Characterization of Salt Domes for Storage and Waste Disposal

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ABSTRACT

Gulf Coast salt domes are currently being studied for waste disposal and storage purposes. Specific applications are radioactive waste disposal, oil and gas storage and compressed air energy storage. This paper describes the geophysical techniques currently being used to characterize the geologic and hydrologic aspects of the salt domes for suitability for such storage purposes.

Geological and hydrological characterization of the salt domes is done with detailed gravity work, shallow high resolution reflection seismic surveys, surface electrical resistivity, and down-hole geophysical logging to add a third dimension to all of the surface techniques. Borehold geophysical logs are also used to determine stratigraphy around the dome with respect to confining beds that affect ground water flow. Salinity profiles are also determined by use of electrical logs.

The logic of the combined geophysical surveys will be discussed, as well as their relative economics and their relationship to the overall characterization effort.

INTRODUCTION

Gulf Coast salt domes are being utilized to store oil and gas in solution and dry-mined cavities. Studies are underway to utilize these domes much more extensively for the storage of petroleum products as well as for radioactive and hazardous chemical waste disposal and for compressed air energy storage. Plans for combined use of one facility for mining and storage or multi-use storage exist.

The occurence of salt domes within the northern Gulf Coast Geologic Province is shown in Figure 1. Salt domes occur offshore along the continental margin, on and offshore along the Louisiana coast, and inland in the three interior basins in east Texas, northern Louisiana, and south central Mississippi.

The earliest evaporite units in the northern Gulf Coast are the Triassic/Jurassic-Louann Salt and Werner Formation. The Louann Salt, which may average 5000 feet in thickness where not deformed, forms the domes and other salt structures in the Gulf Coast salt dome basins. From the Jurassic and continuing to the present, the Gulf Coast has been an active depositional basin. The earliest depocenters were located near the inner boundary fault systems and with time they shifted basinward (Figure 1). The current depocenter is located offshore at the edge of the continental margin. The basin sediments consist of marine clastics and carbonates, and nonmarine, primarily fluvial, clastics.

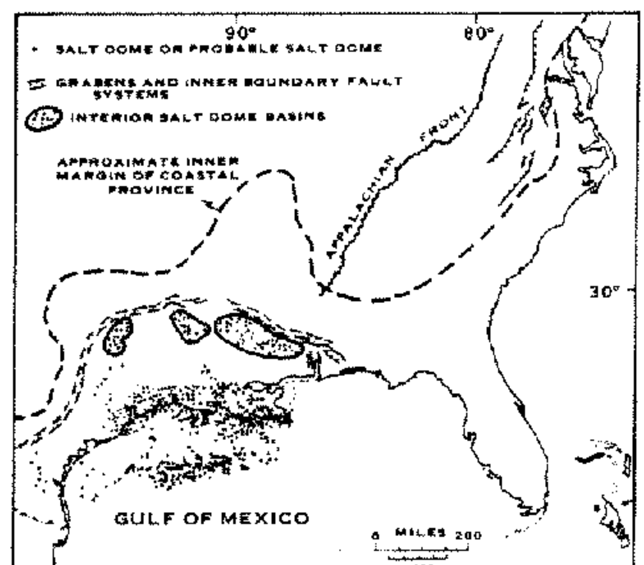

Figure 1. Northern Gulf Coast Geologic Province showing salt domes, interior salt dome basins and coastal and offshore domes.

Horizontal movement of salt in response to differential loading at active depocenters has strongly influenced the structures found in Gulf Coast sediments. In general the period of activity of such structures, which include major faults and salt domes, corresponds to the period when differential loading was occurring. The interior salt dome basin's relative geologic stability is primarily due to the long period since differential sedimentation took place there. Stratigraphic evidence implies an end of relative movement sometime in the Tertiary. The coastal Louisiana domes are located at more recent delta front depocenters and in many cases, such as the Five Island domes, show geomorphic evidence of movement of the salt stock as late as Pleistocene time. A diagram illustrating a conceptualized salt dome growth is given in Figure 2, (Kupfer, 1967, Kehle, 1978b).

Small relative movements of domes with respect to their surrounding sediments are an issue in the licensing of salt domes for nuclear waste disposal, because of the requirement for integrity of the facility for a fraction of a million years. For this reason interior salt basin domes were selected for continued study for radioactive waste storage.

This paper will describe an exploration approach to characterizing the geometry of salt domes and their surrounding geology that has been developed over the last several years. The salt domes so investigated have been located in all three interior salt dome basins and in the Louisiana coastal area. Applications for the domes have included oil storage, dry and solution salt mining, hazardous chemical waste and nuclear waste storage and disposal. The specific objects of the exploration efforts described in this paper have been the size and shape of the salt stock in the upper 5000 feet, and the geohydrologic characterization of the above-dome and near-dome sediments. Internal investigations of domes will also be discussed.

SIZE AND SHAPE OF THE DOMES
(Upper 5000 feet)

A typical dome being considered for storage or waste disposal is shown in Figure 3. These domes are typically large by Gulf Coast standards (2000 to 5000 acres at the repository level) and are within 1000 feet of the ground surface. Overhang is common, and in most cases the utilized space would be located within the overhang depth range. The caprock material encountered is primarily anhydrite with some calcite and gypsum. The caprock porosities vary from zero to high values. The surrounding sediments are Recent, Pleistocene and Tertiary clays, sands and limes with Cretaceous sediments at depth. A stratigraphic column representing the geology in the near-vicinity of a dome in north Louisiana shows the formations and lithologies typical of the interior salt dome basins (Table 1). Coastal domes typically have Recent to Pleistocene clastics in the upper few thousand feet. The near-dome lithology and structural complexity vary.

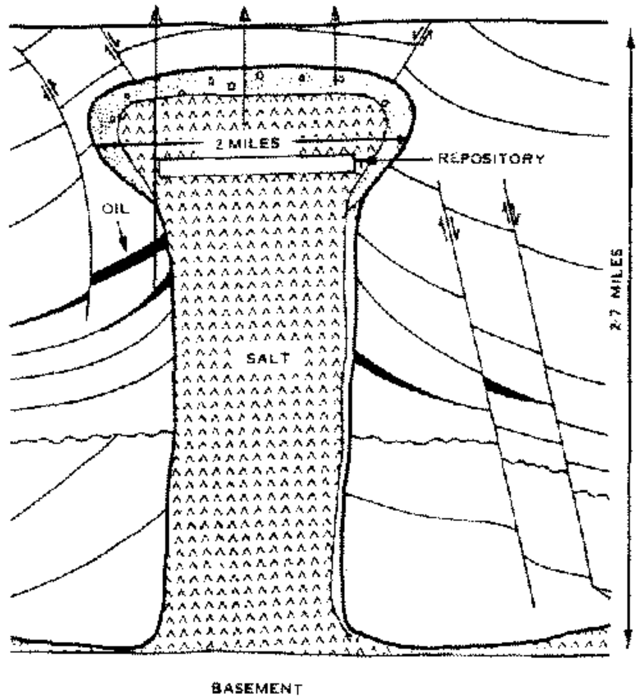

Figure 3. Typical salt dome being studied.

Salt domes commonly provide structural and stratigraphic traps for oil and gas accumulation and for this reason almost every Gulf Coast salt dome has had at least a minimal amount of oil exploration directed toward it. Bore holes in the flanks of domes, seismic reflection and gravity data are usually available in the vicinity of a dome of interest.

The size and geometry of the domes at the depths of

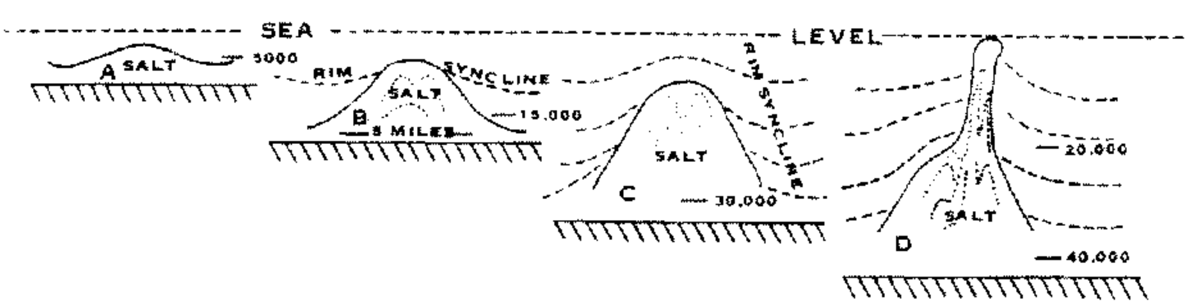

Figure 2. Conceptualized salt dome growth. (From Kupfer, 1976).

TABLE 1

Stratigraphic Column Typical of the North Louisiana Interior Salt Dome Basin

Age	Group or Formation	Lithologic Character	Thickness (Feet)
Recent	Alluvium	Gravel, Sand Silt, Clay	25
Pleistocene	Tarraces	Gravel, Sand, Silt, Clay	100
Eocene	Sparta	Sand, Sandy-Clay	260
	Cane River	Clay, Marl	220
Eocene-Paleocene	Wilcox	Sand, Clay	750
Paleocene	Midway	Calcareous Clay	690
Upper Cretaceous	Navarro	Sand, Marl, Clay	375
	Taylor	Chalk, Marl, Clay	575
	Austin	Sand, Marl, Clay	650
	Eagle Ford	Clay, Sand	325
	Tuscaloosa	Sand, Clay	100
Lower Cretaceous	Trinity	Clay, Sand, Limestone, Anhydrite	700

their planned utilization and the structure and lithology of the overlying and surrounding sediments are the specific objects of the exploration effort described here. The geometric information is required to locate the mined or dissolved space to be created at a safe distance from the edge of the dome.

The exploration sequence typically followed by us will now be described. Then the geophysical techniques employed will be described in some detail.

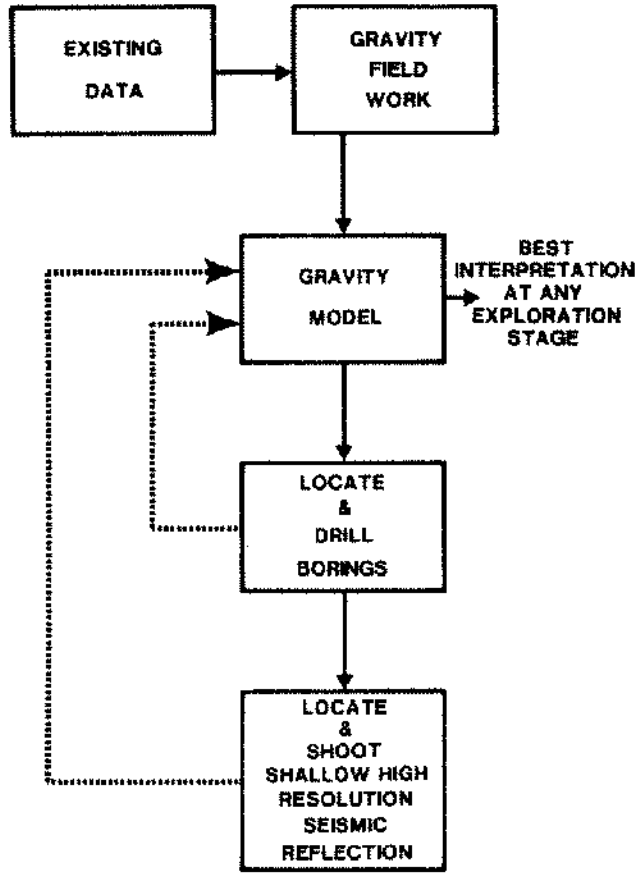

Figure 4. Exploration flow diagram for the study of the size and shape of salt domes and the lithology and structure of their surrounding sediments.

Exploration Sequence

The exploration sequence used to determine the size and geometry of the domes is shown in Figure 4. Existing oil well geophysical logs, gravity data, structural interpretations of the region and other geologic data are assembled to yield the best interpretation of the dome geometry and sediment densities. With this information a gravity field program is planned and executed. The gravity modeling procedure uses the gravity data set, all drilling information and the best sediment density information available, for the construction of a model. The resulting interpretation is then used to locate borings and other exploration elements such as shallow, high resolution seismic reflection lines.

When borings are drilled, geophysical logging of the borings yields, among other data, density profiles with depth and, in the case of borings into the dome, locations of the caprock and salt.

Existing geophysical logs from available oil wells rarely include density information within the upper 5000 feet, and sediment density functions commonly employed in this zone can be in error. Continuous compression wave velocity data are also obtained from the borings. These logs, in conjunction with the density logs, allow computation of synthetic seismograms or the computed response at the boring of the subsurface to a seismic reflection survey executed at the surface. These sythetic seismograms allow for better planning and better interpretation of the high resolution seismic reflection surveys if they are to be utilized.

The reflection studies are typically intended to gain information on the structure and lithology of the near-dome sediments and to provide information on the geometry of the caprock and top of the dome.

After the borings and seismic work and any other exploration activities have yielded more information on the dome geometry and the sediment densities, the gravity modeling is repeated to yield the best interpretation of the dome shape at this stage of the program. At any later stage when additional information is obtained, the modeling process can be repeated to yield a more accurate interpretation based on all of the information at hand. The gravity model can be resident on a large microcomputer or a mainframe.

Gravity Modeling

Gravity techniques have been used to identify the presence and the shape of salt domes for the last 50 years. In the last 10 years sophisticated computer-aided modeling of salt domes has been developed and successfully applied to detail the geometry of salt domes.

The relationship between Gulf Coast salt domes and their associated gravity anomalies is illustrated in Figure 5. The density of salt dome stock averages 2.2 gm/cc, regardless of depth, because the salt, being nonporous, is not compressible. The surrounding sediment density varies from as low as 1.7 gm/cc at the surface to as high as 2.6 gm/cc at depth where it is highly compacted. The deep salt is a strong density anomaly and produces a broad, negative gravity anomaly at the ground surface. The shallow salt and caprock are a positive density anomaly and produce a narrow positive anomaly that is superimposed on the negative anomaly to yield an anomaly of the form shown in the figure. The anomaly shown in Figure 5 is not as directly measured at the surface because a component of the surface field is in response to the geometry and density contrasts in the pre-salt basement. The anomaly due to the salt dome results from the regional gravity field (that occurring due to the pre-salt basement) being subtracted from the observed gravity field (Figure 6). The derivation of the regional gravity field requires strong judgment and is usually accomplished by either graphically fitting polynomial curves to the area gravity field or by automated or manual frequency filtering.

Once the anomaly due to the salt dome has been isolated, the dome can be modeled. We use an interative forward solution by which a dome shape and density distribution are estimated, and then the surface gravity anomaly that would result is computed. The computed gravity field is then compared to the actual collected gravity data, and the shape of the salt dome model is altered in response to the differences noted. This process is continued until an acceptable fit is reached. To accomplish this we use a modification of the Talwani-Ewing method (Talwani, 1960) which is demonstrated by Figure 7. In order to compute the gravity anomaly at a point P due to an irregular three-dimensional density anomaly, the anomaly is subdivided into a series of thin discs, and the contribution of each disc is combined by integrating from the bottom of the anomaly to the top. The process is repeated for each desired point P on the ground surface. The final result is the gravity anomaly that would be produced by the specified density anomaly.

Available gravity data coverage in the Gulf Coast is usually at least a station every mile. In the vicinity of some salt domes, previous explorationists have utilized gravity measurements and increased the data density considerably. Modeling the shallow (upper 5000 feet) requires a greater data density than would be required for deeper interests and therefore it is normal to need to collect additional

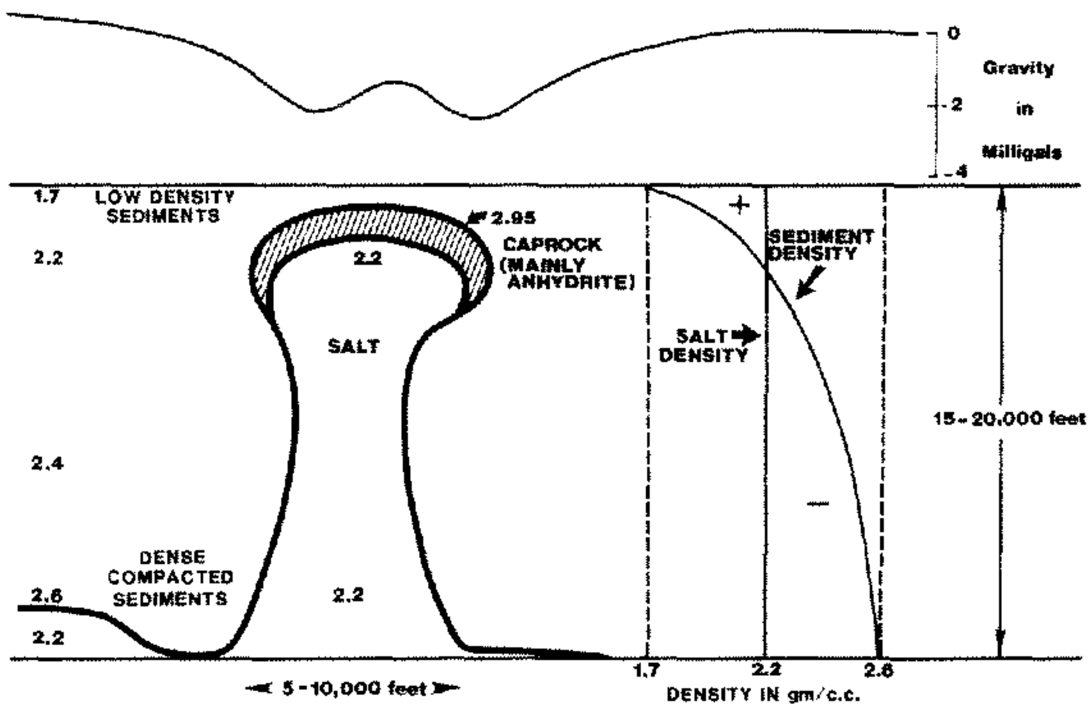

Figure 5. Gulf Coast salt dome and its associated gravity anomaly. The density anomaly created by the constant density salt and the sediments which increase in density with depth is illustrated. Caprocks composed mainly of anhydrite are common in the interior salt dome basins.

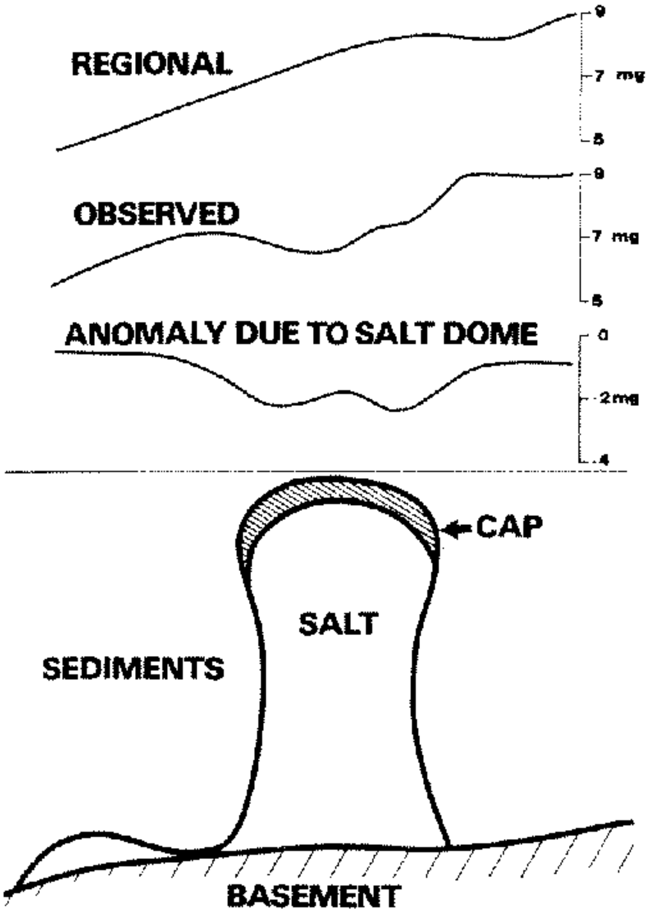

Figure 6. The observed gravity field must have the regional field due to the pre-salt basement subtracted from it to yield the gravity anomaly due to the salt dome.

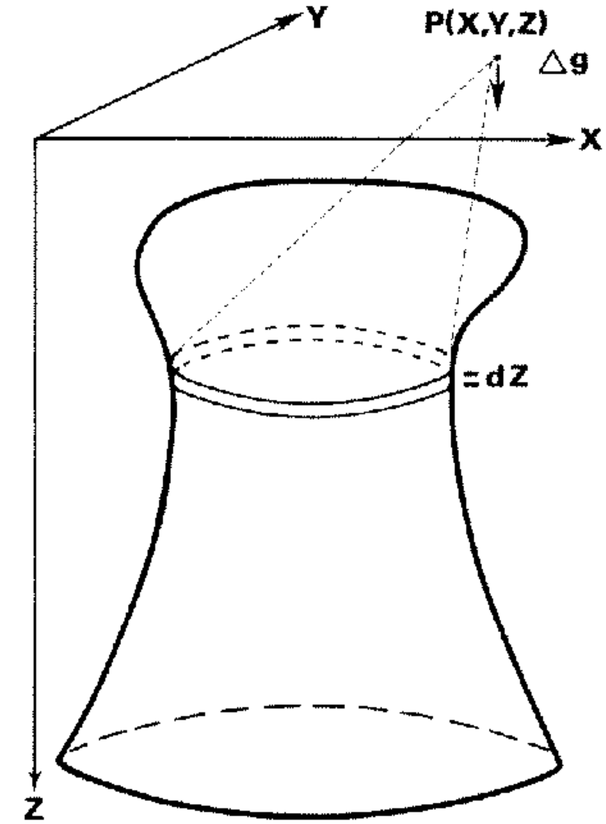

Figure 7. The Talwani-Ewing calculational scheme. The gravity anomaly at a point P due to a three dimensional density anomaly is computed by dividing the density anomaly into thin discs of irregular section, calculating the response at point P and then integrating from the bottom of the anomaly to the top.

gravity readings. The equipment and general operating procedures used by Gulf Coast petroleum exploration gravity crews is adequate for the required data collection.

The minimum data density that we feel to be adequate is shown in Figure 8. Gravity stations should be required to be a minimum of 1000 feet apart over the dome and dome flanks where the anomaly can be steep and can be positive or negative, a minimum of 2500 feet apart where the anomaly remains steep, and 4000 feet apart out to the end of the anomaly. Our specifications for gravity data collection above domes are typically as follows: Loop closures should be kept below .5 milligal for the gravity meter, 100 feet for horizontal control and 0.5 feet for vertical control. It is hoped the resulting station error will average less than 0.1 milligal. During modeling, maximum deviation of the computed gravity set from the collected data set should be between 0.5 and 0.2 milligal, depending on the sediment density information and the geometric complexity of the caprock.

High Resolution Seismic Reflection Surveys

During the investigation of several interior basin salt domes for proposed nuclear waste isolation or disposal of high level radioactive waste, shallow high resolution seismic reflection surveys were executed to help determine the near-dome and over-dome sedimentary structure and lithology, and to better define the dome/sediment interface where possible.

The project included approximately 8 miles of high resolution reflection survey in radial arms around each dome. The radial line's depth of interest was from a few hundred feet to about 3000 feet.

High resolution seismic reflection work in salt dome study refers to some modification of conventional reflection technology to enable the detection of "thinner" beds. Implied in the term is a relatively shallow depth of interest. The techniques used in high resolution involve generating and recording higher frequency signals than conventional reflection surveys and using smaller scale field recording operations, i.e., closer geophone group spacings, higher digital sampling rates of the incoming signal, shorter re-

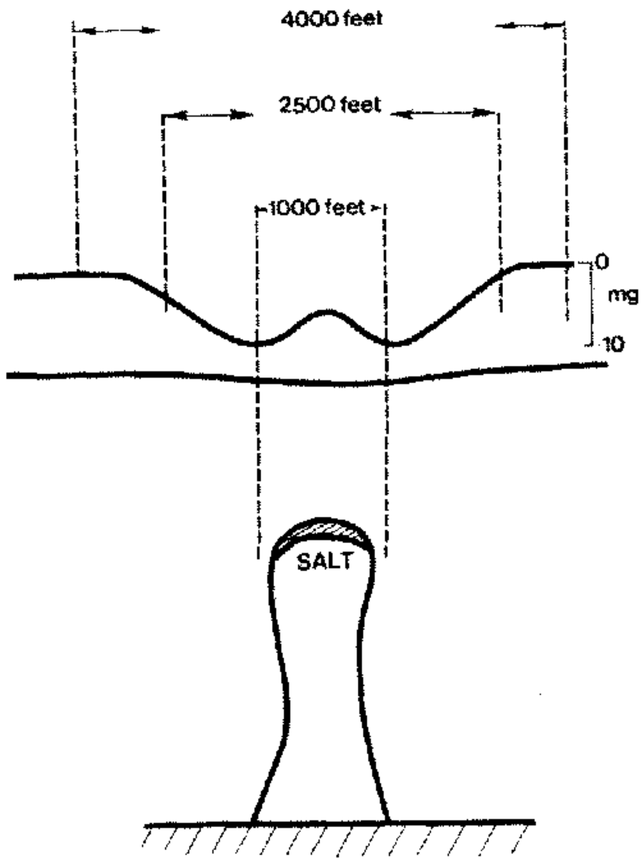

Figure 8. The minimum gravity data density advised for shallow interior basin salt domes shown as a function of the shape of the gravity anomaly due to the dome. Densities achieved by us on specific projects have varied above and below this density.

cording lengths, lower energy seismic sources, and smaller field crews than conventional reflection practices.

In designing a survey, cost must be considered carefully. Maximum and minimum depths of interest, resolution desired, and amount of surface coverage needed must be balanced in light of exisiting hardware, crew size/ and production rates.

Unlike the previously described gravity collection, shallow high resolution seismic reflection surveys in the vicinity of salt domes are not standard and cannot be achieved using field and data processing procedures standard to the Gulf Coast. Prior to field work, synthetic seismograms computed from velocity and density logs made in borings on and around the dome were used to estimate which reflectors are the targets of the survey. The synthetic seismograms are computed by assuming the field recording parameters (mainly frequency content of the recorded signal) and are reasonable predictors of the ability of a reflection survey to record the reflection from a given subsurface zone. This information allows the geophysicist in the field to judge whether the field data collection parameters are near optimum. Data processing of high resolution reflection data follows the state of the art in processing digitally recorded conventional reflection data, but there are enough differences that it should be done by a geophysicist and data processing center experienced in the application.

An interpretation technique useful in cases of complicated geometry and velocity changes is forward modeling. By means of a computer program, a time section is computed from an assumed subsurface geologic condition. This computed time section is then compared to the actual time section from the collected data. Near the flank of a salt dome, forward modeling can be carried out simultaneously with seismic and gravity data.

The discussion to this point concerns shooting and interpreting high resolution reflection seismic surveys along relatively straight lines and interpreting the results in cross sections. This two-dimensional approach is standard and is valid as long as there is enough symmetry in the subsurface to allow the location of profiles in such a way that the two-dimensional approach yields acceptable results. Lacking such subsurface symmetry, a field of geophone groups and shot points (rather than a line) can be used, and the data can be interpreted three dimensionally. Our choice of radial seismic lines intersecting the salt domes at right angles to the dome's structural contours is an attempt to utilize subsurface symmetry to allow the use of two-dimensional seismic reflection surveys.

Downhole Geophysical Logging

The traditional uses of downhole geophysical logging are to allow correlation between boreholes for structural studies and to determine the physical properties of the materials penetrated by the boring. These same uses are important in describing the geohydrologic environment in the vicinity of the domes. As the primary downhole information gathering technique of the oil industry, geophysical logging has developed into a highly sophisticated technology. The variety of tools and interpretation techniques available require expertise in this area to design a cost-efficient and effective logging program, particularly when the technical requirements of the program differ from those of the oil industry.

The application of density and velocity logs to gravity modeling and high resolution reflection interpretation, discussed above, allows surface and subsurface data to be used together, greatly improving the resulting interpretation.

Other Exploration Surveys

Additional geophysical techniques have been used by us and others when they appeared cost-effective and otherwise feasible. If new borings are to be drilled near the flanks of the salt dome, two downhole survey techniques have proven valuable in estimating the distance between the boring and the dome. They are borehole gravity and

ULSEL, ultra, long-spaced electrical logs (Schlumberger, 1974), and their effectiveness lies in the fact that the salt stock is both a density and a resistivity anomaly.

Borehole refraction is a seismic survey shot typically with shallow shot holes near the surface and geophones down deep boreholes in the salt dome or in existing dry mines. The survey provides an interpretation of the location of the salt/sediment interface. Other patterns for these surveys include hole-to-hole and ground-to-two holes. The technique is attractive when deep borings suitable for this purpose or an existing dry mine are available.

DOME INTERNAL INVESTIGATIONS

None of the techniques described in the previous section yields appreciable information about the interior of the salt stock. Salt domes consist primarily of halite with anhydrite as the major secondary mineral. The dome salt is vertically foliated and metasedimentary in character. Porosities are very near zero, and permeabilities are normally not measurable. Large vertical structural features formed during the growth of the domes can be zones of included sediment, gas/ and brine. These zones create difficult mining conditions when encountered in existing mines in salt domes (Kupfer, 1967). It is important to locate any such feature as far in advance of the main studies as possible.

Geophysical well logging has been used by us and others to determine the lithology near the borehole for holes drilled in salt.

Radar has been used in every currently existing dry salt mine in the Gulf Coast. Most of the work has been carried out by Professor Unterberger, who has published his results at previous International Salt Symposium meetings (Unterberger, 1978). Radar is potentially well-suited for exploration in salt because its penetration is greater in that medium than in any other rock (Cook, 1975). Borehole radar is under concurrent development by several groups (Rubin, 1978), but to our knowledge it has not been used, except experimentally in Gulf Coast salt domes. When developed, borehole radar will have strong application to salt dome exploration by looking out from borings drilled in salt to detect discontinuities, such as the edge of the salt stock, and zones of included sediment, water or gas.

GEOHYDROLOGIC CHARACTERIZATION OF THE NEAR-DOME ENVIRONMENT

The geohydrologic environment above and around the dome needs to be characterized to the extent that ground water resources can be protected from contamination with the stored waste or product. The level of detail required varies strongly with the application. The lithology, porosity and permeability of the surrounding sediments and the chemistry of the pore water are routinely measured by downhole geophysical logs. The choice of log functions and the interpretation approaches are well documented in the literature (Keys, 1976).

The shallow geohydrologic environment in the vicinity of the surface facilities commonly needs to be characterized for surface waste storage or spill control designs.

The exploration program designed to study the near-surface geology at domes being recently considered for nuclear waste storage consisted of field mapping, remote sensing, geophysically logged shallow borings and surface geophysical surveys (mainly resistivity soundings and electro-magnetic horizontal profiles). The use of shallow geophysics varied in each interior basin, but in each case it was valuable and cost-efficient.

The near-surface geology encountered at locations in each of the interior salt dome basins is typified in Figure 9 and shows the response of a horizontal resistivity profile to the subsurface. In each basin our resistivity field work consisted of a mix of vertical soundings and horizontal profiles using the Wenner array (Dobrin, 1976). The "A" spacing of the Wenner array (distance between electrodes) is approximately the depth of penetration. The resistivity measurements were used in close conjunction with resistivity logs made in shallow borings and with the surface and shallow subsurface geologic mapping to characterize the near surface geohydrologic environment.

At a salt dome in northern Louisiana, Tertiary deposits are blanketed by a cover of Quaternary terrace sands and silts, making correlation between borings difficult due to the amount of Tertiary structure. Resistivity profiling was very successful in mapping the Tertiary lithology and structure under the Quaternary cover. Besides helping to correlate between borings, the profiling made the selection of new boring locations more logical. The success of the technique was due to the high resistivity contrasts between the Tertiary units, which fortuitously alternated between sand (high resistivity) and clay (low resistivity), and the relative thinness of the Quaternary cover, which averaged 30 feet. We were not successful in mapping the Quaternary/Tertiary unconformity owing to the variability of the lithology at that contact.

In Perry County, southern Mississippi, the resistivity technique was unsuccessful in mapping either the Tertiary geology or the Quaternary/Tertiary contact due to the thickness (100 to 10 feet) and very high resistivities of the overlying fluvial sands and gravels. Resistivity profiling was very useful, however, in mapping the geology of the fluvial deposits, particularly buried channels, as shown on Figure 9.

At an east Texas salt dome, the Tertiary units crop out. A combination of vertical probes and horizontal profiling was used in conjunction with resistivity-logged shallow borings to aid in the geologic mapping at that site.

Downhole geophysical logging functions used in the shallow geologic mapping program were resistivity and

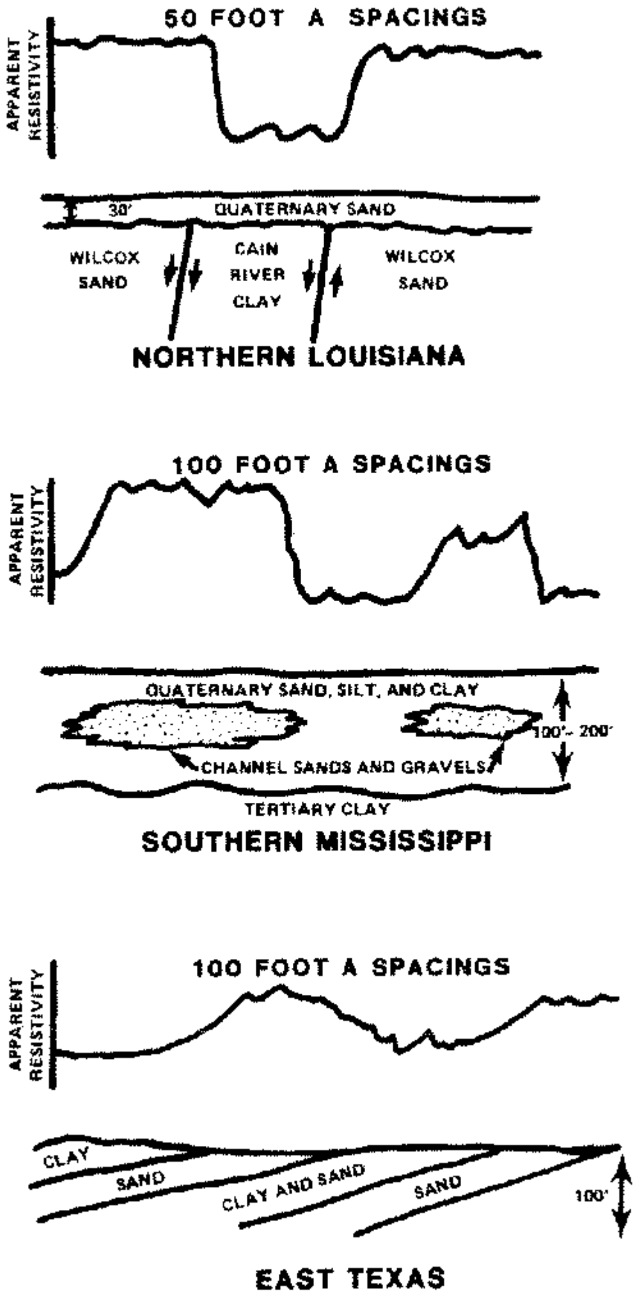

Figure 9. Typical near surface geology encountered at interior basin locations and the response of horizontal resistivity profiling to each condition.

gamma ray in almost every hole. Neutron logging was used to aid in lithology determination in some holes.

ACKNOWLEDGMENTS

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