has occurred several times in the past and continues today. Salt dissolution occurred during the Triassic, Cretaceous, and Cenozoic and continues in the present. The extent of salt dissolution during these times has been only locally determined because the effects of earlier and later dissolution are difficult to separate.

Much of the dissolution over the crest of the southern Central Basin Platform occurred before the Cretaceous, because these units are minimally deformed across and on the south edge of the uplift (Adams, 1940; Wessel, 1988a, b). In a detailed study of the Yates field, Wessel (1988a) showed that Cretaceous strata are warped downward and faulted along the Pecos River in the area of the Alibates-Salado-Tansill interval thinning and salt pinch out, showing that dissolution continued in this area after the Cretaceous. Although similar high-resolution data have not been collected and interpreted in the Howard-Glasscock area, slight dips on Cretaceous strata and complex Quaternary deposits (Eifler and others, 1974) suggest that deformation may have occurred before, as well as after, the Cretaceous.

A major regional episode of salt dissolution occurred during regional Cenozoic uplift when the entire area was uplifted from near sea level to its present elevation (Baker, 1977; Gustavson and others, 1980; Gustavson and others, 1982; 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 1,000 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. 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).

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 relationship between surface depression 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 (Howard and Love, 1945; Rawson, 1982; Richter and Kreitler, 1986; Dutton,

1987; Richter and others, 1990; 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 rate and process of salt dissolution (Swenson, 1974; Gustavson and others, 1980; Gustavson and Simpkins, 1989; Paine and others, 1994).

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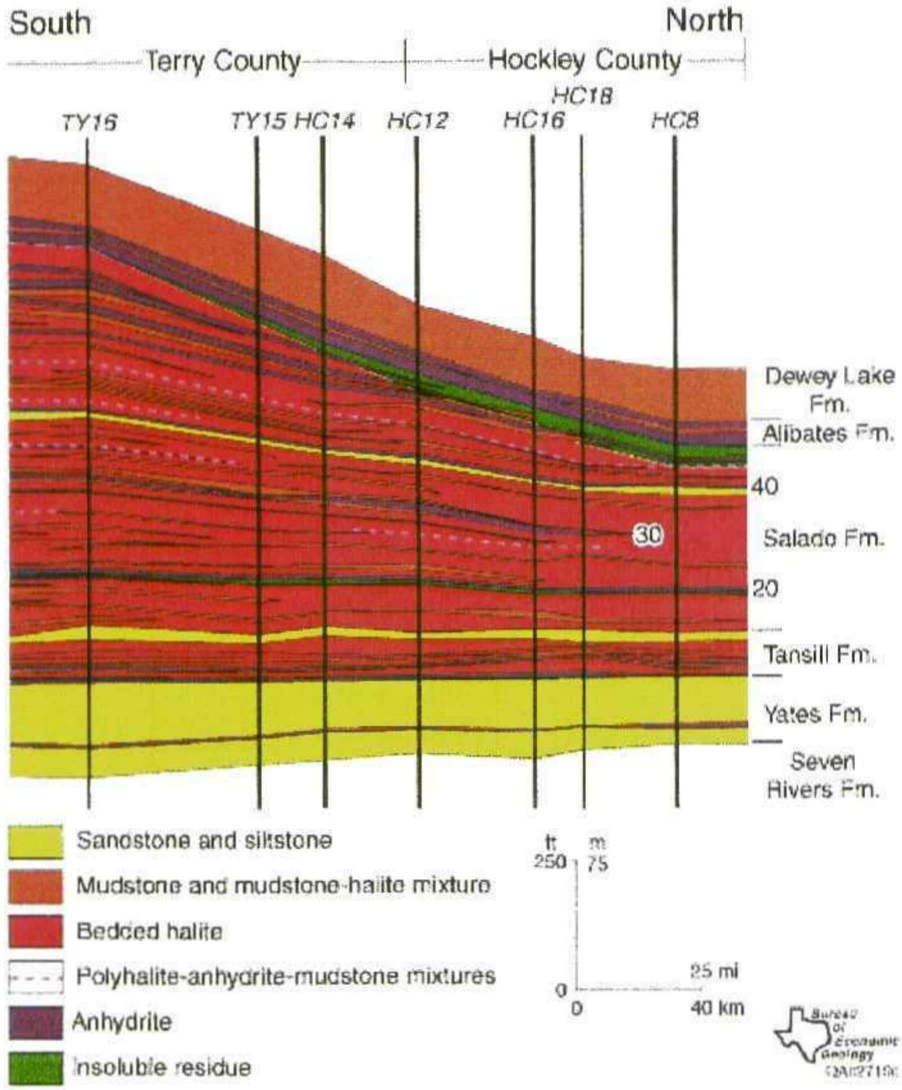
Case Study 1: Permian facies controls on the north margin of the Midland Basin

Case Study 1: Permian Facies Controls on the North Margin of the Midland Basin



Detail of north-south cross-stratigraphic section in the deep part of the northern Midland Basin showing salt-character changes controlled by Permian facies change and base of sequence dissolution. Cross-section location is shown on study area index map.

Thinning is observed in the salt-bearing interval near the north edge of the Midland Basin. The structure on the Yates shows that the current structural margin of the Midland Basin is defined by the Matador Arch and Roosevelt positive. The following change in salt thickness and quality are noted along a dip section on this Permian structure. Between Terry well 16 and Hockley well 8, the salt section below the top of salt and above the Tansill siliciclastics thins from 650 to 320 ft. Most of this thinning occurs gradually, with each individual bed decreasing in thickness by about one half. For example, anhydrite bed 20 decreases from about 8 to about 2 ft thick, and the overlying halite decreases from 150 to 100 ft thick. Anhydrite bed 30 and several thin polyhalite beds pinch out or decrease to a thickness that does not produce a recognizable signature on logs. Above anhydrite bed 50 the thickness changes follow a different pattern. The upper 150 ft of the salt section in Terry County, containing four anhydrite beds and two mudstone intervals, thins to 40 ft of mudstone with one recognizable anhydrite bed at the north edge of Hockley County. The halite beds pinch out sequentially into mudstone to the north, so that the top of the halite climbs up the stratigraphic section toward the south. Anhydrite beds extend further to the north than the halite, but they also pinch out. The two Alibates anhydrite beds can be traced across the area with little change in thickness.

Thickness changes below bed 50 are interpreted as the result of depositional effects related to slower Permian subsidence, and, therefore, creation of less accommodation toward the depositional basin margin. Decreased accommodation did not result in formation of more mudstone-halite, indicating that variation in the depositional environment was subtle. In fact, salt quality in the area of less accommodation may be superior for some salt-cavern designs because anhydrite beds are thinner and less abundant in the area of thinner salt section.

Thickness changes observed above bed 50 could be interpreted several ways: (1) as the result of salt nondeposition, (2) as base-of-cycle dissolution, or (3) as regional dissolution. Current depth of salt >1,900 ft below surface suggests that modern dissolution is not a likely process. Observed map distribution of the salt beds corresponds closely to Midland Basin structure. I tentatively propose that the observed thickness changes correspond to a change in depositional style during the final stages of Salado deposition in which salt deposition was focused in the topographically low areas in the basin center. Evidence to support this is the unusually clean profile (low gamma-ray-log profile) of these upper salt beds, which suggests a change to rapid episodic salt deposition in isolated depocenters. Additional fabric and geochemical evidence is needed to support this interpretation. Any thin salt beds deposited toward the basin margin could then have been removed by base-of-cycle dissolution, or by dissolution under burial conditions prior to Alibates deposition, at the end of the Permian, or during the Mesozoic.

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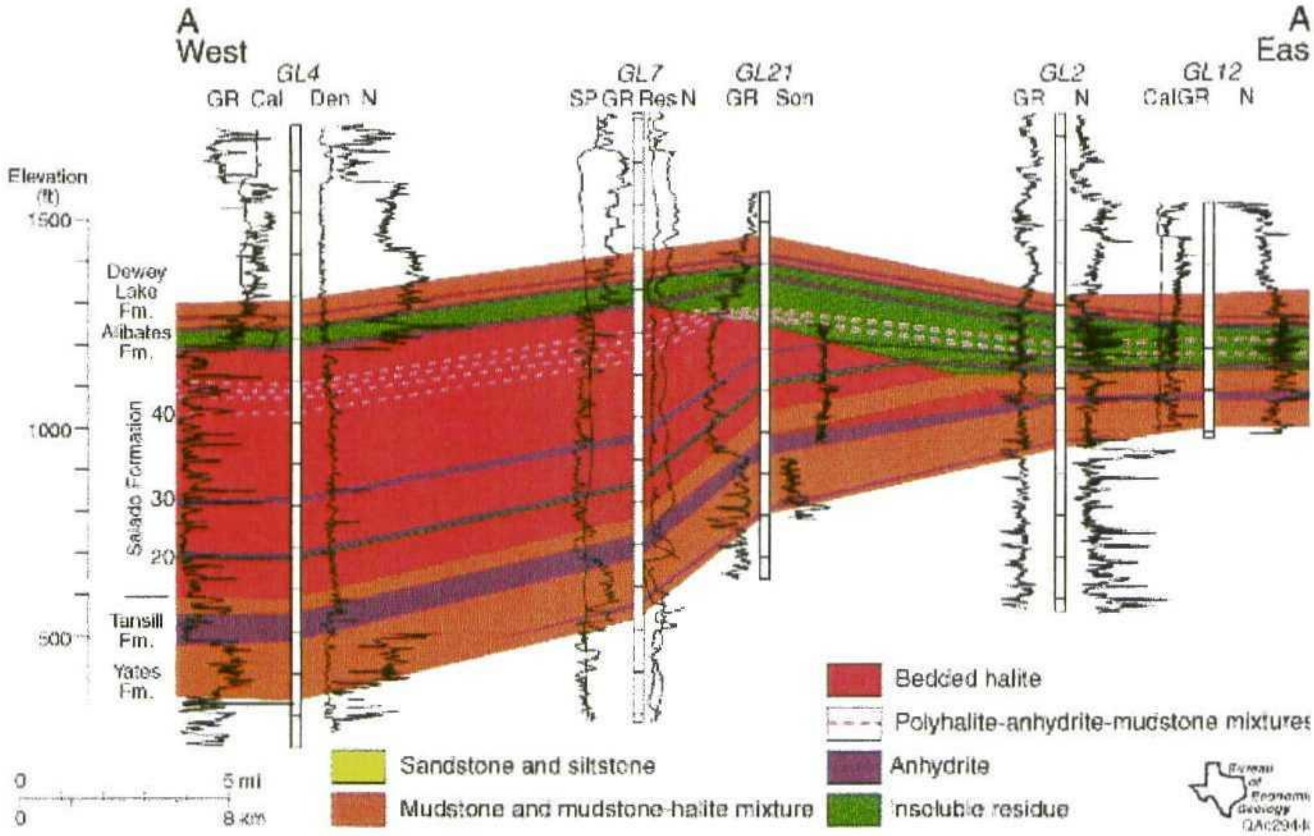
Case Study 2: Post-Permian dissolution at a structural positive on the Eastern Basin Margin

Case Study 2: Post-Permian Dissolution at a Structural Positive on the Eastern Basin Margin



East-west structural cross section near the east edge of the Midland Basin showing salt-character changes controlled by post-Permian dissolution overprinted on Permian facies changes. Cross-section location is shown on study area index map.

Regionally, the salt and salt-bearing interval thins toward the east edge of the Midland Basin. This east-west structural cross section across the Howard-Glasscock high shows salt character changes in this area. Structure on top Yates shows that the gentle west-dipping basin structure is complicated in this area by a well-defined east-west striking uplift along the Howard-Glasscock county line. South of this uplift, irregularities on the Yates surface suggest a complex structure at depth, interpreted to be a graben.

The Salado salt-bearing interval progressively thins from 580 ft offstructure at the west end of the cross section, to no salt at the east end. Structure on the Alibates shows a reversal of dip from the regional trend and from the dip in the Yates in the area of no salt. This is the typical geometry produced by salt dissolution in the burial environment. Anhydrite and polyhalite beds within the salt-bearing interval can be traced into the insoluble residue. Closer inspection shows that the burial dissolution crosscuts a Permian trend toward thinner units, most clearly seen in the lower Tansill carbonate-anhydrite unit. The lower Tansill thins from 65 ft offstructure to 15 ft on the east end of the cross section. The salt-bearing interval also thins by 100 ft between the two westernmost wells, and relationships between the top salt and correlated horizons within the salt show that this is not the result of dissolution of the uppermost salt but of incremental thinning of each unit, a pattern similar to that seen toward the north basin margin in case study 1. The siliciclastic unit in the upper Tansill shows a reverse trend, becoming thicker on the structural high. This is partly an effect of merging insoluble residue with mudstone beds, but may also include an effect of increased mudstone thickness toward the paleo-high, reflecting more exposure in an area of decreased accommodation. A calculation to approximate the amount of residue expected from dissolution of 580 ft of salt from GL4, at typical regional values of 75 percent salt and 25 percent insoluble, yields a residue thickness of 145 ft. The measured thickness of residue between markers in the easternmost well GL 12 equivalent to the 580 ft of salt section in the GL 4 well is only about 100 ft, further supporting an interpretation of a depositional thinning trend that parallels and is accentuated by burial dissolution.

Post-Permian dissolution overprints on Permian facies changes are common in the Midland Basin. Where this relationship exists, it indicates that the post-Permian uplift responsible for exposing the salt to a near-surface setting where it underwent dissolution has reactivated the structures that caused reduced subsidence during the Permian. Post-Permian dissolution overprints on Permian facies changes were seen throughout the eastern shelf beneath the Rolling Plains and on the Ozona Platform beneath west Edwards Plateau.

The area of dissolution and subsidence south of the Howard-Glasscock high lies at depths of 1,500 ft below land surface, which makes it one of the deepest areas of salt dissolution seen in the study area. Surface geology at a 1:250,000 scale (Eifler and others, 1994) shows relatively flat-lying Cretaceous strata at the surface above the salt-dissolution area, suggesting that most of the salt dissolution in this area preceded the deposition of Cretaceous units. This timing might also indicate that dissolution took place under shallower burial conditions than presently exist. Complex Pleistocene deposits in this area may be indicators of post-Cretaceous salt dissolution in this area but further localized study is needed to confirm salt dissolution in this area. Deformation of Cretaceous strata can be seen in exposures at the spring in Big Spring, Howard County.

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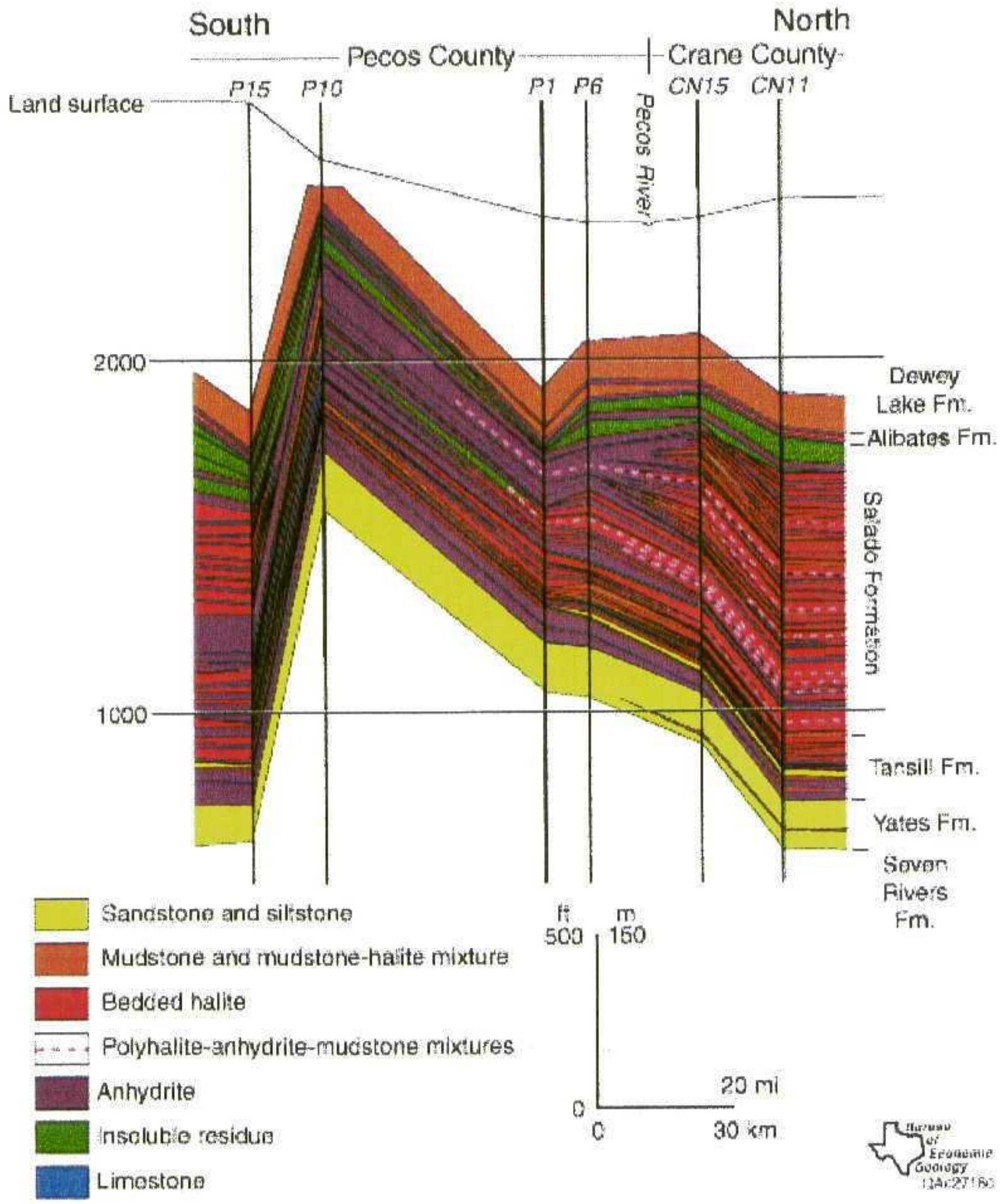
Case Study 3: Post-Permian dissolution over the Central Basin Platform in the Pecos Valley area

Case Study 3: Post-Permian Dissolution over the Central Basin Platform in the Pecos Valley Area



Detail of east-west stratigraphic cross section near the east edge of the Midland Basin showing salt-character changes controlled by post-Permian dissolution over the Capitan Reef tend. Cross-section location is shown on study area index map.

Part of the north-south stratigraphic cross section across the Pecos Valley and uplifted southern Central Basin Platform was selected in an area at the west end of the uplifted area where some salt is preserved and several useful caliper logs are available. Multiple changes in salt quality are noted on this structural cross section of this area. Salt has been completely dissolved on the crest of the structure at Pecos County well 10. Salt has been dissolved to depths between 700 and 800 ft beneath the Pecos valley alluvium, and here it forms a depression in the top Alibates structure on top of the more regional structural positive. Where salt occurs at greater depths away from the uplift, less salt has been dissolved.

Anhydrite beds thicken across the Central Basin Platform, probably in response to increased water depth and better circulation during deposition in this area of slightly greater subsidence. Thicker anhydrite beds begin at about the same place that dissolution cuts deeply into the section, compounding the problem of determining how much salt has been dissolved. Measured salt thickness in the interval where salt is preserved documents the relatively low percent salt, which is between 46 and 64 percent in the percent salt map. Although percent salt could potentially be in error because of the salt dissolution, inspection of the logs and cross section supports the conclusion that the percent salt decrease is because of increased anhydrite bed thickness. Potential but discounted sources of error are: (1) sampling effects because a different stratigraphic interval is included in each calculation as the top salt varies stratigraphically across the dissolution zone, and (2) some effects of dissolution, if some salt has been removed interstratally within the salt section. Predictions of residue thickness based on stratigraphy of adjacent areas where salt is preserved yielded values similar to those observed. For example, Pecos 1 contains 215 ft of residue stratigraphically equivalent to 620 ft of salt section in Crane 11; this reduction could occur in a section containing 65 percent salt.

Interpretation of this cross section is complemented by maps and cross sections from the Yates Field area (Wessel, 1988a) that show structure of the Cretaceous in outcrop. In the Yates area, at the east end of the south part of the Central Basin Platform, the Cretaceous strata have been deformed on the north side of the structure in the Pecos Valley, but have not been deformed across the top of the structure or on the south side. This supports the conclusions of Adams (1940), based on stratigraphic interpretation, that salt dissolution across much of the structure was pre-Cretaceous. Cenozoic and potentially ongoing dissolution has occurred in the Pecos Valley. This is a common model for understanding salt dissolution; active dissolution may be found on the flanks of the structure where initial dissolution removed accessible salt from the crest of the structure. The surface mapping by Wessel (1988a) also emphasizes the role of faults and fractures formed by salt dissolution in focusing further dissolution.

This relationship between the structural high, topographic low, and area of salt dissolution is similar to the relationship 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 that overlie preserved salt (Gustavson and Simpkins, 1989).

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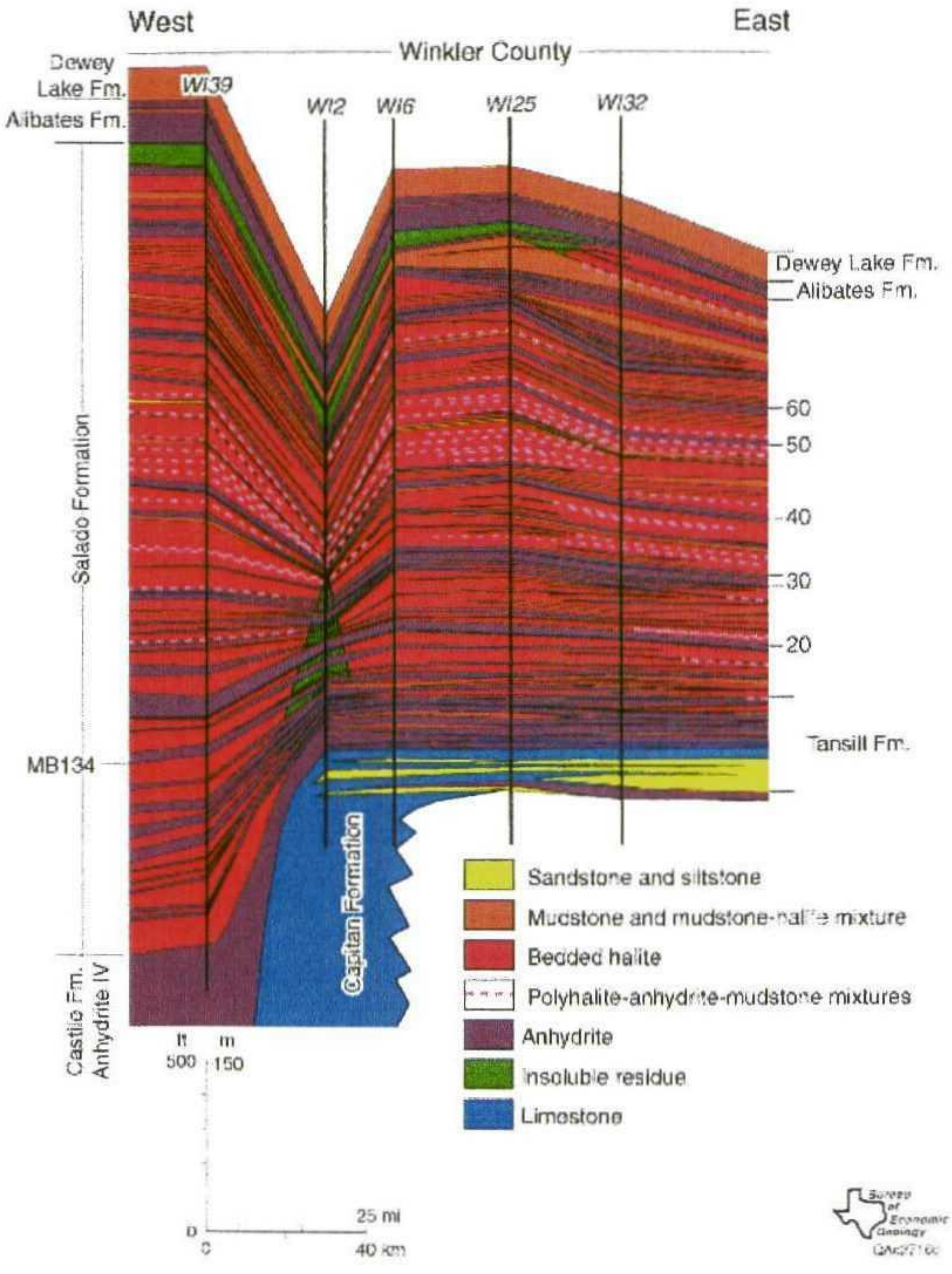
Case Study 4: Post-Permian dissolution over the Capitan Reef

Case Study 4: Post-Permian Dissolution over the Capitan Reef



Detail of east-west stratigraphic cross section near the east edge of the Midland Basin showing salt-character changes controlled by post-Permian dissolution over the Capitan Reef trend. Cross-section location is shown on study area index map.

The salt-dissolution feature in Ward and Winkler Counties is another significant variation from those described in cases 1, 2, and 3. A depression of as much as 1,500 feet in the top Alibates structure is filled with post-Permian sediments to depths of as much as 2,000 ft below land surface. Net salt thins from 600 ft on the Central Basin Platform to a measured minimum of 128 ft in the depression. Net salt thickens again west of the depression to 1,000 ft.

Cross-section relationships show that: (1) the thin in the salt is the result of dissolution, not facies changes, and (2) salt has locally been dissolved from the bottom of the salt as well as from the top. The facies changes in this area are readily understood in the context of case 1 and case 3. Anhydrite beds start to thicken across the Central Basin Platform in western Ector County, east of the dissolution feature. Although individual bed correlations are tentative through the area of salt dissolution, caliper log character shows that salt is missing from the base of the Salado above a thick Tansill siliciclastic and anhydrite section. The salt-dissolution interval is condensed relative to adjacent areas, although some of the halite is represented by siliciclastic insoluble residue between anhydrite beds.

The Ward-Winkler salt-dissolution area lies along the trend of the Capitan Reef. Hiss (1975b, 1976, 1980) has proposed a genetic relationship based on a model where fresh ground water, moving through the highly transmissive Capitan aquifer from the Glass Mountains recharge area, has moved up through fractures into the salt. The Ward-Winkler salt dissolution is part of a larger system of depressions on the Alibates that follow the Capitan Reef trend into New Mexico toward its outcrop in the Guadalupe Mountains (Hiss, 1976). The geometry on top of the Guadalupian strata (top Yates, Capitan, and Bell Canyon) shows that beneath the dissolution area these units are dipping steeply to the west. Although the Capitan Reef or back reef may have been a relatively positive feature during deposition, Late Permian and post-Permian deformation has warped the western reef edge downward, relative to the platform. The present structural high on both the top Yates and the top Alibates maps and lies east of the main Capitan Reef (Hiss, 1975a) and east of the salt-dissolution zone. Therefore, the style of dissolution contrasts with that observed in case 3 on the southern Central Basin Platform, where dissolution was focused on the crest as well as the flanks of the structural uplift. The observations made in this study support the aquifer dissolution model of Hiss (1976).

The Ward-Winkler salt-dissolution feature is not related to a surface depression. The relationship between this feature and past drainage has been explored by Bachman (1984) and Hiss (1976). The timing of dissolution is not well constrained. Historic subsidence and recent formation of the collapse feature at the Wink Sink (Baumgardner and others, 1982; Johnson, 1987) on the east edge of the paleodissolution feature indicates that salt dissolution may be ongoing in this area.

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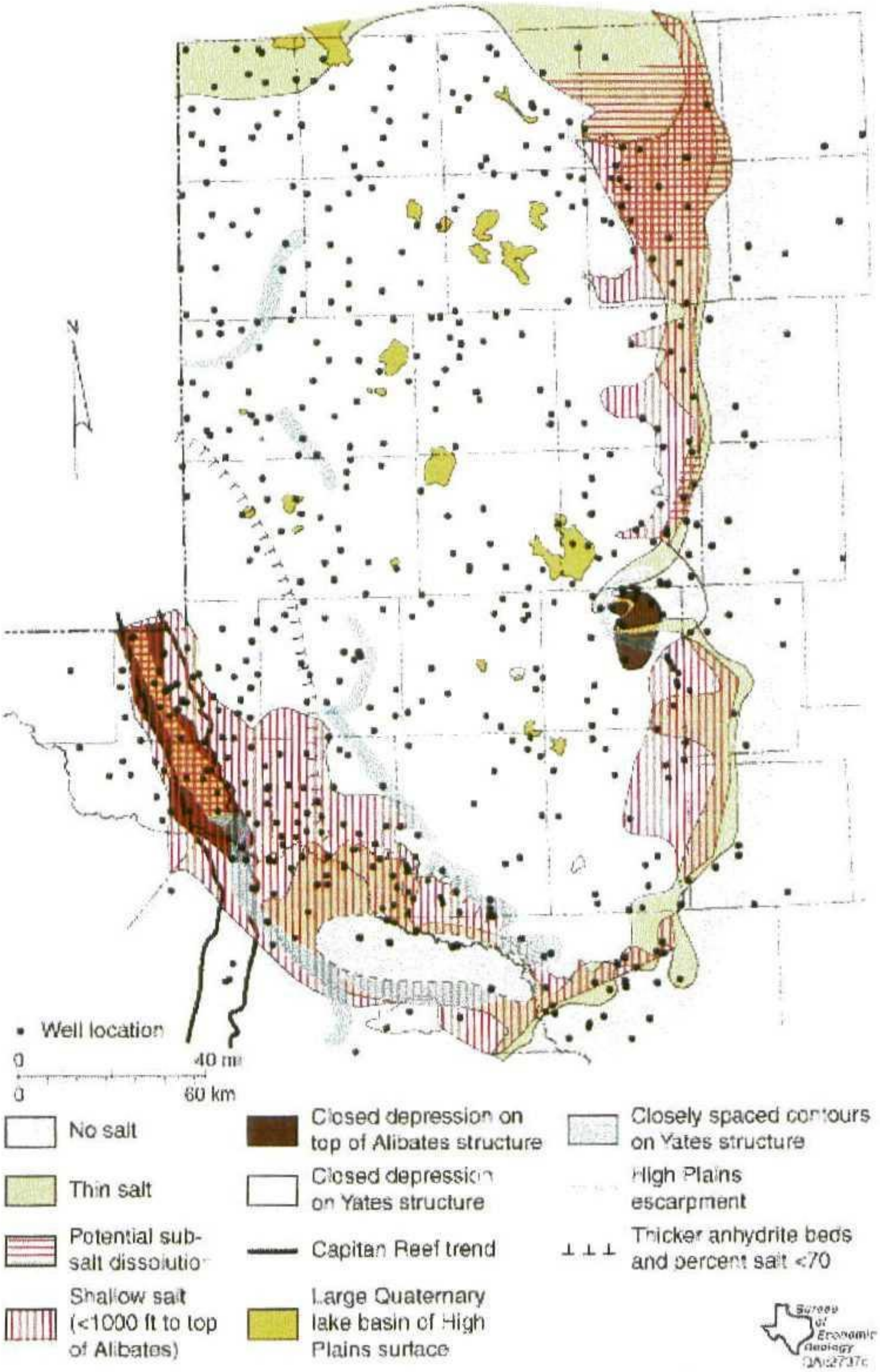
Methods for site evaluation

Methods for Site Evaluation



Areas where changes in salt-thickness, salt-quality, or salt-dissolution trends are noted or potentially exist.

Geologic data can be applied to engineering needs, risk reduction, and assessing the future stability of the salt during site evaluation for solution-mined caverns. Geologic data include salt-bed thickness, salt quality, the type of salt dissolution, and the distribution of associated non-salt beds that may be of interest as horizons in which to set seals or as potential permeable beds to be avoided.

Regional trends and facies relationships are the basic tools to assess salt-bed thickness and quality. Facies models of the Permian depositional environment (Fracasso and Hovorka, 1986; Hovorka, 1994) suggest that salt beds have high continuity over the region. Mapping high-frequency cycles over the Midland Basin study area supports this model and provides confidence that experiences with salt quality in one part of the Midland Basin are likely to be reproduced in other areas. Measurement of individual salt-bed and interbedded non-salt units shows horizontal continuity of strata over wide areas and relatively minor variation in maximum salt-bed thickness and impurity content. Average net salt and percent salt show gradual regional variations from >75 percent salt in updip areas, where net-salt thickness is <400 ft, to <70 percent salt in areas where net salt is >600 ft. Throughout the study area, salt is interbedded with non-salt. Mudstone interbeds more than a few feet thick occur at intervals of 10 to 30 ft. Anhydrite beds 2 to 30 ft thick occur regularly through the salt at spacing of 50 to 150 ft. Some of the thickest and most pure salt beds are found near the top of the Salado Formation along the Midland Basin axis. These units, however, show the most complex facies relationships of any unit examined in the study. The complexity observed at a regional scale suggests that there may be variation over short distances in the character and thickness of the upper salt units. If these beds are a significant component of the engineering design for the cavern, I suggest that site-specific data be acquired to address the heterogeneity of these units.

The observations made in this study support the validity of the common practice of assessing a solution-mined site based on examining logs of wells in the area. The exception to this rule is areas where complex facies variations are expected. In this study, most of the areas where complex facies variations are expected generally overlap areas where there is risk of salt dissolution described in the following paragraphs and shown in this figure. The east and north margins of the Midland Basin are areas of depositional salt thinning. Across the Central Basin Platform, facies changes to more abundant and thicker anhydrite beds are observed, and the effect of these relatively high-strength, low-solubility units on salt-cavern design should be assessed. The area of most abrupt lateral changes corresponds approximately to the structural platform edge.

Salt dissolution may create risk factors to be assessed in salt-cavern design for three reasons. (1) Dissolution can cause the salt to thin over a short distance laterally into water-bearing, mechanically weak insoluble residue. The geometry of the salt-dissolution edge may be complex and difficult to map because of hidden hydrologic controls and the potential of feedback mechanisms to focus dissolution where previous dissolution has created fractures and breccia. (2) Drilling and other invasive activities have the potential to create fractures and conduits that might focus future dissolution around the facility. Therefore, in an area of active dissolution, a thick, preserved salt section might have a risk of developing engineering problems. (3) In an area of salt dissolution, there is increased risk that some beds within the salt, particularly carbonates and sandstones, may have had halite cement dissolved and, as a result, allow leakage from the caverns. Overlying beds such as the Alibates, that are commonly used for setting casing and seals, may also be of variable quality in areas of salt dissolution because of fracture permeability and hydration of anhydrite to gypsum.

The reality of these risk factors has not been tested in this study. I show the areas of interpreted salt dissolution and recommend that the potential risks associated with past or ongoing salt dissolution be assessed for sites developed near those areas. Other factors that might create potential for dissolution are also shown. High elevation contrast may create hydrologic gradients and favor active dissolution. Areas of focused structural deformation having the potential to create fractures are also mapped, although they have no correspondence to thin salt at the regional scale mapped. Large saline lakes and Pleistocene lake deposits are also shown because of the unassessed potential risk that salt dissolution may have played a role in basin formation.

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Conclusions

Conclusions

This report compiles basic descriptive information about the geometry of salt in the Midland Basin as well as guidance for site-specific evaluation of salt quality and geometry in the context of use of this salt for solution-mined caverns. Thick and laterally homogeneous bedded salt is found in the Salado Formation beneath a 31-county area including the Midland Basin, Central Basin Platform, and associated areas. Regional and local variation in salt thickness, percent salt, structure on the top and bottom of the salt, and depth to salt are mapped throughout this region.

The geometry of salt is the product of interaction between depositional trends and postdepositional dissolution; reference to these two controls are used to aide both in describing the salt geometry and as a mechanism for interpreting relationships. Depositional geometry of the Salado Formation was fairly simple, with a gentle westward thickening from areas of little or no accumulation on the east to a maximum thickness in the Delaware Basin. The salt is divided into high-frequency genetic cycles composed of a basal anhydrite, overlain by halite, muddy halite, and mudstone. Many incomplete cycles containing only the halite, muddy halite, and mudstone facies are recognized within the master cycles defined by anhydrite beds at the base. Examination of the high-frequency cycles defining the stratigraphy within the Salado Formation shows that the observed westward thickening is an effect of greater accommodation (greater relative subsidence) during salt deposition, so that each individual salt bed thickens toward the west. The cycles in the upper part of the Salado Formation show a change from this pattern in that they are thickest along the present Midland Basin axis, contain thick but laterally discontinuous beds, and pinch out into mudstone toward the edges of the Midland Basin.

Depositional geometry of the salt has been modified by several episodes of postdepositional dissolution. The first postdepositional dissolution events probably occurred in terrestrial environments that preceded and followed Alibates deposition. A significant episode of dissolution occurred after significant warping of the Permian strata but prior to Cretaceous deposition. Dissolution occurred during the Cenozoic and continues today.

Substantial thicknesses of salt have been dissolved along the east margin of the basin, along the Central Basin Platform in the Pecos Valley, and over the Capitan Reef margin in Ward and Winkler Counties. Minimum postdepositional dissolution is seen in areas where the salt lies at depth below the most active near-surface hydrologic regime, typically at depths of more than 1,000 ft in the structural basin.

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 present-day structure on the top of the Alibates Formation/Rustler anhydrite follows the long-lived structural pattern of the basin, so that positive areas during deposition have been uplifted more strongly than basinal areas. Postdepositional warping has therefore exposed thin marginal salt to more intense dissolution by placing it at higher elevations than basinal salts.

A change from this pattern is noted where salt has been dissolved in the Winkler-Ward County area. The general trend of thickening of the salt-bearing unit across the Central Basin Platform suggests that this area was subsiding during Salado deposition and is an area of subsidence west of the Central Basin Platform structural positive. In this area, a hydrologic model where salt dissolution is related to interstratal dissolution above the highly transmissive Capitan aquifer is accepted.

Modern landforms are overprinted on the structural elements. Areas where salt is present at shallow depths may influence landform development because salt has been dissolved, creating low areas, and overlying strata have collapsed, been brecciated, and are therefore easily eroded. The Pecos Valley generally overlies an area of salt dissolution on the south end of the Central Basin Platform. In this area, salt was probably relatively thick during deposition but has been removed over the uplift and at the hydrologically active areas along the valley.

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Acknowledgments

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8/31/99 MEETING

B-QUICK CLASS I APPLICATION

MR QUICK, B ALLEN -
W PRICE, M KEELING, R.C. ANDERSON

OPEN - PROCESS PERMITTING -

If PROTEST - HEARING
THEN WQCC "

- DP + POSSIBLE 711 PERMIT -
- copies 2 - SF 1 - CC DISTRICT
- ML WRONG PN - ? (GW Issues) (Public notice NEED INFO)
- gas storage wells
- control of area
- Each well operation -
- If statement - must have logs before!! + cavity configuration
- 30 year lease - C-101 To SF + CC district!
- must have SONAR before permit approved!
- Issues on Class I change To class II ⇒ class I
- Bonding well + surface issues
- (1) need detail operations + subsurface ENVR.
- NEED DETAIL INFO CONCLUSIONS & REC
- Item #3
- APPENDIX "B" wash-out pit close sect diagram - ?
  need detail drawing!!

#4 LANDOWNER within ONE-MILE - ? NEED!
LEASE OWNERS " " - ?

5. DETAILS — not sufficient

6. TYPE of WASTE - soil, mud, etc?
PAPER-WORK! MANIFEST! - C-138 - ? process
GEN CERTIFICATE! WASTE DETERMINATION!

7. modify 1 1/3 [illegible]!

A(2) - WASHOUT pit! H_2S MONITORING

A(4) see process APPENDIX

B(1) - inspect + records — 5 years
B(2)
B(3) ground water - ? well remove

(C) need process & disposal procedures!
No other waste?

F(2) need three!! annual / full WQCC

F(7) add LINER perimeter bermed fenced!
[illegible] - ? fence:

F(5)(a) closure plan!!

page (3)

8

A(1) 2 SF 1 - Fast

A(2) Bond prior to Re-enter $5000 plug Bond

Closure Bond?

100% pres to operator!

A(3) C-101 need

A(5) Appendix "C" — Evaluate Each well!!
schematic & TABLE!
one-mile area of Review!

A(6) wells (oil) + water wells
Hydrogeology & quality!

A(7) check!!

A(8) app E Site Inspection

8 B(1) EMERGENCY PHONE #

8 B(2) SIGN!

B(3)

C(1)(a)

C(1)(d) must be prior!
(e) " " "
(f) " " "

C(1)(h) cavern LPG — demonstrate No-Interaction
Horz Limits (Sub-surface) — 10,000 years
communication?
C(1) J — cross-section area!
sell Brine? (Roof cavern-overburden collapse calculation!)

(c)(1)(K) - need to address -

C(1)(L) - (Prove & Log) cement Bond Log's

(c)(1)(m) OCD must be on site!!
OCD will need REQ'S — MIT'S
(c)(1)(n) Need max Inj pressure!
(c)(1)(n) - Before permit - Approval
C(1)(o) need method!

(c)(1)(p) DELETE (TCLP) - need GEN chem!

(c)(1)(q) OK

(c)(1)(r) MUTE!

(c)(1)(s) VALID only in (2) well system

+ pressured to 100 psi + MONITORING!

(c)(1)(t) record life of well (+5)

(c)(1)(u) fenced + locked!

(c)(1)(v) - (INJ + FLOW rate recording)

(c)(1)(w) - If ?? (Both)

(c)(1)(x) OCD REG NOT APPROPRIATE!

Produced water issue! where does it go!

(c)(1)(y) OK

(c)(1)(z) - + ANNULAR pressure of 2-well (c)(1) aa continuous monitoring —

(c)(1)(bb) need (3)? if required! ground water

shall gave MW?

demonstrate no deep Ground water!

(c)(1) cc contingency plan!

SX - HCA must have closure plan! + cost est!

9(A) contingency plan shall be submitted!

10(A) > Appendix F must site specific!

10.(B) need all information on June 11, 1998

B. QUICK, Inc.
9535 Forest Lane • Suite #123 • Dallas, Texas 75243
Office: (972) 644-4259 • FAX: (972) 669-3911

March 24, 1999

Mr Mark Ashley
Oil Conservation Division
2040 South Pacheco Street
Santa Fe, New Mexico 87505

Re: Class I Exempt Non-Hazardous Disposal Well Permit

Dear Mark,

I am writing to let you know that I have retained the services of Safety and Environmental Solutions, Inc of 703 East Clinton, Suite 103, Hobbs, NM 88241. After careful consideration I have selected this company because of their expertise in the field and their proximity to the location. They are gathering and will submit the additional information you require for the securing of the Class I Exempt Non-Hazardous Salt Cavern Disposal Well Permit for which I have made application to OCD for several sites near Monument, NM.

I am confident that salt cavern disposal of oil field waste is the most environmentally responsible option available. It should also have a positive economic impact on the petroleum industry's cost of waste disposal.

The information you requested will be forthcoming shortly. I am enclosing my business card, please feel free to contact me or Mr Bob Allen of Safety and Environmental Solutions at 505-397-0510 if you have any questions.

Thank you in advance for your efforts to expedite the permitting of these caverns.

Regards,

Bill Quick

Bill Quick

Cc: Bob Allen

OGRID 19942

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 6
1445 ROSS AVENUE, SUITE 1200
DALLAS, TX 75202-2733

RECEIVED
NOV 2 1998
OIL CONSERVATION

October, 30, 1998

Mr. Bill Quick
3340 Quail View Dr.
Nashville, Tennessee 37214

Dear Mr. Quick:

Enclosed, per our telephone conversation on Thursday, October 29, is a copy of an Environmental Protection Agency publication used extensively to determine a waste steam's eligibility for injection into Class II wells. As I stated in our call, the State of New Mexico administers the underground injection control program and as such, they will have the best perspective as to what type of injection well permit you should apply for. If they encourage you to apply for a Class I permit, they should have justifications that they could provide you for that recommendation.

Sincerely yours,

Ray Leissner

Ray Leissner
Underground Injection Control
Region 6, EPA

cc w/o encl. : Mr. David Catanach, NMOCD
Mr. Roger Anderson, NMOCD

B. QUICK, Inc.

9535 Forest Lane • Suite #123 • Dallas, Texas 75243
Office: (972) 644-4259 • FAX: (972) 669-3911

October 26, 1998

c: Roger ✓
Mark ✓
Wayne ✓

Ms Lorrie Wrotenbery
Director New Mexico OCD
2040 South Pacheco
Santa Fe, New Mexico 87505

Dear Lorrie,

Thank you for the time you allowed me at the International Petroleum Conference in Albuquerque reviewing my pending application for a Waste Disposal Permit. As you may recall I have four salt caverns in Lea County with a combined capacity of 3 Million barrels.

I am confidant that the utilization of salt caverns in the Permian Basin is the most efficient and the most environmentally responsible method of waste disposal. If this property is permitted as a Class I Exempt Waste Site, it should provide substantial savings to the Petroleum Industry over the alternative of shipping waste a long distance.

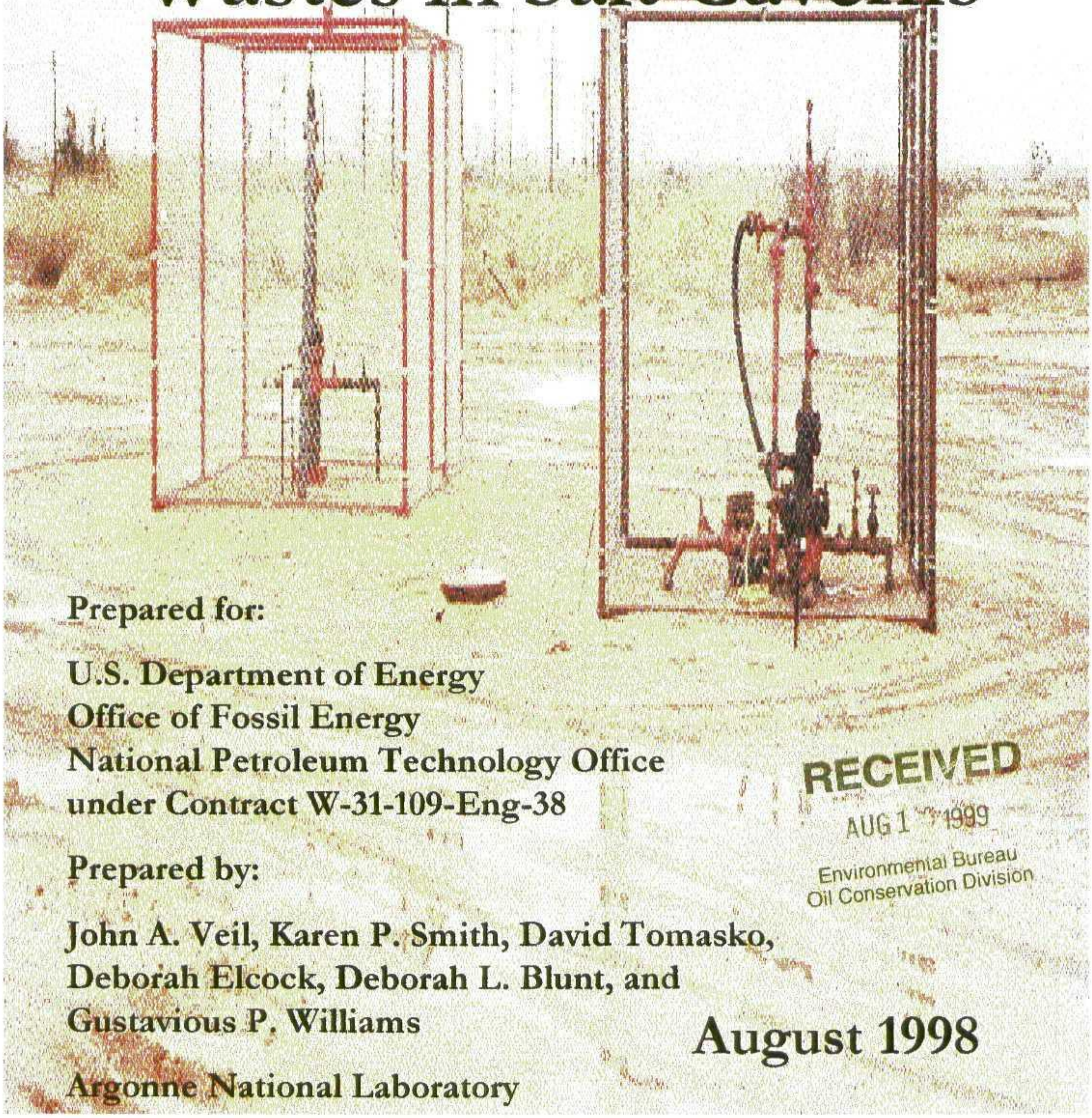
My plans are to agressively persue this project. Should I need to submit any further information or if there is anything else I need to do, please let me know. I am currently working out of my Nashville office at 3340 Quail View Drive, Nashville, TN 37214. My phone is 615-874-1077.

Thank you again for your help.

Regards,

Bill Quick

Disposal of NORM-Contaminated Oil Field Wastes in Salt Caverns



Prepared for:

U.S. Department of Energy
Office of Fossil Energy
National Petroleum Technology Office
under Contract W-31-109-Eng-38

Prepared by:

John A. Veil, Karen P. Smith, David Tomasko,
Deborah Elcock, Deborah L. Blunt, and
Gustavious P. Williams

Argonne National Laboratory

August 1998

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Acronyms and Abbreviations

API	American Petroleum Institute
CEDE	committed effective dose equivalent
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CSA	Canadian Standards Association
DCF	dose conversion factor
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ESR	Early Storage Reserve
GCC RASA	Gulf Coast Regional Aquifer-System Analysis
ICRP	International Commission on Radiological Protection
IOGCC	Interstate Oil and Gas Compact Commission
LAC	Louisiana Administrative Code
LDEQ	Louisiana Department of Environmental Quality
LDNR	Louisiana Department of Natural Resources
LPG	liquified petroleum gas
MCL	maximum contaminant levels
MDEQ	Michigan Department of Environmental Quality
NMAC	New Mexico Administrative Code
NMED	New Mexico Environment Department
NORM	naturally occurring radioactive materials
NOW	nonhazardous oil field wastes
NRC	U.S. Nuclear Regulatory Commission
OCC	Oklahoma Corporation Commission
OCD	Oil Conservation Division
RCRA	Resource Conservation and Recovery Act
RMLLRWB	Rocky Mountain Low-Level Radioactive Waste Board
SDWA	Safe Drinking Water Act
SPR	Strategic Petroleum Reserve
TAC	Texas Administrative Code
TRC	Texas Railroad Commission
UIC	Underground Injection Control
WIPP	Waste Isolation Pilot Plant

**Disposal of NORM-Contaminated
Oil Field Wastes in Salt Caverns**

John A. Veil, Karen P. Smith, David Tomasko, Deborah Elcock,
Deborah L. Blunt, and Gustavious P. Williams

Executive Summary

Salt caverns have been used for several decades to store various hydrocarbon products. In the past few years, four facilities in the United States have been permitted to dispose of nonhazardous oil field wastes (NOW) in salt caverns. Several other disposal caverns have been permitted in Canada and in Europe for similar wastes. To date, caverns have not been used to dispose of oil field wastes that have been contaminated with naturally occurring radioactive materials (NORM). There are only a few approved methods for disposing of NORM wastes and only a handful of commercial disposal facilities that are licensed to accept NORM waste. This report evaluates the feasibility, legality, economics, and human health risk of disposing of NORM-contaminated oil field wastes in salt caverns.

Oil and gas production and processing operations sometimes accumulate NORM at elevated concentrations in by-product waste streams. The sources of most of the radioactivity are isotopes of uranium-238 (U-238) and thorium-232 (Th-232), which are naturally present in subsurface formations from which oil and gas are produced. The primary radionuclides of concern in NORM wastes are radium-226 (Ra-226) of the U-238 decay series and radium-228 (Ra-228) of the Th-232 decay series. Other radionuclides of concern include radionuclides that form from the decay of Ra-226 and Ra-228, such as radon-222 (Rn-222). The production waste streams most likely to be contaminated by elevated radium concentrations include produced water, scale, and sludge. Spills or intentional releases of these wastes to the ground can result in NORM-contaminated soils that must also be disposed of.

Currently, no federal regulations specifically address handling and disposal of NORM wastes. In the absence of federal regulations, individual states have taken responsibility for developing their own regulatory programs. These programs have been evolving rapidly over the last few years. The existing state regulatory programs establish requirements for (1) NORM exemption standards or action levels; (2) licensing of parties possessing, handling, or disposing of NORM waste; (3) the release of NORM-contaminated equipment and land; (4) worker protection; and (5) NORM waste disposal. This study evaluates the potential for salt cavern disposal of NORM waste in five states that have existing or proposed NORM disposal regulations and that have expressed serious interest in disposal of NOW in salt caverns. These states are Louisiana, Mississippi, New Mexico, Oklahoma, and Texas. Each of these state programs addresses the disposal of NORM waste into Class II injection wells, either directly or indirectly.

The regulation of underground injection of NORM waste is relevant to the potential disposal of NORM waste in salt caverns, because disposal into salt caverns is considered by most states to equate to underground injection into Class II wells. A review of federal regulations and regulations from the five states listed above indicated that there are no outright prohibitions against NORM disposal in salt caverns or other Class II wells, except for Louisiana, which prohibits disposal of radioactive wastes or other radioactive materials in salt domes. Presently, however, only Texas and New Mexico are working on disposal cavern regulations, and no states have issued permits to allow cavern disposal of NORM waste.

Most NORM-contaminated produced water is disposed on-site through injection wells and is not the primary focus of this report. Other types of NORM waste are presently disposed of both on oil production sites and at off-site commercial disposal facilities. A majority of these NORM wastes are disposed of through underground injection, a significant portion of which presently takes place at a commercial injection facility located in eastern Texas. Several companies offer the service of coming to an operator's site, grinding the NORM waste into a fine particle size, slurrying the waste, and injecting it into the operator's own disposal well. One company is developing a process in which the radionuclides are dissolved out of the NORM wastes, thereby leaving NOW and a contaminated liquid stream that is injected into the operator's own injection well. Smaller quantities of NORM are disposed of through burial in landfills, encapsulation inside the casing of wells that are being plugged and abandoned, or land spreading.

It appears that disposal of NORM waste in salt caverns is technically feasible because the NORM waste is physically and chemically similar to NOW, which is already being disposed of in salt caverns. Its primary difference from NOW is the presence of radionuclides in NORM. The presence of radionuclides may require additional safety precautions when handling the NORM waste, but the actual disposal would be no different from NOW.

It is difficult to quantify the total cost for disposing of NORM waste. The cost components that must be considered, in addition to the actual disposal cost, include analytical costs, transportation costs, container decontamination costs, and possibly permitting costs. One other cost component that cannot readily be quantified, but is important nonetheless, is the potential for long-term liability if the disposal site eventually causes environmental contamination and is subject to a Superfund cleanup. Current NORM waste disposal costs range from $15/bbl to $420/bbl. The costs presented in this study reflect the information provided by disposal companies to the authors in early 1998 and may not reflect actual total disposal costs. It is also difficult to compare cost figures from one disposal company with those of another company because the companies do not always include the same types of services in their quoted prices.

Operators of the four permitted disposal caverns in Texas were contacted to see if they had made any estimates of what they might charge customers if they were authorized to accept NORM wastes. They currently charge from $1.95/bbl to $6/bbl to dispose of NOW wastes. To be authorized to dispose of NORM wastes, cavern operators would need to upgrade their aboveground waste handling facilities and analytical capabilities, among other things. Although none of the cavern operators had even preliminary cost estimates, one operator believed that he could realistically operate at costs below $150/bbl, the cost charged by the company receiving the majority of NORM waste in this country. He also noted that if regulatory agencies allow NORM disposal in caverns, competition would drive the price lower (Moore 1998). NOW disposal caverns have proven cost-competitive with other NOW disposal facilities in the same geographic area. This study does not constitute a formal market analysis, and the costs to upgrade a cavern disposal operation for NOW to one that disposes of NORM waste have not been quantified. Nevertheless, there is a reasonable chance that NORM waste disposal caverns would be able to compete economically with existing off-site commercial NORM disposal facilities once regulatory agencies allow the practice to occur.

Argonne National Laboratory (Argonne) has previously analyzed the potential radiological doses associated with several disposal methods, including underground injection into Class II disposal wells (Smith et al. 1996). Recently, Argonne completed an analysis of the potential human health risks resulting from exposure to contaminants released from the caverns in domal salt formations used for NOW disposal (Tomasko et al. 1997). The evaluation assumes normal operations but considers the possibility of leaks in cavern seals and cavern walls during the post-closure phase of operation. The current study builds on the previous Argonne work in NORM risk assessment and salt cavern disposal and follows the Tomasko et al. (1997) methodology to the extent possible. NORM waste contains the same chemical contaminants as NOW but also contains radionuclides. The risk from the chemical contaminants in NORM remains the same as the risk estimated for NOW (Tomasko et al. 1997). In this study, a separate radiological risk analysis was performed. Initially, several radionuclides were considered as potential contaminants of concern for the assessment. All but two of these were subsequently dropped from further consideration because of low predicted activities produced by a combination of their high retardation coefficients and short half-lives at a time of 1,000 years in the future, the time frame selected for the risk analyses. The remaining contaminants were Ra-226 and Rn-222.

The release scenarios considered in both the NOW analysis and this study included inadvertent intrusion by unintentionally drilling a well into a closed cavern; failure of the cavern seal because of increased pressure from salt creep and geothermal heating; release of contaminated fluid through cracks, leaky interbeds, or nonhomogeneous zones composed of higher permeability material; and partial cavern roof fall. Most releases would be to deep aquifers at or near the top of the cavern, although under two scenarios, released contaminants could move upward through the well casing and leak into shallow aquifers. To be consistent with Tomasko et al. (1997), the probability of cavern failure was based on "best-estimate" and "worst-case" estimates provided by a panel of experts. Averaged best-estimates for the different scenarios ranged from 0.006 for partial roof fall plus cavern seal failure and fluid release at shallow depth to 0.1 for partial roof fall plus fluid release at depth. Averaged worst-case estimates ranged from 0.04 for seal failure with fluid release at shallow depth, to 0.29 for partial roof fall plus fluid release at depth. To provide an even more conservative estimate, we used the true worst-case condition — the 100% Probability of Release case — under which all caverns release fluids during the 1,000-year period of concern.

Once contaminated fluids leave the cavern, they are expected to migrate laterally through different formations and aquifers. During the time the fluids travel from the point of release to the receptor site (assumed to be 1,000 ft laterally from the cavern at either the depth of the cavern [1,000 ft] or a shallow depth [50 ft]), various physical, chemical, biological, and radiological processes occur that reduce the concentration of the contaminants. Fate and transport modeling was used to estimate the contaminant concentrations at the receptor point (exposure point concentrations).

Risk calculations were then conducted on the basis of the exposure point concentrations and standard assumptions regarding drinking water intake rates, exposure time, duration, and frequency. The risk was estimated for persons who, during the next 1,000 years, drink groundwater taken from a well at the receptor site. The estimated worst-case cancer risks from the chemical contaminants of NORM waste are very low (1×10^{-8} to 2×10^{-17}), and even under the extremely conservative 100% Probability of Release case, the highest chemical contaminant risk is 2×10^{-7}. The excess cancer risks estimated for the radiological contaminants are orders of magnitude lower; even for the100% Probability of Release case, risks are 1×10^{-13} to 3×10^{-22}, and, consequently, are dwarfed by the risks from the chemical contaminants.

The risk calculations are intended to estimate the risk over the 1,000 years following cavern sealing. It is unlikely that an abandoned cavern would begin leaking immediately. Leakage, if it occurred, would most likely begin many years after the cavern was sealed. The fate and transport models, however, estimate the concentration of contaminants at a time 1,000 years after the release of contaminants, not after cavern sealing. Therefore, the risk estimates are effectively measuring the risk over a period of time longer than 1,000 years. This procedure provides an additional measure of conservatism to the risk estimates.

The size of the hypothetical cavern used in these risk calculations (one million ft^3) is, for the sake of consistency, the same as was used in Tomasko et al. (1997). The hypothetical cavern is somewhat smaller than the existing disposal caverns in Texas. The volume of fluid potentially released from the cavern is proportional to the volume of the cavern that is filled with fluid; therefore, larger caverns would release proportionately more fluid. Because actual cavern volumes are on the same order of magnitude as the hypothetical cavern, the fluid volumes released and the estimated risks from the actual caverns are expected to be on the same order of magnitude as those calculated here, which remain lower than accepted risk thresholds.

The use of the results of this report include a number of caveats. First, the assessment does not address risks to workers at the cavern disposal site. Smith et al. (1996) estimate radiation doses to workers involved in cleaning pipes, cleaning vessels, and working in storage yards where NORM-contaminated equipment is cleaned prior to NORM waste disposal. The risk to workers is likely to be the same regardless of the ultimate disposal method used. Second, the assessment does not determine whether any health effects will occur in the future; it only estimates cancer risk and potential for noncancer effects. Third, risks have only been estimated for contaminants for which toxicity values were available; just because there is no toxicity value does not mean there is no risk.

The approach used in this study is subject to several uncertainties that could affect the results. These uncertainties include an extrapolation from high levels to low levels of radiation exposure, the necessity to model exposure data because no cavern exposure data exist, and the difficulty in distinguishing background concentrations of radionuclides from introduced concentrations.

1. Introduction

In 1995, the U.S. Department of Energy (DOE), Office of Fossil Energy, asked Argonne National Laboratory (Argonne) to conduct a preliminary technical and legal evaluation of disposing of nonhazardous oil field waste (NOW) into salt caverns. That study concluded that disposal of NOW into salt caverns is feasible and legal. If caverns are sited and designed well, operated carefully, closed properly, and monitored routinely, they can be a suitable means of disposing of NOW (Veil et al. 1996). Considering these findings and the increased U.S. interest in using salt caverns for NOW disposal, the Office of Fossil Energy asked Argonne to conduct further research on the cost of cavern disposal compared with the cost of more traditional NOW disposal methods and on preliminary identification and investigation of the risks associated with such disposal. The cost study (Veil 1997) found that disposal costs at the four permitted disposal caverns in the United States were comparable to or lower than the costs of other disposal facilities in the same geographic area. The risk study (Tomasko et al. 1997) estimated that both cancer and noncancer human health risks from drinking water that had been contaminated by releases of cavern contents were significantly lower than the accepted risk thresholds.

Since 1992, DOE has funded Argonne to conduct a series of studies evaluating issues related to management and disposal of oil field wastes contaminated with naturally occurring radioactive material (NORM). Included among these studies were radiological dose assessments of several different NORM disposal options (Smith et al. 1996).

In 1997, DOE asked Argonne to conduct additional analyses on waste disposal in salt caverns, except that this time the wastes to be evaluated would be those types of oil field wastes that are contaminated by NORM. This report describes these analyses. Throughout the remainder of this report, the term "NORM waste" is used to mean "oil field waste contaminated by NORM".

The remainder of this report consists of eight sections. Section 2 provides background on the development, use, and closure of salt caverns that may be used for disposal of NORM waste. Section 3 describes specific hydrogeologic conditions of locations where salt caverns are most likely to be used for oil field disposal. Section 4 provides background information on NORM occurrence and chemistry and existing NORM waste management practices. Chapter 5 assesses the feasibility of disposing of NORM waste in salt caverns. Chapter 6 outlines the state and federal regulations that affect cavern disposal of NORM waste. Chapter 7 summarizes the costs associated with disposing of NORM wastes. Chapter 8 describes the analysis used to assess the risks associated with cavern disposal of NORM waste. Finally, Section 9 summarizes the results of the analyses.

2. Background on Salt Caverns

2.1 U.S. Salt Formations

Salt deposits occur in two major forms in the United States: bedded salt and salt domes. Although salt deposits occur in many parts of the United States, the occurrence of salt in quantities and locations that would promote commercial development is limited. Figure 1 (from Veil et al. 1996) shows the location of the major U.S. subsurface salt deposits. In 16 states salt occurs in sufficient quantity to be mined by either excavation or solution mining or to be recovered through solar evaporation. These states with major salt deposits are Alabama, Arizona, Colorado, Kansas, Louisiana, Michigan, Mississippi, Montana, New Mexico, New York, North Dakota, Ohio, Oklahoma, Pennsylvania, Texas, and Utah (Veil et al. 1996).

Bedded salt formations occur in layers interspersed with such sedimentary materials as anhydrite, shale, dolomite, and other more soluble salts (e.g., potassium chloride). These materials have varying degrees of permeability, but all are generally low (Freeze and Cherry 1979). The bedded salt deposits are tabular and can contain significant quantities of impurities.

Salt domes are large, nearly homogeneous formations of sodium chloride, although they may contain nonhomogeneous zones. Pfeifle et al. (1995) report that the typical anhydrite ($CaSO_4$) content of Gulf Coast salt domes averages less than 5%. Salt domes were created by geological processes that spanned millions of years (Chilingarian et al. 1989). Approximately 30 million years ago, salt buried by more dense materials flowed to form pillows. Because of its lower density, salt flowed upward to form diapirs (domes or anticlinal folds whose overlying rocks have been ruptured by the squeezing up of the more plastic salt core) and pierced overlying units.

As the salt passed upward through the overlying sediments, long, finger-like projections developed. The depth of the intruded salt (sedimentary piercements) can be greater than 10,000 ft (Whiting 1981), and the top width of the salt domes ranges from about 0.5 to 2.5 miles (Chilingarian et al. 1989). If the intruded salt contacted undersaturated water, dissolution would occur. Through a complex interaction of dissolution, recrystallization, hydration of anhydrite to form gypsum, sulfate reduction, cementation, etc., a caprock was often formed. Although caprocks are common in the vicinity of salt domes, they are not always present (Linn 1997).

At the top of the caprock, a region of limestone frequently developed. This limestone may have been formed by a number of processes, including reduction of the calcium-sulfate caprock and precipitation from calcium-sulfate-rich water (Werner 1986).

2.2 Creation of Salt Caverns

To create salt caverns, water that is not fully salt-saturated is injected into a salt stock, and the resulting brine solution is withdrawn. This method is referred to as solution mining (Testa 1994). The development and shape of the salt cavern can be controlled by the method used for construction. In the direct circulation method, fresh water is injected through a tubing string from the surface, and brine is withdrawn through an annular space between the tubing and final casing. In the reverse circulation method, fresh water enters through the annulus, and brine is removed through the tubing string. A combination of these two methods, or other more complicated methods, can be used to obtain a desired cavern shape. The American Petroleum Institute (API) provides illustrations and more details on these methods (API 1994). Figures 2 and 3, taken from Veil et al. (1996), provide general schematic drawings of salt caverns used for waste disposal for caverns in domal salt and bedded salt, respectively. These figures are not drawn to scale or intended to show detailed construction features.

The petroleum industry has constructed many salt caverns for storing hydrocarbons. Several organizations have developed standards and guidance for designing and operating hydrocarbon storage salt caverns (CSA 1993; API 1994; IOGCC 1995). Readers desiring more details on design, location, and construction of salt caverns are referred to these reports.

2.3 Uses of Salt Formations and Salt Caverns

As salt intruded the Cenozoic sediments along the Gulf Coast, various minerals were often precipitated in the vicinity of the caprock. Along with the minerals, oil was frequently trapped under the edge of the caprock. Because of the high probability of finding oil and other valuable minerals, salt domes have been extensively explored and mined for more than 100 years. Starting in the late 1800s, salt domes were commercially mined for salt by various leaching techniques. The shapes of the resulting caverns were often irregular because of the techniques applied, but a number of caverns, such as West Hackberry Cavern 11, are nearly symmetrical (Tomasko 1985).

Salt caverns are used for storing hydrocarbons. The earliest cavern storage in salt domes for liquefied petroleum gas (LPG) started in 1951; LPG storage in bedded salt started somewhat sooner, in the early 1940s (Querio 1980). Some of the liquified products stored include propane, butane, ethane, fuel oil, gas, and crude oil. Private industry in the United States operates a large number of caverns for storing liquid petroleum products, petrochemicals, and natural gas.

DOE acquired the rights to some existing caverns for the Early Storage Reserve (ESR) of the Strategic Petroleum Reserve (SPR). The ESR was designed to store 250 million barrels of oil, about two-thirds of which were to be placed in solution-mined caverns and one-third in a conventional rock salt mine. Acquisitions for the ESR were made about 1977. The SPR now has a capacity of 680 million barrels, and the rock salt mine has been removed from the program (Diamond 1997).

2.4 Waste Disposal in Caverns

Use of salt caverns for waste disposal in the United States has been limited. A summary of current waste disposal practices, exclusive of NORM wastes, is given in Veil et al. (1996), along with a discussion on using caverns for waste disposal in Canada, the United Kingdom, Germany, the Netherlands, and Mexico. In the United States, the Railroad Commission of Texas has issued six permits for disposal of NOW in salt caverns; four of these are operational. None of the six Texas facilities are authorized to dispose of NORM wastes in their caverns. NORM wastes are not approved for cavern disposal in Canada or the United Kingdom. To the authors' knowledge, NORM wastes are not being disposed of in salt caverns anywhere in the world at this time.

2.5 Disposal Cavern Operation

Initially, the caverns would be filled with brine. Wastes would then be introduced as a slurry of waste and a fluid carrier (brine or fresh water). Three scenarios are possible for introducing the waste material: (1) the waste can be pumped down tubing to the bottom of the cavern and the displaced brine can be withdrawn through an annulus; (2) the waste can be pumped down an annulus and the displaced brine can be withdrawn through the tubing; and (3) the waste can be injected through one well and the brine withdrawn from another well.

As the slurry is injected, the cavern acts as an oil/water/solids separator. The heavier solids sink to the bottom of the cavern and form a pile. Any free oils and hydrocarbons float to the top of the cavern because they are less dense than water. An organic blanket could be injected into the cavern to prevent additional leaching of the cavern's roof by water that is not fully saturated with salt. Clays in the slurry and dissolved chemical constituents from the waste can mix with the brine, forming a suspension above a brine/waste interface. Clean brine displaced by the incoming slurry would be removed from the cavern and either sold as a product or disposed of in an injection well.

Early in the life of the disposal cavern, clean brine is withdrawn from hundreds of feet above the surface of the waste pile or interface. As the cavern fills, the brine becomes dirtier (i.e., it will have a higher clay, oil, and dissolved waste constituent content). This dirty brine can produce operational difficulties (e.g., clogging of pumps) and additional expenses (Veil et al. 1996). The cavern is considered to be "full" of waste when return of disposed material with the displaced fluid becomes a problem. When the cavern is full, the operator seals the cavern.

2.6 Post-Closure Cavern Behavior

Once the cavern had been filled with waste, the cavern would be sealed and the borehole plugged with cement. Plugs would be placed in the well bore above and below water-bearing intervals to isolate these intervals permanently.

A waste-filled cavern that has been sealed is subject to a number of complex physical processes: reduction in cavern volume caused by salt creep (the process by which salt surrounding the cavern flows into the cavern space as a pseudofluid [Bishop 1986; Freeze et al. 1995]); convective mixing in the upper, brine-filled portion of the cavern; differential settling and compaction of solids; chemical reaction and compaction of the waste material; and an increase in pressure produced by the combined effects of salt creep and the addition of sensible heat (heat derived from the geothermal gradient vertically across the cavern — approximately 13°F per 1,000 ft at a depth of 1,000 ft [Tomasko 1985]).

During a transient period of several years after closure of a cavern filled with brine, pressure can exceed the lithostatic value (pressure in surrounding salt) because of thermal expansion of the brine. The amount of overpressurization is a function of cavern size (Berest and Brouard 1995). Similarly, cavern pressure can exceed the lithostatic value after a longer time period when, due to salt creep, brine pressure will balance average lithostatic pressure, resulting in a slight excess of brine pressure at the top of the cavern (Langer et al. 1984; Wallner 1986). This overpressurization occurs because lithostatic pressure increases linearly with depth, whereas brine pressure is constant within the cavern.

The presence of a small quantity of gas in the sealed cavern can mitigate the effects of pressure buildup because the gas drastically increases the cavern compressibility (Berest et al. 1997). Tomasko et al. (1997) discuss several ways in which gases could potentially be produced in a sealed disposal cavern, including bacterial degradation of the waste, corrosion, and natural releases from the salt formation itself (e.g., carbon dioxide, hydrogen sulfide, hydrogen, methane, etc.), but conclude that significant gas production is unlikely.

A recent study of the behavior of brine-filled, sealed caverns suggests that the permeability of the material surrounding the cavern can also influence pressure buildup (Wallner and Paar 1997). Because of a very slow pressure increase within a sealed salt cavern, the pressure at the top of the cavern would only exceed the lithostatic value after a long time (on the order of thousands of years for a 1,000-ft-tall cavern). Because the rock salt formation could become permeable if the fluid pressure exceeded the stress in the salt, small leakage rates of fluids from the top of the cavern are predicted. This leakage would compensate for the overpressurization at the top of the cavern and return the system to an equilibrium condition.

Although the pressurization of sealed caverns containing liquids or dry granular wastes is currently under investigation (e.g., Langer et al. 1984; Wallner 1986; Berest and Brouard 1995; Wallner and Paar 1997; Berest et al. 1997), little research has been directed at predicting pressure behavior in caverns containing a combination of NORM and NOW. Cavern behavior is expected to be similar to that discussed above, with the exception that the compressibility of the wastes may alter the time scale and magnitude of the system response. More study of actual waste disposal caverns would help to clarify this issue.

3. Hydrogeology

Most salt formations of interest for NOW and NORM waste disposal occur along the Gulf Coast in Texas and Louisiana, the Permian Basin of New Mexico, and in other states, such as Kansas and Michigan, that have salt domes. The following subsections discuss hydrogeological conditions for the Gulf Coast, the western Texas panhandle, and New Mexico. A composite of these areas is then used as the basis for the generic risk analysis described in Section 8. This information is particularly useful in calculating the fate and transport of contaminants that are released from caverns.

3.1 Gulf Coast Hydrogeology

Salt domes along the Gulf Coast of the United States are located in the Coastal Plain Physiographic Province (Back et al. 1988). This province is underlain by a gulfward thickening wedge of unconsolidated to semiconsolidated sedimentary rocks (sand, silt, and clay derived from erosion of nearby continental upland areas). These sediments overlie consolidated rocks of Mesozoic Age and range in thickness from a few feet near their landward limit to more than 30,000 ft in southern Louisiana.

As part of the Gulf Coast Regional Aquifer-System Analysis (GCC RASA) program, the depth to groundwater was evaluated for a 230,000-square-mile study area that included coastal regions in Texas, Louisiana, Mississippi, and Florida (Williams and Williamson 1989). On the basis of data from 6,825 wells, the depth to the water table ranges from 0 to 74 ft, with a median value of 20 ft. This shallow groundwater system is composed primarily of sands interbedded with deposits of silt and clay. Where the silts and clay have been eroded and the aquifer is in communication with the atmosphere, the aquifer is unconfined. Confined to semiconfined conditions exist where low-permeability clays and silt overlay the more permeable sands (Hanor 1993). Beneath the shallow groundwater system are other sequences of clays and silts, interspersed with beds of sand. The sand areas constitute other potential aquifers that are predominantly confined (Capuano and Jan 1996).

Recharge to the shallow groundwater system is derived from precipitation. The majority of recharge occurs in areas where the clay and silt layers are absent. Discharge of this aquifer occurs to surface waters, underlying deeper aquifers, and pumping wells.

3.2 Texas and New Mexico Hydrogeology

Bedded salt occurs in the Texas panhandle area and West Texas, as well as in central and southeastern New Mexico. These bedded salts are located, for the most part, in deep formations (the top of salt occurs at a depth of 500 to 2,000 ft below the land surface, and the salt is about 1,000 to 3,000 ft thick). Although most of these bedded salts occur below 1,000 ft, some in West

Texas can be much shallower (e.g., one of the West Texas disposal caverns starts at a depth of about 700 ft [Hickerson 1995]).

Overlying the bedded salt layers are the Ogallala fluvial aquifer, which is composed of stream and river deposits, and the Dockum aquifer, which is composed of fluvial and lacustrine (lake) deposits (Bassett and Bentley 1982). These aquifers make up a shallow, freshwater system that is used for domestic, municipal, industrial, and agricultural purposes. The combined thickness of these two aquifers can be as great as 2,300 ft (Bair et al. 1985). The Ogallala is the shallower of the two aquifers and occurs at a depth ranging between 20 and 400 ft (Wood and Sanford 1995). It ranges from 0 to 800 ft thick (Seni 1980), and it underlies about 134,000 square miles of land from Nebraska to New Mexico (Back et al. 1988). Its principal composition is sand and gravel. Groundwater velocity in this aquifer is estimated to be about 100 ft/year.

The Dockum aquifer lies below the Ogallala aquifer. Locally, its depth is variable; it can outcrop at the surface or occur as deep as 800 ft below the ground. It is typically composed of a sandstone and conglomerate unit (fluvial) overlying a fine silt and clay unit (lacustrine). The thick Permian evaporite-bearing unit beneath the Dockum is an aquitard and a barrier to vertical groundwater flow. Depth to bedded salt ranges from about 500 to 2,000 ft. The uppermost extensive salt is the Salado Formation. Where this unit has been dissolved, various older formations (e.g., Seven Rivers, Grayburg, San Andres, and Castile) contain the uppermost salt units. In some areas, salt has been completely removed. At the depth of the salt, the velocity of groundwater is estimated to be about 10 ft/year.

Bedded salts are being developed for low-level nuclear waste disposal at the Waste Isolation Pilot Plant (WIPP) in New Mexico. This facility has been constructed and will shortly begin operation. It is located at a depth of 2,150 ft below the ground surface in the Salado Formation (DOE 1990). The Ogallala and Dockum aquifers are absent in this area of New Mexico, and the shallowest groundwater of consequence occurs in the Culebra Dolomite of the Rustler Formation at a depth of about 750 ft.

Recharge to the shallow groundwater system in the semiarid Texas/New Mexico environment is derived from precipitation. Wood and Sanford (1995) estimate the annual recharge to be 11±2 mm/yr. Recharge is small because of high potential evaporation, plant transpiration, limited precipitation, and runoff. In the past, discharge was to springs; other, deeper, groundwater systems; and pumps. Because of heavy pumping, most of the discharge springs are now dry, and the only discharge is to deeper aquifers.

In general, water quality in Texas and New Mexico decreases with depth. For example, the Rustler Formation water quality is generally poor; total dissolved solids range from 286 mg/L in Ward County to 157,000 mg/L in Winkler County. Chloride concentrations can be as high as 89,700 mg/L in Winkler County, Texas (Richey et al. 1985). Because of this poor water quality, water for public water supply, irrigation, industry, livestock, and rural domestic use is often obtained from overlying aquifers, such as the Santa Rosa Sandstone Formation in the Dockum and from the Cenozoic alluvium in the Delaware basin (including the Ogallala aquifer, if present). In the Texas panhandle area, similar observations have been made regarding groundwater quality (Bair 1987); i.e., total dissolved solids and the concentration of brine increase with depth.

4. Regulatory Considerations

This section evaluates the major state and federal environmental requirements as they apply to disposal of NORM wastes in salt caverns. No attempt is made to encompass all types of permits, licenses, or approvals that must be obtained by an operator, including zoning approvals, mineral rights, and construction, safety, and fire code requirements.

4.1 Hazardous Waste Status of NOW and NORM Waste

The most important distinction between oil field wastes and many other types of industrial wastes is that the former are exempted from the hazardous waste requirements of the Resource Conservation and Recovery Act (RCRA). On July 6, 1988, the U.S. Environmental Protection Agency (EPA) issued a regulatory determination that exempted any wastes arising from the exploration, development, and production of crude oil, natural gas, and geothermal energy from regulation as hazardous wastes under RCRA Subtitle C (53 FR 25477). On March 22, 1993, the EPA clarified the 1988 determination and exempted many other wastes that were uniquely associated with exploration and production operations from RCRA Subtitle C requirements (58 FR 15284). Given the federal exemption from RCRA for oil field wastes, the waste management requirements faced by most operators will be state requirements.

The difference between NOW and NORM waste is the presence in the latter of radionuclides above a state-specified action level. The presence of those radionuclides does not change the waste's exempt status under RCRA as long as the waste itself, exclusive of the radiological components, is an exempt waste. Therefore, most oil field NORM waste is not hazardous waste.

The term "nonhazardous oil field waste" should not be interpreted to mean that no hazardous substances are found in oil field wastes. At least two oil- and gas-producing states, California and Louisiana, do not follow the blanket RCRA exemption for exploration and production wastes and associated wastes. In these states, each batch of waste is tested for specified parameters to determine whether the waste is hazardous. Those wastes found to be hazardous must be managed at a hazardous waste management facility, which typically is much more expensive than management of a NOW disposal facility.

4.2 Summary of NORM Regulations

No existing federal regulations specifically address handling and disposal of NORM wastes. In the absence of federal regulations, individual states have taken responsibility for developing their own regulatory programs. These programs have been evolving rapidly over the last few years. Many states have promulgated NORM regulations, and many others are reviewing the magnitude of NORM issues within their borders and the need for specific regulations.

The existing state regulatory programs establish requirements for (1) a NORM exemption standard or action level; (2) licensing of parties possessing, handling, or disposing of NORM waste; (3) the release of NORM-contaminated equipment and land; (4) worker protection; and (5) NORM waste disposal. The action level defining when waste must be managed as NORM varies from state to state. In general, state action levels range from 5 to 30 picocuries per gram (pCi/g) of total radium (i.e., radium-226 [Ra-226] plus radium-228 [Ra-228]). Several states have established two action levels, depending upon the radon emanation rate[1] of the waste. In these states, the action level is 5 pCi/g total radium if the radon emanation rate exceeds 20 pCi per square meter per second ($pCi/m^2/s$) and 30 pCi/g total radium if the radon emanation rate is below that level. A picocurie (pCi) is equal to 10^{-12} curies[2].

Most state regulations currently approve the following disposal methods for waste exceeding the NORM action levels: (1) burial at either a licensed NORM waste or low-level radioactive waste disposal facility, (2) downhole disposal via encapsulation inside the casing of a plugged and abandoned well, and (3) underground injection into subsurface formations via a permitted Class II well. A few states also allow NORM waste to be disposed of via land spreading, provided that specific criteria are met. The State of Michigan also allows NORM waste containing up to 50 pCi/g radium to be disposed of in landfills that are permitted to accept only nonhazardous wastes (MDEQ 1996).

Downhole encapsulation and underground injection of NORM waste typically are approved on a case-by-case basis only and, in the case of underground injection, may require a modification to the existing Class II permit. In Texas, two commercial facilities have been permitted to receive and dispose of NORM waste via underground injection.

This report evaluates the regulatory aspects of salt cavern disposal of NORM waste in five states: Louisiana, Mississippi, New Mexico, Oklahoma, and Texas. Each of these states, except Oklahoma, has already enacted NORM regulatory programs and has expressed serious interest in disposal of NOW in salt caverns. Oklahoma currently is considering a draft set of NORM regulations. None of the NORM regulations promulgated or proposed in these five states specifically address the disposal of NORM waste in salt caverns. Each of these state programs,

[1] The radon emanation rate is the fraction of radon atoms that escape the grain material containing the parent nuclide into the gaseous, porous space between the grains.

[2] A conventional unit, the curie (Ci) is defined as the quantity of a given radionuclide in which 3.7×10^{10} atoms undergo nuclear transformations each second. One Ci is roughly equal to the decay rate of one gram of Ra-226.

however, addresses the disposal of NORM waste into Class II injection wells, either directly or indirectly. The regulation of underground injection of NORM waste is relevant to the potential disposal of NORM waste in salt caverns because disposal into salt caverns is considered by most states to be equivalent to underground injection into Class II wells (Veil et al. 1996).

4.2.1 Louisiana

In Louisiana, the NORM regulations promulgated by the Louisiana Department of Environmental Quality (LDEQ) are contained in the Louisiana Administrative Code (LAC), Title 33, Part XV, Chapter 14, "Regulation and Licensing of Naturally Occurring Radioactive Material." The agency responsible for implementation of these regulations is the LDEQ Office of Air Quality and Radiation Protection, Radiation Protection Division. Under Section 1404(A)(1) of these regulations, waste containing ≥5 pCi/g Ra-226 or Ra-228 above background must be managed as NORM waste.

In Section 1412(B), the regulations identify several forms of disposal as acceptable for NORM waste. Underground injection of NORM waste is not specifically identified in the regulations as an approved disposal option. However, Section 1412(B)(2) states that disposal of NORM waste by alternate methods is allowed, provided approval in writing is obtained from the Radiation Protection Division. Under this provision, underground injection may be allowed on a case-by-case basis in Class II injection wells. In addition, Sections 1412(B)(3) and (4) establish special provisions for the disposal of regulated NORM wastes at commercial NOW disposal facilities, including commercial Class II injection wells, regulated by the Louisiana Department of Natural Resources (LDNR.). In Louisiana, Class II injection wells are regulated and permitted by the LDNR Office of Conservation in accordance with Statewide Order No. 29-B (LAC 43:XIX).

Under this regulatory scenario, the disposal of NORM into either a commercial or noncommercial Class II well would require a specific license from the LDEQ and a Class II permit from the LDNR. To date, however, there has been only one instance in which NORM wastes have been disposed of in a noncommercial Class II well, and there have been no permitted disposals of NORM into a commercial Class II well (Talbot 1998).

With respect to the injection of NORM into salt caverns in Louisiana, the regulatory scenario is complicated by the existence of a statute specifically restricting the disposal of radioactive material into salt domes (Louisiana Revised Statute 30:2117). Part B of this statute states that "...no salt dome within the jurisdiction of the state of Louisiana shall be utilized as a temporary or permanent disposal site for radioactive waste or other radioactive material of any nature by any person." This statute, originally enacted in 1979, probably was not written with consideration to NORM disposal issues; however, NORM disposal in salt caverns probably would not be allowed in Louisiana without amendment to this statute.

4.2.2 Mississippi

In Mississippi, petroleum industry NORM waste is regulated by two agencies. The Department of Health has promulgated general NORM regulations under Part 801, Section N, of the Regulations for Control of Radiation in Mississippi. Under Section 801.N.4(a)(1), waste containing greater than 5 pCi/g Ra-226 or Ra-228 above background must be managed as NORM waste. The Mississippi State Oil and Gas Board has promulgated two rules specific to the disposal and control of petroleum industry wastes exceeding the Department of Health's action level defining NORM waste. Rule 68 of the Oil and Gas Board Statewide Rules and Regulations specifically addresses the disposal of NORM waste in wells that are about to be plugged and abandoned. Rule 69 establishes regulations for the control of NORM to ensure that radiation exposures to workers and the general public are minimized.

In Rule 68, Section IV.D, underground injection of NORM waste into a well about to be plugged and abandoned is identified as an allowable disposal method, provided specific limitations are met and approval is obtained from the Oil and Gas Board. Limitations contained in Section V of this rule address minimum depth below the base of the lowest underground source of drinking water, pressure test requirements, plugging requirements, and required well marker information. Any well in which NORM waste is injected must be permitted as a Class II injection well under Rule 63 of the Statewide Rules and Regulations, even though the well will subsequently be plugged and abandoned and not used again for underground injection.

Currently, there are no rules or regulations in Mississippi specifically addressing the disposal of NORM waste into active Class II injection wells. Section N.12(a) of the Health Department regulations lists several general standards for NORM waste disposal that are unrelated to underground injection. However, this section also provides for the disposal of NORM waste by alternate methods, provided approval is obtained from the Health Department. This language allows the state flexibility in addressing NORM waste disposal options such as underground injection into Class II wells. Because Class II wells are regulated by the State Oil and Gas Board under Rule 63, it is likely that the Oil and Gas Board would be the agency responsible for allowing or disallowing the disposal of NORM waste in Class II wells. This form of disposal could require modifications to Rule 63, or the promulgation of a new rule; however, to date, the Oil and Gas Board has not considered this issue (Ford 1998).

4.2.3 New Mexico

In New Mexico, the regulation of NORM waste has been divided between two agencies. The New Mexico Environment Department (NMED) regulates the possession, use, disposal, transfer, and storage of NORM waste under Title 20 of the New Mexico Administrative Code (NMAC), Chapter 3, Part I, Subpart 14. The New Mexico Oil Conservation Division (OCD) regulates the disposal of petroleum industry NORM waste under Title 19 NMAC, Chapter 15, Part I, Rule 714. Under Section 1403(A) of the NMED regulations, waste containing greater than 30 pCi/g Ra-226 above background must be managed as NORM waste.

Under Section 1407(B) of the NMED regulations, the disposal of NORM waste by deep-well injection is allowed, provided that a general license is obtained from the NMED and applicable rules established by the OCD are complied with. The OCD regulations specific to underground injection of NORM waste are contained in Rule 714, Section E. This section states that underground injection of NORM waste will be permitted in Class II wells on a case-by-case basis, provided that such injection is performed in a manner that is protective of the environment, public health, and fresh waters, and is in compliance with the OCD rules pertaining to injection. Despite these provisions, to date, the underground injection of regulated NORM waste has not occurred in New Mexico because there has been some disagreement between the OCD and the Rocky Mountain Low-Level Radioactive Waste Board (RMLLRWB) regarding which agency had regulatory authority over the management of NORM waste (Anderson 1998). On June 1, 1998, the RMLLRWB amended its Rule 1 to exclude from its authority the "placement or injection of oil and gas NORM in oil and gas wells in accordance with any applicable state regulations, as long as the oil and gas NORM is produced within the region and the wells are owned or operated by the person(s) who produced the oil and gas NORM." This amendment should allow future disposal of NORM via injection into Class II wells in New Mexico under the OCD rules in some cases.

A rule-making process is currently underway to address the development of regulations for the disposal in salt caverns of exploration and production waste not suitable for injection in Class II wells (e.g., sludges, tank bottoms, and other solid waste). Any proposals for the disposal of regulated NORM into salt caverns would go through a similar public, rule-making process. Such a process, however, could be quite controversial because salt cavern disposal of NORM waste could be construed to be related to the DOE's proposed WIPP near Carlsbad, New Mexico, which has been the target of significant levels of opposition within the state (Anderson 1998).

4.2.4 Oklahoma

The Oklahoma Department of Environmental Quality has drafted a set of NORM regulations that, if promulgated, will be contained in Title 252, Chapter 400, Subchapter 19 of the Oklahoma Administrative Code. Under Part 3 of these proposed rules, materials containing greater than 30 pCi/g of Ra-226 or Ra-228 will need to be managed as NORM wastes. Under Part 11, owners and operators of Class I and Class II injection wells who are authorized under a general NORM permit will be allowed to dispose of NORM waste in these injection wells, provided the owner is in compliance with all applicable underground injection control rules and permit conditions, and that the sludges and scales to be injected are in the form of a pumpable slurry in which the entrained solids are so fine grained that they will not plug the injection formation.

In Oklahoma, Class II injection wells are regulated and permitted by the Oklahoma Corporation Commission (OCC) under Section 165 of the Oklahoma Administrative Code, Chapter 10, Subchapter 5 (165:10-5-1 through 15). Currently, these rules do not address injection of materials containing NORM. Rules promulgated by the Department of Environmental Quality regarding the disposal of regulated NORM in Class II wells would need to be integrated with existing OCC Class II regulations and permit requirements; this probably would require a formal rule-making process (Fiddler 1998).

4.2.5 Texas

In Texas, the regulation of NORM waste has been divided among agencies. The Texas Department of Health regulates the possession, use, transfer, and storage of NORM waste under Part 46 of the Texas Regulations for Control of Radiation. The Texas Natural Resources Conservation Commission has jurisdiction over the disposal of non-oil-and-gas NORM wastes. The Railroad Commission of Texas (TRC) regulates the disposal of oil and gas waste contaminated with NORM under Title 16, Part I, Chapter 3, Rule 94 of the Texas Administrative Code (TAC). Under Section 46.4(a)(1)(i)(b), wastes containing concentrations less than or equal to 30 pCi/g Ra-226 or Ra-228 are exempt from the NORM regulations, provided that the radon emanation rate is less than 20 pCi/m^2/s. If the radon emanation rate exceeds this limit, the wastes are exempt only if the radium concentrations are less than or equal to 5 pCi/g.

Under 16 TAC I.3.94(f), the regulation states that oil and gas NORM waste may be disposed of via injection if a permit is obtained. The TRC will issue a permit provided the applicant demonstrates that the disposal will be conducted in a manner that is protective of public health, safety, and the environment. The permit will specify necessary construction and operating requirements. Currently, underground injection of NORM waste is occurring in Texas at two commercial facilities owned by Newpark Environmental Services, Inc. and Lotus LLC. To date, there has been only one instance of noncommercial injection of regulated NORM waste in Class II wells in Texas (Ginn 1998).

4.3 Salt Caverns and the Underground Injection Control Program

Veil et al. (1996) contains a detailed discussion of the Safe Drinking Water Act's (SDWA's) Underground Injection Control (UIC) program and how it relates to cavern disposal. The key elements are summarized below.

4.3.1 Federal UIC Requirements

Unlike most other methods for disposing of nonhazardous oil field waste, injection wells are subject to the requirements of the UIC program (see EPA regulations at 40 CFR 144-146). EPA's regulations define a well as a bored, drilled, or driven shaft, or a dug hole, whose depth is greater that the largest surface dimension. An injection well means a well into which fluids are being injected. All injection wells are assigned to one of five classes. Class II wells inject fluids that are brought to the surface in connection with natural gas storage operations or conventional oil or natural gas production. Injection wells for disposing of produced water are Class II wells. Likewise, salt caverns for disposing of NOW and NORM waste and the wells leading from the surface to the caverns are Class II wells. Throughout this report, the term "salt cavern" includes not only the actual cavern (injection zone portion) but also the wells used to inject materials into the caverns.

Most types of NOW are brought to the surface with oil and gas production. However, it is not possible to claim that the primary types of NORM waste (i.e., sludge, scale, and contaminated soil) are brought to the surface in their final form. Although the chemical and radiological constituents of these wastes come from the subsurface, the wastes themselves are not formed until the fluids are at the surface. There has been some uncertainty among state regulatory agencies as to whether these wastes are eligible for injection into Class II wells. In February 1996, the Ground Water Protection Council asked the EPA to clarify that all exempted oil field wastes can be injected into Class II wells. In June 1996, the EPA responded to the request in a letter from Robert Blanco, Acting Director of EPA's Ground Water Protection Division (Blanco 1996). The letter does not provide further guidance, but rather concludes that the EPA trusts the judgement of states that administer their own UIC programs as to whether a particular waste meets the criteria for Class II fluids.

States seeking authority to administer the UIC program may obtain primacy in two ways. Under Section 1422 of the SDWA, states must demonstrate that their regulations are at least as stringent as those adopted by the EPA. To provide greater flexibility than what is allowed under the Section 1422 requirements for states administering Class II programs, Congress added Section 1425 to the SDWA, which requires states seeking delegation to have an underground injection program that meets the requirements of Section 1421(b)(1)(A)-(D) and that would be effective enough to prevent any underground injection that would endanger drinking water sources.

4.3.2 State UIC Requirements

Many of the oil- and gas-producing states have obtained the authority to administer the UIC program. Veil et al. (1996) summarize state UIC regulations and report on contacts with regulatory agencies in 11 oil-producing states where salt caverns exist to determine whether the state had any regulations that either authorized or prohibited cavern disposal. Of those states, only Texas had authorized any NOW disposal caverns, four of which are in operation. Texas has initiated a rule-making process for the development of regulations addressing the injection of NOW into salt caverns. This process has been sidetracked by two issues regarding the injection well rules — notice requirements and financial security requirements. When those two issues have been resolved, the state will move forward with the salt cavern disposal rules. New Mexico is presently developing NOW cavern disposal regulations. No other states are presently working on NOW or NORM cavern disposal regulations, although Louisiana and Mississippi have previously expressed serious interest in cavern disposal for NOW.

4.4 Regulatory Barriers

A review of federal UIC regulations and NORM and UIC regulations from the five states that have expressed some interest in cavern disposal indicated that there are no outright barriers or prohibitions against NORM disposal in salt caverns, except for Louisiana, which prohibits disposal of radioactive wastes or other radioactive materials in salt domes. Presently, however, only Texas and New Mexico are working on disposal cavern regulations, and no states have issued permits to allow cavern disposal of NORM waste. State regulatory agencies may need to revise their NORM waste management or UIC regulations to accommodate cavern disposal. These agencies may need time to further investigate the concept of NOW disposal in caverns before they are willing to develop regulations and issue permits authorizing NORM waste disposal in caverns.

5. Background on NORM

5.1 NORM Occurrence and Chemistry

Oil and gas production and processing operations sometimes accumulate NORM at elevated concentrations in by-product waste streams. The sources of most of the radioactivity are isotopes of uranium-238 (U-238) and thorium-232 (Th-232) naturally present in subsurface formations from which oil and gas are produced. The primary radionuclides of concern in NORM wastes are Ra-226 of the U-238 decay series, and Ra-228 of the Th-232 decay series. Other radionuclides of concern include radionuclides that form from the decay of Ra-226 and Ra-228; these decay progeny are shown in Figures 4 and 5, which depict the decay chains for U-238 and Th-232, respectively.

The production waste streams most likely to be contaminated by elevated radium concentrations include produced water, scale, and sludge (Smith et al. 1996). Spills or intentional releases of these waste streams to the ground can result in NORM-contaminated soils that must also be disposed of. Radium, which is slightly soluble, can be mobilized in the liquid phases of a formation and transported to the surface in the produced water stream. Dissolved radium either remains in solution in the produced water or precipitates out in scales or sludges. Conditions that appear to affect radium solubility and precipitation include water chemistry (primarily salinity), temperature, and pressure.

NORM contamination of scale and sludge can occur when dissolved radium coprecipitates with other alkaline earth elements such as barium, strontium, or calcium. In the case of scale, the radium coprecipitates, primarily with barium, to form hard, insoluble sulfate deposits. Scale typically forms on the inside of piping, filters, injection wellhead equipment, and other water handling equipment, but also can form as a coating on produced sand grains. In the case of sludge, radium can be present in several forms. It can coprecipitate with silicates and carbonates that form in the sludge, or it can be present in pieces of barium sulfate scale that become incorporated into the sludge. NORM-contaminated sludges can accumulate inside piping, separators, heater/treaters, storage tanks, and any other equipment where produced water is handled. The EPA estimates that approximately 25,000 tons of NORM-contaminated scale and 225,000 tons of NORM-contaminated sludge are generated annually by the petroleum industry (EPA 1993).

In addition to their radioactive characteristics, NORM wastes also have physical and chemical characteristics typical of NOW. Tomasko et al (1997) assumed that a typical NOW stream going to a disposal cavern consists of accumulated heavy hydrocarbons, paraffins, inorganic solids, and heavy emulsions.

5.2 NORM Management Practices

The presence of NORM in oil and gas wastes has been recognized since the 1930s. NORM was not recognized as a waste management issue, however, until the mid-1980s, when the industry and regulators realized that NORM occurrence was more widespread than originally thought and that activity levels could be high. The petroleum industry adopted methods for managing and disposing of NORM-contaminated wastes that are more restrictive than past practices and are likely to provide greater isolation of the radioactivity. Simultaneously, state agencies have promulgated NORM regulations that establish new, more restrictive standards for the management and disposal of NORM wastes. These actions have served to limit the number of available disposal options for NORM wastes, thereby increasing waste management costs.

The largest volume oil and gas waste stream that contains NORM is produced water. Except at offshore platforms, which discharge produced water to the ocean, nearly all produced water is injected into the subsurface through injection wells. At this time, the radium content of produced water going to injection wells is not regulated. Consequently, radium that stays in solution in the produced water stream does not present a significant waste management problem from a regulatory perspective and is not considered further in this study.

Some operators dispose of NORM wastes at their own sites although, most use off-site commercial disposal facilities. Pipes and casing with NORM contamination may be recycled as scrap steel if NORM levels are below background concentrations. In the past, NORM was commercially managed by surface treatment, through which NORM was blended with nonradioactive materials to reduce the NORM activity below action levels and to spread on the land. Today, the primary method used for disposal of NORM wastes is underground injection. Smaller quantities of NORM waste are disposed of at licensed radioactive waste landfills, encapsulated in the casing of a well being abandoned, or managed on lease sites through land spreading.

Only four off-site commercial NORM disposal companies have been identified in the United States; two of these inject the NORM waste underground and the other two bury NORM waste in landfills. Identification of disposal companies by name in the following sections does not constitute an endorsement of those companies or provide any indication of their performance capabilities. The companies are included solely to provide an indication of the types of commercial disposal options available to operators in the early 1998 time frame.

5.2.1 Underground Injection

NORM-contaminated scales, sludges, and other solid wastes have also been disposed of through underground injection wells. McArthur et al. (1995) report on a NORM waste injection project in the North Slope Alaska oil field developed by two major producing companies. Approximately 100 tons of NORM solids were cleaned from 3,000 oil production pipes and casing. The resulting solids were processed to a particle size of less than 80 micrometers (μm), slurried with 10,000 bbl of water, and then injected into a Class II injection well.

Two of the four U.S. commercial NORM disposal companies utilize underground injection. Newpark Environmental Services, Inc., operates a NORM disposal facility near Winnie in eastern Texas that receives the majority of all NORM wastes disposed of commercially in the United States. In July 1997, Lotus, LLC opened a NORM disposal facility in western Texas near Andrews. Both facilities crush, mill, and slurry the incoming NORM waste before injecting it.

DOE has funded BPF, Inc., to develop a mobile NORM treatment system. The BPF process dissolves the radioactive component of NORM into an aqueous solution that can then be disposed of through underground injection. The residual solids no longer contain radioactivity above levels of regulatory concern and can be disposed of as NOW (Capone et al. 1997). As of summer 1998, the BPF process is at the pilot-scale stage of development.

Other disposal contractors (e.g., Apollo Services and National Injection Services) will come to an operator's site and process NORM wastes so that they can be injected through the operator's own injection well. The process consists of grinding and milling the waste to a small particle size, slurrying the waste to facilitate pumping, and injecting to formations at fracture pressure (Sipple-Srinivasan et al. 1997). Apollo Services and National Injection Services are primarily disposing of drilling wastes at offshore platforms, but can also accommodate NORM wastes.

5.2.2 Landfill Disposal

The other off-site commercial NORM waste disposal option in the United States is burial in landfills. US Ecology operates a low-level radioactive waste landfill on DOE's Hanford site in southeastern Washington State. The landfill is primarily designed to handle radioactive wastes other than oil field wastes, but oil field NORM waste is accepted. Because of its location remote from most oil-producing areas and the higher costs associated with general low-level radioactive waste management requirements, US Ecology receives relatively little NORM waste. For example, in 1997, US Ecology received less than 500 ft^3 of NORM wastes.

Envirocare of Utah, Inc., also operates a landfill for mixed wastes and low-specific activity radioactive wastes in Clive, Utah, that has accepted NORM waste for disposal.

5.2.3 Encapsulation and Downhole Disposal

Under the encapsulation and downhole disposal option, an operator encapsulates NORM waste either inside a section of pipe that is then sealed on both ends and lowered into a wellbore or directly in the wellbore. A plug is placed on top of the waste-containing zone. Scaife et al. (1994) report on two encapsulation projects conducted in the offshore Gulf of Mexico. In the first project, NORM waste was placed into eight joints of casing as the pipe was being lowered into the hole. In the second project, 31 drums of NORM waste were placed into 21 joints of casing on shore and sealed on both ends. The sealed joints were transported offshore and lowered into the well bore. In both projects, cement plugs were placed on top of the waste-containing joints.

Encapsulation works well for NORM waste disposal, but each well can handle only a relatively small volume of waste. Because of this restriction, the process is not widely used.

5.2.4 Land Spreading

The principle behind land spreading is to mix NORM wastes having an activity concentration higher than the action level with clean soil so that the resulting blend has an activity concentration lower than the action level. Sanifill/Campbell Wells operated a commercial land spreading site until recently, when it no longer was economical to operate. Some producers utilize land spreading on their lease site to blend patches of high-activity NORM soils with low-activity NORM soils. However, the present use of land spreading for disposal of NORM waste is limited.

6. Technical Feasibility of NORM Waste Disposal in Salt Caverns

The main purpose of this report is to evaluate various aspects of NORM waste disposal in salt caverns. The first question to answer is whether cavern disposal is technically feasible for NORM waste (exclusive of produced water, which is disposed of primarily through injection wells) given the current state of technology. The answer is clearly yes. NORM waste is physically and chemically similar to NOW. Its primary difference from NOW is the presence of radionuclides. The presence of radionuclides may require additional safety precautions when handling the NORM waste, but the actual disposal would be no different from NOW. NOW waste is currently being disposed of in four U.S. salt caverns and in several Canadian caverns without technical difficulties. There is no technical reason why these caverns or other future disposal caverns could not accept NORM waste equally well.

7. Cost of NORM Waste Disposal

7.1 Elements of Cost

The total cost of NORM waste disposal comprises several cost components. In addition to the disposal cost, operators must consider costs associated with transportation, physical inspection, radionuclide and chemical analysis, and container decontamination. Given the limited number of off-site commercial disposal sites available, transportation costs from remote locations can represent a significant component of total cost. Operators must consider all cost components before selecting a disposal option. To the extent possible, it will be indicated whether the cost figures presented in this chapter reflect just the cost of disposal or also include other costs.

In addition to direct costs, there are other important potential costs, such as long-term liability under the Superfund law. Remediation costs, if the disposal activity results in environmental contamination, can be substantial. The EPA estimates the average cost for cleaning up a Superfund site is approximately $30 million in 1994 dollars (60 FR 20330, April 25, 1995). Long-term liability costs are not quantified here because they represent a future potential cost, not an actual current cost. Liability insurance rates paid by operators include the insurer's perception of long-term liability from all phases of the operator's business, including waste disposal. The incremental insurance costs associated with NORM waste disposal were not identified in this study.

7.2 Historical NORM Waste Disposal Costs

The API surveyed the U.S. oil and gas industry in 1992 to learn how NORM waste was disposed of, how much it cost for disposal, and what volume of NORM required disposal (API 1996). The results of that survey indicated that disposal costs varied greatly, depending on the specific activity of the NORM, the number of drums being disposed of, and the disposal option selected. Disposal costs from API (1996) are summarized in Table 1. The costs ranged from $49 to $3,333 per 55-gal drum, with an average of $544 per drum (equivalent to $415 per 42-gal bbl). For some of the disposal options, various additional costs are identified, including radiological analysis ($100 – $500 per sample), chemical analysis ($250 – $500 per sample), transportation ($6 - $40 per drum), "pretreatment washing volume reduction" ($10 – $25 per drum), permitting and manifesting, administrative costs, and non-NORM waste disposal costs.

7.3 Current NORM Waste Disposal Costs

The costs presented in the previous section are costs that operators faced in 1992. Some of the disposal options available in 1992 are no longer available, particularly the commercial surface treatment facility in Louisiana. That facility is currently going through closure because the operation is no longer profitable.

In general, NORM waste disposal costs have decreased between 1992 and 1998. The following sections provide current information on the cost of off-site commercial disposal companies and other companies that provide disposal services at an operator's site using an existing injection well. These costs are summarized in Table 2. Cost information was collected directly from disposal companies and from oil and gas operators.

7.3.1 Costs for Off-site Commercial Disposal of NORM Waste

The costs presented below are those reported to the authors in early 1998. They are included in this report for comparative purposes at one point in time. There is no guarantee that these costs reflect the actual costs that would be charged to customers or that these companies still charge the same fees. Most commercial disposal companies will negotiate more favorable rates than those described below for customers with large volumes of waste.

Newpark Environmental Services, Inc., charges $196.50 per 55-gal drum or $150/bbl for disposal of NORM wastes through injection. This cost includes inspection and verification of contents as well as the necessary analytical costs. The cost of decontamination is $25 for a drum and $150 for a bulk container (Sammons 1998). Transportation costs are not included in these figures.

Lotus LLC began accepting NORM waste in 1997. Lotus charges $132 per 55-gal drum and $100/bbl for disposal by injection. Gamma spectroscopy analysis costs an additional $100 per sample. Transportation cost is not included but is estimated to be about $3 per loaded mile for a full 72-bbl roll off box (Kelly 1998).

US Ecology operates a low-level radioactive waste disposal landfill that receives various types of radioactive waste, including NORM waste. Because the facility primarily receives radioactive wastes other than oil field wastes, the requirements are more stringent and costs are higher. Base disposal costs range from $500 to $550 per 55-gal drum or from $66.67 to $73.33 per cubic foot, depending on the volume. The State of Washington does not recognize the RCRA exemption from hazardous waste status for exploration and production wastes. Therefore, each waste stream must be analyzed for hazardous waste characteristics and radionuclides. Transportation cost is not included but is estimated to be about $2.10 per mile based on a full truck load. All waste generators shipping waste to US Ecology must obtain a site use permit from the Washington Department of Ecology. Obtaining the site use permit will add to the total cost. All shipments are subject to a minimum disposal charge of $2,500 (White 1998).

Envirocare of Utah, Inc. operates a landfill for mixed wastes and low-specific activity radioactive wastes that has, on occasion, accepted NORM waste for disposal. Envirocare declined to provide a standard price for disposal but indicated that it set prices on a case-by-case basis. According to the company contact, Envirocare is competitive when bidding on large disposal jobs but is not competitive on small jobs because its overhead costs, set for all low-level radioactive waste disposal activities, is quite high and is constant regardless of the job size. For large jobs, the overhead is spread over many drums of waste and is therefore low on a cost per drum basis (Rafati 1998).

7.3.2 Costs for On-site Commercial Disposal of NORM Waste

The four companies discussed in this section process and dispose of NORM waste on-site. All four companies use the operator's injection well to dispose of the NORM wastes.

BPF, Inc., is developing a system that dissolves the radioactive component of NORM into an aqueous solution that can then be disposed of through underground injection. The residual solids no longer contain radioactivity above levels of regulatory concern and can be disposed of as NOW. The process is currently at the pilot stage of development. BPF estimates that costs of the full-scale system, when commercially available, will be approximately \$140/bbl ± 20%. These costs would include an initial survey, obtaining the necessary permits, labor, off-site disposal costs for the resulting NOW solids, chemicals, and a final survey. The cost of an injection well is not included if the operator does not already have a functioning injection well (Bush 1998).

At least two companies, Apollo Services and National Injection Services, provide NOW and NORM disposal at an operator's site. Wastes are ground up, slurried, and injected into the operator's own injection well. The process of injecting ground and slurried NORM waste could potentially plug the receiving formation. Operators should consider the potential cost of an injection well workover when estimating total disposal costs for these companies.

As of early 1998, Apollo was primarily disposing of NORM at offshore platforms. Apollo estimates that NORM waste disposal costs range from \$100/bbl to \$300/bbl, depending on the volume of NORM to be disposed of (Reddoch 1998).

National Injection Services disposes of NOW and NORM through on-site injection. National's cost ranges from \$15/bbl to \$150/bbl, depending on the nature of the materials to be disposed of (Page and Guidry 1998).

7.4 Actual Disposal Practices and Costs

To provide another perspective on NORM waste disposal, several major U.S. oil and gas producers were asked how they dispose of their NORM wastes. Contact persons at these companies agreed to provide information under the condition that their companies not be identified by name. Therefore, companies are identified as Company A, Company B, etc.

Company A disposes of about 600 bbl/year of NORM waste from offshore and the eastern United States. at a commercial injection well facility. The cost for disposal and decontamination of containers is $150/bbl, and the cost for lab analyses, transportation, and handling added another $30/bbl.

Company B used to operate its own offshore injection well for disposing of offshore NORM waste but now sends all of its NORM wastes to a commercial injection well facility. Disposal costs range from $125/bbl to $200/bbl. The typical cost rate for a 15-barrel cuttings box is $150/bbl. Company B does some analytical work before shipping at a cost of $100/test. Transportation costs are estimated to be $25/bbl.

Company C sends much of its NORM waste to a commercial injection well facility. In the past, Company C operated annular injection wells offshore for NORM disposal. Disposal costs at these wells ranged from $500/bbl for "trouble-free" projects to more than $2,000/bbl for "trouble-plagued" projects. As less expensive commercial alternatives became available, Company C opted for off-site commercial disposal. Company C needs to dispose of a large volume of NORM-contaminated soils from remediation projects and recently opted to develop its own onshore injection well to handle these wastes. Cost figures are not yet available, but the contact person noted that capital and operating costs are high. In order to make the process cost effective on a $/bbl basis, the project needs to handle a large volume of wastes.

Company D also sends most of its NORM waste to a commercial injection well facility. During lease abandonment, Company D sometimes blends patches of NORM-contaminated soils with clean soils to reduce the aggregate NORM activity below levels of regulatory concern. In other cases, large volumes of NORM-contaminated soils are excavated and sent off-site for disposal. Company D did not provide specific cost figures but indicated that it had received a significant discount from the disposal company's standard rates for one particularly large project.

Two companies operating in Alaska utilize different NORM disposal methods. Company E ships all its Alaskan NORM waste to the Newpark facility in Texas, whereas Company F grinds and slurries NORM waste and injects it into the company's own injection well. No cost information is available for these projects.

One disposal option that was not mentioned by any of the companies is encapsulation in pipes and casing and downhole disposal during plugging and abandonment. This practice is probably occurring, but the costs tend to be higher than other options (see Table 1). If a company has NORM waste at the same location where it is plugging and abandoning multiple wells, this option may be cost effective.

7.5 Prospects for Cost-Effective NORM Waste Disposal in Salt Caverns

The preceding sections describe the range of costs for disposal of NORM waste. The majority of all NORM wastes sent off-site for disposal are presently going to Newpark's facility. Newpark's disposal cost is about $150/bbl. The Lotus facility charges about $100/bbl. These are the cost targets that a salt cavern disposal facility would need to meet or beat to be cost competitive.

Long-term liability costs are an important consideration for major operators. Under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), companies that dispose of wastes into sites that later become Superfund sites have joint and several liability. This means that a company that contributes only a small portion of a disposal site's waste volume can potentially be held liable for a large portion of the remediation costs if some or all of the other waste contributors are out of business or are otherwise unable to pay. Given that background, prudent companies that have historically disposed of waste at a particular disposal site will think twice before extending their potential liability to new disposal sites, even if the new disposal sites are less costly. Any new disposal cavern company will have to overcome not only long-term liability concerns of potential customers, but also the customers' lack of familiarity with a new disposal technology.

One way to win customers is to offer lower costs. Operators of the four permitted disposal caverns in Texas were contacted to see whether they had made any cost estimates of what they might charge customers if they were authorized to accept NORM wastes. They currently charge from $1.95/bbl to $6/bbl for NOW wastes. To be authorized to dispose of NORM wastes, cavern operators would need to upgrade their aboveground waste handling facilities and analytical capabilities, among other things. Although none of the cavern operators had even preliminary cost estimates, one cavern operator felt that it could realistically operate at costs below $150/bbl, Newpark's cost. He also noted that if regulatory agencies allow NORM disposal in caverns, competition will drive the price lower (Moore 1998).

NOW disposal caverns have shown that they are cost competitive with other NOW disposal facilities in the same geographic area (Veil 1997). This study does not constitute a formal market analysis, and the costs to upgrade a cavern disposal operation for NOW to one that disposes of NORM waste have not been quantified. Nevertheless, there is a reasonable chance that NORM waste disposal caverns would be able to compete economically with existing off-site commercial NORM disposal facilities once regulatory agencies allow the practice to occur.

8. Risks from Disposal of NORM Waste in Salt Caverns

Tomasko et al. (1997) provide a detailed description of the assumptions and calculations used to estimate the human health risk of NOW disposed of in salt caverns. To the extent possible, the risk estimates in this report for disposing of NORM waste in salt caverns follow the same set of assumptions and calculations. NORM waste still has similar chemical properties to NOW, but also has radioactive properties that may increase the risk. The risk calculations for NOW are not repeated in detail here; NORM risk calculations are described.

8.1 Contaminants of Potential Concern

Contaminants of potential concern at a site are those that may be hazardous to human health and/or the environment under current or future site conditions. Identifying the contaminants of potential concern helps focus the risk assessment on those contaminants that may be of potential significance to human health. This study does not address potential ecological risks. However, they are likely to be low, because under most release scenarios, cavern fluids are released to groundwater not surface water.

As the risk assessment is conducted, it may be determined that the risks associated with some potential contaminants are insignificant and can be dropped from further consideration. For example, the susceptibility of some potential contaminants to transport through environmental media may be insufficient to allow them to come in contact with humans. In such cases, the contaminant need not be considered further in the risk assessment.

Tomasko et al. (1997) identified contaminants of potential concern in NOW on the basis of information presented in EPA's 1987 Report to Congress (EPA 1987) and a later draft pertaining to Selected Associated Wastes (EPA 1994). The chemical contaminants in the NOW include benzene, lead, arsenic, cadmium, chromium, and boron. After further evaluation of the physical and chemical properties of lead and boron that would serve to minimize their availability to be transported, Tomasko et al. (1997) dropped these two contaminants from further consideration.

The primary radioactive contaminants of potential concern in NORM include Ra-226, Ra-228, and their decay progeny (see Figures 4 and 5, respectively). Ra-226 is brought to the surface in the dissolved phase, and then it precipitates out into scale or sludge. Ra-226 has a half-life of 1,600 years and decays directly to Rn-222 (half-life of 3.8 days) through alpha and gamma emission. Rn-222 and its first four decay progeny have relatively short half-lives and will reach secular equilibrium[3] with the Ra-226 parent in approximately one month. The remaining

[3] Secular equilibrium refers to the stable relationship established in nature between a radioactive element that has a long half-life and a decay product that has a much shorter half-life. For example, Ra-226 has a half-life of about 1,600 years. As this element decays and emits radiation, Rn-222, which has a half-life of about 3.8 days, is produced. Over time (after seven progeny half-lives), an equilibrium is established between the concentration of these two

radioactive progeny — lead-210 (Pb-210), bismuth-210 (Bi-210), and polonium-210 (Po-210) — will eventually reach secular equilibrium with Ra-226 after approximately 150 years because of the longer half-life of Pb-210 (22 years).

Ra-228 has a half-life of 5.8 years. The first progeny of Ra-228 is actinium-228 (Ac-228), which has a short (6.1 hours) half-life, thus yielding rapid ingrowth to secular equilibrium (approximately two days). The Ac-228 isotope decays by beta and gamma emission to Th-228, which has a half-life of 1.9 years. The Th-228 radioactive progeny all have much shorter half-lives than the Th-228 parent, thus resulting in secular equilibrium within one month. Similarly, Th-228 will reach transient equilibrium with the original Ra-228 isotope after approximately five years.

8.2 Contaminant Concentrations at the Time of the Release

In the event of a release, some of the brine overlying the waste would leave the cavern. This brine would contain dissolved contaminants of potential concern. No data are available to show the chemical or radiological characteristics of the cavern brine at the time of release, because no disposal cavern has yet been closed. For the radiological contaminants, the total radium activity in the cavern is assumed to be 2,000 pCi/L in order to be consistent with previous studies (e.g., Smith et al. 1996). A cavern approved for NORM disposal may very well also be authorized to accept NOW; in such a case, the total cavern contents would only contain a small proportion of NORM. As a conservative measure, however, this study assumes that the entire cavern contents would be NORM waste and that any brine released from the cavern would contain 2,000pCi/L of radium. Although definitive data describing the concentration ratio of Ra-226 to Ra-228 is not available, a ratio of 3:1 was used in this study based on Smith et al. (1996). Under these conditions, the Ra-226 activity would be 1,500 pCi/L, and the Ra-228 activity would be 500 pCi/L. In addition, the initial activity of any short-lived progeny was obtained by assuming that the daughters are in secular equilibrium (i.e., their activities would be the same as those of the parents).

8.3 Fate and Transport for Contaminants of Potential Concern

This study analyzes the health risk to humans at a receptor site. That receptor site is assumed to be a drinking water well located 1,000 ft from the cavern in a horizontal direction. For completeness, two well completion depths are considered: (a) a shallow completion in a surficial aquifer (at a depth of 50 ft) and (b) a well completed at the depth of the salt cavern (1,000 ft). For the postulated release scenarios described in Section 8.4.1, brine containing NOW and NORM waste would be discharged from the cavern and enter the surrounding rock or aquifer. The brine and its contaminants would then be transported laterally to the location of the

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elements such that the activity of each element is equal.

receptor well, where they would be pumped to the ground surface. Because of low-permeability layers, no significant vertical migration would occur for releases at the depth of the cavern.

Groundwater flow velocities are typically very slow, so that the time for transport of the contaminants to the receptor site is many years. The chemical and radiological characteristics of the brine after it has reached the receptor site would be different from those at the time of the release because physical, chemical, biological, and radiological processes would modify the brine during the long transit to the receptor site. One example of this that was used by Tomasko et al. (1997) is the retardation coefficient. As a contaminant plume moves away from the cavern release site, some fraction of each contaminant adsorbs onto solid surfaces and effectively retards the velocity of that contaminant's movement. The higher the retardation coefficient, the slower the contaminant migrates.

For radionuclides, initial activities would be reduced over time by radioactive decay, in addition to retardation. Because of large retardation coefficients and/or short half-lives, all of the potential radiological contaminants of concern mentioned in Section 8.1, except for Ra-226 and its decay progeny Rn-222, have been eliminated from the risk analysis. These contaminants of concern are the same as those discussed by Smith et al. (1996) for subsurface disposal. Details on the fate and transport of Ra-226 and Rn-222 are provided below.

The interaction of radium with geological materials and soils is highly variable. Distribution coefficients (mass of solute sorbed on solid surfaces per solid mass divided by the mass of solute per volume of solute [Freeze and Cherry 1979]) range from about 50 mL/g to about 1,000 mL/g (Sheppard et al. 1984). Within the pH range of 4 to 8, radium does not readily form chemical complexes and readily coprecipitates with barium sulfate, carbonates, and ferric hydroxides. To produce conservative results, this study assumed a distribution coefficient of 50 mL/g. Assuming a bulk density of 1.7 g/cm^3 and a porosity of 0.1 for the rock through which the released fluids would travel, [to be compatible with Tomasko et al. (1997)], the retardation coefficient for radium would be about 850. Sorption of radium onto a solid surface produces a retardation of radium's transport velocity in groundwater; that is, the velocity of the center of mass of a contaminant plume of radium will move at a retarded velocity of V/R, where V is the velocity of groundwater and R is a retardation coefficient. For this value of retardation, the velocity of the center of the mass of radium would be 850 times less than that of the groundwater (Freeze and Cherry 1979). In 1,000 years, radium would travel about 12 ft considering a groundwater velocity of 10 ft/year.

The radioactive decay of Ra-226 produces Rn-222 along the flow path between the point of release and the receptor site. Under saturated groundwater conditions, Rn-222 will be in the aqueous phase. If exposed to air, Rn-222 will leave the liquid phase and become a gas (Graves 1989). Because Rn-222 is a noble gas, it will have an inert behavior while in groundwater (Tanner 1964; Sanford et al. 1996) and its distribution coefficient will be essentially zero. It will not undergo significant retardation, and its center of mass will move at about the velocity of the groundwater. Its retardation coefficient is therefore assumed to be 1.0. Even though Rn-222 will move much faster than its parent (Ra-226), as it moves away from the Ra-226 parent, its short half-life quickly reduces its concentration, and high concentrations of radon will occur only in the immediate vicinity of the parent.

8.4 Exposure Assessment

This section provides information needed to estimate the intake of NORM contaminants that increase human health risks. In this study, exposed individuals are expected to be those drinking groundwater contaminated by releases of NORM constituents from salt caverns containing NORM wastes. The exposure pathway would consist of release from the cavern (or casing or seal), transport through groundwater, and human exposure through ingestion of the contaminated groundwater. Potential exposure from inhalation of Rn-222 and its decay products from groundwater use inside a house was also evaluated. This section describes the scenarios and mechanisms that could lead to human exposure to NORM constituents and estimates radiological doses and human health risk to a potential receptor.

Once the cavern was full of waste, it would be sealed and abandoned. At the time of sealing, the cavern would be mostly filled with solids and semisolids that were not fully compacted. Brine would remain between the top of the cavern and the top of the waste mass. The pressure in the cavern would increase because of the combined effects of the addition of sensible heat from the surrounding salt and salt creep. Under these conditions, any breach of the cavern integrity would result in a release of some of the brine that contains soluble chemical and radiological contaminants from the waste. The solid wastes, however, would remain in the cavern.

When risks to the public from disposing of NORM waste in caverns are being assessed, potential release modes must be determined. Currently, little information exists on accidents for cavern disposal systems because there are only a few disposal caverns in operation and they have been operating for only a few years. However, what little accident information exists from disposal and storage caverns indicates that the caverns are safe and that the only accidents that have occurred were associated with surface facilities. Because insufficient information exists to quantify release probabilities for cavern disposal, results from the LPG storage industry and the SPR are used in this study as a basis for identifying potential release scenarios.

Although LPG industries and the SPR have a long history of safe operations, a statistically meaningful database for risk analysis is absent. To overcome this difficulty, a subjective, semiquantitative methodology was developed by Radian Corporation to evaluate risks for the LPG industry (Radian Corporation 1995). This methodology, developed by a panel of experts in the field of salt-cavern conversion for LPG storage, was based on a modified-Delphi approach (Brown and Helmer 1964) in which variability of the estimated parameters is reduced through group interaction. The Radian study identified 22 accident scenarios that could lead to releases to the environment. These accident scenarios can be grouped into three general categories: (1) cavern development and conversion, (2) cavern filling, and (3) post-closure releases. For this NORM waste disposal study, impacts were analyzed only for post-closure releases. Impacts from the first two scenarios are better addressed in a second tier assessment, in which site-specific information would be used and more detailed design parameters would be defined.

Five release scenarios, based on the Radian findings, are discussed in this section: (1) inadvertent intrusion, which could produce a release of cavern fluid to the ground surface; (2) failure of the cavern seal, which could release contaminated fluid to the groundwater (the release could be either at the depth of the cavern or at more shallow depths); (3) release of contaminated fluid through cavern cracks; (4) release of contaminated fluid through leaky interbeds or nonhomogeneous zones of higher permeability material; and (5) a partial cavern roof fall, which could release contaminated fluid to deep or shallow groundwater, depending on the condition of the cavern seal. A discussion of each scenario is provided below.

8.4.1 Cavern Release Scenarios

8.4.1.1 Inadvertent Intrusion

In the inadvertent intrusion scenario, an exploratory well for oil or minerals penetrates a hypothetical waste disposal cavern that has a volume of one million ft^3 (about 7.5 million gal)[4]. If the cavern contains 750,000 ft^3 of waste when full, approximately 2 million gal of brine lies above the waste. Groundwater wells probably would not reach the cavern because drinking or irrigation water could be obtained at shallower depths, and groundwater at the depth of the cavern would probably not be potable because of brine. Tomasko et al. (1997) estimate that a maximum of about 2,000 gal of contaminated fluid would flow from the cavern toward the surface. This value is about 0.1% of the fluid present in the cavern. In addition to brine and dissolved waste constituents, drilling muds and other associated fluids would also flow toward the surface.

If the blowout-protection system of the well failed, fluids from the cavern could spill onto the ground surface and form a pool in the vicinity of the well pad or be discharged into a lined

[4] This volume was selected to be consistent with Tomasko et al. (1997). The actual disposal caverns in Texas are somewhat larger, but are of the same order of magnitude. Hydrocarbon storage caverns, such as those used in the SPR, are much larger. For example, the only Texas disposal cavern located in domal salt has a volume of about 18 million gal. The volume of fluids likely to escape from larger caverns would be proportionately larger than those calculated here, but are estimated to be of the same order of magnitude.

pond. If the discharge occurred directly to the ground and the local topography was depressed, a small surface pond would form. If the pond had a radius of 25 ft, the depth of the spill would be about 1 in. without considering evaporative losses. For a spill this small, fluids from the cavern would not reach the underlying unconfined aquifer that occurs at a median depth of 20 ft, but would form a contaminated zone in the unsaturated soil. If the porosity of the soil was 0.3 (Freeze and Cherry 1979), a mass-conservation calculation shows that the penetration depth of the fluids from the cavern would be less than 6 in. Mobilization of contaminants out of the contaminated zone could then occur by leaching. However, remediation activities at the site (e.g., removal of contaminated soil) would occur before the contaminants could dissolve and be transported by advection and dispersion to the water table.

This scenario is unlikely to occur, however. When issuing underground injection permits, agencies typically request an area of review that identifies active and inactive wells within a certain radius of the proposed well. Disposal caverns should be identified during the area of review. If an inadvertent intrusion still occurs, it would last for a short time and the pond water would be very unappetizing (i.e., the water would have a very high turbidity because of the drilling mud, it would be very salty [saturated brine], it would be oily because of the presence of organic materials, and it would probably have an unpleasant odor). Because the volume of released fluid for this scenario would be small, the effects would be of very short duration, the liquid would not be potable, and such a spill would be quickly remediated, this scenario was eliminated from further analysis.

8.4.1.2 Release through the Cavern Seal

For this scenario, the pressure in the cavern is assumed to become sufficiently high that the cavern seal fails because of a crack in the plug, dissolution of salt around the seal, or by some other means. Contaminated fluid then moves up the wellbore toward the ground as the pressure in the cavern is reduced to the hydrostatic value. The wellbore would have cement plugs installed during cavern closure and abandonment. With time, the well casing might deteriorate because of the presence of brine in the vicinity of the caprock or the top of the cavern if a caprock was not present. For anticipated conditions, the well casing would corrode and fail near the top of the cavern first. With additional time, the well casing would fail at shallower depths.

If the cavern had an initial brine volume of 1,000,000 ft^3 and it was filled to three-quarters capacity with NOW and NORM, about 250,000 ft^3 of free brine and 750,000 ft^3 of waste would be present. Tomasko et al. (1997) report that if the cavern failed at a pressure equal to the lithostatic value (approximately 1,500 psi for a cavern located at a depth of 1,500 ft), a maximum of only about 0.1% of the free liquid (about 2,000 gal) would exit the cavern because of the effects of compressibility (Streeter 1961), assuming the wellbore was free of liquid and at atmospheric pressure. If the well bore contained water, or if the released volume was greater than the volume of the wellbore up to the location of the deepest plug, less than 0.1% of the fluid would escape from the cavern. For conservative results, this study assumes that the full 0.1% volume would be released.

Flow of the released fluid would be greatly restricted in the wellbore at the locations of the cement plugs. Flow through the cement plugs would resemble flow through a porous medium having a low hydraulic conductivity (about 1×10^{-8} to 1×10^{-5} cm/s); we conservatively assumed that the hydraulic conductivity would be similar to that of cemented sandstone (Maidment 1993). If the cavern fluid moved up the borehole at a rate equal to the saturated hydraulic conductivity of the cement (Freeze and Cherry 1979), it would have a velocity of between 3×10^{-5} and 3×10^{-2} ft/d. For a cavern at a depth of 1,500 ft, fluid would not reach the surface for about 140 years if the well casing remained intact and evapotranspiration did not deplete the volume of free liquid near the ground surface.

While moving up the borehole, fluid from the cavern could also move laterally into adjoining formations if the well casing had failed. Because the casing would probably be made of ordinary steel, there is a high probability that it would fail when exposed to groundwater containing brine over a time period ranging into the thousands of years. Two possible cases are considered under this scenario: (1) the casing fails at the depth of the cavern (at or near the cavern roof) and contaminated fluid is released to a deep aquifer and (2) the casing fails at a shallow depth and releases fluid to a near-surface aquifer. The released fluid is then transported horizontally to the receptor site. Because of hydrogeological differences between the aquifers considered, these scenarios are discussed separately below.

For a deep casing failure, fluid moving up the wellbore would move into the deep aquifer and be transported laterally. The presence of low-permeability beds at shallower depths would prevent vertical transport of the contaminated fluid to overlying aquifers and the ground surface. If the wellbore had a diameter of 2 ft and the ambient groundwater velocity was 10 ft/yr, contaminated water would enter the surrounding porous medium for a period of about 0.2 year.

The extent and magnitude of contamination created by this type of release would depend on the hydrological properties of the material in the vicinity of the failed casing, the volume of fluid that was released, the duration of the discharge, and the transport properties of the contaminants. In the vicinity of the cavern, hydrological properties are unlikely to favor rapid transport of the contaminants. For example, the groundwater velocity at depth is estimated on the basis of engineering judgment to be less than 10 ft/yr. Because of adsorption and subsequent retardation, contaminants (particularly metals and Ra-226) would be transported at even lower velocities.

Data needed to conduct a risk assessment include not only the extent of contamination created by the release, but also the concentration of the contaminant. In general, the downstream concentrations of contaminants depend on the length of time that the cavern acts as a source of contaminated fluid. For either a release at the depth of the cavern or to a shallow aquifer, the cavern is assumed, through engineering judgement, to depressurize to conditions in the wellbore within one day, a conservative assumption. Fluid released during the depressurization would then be swept into adjacent aquifers by moving groundwater (10 ft/yr at the depth of the cavern or 100 ft/yr for a shallow release). Under these conditions, a 2-ft wellbore would act as a source of contamination for 0.2 and 0.02 years at the depth of the cavern and in a shallow aquifer, respectively. After the system depressurized, salt creep would once again occur, and the pressure in the cavern would increase, particularly if the point of failure self-heals. Because of this repressurization, the seal might again fail, and the process would then repeat itself as a series of short, pulsed releases. Because the time between releases would be long (repressurization is a slow process), the pulses of contamination would not interact with each other along the flow path.

After release, the contaminants would be transported in the direction of lower hydraulic head (pressure) and would undergo sorption (loss of material to particle surfaces), dispersion (reduction in concentration produced by nonuniform fluid velocities), degradation (decrease in concentration produced by chemical or biological interactions), and radioactive decay. Calculations for radionuclide concentrations at the receptor site were performed with a one-dimensional analytical solution (Tomasko 1991; 1994) that incorporates advection, dispersion, sorption, and radioactive decay of the parent radionuclides. Progeny product activity was estimated by assuming secular equilibrium.

For transport calculations, the groundwater velocity was assumed to be 10 ft/yr and dispersion was assumed to be scale dependent; dispersivity was set equal to one-tenth of the travel distance (Lallemand-Barres and Peaudecerf 1978). Contaminant concentrations in the groundwater were evaluated at the receptor site at a time of 1,000 years in the future, a typical value for risk analyses. A compilation of contaminant concentrations for these conditions is given in Table 3. The 1,000-year value was selected for consistency with risk analyses performed for the NOW material. The risk calculations are intended to estimate the risk over the 1,000 years following cavern sealing. It is unlikely that an abandoned cavern would begin leaking immediately after being sealed. Leakage, if it occurred, would most likely begin many years after the cavern was sealed. The fate and transport models, however, estimate the concentration of contaminants at a time 1,000 years after the release of contaminants, not after cavern sealing. Therefore, the risk estimates are effectively measuring the risk over a period of time longer than 1,000 years. This provides an additional measure of conservatism to the risk estimates. Because NORM is not considered to be a low-level waste (DOE Order 5820.2A - DOE 1988), more stringent calculations, such as evaluating the maximum concentration within 10,000 years (NRC 1981), is not required.

For the second alternative, the cavern seal is again assumed to fail; however, the well-bore casing at depth is assumed to be intact. Contaminated fluid would then flow up the well-bore and exit the casing at a failure point adjacent to a shallow groundwater aquifer, such as the Dockum or the Ogallala. The initial concentration of the contaminants entering the system would be the same as for the scenarios discussed above, and there would be no substantial dilution. The duration of the source term would be 10 times less than that used at depth because of the higher groundwater velocity in the shallow groundwater system (100 ft/yr). For a release to shallow groundwater, the radionuclide activities would be larger than those discussed above for releases to deep aquifers because of shorter travel time and fewer half-life decays (Table 2). In spite of the higher velocity and shorter travel time for a shallow groundwater release, the radionuclide concentrations at the receptor site 1,000 years after the release would all be much less than the proposed or final EPA maximum contaminant levels (MCLs). The final MCL for combined Ra-226 and Ra-228 is 5 pCi/L (40 CFR 141.15). The EPA's proposed MCLs for Ra-226 and Ra-228 are 20 pCi/L and for radon is 300 pCi/L (July 18, 1991 *Federal Register*, 56 FR 33050).

8.4.1.3 Release of Contaminated Fluid through Cracks

During pressurization of the cavern because of the combined effects of thermal heating and salt creep, cracks might develop that would release fluid into the surrounding material, thereby reducing the pressure in the cavern. The volume of fluid released would be a function of the pressure in the cavern, the volume of the cracks, and the crack pressure. If the pressure in the cracks was atmospheric, the volume of fluid released would be the same as that discussed under the previous scenario (2,000 gal). However, the actual volume released could be much less if the cracks were at the local hydrostatic or lithostatic pressure. For conservative results, the volume of released fluid is assumed to be 2,000 gal.

Cracks could self-heal after fluid release because of additional salt creep. With repressurization of the cavern, the cracks could once again open and produce a series of short contaminant pulses (probably on the order of hours to days in duration). These pulses would not interact with one another because of the time needed to repressurize the cavern to a value that approaches or exceeds the local lithostatic value. Because of gradients in the lithostatic pressure, cracks would open in a vertically upward direction (Diamond 1997). With time, the contaminated fluid in the cracks could reach a deep underground aquifer and be transported laterally to the location of a potential receptor (assumed to be 1,000 ft away from the point of release).

The contaminant concentrations at the location of the receptor 1,000 years after the release into the underground aquifer would be the same as those presented above for failure of the cavern seal with a subsequent pulsed release at the depth of the cavern. The resulting contaminant concentrations would all be much less than their associated MCLs.

8.4.1.4 Release of Contaminated Fluid through Leaky Interbeds or Nonhomogeneous Zones

For this scenario, the cavern is assumed to have a leaky interbed or heterogeneity that allows communication with the outside environment. As the cavern pressure rose because of thermal effects and salt creep, fluid would be discharged into the interbed, where it would be laterally transported under existing hydraulic gradients. Fluid velocity in the interbed is assumed to be 10 ft/yr. In this way, the entire fluid volume of the cavern would eventually be discharged into surrounding material.

Assuming a cavern height of 1,750 ft (top of cavern at a depth of 1,500 ft plus 250 ft of free brine), Tomasko et al. (1997) calculated that it would take about 14,000 years to discharge the cavern fluid to the interbed for a steady-state volumetric creep rate of -0.007%/yr based on typical salt parameters and a cavern depth of 1,500 ft. For 2 million gal of free brine in the cavern, the steady-state leak rate would, therefore, be about 150 gal/yr.

The leaking brine would mix with in-situ water and be transported down gradient. Because of this mixing, the contaminant concentrations would be reduced by dilution. For a cavern with a diameter of 100 ft, an interbed thickness of 20 ft, and a groundwater velocity of 10 ft/yr, the dilution factor would be 1,000 (Tomasko 1991; Tomasko et al. 1997).

Table 2 lists the contaminant concentrations at the receptor site for this scenario at a time of 1,000 years after the cavern has begun to leak. All of the concentrations are very small compared with their MCLs.

8.4.1.5 Partial Cavern Roof Fall

Loss of cavern integrity through a partial roof fall coupled with failure of the cavern seal could produce impacts similar to those described in Section 8.4.1.2. Under these conditions, the cavern would discharge fluid in a series of short pulses separated by periods of low to no discharge when the pressure in the cavern was increasing because of salt creep. If a partial roof fall occurred without failure of the cavern seal, contaminated fluid would be released in a series of short pulses. A partial roof fall coupled with a release through leaky interbeds or non-homogeneous zones of higher permeability material would be manifested as a long, slow release. Contaminant concentrations for these various scenarios are given in Table 3.

8.4.2 Probabilities of Occurrence

Another factor that is needed in performing a risk assessment, in addition to the concentrations of the contaminants of concern, is the probability that a given scenario would occur. Because there is no operational history for disposing of NOW in salt caverns, the probabilities of occurrence for the release scenarios described above are uncertain. Under the most optimistic conditions, no releases would ever occur, and the associated probabilities of occurrence would be zero. For the most pessimistic conditions, releases would always occur and the probabilities of occurrence would be 1.0.

To reduce the uncertainty in the range of the probabilities of occurrence, Tomasko et al. (1997) distributed a questionnaire to experts in the field of salt disposal. The panel of experts was asked to provide both a "best-estimate" and a "worst-case" estimate of the probability of occurrence for each of the release scenarios. In the context of this questionnaire and study, best estimate did not refer to the "best-case" or the best or least risky case, but rather it referred to the probability of occurrence that was most likely in the best judgment of the expert. Similarly, "worst-case" referred to the least likely probability of occurrence in the best judgment of the expert, rather than to the most risky case.

The estimates received from the expert panel were aggregated to form consensus values for each of the probabilities of occurrence. Table 4 lists the best-estimate and worst-case aggregated probabilities of occurrence (and their ranges) for the release scenarios previously discussed (Tomasko et al. 1997). For all cases, the highest probabilities of occurrence were for a partial fall of the roof (0.10 and 0.29, respectively). The lowest probabilities of occurrence were for: (a) a partial roof fall with a cavern seal failure and release to a shallow aquifer (0.006 and 0.051, respectively), and (b) a cavern seal failure with subsequent release to a shallow aquifer (0.012 and 0.040, respectively).

To provide an even more conservative estimate, we additionally calculated the true worst case condition by assuming that all caverns would have releases during the 1,000-year period of concern (i.e., probability = 100%). This situation is shown on Figures 4, 5, and 6 as the 100% Probability of Release case.

8.4.3 Exposure Point Concentrations

Section 8.4.1 provides estimates of concentrations at the receptor site (1,000 ft laterally from the point of release), assuming NORM constituents are released from the salt cavern. Section 8.4.2 provides best- and worst-case estimates of the probabilities that each of these release scenarios would occur. The exposure point concentration used in estimating risk is the product of the expected concentration, assuming release occurs, and the estimated probability of occurrence. Table 5 summarizes the exposure point concentrations for Ra-226 for each scenario, assuming best- and worst-case probabilities of occurrence. Exposure to Rn-222 in indoor air could also occur following volatilization during showering. A worst-case bounding estimate of potential risk associated with the inhalation pathway was evaluated on the basis of the worst-case scenario (i.e.,100% Probability of Release case, roof fall and cavern seal failure and release at shallow depth). The estimated Rn-222 exposure point concentration in groundwater for this scenario is 4×10^{-9} pCi/L. It was estimated that the activity concentration of Rn-222 in indoor air following volatilization from groundwater would be 0.01% of the initial concentration in the groundwater (i.e., 4×10^{-13} pCi/L) (Milvy and Cothern 1990). The exposure point concentration, which for inhalation is expressed in units of working level (WL), is equivalent to 1×10^{-15} WL (assuming an equilibrium factor of 0.267).

8.4.4 Estimation of Radiological Doses and Carcinogenic Risks

Radiation exposure pathways can be separated into external and internal components. External exposure, which occurs when the radioactive material is outside of the body, is a concern primarily only for gamma radiation because it can easily penetrate tissue and reach internal organs. Internal exposure occurs when the radioactive material is taken into the body through inhalation or ingestion. For internal exposures, alpha and beta particles constitute the dominant concern because their energy is almost completely absorbed in cells and because of their potential for causing biological harm. For this study, the only exposure pathway considered is ingestion of groundwater, hence exposures are limited to internal exposures.

Exposure to internally deposited radioactive contaminants is expressed in terms of the 50-year committed effective dose equivalent (CEDE). This concept, developed by the International Commission on Radiological Protection (ICRP 1977), represents the weighted sum of the dose equivalent in various organs. The CEDE incorporates consideration of the radiosensitivity of different organs, the biological effectiveness of different types of radiation, and the variable retention time in the body for different radionuclides. The unit of dose equivalent is the rem (or mrem, 10^{-3} rem). A rem measures the ability of a specific type of radiation to damage biological tissue.

The metabolic behavior of radium in the body is similar to that of calcium. Thus, a fraction of ingested radium is deposited in bone, where it can remain over a long period. Chronic intake of radium can result in very high concentrations in the bone and cause ionization of cellular components in bone and the subsequent mutation of affected cells. For this study, CEDEs for Ra-226 were calculated by using the appropriate dose conversion factor (DCF) provided in Federal Guidance Report 11 (EPA 1988), and the following equation:

$$CEDE = C_i \times I_{ing} \times EF \times ED \times DCF_{ing},$$

where:

CEDE = committed effective dose equivalent (mrem),
Ci = exposure point concentration/activity (pCi/L),
I_{ing} = ingestion rate (L/day) - assumed to be 2 L/day,
EF = exposure frequency (d/yr) - assumed to be 350 d/yr,
ED = exposure duration (yr) - assumed to be 70 yr, and
DCF_{ing} = ingestion dose conversion factor for Ra-226 (1.3×10^{-3} mrem/pCi).

The resulting CEDEs are shown in Table 5. The highest estimated CEDE is 1×10^{-8} mrem. For comparison purposes, Americans receive an average dose of 360 mrem per year (or roughly 36 billion times as much) from natural radiation.

Doses resulting from inhalation of radon were calculated as follows:

$$WLM = C_{wl} \times I_{inh} \times ET \times EF \times ED / CF,$$

where:

WLM = working level month(s),
C_{wl} = exposure point concentration (WL),
I_{inh} = inhalation rate (m^3/h) – assumed to be 0.83 m^3/h,
ET = exposure time (h/d) – assumed to be one 10-minute shower per day (0.17 h/d),
CF = conversion factor for inhalation (204 m^3/mo) – the product of the inhalation rate (1.2 m^3/h) and the number of working hours in 1 month (170 h/mo).

The maximum upper-bound estimate of dose to a resident from inhalation of indoor radon is 2×10^{-14} WLM.

The major radiological health concern from exposure to NORM is induction of cancer. The EPA classifies all radionuclides as Group A (known) carcinogens. Radionuclides are also mutagenic (can cause genetic mutations), teratogenic (can cause birth defects), and highly toxic. However, because the cumulative risk of cancer is many times greater than the risk of genetic or teratogenic effects (EPA 1989) and because there are so few data quantifying the relationships between dose and effect for noncancer effects of low doses of Ra-226, only cancer risks are estimated in this report.

The development of radiation-induced cancer is a stochastic process and is considered to have no threshold dose (i.e., the probability of occurrence, not the severity of effect, increases with dose, and there is no dose level below which the risk is zero). The relationship between radiation dose and development of cancer is well characterized for high doses of most types of radiation, but for low doses it is not well defined. Low levels of radiation exposure may present a health risk, but it is difficult to establish a direct cause-and-effect relationship because of the lack of data and the presence of compounding environmental stresses. Therefore, the risk from low levels of radiological exposure must be extrapolated from data for increased rates of cancers observed at higher doses. For this assessment, radiation doses associated with ingestion were converted to carcinogenic risks by using risk factors given in ICRP Publication 60 (ICRP 1991). The ICRP risk factors for the public are 5×10^{-7} per mrem for the increased probability of fatal cancer over a lifetime, and 6×10^{-7} per mrem for the increased probability of cancer incidence over a lifetime. The estimated dose from inhalation of Rn-222 and its decay products (in units of WLM) was converted to risk using a risk factor of 3.5×10^{-4} per WLM recommended in the BEIR IV study (National Research Council 1988).

The risk levels from Ra-226 calculated on the basis of these assumptions are shown in Table 5. The highest estimated cancer risk due to NORM released from salt caverns is 1×10^{-13} for the 100% Probability of Release case for the failure pathway that assumes roof falls, cavern seal failures, and contaminant release at shallow depth. The lowest estimated risk, 7×10^{-24}, is for the best-estimate probability for the failure pathway in which fluid is released from a crack.

The risk from exposure to indoor Rn-222 is insignificant (i.e., orders of magnitude lower) in comparison with the risk estimated for ingestion of groundwater. The maximum risk from inhalation of Rn-222 was estimated to be 6×10^{-18} for the worst-case scenario (compared with the maximum risk from Ra-226 ingestion, 1×10^{-13}). The cancer risks presented in Table 5 for ingestion of Ra-226 in groundwater are representative of the cumulative lifetime risk resulting from all radionuclides and pathways because the incremental risk from inhalation of Rn-222 is negligible. Estimated lifetime risks due to NORM and NOW releases from salt caverns are presented in Table 6. The maximum estimated lifetime risk from NORM is 1×10^{-13}; the maximum estimated lifetime risk from NOW is 2×10^{-7}. These maximum risks occur for the 100% Probability of Release case; the best-case and worst-case estimate scenarios have even lower risks. The risks from Ra-226 are several orders of magnitude lower than NOW, and they can be considered insignificant in comparison. In all cases, the estimated NORM and NOW human health risks due to ingesting groundwater contaminated with NOW and NORM releases from disposal in salt caverns are significantly below the target risk range (10^{-4} to 10^{-6}) that the EPA established for remedial actions at National Priority List sites (40 CFR 300.430(e)(2)(i)(A)(2)).

The chemical constituents of NORM pose a noncancer as well as a cancer risk. On the other hand, the radiological constituents of NORM are considered to pose only a cancer risk. Therefore, the noncancer risk of NORM waste is the same as the noncancer risk attributed to NOW. Tomasko et al. (1997) estimated worst-case noncancer risks (expressed as hazard quotients) for NOW ranging from 6×10^{-5} to 1×10^{-7}. The accepted risk threshold for noncancer risks is a hazard quotient of less than 1.0.

8.5 Uncertainties

The approach outlined in the previous sections is subject to several uncertainties that could affect the results. However, because the estimated risks are so low, it is doubtful that resolving the uncertainties would cause the risks to increase so much that they would become significant. Uncertainties that could affect the results include the following:

- *Extrapolation from high levels to low levels of radiation exposure.* The estimated risks presented in this study are based on the assumption that no lower threshold exists for radiation carcinogenesis, so health effects increase linearly with radiation dose. Such extrapolation of data from studies of human populations exposed to high levels of radiation to much lower doses is a major source of uncertainty in determining the risk of cancer from exposure to low levels of ionizing radiation.

- *Modeled exposure data.* Because no waste disposal caverns have been used for NORM wastes, and no cavern used for NOW has been closed, no actual data exist for use in the analysis. Although the authors believe the models and assumptions used in this study are appropriate, there are no data to verify their accuracy.

- *Effect of Background.* It is difficult to distinguish background concentrations of radionuclides from introduced concentrations.

8.6 Sensitivity of Risks to Operating Procedures and Regulatory Structures

The risk estimates calculated above indicate that the potential for human health risks associated with disposal of NORM waste in salt caverns is very low. These risks were estimated assuming normal operating conditions and standard operating procedures for cavern closure. Any relaxation in design, monitoring, or operating practices could increase these risks.

Although the risks associated with spills, accidents, and equipment leaks during normal operations were not evaluated in this study, it is likely that contaminants released during such occurrences would present greater risks than those derived from the cavern itself. Consequently, care should be taken to ensure that operating practices continue to be monitored in a way that minimizes the occurrence of surface accidents.

9. Findings and Conclusions

NORM contamination is found in some oil field produced water, pipe scale, and sludge. Spills or releases of these materials have contaminated soil at some sites. The majority of NORM waste is currently being disposed of through underground injection, particularly at one commercial disposal facility in Texas. NORM waste is also disposed of through burial in landfills, encapsulation inside the casing of wells being plugged and abandoned, and land spreading. Several companies are now or soon will be disposing of NORM on an operator's site by treatment and disposal through the operator's injection well. This report evaluates the technical feasibility, legality, economics, and human health risk of an alternative NORM waste disposal option — disposal in salt caverns. The major findings and conclusions of the report follow.

9.1 Technical Feasibility

NORM waste is physically and chemically similar to nonhazardous oil field waste (NOW). Its primary difference from NOW is the presence of radionuclides in NORM waste. The presence of radionuclides may require additional safety precautions when handling the NORM waste, but the actual disposal process would be no different from that for NOW. NOW waste is currently being disposed of without difficulties in four U.S. salt caverns and in several Canadian caverns. There is no technical reason why these caverns or other future disposal caverns could not equally well accept NORM waste other than produced water, which is disposed of primarily by injection.

9.2 Legality

No existing federal regulations specifically address handling and disposal of NORM wastes. In the absence of federal regulations, individual states have taken responsibility for developing their own regulatory programs. These programs have been evolving rapidly over the last few years. Salt caverns used for disposal of oil field wastes are considered to be Class II injection wells under most state regulations. A review of federal UIC regulations and NORM and UIC regulations from the five states that have expressed some interest in cavern disposal indicated that there are no outright prohibitions against NORM disposal in salt caverns, except for Louisiana, which prohibits disposal of radioactive wastes or other radioactive materials in salt domes. Presently, however, only Texas and New Mexico are working on disposal cavern regulations, and no states have issued permits to allow cavern disposal of NORM waste.

9.3 Economics

Current NORM waste disposal costs range from $15/bbl to $420/bbl. These costs reflect the information provided by disposal companies to the authors in early 1998 and may not reflect actual total disposal costs. It is also difficult to compare cost figures from one disposal company to another because the companies do not always include the same types of services in their quoted prices.

None of the existing Texas NOW disposal cavern operators have made even preliminary estimates of what they would charge to dispose of NORM waste if the regulatory agency gave them approval to do so. NOW disposal caverns have proven cost competitive with other NOW disposal facilities in the same geographic area. This study does not constitute a formal market analysis, and the costs to upgrade a cavern disposal operation for NOW to one that disposes of NORM waste have not been quantified. Nevertheless, there is a reasonable chance that NORM waste disposal cavern companies would be able to install the additional waste handling equipment and implement expanded monitoring and worker safety procedures and still compete economically with existing off-site commercial NORM disposal facilities once regulatory agencies allow the practice to occur.

9.4 Human Health Risk

Caverns are located deep below the earth's surface. The process of filling caverns with waste is performed at low pressure and should not cause cavern failure. Following cavern plugging and closure, internal cavern pressure could increase from salt creep and geothermal heating to a point at which leaks or releases might occur. Even if such releases did occur, the likelihood that contaminants would migrate off-site to a potential human health receptor site (a drinking water well) is small. On the basis of assumptions that were developed for a generic cavern and generic NORM wastes, the estimated worst-case human health risks from the chemical contaminants of NORM waste are very low (excess cancer risks of between 1×10^{-8} and 2×10^{-17}), and the hazard quotients (referring to noncancer health effects) for NOW are between 6×10^{-5} and 1×10^{-7}. These values are identical to the risks estimated by Tomasko et al. (1997). Even under the extremely conservative 100% Probability of Release case, the highest risk from the chemical contaminants of NORM waste is 2×10^{-7}. Normally, risk managers consider risks of less than 1×10^{-6} and hazard quotients of less than 1.0 to be acceptable. The excess cancer risks estimated for the radiological contaminants are orders of magnitude lower; even for the 100% Probability of Release Case, risks are estimated at 1×10^{-13} to 3×10^{-22} and, consequently, are dwarfed by the risks from the chemical contaminants. No noncancer health risks were estimated for radionuclides.

The risk calculations are intended to estimate the risk over the 1,000 years following cavern sealing. It is unlikely that an abandoned cavern would begin leaking immediately. Leakage, if it occurred, would most likely begin many years after the cavern was sealed. The fate and transport models, however, estimate the concentration of contaminants at a time 1,000 years after their release, not after cavern sealing. Therefore, the risk estimates are effectively measuring the risk over a period of time longer than 1,000 years. This provides an additional measure of conservatism to the risk estimates.

The size of the hypothetical cavern used in these risk calculations is somewhat smaller than the existing disposal caverns in Texas. The volume of fluid released from the cavern would be proportional to the total volume of the cavern; therefore, larger caverns would release proportionately more fluid. Because actual cavern volumes are on the same order of magnitude as the hypothetical cavern, the estimated risks from the actual caverns are expected to be on the same order of magnitude as those calculated here, which remain lower than accepted risk thresholds.

9.5 Conclusions

This report provides evidence that cavern disposal of NORM waste poses a very low human health risk and is most likely technically feasible. From a legal perspective, there are no "fatal flaws" that would prevent a state regulatory agency from approving cavern disposal of NORM, except for Louisiana, which prohibits disposal of radioactive wastes or other radioactive materials in salt domes. Agencies in the other states may need to revise their NORM waste management or UIC regulations to accommodate the practice, however, and Louisiana would additionally need to modify its statute.

Cavern operators would probably charge more for NORM waste disposal than the $1.95/bbl to $6/bbl that they currently charge for NOW disposal. Given that those companies handling most of the NORM waste are currently charging $100/bbl or more for NORM waste disposal, there is probably plenty of leeway to make facility upgrades and still produce a profit. The ability for a NORM waste disposal cavern to be cost competitive looks promising, assuming regulatory agencies approve the practice.

10. References

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Table 1 - 1992 NORM Disposal Costs (from API 1996)

Disposal Method	Disposal Cost per 55-gal Drum			Additional Costs
	Low	Average	High	
Landfill - Washington	$395	$515	$730	None
Landfill - Utah	$300	$500	$700	Radiological analysis, physical properties check, transportation, waste profile, decontamination of vehicle
Surface treatment - Louisiana	$100	$210	$325	Radiological and chemical analysis, physical properties check, transportation, waste profile, packing
Injection - Texas	$49	$206	$1,000	Radiological and chemical analysis, physical properties check, transportation, waste profile, packing
Recycling steel - China	No cost - steel purchase price pays for transportation costs			
Encapsulation in pipes and disposal in abandoned wells	$792	$1,081	$3,333	None
Injection into private wells	$151	$916	$2,300	None

Table 2 - 1998 Commercial Disposal Costs for NORM

Disposal Company	Disposal Method	On-site/Off-site	Costs ($/bbl)
Newpark Environmental Services, Inc.	Injection	Off-site	$150
Lotus LLC	Injection	Off-site	$100
US Ecology	Landfill	Off-site	$380 - $420
Envirocare of Utah, Inc.	Landfill	Off-site	Variable - no costs provided
BPF, Inc.	Treatment/injection	On-site	$140[a]
Apollo Services	Injection	On-site	$100 - $300
National Injection Services	Injection	On-site	$15 - $150

[a] BPF is not in commercial operation as of summer 1998. The costs presented here are projected costs for commercial-scale operation.

Table 3 - Summary Table of NORM Activities for Release Scenarios

Release	Contaminant	Retardation	Initial Activity Concentration (pCi/L)	Activity Concentration at 1,000 yr (pCi/L) after Contaminant Migrates Away from Cavern
Cavern seal fails, releases fluid at depth	Ra-226	850	1,500	8.1×10^{-18}
	Rn-222	1	1,500	8.1×10^{-18}
Cavern seal fails, releases fluid to shallow aquifer	Ra-226	850	1,500	4.1×10^{-9}
	Rn-222	1	1,500	4.1×10^{-9}
Release from crack	Ra-226	850	1,500	8.1×10^{-18}
	Rn-222	1	1,500	8.1×10^{-18}
Release from leaky interbed	Ra-226	850	1,500	1.5×10^{-13}
	Rn-222	1	1,500	1.5×10^{-13}
Roof fall + release at depth through crack	Ra-226	850	1,500	8.1×10^{-18}
	Rn-222	1	1,500	8.1×10^{-18}
Roof fall + release at depth through leaky interbed	Ra-226	850	1,500	1.5×10^{-13}
	Rn-222	1	1,500	1.5×10^{-13}
Roof fall + cavern seal failure + release at depth	Ra-226	850	1,500	8.1×10^{-18}
	Rn-222	1	1,500	8.1×10^{-18}
Roof fall + cavern seal failure + release at shallow depth	Ra-226	850	1,500	4.1×10^{-9}
	Rn-222	1	1,500	4.1×10^{-9}

Table 4 - Probabilities of Occurrence for Specified Release Scenarios

Release Scenario	No. of Responses	Best-Case Estimate[a]	Range	Worst-Case Estimate[b]	Range	100% Probability of Release Case[c]
Cavern seal fails, releases fluid at depth	5	0.031	0.0005 to 0.1	0.12	0.002 to 0.25	1.0
Cavern seal fails, releases fluid to shallow aquifer	5	0.012	0.0001 to 0.05	0.040	0.001 to 0.10	1.0
Release from crack	5	0.022	0.0001 to 0.10	0.120	0.001 to 0.35	1.0
Leaky interbeds release fluid at depth	5	0.022	0.0001 to 0.10	0.120	0.001 to 0.35	1.0
Roof fall + release at depth through crack	5	0.100	10^{-6} to 0.50	0.290	10^{-5} to 1.0	1.0
Roof fall + release at depth through leaky interbed	5	0.062	5×10^{-6} to 0.2	0.163	2×10^{-5} to 0.35	1.0
Roof fall + cavern seal failure + release at depth	5	0.062	5×10^{-6} to 0.2	0.163	2×10^{-5} to 0.35	1.0
Roof fall + cavern seal failure + release at shallow depth	5	0.006	1×10^{-7} to 0.02	0.051	1×10^{-6} to 0.10	1.0

[a] Most likely probability of the release scenario occurring as estimated by an expert panel.
[b] Least likely probability of the release scenario occurring as estimated by an expert panel.
[c] Probability that the release scenario will occur at every cavern during the 1,000-yr period of concern (the true worst-case circumstance).

Table 5 - Exposure Point Concentrations, Committed Effective Dose Equivalents, and Carcinogenic Risks Estimated *for Ingestion of Ra-226 in Groundwater*[a]

	Best-Case Probability Estimates			Worst-Case Probability Estimates			100% Probability of Release Case		
Release Scenario	Exposure-point Concentration (pCi/L)	Committed Effective Dose Equivalent	Estimated Cancer Risk	Exposure-point Concentration (pCi/L)	Committed Effective Dose Equivalent	Estimated Cancer Risk	Exposure-point Concentration (pCi/L)	Committed Effective Dose Equivalent	Estimated Cancer Risk
Cavern seal fails, releases fluid at depth	3×10^{-19}	2×10^{-17}	1×10^{-23}	1×10^{-18}	6×10^{-17}	4×10^{-23}	8×10^{-18}	5×10^{-16}	3×10^{-22}
Cavern seal fails, releases fluid to shallow aquifer	5×10^{-11}	3×10^{-9}	2×10^{-15}	2×10^{-10}	1×10^{-8}	6×10^{-15}	4×10^{-9}	2×10^{-7}	1×10^{-13}
Release from crack	2×10^{-19}	1×10^{-17}	7×10^{-24}	1×10^{-18}	6×10^{-17}	4×10^{-23}	8×10^{-18}	5×10^{-16}	3×10^{-22}
Release from leaky interbed	3×10^{-15}	2×10^{-13}	1×10^{-19}	2×10^{-14}	1×10^{-12}	7×10^{-19}	2×10^{-13}	1×10^{-11}	5×10^{-18}
Roof fall + release at depth through crack	8×10^{-19}	5×10^{-17}	3×10^{-23}	2×10^{-18}	1×10^{-16}	9×10^{-23}	8×10^{-18}	5×10^{-16}	3×10^{-22}
Roof fall + release at depth through leaky interbed	9×10^{-15}	6×10^{-13}	4×10^{-19}	2×10^{-14}	2×10^{-12}	9×10^{-19}	2×10^{-13}	1×10^{-11}	5×10^{-18}
Roof fall + cavern seal failure + release at depth	5×10^{-19}	3×10^{-17}	2×10^{-23}	1×10^{-18}	8×10^{-17}	5×10^{-23}	8×10^{-18}	5×10^{-16}	3×10^{-22}
Roof fall + cavern seal failure + release at shallow depth	2×10^{-11}	2×10^{-9}	9×10^{-16}	2×10^{-10}	1×10^{-8}	8×10^{-15}	4×10^{-9}	2×10^{-7}	1×10^{-13}

[a] Risks presented in this table are solely from the radiological constituents of NORM and do not include any risks from the chemical constituents of NORM.

Table 6 - Estimated Cancer Risks and Hazard Quotients from NORM and NOW

Release Scenario	Best-Case Estimate			Worst-Case Estimate			100% Probability of Release Case		
	Cancer Risk		Hazard Quotient	Cancer Risk		Hazard Quotient	Cancer Risk		Hazard Quotient
	NOW[a]	NORM[b]		NOW[a]	NORM[b]		NOW[a]	NORM[b]	
Cavern seal fails, releases fluid at depth	5×10^{-18}	1×10^{-23}	7×10^{-8}	2×10^{-17}	4×10^{-23}	3×10^{-7}	2×10^{-16}	3×10^{-22}	2×10^{-6}
Cavern seal fails, releases fluid to shallow aquifer	3×10^{-9}	2×10^{-15}	1×10^{-5}	9×10^{-9}	6×10^{-15}	5×10^{-5}	2×10^{-7}	1×10^{-13}	1×10^{-3}
Release from crack	4×10^{-18}	7×10^{-24}	5×10^{-8}	2×10^{-17}	4×10^{-23}	3×10^{-7}	2×10^{-16}	3×10^{-22}	2×10^{-6}
Release from leaky interbed	3×10^{-16}	1×10^{-19}	2×10^{-8}	1×10^{-15}	7×10^{-19}	1×10^{-7}	1×10^{-14}	5×10^{-18}	6×10^{-7}
Roof fall + release at depth through crack	2×10^{-17}	3×10^{-23}	2×10^{-7}	5×10^{-17}	9×10^{-23}	6×10^{-7}	2×10^{-16}	3×10^{-22}	2×10^{-6}
Roof fall + release at depth through leaky interbed	7×10^{-16}	4×10^{-19}	5×10^{-8}	2×10^{-15}	9×10^{-19}	1×10^{-7}	1×10^{-14}	5×10^{-18}	6×10^{-7}
Roof fall + cavern seal failure + release at depth	1×10^{-17}	2×10^{-23}	1×10^{-7}	3×10^{-17}	5×10^{-23}	4×10^{-7}	2×10^{-16}	3×10^{-22}	2×10^{-6}
Roof fall + cavern seal failure + release at shallow depth	1×10^{-9}	9×10^{-16}	7×10^{-6}	1×10^{-8}	8×10^{-15}	6×10^{-5}	2×10^{-7}	1×10^{-13}	1×10^{-3}

[a] This is the risk from the chemical constituents of NORM waste. It is exactly the same as the risk from NOW as reported in Tomasko et al. (1997).
[b] This is the risk from the radiological constituents of NORM waste.

Figure 1 - Major U.S. Subsurface Salt Deposits

(from Veil et al. 1996)

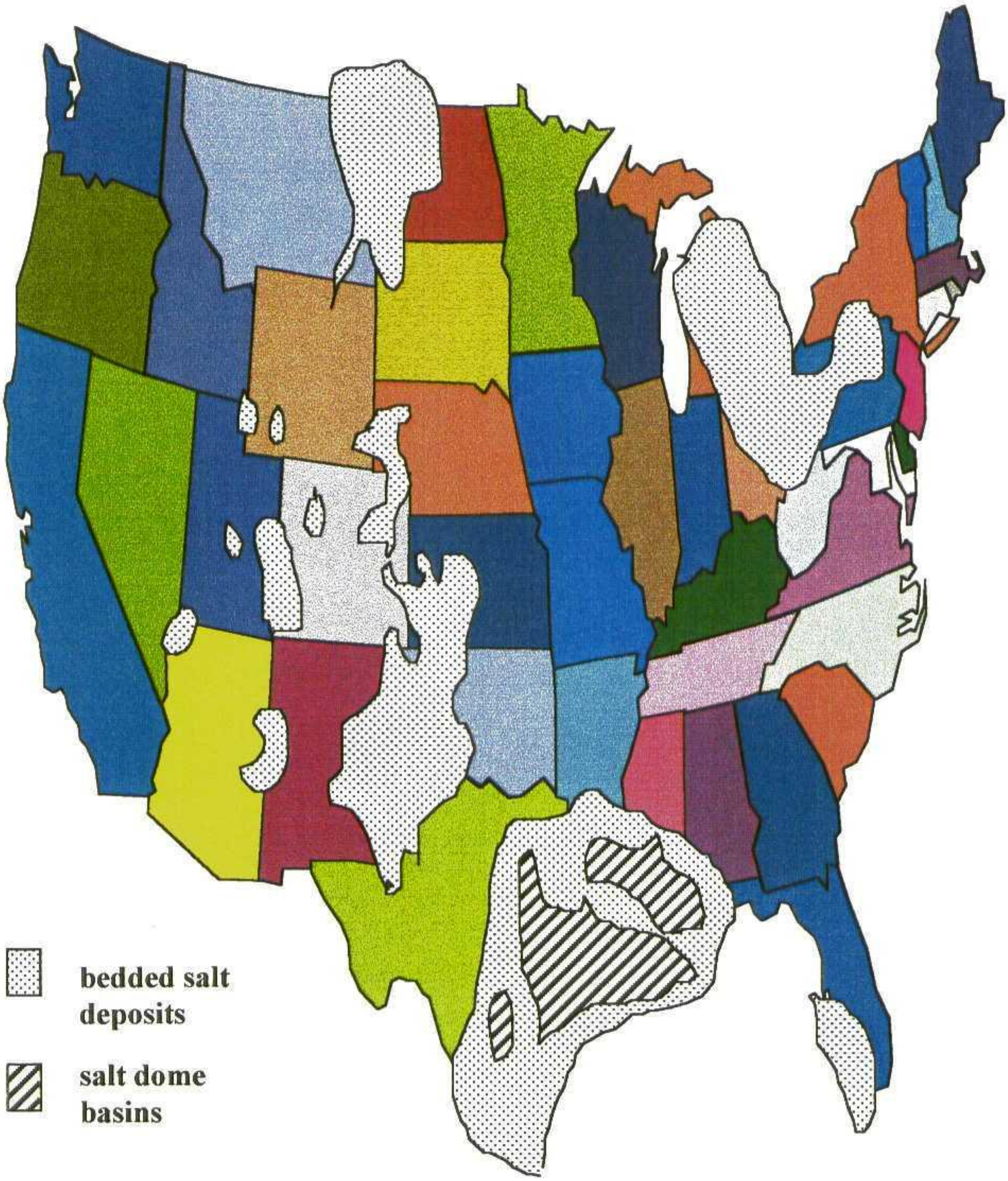


Figure 2 - Idealized Cavern in a Salt Dome Formation
(from Veil et al. 1996)

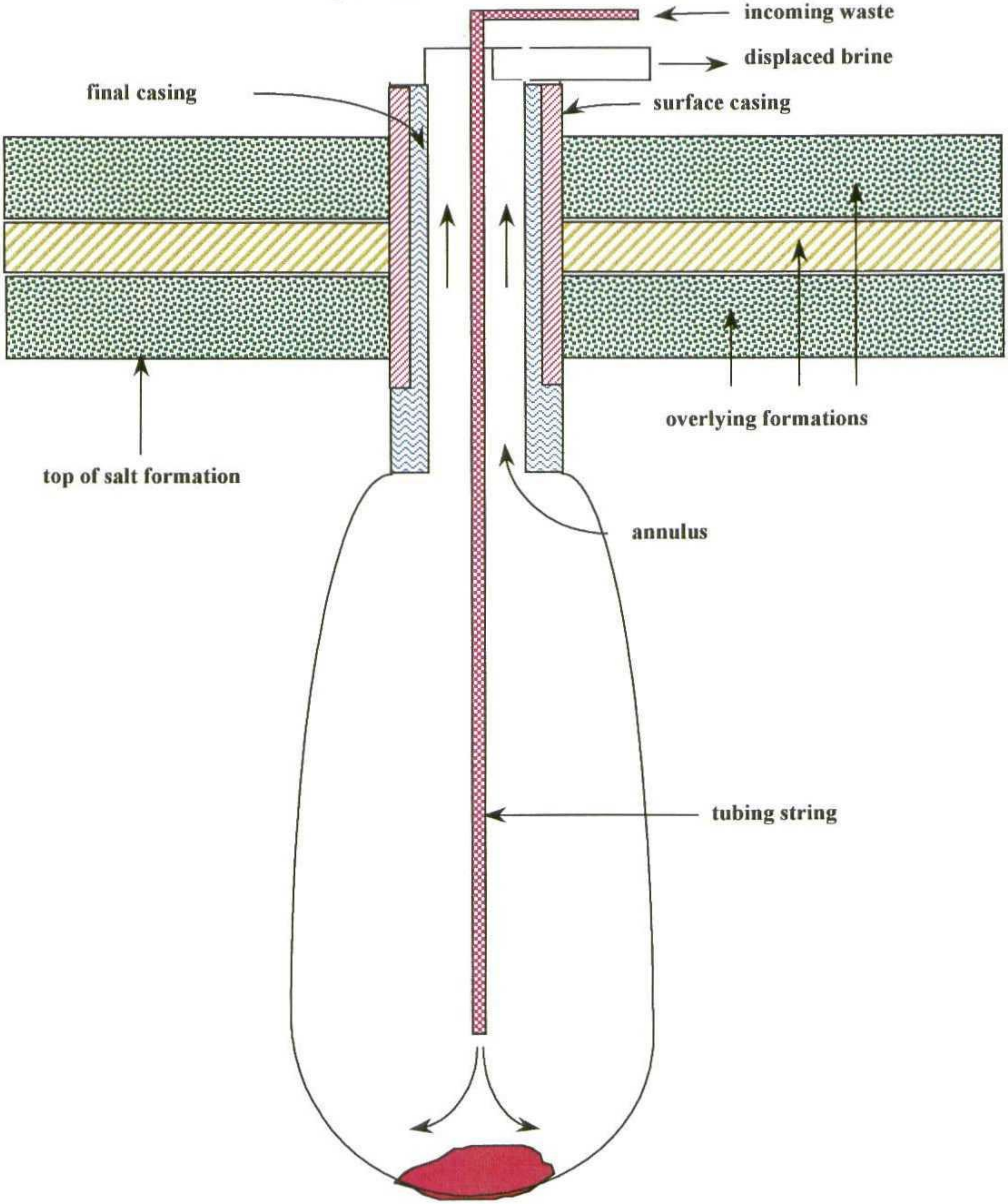


Figure 3 - Idealized Cavern in a Bedded Salt Formation (from Veil et al. 1996)

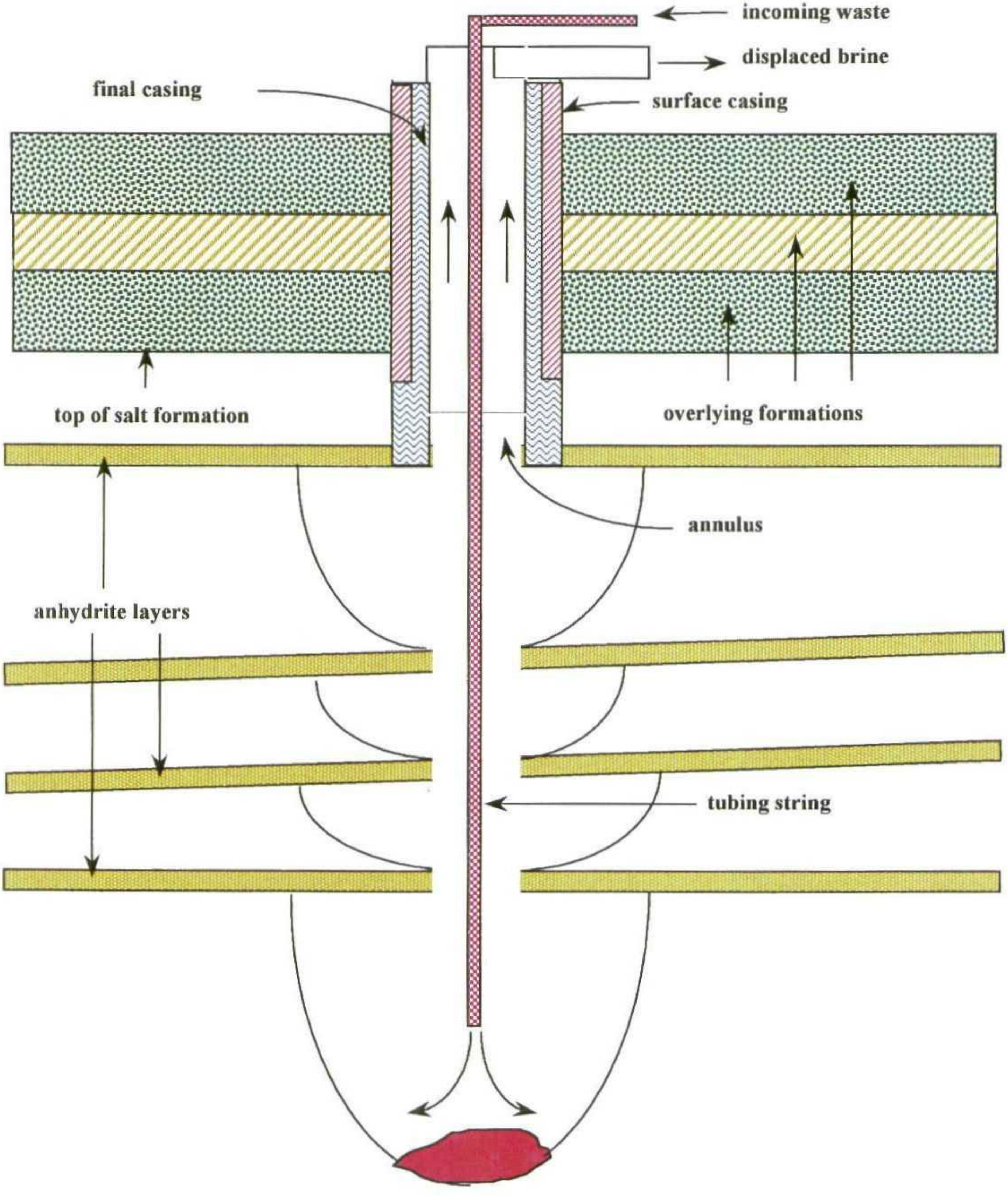


Figure 4 - Uranium-238 Decay Series (from Smith et al. 1996)

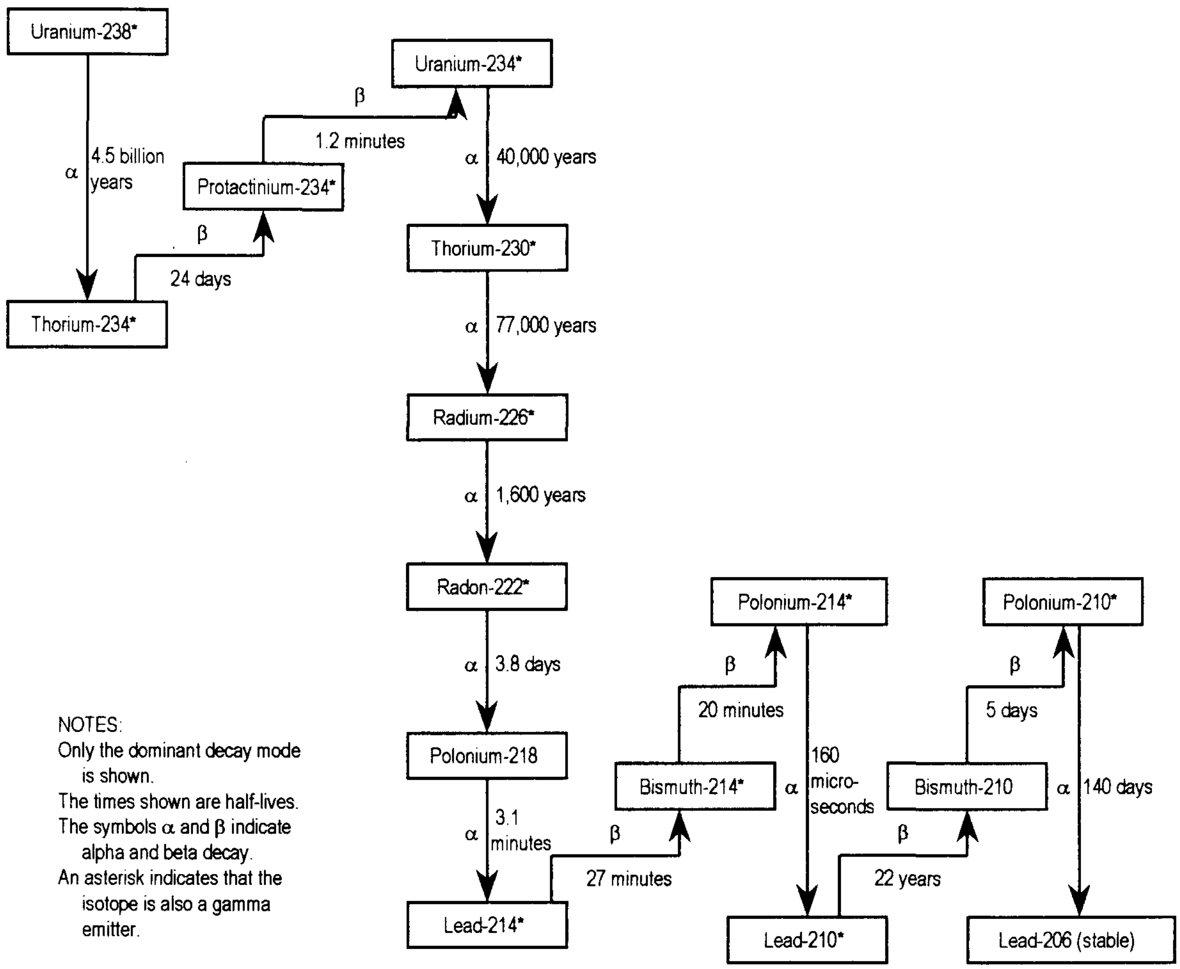
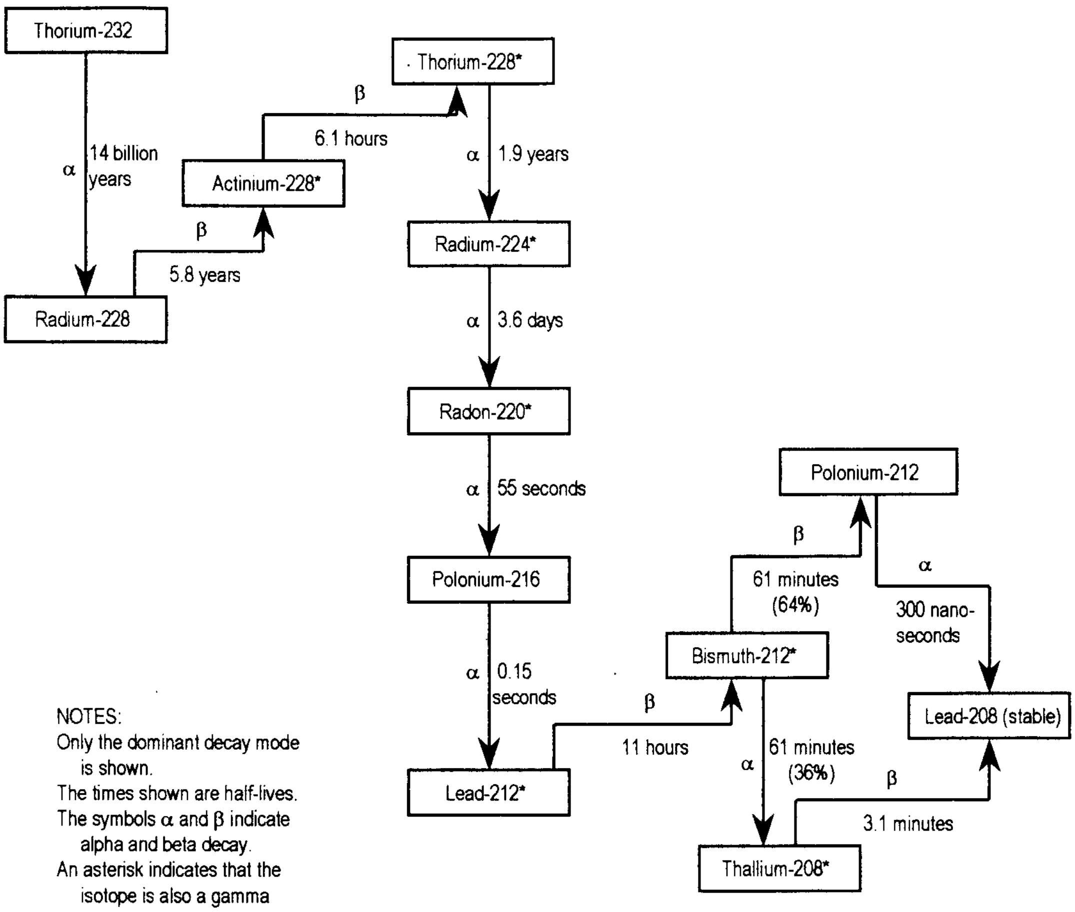


Figure 5 - Thorium-232 Decay Series (from Smith et al. 1996)



NOTES:
Only the dominant decay mode is shown.
The times shown are half-lives.
The symbols α and β indicate alpha and beta decay.
An asterisk indicates that the isotope is also a gamma emitter.

BILL QUICK
President

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SEP 28 1998

August 25, 1998

Mr. Roger C. Anderson
Environmental Bureau Chief
State of New Mexico
2040 S. Pacheco
Santa Fe, New Mexico 87505

Re: application for permit

Dear Roger:
As per our telephone conversation this week, I would appreciate being informed of any additional requirements from the list provided June 11, 1998 to B. Quick, Inc. for pending permit application for disposal in salt caverns of non-toxic Class 1 waste.

I have contacted qualified engineering firms and equipment suppliers and have been advised that the cost to comply to the list provided in the June 7, 1998 letter would be quite expensive.

Therefore, a complete and updated list of requirements would be most helpful and could save some cost. Your efforts on this matter are greatly appreciated.

Best regards,

Bill Quick
B. Quick, Inc.

cc: Wayne Price

OIL CONSERVATION DIVISION
2040 South Pacheco Street
Santa Fe, New Mexico 87505
(505) 827-7131

June 11, 1998

CERTIFIED MAIL
RETURN RECEIPT NO. P-288-259-075

Mr. Bill Quick
B. Quick, Inc.
9535 Forest Lane
Dallas, Texas 75243

RE: Request for Additional Information
B. Quick, Inc.
Class I Non-hazardous Salt Cavern Disposal Well for Oilfield Waste
UIC-CLI-006
Lea County, New Mexico

Dear Mr. Quick:

The New Mexico Oil Conservation Division (OCD) has reviewed the Permian Brine Sales, Inc. (Permian) discharge plan application dated September 15, 1995. It contains Permian's request to operate a Class I non-hazardous salt cavern disposal well for oilfield waste. The proposed disposal well is located in the SE/4 SE/4 of Section 34, Township 19 South, Range 36 East, Lea County, New Mexico. On August 14, 1997 the Permian lease was terminated, and B. Quick, Inc. (Quick) assumed control. Based on the information provided, the OCD is requiring the following additional information before the review process can be completed:

1. Type of Operation

   Indicate the major operational purpose(s) of the facility (ie. Effluent Disposal, In Situ Extraction).

2. Name of Operator or Legally Responsible Party and Local Representative

   Include address and telephone number.

3. Location of Discharge Plan Facility

   Give a legal description of the location (i.e. 1/4. 1/4, Section, Township, Range) and county. Use state coordinates or latitude/longitude on unsurveyed land. Submit a large scale topographic map, facility site plan, or detailed aerial photograph for use in conjunction with the written material. It should depict the location of the injection well(s), storage tanks and/or ponds, process equipment, relevant objects, facility property boundaries, and other site information required in Sections 5 through 9 below. If within an incorporated city, town or village provide a street location and map.

4. Landowner(s)

Attach the name, telephone number, and address of the landowner(s) of record of the facility site and landowners within one-half mile of the site.

5. Facility Description

Attach a detailed description of the surface and subsurface facility with a diagram indicating location of fences, pits, berms, and tanks on the facility. The diagrams of the facility should depict the locations of discharges, storage facilities, disposal facilities, processing facilities and other relevant areas including drum storage. Show the facility/property boundaries on the diagram. Include process flow in the diagrams.

6. Type and Quantities of Fluids Stored or Used at the Facility

List all fluids stored or used at the facility (e.g. High TDS salt water, hydrocarbons, etc.). Include general composition, whether a solid or liquid, source, average daily volume produced, estimated volume stored, location (yard, shop, drum storage, etc), and type of containers (tank, drum, etc).

7. Transfer, Storage and Disposal of Fluids and Solids

A Provide sufficient information to determine what water contaminants may be discharged to the surface and subsurface within the facility. Information desired includes whether tanks, piping, and pipelines are pressurized, above ground or buried. If fluids are drained to surface impoundments, skimmer pits, emergency pits, sumps, etc. for further transfer and processing, provide size and show if these units are lined or unlined. Provide fluid flow schematics with sufficient detail to show individual units.

(1) Tankage and Chemical Storage Areas - Storage tanks for fluids other than fresh water must be bermed to contain a volume one-third more than the largest tank. If tanks are interconnected, the berm must be designed to contain a volume one-third more than the total volume of the interconnected tanks. Chemical and drum storage areas must be paved, curbed and drained such than spills or leaks from drums are contained on the pads or in lined sumps.

(2) Surface impoundments - Date built, use, type and volume of materials stored, area, volume, depth, slope of pond sides, sub-grade description, liner type and thickness, compatibility of liner and stored materials,

installation methods, leak detection methods, freeboard, runoff/runon protection.

(3) Leach fields - Type and volume of effluents, leach field area and design layout. If non-sewage or mixed flow from any process units or internal drains is, or has been, sent to the leach fields, include dates of use and disposition of septic tank sludges.

(4) Solids disposal - Describe types volumes frequency and location of on-site solids dried disposal. Typical solids include sands, sludges, filters, containers, cans and drums.

B For each of the transfer/storage/disposal methods listed above:

(1) Describe the existing and proposed measures to prevent or retard seepage such that ground water at any place of present or future use will meet the WQCC Standards of Section 3103, and not contain any toxic pollutant as defined in Section 1101.TT.

(2) Provide the location and design of site(s) and method(s) to be available for sampling, and for measurement or calculation of flow.

(3) Describe the monitoring system existing or proposed in the plan to detect leakage or failure of any discharge system. If ground water monitoring exists or is proposed, provide information on the number, location, design, and installation of monitoring wells.

C Off-Site Disposal

If wastewaters, sludges, solids etc. are pumped or shipped off-site, indicate general composition (e.g. waste oils), method of shipment (e.g. pipeline, trucked), and final disposition (e.g. recycling plant, OCD-permitted or domestic landfill). All non-exempt wastes will be tested for hazardous constituents per 40 CFR 261 pursuant to EPA approved methods. Approval from the OCD using Form C-138 is required prior to disposal. Include name, address, and location of receiving facility. If receiving facility is a sanitary or modified domestic landfill show operator approval for disposal of the shipped wastes.

D Proposed Modifications

(1) Describe in detail the proposed changes. Provide the information requested in A. and B. above for the proposed modified facility and a proposed time schedule for construction and completion. (Note: OCD has developed specific guidelines for lined surface impoundments that are available on request.)

(2) Describe the proposed closure of ponds, pits, leach fields, etc. so that existing fluids are removed, and emplacement of additional fluids and runoff/runon of precipitation are prevented. Provide a work plan and a proposed time schedule for closure.

E All facilities must demonstrate the integrity of buried piping prior to commencement of operations and every five there after. If the facility contains underground process or wastewater pipelines the age and specifications (i.e., wall thickness, fabrication material, etc.) of said pipelines should be submitted. A proposed hydrostatic test method and schedule for testing of piping must be included as part of the submittal. All lines must be tested to a pressure of 3 pounds per square inch above the normal operating pressure in the line, and a duration time for the test will also be proposed for OCD approval. If hydrostatic tests have already been conducted, details of the program and the results should be submitted.

F Inspection, Maintenance and Reporting

(1) Describe proposed routine inspection procedures for surface impoundments and other transfer, storage, or disposal units including leak detection systems. Include frequency of inspection, how records are to be maintained and OCD notification in the event of leaks.

(2) If ground water monitoring is used to detect leakage or failure of the surface impoundments, leach fields, or other approved transfer/storage/disposal systems provide:

(a) The frequency of sampling, and constituents to be analyzed.

(b) The proposed periodic reporting of the results of the monitoring and sampling.

(c) The proposed actions and procedures (including OCD notification) to be undertaken by the discharger in the event of detecting leaks or failure of the discharge system.

(3) Discuss general procedures for containment of precipitation and runoff such that water in contact with process areas does not leave the facility, or is released only after testing for hazardous constituents. Include information on curbings, drainage, disposition, notification, etc.

(4) Describe methods used to detect leaks and ensure integrity of above and below ground tanks, and piping. Discuss frequency of inspection and procedures to be undertaken if significant leaks are detected.

(5) Submit a general closure plan describing what actions are to be taken when the facility discontinues operations. These actions must include:

(a) Removal of all fluids, contaminants and equipment.

(b) Grading of facility to as close to the original contour as is practical.

(c) Proper disposal of fluids, sludges and solids pursuant to rules and regulations in effect at the time of closure.

8. Underground Injection/Extraction Well Facilities

All effluent disposal wells and in situ extraction wells must meet the requirements of Part 5 of the WQCC Regulations in addition to other applicable requirements of WQCC and OCD Rules and Regulations.

A General Provisions

Before drilling, deepening, or plug back operations, the operator of the well must file the following plans, specifications, and pertinent documents with the OCD 90 days prior to start-up of the planned operation.

(1) Form C-101 "Application for Permit to Drill, Deepen, or Plug Back" (OCD Rules 102, and 1101), and a "Notice of Intent to Discharge" in accordance with WQCC regulation 1201 (New facilities only) must be filed with the appropriate OCD District Office prior to start-up of planned operations.

(2) A Division approved plugging bond in the form of a surety bond or other

adequate assurances, such as financial statements or other materials acceptable to the Director, such as: (1) a surety bond; (2) a trust fund with a New Mexico bank in the name of the State of New Mexico, with the State as Beneficiary; (3) a non-renewable letter of credit made out to the State of New Mexico; (4) liability insurance specifically covering the contingencies listed in this paragraph; or (5) a performance bond, generally in conjunction with another type of financial assurance. Such bond or materials shall be approved and executed prior to discharge plan permit approval and shall become effective upon commencement of construction. If an adequate bond is posted by the discharger to a federal or another state agency, and this bond covers all of the measures referred to above, the Director shall consider this bond as satisfying the bonding requirements of this Rule wholly or in part, depending upon the extent to which such bond is adequate to ensure that the discharger will fully perform the measures required hereinabove.

(3) The proposed drilling, evaluation, and testing, programs. Include casing and cementing program, logging procedures, coring program, and deviation checks.

(4) A topographic map that depicts surface bodies of water, watercourses, springs, mines, quarries, water wells (specify use of water), local and regional drainage, and other pertinent surface features within two miles from any proposed well will be provided.

(5) A map showing the number, name, and location of all producing oil and gas wells, injection wells, and abandoned holes within the area of review. The area of review for each well or well field will be an area which extends one mile from the well. A circle representing the area of review will be drawn around each proposed injection well.

(6) Attach a tabulation of data on all wells of public record, and other shafts or conduits within the area of review which penetrate the proposed injection zone. Such data will include a description of each well's type, construction, date drilled, location, depth, record of completion, and a schematic of any plugged well illustrating all plugging detail.

Identify those wells which may provide a pathway for migration of contaminant through being improperly sealed, completed or abandoned. Detail what corrective action will be taken prior to start up of operations to prevent any movement of contaminants into fresh water resources of less than/equal to 10,000 mg/l TDS through such conduits due to the proposed injection activity (e.g. plugging open holes). Include completion and plugging records.

If information becomes available after operations have begun, which indicates the presence of a conduit that will require plugging then the injection pressure will be limited to avoid movement of contaminants through such a conduit into protected groundwater.

(7) All applicants must furnish proof that a copy of the discharge plan application has been furnished, by certified or registered mail, to the owner of the surface land on which the well is to be located and to each leasehold operator within one-half mile of the well location.

(8) Maps and cross-sections indicating the general vertical and lateral limits of all ground water having 10,000 mg/l or less TDS within two miles of the site. Show the position and give the geologic name of such ground water within this area relative to the injection formation. Indicate the direction of water movement, where known, for each zone of ground water.

B Additional Information

(1) All facilities will be identified by a sign posted at the entrance. If the well is not within the facility boundaries, it will be identified by a separate sign posted within 20 feet of the well. All signs will be of durable construction and lettering thereon will be kept in legible condition and shall be large enough to be legible under normal conditions at a distance of 50 feet. Each sign will show the facility name discharge plan number, the well number, the name of the lease, the name of the lessee, owner or operator, and the location by quarter-quarter section, township, and range.

(2) Access for emergency response will be identified. Names, addresses, and phone numbers will be provided.

(3) OCD approval will be obtained from the Director prior to performing remedial work or any other workover. Approval will be requested on OCD Form C-103 "Sundry Notices and Reports on Wells" (OCD Rule 1103.A.) with copies sent to the appropriate District Office.

Provide evaluation, completion and well workover information. Include all logs, test results, completion reports and workover descriptions.

(4) The OCD will be notified when operations of the well are discontinued for a period in excess of six months.

(5) The OCD will be notified prior to any transfer of ownership, control, or possession of the well. A written commitment to comply with the terms and conditions of the previously approved discharge plan and a bond must be submitted by the purchaser and approved by the OCD prior to transfer.

C Effluent Disposal Wells

Injection will be limited to exempt, and/or non-hazardous oil field wastes. All wastes will be surveyed for Naturally Occurring Radioactive Material (NORM) pursuant to 20 NMAC 3.1 Subpart 14. All non-exempt oil field waste will be tested for the hazardous constituents per 40 CFR 261 pursuant to EPA approved methods, and will require approval from the OCD prior to acceptance and disposal. Requests will be made using OCD Form C-138.

(1) Class I Exempt, and/or Non-Hazardous Salt Cavern Disposal Wells

(a) Distance to all populated areas, industrial facilities, and all rights of way within a two mile radius of the well will be provided.

(b) Current uses of all adjacent properties within a two mile radius of the well will be provided.

(c) Proximity to other subsurface activities will be provided. The minimum distance between caverns will be a S/D of 4:1, where S equals the distance between cavern centers and D equals the average maximum diameter of the caverns, unless site specific geomechanical studies show that caverns may be closer.

(d) Actual or estimated depth to cavern top will be provided using logs or other appropriate methods.

(e) Actual or estimated proximity to salt boundary will be provided using logs or other appropriate methods.

(f) A chemical analysis of fresh water from two or more fresh water wells within one mile of the proposed disposal well will be provided. Analysis will be for hazardous constituents per 40 CFR 261 and general chemistry pursuant to EPA approved methods. At least one fresh water well will be up-gradient, and one down-gradient from the proposed disposal well.

(g) Data regarding the potential for seismic activity, regional stress and strain, structural anomalies, and mechanical and chemical properties of the salt formation will be provided.

(h) All active or abandoned conventional and solution mining activities within 10 miles of the well will be provided.

(i) Maps and cross-sections detailing the stratigraphy, structure, and lithology of the formations from the land surface to the underlying formations showing the bedded salt, anhydrite layers, formations above the bedded salt, the confinement strata. Include appropriate geologic names.

(j) Potential for ground subsidence for the proposed storage facility will be provided. A plan outlining the design and implementation of subsidence monitoring will be provided.

(k) The corrosion history will be reviewed for wells within the area of review. Cathodic protection will be required based on current usage in the area of review.

(l) Casing will be designed for the life expectancy of the well to avoid corrosion, losses of disposal fluids, and potential contamination of fresh water resources. A minimum of one casing string will be set below all fresh water bearing strata, and cemented to the surface. All intermediate and production casing strings will be cemented to the surface. All cement tops, and cement integrity will be verified by cased hole logging methods.

(m) Submit a proposed plan for cavern and well integrity testing. Cavern and well integrity will be demonstrated prior to beginning operations and annually thereafter, and after any workover. The cavern and well will be isolated from one another and each tested to 1.5 times the average operating pressure or 300 psi, whichever is greater, for four hours with zero bleed-off. The cavern pressure must be allowed to stabilize to a rate change of less than 10 psi in 24 hours prior to testing. If integrity of the cavern or well cannot be demonstrated, the well will be shut-in and the OCD Santa Fe Division Office notified immediately.

(n) The cavern size and configuration will be surveyed, using an OCD approved method, prior to beginning operations, and prior to discharge plan renewal, or at least every five years thereafter, or more frequently as the Director may require.

(o) The cavern will be equipped with a hydrocarbon blanket prior to operations to avoid excessive leaching of the cavern roof. Blanket volumes will be sufficient to effectively coat the entire cavern roof. Proposed blanket volumes will be provided. Prior to each discharge plan renewal, or at least every five years, the cavern roof and blanket will be monitored using an OCD approved method.

(p) After the hydrocarbon blanket is in place, and prior to beginning operations at the facility, the cavern will be completely filled with fully saturated brine. Chemical analysis of the brine will also be provided prior to beginning operations. Chemical analysis will include testing for hazardous constituents per 40 CFR 261 and general chemistry pursuant to EPA approved methods.

(q) All wireline logs run for the purpose of evaluating the formation, cavern, and well bore will be provided.

(r) If liners are utilized, they will be designed in accordance with casing requirements and have an overlap of 100 feet in the previous casing string.

(s) Tubing will be equipped with a mechanical packer set within 100 feet above the casing shoe of the lowermost casing string. The casing/tubing annulus will be loaded with an inert packer fluid.

(t) Records of all wastes accepted for disposal will be maintained at the facility. For each volume of waste received, the record will indicate the generator, type, volume, chemical makeup, salinity, and percent solids of such waste.

(u) Acceptance and disposal of wastes at the facility will occur only when an attendant is on duty. The facility will be secured when no attendant is present.

(v) The maximum injection pressure at the wellhead will be limited to 0.2 psi/ft times the depth of the upper most perforations or the casing shoe. The maximum injection pressure shall not initiate new fractures or propagate existing fractures in the confining zone, or cause the movement of injection or formation fluids into ground water have 10,000 mg/l or less TDS. Pressure limiting devices will be installed which will limit the pressures to OCD limits. Pressure limiting devices will be demonstrated annually to operate to the satisfaction of the OCD.

(w) Waste emplacement and brine withdrawal will be down the tubing. Waste emplacement and brine displacement will be volume for volume.

(x) The carrier fluid used to facilitate disposal will be exempt and/or non-hazardous fully saturated brine. The volumes used for disposal are to be recorded and maintained at the facility with results submitted to the OCD Santa Fe Division Office.

(y) The final disposition of the displaced brine will be provided. All displaced brine volumes will be measured, and recorded with results submitted to the OCD Santa Fe Division Office.

(z) Continuous monitoring and recording devices will be installed and mechanical charts made of cavern pressure, injection pressure, flow rate, and flow volumes. All records will be maintained until final closure is achieved.

(aa) Ground subsidence monitoring will be conducted and recorded at least every five years. Monitoring will take place in the same season of the year. All records will be maintained until final closure is achieved.

(bb) A minimum of one monitor well will be installed upgradient and a minimum of one monitor well will be installed downgradient from the disposal cavern to monitor ground water for potential leakage from the disposal cavern. All wells will be sampled quarterly, from the beginning of operations until final closure is achieved, for hazardous constituents per 40 CFR 261 and general chemistry pursuant to EPA approved methods. Ground water elevations will be measured quarterly for all wells. Sample results and ground water elevations will be submitted to the Santa Fe Division Office.

(cc) In the event of a fluid loss or abnormal pressure increase and/or decrease, the well will be shut-in and the Santa Fe Division Office notified immediately.

(dd) All personnel associated with operations at the cavern disposal facility will have appropriate training in accepting, processing, and disposing of exempt, and non-exempt non-hazardous oil and gas wastes to insure proper disposal. All training documentation will be maintained until final closure is achieved.

(ee) All routine maintenance work on the well and all associated equipment will be recorded and maintained by the operator for the life of the well.

(ff) After disposal operations are completed, and prior to shut-in, the hydrocarbon blanket present within the cavern will be removed and disposed of or recycled according to OCD rules. All oil and gas wastes and carrier fluids remaining at the surface, and facility equipment will be disposed of according to OCD rules. Any remaining cavern space will be completely filled with fully saturated brine. The cavern and its roof will be tested for stability, and size and configuration determined using an OCD approved method. The cavern, wellbore, and cement will be tested for integrity using an OCD approved method.

(gg) Prior to plugging and abandonment the well will be shut-in according to OCD rules and the cavern pressure continuously monitored and recorded until the OCD deems the cavern stable and suitable for plugging and abandonment. Recorded pressures will be submitted to the OCD quarterly. Shut-in pressure will not exceed overburden pressure. Provide a procedure for any intentional pressure releases during shut-in. Any fluids released as a result of pressure releases will be disposed of according to OCD rules.

(hh) After stabilization is achieved, a cast iron bridge plug will be set within thirty feet of the casing shoe, and pressure tested to the maximum anticipated differential pressure across the plug for ten minutes, with no pressure loss. The bridge plug will then be capped to the surface with cement, and marked in accordance with OCD rules.

(ii) After plugging and abandonment, all surface equipment will be removed and the ground surface returned to natural conditions pursuant to the closure plan.

(jj) The OCD will be notified 72 hours prior to all testing, surveying, or monitoring. A complete record of all testing, surveying, or monitoring will be filed in the Santa Fe Division Office within 30 days.

(kk) All records of waste volumes disposed of, and brine volumes produced will be submitted to the Santa Fe Division Office quarterly along with required chemical testing.

9. Spill/Leak Prevention and Reporting Procedures (Contingency Plans)

It is necessary to include in the discharge plan submittal a contingency plan that anticipates where any leaks or spills might occur. It must describe how the discharger proposes to guard against such accidents and detect them when they have occurred. The contingency plan also must describe the steps proposed to contain and remove the spilled substance or mitigate the damage caused by the discharge such that ground water is protected, or movement into surface waters is prevented. The discharger will be required to notify the OCD Director in the event of significant leaks and spills. This commitment and proposed notification threshold levels must be included in the contingency plan.

A Prevention

Describe how spills and leaks will be prevented at the facility. Include specifically how spillage/leakage will be prevented during truck loading and at major transfer points within the facility. Discuss general "housekeeping" procedures for areas not directly associated with the above major processes.

B Containment and Cleanup

Describe procedures for containment and cleanup of major and minor spills at the facility. Include information as to whether areas are curbed, paved, and drained to double lined sumps with leak detection; final disposition of spill materials; etc.

C Notification

Propose a schedule for OCD notification of spills. The OCD requires the discharger to notify the appropriate OCD District Office and the OCD Santa Fe Division Office within 24 hours and written subsequent notification of minor spills or within 15 days (OCD Rule 116 and WQCC 1203).

10. Site Characteristics

A The following hydrologic/geologic information is required to be submitted with all discharge plan applications.

(1) Provide the following information and attach or reference source information as available (e.g. driller's logs):

(a) Soil type(s) (sand, clay, loam, caliche);

(b) Depth to rock at base of alluvium (if available).

(2) Provide information on:

(a) The flooding potential at the discharge site with respect to major precipitation and/or run-off events; and

(b) Flood protection measures (berms, channels, etc.), if applicable.

B Additional Information

Provide any additional information necessary to demonstrate that approval of the discharge plan will not result in concentrations in excess of the standards of WQCC Section 3103 or the presence of any toxic pollutant (Section 1101.TT.) at any place of withdrawal of water for present or reasonably foreseeable future use. Depending on the method and location of discharge, detailed technical information on site hydrologic and geologic conditions may be required to be submitted for discharge plan evaluation. **Check with OCD before providing this information.** However, if required it could include but not be limited to:

(1) Stratigraphic information including formation and member names, thickness, lithologies, lateral extent, etc.

(2) Generalized maps and cross-sections;

(3) Potentiometric maps for aquifers potentially affected;

Mr. Bill Quick
June 11, 1998
Page 15

(4) Porosity, hydraulic conductivity, storativity and other hydrologic parameters of the aquifer;

(5) Specific information on the water quality of the receiving aquifer; and

(6) Information on expected alteration of contaminants due to sorption, precipitation or chemical reaction in the unsaturated zone, and expected reactions and/or dilution in the aquifer.

11. <u>Other Compliance Information</u>

Attach such other information as is necessary to demonstrate compliance with any other OCD rules, regulations and/or orders. Examples include previous Division orders or letters authorizing operation of the facility or any surface impoundments at the location.

A surface waste management facility permit, pursuant to OCD Rule 711, will also be required since the proposed disposal facility will involve the management of wastes on the surface.

If Quick has any further questions or comments please contact me at (505) 827-7155.

Sincerely,

Mark Ashley
Geologist

enclosure

xc: Jim Bruce, Attorney at Law, P.O. Box 1056, Santa Fe, New Mexico 87504
OCD Hobbs Office

P 288 259 075

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PS Form **3800**, April 1995