GEOLOGY AND GEOHYDROLOGY OF THE EAST TEXAS BASIN--
A REPORT ON THE PROGRESS OF NUCLEAR WASTE
ISOLATION FEASIBILITY STUDIES (1981)

by

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INTRODUCTION

During FY81, studies of the East Texas salt domes continued to evaluate those problems that must be solved before approving a salt dome for burial of nuclear waste. Questions addressed were (1) Will the integrity of the hydrologic system prevent a release and migration of radioactive isotopes to the biosphere? (2) Will either tectonic or structural instability preclude a secure repository? The U.S. Geological Survey (in Bredehoeft and others, 1978, p. 3), the U.S. Department of Energy (DOE) (1980, in NE-0007, table 11-9), and the U.S. Office of Nuclear Waste Isolation (ONWI) (1980, in ONWI 33(2), p. 9-17) recognize the same key questions, although they are expressed in different ways.

The purpose, method of approach, and conclusion of each generic task are described. It is hoped that conclusions will contribute a series of solutions, which, on integration with other researchers' efforts, will help answer the generic problems of deep burial of nuclear waste in a salt dome.

Solutions to problems are possible primarily because of the extensive data base available on the East Texas Basin. For example, reconstructing the history of the infilling of the East Texas Basin can be accomplished because of thousands of electric logs and miles of seismic and regional gravity coverage. Similarly, the hydrologic studies have been facilitated greatly by the computerized data bank of the Texas Department of Water Resources. These data resources in general are not available equally for the Mississippi or North Louisiana Basins, and because of limited data, the questions of hydrologic and tectonic stability of salt domes may be difficult to answer adequately in those other parts of the Gulf Basin. We hope that the information in this report will be applicable, in a generic sense, to domes in other basins.

The specific technical tasks accomplished in FY81 are as follows:

1. Near-Dome Hydrology

   a. Completion of a three-dimensional ground-water model around Oakwood Dome in the East Texas Carrizo aquifer. This model includes a detailed description of depositional facies that control aquifer heterogeneity and anisotropy.

   b. Detailed study of the water chemistry in the Carrizo-Wilcox aquifer around Oakwood Dome and the lithological controls on the water chemistry.

   c. The significance of saline plumes in the Carrizo-Wilcox aquifer that are associated with salt domes.

2. Deep-Basin Hydrology

   a. Study of fluid potentials in the Woodbine and deeper saline aquifers to determine basin hydrodynamics.

   b. Study of the chemical composition of the deep saline waters to determine origin, chemistry, and role as a geochemical indicator of deep-basin fluid migration.

   c. Study of false cap rock on Butler Dome as an indicator of deep-basin fluid migration upward along dome flanks into shallow meteoric aquifers.

3. Role of Salt Dome Cap Rock in Preventing Salt Dome Dissolution

   a. Completion of Oakwood cap rock studies.

   b. Petrographic analyses of Richton, Cypress Creek, Vacherie, Rayburn's, Winfield Domes and a salt structure in the Gulf of Mexico and comparison with Oakwood and Gyp Hill cap rock.

4. Internal Structures of Oakwood Salt Dome Core

   a. Study of the chemical composition of the Oakwood salt core.

   b. Study of fluid inclusions at the cap rock/salt contact.

c. Strain analysis of the salt and its implications to mechanism of dome growth and future deformation.

5. Tectonics of the East Texas Basin

    a. Study of the geology of the fault systems in the East Texas Basin.

    b. Monitoring of seismic activity in the Mount Enterprise fault system.

6. Stratigraphic Studies of Salt Domes

    a. Study of the initial mobilization of salt by sediment loading during Late Jurassic - Early Cretaceous time.

    b. Study of the mobilization of salt during Late Jurassic to Tertiary times.

    c. Evaluation of salt dome growth rates.

WORK BEFORE FY81

The Department of Energy contracted with the Bureau of Economic Geology for an East Texas salt dome study beginning January 1, 1978. The first 3 months were employed in an evaluation of earlier work in the region. A matrix of properties of salt domes modified from Brunton and others (1977) was used to screen domes. In a report by Kreitler and others (1978), three domes were selected for more detailed studies. These domes were Keechi and Palestine Domes in Anderson County and Oakwood Dome on the Freestone and Leon county boundary.

It was noted that each dome may be problematical for isolation of nuclear waste, but their selection permitted in-depth studies of problems associated with most other interior salt domes of the Gulf Coast. The Keechi Dome appeared slightly smaller than the recommended minimum size, although such an arbitrary criterion is questionable (given possible future emphasis on smaller, regional repositories). The Palestine Dome has a history of brine operations, which may have altered its hydrologic integrity. Oil has been produced from beneath an overhang on Oakwood Dome.

After 9 months of work, the FY78 report by Kreitler and others (1978) summarized progress; only major findings from this report are listed as follows:

(1) From areal surveying, a fault, which was clearly active during the Quaternary, was located on the Trinity River, 17.6 km (11 mi) east of the Oakwood salt dome.

(2) Areal reconnaissance and literature studies indicated that there were collapse structures overlying Palestine salt dome that were related to many old brine wells.

(3) For regional subsurface studies, all well logs were acquired, and 26 of 50 cross sections were completed.

(4) For domal subsurface studies, different attitudes of beds adjacent to the Keechi, Oakwood, and Palestine salt domes were noted.

(5) From regional hydrologic studies of potentiometric surfaces for the Carrizo-Wilcox and Queen City aquifers, recharge-discharge relationships were defined, and an important ground-water divide was recognized to transect the northern third of the East Texas Basin.

In FY79, follow-up studies of the Palestine salt dome cast further doubt on the hydrologic stability of that dome; therefore, that dome has been rejected as a potential area for nuclear waste isolation. The accomplishments of FY79 are discussed in Kreitler and others (1980a, b); only major findings are listed below.

(1) Salt diapirism in the East Texas Basin was initiated during the Late Jurassic by differential loading from Schuler-Travis Peak strata.

(2) Salt domes can be characterized by analysis of the geometry of the domes and the surrounding strata. These characterizations fit previously defined growth models.

(3) Although Oakwood salt dome is apparently in direct contact with the Wilcox aquifer, salinities observed around the dome do not indicate significant dome solution.

(4) Ground-water flow in the Carrizo-Wilcox aquifer is controlled predominantly by topography.

ACCOMPLISHMENTS OF FY80

Results of research during FY80 are reported in a DOE contract report and in Bureau of Economic Geology Geological Circular 81-7 (Kreitler and others, 1981).

Surface Geology

Interpretation of the initial shallow borings at Oakwood salt dome was completed, and the results helped establish the dome's surface structure and stratigraphy. This study also initiated another shallow drilling project to determine thickness variations of the modern floodplain deposits in the central dome area to evaluate structural and hydrologic integrity of the crest of Oakwood Dome. This second drilling project was completed at the end of FY80. Geomorphic studies suggest that Oakwood Dome is in a less mature geomorphic stage than are the Keechi or Palestine Domes, and further research might explain the origin of different geomorphic features (topographic depressions, anomalous drainage patterns, etc.) over the dome.

Studies of Pleistocene terraces of the Trinity River revealed no evidence indicating that the terraces were warped from dome uplift.

Microseismic monitoring at the Mount Enterprise fault system has been recording possible microseismic events since February 1980. Several recordings show possible events, and a more complete monitoring system was implemented to evaluate tectonic stability of the fault system.

Remote Sensing

Lineament studies of aerial photographs and Landsat imagery have been completed. More than 8,300 lineaments were identified on aerial photographs of an area of over 15,400 km^2 (6,006 mi^2). The lineaments have a mean length of 0.9 km (.56 mi) and a density of 0.5 km/km^2. They display a bimodal distribution with prominent northwest and northeast peaks. These trends agree well with known fracture patterns in the Gulf Coast. Calculation of an index of preferred orientation of lineaments shows that shallow domes have affected regional lineament trends to a greater extent than have deeper domes, possibly reflecting a higher degree of fracturing above shallow domes. The Elkhart-Mount Enterprise fault system, however, is poorly reflected in the lineament trends. The validity of these studies was assessed by field checks and statistical tests on the effects of scale, observation time, and other parameters of data collection.

The Landsat study used 1:250,000-scale, band 5, black-and-white imagery. The study area of 70,700 km^2 (27,573 mi^2) covers both the Mexia-Talco and the Elkhart-Mount Enterprise fault zones. More than 260 lineaments were identified that had an average length of ~10 km (7 mi) and a density of 0.04 km/km^2. The Mexia fault trend is reflected by these lineaments, whereas the Talco and Mount Enterprise fault trends are not.

Stream drainage was analyzed for 6 drainage basins over inland domes and 10 off-dome control basins. Stream drainage over two coastal domes was studied for comparison, but the small size of these drainage networks precluded meaningful analysis. This type of analysis was also found to be unsuitable for the study of the Elkhart Graben area because possible vertical fault movement is not detectable by these methods.

Hydrology

The Oakwood Dome hydrology drilling program, in which the Bureau directed the design of each well and coordinated efforts of Law Engineering and Testing Company (LETCO) and the drilling contractor, terminated in December 1979 after five production wells were completed and core of the Wilcox cap rock and salt was obtained. Data from pumping tests in each production well were analyzed to obtain estimates of hydraulic conductivity and storativity for the Wilcox and Carrizo aquifers. Thirty water samples from the production wells and wells drilled in the shallow boring program were chemically analyzed. The chemical analyses have helped verify hypotheses that the area over the dome is a recharge area. Water chemistry and water-level data obtained from existing water wells surrounding the dome complement these data. A total of 49 plugs have been extracted from the Wilcox core and tested for permeability and porosity.

The water-level and weather-monitoring program was conducted at Oakwood for most of FY80. The program includes continuous water-level measurements in 3 wells, weekly and biweekly measurements in 13 wells, and continuous recording of barometric pressure and rainfall. All these data have been used to detect recharge events over the dome, a vital process in evaluating the hydrologic isolation of the salt dome.

Results of additional study of pressure-depth relationships in the Wilcox-Carrizo have helped verify the existence of ground-water discharge along the Trinity and Sabine Rivers. Findings on mechanisms of discharge from the Wilcox-Carrizo system have been used to identify potential discharge sites around Oakwood Dome.

A preliminary analysis of pressure data from the Woodbine Formation showed that widespread hydrocarbon production from the unit has lowered pressures considerably, important in the evaluation of long-term hydrologic stability of the East Texas Basin.

A three-dimensional ground-water flow model was designed for the Eocene sediments in the Oakwood Dome area using data from the drilling and monitoring program. The model takes into account structure and stratigraphy (including uplift over the dome), topographically induced recharge and discharge, and lateral subsurface flow from adjacent areas. The integrated finite difference mesh for the model was set up on the computer. Boundary conditions and leakage coefficients were designated and incorporated into the model.

Subsurface Studies

Subsurface studies were aimed toward an understanding of the effects of basin infilling on initiating and controlling the growth of salt domes. These studies were divided into two groups: early stratigraphy, comprising the Jurassic and Lower Cretaceous, during which salt mobilization started; and late stratigraphy, comprising all younger strata.

Early stratigraphy

Fourteen regional dip and strike cross sections across the entire East Texas Basin have been constructed by means of electric logs. A long Teledyne seismic line with two branches, together constituting over 320 km (200 mi), in the western part of the basin was interpreted and correlated with well data. This interpretation was complemented by regional gravity data (to distinguish salt anticlines from turtle structures) and synthetic seismograms. In addition, seismic sections through Oakwood and Keechi Domes, which were obtained from other sources, have enabled construction of isochore structural maps on three deep horizons: (1) top Louann Salt; (2) top Cotton Valley Group; and (3) top Pettet Member (lower Glen Rose Formation). Seismic interpretation suggested that salt flowage began before the end of Smackover deposition (Late Jurassic) in the Oakwood area on the basin margin, but did not begin until Schuler-Travis Peak deposition (Late Jurassic-Early Cretaceous) in the center of the basin.

Late stratigraphy

Study of depositional systems in the Upper Cretaceous Nacatoch Sand was completed. The Nacatoch Sand consists of marine sandstones and mudstones derived from source areas to the northwest, north, and northeast. Nacatoch sands in the southern part of the East Texas Basin are restricted to thin, erratic bodies and are not considered a threat to the hydrologic integrity of salt domes as nuclear waste repositories.

The following regional structure, isochore, and facies maps were prepared:

Structure -- Top Pecan Gap, Woodbine, Georgetown, Paluxy, Glen Rose, James, Travis Peak, Cotton Valley.

Structure -- Base Austin, Woodbine.

Isochore -- Wilcox, upper Navarro, Woodbine, Paluxy, Washita, Fredericksburg. Top Pecan Gap to base Austin, base Austin to top Buda, top Paluxy to top Glen Rose, top Glen Rose to top James, top Travis Peak to base Schuler, top Travis Peak to top Cotton Valley.

Facies Maps -- Wilcox, Nacatoch, Woodbine, Paluxy.

Dome-Specific Subsurface Studies

To evaluate criteria for determining the geologic stability of East Texas salt domes, the subsurface geology and geometry of the 15 domes in the East Texas Basin that are less than 916 m (3,000 ft) deep were studied in detail. Structure-contour maps were drawn for the salt domes, and cross sections of the 15 domes were constructed. It was considered that domes with nearly vertical sides, such as Hainesville, Bethel, Oakwood, Grand Saline, Palestine, and perhaps Steen, Brooks, and Butler, have the least potential for sediment loading of their flanks to promote additional dome growth. Domes with less steeply inclined flanks are Bullard, Whitehouse, Keechi, Mount Sylvan, and Boggy Creek. Because of poor well control, the geometries of Brushy Creek and East Tyler Domes are insufficiently known to be classified.

Isochore and structure-contour maps of various stratigraphic units and sections at true scale and with a vertical exaggeration of 5.9 were completed for the area within an approximate 8-km (5-mi) radius of each dome.

The timing of rim syncline migration toward shallow salt domes has been determined by tracing the position of isochore maxima. Migration time varied from latest Jurassic or earliest Cretaceous, as at Mount Sylvan Dome, to Late Cretaceous, as at Bethel Dome.

Petroleum resources data on producing formations have been tabulated for the entire basin. An analysis of hydrocarbon production and entrapment in the central part of the East Texas Basin revealed that traps formed over deep salt structures (>1.8 km [6,000 ft] deep) account for 68 percent of the total gas production and 77 percent of the total oil production from the central part of the basin. In this same area, turtle-structure anticlines have been the source of 22 percent of the oil produced and 7 percent of the gas produced. Conversely, entrapments near shallow salt diapirs have yielded only 5 percent of the total gas produced and less than 1 percent of the oil extracted. Consequently, the potential for future hydrocarbon exploration and production in the shallow East Texas domes is considered minimal, and therefore future production does not seem to negate shallow salt domes as potential nuclear waste repositories.

Oakwood salt core

Fifty-seven meters (188 ft) of salt core were logged, photographed, and slabbed. Core analyses included lithologic properties such as grain size, color, transparency, and anhydrite content as well as structural properties such as orientation, type, and intensity of strain fabrics and presence of transposition and folds. Thin sections, thick sections (3 mm), and polished slabs have been used to study the microstructures. These studies suggest that deformation and emplacement of salt were followed by recrystallization of the uppermost 2 m (6 ft) of salt under conditions of low differential stress.

The layering and foliation readings have been analyzed to enable construction of the large salt folds penetrated by the core. This geometric analysis suggests that the mushroom-shaped crown of the salt dome has been truncated to levels below the original diapiric crest, probably by ground-water solution, a very significant process that must be evaluated at any site dome.

Oakwood cap rock

Cap rock on Oakwood Dome is the result of multiple stages of diagenesis. The anhydrite section was formed by deep formation waters, not by meteoric ground water. The cap rock also appears to represent an impermeable seal, a fact of great importance in predicting hydrologic isolation of the crestal parts of interior salt domes. Samples have undergone chemical, porosity, and permeability analyses. More than 75 petrographic thin sections have been made and are being studied.

METEORIC HYDROLOGY

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Purpose

The purpose of studying meteoric (fresh-water) hydrology is to address problems of salt dome dissolution and contaminant transport in the meteoric section. The study focuses primarily on Oakwood Dome. The meteoric section is the interface between the repository and the biosphere and is characterized by relatively rapid rates of ground-water circulation. Therefore an understanding of the hydrogeology of the meteoric section is critical to waste isolation.

Data Collected and Methods of Analysis

Ground-water model of Oakwood Dome area

Data used in this study were collected during the previous two fiscal years. The method of analysis of ground-water flow near Oakwood Dome is based on three-dimensional ground-water flow modeling by numerical methods. The computer program being used is TERZAGI (Narasimhan and Witherspoon, 1977 and 1978; Narasimhan and others, 1978; Fogg, 1980). The modeling strategy (i.e., boundary conditions, principal factors considered, and assumptions) are outlined in Fogg (1981) and Fogg and Seni (in preparation). During FY80 the following were added to the model: (1) an upper boundary condition that accounts for topographically controlled leakage between the Queen City and Wilcox-Carrizo aquifers; (2) heterogeneous hydraulic conductivity distributions in the Wilcox; and (3) more realistic lateral boundary conditions near the Trinity River which allow for both vertical leakage and flow downdip into the deep-basin section of the Wilcox.

The heterogeneous hydraulic conductivity distributions were derived from (1) field pumping tests and lab-permeameter tests of core samples and (2) mapping of hydrostratigraphic facies in the Wilcox using electric logs (refer to Seni and Fogg, in preparation; and Fogg and Seni, in preparation).

Chemical environment around Oakwood Dome

Ground-water samples from the Carrizo-Wilcox aquifer were collected in the East Texas Basin. Samples were analyzed for standard water chemistry, pH, redox values, carbon-14, and δC^{13}. Samples are still being analyzed for δO^{18}, δS^{36}, and Cl^{36}. Clays in the Wilcox core were analyzed for exchangeable cations. Calcite cements in the Wilcox core were analyzed for δO^{18} and δC^{13} to determine their origin. The lignites in the core were analyzed for vitrinite reflectance to evaluate the degree of organic maturation.

Salt dome dissolution

A summary that reviewed the origin of surface saline features overlying salt domes in the East Texas Basin was conducted. This review entailed a simple comparison of (1) physiographic features over each dome, (2) minimum vertical relief between top of each dome and the overlying, topographically lowest point, and (3) dates of discovery of the domes. Apparent rates of dissolution of Oakwood salt dome were calculated by applying Darcy's law to the brackish water plume associated with the dome. Salt erosion rates were then calculated by assuming various values of dome surface area over which the dissolution might be taking place. Effects of advective dispersion on the plume were tested by invoking an analytical solution of the advection-dispersion equation.

Conclusions

Ground-water modeling of Oakwood Dome area

The Oakwood ground-water flow model is still being tested and calibrated, and thus the conclusions listed below are preliminary.

1) Fluvial channel-fill sands in the Wilcox appear to have higher hydraulic conductivities than other Wilcox sand facies by about two orders of magnitude (fig. 1). Thus, the distribution and interconnectedness of these sands should be important controls on fluid flow. Mapping of these channel-fill facies in three dimensions and integrating them with hydraulic conductivity data lead to the following two important conclusions.

2) Average magnitudes of ground-water velocities in the Wilcox in the immediate dome vicinity may be as much as four orders of magnitude lower than elsewhere in the system as a result of Wilcox facies changes near the dome (fig. 2). This may be another factor (in addition to cap rock) isolating the salt in Oakwood Dome from Wilcox ground-water circulation. During fluvial Wilcox deposition, Oakwood Dome apparently was growing fast enough to uplift land surface, thereby deflecting Wilcox streams of deposition away from the dome area and leaving relatively muddy, interchannel facies near the dome. Similar hydrostratigraphic facies changes are observed in the Wilcox around other domes in the basin and might also be expected around domes in the Louisiana and Mississippi interior salt dome basins.

3) Because the fluvial channel-fill facies are dip-oriented, velocity vectors computed by the model indicate that contaminants escaping from the dome would tend to migrate downdip toward the deep-basin (saline) section of the Wilcox rather than migrate along strike toward discharge points along the Trinity River (fig. 2). Hydraulic gradients computed by the model and measured in the field would indicate different flow directions. But these gradients may give a false indication of flow direction because of the regional anisotropic hydraulic conductivities caused by Wilcox depositional systems.

4) Velocity directions computed by the model do not indicate northeastward ground-water flow from Oakwood Dome toward Upper Keechi Creek, as was inferred from the orientation of the brackish water plume associated with the dome (Fogg and

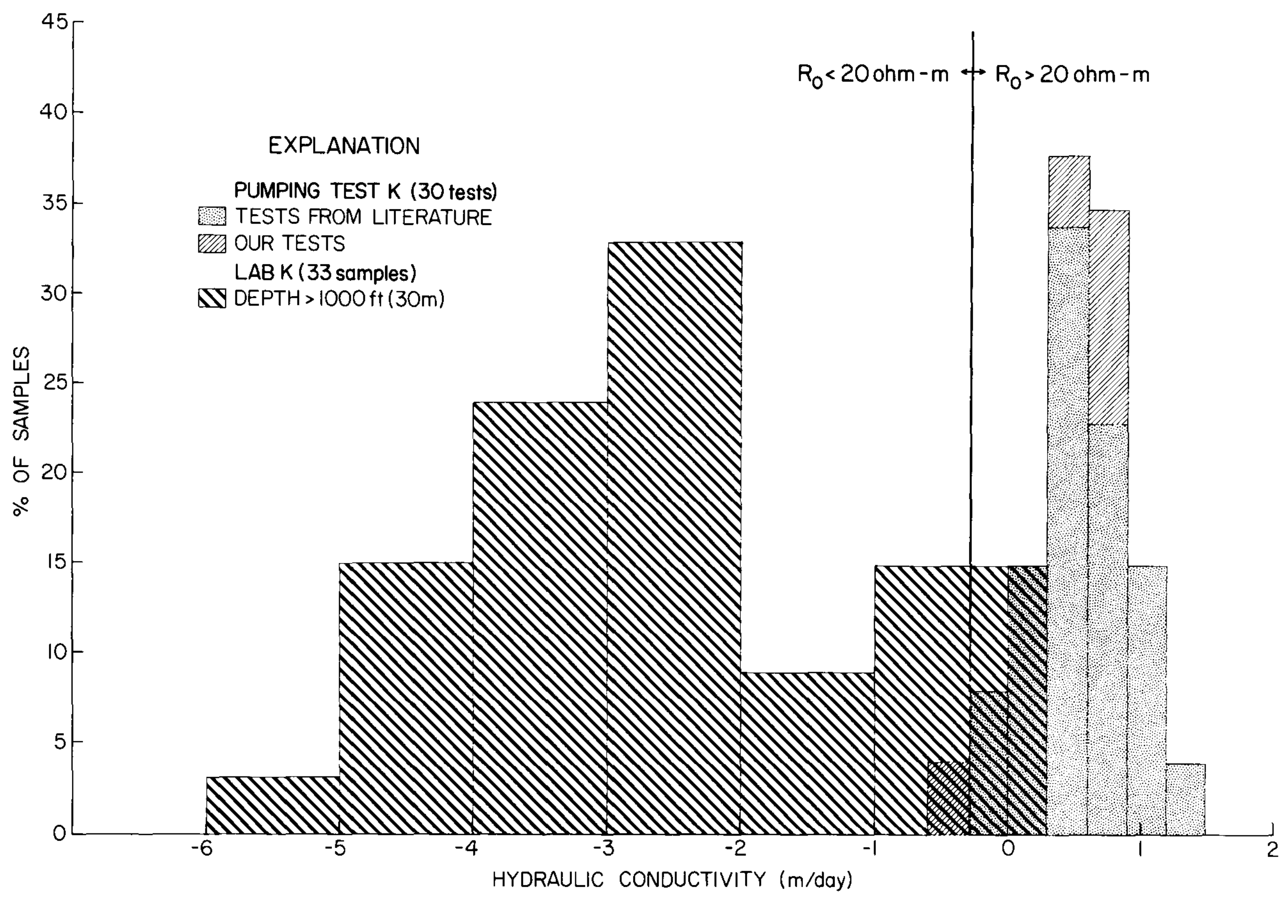

Figure 1. Histograms showing results of hydraulic conductivity measurements derived from pumping tests and lab permeameter tests. The histogram on the right represents pumping test values, all of which are in relatively clean, channel-fill sands. The histogram on the left represents lab values from interfluvial sands, all of which are in relatively muddy, interchannel sands. The channel-fill sands are recognized on induction resistivity logs by their relatively high resistivity (>20 ohm-m) and blocky character.

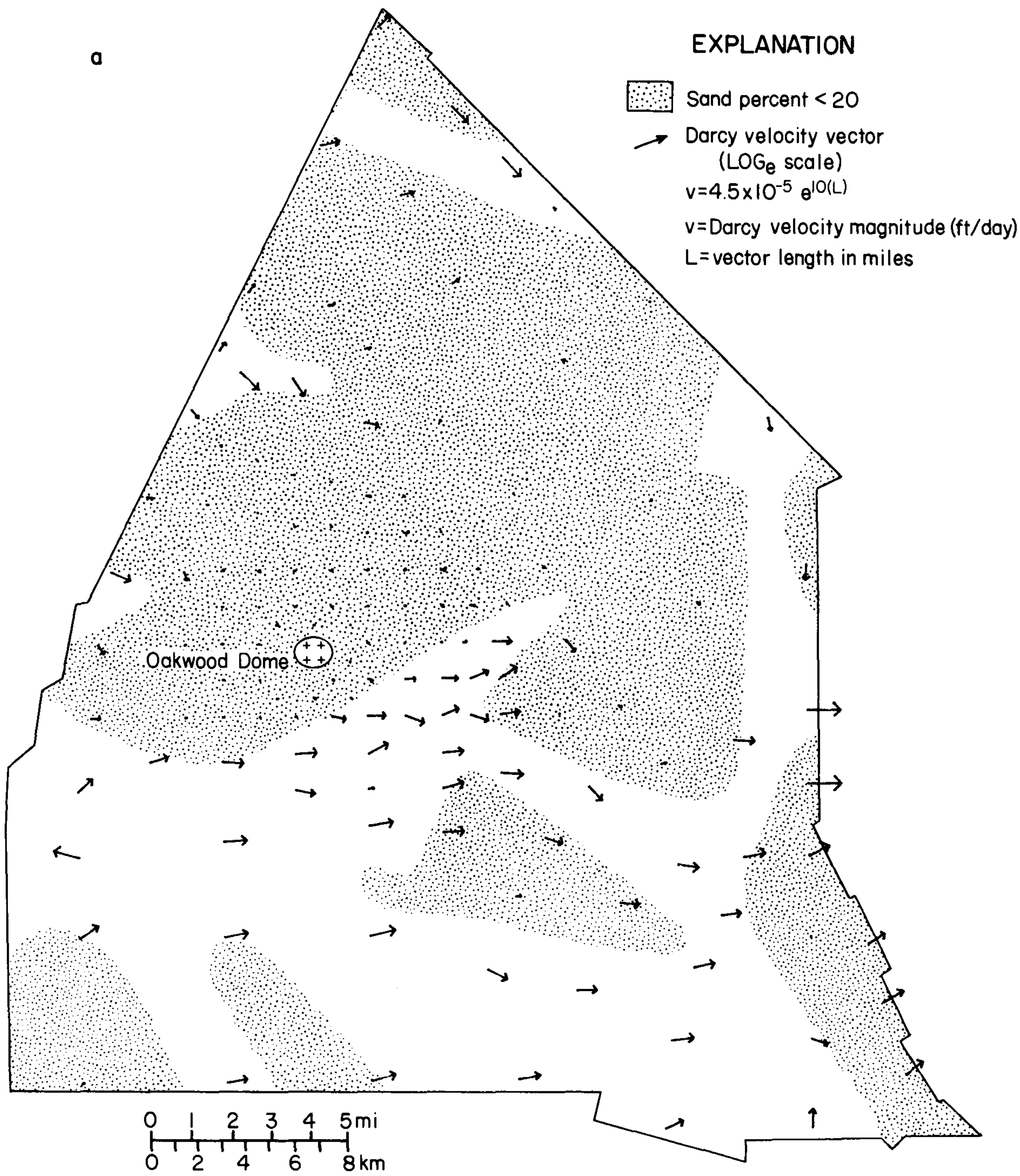

Figure 2. Maps of velocity vectors computed by the model for each nodal point in (a) the lower layer and (b) the middle layer. Ground-water velocities in the channel-fill facies are greater than those in the interchannel facies by as much as 10^3.

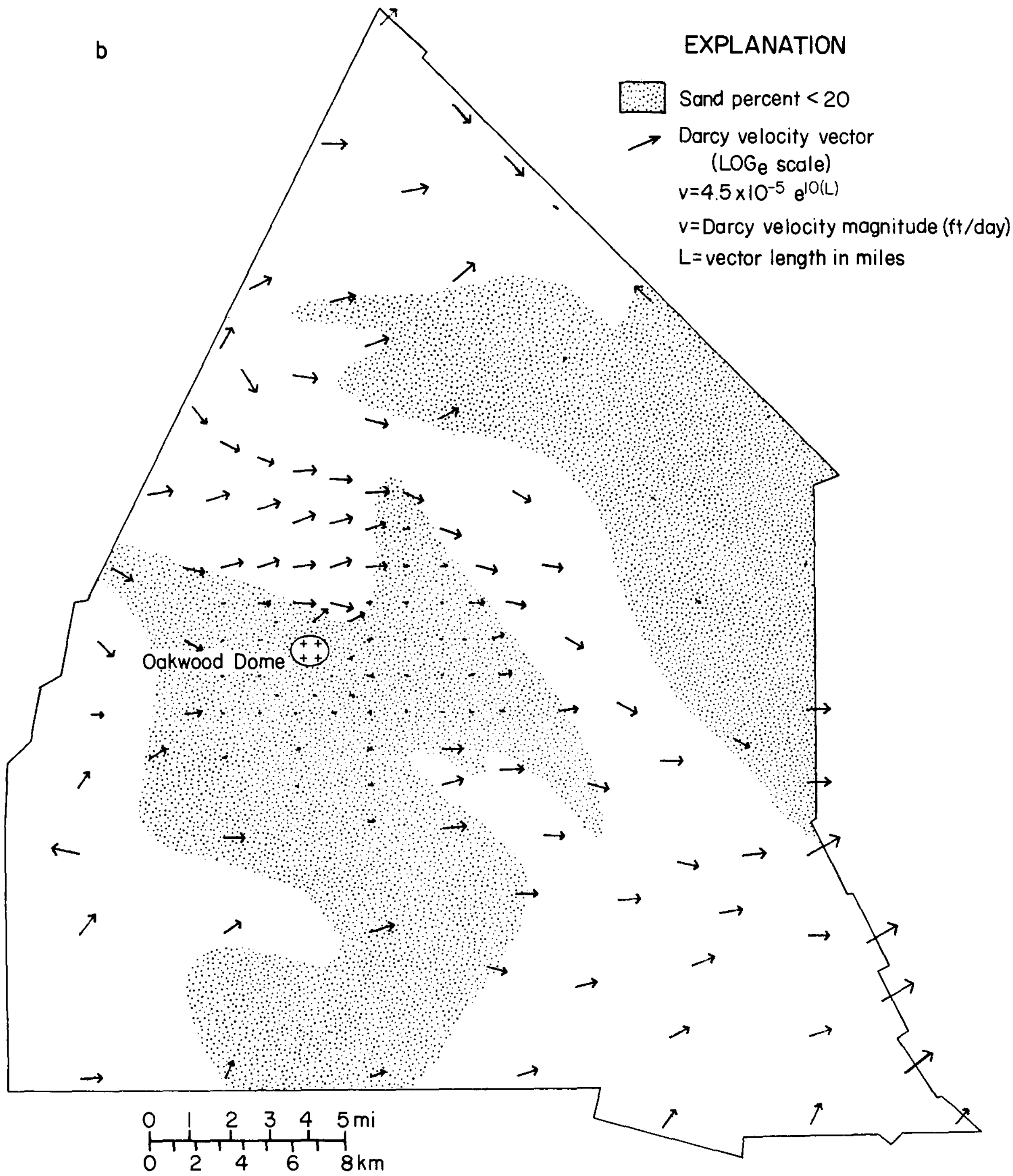

Figure 2 (continued).
Average velocities range from approximately 10^{-1} to 10^{-4} ft/day. Regional hydraulic gradients in some parts of these maps are not colinear with the velocity vectors, owing to the regional anisotropy introduced by the dip-oriented channel-fill facies.

others, 1980; Fogg and Kreitler, 1981). Even if ground-water discharge at Upper Keechi Creek is added to the model near the terminus of the plume, computed flow directions still indicate flow to the east and southeast. This may suggest that the plume is not associated with salt dome dissolution. Additional simulations involving different boundary conditions and anistropic hydraulic conductivity values are being investigated to determine the accuracy of model results in the plume vicinity.

5) Neither recharge over the dome nor the dome itself induce significant vertical components of ground-water flow.

6) Topographically influenced vertical leakage operates on a regional scale, but does not appear to be capable of causing "short-circuited" ground-water discharge from the Wilcox at local topographic lows near the dome.

7) Were it not for the boreholes that extend through the salt overhang of Oakwood, the meteoric hydrogeology of the dome area could be characterized adequately with perhaps as few as five additional drill sites. Such a small number of sites is feasible because the modeling analysis has given us the necessary insight to identify the key problems and the area to drill to solve them. Major priorities of the program would be as follows:

(a) Sample the brackish water plume to verify its origin and flow direction.

(b) Measure hydraulic conductivities in the non-channel-fill ("muddy") sands to determine more accurately just how much lower they are than those of the channel-fill sands.

(c) Determine how interconnected the various sand facies are by running long-term (approximately several days) pumping tests in these facies. Existing data indicate that where the channel-fill sands compose less than 20 percent of the section, they are probably not interconnected. The lowest velocities computed by the model are where these sands are interpreted to not be interconnected.

(d) Measure vertical hydraulic gradients in suspected ground-water discharge sites (i.e., Buffalo Creek and Upper Keechi Creek) to determine whether the Wilcox-Carrizo discharges at these sites.

Alone, such a program would not provide much information, but integrated with the model and with what is already known about the system, the hydrogeology around the dome could be described in great detail and with a high degree of confidence.

Salt Dome Dissolution

1) Five salt domes (Palestine, Brooks, Grand Saline, Steen, and Butler) in the East Texas Basin have overlying surface saline features (fig. 3). These domes are the shallowest domes in the basin and were generally the earliest discovered. With the possible exception of Butler, the saline features associated with each of these domes occur within or below well-defined depressions, which are suggestive of dissolution-induced collapse. None of the other domes have such depressions. The salines are interpreted to have evolved through a three-step process:

(a) Penetration of the shallow zone of relatively rapidly circulating ground water by either dome growth or surface erosion (each of these domes is located in a topographically low stream valley);

(b) acceleration of dissolution rates owing to the more rapid ground-water flow rates; and

(c) collapse or subsidence of overburden into dissolution cavities, thereby creating additional topographic relief and even faster rates of ground-water circulation.

In the deeper flow systems, the presence of cap rock and muddy facies around a dome may be sufficient to reduce dissolution rates to negligibly small values.

2) These five domes were generally discovered early because of their surface salines. They were explored first as potential sources of salt and then later for hydrocarbons. Thus, a repository in a dome having a surface saline would be most

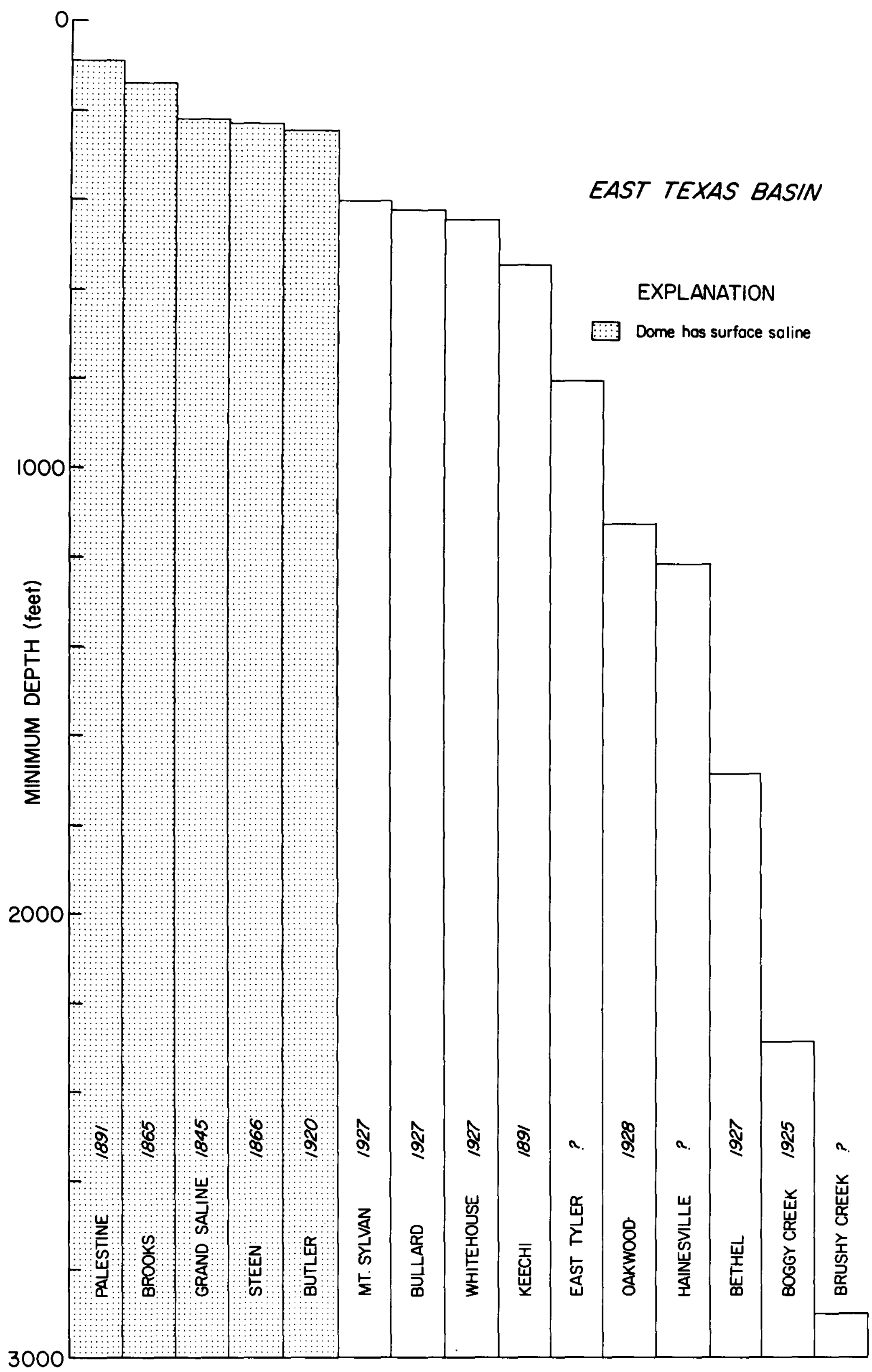

Figure 3. Chart showing dome depths and dates of discovery. The earliest domes to be discovered were found by virtue of their surface salines. Only the five shallowest domes have surface salines.

likely to be breached if it were accidentally intruded while exploring for or mining salt resources.

3) The shallower the dome is, the greater the probability that it will be hydrologically unstable.

4) The brackish water plume at Oakwood Dome would indicate an insignificant rate of salt erosion (~10 meters/10^4 yr) if it is assumed that NaCl in the plume is derived from the entire surface of the dome in contact with the Wilcox. However, it is much more probable that localized dissolution (e.g., along a fault, a fracture in the cap rock, or where a sand body touches the dome) would occur. If the plume at Oakwood is derived from an area of 10^4 m^2, for example, the salt erosion rate over that area could be as great as 2,000 meters/10^4 yr. In fact, if the salinity of a plume around a dome in the basin were too low to detect on electric logs (<500 milligram/liter), a plume could still represent a very large salt erosion rate if the dissolution were localized.

5) If localized dissolution were occurring on a dome, one would expect to see subsidence features representing hundreds of meters of displacement, but no such features have been found. If, however, a dome grows differentially (e.g., via salt spines moving independently), continued influx of salt into the local dissolution zone would prevent the development of a cavity. Future studies must address whether this can occur.

6) The characterization of a final candidate dome should include high-resolution seismic studies to define in detail the surface of the dome. If the surface includes any irregularities that could be caused by localized dissolution, these irregularities should then be explored further by drilling.

Geochemical environment around Oakwood Dome

1) The chemical composition of Wilcox-Carrizo ground waters surrounding Oakwood Dome suggest slight dissolution of the Oakwood salt dome. The Cl^-

concentration of 130 mg/l in well TOH-2A is higher than regionally observed in the aquifer. The $SO_4^{=}$ concentration of 35 mg/l is also higher than normally observed in the aquifer. The higher Cl^- could result from dome dissolution or from the brackish waters commonly observed at the base of the Wilcox, where this higher chloride value was measured. Results of chlorine-36 analysis may distinguish between these different sources. The high sulfate values may be from cap rock anhydrite dissolution. Isotopic analyses currently underway may distinguish sulfate originating from the anhydrite cap rock from sulfate originating from the oxidation of pyrite within the aquifer.

2) In some cases the brackish water commonly observed deep within the Wilcox may be related to high sodium and bicarbonate concentrations and not to high chloride concentrations. Interpretation of resistivity curves from monitoring wells on the flank of Oakwood Dome shows an increased salinity at depth. The increased salinity, however, results primarily from increases in the sodium and bicarbonate ions, not from the chloride ion (fig. 4).

3) The chemical composition of the ground water around Oakwood Dome rapidly evolves from an oxidizing, acid ground water in the recharge zone to a reducing, basic ground water in the artesian section. These reducing basic ground waters in a montmorillonite-rich aquifer appear to be an optimum medium for chemical retardation of most radionuclides that might be released from a repository.

This reducing, basic chemical composition is a result of the generation of a Na-HCO_3 water. A Na-HCO_3 ground water is generated in the Wilcox-Carrizo aquifer by the following reaction (Foster, 1950):

$$CaCO_3 + H_2CO_3 + (Na\text{-}Clay) = 2Na^+ + 2HCO_3^- + (Ca\text{-}Clay).$$

Ground water flowing down gradient evolves from a Ca-Mg-HCO_3 water in the recharge zone to a Na-HCO_3 water in the artesian section. Na^+ and HCO_3^- concentrations increase in a 1:1 molar ratio to a maximum of 15 millimoles/liter

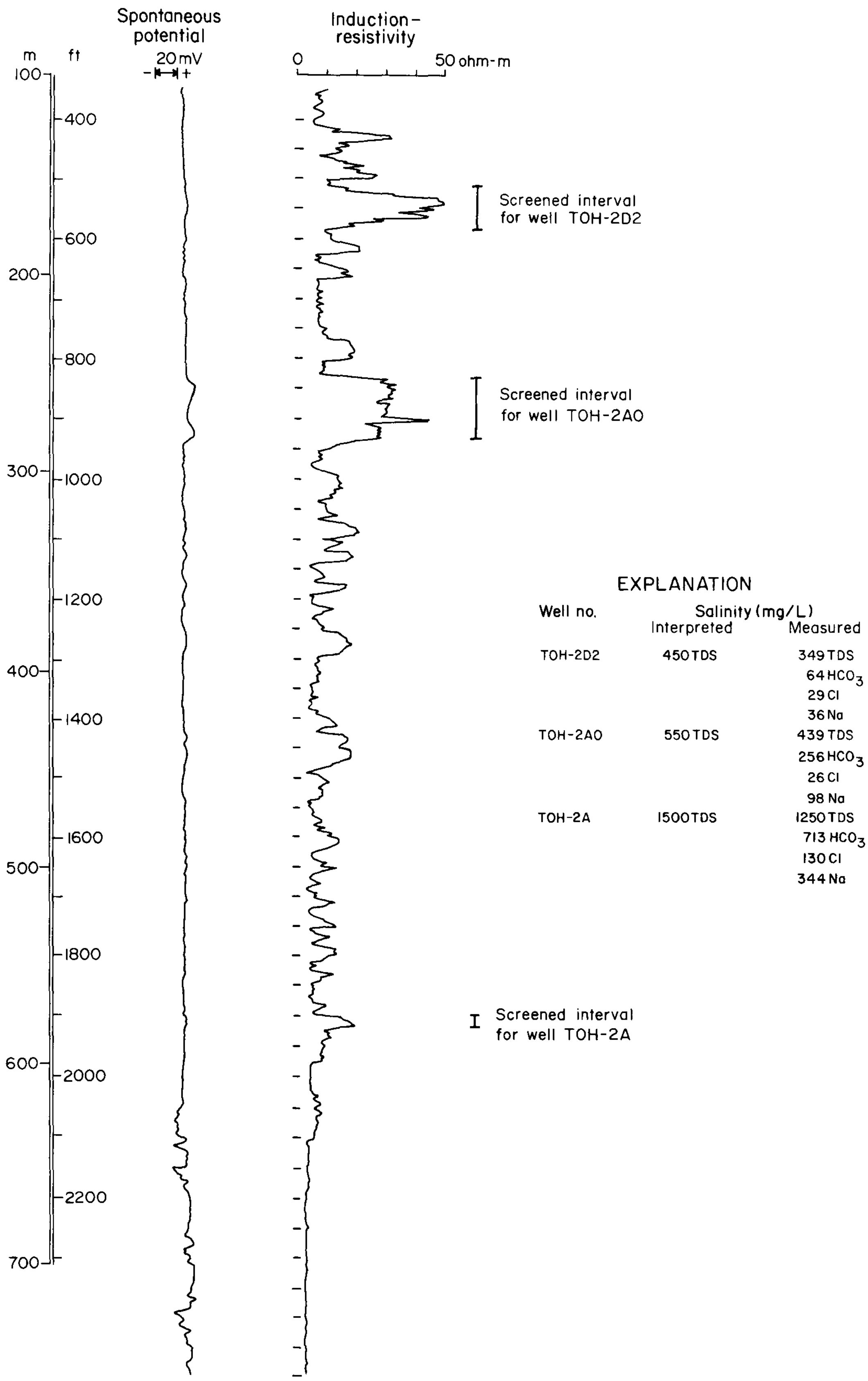

Figure 4. Relationship between salinity interpreted from resistivity logs and actual chemical composition. Increased salinity results primarily from increased sodium and bicarbonate concentrations, not increased chlorinity.

(mmoles/l) HCO_3^-, corresponding to increasing age since recharge (maximum 25,000 yr B.P.).

The following changes in water chemistry and aquifer mineralogy have resulted from this reaction. Because of cation exchange, Ca^{++} concentrations in the water decrease with depth. Montmorillonite clays at shallow depths are dominated by Ca^{++} at exchange sites, whereas Na^+ dominates exchange sites of montmorillonite at greater depths (fig. 5). As water moves down the hydraulic gradient, HCO_3^- concentration increases to 5 mmole, pH increases from 6 to 9 (fig. 6), and δC^{13} of HCO_3^- shifts from ≈-20 to ≈-10°/oo. Anaerobic fermentation (coalification) appears to generate additional CO_2. Negative redox values measured in the deep aquifer and vitrinite reflectance values indicating change from high-grade lignite to subbituminous coal with increasing depth also suggest that coalification contributes additional CO_2.

Corrected carbon-14 ages for HCO_3^- increase linearly with increasing HCO_3^- concentrations. The reaction rate for generating Na-HCO_3 waters in the Wilcox-Carrizo aquifer is 0.65 mmoles/l/1,000 years. Eh values of the ground waters shift from ≈+100 mV (millivolts) in the recharge zone of the Wilcox-Carrizo to ≈-100 mV in the deep artesian section of the aquifer. Eh values decrease linearly with increasing age of the ground water (fig. 7).

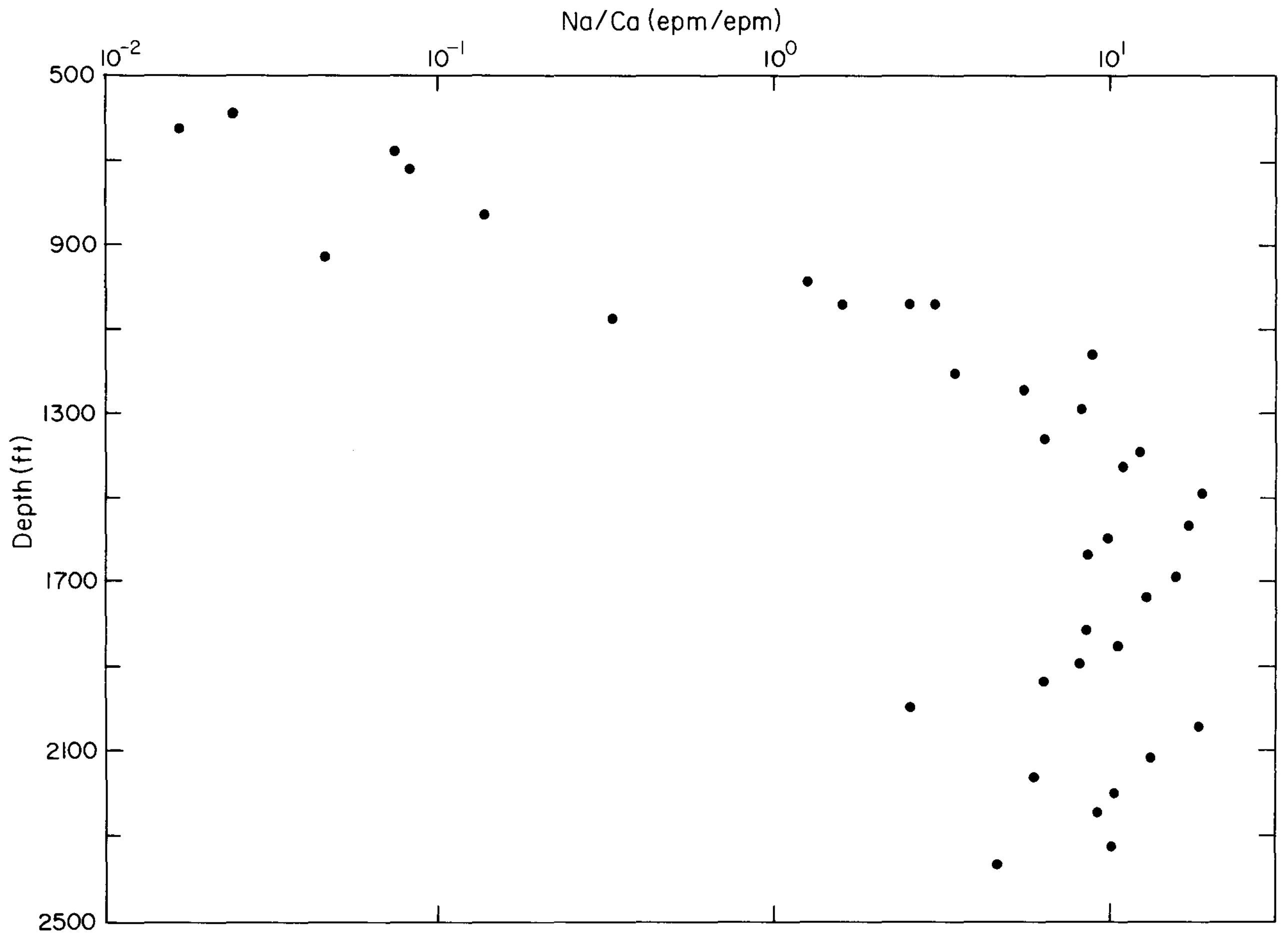

Figure 5. Ratio of Na and Ca exchangeable cations versus depth in Wilcox shale from LETCO TOG #1.

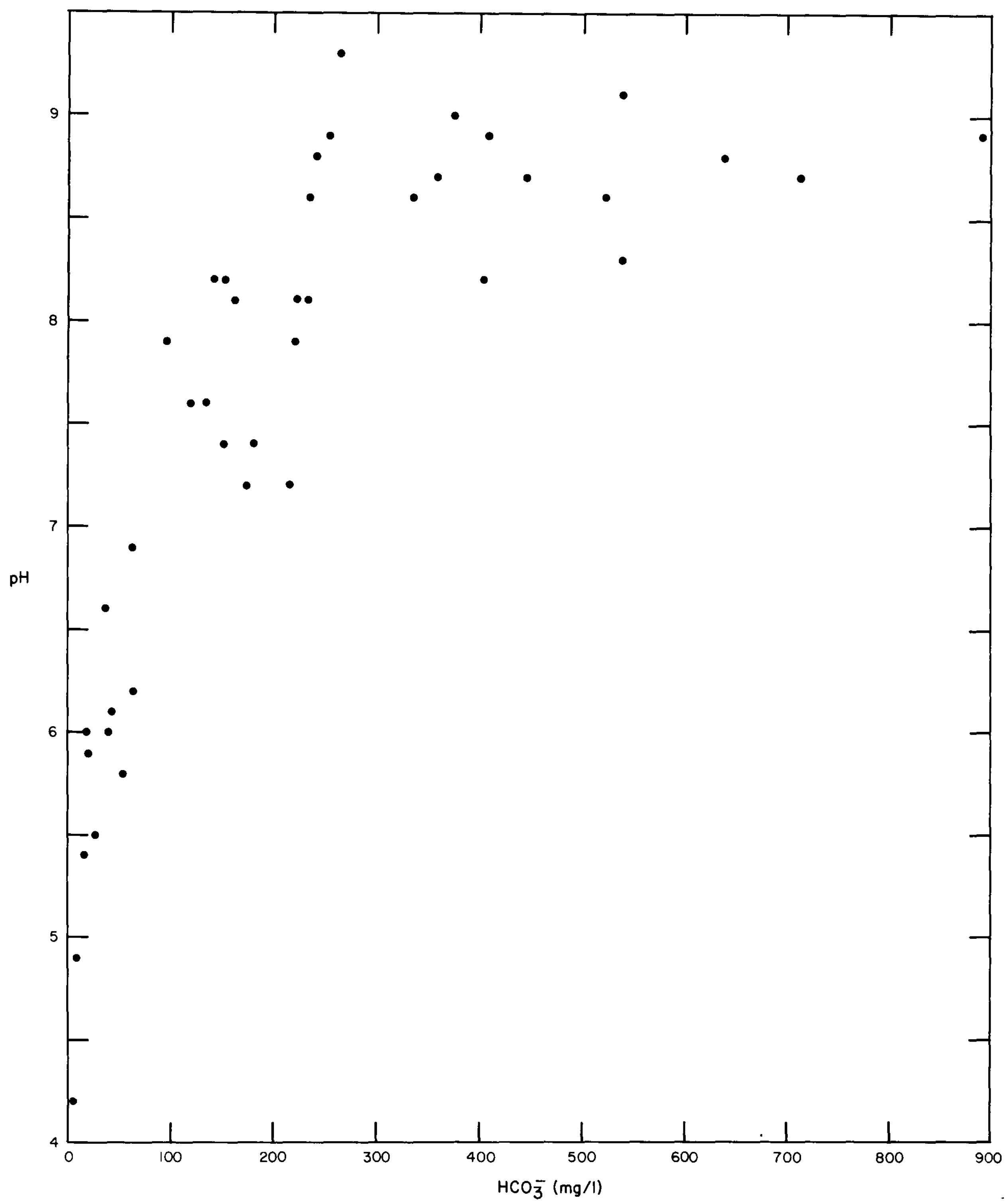

Figure 6. Relationship between bicarbonate and pH. A closed geochemical system is implied where increases in bicarbonate cause an increase in pH. (Bicarbonate concentrations less than 5 mmoles.) An open geochemical system is implied where increases in bicarbonate are independent of pH. Coalification of organics is the probable additional source of carbon dioxide.

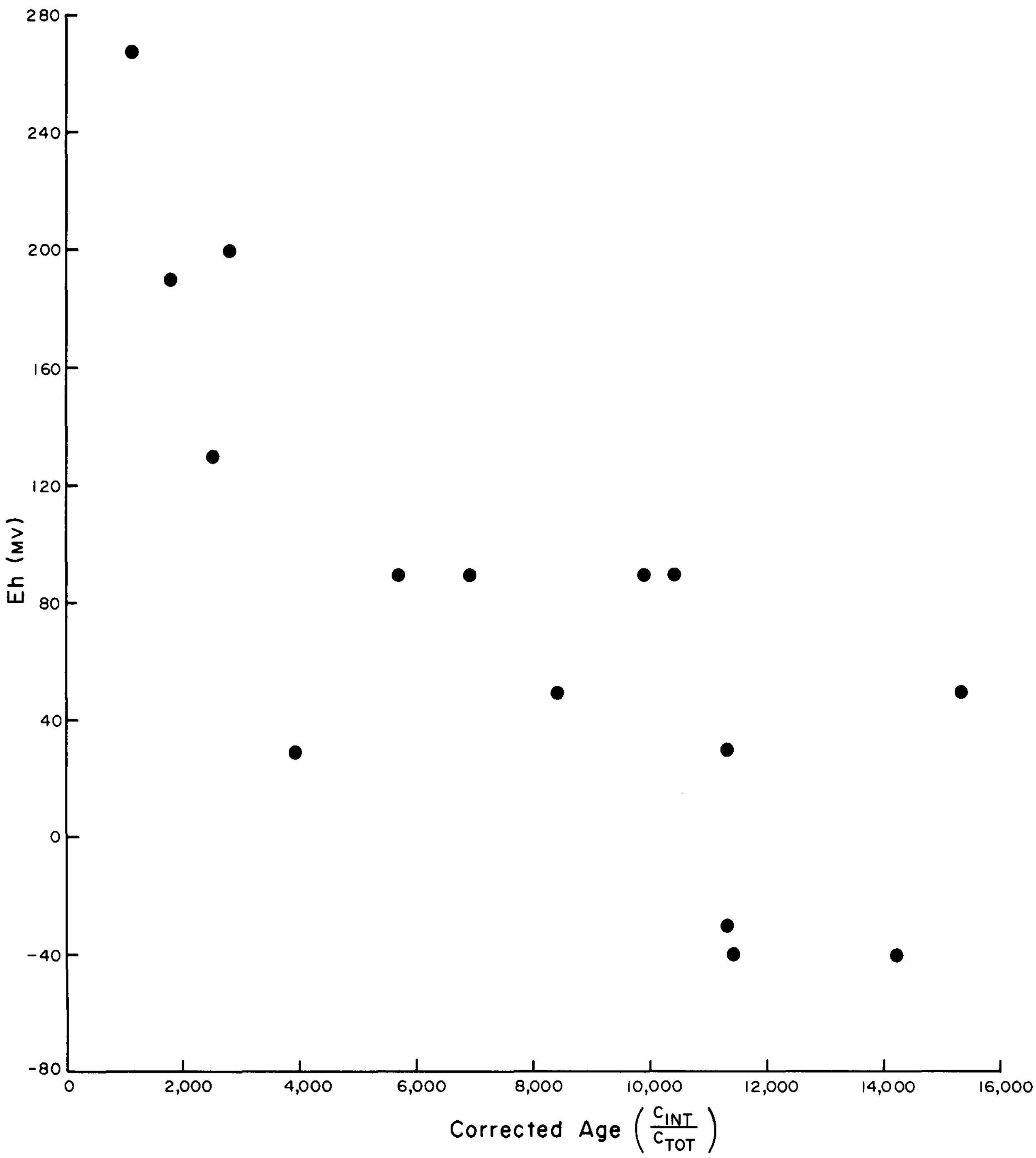

Figure 7. Relationship between Eh and age of the water. The ground waters become more reducing the older they are and the longer the flow distance.

DEEP-BASIN HYDROLOGY

C. W. Kreitler, G. E. Fogg, and E. W. Collins

Purpose

The location of a repository in a salt dome will be approximately 3,000 ft below land surface. Because of this depth, a potential radioactive leak from a repository might initially enter deep saline aquifers rather than shallow meteoric aquifers. The purpose of the deep-basin hydrology task is to characterize the hydrodynamics and geochemistry of the deep saline aquifers and investigate pathways between the saline aquifers and the meteoric aquifers. The investigations for FY81 were the first part of a 2-year program and are therefore preliminary.

Methods of Analysis

Three areas were pursued in the deep-basin hydrology task. (1) Collect and analyze available pressure data from the saline Cretaceous and Jurassic aquifers in the East Texas Basin. Approximately 300 drill-stem test pressure measurements were obtained from the computerized files of Petroleum Information Corporation and scout cards. (2) Collect and analyze available water chemistry from saline Cretaceous and Jurassic aquifers in the East Texas Basin. Approximately 600 water chemistry analyses were obtained from published and unpublished files of the Texas Department of Water Resources, the U.S. Bureau of Mines, and the University of Oklahoma Information System. (3) Study the false cap rock on Butler Dome, East Texas Basin, to determine whether there is evidence of fluid migration from saline aquifers to meteoric aquifers along the dome flanks. The Butler Dome studies were accomplished by field mapping to determine spatial distribution of false cap rock, petrographic studies to determine the type of calcite cementation, and isotopic studies to determine sources of the carbon and oxygen in the calcite cements.

Conclusions

Pressure data from the deep saline aquifers suggest that there may be two hydrologic systems: (1) the Upper Cretaceous aquifers (shallower than 6,000 ft) and (2) the Lower Cretaceous and Upper Jurassic aquifers (deeper than 6,000 ft). The Upper Cretaceous aquifers (e.g., the Woodbine Formation) probably were initially normally pressured (i.e., a vertical pressure gradient of ≈ 0.43 psi/ft). The deeper aquifers (Glen Rose, Hosston, Travis Peak Formations) are slightly overpressured (even when considering pressure gradients for brines) (fig. 8). More rapid ground-water circulation is suggested for the shallower saline aquifers with normal pressure-depth curves (e.g., Woodbine), and restricted circulation is suggested for the deeper, overpressured aquifers (e.g., Glen Rose and deeper).

Basin-wide pressures in the Woodbine Formation have dropped significantly because of oil production in the East Texas Field. These pressure drops have two implications to the waste isolation problem. (1) The Woodbine has good hydrologic continuity, suggesting that the sands are laterally extensive. (2) Currently, there is inadequate hydraulic potential to drive fluids from the Woodbine into the shallower meteoric Wilcox aquifer. Whether these low pressures will remain after oil production in the East Texas Field ceases is unknown.

The water chemistry data also suggest two different hydrologic systems: (1) the Upper Cretaceous aquifers (shallower than 6,000 ft) and (2) the Lower Cretaceous and Upper Jurassic saline aquifers (deeper than 6,000 ft). The chemical composition of the saline waters in the Upper Cretaceous aquifers is a Na-Cl water (figs. 9, 10). The chemical composition of the deeper waters is a Na-Ca-Cl water with much higher total dissolved solids. The increased calcium content may be caused by clay reactions, albitization, or anhydrite reduction. These deeper, higher TDS waters may result from greater rock-water interactions in an older, more closed system than the shallower

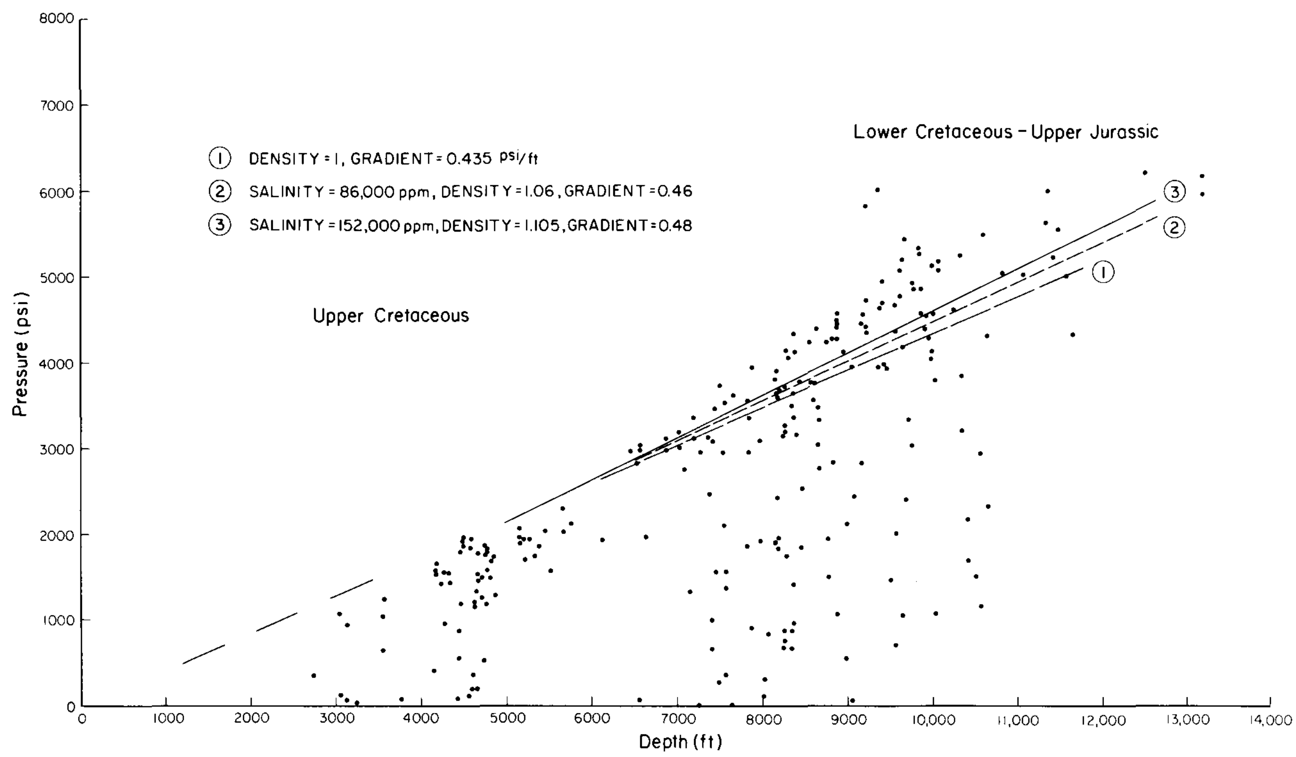

Figure 8. Pressure versus depth for deep saline formations in the East Texas Basin. Pressure for Upper Cretaceous sands (e.g., Woodbine) are currently either hydrostatic or underpressured. Samples from the Lower Cretaceous suggest some overpressuring.

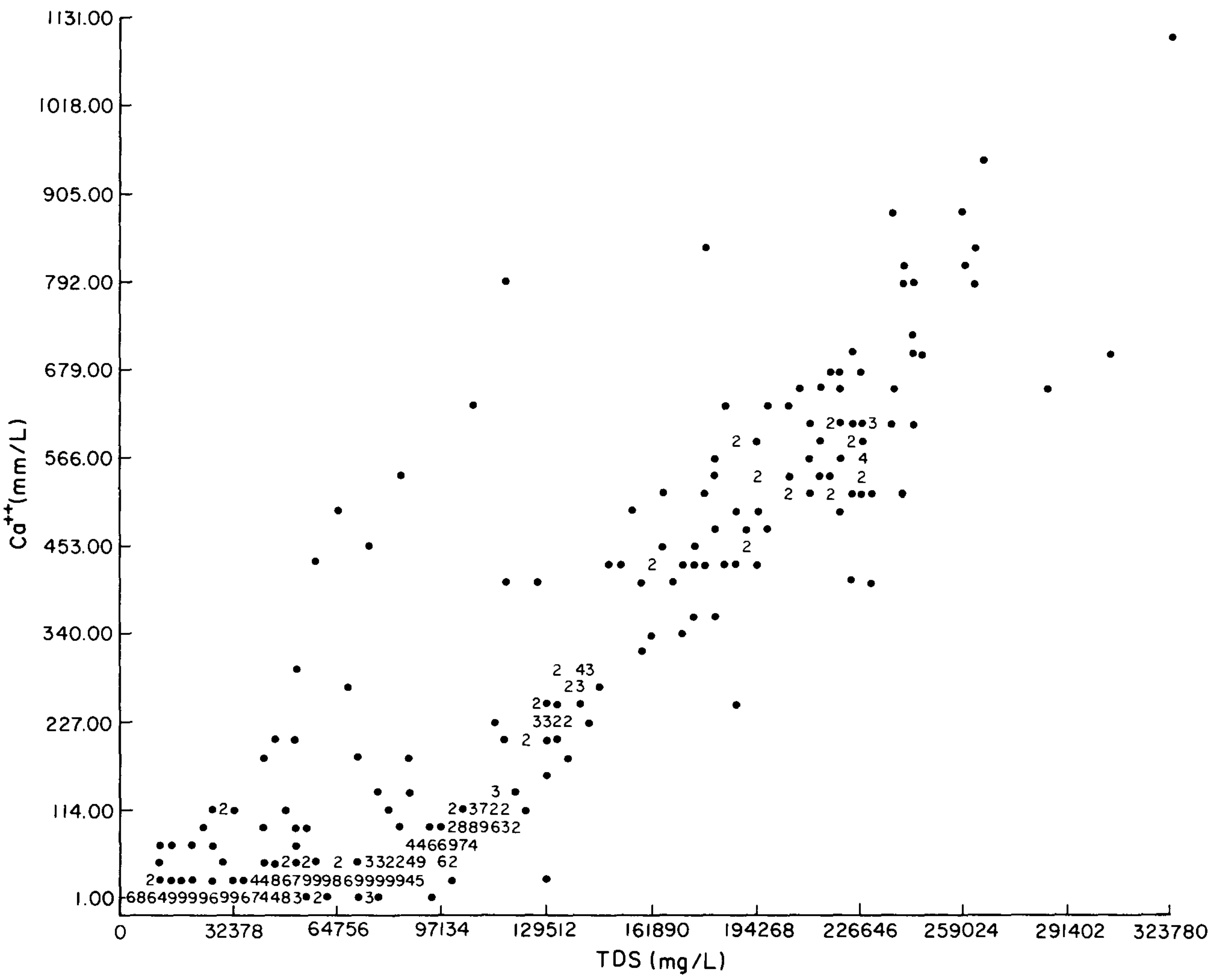

Figure 9. Calcium concentration versus total dissolved solids for deep saline formations in the East Texas Basin. The typical chemical composition for waters with TDS < 100,000 mg/l is a Na-Cl water. In contrast, at concentrations higher than 100,000 mg/l a Na-Ca-Cl water occurs.

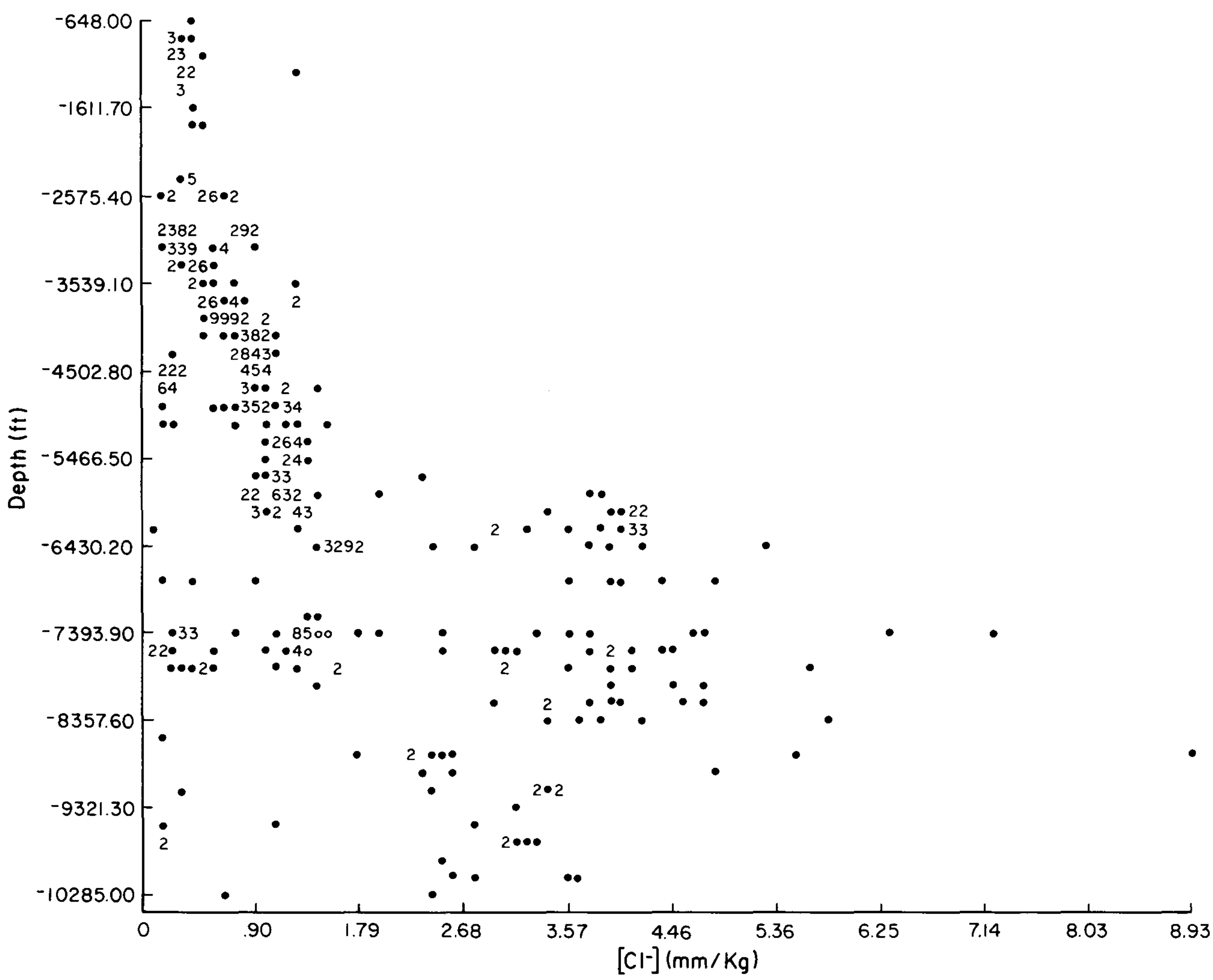

Figure 10. Chloride activity versus depth for deep saline formations in the East Texas Basin. Chloride activity increases linearly to a depth of approximately 6,000 ft. At depths greater than 6,000 ft, chloride activities are significantly higher and poorly distributed. This shift in chloride activity at 6,000 ft coincides with the development of the Na-Ca-Cl water (fig. 9).

Na-Cl waters. A repository in a salt dome would be located at such a depth that a leak from the repository would be into the shallower Na-Cl waters.

Studies of false cap rock at Butler Dome indicate that deep basinal waters have discharged up along the flanks of the dome or a fault associated with the dome. The false cap rock is a calcite-cemented Carrizo sandstone. The calcite cement is poikilotopic, indicating that a single fluid saturated the typically non-indurated sandstone and caused pervasive calcite cementation. The δC^{13} values of the calcite are in the range of -20°/oo to -32°/oo (PDB), suggesting a deep-basin petrogenic origin to the carbon. The δO^{18} values of the calcite range from -8.2°/oo to -9.4°/oo (PDB) (table 1) and suggest that the discharging fluids were deep high-temperature waters. The distribution of the cemented Carrizo is localized on the south side of a radial fault off the dome. Discrete calcite concretions occur on the north side of the fault and, on the basis of the heavier oxygen isotopes (table 1), appear to have formed from meteoric waters. The cementation is limited to Carrizo and overlying Reklaw Formations, but is not found in the overlying Pleistocene terrace deposits. This suggests that fluid migration occurred pre-Pleistocene.

Table 1. Isotopic composition of calcite from calcite-cemented Carrizo sandstone, south side of fault, and calcite concretions, north side of fault, Butler Dome.

Calcite from Calcite-Cemented Sandstone--South Side of Fault

Sample No.	δC^{13}	δO^{18}
1	-29.2	-8.4
2	-22.1	-8.2
3	-28.8	-8.5
4	-25.8	-8.2
5	-26.6	-8.0
6	-30.5	-8.7
7	-24.9	-8.9
8	-31.5	-8.5
9	-32.2	-8.5
10	-25.4	-9.4
11	-21.9	-8.9
12	-27.2	-8.8
13	-25.6	-8.3
14	-31.1	-8.6
15	-20.1	-8.7
16	-23.6	-8.3

Calcite from Calcite-Cemented Concretions--North Side of Fault

Sample No.	δC^{13}	δO^{18}
C_1	-23.4	-3.4
C_2	-24.7	-3.5
C_3	-19.1	-4.1
C_4	-19.0	-4.1

CAP ROCK

S. P. Dutton, C. W. Kreitler, and B. Bracken

Purpose

Cap rock studies were designed to determine when and under what conditions cap rock formed, and then to evaluate its present effectiveness as a natural barrier to further dome dissolution. Cap rocks such as the one on Oakwood Dome appear to be effective seals preventing further salt dissolution. Other domes, such as Gyp Hill, are currently undergoing dissolution, and its cap rock is not a barrier. If a waste repository is to be placed in any salt dome, it is critical to understand the origin of cap rock and the relation between cap rock formation and salt dome dissolution.

Data Collected and Method of Analyses

During FY81, petrographic investigations of cap rock from other salt domes in the Gulf Coast region were conducted to study the hypothesis that some cap rocks formed at depth in the past and are not the result of shallow meteoric ground-water processes. Thin sections from Cypress Creek and Richton Domes, Mississippi; Rayburn's and Vacherie Domes, Louisiana; and a Gulf of Mexico salt structure were available for comparison with Gyp Hill and Oakwood. In addition, a sample of anhydrite cap rock from beneath the Oakwood Dome salt overhang was studied in thin section.

Conclusions

Unconsolidated cap rock (fig. 11) on a Gulf of Mexico salt structure (Well 114-A, drilled by Shell Oil Company) formed by salt dissolution in a shallow marine environment. Cap rock may form on other shallow domes in the shelf and slope

Figure 11. Partially dissolved anhydrite crystals from a Gulf of Mexico salt structure, well 114-A. The sample is from cuttings recovered at a depth of 402.3 to 402.6 m (1,320 to 1,321 ft). Photo width is 2.6 mm.

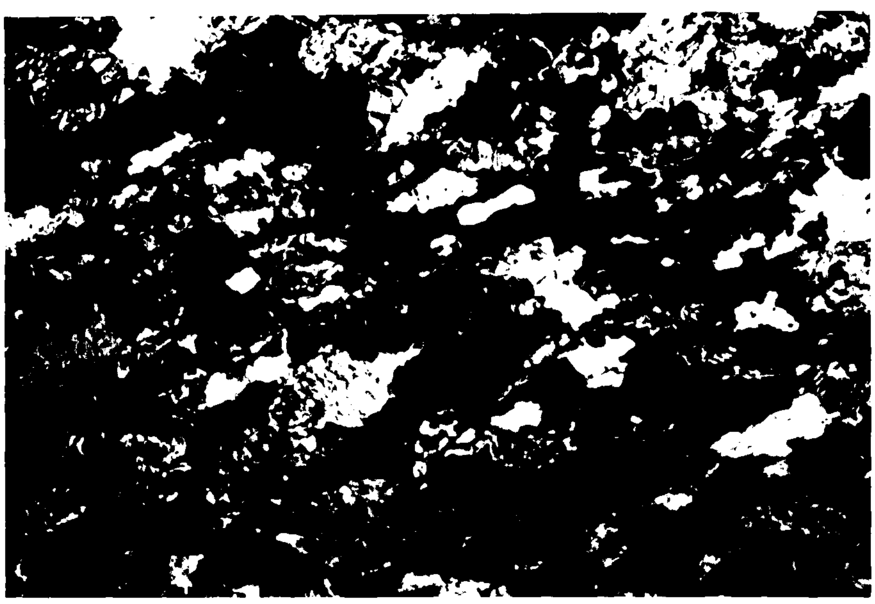

Figure 12. Anhydrite from Oakwood Dome flank; strong preferred orientation of crystals are parallel to the side of the salt dome. Sample from McBee #1 Sherman, depth about 1,524 m (5,000 ft). Photo width is 2.6 mm.

deposits of the Gulf of Mexico by this process, but neither Gyp Hill nor Oakwood cap rock formed in this way.

The sample of anhydrite cap rock (fig. 12) from the deep flank of Oakwood Dome (McBee #1 Sherman, depth 5,000 ft) provides evidence that flanks of salt domes have the same potential for solution as does the top of the domes. The existence of this sample shows that cap rock can form at depth in saline aquifers, and it helps further substantiate the hypothesis that anhydrite cap rock on top of Oakwood could have formed at depth.

Cap rock from Rayburn's Dome closely resembles Gyp Hill cap rock. Near the base of the cap rock, the predominant texture is a porous anhydrite sandstone in which the grains are held together by patches of fibrous gypsum (fig. 13). This texture appears to represent a step that is missing in Gyp Hill, in which the porous anhydrite is only partially cemented by gypsum. No fine-grained anhydrite subgrains or interpenetrating grain boundaries were observed.

In contrast to Rayburn's cap rock, the Vacherie cap rock is similar to cap rock on Oakwood Dome. Anhydrite at the base of the cap rock appears recrystallized and has a tight granoblastic texture similar to Oakwood anhydrite (fig. 14). No gypsum was observed in the anhydrite section at the base of the cap rock.

Cypress Creek cap rock appears to provide an intermediate anhydrite texture between Oakwood and Gyp Hill cap rocks. Anhydrite at the base of Cypress Creek is tightly packed, but the crystals commonly retain their elongate, prismatic shape. They do not appear to be recrystallized to the moderately well-developed granoblastic texture found in Oakwood cap rock. However, in contrast to Gyp Hill, no porosity was observed, and gypsum is not present at the base of the cap rock. There is a sharp contact, with no cavity, between the salt and the cap rock (fig. 15).

At Richton Dome a cavity separates the salt from the cap rock, and loose anhydrite may be present in this zone (S. Fuerst, personal communication, 1980). The

Figure 13. Patches of fibrous gypsum (G) in porous anhydrite sandstone, Rayburn's cap rock, 32.9 m (108 ft). Photo width is 0.5 mm.

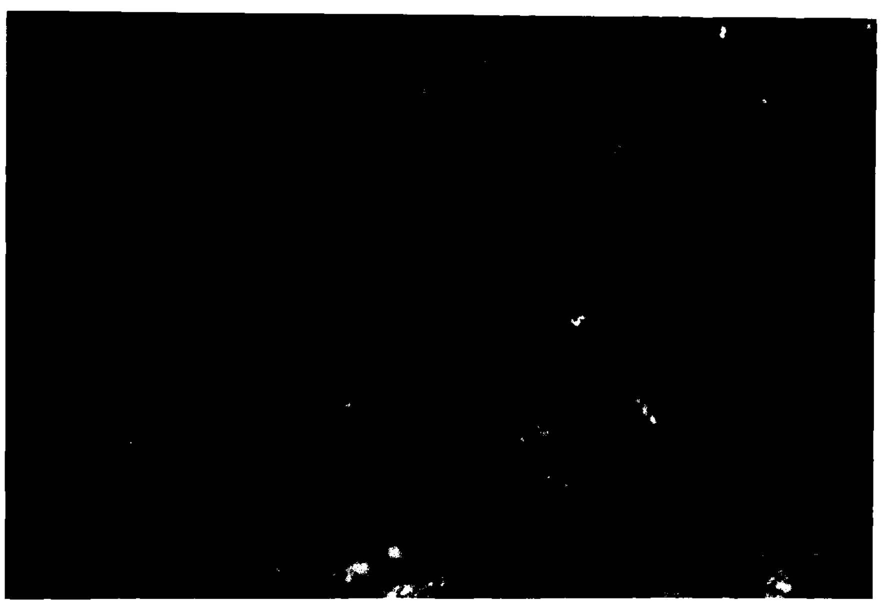

Figure 14. Tightly interlocking, xenoblastic crystals of anhydrite in Vacherie cap rock, depth 228.6 m (750 ft). Photo width is 2.0 mm.

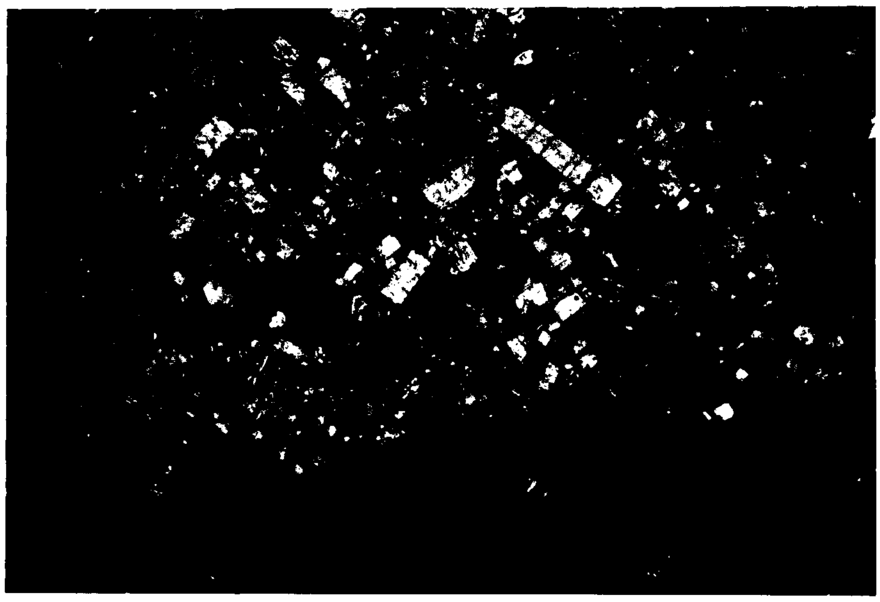

Figure 15. Sharp contact between salt and anhydrite cap rock at Cypress Creek Dome, depth 422.5 m (1,386 ft). Photo width is 6.2 mm.

Figure 16. Gypsum-filled fracture (G) within anhydrite cap rock (A) at Richton Dome. Depth is 193.2 m (634 ft); photo width is 2.6 mm.

anhydrite section contains abundant gypsum-filled fractures (fig. 16), the deepest occurrence of gypsum being only 7.3 m (24 ft) above the cavity. Calcite and sulfur commonly occur in association with the gypsum veins.

The presence of gypsum, calcite, and/or sulfur in the anhydrite section of Gyp Hill, Rayburn's, and Richton cap rocks indicates that the anhydrite is not an impermeable seal on these domes. The absence of these minerals in the anhydrite section of Oakwood, Vacherie, and Cypress Creek suggests that the anhydrite cap rock on these domes may function as an impermeable seal.

INTERNAL DOME STRUCTURES

M. P. A. Jackson

Purpose

The study of the rock salt and cap rock contact in core from Oakwood Dome, East Texas, advances knowledge of how rock salt deforms on scales varying from single grains to tens of meters and examines how rock salt was modified during the formation of cap rock. The study also assesses the implications of these findings to the use of salt stocks for storing nuclear wastes, particularly future creep or fracture of domal rock salt and the rock's ability to recover from deformation and seal itself.

Data Collected and Methods of Analysis

During FY81, the following data were collected:

a) Geochemical analysis of 38 specimens of rock salt for 24 elements by inductively coupled plasma atomic emission spectroscopy (ICP) and for bromine and sulfate by wet chemical methods.

b) Heating and freezing of four halite specimens containing fluid inclusions.

c) Axial ratios and orientations of 2,400 halite grains, measured in the 3 principal planes of strain at 8 locations along the core. Graphical and computer processing of data yielded eight three-dimensional strain analyses; the deformation path followed by the rock salt was also calculated.

d) Observations of textures and modal analyses using a conventional polarizing microscope.

Conclusions

The report for FY80 described the lithology and macro-scale structure of the Oakwood salt core. During FY81 we interpreted the microstructures, geochemical analyses, fluid-inclusion studies, and strain analyses. The results should be read in conjunction with the report for FY80.

Brines were present just below the cap rock, whereas the crest of the salt stock was truncated and recrystallized. Water that dissolved the rock salt either percolated through fractures in the anhydrite cap rock or entered along the rock salt - cap rock contact. Absence of a cavity along the contact indicates that the salt stock is not being dissolved in the zone intersected by the borehole, and that diapiric rise of rock salt compensated for past dissolution. Successive events of salt dissolution and rise of diapiric rock salt resulted in the anhydrite residue accreting against the base of the cap rock, a process that we believe accounts for the lamination of the anhydrite cap rock. If all the cap rock were derived by residual accumulation of such low concentrations as the 1.3 ± 0.7 percent anhydrite measured in the salt core, more than 6 km of rock salt must have been dissolved (slightly more than the present height of the salt stock).

Downward movement of intercrystalline brine from the base of the cap rock formed two recrystallized zones, separated by a sharp contact, in the top 2 m of salt core. The underlying R-2 zone (140 cm wide) has undergone recovery and primary recrystallization, indicated by reduction in grain size and degree of preferred orientation and by more equant crystals and smoother grain boundaries. In contrast, the overlying R-3 zone (60 cm wide) has undergone secondary recrystallization, indicated by dramatic increase in grain size and smoothness of grain boundaries. The more advanced recrystallization of the R-3 zone is inferred to have been due to higher concentrations of intercrystalline water.

The mean percentage of brine trapped within cuboid negative crystals in halite grains increases from 0.005 in the lower part of the R-3 zone to a maximum of 0.05 in the upper 25 cm of the R-3 zone just below the cap rock. Most of these fluid inclusions contained bubbles of compressed gas that expanded when the inclusions were experimentally breached. The liquid and gas homogenized at 35° to 45°C, suggesting trapping at depths of about 1,000 m.

Bromine contents of Oakwood halite average 45 ppm and range from 37 ppm to 50 ppm throughout the salt core. These values are intermediate between first-cycle halite (precipitated from sea water) and second-cycle halite (precipitated from brines derived by re-solution of first-cycle halite). All the rock salt has therefore been chemically recycled by recrystallization in the presence of some water. However, in the case of the foliated rock salt, which constitutes 96 percent of the salt core, this recrystallization was syntectonic, rather than post-deformational like the unfoliated R-2 and R-3 zones. The R-3 zone, characterized by the most recrystallized microstructure, also contains the lowest bromine contents, indicating the greatest amount of chemical recycling.

The foliated rock salt shows a statistically significant upward decrease in mean finite-strain magnitude from 50 percent to 39 percent shortening parallel to the $\underline{Z}$ principal axis of shortening. Similarly the $\underline{k}$ values of finite strain decrease upward from 0.5 to 0.1, a measure of the increasing dominance of oblate strains (flattening) over prolate strains (constriction); halite grains become more pancake-shaped upward. The unfoliated salt has a weak oblate strain fabric indicative of uniaxial compression along a vertical axis. This compression was induced by upward movement of the diapiric salt against the cap rock. The deformation path of halite during its rise toward the cap rock has been reconstructed. This trend shows that although the large-scale internal structure of Oakwood Dome is more complex than that of experimental models of layered, but otherwise homogeneous materials, the upward trends of internal strains are similar in both natural and experimental models.

Upward movement of rock salt and concomitant closure of the inferred solution cavity along the cap rock contact also marked the base of the anhydrite cap rock. Several structures indicate vertical shortening and lateral extension of the base of the cap rock: subvertical, weakly buckled, halite-filled extension veins; subhorizontal, dark, stylolitic pressure stripes representing laminae from which anhydrite has been dissolved under pressure causing enrichment of a dark residue, possibly pyrite; and inclined shear fractures that displace both the pressure stripes and the primary laminae.

In conclusion, vertical compression is recorded in extension veins, pressure stripes, and microfaults in the base of the cap rock. Compression is also manifested in the superposition of flattening strains on less oblate strains, the latter resulting from constrictive flow of rock salt deep in the trunk of the diapir. This uniaxial compression indicates that rock salt pressed against the base of the cap rock. This upward pressure enabled anhydrite sand that had dissolved out of rock salt at the diapir crest to be accreted to the base of the cap rock to form the laminated anhydrite rock. Upward pressure also explains the tight seal of the cap rock - salt contact, despite evidence for repeated salt dissolution in the past.

STRATIGRAPHIC STUDIES OF SALT DOMES

S. J. Seni, M. K. McGowen, D. Wood, and R. Conti

Purpose

The study of stratigraphy around salt domes addresses the problems of tectonic stability and the possibility of dome-influenced facies changes. Stratigraphic research in FY81 concentrated on four areas: (1) site-specific studies of Wilcox Group sand-body geometry in and around the area of Oakwood Salt Dome, (2) salt dome growth rates, (3) Jurassic and Lower Cretaceous mobilization of salt by sediment loading, and (4) Cretaceous and Tertiary history of salt mobilization.

Data Collected and Method of Analysis

Sand-body geometry in Wilcox Group around Oakwood Dome

Over 300 well logs were used to define the lithostratigraphy and the hydrostratigraphic facies around Oakwood Dome. In FY81, close-spaced cross sections and maps of net and percentage sandstone with resistivities greater than 20 ohm-m provided data for a three-dimensional ground-water flow model.

Salt dome growth rates

Data were collected for study of salt dome growth rates during the previous 2 fiscal years. The methods of analyses are based on interpretation of structure and isopach maps constructed from more than 2,000 well logs. Thickness changes were used to define dome growth phases. Rates of salt pillow uplift were also measured by stratigraphic thinning of strata over the crest of the structure. Rates of diapiric growth were inferred to equal the maximum rate of deposition in salt withdrawal basins.

Jurassic and Lower Cretaceous salt mobilization by sediment loading

Data used in this study included regional seismic sections, core analyses, and interpretation of over 400 well logs. Depositional facies, isopach, and structure contour maps were constructed to analyze the relationship between early sediment loading and initiation of salt movement.

Cretaceous and Tertiary history of salt mobilization

Data were collected for study of salt mobilization during the previous 2 fiscal years. Methods of analyses are based on interpretation of structure and isopach maps and regional and local cross sections constructed from more than 2,000 well logs. Salt mobilization was quantified by analysis of the volume and timing of salt withdrawal basins.

Conclusions

Sand-body geometry in Wilcox Group around Oakwood Dome

Net and percentage maps of sandstone with resistivities greater than 20 ohm-m illustrate the distribution of highly resistive and highly transmissive sandstones in the Wilcox Group (fig. 17) in the southern part of the East Texas Basin. The Wilcox Group also provides an example of the effect of syndepositional dome growth on sedimentation and thickness (fig. 18). Oakwood Dome and other domes in the southern part of the East Texas Basin are preferentially located in mud-rich interchannel facies of the Wilcox Group because syndepositional uplift from dome growth formed areas of positive relief over the domes. Local domal topography caused fluvial channels to flow around the over-dome areas. The Wilcox Group is thick and characteristically composed of sand-rich channel-fill facies in rim synclines flanking the domes because subsidence from salt withdrawal favored vertical aggradation.

Figure 17. Net sandstone with resistivities greater than 20 ohm-m, middle third of Wilcox Group, southern part of the East Texas Basin.

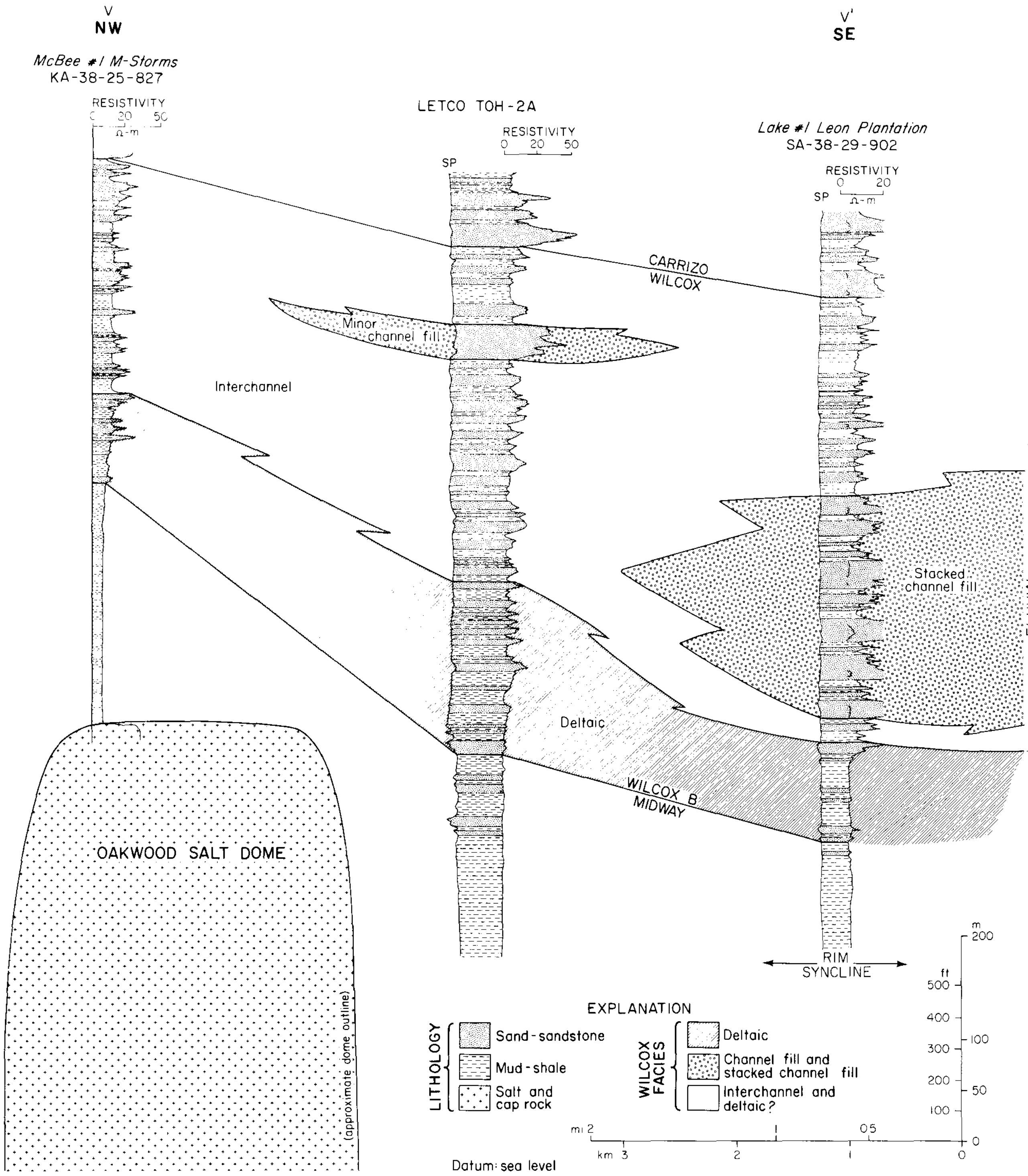

Figure 18. Cross section of Wilcox Group around Oakwood Dome showing sand-poor strata over the dome and sand-rich facies in rim syncline.

Salt dome growth rates

Calculations of sedimentation rates in salt withdrawal basins indicate that maximum dome growth rates of 0.15 to 0.22 mm/yr occurred in the Early Cretaceous and that rates declined irregularly into the Tertiary (fig. 19). For example, peak growth rates of Oakwood Dome are 0.087 mm/yr during deposition of the Lower Cretaceous Glen Rose Group, and rates declined to 0.036 mm/yr in the Late Cretaceous and Tertiary (fig. 20).

Rates of salt pillow uplift calculated by stratigraphic thinning show similar trends to growth rates of salt domes. Maximum growth rates for pillow uplift are 0.1 mm/yr in the Early Cretaceous, and rates subsequently declined to 0.01 mm/yr in the Late Cretaceous.

Jurassic and Lower Cretaceous salt mobilization by sediment loading

Integration of electric log, core, and seismic data shows that salt flow was extensive in the Late Jurassic. A major shift from carbonate to clastic sedimentation with resultant uneven loading by fan-delta systems is the inferred mechanism that led to salt movement and diapirism early in basin history (fig. 21). During Jurassic and Early Cretaceous time, deltaic depocenters shifted basinward. Sequential salt movement away from prograding depocenters resulted in a complex array of domes and anticlines, the younger Jurassic and Early Cretaceous salt structures being located in basin center.

Cretaceous and Tertiary history of salt mobilization

Diapiric dome growth was most active in the center of the East Texas Basin in the Early Cretaceous. This period of diapiric activity is associated with rapid rates of sedimentation (fig. 19), suggesting the continued importance of sediment loading to induce diapirism. Basinwide, diapiric activity declined through the Late Cretaceous and early Tertiary. A subordinate peak of diapiric activity is associated with growth

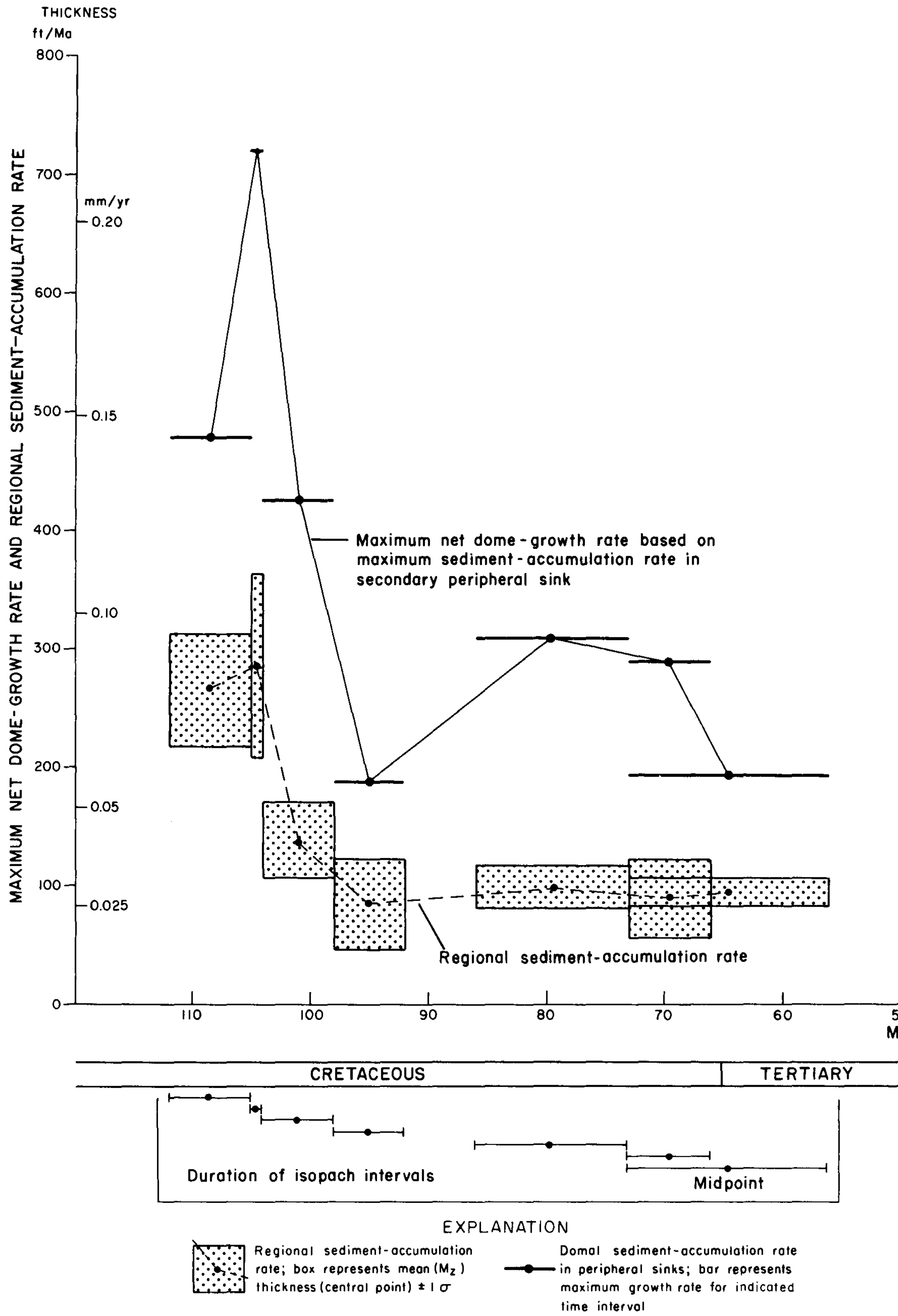

Figure 19. Graph of regional sediment-accumulation rate (± 1 σ) and maximum net dome-growth rate. Maximum rate of net dome growth is inferred to equal maximum rate of sediment accumulation in salt withdrawal basins.

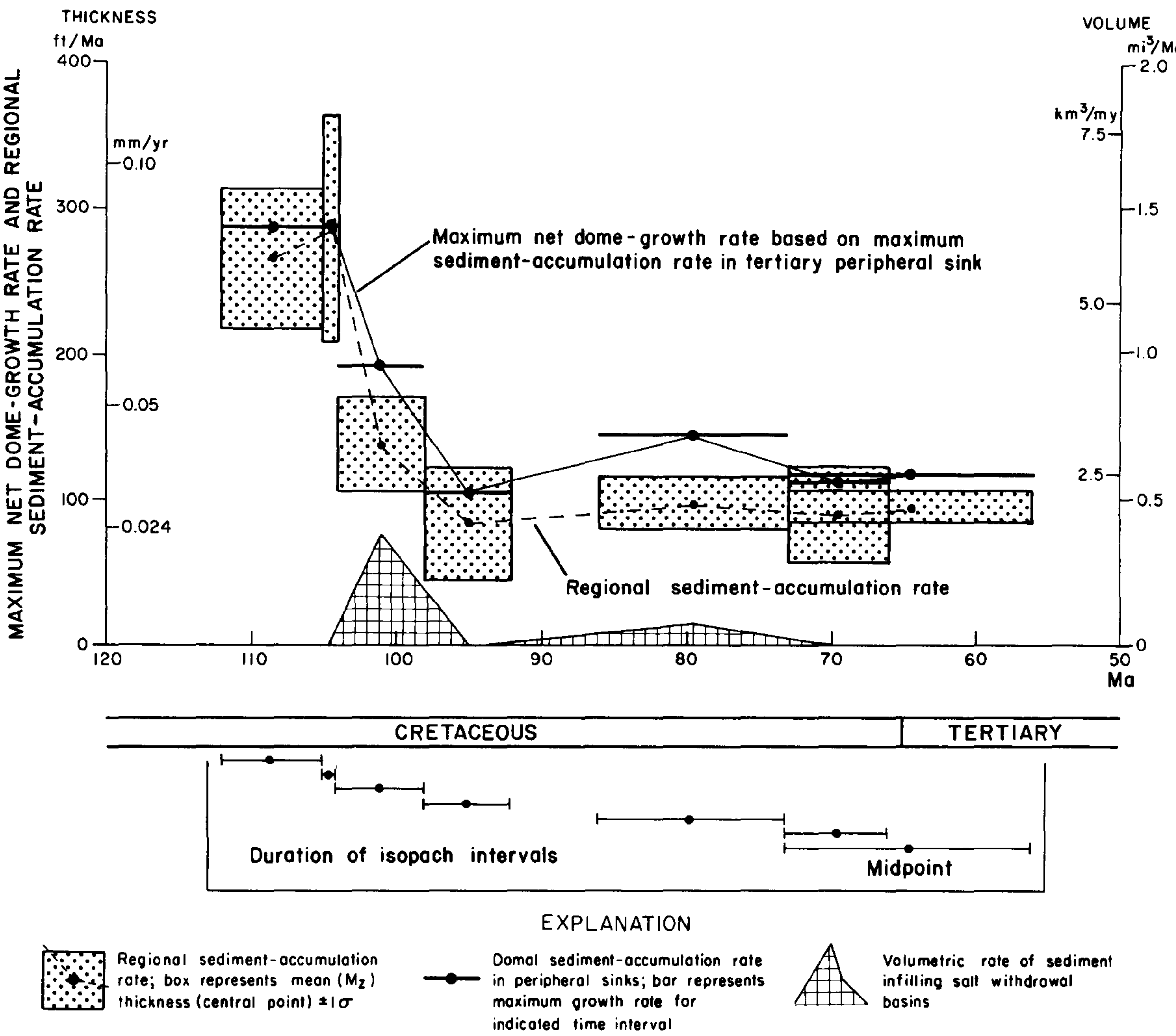

Figure 20. Graph of Oakwood Dome net-growth rate, regional sediment-accumulation rate (± 1 σ), and volumetric rate of salt movement.

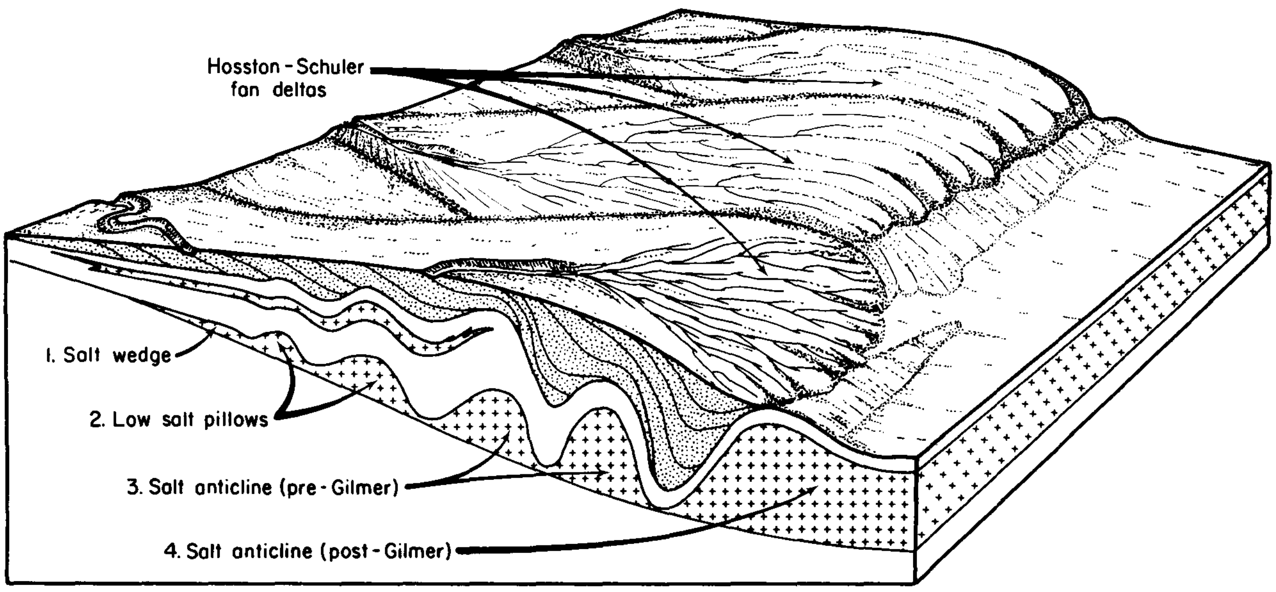

Figure 21. Block diagram of Hosston-Cotton Valley fan-delta lobes and migration of underlying salt away from areas of sediment loading.

of Hainesville and Bethel Domes around the updip margin of the basin during the Late Cretaceous. This late period of dome growth is associated with slow rates of sedimentation, suggesting the influence of erosion as an additional mechanism to initiate dome growth by exposure and extrusion of a salt pillow.

BASIN TECTONICS

M. P. A. Jackson, B. Wilson, and W. D. Pennington

Purpose

Surface and subsurface studies of the tectonics of the East Texas Basin describe the distribution, geometry, displacement history, and possible origins of the principal fault systems to assess the risk of seismic shocks to a nuclear-waste repository in the Gulf Coast. Microseismic activity in the basin is also being monitored. The results, which concern the interplay among sedimentation, faulting, and halokinesis (gravity-induced salt flow), can be applied to any Gulf interior salt basin.

Data Collected and Methods of Analysis

Surface data were derived from maps of the Geologic Atlas of Texas (Barnes, 1965, 1966, 1967, 1968, 1970, and 1972), air photographs at scales of 1:17,400 to 1:25,500, and band-5 Landsat imagery at a scale of 1:250,000. Subsurface data are based on 780 km of reflection-seismic lines supplemented by electric logs from 232 wells extending to the lower stratigraphic units; cuttings were examined from 5 of these wells. Microseismic activity was monitored by one (during the first half of 1981) to as many as five stations (since June 1981).

Conclusions

All the faults have normal displacement and grew coevally with deposition more than approximately 120 million years ago (Ma). They appear to be related to salt mobilization.

The Mexia-Talco fault zone is a peripheral graben system around the western and northern margins of the basin (fig. 22). The zone coincides almost exactly with the updip limit of the Middle Jurassic Louann Salt and was active from the Jurassic to the

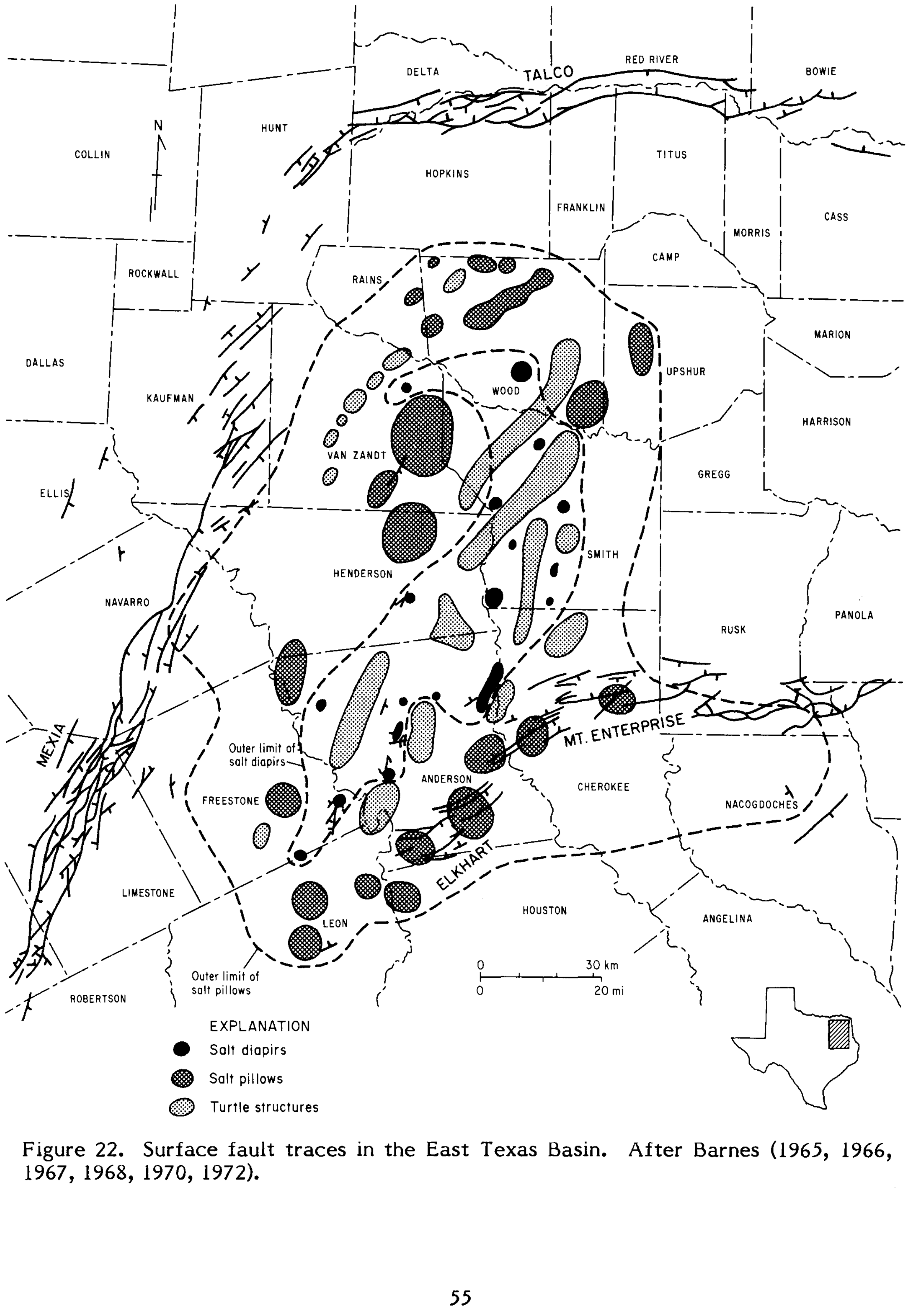

Figure 22. Surface fault traces in the East Texas Basin. After Barnes (1965, 1966, 1967, 1968, 1970, 1972).

Eocene. The fault zone formed by pull-apart between autochthonous salt-free strata outside the basin and allochthonous strata underlain by a décollement zone of mobile salt; salt mobility allowed basinward creep of the strata into the basin. Horizontal translation of the post-Louann strata has been estimated to be at least 0.5 km (Crosby, 1971); how much the salt itself moved is conjectural.

All faults not included in the peripheral fault zones are referred to as the central-basin faults. Normal faults in parallel arrangement are abundant in the deep subsurface over the salt pillows and diapirs; very few of these faults reach the Eocene strata at surface. The central-basin faults are concentrated on the crests of salt-related anticlines such as salt pillows and turtle structures and are oriented parallel to the hinge lines of the anticlines. The crests of these structures therefore split and collapsed by folding-related extension.

The Elkhart Graben constitutes the western end of the Elkhart-Mount Enterprise fault zone on the southern flank of the basin. The graben consists of parallel faults with multiple offsets defining a graben approximately 40 km long. The graben is spatially related to the central-basin faults, in that it forms the southern component of a fan of central-basin faults. The graben also appears to be genetically related to the central-basin faults because it, too, is situated on the crests of two broad, salt-cored anticlines.

The Mount Enterprise fault zone is a regular array of parallel and en echelon faults, which are largely downthrown to the north in multiple offsets. The Mount Enterprise Fault itself forms the largest and most southern component of the fault zone. Unlike other fault zones, this zone is not obviously connected to salt-related structures such as anticlines or subcrop limits or to other basinal structures. The eastern and western ends of the fault zone were most active between 120 Ma and 40 Ma, whereas the central parts were most active after 40 Ma. At least one fault in the western part of the fault zone is a long-lived listric normal growth fault, downthrown to the north and based in the Louann Salt (fig. 23). This fault suggests that in the Jurassic the southern margin of the basin sloped northward away from a platform. Growth faulting could have resulted from uneven thicknesses of salt or rapid subsidence in the basin center. Once initiated, growth of the fault would have been perpetuated by loading of sediments trapped on the downthrown northern side, even though source areas lay to the north since the Late Jurassic.

The faults of East Texas share a number of characteristics that indicate low seismic risk. Normal displacements ensure that stresses are neutralized by tensile fracture at low stresses because the tensile strength of materials is generally much lower than their compressive strength. Furthermore most of these faults are apparently related to slow gravitational creep of salt and its sedimentary overburden rather than to movement of lithospheric plates; this also indicates a low seismic potential. Moreover future movement on the Mexia-Talco fault zone can be discounted because it is crossed by undeformed Pleistocene terraces (Turk, Kehle, and Associates, 1978). Similarly only a few of the central-basin faults extend to the Lower Tertiary stratigraphic units exposed at the surface.

Nevertheless, grounds for caution remain. Collins and others (1980) described normal faults exposed in the Trinity River along strike of the northern flank of the Elkhart Graben. One fault offsets the Eocene Claiborne Group with a throw of 66 cm and the base of a Quaternary terrace by 5 cm. These authors also cite releveling data suggesting a southward downthrow of 13 cm in 30 years on an inferred fault south of the Mount Enterprise fault zone. The Mount Enterprise fault zone is the least understood zone in East Texas because of poor subsurface information. At least one seismic profile indicates that it is based in the Louann Salt, like the Mexia-Talco fault zone; that the Mount Enterprise fault zone is related to salt creep is encouraging. Nevertheless, a compelling reason for detailed study of the Mount Enterprise fault zone is the prevalence of microseismic tremors in this area, a notable example being

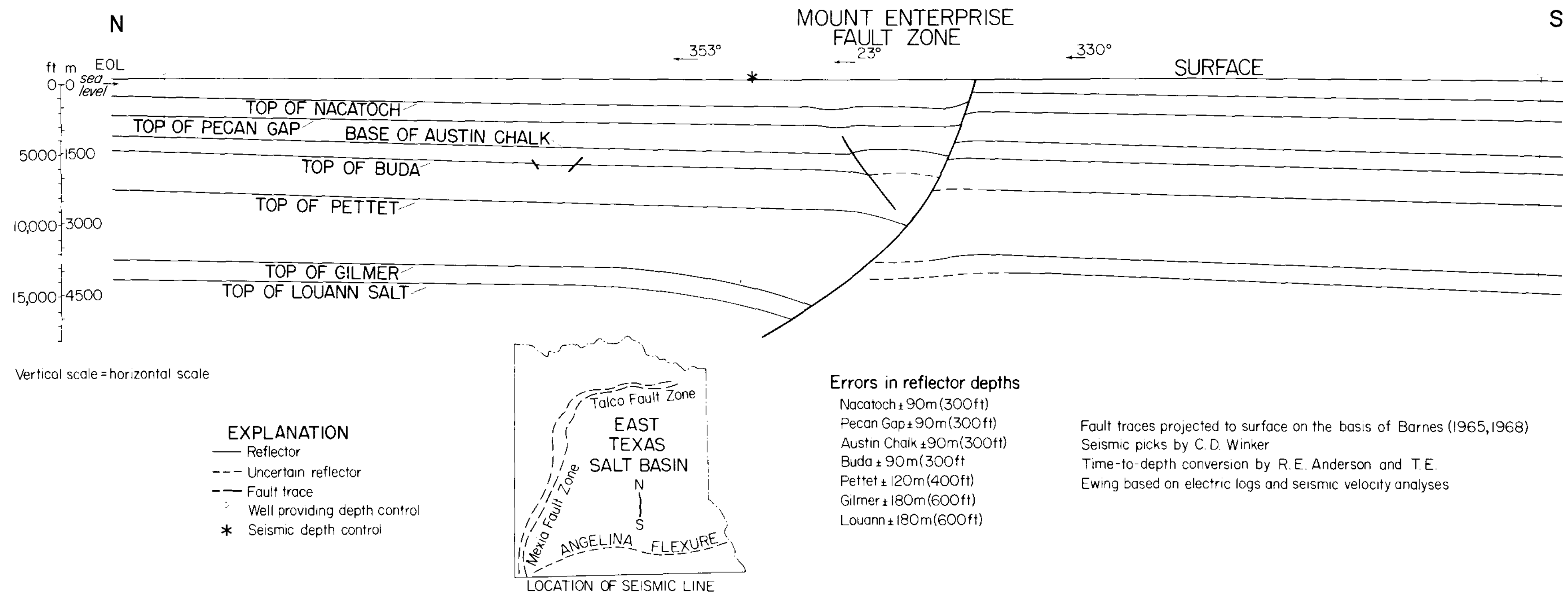

Figure 23. Time-to-depth converted seismic section across the central part of the Mount Enterprise fault zone. A large growth fault, downthrown to the north and based in the Louann Salt, shows listric-normal geometry, decreasing cumulative displacement with time, and a rollover anticline on the downthrown side.

the Jacksonville earthquake of November 6, 1981, which had a Richter intensity of 3.5 to 4.0. Five seismic events have been recorded since June 1981. The two largest events had Richter magnitudes of 3.2 (fig. 24).

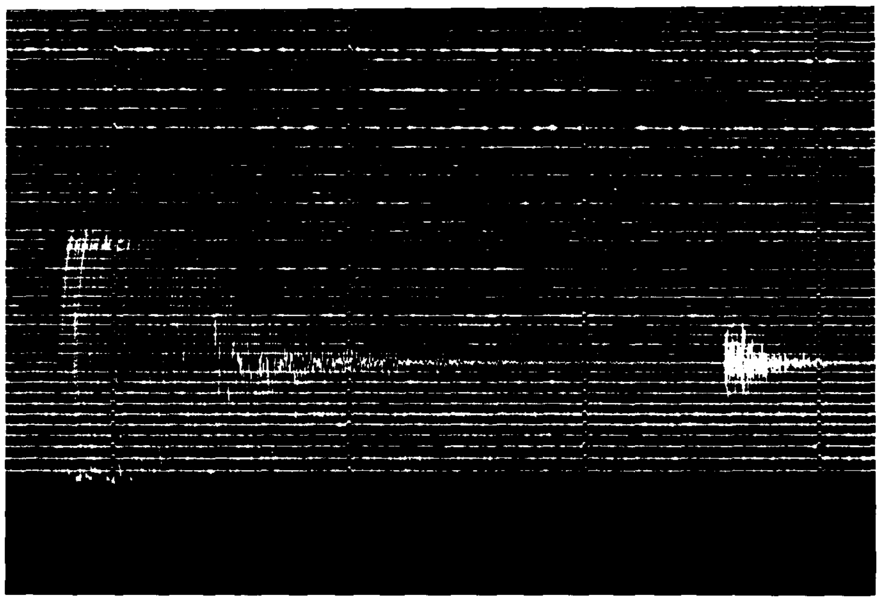

Figure 24. Seismic event from Mount Enterprise fault system. Richter magnitude: 3.2. Date: November 7, 1981.

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REFERENCES

Barnes, V. E., 1965, Tyler sheet: University of Texas, Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

______________ 1966, Texarkana sheet: University of Texas, Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

______________ 1967, Sherman sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

______________ 1968, Palestine sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

______________ 1970, Waco sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

______________ 1972, Dallas sheet: The University of Texas at Austin, Bureau of Economic Geology, Geologic Atlas of Texas, scale 1:250,000.

Bredehoeft, J. D., England, A. W., Stewart, D. B., Trask, N. J., and Winograd, I. J., 1978, Geologic disposal of high-level radioactive wastes--earth-science perspectives: U.S. Department of the Interior Geological Survey Circular 779.

Brunton, G. O., Laughon, R. B., and McLain, W. C., 1977, Screening specifications for Gulf Coast salt domes: Oak Ridge National Laboratories, Report Y/OWI/TM-48.

Collins, E. W., Hobday, D. K., and Kreitler, C. W., 1980, Quaternary faulting in East Texas: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-1, 20 p.

Crosby, D. W., 1971, Gravity and mechanical study of the Great Bend in the Mexia-Talco fault zone, Texas: Journal of Geophysical Research, v. 76, no. 11, p. 2690-2705.

Fogg, G. E., 1980, Aquifer modeling at Oakwood Dome, in Kreitler and others, Geology and geohydrology of the East Texas Basin: a report on the progress of nuclear waste isolation feasibility studies (1979): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-12, p. 35-40.

Fogg, G. E., 1981, Aquifer modeling of the Oakwood salt dome area, in Kreitler and others, Geology and geohydrology of the East Texas Basin: a report on the progress of nuclear waste isolation feasibility studies (1980): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-7, p. 139-149.

Fogg, G. E., and Kreitler, C. W., 1981, Ground-water hydrology around salt domes in the East Texas Basin: a practical approach to the contaminant transport problem: Bulletin of the Association of Engineering Geologists, v. 23, no. 4, p. 387-411.

Fogg, G. E., Kreitler, C. W., and Dutton, S. P., 1980, Hydrologic stability of Oakwood Dome, in Kreitler and others, Geology and geohydrology of the East Texas Basin: a report on the progress of nuclear waste isolation feasibility studies (1979): The

University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-12, p. 30-32.

Fogg, G. E., and Seni, S. J., in preparation, Aquifer modeling of the Oakwood salt dome area: The University of Texas at Austin, Bureau of Economic Geology.

Foster, M. D., 1950, The origin of high sodium bicarbonate waters in the Atlantic and Gulf Coastal Plain: Geochimica et Cosmochimica Acta, v. 1, p. 33-48.

Kreitler, C. W., Wermund, E. G., Guevara, E. H., Giles, A. B., and Fogg, G., 1978, Preliminary evaluations of salt domes in East Texas for the National Waste Terminal Storage Program: The University of Texas at Austin, Bureau of Economic Geology Interim Contract Report, prepared for the U.S. Department of Energy, 38 p.

Kreitler, C. W., and others, 1980a, Evaluating the potential of East Texas salt domes for isolation of nuclear wastes: The University of Texas at Austin, Bureau of Economic Geology, Contract Report prepared for the U.S. Department of Energy, 116 p.

Kreitler, C. W., and others, 1980b, Geology and geohydrology of the East Texas Basin, a report on progress of nuclear waste isolation feasibility studies (1979): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-12, 116 p.

Kreitler, C. W., and others, 1981, Geology and geohydrology of the East Texas Basin, a report on the progress of nuclear waste isolation feasibility studies (1980): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-7, 207 p.

Narasimhan, T. N., and Witherspoon, P. A., 1977, Numerical model for saturated-unsaturated flow in deformable porous media, part 1, theory: Water Resources Research, v. 13, no. 3, p. 657-664.

Narasimhan, T. N., and Witherspoon, P. A., 1978, Numerical model for saturated-unsaturated flow in deformable porous media, part 3, applications: Water Resources Research, v. 14, no. 6, p. 1017-1034.

Narasimhan, T. N., Witherspoon, P. A., and Edwards, A. J., 1978, Numerical model for saturated-unsaturated flow in deformable porous media, part 2, the algorithm: Water Resources Research, v. 14, no. 2, p. 255-261.

Office of Nuclear Waste Isolation, 1980, NWTS criteria for the geologic disposal of nuclear waste: site qualification criteria: ONWI-33 (2).

Seni, S. J., and Fogg, G. E., in preparation, Wilcox Group facies and syndepositional salt dome growth, southern East Texas Basin: The University of Texas at Austin, Bureau of Economic Geology, report prepared for U.S. Department of Energy.

Turk, Kehle, and Associates, 1978, Tectonic framework and history, Gulf of Mexico region: Report prepared for Law Engineering Testing Company, Marietta, Georgia, 29 p.

U.S. Department of Energy, 1980, Statement of position of the United States Department of Energy in the matter of proposed rulemaking on the storage and disposal of nuclear waste: DOE/NE-0007.