An Investigation
of the
UTILITY OF GULF COAST SALT DOMES
for the
STORAGE OR DISPOSAL OF RADIOACTIVE WASTES

INSTITUTE FOR ENVIRONMENTAL STUDIES
LOUISIANA STATE UNIVERSITY
BATON ROUGE, LOUISIANA

Prepared for
THE OFFICE OF WASTE ISOLATION
UNION CARBIDE CORPORATION — NUCLEAR DIVISION
DEPARTMENT OF ENERGY

MASTER

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by

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ACKNOWLEDGMENTS

The Institute wishes to acknowledge the contributions of office staff Evelyn Jeansonne, Marie Champagne, Kay Crochet, Marianna Kiegley, Vicki Pilgrim, Elaine Poirier, and Kathi Whitehead; and also to draftswomen Norma Duffy and Suzanne Jambon to the preparation of this report.

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I. INTRODUCTION AND APPRAISAL

I. INTRODUCTION AND APPRAISAL

J. D. Martinez

This third annual report of the Gulf Coast salt dome investigation by the Institute for Environmental Studies for the Office of Waste Isolation under Sub-contract No. 4112 provides an opportunity to satisfy two requirements. The first and most essential one is to provide detailed reports of the work and accomplishments of each principal activity funded under this contract. A second important requirement is to assess now, if possible, the effectiveness of the methodology that was selected to carry the study toward its ultimate goals. This evaluation is incorporated in the various sections of this report that are written by the senior investigators who head up the principal sections of the research team.

This contribution of the individual presentations is very useful and, in fact, essential. However, it has become increasingly obvious that the various subsets of this entire program are inextricably bound together, and an assessment of the validity of our approaches must be made at a level at which these interrelations can be considered, as well as at the level of the activities which have been identified as specific from the onset of the investigation.

At the beginning of the study the lines of demarcation between the two principal goals: (1) a determination of tectonic stability and, (2) a determination of hydrologic stability, were quite distinct. Furthermore, even the subsets of monitoring of current movement, Quaternary studies, and regional geology and tectonics in one category, and plume studies and caprock studies in the other category, appeared to be essentially isolated topics.

As all of these studies have proceeded, the initially sharp lines of demarcation have become blurred, although not to the extent of requiring a reorientation of organization. What has happened is an increasing awareness that relationships as outlined below are very important in pursuing specific goals. Quaternary studies, designed to evaluate tectonic stability, must consider salt dissolution and evidence provided by caprock in assessing the significance of topographic lows over interior domes in contrast to topographic highs over those in the coastal belt. Any disruptions of beds of Quaternary age must be evaluated not only in terms of possible uplift in the Pleistocene or Holocene, but also in terms of possible collapse due to dissolution which might be recorded in the character and thickness of caprock over the dome in question. Also, tectonic studies designed to determine rates of movement from the stratigraphic record must include a consideration of amount and rates of dissolution based on caprock thickness.

The data developed from wells drilled for hydrologic studies has contributed important evidence pertinent to studies of tectonic stability. Conversely, structural and stratigraphic relations determined by regional and local geologic studies provide an important basis for constructing models of dissolution and hydrologic transport.

Finally, the monitoring of current tectonic movement is heavily dependent on analysis by numerical modelling which, in turn, is absolutely dependent on a thorough knowledge of geologic parameters largely determined through these other studies.

Bearing these kinds of interrelationships in mind, one can make a tentative assessment of the methodology currently being employed in the various areas of our investigation. This appraisal represents an overview which is detailed much more precisely in each section of this report.

A consideration of planning, approaches, and implementation of tectonic stability studies based on monitoring dome movement leads this writer to the conclusion that we are proceeding on target. It will be about two years before estimates of existence and degree of movement will be significant. The degree of significance will improve with time. In the event a monitored site is selected for further development, employment of this instrumented system for long-time observation will be most important.

The focus on tectonic stability through study of the Quaternary overlying domes has become of increasing importance. It is essential to the investigation that this work continue to receive high priority. In the final analysis it may provide the most definitive of all evidence of the degree of tectonic stability.

Mesozoic and Tertiary studies, sometimes thought of in our group as deep geology and often referred to as regional geology, has initially given our study a valuable insight concerning the regional and local setting of Gulf Coast domes as well as factors involved in their tectonic emplacement and movement. Much more needs to be learned of this larger problem. A paucity of data in the North Louisiana Salt Dome Basin has proved frustrating in this regard, particularly in our assigned goal to determine rates of movement. A major advance has been made in our group this year in evaluating and attempting to apply growth curves from stratigraphic data to a determination of tectonic stability. An excellent analysis has been made of the method which illustrates the approach and variables. It is obvious from this analysis that the assumptions required make this approach questionable. On the other hand, the fact that preliminary calculations from north Louisiana are in general

agreement in magnitude with those of Netherland and Sewell in Texas warrants a continued effort. This effort is further justified by the interest of certain in-house investigators and others in this approach. It is too early to count the returns in this matter. More data will help to refine our judgement.

The studies of hydrologic stability--utilizing well log data to determine the presence or absence of saline plumes in underground aquifers--continue to appear reliable and to be a valid methodology. The use of water wells to provide direct verification of this approach is underway. Indications, so far, are that electric log interpretations of salinity are essentially correct. This successful pursuit of the problem lends further encouragement to the work underway on numerical modelling of domal salt plumes in ground water. Thus far, studies using these quantitative techniques and other more qualitative determinations have proven useful in the development of preliminary evaluations of the presence and magnitude of dissolution.

Caprock studies have continued with the ultimate goal of assessing long range hydrologic stability. Progress in this effort has been much slower than anticipated, principally due to inability to secure adequate cores of use to the study. However, it is very important to continue this effort because of the basic need to understand caprock formation insofar as other efforts are concerned, as well as because of its role in evaluating hydrologic stability.

The study of hydrologic isolation of mined openings in salt domes, which was undertaken after initiation of the OWI contract, has assumed increasing importance. The designation which has been applied to this study underplays its potential breadth. The study of hydrologic stability

as originally conceived addresses the question of the extent of dissolution of salt from the outer surface of the dome. The mine hydrology study is, by way of contrast, equally broad and has the purpose of evaluating past, present, and potential entrapment and movement of fluids through any part of the salt stock. It deals with internal characteristics of the entire stock. Good progress has been achieved with the first phase of the study which includes mine inspections and interviews with responsible mine personnel to ascertain the presence and extent of mine leaks. Delays in this phase have been principally due to the proprietary nature of the mine operations and reluctance of some mine operators to grant access and to review operating problems. Continuing efforts will be made to remove these difficulties.

It is most important to assess current theories of leaks in mines and to develop and test new ideas. The rationale of this approach is to develop sufficiently viable and supportable explanations to provide base line data from which an analysis of cores from study domes can be used to predict internal characteristics of part of the stock or the entire stock as they affect movement of water. A direct approach which appears most promising in a study of active mines is the use of geochemical techniques to fingerprint and/or date waters which flow into mine openings.

Good progress has been made this year in the development of our geochemical capability. It should be continued and used whenever possible to expand our knowledge and understanding in all facets of the study where it has applicability. Its employment will be critical in analysis of cores to be secured from projected deep holes in salt.

Finally, our continued progress will be largely dependent on new data either developed by the Institute directly or through outside contractors.

We must retain the primary role in planning for data acquisition, checking operations which produce it, and have control over analyses of the final data. In this way sequential adjustments will be made that will permit advances in knowledge of salt dome geology and provide a basis for evaluating suitability of Gulf Coast salt domes for the isolation of radioactive wastes.

II. SUMMARY OF FINDINGS AND RECOMMENDATIONS

- A. Tectonic Stability
- B. Hydrologic Stability

II. SUMMARY OF FINDINGS AND RECOMMENDATIONS

E. J. Newchurch

The preceding section of this report includes an appraisal of the overall salt dome project underway at the Institute, and provides a broad summary of the accomplishments to date within the context of achieving our basic goals. Meanwhile, in the sections following, the findings and recommendations which flow from the research reported are enumerated. It will be observed that certain of the work which was originally designed to speak to the question of tectonic stability is providing information bearing on the question of hydrologic stability. In other instances, the reverse is true.

In this section, an attempt has been made to summarize all of the salient findings and recommendations, ordered as to their bearing on tectonic stability and hydrologic stability, respectively, without regard to the organizational approach to achieving the results. Thus, it is hoped that all of our results will be put into the perspective of the two prime goals which gave rise to the project at the Institute: (1) a determination of tectonic stability, and (2) a determination of hydrologic stability, of north Louisiana salt domes.

II-A. TECTONIC STABILITY

1. Findings

The growth rates of salt domes in the North Louisiana Salt Dome Basin during Mesozoic and Tertiary times were estimated from stratigraphic studies using available well data. The resulting maximum values of average growth during the major stratigraphic intervals follow. These

growth rates are generally comparable to those reported by Netherland and Sewell for domes in the east Texas basin.

- + Cenozoic: 0.03 mm/yr
- + Upper Cretaceous: 0.02 mm/yr
- + Lower Cretaceous: 0.04 mm/yr
- Definitive conclusions concerning possible tectonic movement during Quaternary time have not yet been reached.
 - + A preliminary analysis of a Quaternary borings program at Vacherie dome indicates no discontinuities or warping that can be attributed to tectonic instability.
 - + The elevation of the Quaternary deposits in the valley over Vacherie dome is concordant with the elevations of the Quaternary deposits in the neighboring valleys to the north and south, again suggesting no tectonic instability during Quaternary time.
 - + In contrast, arcuate lineations in Quaternary deposits on the eastern flank of the dome provide the only suggestion of possible upward movement of the salt during Quaternary time.
- Possible current tectonic movement is being studied by a geomechanics program which is in a late-intermediate stage of development.
 - + Numerical modelling studies, supported by field data from tiltmeters, laser ranging, precise leveling and engineering soils studies, are designed to provide realistic estimates of any current vertical crustal movements over Vacherie and Rayburn's domes, particularly after an additional two years of data gathering and analysis.
 - + The system developed for estimating vertical dome movement also can be used in the future as a monitoring system, if one of the study domes is selected for a pilot storage facility.

- Additional findings bearing on tectonic stability and related subjects are enumerated below.
 - + The extent of erosion predicted for the next 250,000 years is too small to be of any concern as regards possible exposure of a nuclear waste repository.
 - + Further analysis of earlier seismic studies indicates that the base of the salt layer from which Vacherie dome rose is at 16,000 to 17,000 feet below sea level.
 - + Interpretations of compiled gravity data support previous views that Vacherie dome is elliptical, and somewhat larger than Rayburn's and Prothro domes which are more nearly circular.
 - + Water-insoluble mineral grains from salt samples taken in Weeks Island and Cote Blanche mines (mostly anhydrite) show a variety of morphologic and surface characteristics that may prove useful in interpreting the diagenetic history of salt and perhaps the growth history of the salt domes.
 - + A numerical model of the natural temperature field around a salt dome, now nearly completed, may provide information on the connectivity of the dome to its mother salt.
 - + More than 500 structural and stratigraphic maps of the North Louisiana Basin, prepared using computer compilation and plotting methods, are on file at LSU.

2. Recommendations

- Regional Geology studies proposed for fiscal 1978 are designed to define more clearly the shapes and the structural and stratigraphic settings of Vacherie and Rayburn's domes, as well as to further enhance our understanding of the structure, stratigraphy, and geologic history of the

North Louisiana Salt Dome Basin. Proposed studies include those listed below.

- + Conduct additional seismic surveys of Vacherie and Rayburn's salt domes, designed to provide: (1) detailed data on deformation above and around the domes down to 5,000 feet; (2) similar data to depths of 20,000 feet to aid in developing the growth histories of the domes; (3) profiling of the domes down to 5,000 feet, utilizing coreholes in the domes for geophone emplacement; and (4) a regional line through that portion of the basin lying between Vacherie and Rayburn's domes.
- + Conduct additional reprocessing of existing seismic data using migration techniques and other computer methods.
- + Compile and analyze additional gravity data from north Louisiana purchased from industry sources in late fiscal year 1977. Also, conduct detailed gravity surveys of Vacherie and Rayburn's salt domes in order to further elucidate the exact shape and form of the uppermost portions of the salt stocks and any caprock present.
- + Continue analysis of the computer-generated structural and stratigraphic maps of the North Louisiana Basin.
- + Review and revise the growth histories of Vacherie and Rayburn's domes as additional well data and seismic data become available.
- + Continue geochemical analyses of salt and other minerals, brines, gases, and hydrocarbons from Gulf Coast salt domes.
- + Conduct detailed analyses of salt cores from Vacherie and Rayburn's domes by a variety of geochemical, petrologic, and structural methods.
- + Conduct extensive Mesozoic and Tertiary boring, and selected coring programs during the next two fiscal years, in order to

prepare detailed geologic maps of the Vacherie and Rayburn's salt dome areas.

- Quaternary Geology studies proposed for fiscal year 1978 will expand both the detail and the scope of the work completed to date. Such studies include those listed below.
 - + Continue the Quaternary borings program at Vacherie and Rayburn's domes, and extend these studies into areas where land access was denied during the past studies.
 - + Delineate the contact between the Quaternary and the pre-Quaternary through the use of seismic refraction methods, supported by selected borings or up-hole seismic studies where anomalous situations are found.
 - + Determine the lateral extent of anomalous lows, and through use of pollen analysis or possible radioactive dating, determine the age of the material in these lows. Attempt deeper penetration with seismic methods in order to locate possible collapse of cap-rock beneath surface lows.
 - + Continue pedologic studies to determine their effectiveness in detecting irregularities that suggest warping of the soil profiles formed above the dome.
 - + Study cases of known Quaternary warping above salt domes, e.g., Five Islands, German and Dutch domes, etc., in order to better interpret boring and seismic profiles at Vacherie and Rayburn's domes.
 - + Continue studies of the significance of the topographic lows above the north Louisiana domes, employing drainage basin analysis.

- + Collect as much detailed elevation data as possible in a broad zone around both Vacherie and Rayburn's domes in order to map the extent and the elevation differences of the Quaternary surfaces.
- + Refine the preliminary conclusions presented here on predicted erosional effects at Rayburn's and Vacherie during the next 250,000 years.
- Geomechanics studies proposed for fiscal year 1978 will provide for continuing data collection from the instrumentation installed to date, as well as for expanding the data base through the implementation of additional instrumentation studies now in the final planning stage. Proposals are listed below.
 - + Install at least one liquid level tiltmeter over Vacherie dome as a "back-up" instrument to the borehole tiltmeters which have been observed to be subject to local anomalies (possibly associated with meteorological events) and instrumentation drift.
 - + Include telemetry in the data acquisition system, such that field data from the relatively distant study domes can be recorded and analyzed daily at LSU.
 - + Conduct precise releveling of the networks over the Vacherie and Rayburn's salt domes during the summer of 1978.
 - + Implement plans for laser ranging surveys over Vacherie and Rayburn's domes in the near future.
 - + De-emphasize the concept of vertical borehole extensometers into salt domes. (Other researchers have encountered technical difficulties with highly sensitive and deep vertical extensometers.)

- + Continue numerical modelling of the domes, and update the model as additional site-specific data are obtained.
- + Determine in situ properties of soils over Rayburn's dome, by a program similar to that employed over Vacherie.
- + Implement the borehole closure study to analyze in situ domal rock salt properties, as planned, when an appropriate borehole (or corehole) becomes available.

II-B. HYDROLOGIC STABILITY

1. Findings

- Four observation water wells have recently been drilled and logged at Vacherie dome. Based on this field work:
 - + Earlier findings are corroborated, suggesting that the saline "plume" east of Vacherie dome does not indicate a significant amount of hydrologic instability.
 - + The relationship between electric log resistivity and water quality that was used earlier to map the saline ground water east of Vacherie dome was confirmed.
 - + The higher hydraulic head of the caprock wells, as compared to those in the Wilcox sands, reveals a possible source for the saline water "plume" east of Vacherie dome.
 - + The Cane River formation, previously thought to have been eroded from the top of the dome, was found more than 300 feet below the surface, suggesting subsidence following salt dissolution subsequent to Cane River deposition, 48 million years ago.

- Quaternary borings at the western end of Vacherie dome encountered three anomalous zones where oxidized fine sandy silts and silty sands reach depths of at least 200 feet.
 - + These are interpreted as lows caused by dissolution and collapse of the underlying salt in pre-Quaternary (e.g., Miocene or Pliocene) times.
- Results of the recently completed drilling program at Rayburn's dome are still being analyzed.
 - + These wells have helped to define the limits of the salt.
 - + The earlier conclusions regarding the distribution of water quality around this dome are tentatively supported.
- Efforts to map saline anomalies in the ground water around Mississippi salt domes met with limited success because of the relative lack of well data for these domes.
 - + Evidence of saline ground-water anomalies, suggestive of hydrologic instability, was found in Tertiary aquifers at Crowville and Leedo domes. The remaining six domes showed no anomalies.
- Petrographic studies of salt and caprock from Gibbsland dome (Louisiana) and Moss Bluff dome (Texas) reveal that:
 - + No consistent trends in anhydrite concentration near the salt/caprock interface were found.
 - + At Gibbsland dome, euhedral crystals of anhydrite concentrate along, and orient with, salt crystal boundaries (a previously unreported finding). The anhydrite appears to have moved through the salt mass.
- Hydrologic stability of salt mines in Gulf Coast domes was assessed by inspection visits, with results as follows.
 - + Grand Saline and Hockley domes in northeast Texas, and Cote Blanche

dome in south Louisiana were essentially dry.

- + Weeks Island dome, although essentially dry for current mining operations, was determined to represent a mine with sufficient inflow of water to possibly jeopardize long term isolation of waste.

2. Recommendations

- Geohydrology studies during fiscal year 1978 are designed to extend our understanding of the hydrologic stability of Vacherie and Rayburn's domes.
 - + Drill additional wells at Vacherie salt dome to determine groundwater flow rates and directions, as well as aquifer characteristics, for the Wilcox group sands. Of particular interest is the eastern end of the dome in the vicinity of the saline "plume."
 - + Assess the new data from shallow borings, designed to study the Quaternary and Tertiary sedimentary structure over Vacherie dome, from the viewpoint of evaluating the geohydrology of the dome.
 - + Drill a minimum of two observation wells at the west end of Vacherie dome, where data on water quality are lacking.
 - + Study the geochemical significance of variations in water quality observed in the water samples collected from the wells at Vacherie and Rayburn's domes. Of particular interest are: 1) the relationship between caprock (and false caprock) formation and the chemistry of the native water; and 2) possible correlations between brackish to saline water in the Wilcox sands and saline water in the caprock.
 - + Conduct a thermal infrared survey over salt dome areas of interest in north Louisiana and Texas. Such surveys have been useful in detecting soil moisture differences along lineations and ground waterseeps. In the case of salt domes, this survey may locate

lineations and faults which are areas of ground-water discharge. Lineations and reported "mineral springs" on Vacherie dome are primary targets.

- + Continue petrographic studies of salt and caprock in an effort to improve our understanding of caprock formation and mechanisms of salt dissolution near the caprock/salt interface. Future studies are planned to sample areas of interest in Weeks Island dome, and caprock and salt cores from the proposed test holes at Vacherie and Rayburn's domes.
- + Continue the inspection of hydrologic conditions in Gulf Coast salt dome mines, with particular attention to anomalous features such as seeps of oil, gas, and water; areas of large crystals which suggest past dissolution and recrystallization; and blow-outs in the ceilings and walls of mined cavities.
- + Continue efforts, and seek new approaches, to obtain entry into Jefferson Island, Belle Isle, and Avery Island salt mines for the purpose of inspecting hydrologic conditions.
- + Continue petrological, geochemical and structural studies which may aid in determining sources of mine waters and conditions which permit water movement into the mines. Close cooperation between current Department of Energy studies of salt domes for crude oil storage and our investigations should prove beneficial to both efforts.

III. GEOMECHANICS

- A. General
- B. Field Instrumentation
- C. Data Acquisition System
- D. Numerical Modelling of Possible Dome Movement
- E. In Situ Dome Rock Salt Properties
- F. In Situ Soil Properties
- G. Ground Water Flow and Salinity near a Salt Dome
- H. Microseismic Monitoring
- I. Natural Temperature Distribution around Salt Domes
- J. Findings and Recommendations

III-A. GENERAL

R. L. Thoms

In previous annual reports for this study (Martinez, et. al., 1975, 1976), it was noted that one of the main objectives of the geomechanics effort was to determine current rates of any possible ongoing salt dome movement. This objective falls within the scope of the salt dome tectonic stability study phase of the overall study. A major portion of this report on the geomechanics effort is dedicated to the dome monitoring study; however, material on ground-water modelling and numerical modelling of natural temperature distributions around salt domes are also included. The objectives of these two studies fall within the scope of hydrologic/ tectonic stability and tectonic stability analyses, respectively, as will be noted in the text specific to those subsections, i.e., III-G and III-I.

In the earlier annual reports, the basic components of a system for monitoring any possible ongoing salt dome movement were described in a relatively preliminary form. The monitoring system and associated planning for effective implementation have been developed further during the 1977 fiscal year and may be described now as being in a late intermediate stage of development. Although the basic components of the system were described in the first annual report by Thoms (Martinez, et al., 1975), a review of the current status of the system appears appropriate at this time. Much of the material presented here is based on reports springing from this research and now published as technical literature (Thoms and Manning, 1976, 1977; and Thoms, et al., 1977).

Figure III-A-1 depicts schematically some of the field instrumentation that will be employed to monitor any movement of the geomechanical

L-R LASER RANGING-----HORIZONTAL MOVEMENTS
M-S MICROSEISMIC MONITORING-----ACOUSTIC EMISSIONS
P-L PRECISE LEVELING-----VERTICAL MOVEMENTS
TM TILTMETER-----ROTATIONS

FIG. III-A-1 SCHEMATIC OF INSTRUMENTATION SYSTEM

system consisting of a salt dome, with caprock, and the surrounding geologic formations.

As indicated in Figure III-A-1, a rim of encircling hills typically occurs over the flanks of the domes currently under study in north Louisiana. If one of these salt domes is moving vertically upward, then the encircling hills will undergo tilting outward from the center of the dome. Simultaneously, the diameter of the "circle" of hills will increase, and there will be vertical movement of the ground surface over the dome relative to a remote benchmark. Further, the gradual movement of the plastic domal salt will store potential energy in the overlying, relatively brittle caprock, until it fractures and thereby emits acoustic signals. The caprock thus will act as a geoamplifier for domal movement, with its fracturing possibly precipitated by effects of distant earthquakes.

The instruments used to monitor the above effects are also depicted schematically in Figure III-A-1. An array of tiltmeters is located in the rim of hills around the dome. These are similar to instruments currently being used in California for earthquake prediction studies, and they are described as having a sensitivity of 1×10^{-8} radians. As noted later in Section III-B, eight such tiltmeters currently are operating over the two study domes, Vacherie and Rayburn's, in north Louisiana.

Laser ranging can be performed between tiltmeter sites to determine any horizontal movements. G. R. Huggett, of the Applied Physics Lab at the University of Washington, has developed a laser ranging instrument suitable for this task. He has visited the Vacherie site, and has made recommendations which will be incorporated in a laser ranging effort over Vacherie and Rayburn's domes now planned for the 1978 fiscal year.

Precise leveling can be employed to measure small vertical crustal movements, and the National Geodetic Survey has completed the installation and first leveling of networks over both Vacherie and Rayburn's domes. These leveling networks were planned and designed by LSU personnel to complement other components of the monitoring system. More detail on this is presented in Section III-B.

Microseismic monitoring, with an array of geophones and recorders, is also indicated in Figure III-A-1. Section III-H includes a summary of the current status of this work.

Effects of distant earthquakes will be monitored over a study dome by a seismograph. Thus, any coincident and perhaps related output from other components of the instrumentation system can be time-linked to possible earthquake effects. J. Dorman, of the Marine Geophysical Laboratory of the University of Texas at Galveston, and consultant to this study, has visited the Vacherie site and also has made recommendations relative to appropriate seismic equipment. Section III-B includes a more detailed treatment of this topic.

The described instrumentation system for monitoring domal movement will generate a relatively large body of data for input into an analysis of dome movement. Thus a systematic plan is justified for the subsequent analysis of the multitude of data that will be obtained. Figure III-A-2 depicts a "flow chart" for the interaction of efforts related to monitoring current rates of dome movement. The overall objective is to analyze data from the monitoring system and to determine the current rate of relative dome movement, which may be upward (positive), zero (stationary), or possibly downward (negative) due to dome dissolution by ground water.

FIG. III-A-2 INTERACTION OF EFFORTS RELATIVE TO MONITORING CURRENT RATES OF DOME MOVEMENTS

Figure III-A-2 is essentially self explanatory. It should be noted that some of the "boxes" representing effort are coupled in more ways than those indicated by connecting direction flow-of-information arrows depicted in the figure. For example, testing to determine in situ properties of soils and domal salt certainly would be guided by geological information associated with a study dome.

The reader will note by Figure III-A-2 that the main data interpretation aid will be finite element modelling of salt movement. Section III-D treats this topic in detail. Obviously the fidelity of numerical modelling of any geomechanical system is limited by the quality of input data on configuration and material behavior of the geologic components involved. Section III-F describes the testing program designed and implemented to obtain the mechanical properties of the soils over Vacherie dome, with particular emphasis on the soils around the tiltmeters where large amounts of data will be collected. Other integral components of the dome monitoring system, as depicted in Figure III-A-2, include field data acquisition and processing systems and testing for in situ domal rock salt properties. These topics are discussed in Sections III-C and III-E, respectively.

With this relatively brief overview of the geomechanics effort, the reader now should be prepared to: (1) integrate the materials present in the following subsections (prepared by individual authors as indicated), and (2) relate these materials to the overall objectives of this study.

III-B. FIELD INSTRUMENTATION

R. L. Thoms and T. A. Manning

1. Tiltmeters

As conceived and proposed earlier in this study, eight tiltmeters currently are in operation over the study domes, with four operating over Vacherie and three over Rayburn's dome. The locations of the tiltmeter installations are depicted in Figures III-B-1 and III-B-2.

Tiltmeter site TM-4 on Vacherie dome is apparently over a perched aquifer, with the water table rising to within two to three feet of the surface during rainy weather. Thus, plans now are being formulated to move it to a more suitable location.

The tiltmeter sites with substantial amounts of relatively reliable data include sites TM-2 and TM-3 over Vacherie. Installation TM-1 over Vacherie and all of those over Rayburn's dome are relatively new. Vacherie TM-1 was installed in late Spring of 1977, and the tiltmeters over Rayburn's dome were all installed in late Summer of 1977. From past experience with earlier installations, the soil around the installations can be expected to consolidate considerably during the first few months of heavy rainfall. Thus the instruments have been set at a fairly low sensitivity until the soil packs around the steel liners of the installation pits.

Tilt data associated with Vacherie installations TM-2 and TM-3 are depicted in Figure III-B-3. Discontinuities in the data indicate a lack of recorded data. Significant difficulties were experienced with the strip chart recorders employed to record data. As described in Section III-C,

FIG. III-B-1 LOCATIONS OF TILTMETER SITES,
VACHERIE DOME

FIG. III-B-2 LOCATIONS OF TILTMETER SITES,
RAYBURN'S DOME

FIG. III-B-3 TILT DATA COLLECTED OVER
VACHERIE SALT DOME

these recorders will be replaced with more reliable cassette recorders with more extensive ranges.

At site TM-3, a general trend of tilt appears to have occurred in a northwesterly direction. This direction of tilt would not be associated with a general vertical "plug movement" of the dome; since tilt in a southwesterly (or northeasterly) direction could be anticipated at TM-3 in that case.

Site TM-4 was flooded in early to mid-February of 1977. Subsequent repair and reinstallation reduced the total amount of recording time substantially.

When more reliable recorders are employed in relatively stable installations the data should become more reliable and continuous. At that time appropriate finite element models of individual sites, as described in Section III-D, with site specific soils properties, collected as described in Section III-C, will be employed to interpret the data. At that time the data and corresponding interpretations will achieve their full significance relative to possible dome movement.

2. Precise Leveling

The National Geodetic Survey established monuments and performed first order leveling* over Vacherie and Rayburn's salt domes in the early summer of 1977. The networks were planned and designed by LSU personnel to monitor any vertical movement of the ground surface over the study domes.

*All lines close upon first order leveling to form circuits. The lines are divided into sections 1 to 2 km in length, and each section is leveled forward and backward. The difference in the two levelings must not exceed $3.0 \text{ mm } (k)^{\frac{1}{2}}$, where K is the distance in kilometers.

The leveling networks also tie together tiltmeter sites. Each local network is tied into the national network of the National Geodetic Survey, and elevations for the local networks will be published by the Survey at a later date. Annual relevelings are planned for the networks as a continuing phase of the monitoring effort.

3. Recording seismograph

A recording seismograph will be installed at the site RS-1 over Vacherie dome as indicated on Figure III-B-1. The sensor (seismometer) will be located in the salt via an existing water observation well that was drilled fifty feet into the salt at that location. The major components of the system have been ordered. Initially, seismograph recordings will be triggered when a preset threshold of seismic activity is exceeded. When telemetry to LSU becomes available, a continuously recording system will be installed.

4. Vertical Borehole Extensometer

This study has been deemphasized over the past year due to the lack of a suitable borehole. In addition, some of the technical problems appear formidable for a vertical borehole extensometer to be anchored into the Vacherie dome. Vacherie dome lies approximately 800 feet below ground surface, and a line-of-sight straight borehole would be difficult to drill to this depth. The sensitivity required for this application would be much greater than that required for conventional subsidence studies. Thus, a line-of-sight borehole is highly desirable to avoid side wall frictional effects on taut cables connecting anchors to a near surface sensing head.

5. Engineering Seismograph

A Nimbus 1200 portable engineering seismograph has been purchased and employed over both Vacherie and Rayburn's domes. The Quaternary geology group has employed the seismograph in their work as described in Section VI-B. Their preliminary results indicate that the caprock and salt over Rayburn's dome can be detected with the seismograph as previously proposed. Detailed results will be available at a later date.

III-C. DATA ACQUISITION SYSTEM

L. K. Paille and R. Q. Perritt

Over the past year, eight tiltmeter installations have been emplaced over Vacherie and Rayburn's domes. Interesting data was obtained almost immediately on ground surface movements due to naturally occurring phenomena such as distant earthquakes and meteorological events (Thoms and Manning, 1976; Thoms, et al., 1977).

The battery powered strip chart data recording systems employed have been satisfactory for applications where relatively frequent servicing trips could be made. However, as the number of operating tiltmeters has increased, a system requiring less frequent servicing is highly desirable.

Each tiltmeter site currently is powered by three 80 amp-hr automobile batteries which must be changed monthly. With conventional battery recharging procedures, monthly servicing trips for eight tiltmeters would require the transport of 24 batteries (1000 lbs.) roundtrip from Baton Rouge to north Louisiana.

The take-up spools on the strip chart recorders have become jammed on occasion, thus causing chart advancement to stop with subsequent loss of data. Furthermore, the recording range of the strip chart recorders has been marginally adequate when the tiltmeters were operating at the sensitivity level required to monitor possible dome movement. Tiltmeter output due to natural events, such as soil consolidation, sometimes caused the recorder pen to drift off scale, thus causing the loss of future data. Also, it has been concluded that a digital output would be more suitable for computer-aided data reduction and interpretation.

After careful assessment of the above considerations, the decision was made to design a new improved data acquisition system. The system will involve two types of sites--remote sites and a central site. The remote sites will be designed for low power consumption so that battery operation is practical. AC power will be available at the central site so power consumption will not be a major concern. The remote site circuit will acquire the data, convert it to digital form, then transmit it via radio link to the central site circuit. The sample interval is switch-selectable from 1 sample/min to 1 sample/day. With the remote site circuit equipped with a digital cassette recorder, all data will be recorded before it is transmitted. The remote site circuit can be operated as a totally independent data acquisition system when the digital recorder is installed and the transmitter removed. A calendar clock will be installed in the remote site circuit so that time is recorded on the cassette. A block diagram for the remote site is shown in Figure III-C-1.

The central site circuit will receive the data from the remote site circuits and record it on magnetic tape. It will also read its own instruments, convert their output to digital form and record it on tape. The central site will also have a calendar clock so the time can be recorded with each sample. After the system is installed, the central site can be connected to Baton Rouge via telephone line. This will enable transmission of the data almost immediately after it is obtained. The operation of the system can be checked every time the system calls in the data by a built-in test routine. The central site block diagram is shown in Figure III-C-2.

Both remote site and central site systems will be microprocessor controlled. This will give the remote and central site systems the ability to make decisions and perform simple arithmetic operations. The subtraction

FIG. III - C - I TILTMETER DATA ACQUISITION SYSTEM, REMOTE SITE

FIG. III-C-2 TILTMETER DATA ACQUISITION SYSTEM, CENTRAL SITE

instructions can be used to subtract off the error caused by the offset voltage of the operational amplifiers. By using the decision making capability of the processor, the high and low values of a given channel of data can be determined for a given time span.

To protect the system from the elements, the electronics package for each site will be enclosed in a watertight box and will have built-in lightning protection.

The instrumentation for each salt dome will consist of three remote sites and one central site. More remote sites can be added if necessary. The design objectives of this data acquisition system are listed below.

1) 16 Analog voltage or current inputs. The remote sites and the central site should be capable of handling up to 16 analog inputs. Three of these inputs will be used for error correcting and self-checking, leaving 13 channels available for analog data.

2) Calendar clock input (parallel digital input). The central and remote site circuits should be capable of reading data from the calendar clock. When the remote site circuit is used as an independent data acquisition system (transmitter not used), it must be capable of reading data from the calendar clock.

3) Low power consumption of remote site circuit. This is one of the most important design objectives. When the circuit is in the standby mode (waiting for next read cycle to begin), the power consumption of the data acquisition system should be negligible when compared to the tiltmeter power consumption. For the remote site power source, a high capacity non-rechargeable battery, such as McGraw Edison's Carbonaire battery, can be used. This would require a battery change once a year. Alternatively, a low capacity battery may be used with a recharging circuit driven by solar

panels. This is the more desirable case since the battery replacement can then be eliminated.

4) System should have computational ability. Both remote and central sites should be able to perform simple arithmetic and logic operations. This means that the remote and central site circuits will have to be microprocessor controlled. By using subtraction instructions, it is possible to subtract off the error caused by the off-set voltage of the operational amplifier. It is also possible to determine the high and low values of a given channel of data for a given time span. This is particularly useful if temperature is being monitored--the high and low temperature for the day can be determined.

5) Versatility. The sequence of operations of the remote or central site systems should be easy to change. With a microprocessor controlled system, changing system operation requires only that the program be changed.

6) Built-in testing routine for remote and central sites. Before the telephone line is installed, the only way to check the system operation is to make a trip to the dome and observe the operation of the system. With a test routine built into the processor program, it will be easy to check system operation. Once the telephone line is installed, system operation can be evaluated by observing the incoming data. The battery voltage will be monitored by each remote and central site so that the power source and recharging circuit can be checked by monitoring the battery voltage as it comes over the telephone line.

7) Reliability. Both remote and central site circuits should be designed to be as reliable as possible to minimize data loss. Every remote site circuit will record its data on magnetic tape before it is transmitted to the central site to avoid loss of data if the radio link fails. At the

central site the data can be recorded before it is transmitted to prevent loss of data on the telephone line.

8) Minimize system maintenance. The two items that will require maintenance are batteries and tape cassettes. If low capacity batteries are used with some sort of recharging device, then batteries will not have to be changed. High capacity nonrechargeable batteries can be used, but they will have to be changed yearly. The cassettes will have to be changed when they get full. The cassettes will last up to 6 months depending on how many inputs are sampled and what the sample rate is.

This data acquisition system will be installed in three stages. First, the remote site circuits will be installed as independent data acquisition systems. The second stage will consist of adding the central site circuits and the transmitters for the remote sites. At this point there will exist one data acquisition system for each salt dome with output stored on a magnetic tape cassette located at the central site. The third and final stage will be the addition of the telephone line to Baton Rouge. Figure III-C-3 shows a block diagram of the entire system.

The components described above will together comprise a very powerful data acquisition system. Field data will be immediately available. Furthermore, if a system failure is detected from the incoming data, plans can be made immediately to repair the system, thus greatly reducing down time.

At this time (September 1977), the remote site circuit is almost complete. There are a few last minute design changes that must be made, but part or all of the remote site circuits should be installed by late December 1977. Since the central site has much in common with the remote site circuits,

FIG. III-C-3 TILTMETER DATA ACQUISITION SYSTEM, COMPLETE

its design should not be difficult. By June of 1978 the central sites should be installed. The telephone line hook-up should follow shortly, providing appropriate arrangements can be made with the local telephone company.

III-D. NUMERICAL MODELLING OF POSSIBLE DOME MOVEMENT

R. L. Thoms, R. M. Gehle, and J. K. Whisman

Preliminary 2-D and 3-D finite element analyses of possible salt movement have been performed in addition to those described in the 1976 annual report. Figures III-D-1 through III-D-5 depict an unloaded reference configuration (Figure III-D-1) and numerical solutions for plane strain and 3-D models of an idealized Vacherie salt dome (Thoms, et al., 1977).

Figure III-D-2 depicts displacements associated with a 2 mm imposed parabolic displacement mode at -5000 ft. Corresponding to the imposed displacement of 2 mm at -5000 ft, the maximum relative vertical displacement at ground surface was approximately 1.2 mm over the dome center. Maximum tilt was approximately 0.8 μ rad over the dome flank.

Figures III-D-3 and III-D-4 represent localized displacements of the system associated with the gravitational attraction of the moon. These results are from numerical experiments which are simplistic at this stage; however, they were carried out to obtain an indication of the feasibility of utilizing earth tide data to obtain some measure of material properties (Harrison, 1976a). In Figure III-D-4, the relatively "soft" surface sands and the "stiff" confined sands at a depth of -2000 ft were interchanged in the model. It can be observed that differences in the surface displacements did occur; however, concerns must exist with uniqueness in interpreting material properties from displacements of nonhomogeneous systems.

The boundary conditions imposed for the moon loadings of Figures III-D-3 and III-D-4 did not take into account associated general

displacements of the earth's crust. Boundary elements appear appropriate for this task (Zienkiewicz, 1976).

Figure III-D-5 represents a 3-D solution for a solid quadrant of the Vacherie dome. A maximum 2 mm displacement amplitude was imposed via an elliptic paraboloid as depicted in this figure. Material properties were based on those assumed for the plane strain models.

All of the above models will be refined as more information specific to the Vacherie dome site is collected. Subsequently, the numerical dome models can be employed to interpret instrumentation data relative to dome movement with a relatively high degree of confidence.

FIG. III-D-1 VACHERIE PLANE STRAIN MODEL

SPATIAL SCALE, 1000 ft.

FIG. III-D-2 VACHERIE PLANE STRAIN MODEL -
IMPOSED DISPLACEMENT

DISPLACEMENTS SCALE, 1 mm

DISPLACEMENTS SCALE, .003 mm

FIG. III-D-3 VACHERIE PLANE STRAIN MODEL-MOON LOADING

FIG. III-D-4 VACHERIE PLANE STRAIN MODEL -
MATERIALS INTERCHANGED, MOON LOADING

FIG.III-D-5 DEFORMED 3-D FINITE ELEMENT DOME MODEL

III-E. IN SITU DOMAL ROCK SALT PROPERTIES

R. L. Thoms

Planning has been performed to develop a technique for determining in situ properties of rock salt. Some writers have noted that conventional laboratory tests may be suspect for determining mechanical properties of domal rock salt because of the relatively large size (e.g., 1 inch) of the salt crystals. Thus, planning for an in situ test to determine rock salt properties, particularly as they relate to salt dome tectonics, appears appropriate.

A borehole testing method for determining in situ properties of rock salt which may be employed for analysis of time dependent tectonic dome movement (Thoms, et al., 1977) is proposed.

Borehole testing of rock salt was apparently initiated by Busch around 1907 (Busch, 1907). More recently, relatively sophisticated studies have dealt with borehole stability in other rocks at depth (Desai and Johnson, 1974, and Gnirk, 1972).

Instruments for testing borehole walls have been developed (e.g., by Menard, 1957; Goodman, et al., 1968; Rocha, et al., 1969; Serata, 1974; and Handy, et al., 1976). Typically, these instruments employ some means of loading the borehole "walls" and monitoring resultant displacements and/or failure loads.

The study would require monitoring the diametrical displacement of previously undisturbed rock salt around a borehole simultaneously at several depths into the dome. A series of relatively simple fixed-in-place closure monitoring calipers would be installed at preselected elevations in a borehole filled with dense drilling fluid. The fluid would be the same fluid

used in drilling the borehole into salt, and would not be pumped out prior to installation of the calipers. Thus the material around the borehole would be relatively unloaded from its original geostatic stress state prior to installation of the monitoring calipers.

The load on the borehole wall could be changed by varying the level of the fluid. Subsequent closure at the fixed-in-place calipers would be recorded as time dependent material response. For boundary conditions, the stress state at some distance from the borehole in the plastic rock salt would be assumed to be hydrostatic in character and of a magnitude due to overburden (Obert, 1962). This study would have the advantage of monitoring the loading (or unloading) of dome rock salt in a relatively undisturbed state.

A number of successful investigations of rock salt behavior have been carried out with physical models (Bradshaw, et al., 1966; Lomenick, 1968; and Obert, 1964). Therefore, assuming scale effects could be discounted, the geostatic stress driven closure of a borehole could be used to obtain a site specific estimate of closure rates of storage caverns to be constructed at similar depths in a particular salt dome.

III-F. IN SITU SOIL PROPERTIES

M. T. Tumay

1. General Objective, Scope and Significance

Studies so far have indicated the appreciable lateral and vertical extent of Quaternary and Tertiary deposits with various geotechnical characteristics surrounding both Vacherie and Rayburn's domes (Martinez, et al., 1975, 1976). From the geomechanics viewpoint it has been shown that deposits directly above the flanks of the domes would be most susceptible to ongoing (if any) dome movement. Previous annual reports outlined the proposed in situ dome movement monitoring systems, and the numerical finite element modelling of dome movement. Four tiltmeters are presently operational over the Vacherie dome; numerical experimentation with possible domal displacement modes is discussed in Section III-D of this report.

Thoms, et al., (1977) report that the fidelity of numerical modelling of any geomechanical system will be limited by the quality of input data on configuration (spatial distribution) and the constitutive relations (material behavior parameters) of the geologic components (salt and surrounding soils/rocks). The importance of proper constitutive laws can not be overemphasized--particularly in the case of geologic media. Computer output from a finite element computer run is of no significance unless the material was properly characterized in the first place.

A constitutive (or stress-strain) law for a geologic medium is dependent on a number of factors such as density, residual stresses, stress history, existence of discontinuities, temperature, time, and existence of liquids in the pores. Many laboratory and field experiments are necessary to evaluate the parameters that define material behavior. Generally these

parameters are evaluated in the laboratory on "undisturbed" samples obtained in the field. Drained or undrained triaxial, direct shear, and consolidation tests are commonly employed for this purpose. The laboratory experiments alone may not be correct since it is difficult to obtain a homogeneous state of stress and strain in the entire test specimen; therefore a test will simulate the field situation only approximately. Perhaps the best way to obtain a realistic constitutive relation is to derive it from a number of direct field measurements of the response of geologic media to applied perturbations (Desai, 1972).

A survey of in situ evaluation methods (borings, standard penetration, cone penetration, vane shear and pressuremeter are the most common) in terms of short term availability, economics, and applicability, revealed that electrical cone soundings coupled with several borings at which disturbed and undisturbed samples are acquired would best suit the immediate goals of this study, and help lay the guidelines for future investigations. The most versatile, rugged, and widely used electrical cone sounding system is manufactured by Fugro-Cesco of Holland, and is locally available through Fugro Gulf, Houston, Texas. Information relating to accuracy and reliability of cone penetrometers as a whole, and the Fugro electrical cone penetrometer in particular, is readily available in the literature (deRuiter, 1971; Schmertmann 1970, 1976).

It was planned to evaluate in situ soil properties in the vicinity of Vacherie dome with particular emphasis on regions where sophisticated equipment to monitor dome movement were installed. Investigations were extended to an approximate depth of 150 ft from the surface. Electrical cone penetrometer sounding techniques were carried out in conjunction with, and to be statistically correlated to, the results of borings at which continuous undisturbed/disturbed soil sampling and testing were contemplated.

The geotechnical parameters and constitutive relations evaluated as a result of such a scheme should achieve the following:

- 1) Help increase reliable interpretation of the output of sophisticated instrumentation (i.e., tiltmeters, borehole closure calipers, laser ranging equipment) embedded and/or emplaced on these deposits to study dome movement.
- 2) Provide an in situ constitutive data base (modulus of elasticity, E ; Poisson's ratio, μ) to be fed into the numerical model of the dome.
- 3) Increase the economy and efficiency of further geotechnical investigations.
- 4) Help evaluate the feasibility of other methods of data retrieval (i.e., ground-water level fluctuations and hydraulic conductivity, electrical conductivity of ground water, temperature measurement, acoustic emission, etc.) from deep deposits by probing techniques.

2. Overview of Current Status

The proposed investigation of in situ soil properties for Vacherie dome was approved October 1976, and the field work was carried out during July and August of 1977. Figure III-F-1 depicts the location of the boring and cone penetration (hereafter referred to as sounding) sites.

During the 1977 fiscal year, steps were also taken to establish a soil mechanics testing capability for determining soil constitutive relations. The system consists of: (1) a 5 ton capacity triaxial shear device which is adaptable to short term undrained/long term drained testing of soils with or without pore pressure measurement (with little modification, rock and salt testing will also be feasible); (2) oedometers with swell test attachment to measure compressibility characteristics; (3) an unconfined compression device; and (4) a laboratory penetrometer to determine relative

strength. The bid for the system, specifications for which were held on research quality level, was awarded to Geonor of Norway on June 1, 1977. Since then, shipment has been made and the system will be operational shortly.

Tests for soil identification (i.e., consistency, grain size distribution) of disturbed samples obtained from borings made along B-M-S lines (Figures VI-B-3 and -4 in this report) constitute the bulk of the laboratory work done at this time. To date (September 1977) 218 consistency limits, 300 sieve analyses and 59 hydrometer analyses have been performed. When completed, this study will provide a statistical evaluation of the spatial distribution of the upper stratification in the vicinity of Vacherie dome. The writer hopes to correlate this data with material behavior characteristics of the soils involved.

A more detailed presentation and discussion of the in situ field work and laboratory studies follows.

3. In Situ Studies at Vacherie Dome

A total of 5 borings and 25 soundings were performed under rigid specifications specifically prepared for this purpose. Of the 25 soundings performed, 5 constituted preliminary trials with cones of varying types and capacities. All 5 boring and 20 sounding logs are presented in this section and in Appendix A.

a. Borings. A review of the previous boring operations done at Vacherie dome for Quaternary studies revealed that disturbed continuous sampling to average depth of 150 ft were successfully done with wall (Shelby tube) samplers with an approximate area ratio of 15 per cent. To improve further on the quality of the samples sought for this study, wall stationary piston samplers (Figure III-F-2) were initially specified. This is basically a Shelby tube sampler with a piston, piston rod, and a modified sampler head. The piston rod is 1/2 inch in diameter and fits

PISTON TUBE SAMPLER

SAMPLER BEING LOWERED INTO DRILL HOLE

SAMPLER DURING SAMPLING OF SOFT SOILS

SAMPLER DURING SAMPLING OF STIFF OR DENSE SOILS

PITCH BARREL SAMPLER

FIG. III-F-2 "UNDISTURBED" SAMPLERS USED IN THE INVESTIGATION

easily inside the hollow drill rod used to lower the sampler into the hole. The unit is lowered on the drill rod since a conical ball bearing catch prevents the piston rod from slipping down. When the sampler reaches the bottom of the hole, the piston rod is held fixed relative to the ground surface, and the thin walled tube is pushed into the soil. A thin walled tube with an outside diameter (D_o) of 3 1/2 inches and an inside diameter of (D_i) of 3 3/8 inches was utilized in this work with an area ratio of 9 per cent. The piston sampler functioned very satisfactorily in the relatively soft upper layers. However, denser stratification encountered generally below 50 ft necessitated the use of pitch barrel samplers.

The pitch barrel sampler (Figure III-F-2) is essentially a Denison sampler in which the inner barrel is spring loaded so as to provide automatic adjustment of the distance by which the cutting edge of the barrel leads the coring bit. As shown in the figure, the outer rotating core barrel with a bit and an inner stationary, spring-loaded, thin wall sampling tube leads or trails the outer barrel drilling bit, depending on the hardness of the material being sampled (Lowe and Zaccheo, 1975). In softer strata the sampling is the same as a thin wall sampler, and the bit merely serves to remove the material from around the tube. In harder materials, the outer barrel cuts a core which enters the tube as the sampler penetrates. In either case, the tube protects the sample from erosive action of the drilling fluid.

The pitch barrel sampler used was $D_o = 3$ inch and $D_i = 2 \frac{1}{4}$ inch, with an area ratio of 7 per cent. Even in the very dense red and tan fine sands and the hard gray silty clays, this type of sampler gave satisfactory results.

The disturbed and undisturbed samples retrieved are presently being classified and catalogued. After the classification of the disturbed samples

is complete, long term (drained) triaxial, and consolidation/swelling tests will be performed on the undisturbed samples. From the technical viewpoint, the time lapse between sampling and testing could be regarded as detrimental. Arman and McManis (1976) in their study on Louisiana soils have shown the basic fallacy of undisturbed samples, and the time lapse in testing is but one of the factors they conclude as causing discrepancy between laboratory and in situ conditions. However, it should be noted that it is the intent here to evaluate the possibility of an in situ testing method, and that laboratory studies will serve as trend setting techniques.

A review of the boring logs (Figures III-F-3, and Figures A-1 through -4 in Appendix A) shows that all of the tiltmeter sites, without exception, display different geotechnical characteristics. The interpretation of the tiltmeter data will bear greatly on the extent and characteristics of the strata in which the tiltmeters are situated. A general and preliminary evaluation is given below:

- 1) Tiltmeter site No. 1. The site is situated in dense strata; therefore minimum interference from ground-water effects should be expected.
- 2) Tiltmeter site No. 2. Presumably this site is the best site as far as type and densification of soils are concerned. However, a very soft stratum was encountered at a depth of 77-99 ft, 84 ft SE of the tiltmeter, the extent of which warrants further study. (See Figure A-2, Appendix A.)
- 3) Tiltmeter site No. 3. The tiltmeter is located in a clayey silt which can create problems when wet.
- 4) Tiltmeter site No. 4. The tiltmeter is located in the least compacted strata encountered in this study. The location and thickness of the clay layer close to the ground surface further decreases the value of the site due to potential ground-water effects. It is recommended to abandon this site.

COMPLETION DEPTH: 200'

* 140 LB. HAMMER DROPPED 30-INCHES.

DATE: 8/8/77

LEGEND:

- PISTON SAMPLE
- ⊗ SPT DRIVE SAMPLE
- ⊗ 3" TUBE SAMPLE

LOG OF BORING NO. 4

VACHERIE SALT DOME
DUBERLY, LOUISIANA

FIG. III-F-3

PAGE 1 OF 2

DEPTH, FT	SYMBOL	SAMPLES	SOIL DESCRIPTION	SHEAR STRENGTH, TSF			BLOWS/FT *	PLASTIC LIMIT			WATER CONTENT			LIQUID LIMIT		
				● Unconfined Compression	○ Pocket Penetrometer	■ Triaxial Compression		+	- - -	○	- - -	+	+	- - -	+	+
			SURFACE ELEV:	0.5	1.0	1.5		10	20	30	40	50	60			
			HARD GRAY SILTY CLAY WITH SILT POCKETS				101									
110			- DARK GRAY BELOW 113'				55/6"									
120			(123.5')				103									
			LIGNITE (126')				99									
			HARD GRAY SILTY CLAY WITH SILT POCKETS (130')				70/6"									
130			VERY DENSE GRAY CLAYEY SILT WITH SILT POCKETS (138')				55/6"									
			HARD GRAY SILTY CLAY WITH SILT POCKETS AND PARTINGS (150')				50/6"									
140			VERY DENSE GRAY CLAYEY SAND WITH SANDY CLAY SEAMS AND POCKETS (162')				86									
			HARD DARK GRAY SILTY CLAY WITH SILT POCKETS AND PARTINGS (192.5')				88									
150			LIGNITE (197')				88									
			VERY DENSE GRAY CLAYEY SAND WITH SILTY CLAY SEAMS				77									
160			TERMINATION DEPTH: 200 FT.				50/6"									
							50/6"									
170							50/6"									
							88									
180							50/6"									
							50/6"									
190							50/6"									
							50/4"									
200							50/3"									

COMPLETION DEPTH: 200'
DATE: 8/8/77

* 140 LB. HAMMER DROPPED 30-INCHES.

SEE SHEET 1 FOR
LEGEND

LOG OF BORING NO. 4
VACHERIE SALT DOME
DUBERLY, LOUISIANA

FIG. III-F-3 (cont'd)

PAGE 2 OF 2

b. Soundings. The traditional method of measuring cone penetrometer resistance involves the advancement of a standard cone with a base area of 10 cm^2 and an apex angle of 60° , at a rate of 2 cm/sec using a double string of rods. Figure III-F-4 shows the types of cones currently available for various sounding purposes. In this study, emphasis was put on the electrical cone penetrometer with friction sleeve. However, in one site the feasibility of using the mechanical Begemann friction cone was also tested.

For a better understanding of the advantages of the electrical cone, a brief summary of the traditional Begemann cone (an extension of the Dutch cone) will be given first. This type of penetrometer has, in addition to the cone tip that can move independently of the inserting rods, a separate friction sleeve with a wall area of 150 cm^2 which is inserted above the cone and can also be moved independently of the outer rods. The procedure of a full cone penetration reading (Figure III-F-5), with cone resistance, q_c , and frictional resistance, f_s , is as follows:

- 1) The outer rods are kept stationary. The inner rods are pushed down to advance the cone 4 cm during which interval cone resistance, q_c , is hydraulically recorded.

- 2) The inner rods are advanced another 4 cm. The cone engages the friction sleeve and the cone and sleeve move down together. The combined value of cone resistance and friction sleeve is again hydraulically recorded.

- 3) The outer rods are pushed down 20 cm and take along the friction sleeve over the last 16 cm and the cone over the last 12 cm. Subsequently the procedure can be repeated.

- A. GEONOR PIEZOMETER CONE
- B. MECHANICAL BEGEMANN FRICTION CONE PENETROMETER
- C. MECHANICAL DUTCH (DELFT) CONE PENETROMETER
- D. ORIGINAL MECHANICAL CONE PENETROMETER
- E. ELECTRICAL CONE PENETROMETER WITH FRICTION SLEEVE

FIG. III-F-4 TYPES OF SOUNDING CONES

FIG. III-F-5 STAGES OF SOUNDING WITH BEGEMANN CONE

Although the simplicity of the equipment and the operation of the mechanical cone is a great advantage, there are several major disadvantages. For example, since the measurement of q_c and f_s are made hydraulically at the surface, elastic compression of the steel rods results in large variations in these measurements. Also friction can develop between the inner and outer rods; soil particles can lodge between the cone and the frictional sleeve and thereby hinder smooth operation. Figure A-15, in Appendix A shows a cone penetration test in which the friction sleeve did not function properly below 29 ft.

Figures III-F-4e and III-F-6 depict the general view and the cross sectional detail of the electric cone penetrometer used in this study. Base area, apex angle, and the area of the frictional sleeve are the same as the standard Begemann cone with the major advantages: 1) the penetrometer has no moving parts; 2) it measures q_c and f_s directly at depth by transducers thus providing virtually continuous soundings; and 3) it has greater structural strength since the rods and the cone form one straight cylindrical shaft.

A detailed discussion and interpretation of the soundings shown in Figures III-F-7 through 9, and Appendix A would be premature at this time. However some general observations can be made.

1) Except for overconsolidated silty clays and very dense fine sands cropping near the surface, the penetrating ability of the cone proved adequate (range 6.5 ft to 123 ft). The sounding depths can be greatly improved by means of incorporating higher reaction loads (a 15 ton truck was used in this study) and some means of fluid circulation to pierce the dense layers; however, this would somewhat curtail the economic advantage (i.e. present cost of sounding is approximately 1/3 to 1/4 of boring with sampling).

1 Conical point (10 cm^2)

2 Load cell

3 Strain gauges

4 Friction sleeve

5 Adjustment ring

6 Waterproof bushing

7 Cable

8 Connection with rods

FUGRO • CESCO

ELECTRIC FRICTION CONE PENETROMETER

FIG. III—F—6

FUGRO GULF, INC.
Consulting Engineers and Geologists

PLATE

FUGRO GULF, INC.
 Consulting Engineers and Geologists

2) Sounding logs provide a reliable continuous profile of strata encountered with details that would be very hard and costly to obtain by regular borings. Figures III-F-3 and -9 depict the considerable detailing that can be achieved by soundings in comparison to boring; Figures III-F-7 through -9 show the reliable replication.

3) A general survey of the sounding logs shows that q_c values generally vary between 50 and 200 kb/cm^2 (ton/ft^2). According to the state of the art report of Mitchell and Gardner (1976), we could estimate the stress-strain modulus of the surface soils as $0.5 \times 10^6 \text{ lb/ft}^2$ - $1.5 \times 10^6 \text{ lb/ft}^2$. Further in situ testing and complementary laboratory evaluations will produce more representative and specific values.

4) Probing techniques can be used to measure ground-water fluctuations and temperature down to reasonable depths (approximately 70 ft) in various locations. For greater depths (to 150 ft), a combination of wash boring and sounding would be necessary.

4. Laboratory Studies

Results of the soil classification tests run on samples obtained from borings made along B-M-S lines (depicted in Figures VI-B-3 and -4 in this report) are summarized in Table III-F-1. Most of the samples exhibit silty soil characteristics. A review of the friction ratio ($F_r = f_s/q_c$) parameter of the sounding logs of the tiltmeter sites also reveals the abundance of silty soils in the immediate vicinity of tiltmeters. This clearly indicates that there is the possibility of capillary action (and frost heave at low temperatures). To model the causes of tilt reliably, it is recommended to record long term ground-water fluctuations.

Due to the very recent establishment of the soil mechanics testing capability, no strength and compressibility test results are reported at this time.

Table III-F-1. Soil classification parameters.

BORING NO.	DEPTH, FT		LIQUID LIMIT	PLASTICITY INDEX	% PASS. NO 4	% PASS. 2 MILLIM	% PASS. NO 200	% PASS. 2 MICRON	CLASSIFICATION	
									AASHTO	UNIFIED
M009	24.3	26.0	26.5	8.90	100	100	49.1	18.0	A-4(3.)	SC(CL)
M009	2.3	4.0	25.0	10.9	99.7	99.0	60.6	15.0	A-6(5.)	CL
M009	20.8	22.0	23.0	4.6	99.4	99.4	51.2	20.0	A-4(3.)	CL
M014	10.0	11.4	57.5	30.7	100	100	100	50.0	A-7-6(19.)	CH
M014	12.5	13.8	23.5	1.8	100	100	84.6	25.0	A-4(8.)	ML
S001	2.5	3.5	32.0	24.8	100	100	66.5	25.0	A-6(12.)	CL
S001	4.	6.			100	100	91.0	22.0	A-4(8.)	
S002		1.5			100	100	65.0	16.0	A-4(6.)	
S002	11.5	13.1			96.0	95.0	59.0	6.0	A-4(5.)	
S005		0.9			100	100	57.0	5.2	A-4(4.)	
S005	2.0	3.6			100	100	56.2	15.0	A-4(4.)	
S005	19.3	21.5	43.0	18.5	100	100	70.7	15.0	A-7-6(11.)	CL
S005	21.5	23.	40.0	10.3	100	100	85.0	0.0	A-6(8.)	ML
S10A	7.5	8.6	26.8	5.9	100	100	67.0	25.0	A-4(6.)	CL
S10A	32.5	34.5	33.0	11.9	100	100	49.9	15.0	A-6(4.)	SC(CL)
S011		1.0			96.9	95.0	44.7	5.8	A-4(2.)	
S011	5.0	8.0			100	100	42.1	22.0	A-4(1.)	
S011	8.0	9.1	28.0	8.5	100	100	33.2	16.0	A-2-4(0.)	SC(CL)
S011	9.1	10.4			100	100	63.1	25.0	A-4(6.)	
S011	11.0	14.0			95.1	92.0	20.5	10.5	A-3(0.)	
S011	20.0	24.5	78.0	51.3	100	100	100	57.5	A-7-6(20.)	CH
S013	0.7	2.0	16.0	0.7	99.4	99.0	54.7	7.5	A-4(4.)	CL
S013	6.1	7.3	43.0	15.6	100	100	69.1	37.5	A-7-6(10.)	ML

Table III-F-1, continued.

BORING NO.	DEPTH. FT		LIQUID LIMIT	PLASTICITY INDEX	% PASS. NO 4	% PASS. 2 MILLIM	% PASS. NO 200	% PASS. 2 MICRON	CLASSIFICATION	
									AASHTO	UNIFIED
B001	16.7	19.2			100	100	100	46.0	A-4(8.)	
B001	35.0	36.0	32.0	7.9	100	100	87.2	10.0	A-4(8.)	ML
B001	40.5	42.0	54.0	32.5	100	100	92.0	41.0	A-7-6(19.)	CH
B001	42.6	43.6	32.0	9.2	100	100	86.2	16.0	A-4(8.)	CL
B001	50.0	54.0	25.0	2.0	100	100	46.2	5.1	A-4(2.)	SM(ML)
B001	20.6	72.2	23.0	4.2	100	100	27.3	2.5	A-2-4(0.)	SC(CL)
B003	2.0	3.0			76.5	69.0	17.0	12.0	A-1-B(0.)	
B003	20.0	21.0	22.0	5.4	100	100	51.3	12.5	A-4(3.)	CL
B003	50.0	50.5	31.5	10.7	100	100	60.9	30.0	A-6(5.)	CL
B003	57.0	59.0	36.3	10.5	100	100	67.4	15.0	A-6(7.)	ML
M001	7.0	8.4	30.0	14.4	98.4	98.0	62.7	14.0	A-6(7.)	CL
M001	22.5	24.5			100	100	92.7	43.0	A-4(8.)	
M001	24.5	26.5			100	100	92.7	33.0	A-4(8.)	
M002	29.8	33.0	40.5	26.1	100	100	72.8	31.0	A-7-6(14.)	CL
M002	37.0	39.0	36.5	17.0	100	100	96.6	20.0	A-6(11.)	CL
M002	124.0	128.0	80.0	52.7	100	100	98.0	42.5	A-7-6(20.)	CH
M006	32.9	34.0	40.0	8.8	100	100	80.7	32.5	A-4(8.)	ML
M007	33.5	36.0	46.0	17.8	100	100	97.0	39.0	A-7-6(12.)	ML
M007	88.0	90.0			100	100	10.6	1.0	A-3(0.)	
M007	20.0	30.0	77.0	51.7	100	100	100	60.0	A-7-6(20.)	CH
M007	160.0	161.5			100	100	21.0	4.0	A-3(0.)	
M007	48.0	49.0			100	100	34.0	22.0	A-3(0.)	

Table III-F-1, continued.

BORING NO.	DEPTH. FT		LIQUID LIMIT	PLASTICITY INDEX	% PASS. NO 4	% PASS. 2 MILLIM	% PASS. NO 200	% PASS. 2 MICRON	CLASSIFICATION	
									AASHTO	UNIFIED
S013	38.0	40.	32.5	10.5	100	100	66.3	13.0	A-6(6.)	CL
S013	35.0	36.4	27.0	6.4	98.4	98.0	73.7	14.0	A-4(8.)	CL
S14A	2.4	4.0			99.1	98.0	56.5	26.0	A-4(4.)	
S14A	6.5	8.5	29.5	7.3	99.6	98.0	52.3	21.0	A-4(3.)	CL
S016	4.3	5.6	36.0	13.3	96.6	95.0	56.3	27.0	A-6(6.)	CL
S016	14.4	15.7	18.0	1.2	100	100	62.8	12.5	A-4(6.)	CL
S016	18.8	19.6	21.0	2.6	100	100	56.4	12.0	A-4(4.)	CL
S016	26.5	30.7	65.0	45.2	100	100	98.1	36.0	A-7-6(20.)	CH
S016	30.5	32.5	54.0	29.2	100	100	93.5	25.0	A-7-6(18.)	CH
S016	17.5	18.0			98.2	98.0	64.9	7.5	A-4(6.)	

5. Conclusions and Recommendations

1) A preliminary evaluation of the tiltmeter sites at Vacherie dome was made. Tiltmeter site no. 4 was found to be inadequate from the viewpoint of loose subsoil conditions and potential ground-water hazard. Plans exist to move this site to a new location. Further study of tiltmeter site No. 2 is also recommended due to an unstable soil stratum that was encountered at depth in the vicinity of the tiltmeter.

2) It is further recommended to make a similar shallow sounding study at Rayburn's dome, with disturbed and undisturbed sampling incorporated into the boring operations of the other studies (i.e. Quaternary).

3) Considering the importance of the tiltmeters in monitoring possible domal displacements, it is recommended to instrument one tiltmeter site each at Vacherie and Rayburn's domes with load cells and piezometers for long term measurement of vertical and horizontal earth resistance and ground-water fluctuations, respectively. This will provide vital information for the eventual numerical modelling of tiltmeter behavior.

4) It is proposed to stress further the in situ testing techniques for the specific requirements of the soils in the area by direct measurement of the stress-strain modulus and compressibility characteristics. Figure III-F-10 shows an expansion/load cell pressuremeter developed at Cambridge, England (Wroth, 1976). This instrument was developed in response to problems with current soils laboratory tests, which often fail to accurately predict the in situ behavior of soils.

As shown in the figure, there are essentially two basic instruments, each performing a different test.

1) The self boring expansion pressuremeter loads the soil radially by inflating a membrane against it using gas pressure. It provides a plot

FIG. III-F-10 EXPANSION/LOAD CELL PRESSUREMETER

of radial strain against applied pressure from which the shear stress/shear strain diagram for the soil is determined, thus providing the stress-strain modulus and Poisson's ratio.

2) The self boring load cell pressuremeter senses the horizontal component of the in situ ground stress by balancing the external load on the instrument from the soil against an internal gas pressure so as to null the output of a load cell fitted flush with the external curved surface of the instrument.

Both instruments also provide a measurement of the pore water pressure using small volume pressure sensors which, in the expansion pressuremeter, are arranged to move outward as the membrane expands. Both instruments are large in size and test a substantial volume of soil. In particular the expansion pressuremeter uses an expanding portion nearly half a meter long.

Both instruments use the self tunnelling technique with drilling fluid circulation developed at Cambridge and shown to cause a minimum of disturbance. There is evidence showing that it causes, with care, less than 0.5 per cent radial strain. Both instruments can be used in soft clays, in stiff clays, and in sands. Either instrument can be used with suitable ancillary apparatus as a rig so that tests can be made completely independently of a drilling rig.

Personal communication with the manufacturers of this instrument (Dalton, 1977) convinced the writer that such an acquisition should replace borings and soundings in the future, and would provide greater efficiency and freedom in the retrieval of the in situ information.

III-G. GROUND WATER FLOW AND SALINITY NEAR A SALT DOME

R. C. Farmer

Consider the case where ground water flows through the porous media which surround the sides of a salt dome. The salt dome and the aquifer may both be assumed to rest on an impervious, horizontal plane. The roof of the aquifer (and the caprock over the dome) may or may not be impervious--thus making the flow in the aquifer confined or unconfined, or a mixture of the two.

Assume, for the case under consideration, that the salt in the dome is leached by the water but not by a simple solution mechanism. An anhydrite crust forms which protects the dome from being dissolved. The rate of salt transfer is controlled by a solution rate of the water and salt at the anhydrite/salt interface; a molecular, counter-diffusion of the fresh water in salt water out through the anhydrite; and by the anhydrite compaction process: The rate-determining steps of these processes have not yet been established.

The description of the source of salt in ground waters, as stated above, pertains to salt domes as they exist today. More complex existing descriptions related to caprock formation are indicative of why salt diffuses from the dome at a certain rate, but do not include a prediction of what that rate of diffusion is (Walker, 1972). For the present study, estimates of either ground-water salinities or salinity gradients at the dome surface will be used to predict saline plumes dispersion. To make the problems of flow through porous media tractable, the medium is assumed to be a maze of interconnecting pores such that a continuum of flow is possible. The resistance to flow in such a model takes the form of very high

apparent viscosities which are functions of the porosity and permeability of the medium. Usually, such flows resemble creeping motion.

Where a saline plume develops downstream from a dome, ambient fresh water will flow over the plume because of buoyancy. Mixing of the streams is a relatively slow process. The high apparent viscosities which correctly consume momentum will not be available to transfer mass.

An appropriate system of conservation equations to describe these flows is shown in Table III-G-1. Numerical solutions to these equations by Pitts have been reported (1976). The equations shown in Table III-G-1 differ from the referenced solutions only in the representation of the viscous term. Flow resistances in viscous flows are proportional to velocity gradients, whereas those in porous flows are proportional to velocity (Baer, 1972). This modification results in a simpler calculation. Appropriate transport coefficients must be specified. These properties may be used in the calculations as functions of position, but only approximate, constant values are known. The salt dome may be initially idealized, geometrically, as a large bump on the bottom surface of a porous medium. Such a distortion of the bottom surface requires care in treating local boundary conditions. Pitts' solutions (1976) correspond to flow in an unconfined aquifer. The confined aquifer case should be simpler and the solution more stable. If pressure oscillations occur in the confined aquifer case, the approximate solution reported by Wu (1976) may be used, although the need to use Wu's approximate solution is not expected. The free-surface flows reported by Pitts (1976) are for conditions of larger convective transport than viscous transport.

Other solution schemes are possible, but none has been reported which is as appropriate as those referenced. If the convective terms

are neglected, the flow around the dome may be approximated as a two-dimensional potential flow. From this solution, the species conservation equations may be solved to determine salinity profiles. Unless the solution proves much more difficult than expected, the two-dimensional solution will probably not be needed. Actually, the two-dimensional solution could be used as an initial guess to start the three-dimensional program, but this too might not be worthwhile.

Geometric specifications typical of a salt dome "submerged" in a porous medium have been made in a program which has previously been used to describe Mobile Bay (Pitts, 1976). From well data in north Louisiana, head gradients are of the order of 1 to 3 (ft/mi). Typical coefficients of permeability for Wilcox sands are 100 gallons per day per square foot (spd/ft²); therefore, average ground water velocities are about 5×10^{-3} (ft/da) (Martinez, et al., 1975). Porosities for Wilcox sand have been calculated from sonic log and density log data for a well at Vacherie dome. This porosity is about 46 per cent. The domes are approximately one mile in diameter. Wilcox sand layers are of the order 500 to 1000 ft thick. These characteristics indicate that the flow is creeping and that techniques to accelerate convergence of iteration schemes are necessary.

Initial calculation results are expected in October 1977. Analytical estimates of the flowfield will be developed and used as initial guesses for the iteration schemes. Stability analyses will be made to determine calculation times for the flowfields of interest.

Table III-G-1. Conservation laws for ground water flows*

Density dependence on salinity:

$$\rho = 1 + \left(\frac{\partial \rho}{\partial S} \right)_T S$$

Conservation of mass when density is independent of pressure:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 = \nabla \cdot \bar{V}$$

Conservation of momentum for nearly parallel flows:

$$\frac{\partial u}{\partial t} = - \nabla \cdot (u \bar{V}) - \frac{1}{\rho} \frac{\partial P}{\partial x} + \mu n u / 2000 \text{ k}$$

$$\frac{\partial v}{\partial t} = - \nabla \cdot (v \bar{V}) - \frac{1}{\rho} \frac{\partial P}{\partial y} + \mu n v / 2000 \text{ k}$$

$$\frac{\partial w}{\partial t} = - \nabla \cdot (w \bar{V}) - \frac{1}{\rho} \frac{\partial P}{\partial z} + \mu n w / 2000 \text{ k} - g$$

Conservation of salinity:

$$\frac{\partial S}{\partial t} = - \nabla \cdot (S \bar{V}) + \frac{\partial}{\partial x} (D_x \frac{\partial S}{\partial x}) + \frac{\partial}{\partial y} (D_y \frac{\partial S}{\partial y}) + \frac{\partial}{\partial z} (D_z \frac{\partial S}{\partial z})$$

where:

x, y, z = Cartesian coordinates

P = pressure

S = salinity

$\bar{V}$ = velocity

g = gravity

Table III-G-1, continued.

D_i = eddy diffusion in direction i

u = the velocity component of $\bar{V}$ in the x direction

v = the velocity component of $\bar{V}$ in the y direction

w = the velocity component of $\bar{V}$ in the z direction

T = temperature

μ = viscosity

n = porosity

k = permeability

*All variables in this table have been non-dimensionalized by using reference values of water density, maximum aquifer depth and velocity, and the magnitude of the maximum change in salinity. Darcy's law has been used for the viscous terms.

III-H. MICROSEISMIC MONITORING

T. A. Manning

In consultation with R. Hardy of the Rock Mechanics Laboratory at Pennsylvania State University, a microseismic monitoring system has been designed and is currently being assembled. The system consists of seven channels of amplification and filtering for monitoring the output of seven transducers. Recording capability consists of a four channel cassette recorder and a twelve channel oscillograph. To aid in the interpretation of the data, an electronic event counter is on order and will be added to the monitoring system.

Initial application of the monitoring system will be on a south Louisiana dome which contains an active salt mine. Access to existing boreholes over Jefferson Island salt dome has been obtained from Diamond Crystal Salt Company, and logs of the boreholes have been acquired from the driller of the holes. Depth measurements indicate that four of the holes are open to the surface of the dome and will be suitable for installation of microseismic monitoring transducers. Mining activity as well as domal subsidence should provide sufficient "noise" to check out and tune the monitoring system. When the system is checked out it will be transferred to one of the north Louisiana study domes.

III-I. NATURAL TEMPERATURE DISTRIBUTION AROUND SALT DOMES

R. L. Thoms and S. L. Oden

It is well known that rock salt is a good thermal conductor relative to other geologic materials typically adjoining Gulf Coast salt domes. Because of the material conductivity contrast, an anomaly in the sub-regional temperature field will be present near a salt dome. That is, a salt dome will act as a relatively superior heat conductor so as to sustain a lower thermal gradient in the vertical direction within the salt as compared to the adjoining geologic formations. Thus, it follows that temperatures should be higher over a relatively shallow dome than in materials found some distance away from the dome, at the same depth.

Selig and Wallick (1966) numerically verified the above generally accepted concepts with finite difference modelling of temperature fields associated with salt domes. They also investigated effects on the temperature fields due to connectivity (or disconnectivity) of the salt plug to its source (mother) salt bed. Differences in temperature fields were detected depending upon whether a dome was connected or disconnected to its source salt bed.

Connectivity of salt domes has direct significance for the tectonic stability phase of the LSU study. For example, Gera (1972) has postulated that salt domes cease to move vertically if they become separated from the source salt bed. However, this postulate can be questioned on the basis that a separated plug will continue to rise if a sufficient bouyant force exists to drive it upward through overlying sediments, despite a lack of "continuing feed" from a source salt bed. In any event, information on the configuration of a site-specific dome can be gained by a numerical, and reasonably realistic, study of its associated temperature fields.

Finite element modelling of the natural temperature field around site-specific salt domes is well underway at LSU. This study falls within the scope of determination of salt dome configuration. Dwyer and Thoms (1975) first employed the finite element method to determine the steady state temperature distribution within and around an idealized salt dome with stored hot wastes; and thus, expertise in this study area existed at LSU previous to the current study.

It is relatively well known that little distinction exists in principle between finite difference methods as employed by Selig and Wallick, and finite element method (FEM) programs (codes) for temperature studies, particularly if the latter uses a "lumped" heat capacity representation. However, most FEM codes typically are more user oriented in the sense that nonrectilinear boundaries of bodies and different materials can be readily represented. This makes FEM temperature codes particularly useful for modelling field problems in geomechanical systems.

For this problem at hand, a significant amount of downhole "shut in" temperature data has been collected around a south Louisiana salt dome (Weeks Island). The data were made available through the generosity of the Shell Oil Company. This data will be used to verify a finite element model of the natural temperature field of Weeks Island salt dome and its surrounding geologic materials.

When verified, the numerical modelling experience will be applied immediately to one of the north Louisiana study domes. A north Louisiana salt dome was not selected for initial temperature modelling because downhole temperature data were not available for verification of numerical results.

It is anticipated that additional information will be gathered from the temperature study for a site-specific study dome, particularly in relation to its connectivity to the source salt bed. This will be a valuable aid in interpreting geophysical data for which multiple interpretations sometimes are possible relative to the configuration of salt domes at depth.

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III-J. FINDINGS AND RECOMMENDATIONS

R. L. Thoms

1. Findings

1) The overall geomechanics program may be classified as in a late intermediate stage of development. At the present time, bounds on vertical dome movement may be estimated. More precise bounds on movement can be established after additional data is obtained. In particular, field data from tiltmeters, laser ranging, and precise releveled (in the summer of 1978), coupled with numerical modelling, should permit realistic estimates of any current vertical crustal movements over Vacherie and Rayburn's salt domes. The system developed for estimating vertical dome movement also can be used in the future as a monitoring system if one of the study domes is selected for a pilot storage facility.

2) The tiltmeters installed over Vacherie and Rayburn's domes have yielded, and will continue to yield, useful information on surface tilting over the flanks of the domes. However, these borehole tiltmeters are affected by meteorological events (rainfall, temperature variations) and instrumentation drift. The original chart recording systems installed with the tiltmeters have proved useful for preliminary data acquisition in the field. Now, a more flexible data acquisition system, with greater range, is being developed which should be valuable for more extensive data collection. The resulting system will permit the collection of considerable amounts of data over long time periods of dome monitoring.

3) Installation of a network of monuments and initial first order leveling have been performed over both Vacherie and Rayburn's domes. If releveled around the summer of 1978, the resulting vertical movements data

should be useful for interpretation of tilt and dome movement. The initial data are currently being employed by a number of workers in all phases of the project.

4) Planning is well along for a laser ranging survey over Vacherie salt dome. The associated precise horizontal distance data, when available, will be used in conjunction with tilt and precise releveling (vertical displacements) data to analyze possible dome movement.

5) Planning is completed and the major components have been ordered for the installation of a recording seismograph over the Vacherie dome. This installation should be completed around February, 1978.

6) A portable engineering seismograph, originally proposed by the geomechanics group, has been extensively employed initially by the Quaternary geology group over both Vacherie and Rayburn's domes. It appears to be possible to map the outline of the very shallow Rayburn's dome, as originally proposed, and also to analyze shallow geological formations as described in the section on Quaternary geology.

7) Numerical modelling of the Vacherie salt dome has developed to the stage where more realistic 3-D and plane strain models have been employed. Detailed information on material properties and configurations of the geologic units over and around the dome is being collected. A second generation 3-D model of the Vacherie dome is well along toward completion, and this model will take advantage of the latest available site-specific information.

A numerical model of the natural temperature field around a salt dome also is nearing completion. This model will be used to gain information on the connectivity of a dome to its "mother" salt bed.

8) The in situ properties of soils around the tiltmeter sites over Vacherie dome have been analyzed by cone penetrometer tests. In addition,

conventional laboratory tests have been performed to assist in the determination of the mechanical properties of the soils. These site-specific properties will be used in the numerical modelling previously described so as to aid in interpretation of field data.

9) Planning has been completed, in general, to analyze in situ domal rock salt properties by a borehole closure study in one, or both, of the study domes.

10) A 3-D finite difference program is being adapted to model saline plumes around salt domes. The program should be useful for determining rates of salt dissolution and associated hydrologic stability of salt domes.

11) A microseismic monitoring system for detecting acoustic emissions is almost completed. After it has been checked out over an actively mined south Louisiana salt dome it will be transferred to one of the north Louisiana study domes. There it will be used to monitor possible microseisms due to any dome growth or dissolution.

2. Recommendations

1) Since the borehole tiltmeters have been observed to be subject to local anomalies (possibly associated with meteorological events) and instrumentation drift, it is recommended that at least one liquid level tiltmeter (Huggett, et al., 1976) be installed over Vacherie dome as a "back-up" instrument.

2) The data acquisition system should include telemetry such that field data from the relatively distant study domes can be recorded and analyzed daily at LSU.

3) Precise releveing of the networks over the Vacherie and Rayburn's salt domes should be performed around the summer of 1978.

4) Laser ranging surveys over Vacherie and Rayburn's domes should be performed in the near future.

5) The concept of a vertical borehole extensometer over the salt domes should be de-emphasized. In addition to considerations noted previously in this report, researchers at the Office of Earthquake Studies in Menlo Park have reported technical difficulties with highly sensitive and deep vertical extensometers that employ taut cables between the anchor points in the borehole and the sensing head (Mortensen, personal communication, August, 1977).

6) Numerical modelling of the domes should continue and be updated as additional site-specific data is obtained.

7) In situ properties of soils over Rayburn's dome should be determined by a program similar to that employed over Vacherie.

8) The borehole closure study to analyze in situ domal rock salt properties should continue as planned when an appropriate borehole (or corehole) becomes available.

In conclusion, the ongoing work should continue as recommended. Essentially no new major field efforts have been introduced since the annual report of 1976. However, some former planning efforts now are recommended for implementation, and one effort (borehole extensometer) has been recommended for de-emphasis.

IV. GEOHYDROLOGY

- A. General
- B. Geohydrologic Studies of Vacherie Dome
- C. Geohydrologic Studies of Rayburn's Dome
- D. Geohydrologic Studies of Mississippi Salt Domes
- E. Caprock Studies
- F. Hydrologic Isolation of Mined Openings in Salt Domes
- G. Findings and Recommendations

IV-A. GENERAL

C. G. Smith, Jr.

During fiscal year 1977, geohydrologic studies have evolved from the assimilation and evaluation of existing data for the various Gulf Coast salt basins to include drilling exploration-observation wells to develop new geohydrologic data at two sites in the north Louisiana Salt Dome Basin: Vacherie and Rayburn's domes.

Drilling of observation wells at Rayburn's dome is proceeding while this report is being written (September 1977). Only one well has been completed to date. A progress report of the drilling activity at Rayburn's dome is included. Analysis of the completed wells will be the subject of a future report.

Drilling of test wells on Vacherie dome has proven to be very valuable for revealing the geologic structure over the dome. The initial and tentative interpretation of the sequence encountered in the water wells indicates that the arrangement of sediments above the salt is, at least in part, a consequence of salt dissolution. Geohydrologic data from these wells have been limited to water samples and a few water level measurements. However, these preliminary data are beginning to aid in the explanation of the ground-water conditions at Vacherie dome. The results of the drilling reported here are tentative, as present wells and future wells will yield new and more significant information as the number of wells and the period of observation and data collection increase.

The study of ground-water salinity patterns near salt domes of the Mississippi Salt Basin listed as "unrejected" by Anderson, et al., (1973) was concluded. The results of this study are reported later in this section. A thermal infrared survey of three domes in north Louisiana and three domes

in east Texas was planned and a contract for the work awarded in February 1977. However, a combination of rains, wet surface conditions and rapidly increasing Spring foliage in the target areas forced the subcontractor to recommend the survey be postponed until the coming Winter, when soil conditions are dry, foliage is minimal and soil moisture differences are more readily detected.

Petrographic studies of caprock have been advanced this year with core samples from the salt/caprock contact of Moss Bluff and Gibbsland domes. These samples are described together with a sample of the contact between salt and included sediment in the Weeks Island mine.

Finally, the study of hydrologic isolation of mined openings in salt domes in Louisiana and Texas progressed during the year with visits by Institute investigators to the Weeks Island and Cote Blanche mines. The contrasting hydrologic conditions of the mines and possible relationships between mine dryness (or wetness) and salt dome-mine configuration is presented.

IV-B. GEOHYDROLOGIC STUDIES OF VACHERIE DOME

C. G. Smith, Jr.

1. Introduction

Vacherie dome has been a principal area of focus for geohydrologic studies since its selection as a proposed study area (Martinez, et al., 1976). The only negative factor identified for this dome in the 1976 analysis of north Louisiana domes was its apparent hydrologic instability--a designation made after analyses of electric logs showed that anomalously saline ground water exists in the Wilcox sands east of the dome. The data presented in Martinez, et al., (1975), has been reevaluated, and a reduced estimate of the dissolved solids content of the water is indicated. The maximum dissolved solids content of water in the anomaly is approximately 4000 ppm. Furthermore, because the Wilcox group appeared to be separated from the salt of the dome by Midway clays, it was concluded that the anomalous salinity may not be a result of active dissolution of salt.

A program of water wells was designed to obtain ground water samples to test the salinity distribution east of the dome and to test aquifers along the north and south flanks of the dome. These wells would check the salinity estimates made from electric logs and indicate ground-water flow directions in the Wilcox sand. This plan was altered because land for drill sites was not available east of the dome. Thus, alternate well locations were selected along the east-west central axis of the dome to investigate hydrologic conditions near the caprock/salt interface. Determination of ground-water flow and salinity distribution is critical to an understanding of salt dome hydrology.

Four wells were drilled during 1977 on Vacherie dome. The analysis of data from these wells is continuing. Continuous water level recorders have not yet been installed on the wells, pending a final round of water sampling by the U.S. Geological Survey (USGS). Analyses of water chemistry and water level records will continue for the duration of the present investigation. Results of the data available to date follow, beginning with descriptions of wells, followed by descriptions of the geology encountered, and concluding with a discussion of the ground-water samples and water level data obtained.

2. Wells Completed

Four observation wells were drilled on Vacherie dome during March, April and May, 1977. These wells have been correlated with electric logs of existing wells. Detailed cross sections incorporating these electric logs are shown in Figures IV-B-1 and IV-B-2. The electric logs used in these cross sections are listed in Table IV-B-1. Figure IV-B-3 presents the same cross sections without vertical exaggeration. Finally, all available well logs were used in Figure IV-B-4 to show the current interpretation of the elevation of the base of the Wilcox group sands at Vacherie dome.

Two of the test wells (designated V-4 and V-5) are located on the north and south flanks of the dome, respectively, and were expected to penetrate as deep as the Midway formation. Two other wells (designated V-6 and V-7) are situated on top of the dome with the intent of penetrating the overlying sediment, caprock, and salt. Table IV-B-2 lists the geologic intervals drilled and the completion information on each of the wells. Well completion descriptions supplied by the drilling contractors, geophysical logs of each well, and drillers logs are presented in Appendix A.

VACHERIE SALT DOME

CROSS SECTION A-A'

APPROX. VERTICAL EXAGGERATION = 2.5

SEE FIGURE IV-B-3 FOR LOCATION

FIGURE IV-B-1

SEE FIGURE IV-B-3 FOR LOCATION

FIGURE IV-B-2

Table IV-B-1. List of electric well logs used in Vacherie salt dome cross sections.

CROSS SECTION A-A'

(Fig. IV-B-1 and IV-B-3)

Well No.	Name	Total depth (feet)	Ground elevation (feet)
1	Pan American Petr. Corp. #1 B. F. Rowland	8962	205 (est.)
2	Louisiana State University Vacherie Salt Dome - Well #4	754	280 (est.)
3	Crow & Ford #1 Jordan	946	240 (est.)
4	Louisiana State University Vacherie Salt Dome - Well #6	594	230 (est.)
5	Louisiana State University Vacherie Salt Dome - Well #5	815	250 (est.)
6	Amerada Petr. Corp. (Formerly by Barnwell Drlg. Co.)	2318	260 (est.)
7	Tesoro Petroleum Corp. #1 Lawhon	7188	227 (est.)

CROSS SECTION B-B'

(Fig. IV-B-2 and IV-B-3)

8	Shuler Drlg. Company Inc., et al #1 M. D. Moore	5184	275 (est.)
9	Louisiana State University Vacherie Salt Dome - Well #7	848	222 (est.)
4	Louisiana State University Vacherie Salt Dome #6	594	230 (est.)
10	Lion Oil Company #1 Woodard	1822	200 (est.)
11	Garfield & Pasternak #1 Woodard Walker	5415	175.5 (est.)

Table IV-B-2. Drilling and completion record of Vacherie salt dome observation wells.

1. Well Number	V-4	V-5	V-6	V-7
2. USGS designation	Wb-373	Bi-181	Bi-180	Wb-372
3. Depth drilled (feet)	754	815	635	848
4. Location	NW $\frac{1}{4}$, Sec 15 T17N, R8W	Center of N $\frac{1}{2}$ of SW $\frac{1}{4}$ of Sec 22 T17N, R8W	NW $\frac{1}{4}$ of NW $\frac{1}{4}$ Sec 22, T17N, R8W	Center of N line of SW $\frac{1}{4}$ of Sec 17 T17N, R8W
5. Screened interval (feet)	475-485	377-387	608-618	796-806
6. Stratigraphic sequence encountered (feet)				
Quaternary Alluvium			0-50	0-30
Sparta Formation			50-225	30-385
Cane River Formation	0-70		255-430	385-570
Wilcox Group	70-482	0-385	430-616	
Midway Group	482-754	385-605		
Upper Cretaceous		605-815		
Caprock			616-635*	570-797
Salt				797-848

*Lost Circulation at 616 feet

FIG. IV-B-3

4/0002/506-4112/37

Wells V-4 and V-5 were drilled on the topographically high areas on the north and south flanks of the dome, respectively. Well V-4 penetrated a relatively normal section, i.e., the formations drilled were in their normal sequence, but each was uplifted by the dome. The Wilcox group appears to be about 50 ft thinner here than in wells further from the dome. Good correlation exists between the electric logs of this well and nearby wells. Drilling stopped in the Midway clay. The well was completed in a sand at the base of the Wilcox at a depth of 475 to 485 ft and the well was pumped at a rate of about 10 gallons per minute.

Well V-5 drilled a sequence of sediments similar to V-4 with the following differences. First, the Cane River formation at the surface in V-4 was not present in V-5. Second, after drilling 210 ft into the Midway clay, Cretaceous sediments (calcareous) were reached at about 604 ft below the surface. From the electric log characteristics, this appears to be the Saratoga, normally occurring 300 ft below the top of the Cretaceous in surrounding wells. Microfossils have been prepared from drill cuttings collected in this interval and a more definite age is expected to be determined for this unit. The occurrence of Cretaceous rocks at 604 ft deep in this well suggests that either: (1) the Midway clay is cut by a fault at 604 ft and dropped down to contact Cretaceous rocks across the fault; or (2) the upper Cretaceous strata were eroded and a thinned Midway group was deposited on the ancient Cretaceous high. No further speculation has been made concerning these or other possibilities as more subsurface information is needed to advance either argument.

Well V-5 was completed in the basal sand of the Wilcox group at a depth of 377 to 387 ft below the surface. The well was pumped at a rate of approximately 20 gallons per minute and water samples were collected.

Wells V-6 and V-7 were expected to be more unique and interesting than the flank wells because they were designed to drill to or through caprock and investigate ground-water conditions near the top of the salt. The geologic section penetrated by these two wells has not yet been unequivocally identified. Ultimate classification of the age of the sediments above the caprock will come only after microfossils from the drill cuttings are identified. If microfossils are not definitive, the interpretation of the stratigraphy will require the combination of results from seismic data, existing and future drilling data, and core data from shallow Quaternary borings. In the light of this uncertainty, the following discussion presents the current interpretations of the geologic sections encountered in wells V-6 and V-7.

Well V-6 is located on the eastern end of the central axis of the dome (Figures IV-B-1, -2 and -3) almost midway between wells V-4 and V-5 to the north and south, respectively. Quaternary sediments were encountered from the surface to a depth of approximately 20 ft. Nearby shallower borings, described in Section VI of this report, provide a much more precise depth of the base of the Quaternary. Between depths of 100 and 270 ft, sands, silts and clays occur which are tentatively identified as Sparta. The determination of Sparta age for these sands is based mainly on the fact that the clayey unit below these sands is assigned Cane River age. Determination of Cane River age for the section between 270 and 430 ft below the surface is based on: (1) the electric log appearance of this unit, and its similarity to Cane River in logs located off the dome; and (2) the glauconitic and calcareous nature of the clay. Below the Cane River, 170 ft of sands and clays were drilled before circulation of drilling fluid was lost in an apparent fracture or cavity at

613 ft below the surface. The interval between the Cane River and this cavity is interpreted as Wilcox sands. The sands show high resistivity in the electric log, and drill cuttings are described as calcareous (Appendix A). Possibly, the Wilcox sands are cemented by CaCO_3 precipitated from water flowing vertically from the underlying caprock. Based on an examination of electric logs, a similar situation appears to occur in Wilcox sands in contact with the caprock of Minden dome, 12 miles north of Vacherie dome. Drilling was halted below the zone of lost circulation when numerous attempts to seal the zone and regain circulation failed. Total depth of the well was 635 ft, terminating in what, based on limited cuttings, appeared to be limestone caprock. No cuttings were returned from the caprock below the lost circulation zone.

Well V-7 is located approximately 1.4 miles west-northwest of V-6 on the western end of Vacherie dome. The first hundred feet of drilling encountered Quaternary sediments and some lignite layers. The lignites are currently interpreted as being part of the Sparta formation occurring at a lower elevation than undisturbed Sparta sands surrounding the dome. The thick, fine sands returned during drilling and indicated on the electric log of this well conform with the description of the Sparta provided by Martin, et al., (1954). Below these sands at a depth of approximately 380 ft below the surface, a zone of distinctive low resistivity occurs. The drill cuttings from this 170 feet thick zone are described as red and gray clays at the top, becoming green, glauconitic and calcareous toward the base. Both the physical description of cuttings and the appearance of this unit on the electric log suggest this formation is the Cane River. The Cane River on well logs surrounding Vacherie dome is distinctive and almost constant in appearance for miles. The Cane River in wells V-6 and V-7 is not precisely identical to existing

well logs but the resemblance is strong and unlike any other portion of the logs. Immediately below the Cane River occurs 230 ft of dense, white to grey anhydrite of the caprock. No Wilcox was drilled in this well above the caprock (Figure IV-B-4). Well V-7 drilled through the caprock into a zone of rapid drilling for approximately 3 to 5 ft beginning at 797 ft and then into 50 ft of salt. The well is completed at 796 to 806 ft at the interface between the salt and the caprock.

3. Geologic Interpretation of Drilling Results

The four test wells give the first new details of the Tertiary section at Vacherie dome. The flank wells (V-4 and V-5) penetrated sections that were uplifted and thinned but otherwise normal with the exception of the extreme thinning (possibly faulting) of the Midway and the shallow occurrence of the Cretaceous (Figure IV-B-3). The caprock wells (V-6 and V-7) are unique in that they appear to contain a relatively undisturbed but down-dropped section with Sparta sands near the surface, underlain by Cane River. Both of these units were previously thought to have been removed by erosion from the crest of the dome.

If the present interpretation (that Sparta and Cane River sections are present over the crest of Vacherie dome) is correct, then several possible conclusions can be drawn.

- 1) The Sparta, Cane River and Wilcox groups have been displaced vertically downward above the dome (note the central lows in Figure IV-B-4).

- 2) Downward displacement may be the result of salt dissolution and removal from the top of the dome and subsequent caprock formation.

3) If (1) and (2) above are correct, subsidence took place in post-Cane River or post-lower Sparta time, beginning not more than 48 million years ago.

4) Assuming conclusions (1) and (2) are correct, the amount of vertical displacement can be estimated.

In Figure IV-B-3, a north to south cross section across Vacherie dome is shown. The Cane River formation is a distinctive unit in electric logs occurring both above the dome and off the flanks. A gently arching projection can be made of the base of the Cane River to a position where it would occur if uplifted and continuous over the dome. Such a projection would place the base of the Cane River 800 ft above its actual elevation in well V-4. A less conservative projection of the base of the Cane River might produce an elevation difference of 1000 ft or more. The assumption that the Cane River has been lowered by 800 ft by dissolution of salt since Cane River time is important because the amount of assumed subsidence divided by the duration gives an average rate of salt dissolution, assuming dissolution was continuous to the present. The removal of 800 ft of salt in 48 million years is an average rate of 1.7×10^{-5} ft/yr (.005 mm/yr). Furthermore, if the salt of Vacherie dome is 5 per cent anhydrite, and the caprock is formed by accumulation of anhydrite as salt is dissolved, then 800 ft of salt would produce 40 ft of caprock. Thus, continuing the argument above, 40 ft of caprock may have formed since Cane River time. A 10 per cent ratio of anhydrite to salt would produce 80 ft of caprock in the same time. Because 235 ft of dense anhydrite was drilled in well V-7, it follows either that: (1) the majority of the caprock at this location was formed before the Cane River time; (2) the ratio of anhydrite to salt is greater than 30 per

cent; or (3) the assumed relationship between salt dissolution, Cane River subsidence, and caprock formation is not correct. The latter possibility is surely partially true. Clearly, a complete understanding of these processes cannot be developed from a partial analysis of two drill holes above the dome. Although this exercise permits estimates of salt dissolution rates to be made, questions are raised. For example, if a volume of salt filling a space having a height of 800 ft and an area of 5×10^6 square ft (the approximate area of the top of the dome) was dissolved during the last 48 million years, and the dome had its present configuration, where did the salt go? What was the source of ground water to dissolve the salt? If salt dissolution produced subsidence in the overlying beds, where are the Cretaceous sediments above the dome? Were they not deposited over the dome, or were they eroded? Is salt dissolution continuing or has it ceased?

Hopefully, continuing observations at the four wells now installed at Vacherie, in conjunction with other geologic studies in the area and new observation wells to be drilled in 1978, will definitely establish the age of the sediments above the dome and answer some of the questions posed above.

4. Geohydrologic Results of Test Wells

The four test wells completed on Vacherie dome have yielded the first new geohydrologic data near the dome. The wells were designed to accomplish the following:

- 1) Drill through the major fresh water aquifers adjacent to the dome and terminate in either the dome or the Midway shale.

2) Provide water samples from selected aquifers (thus far the basal Wilcox Sands, the caprock and the salt interface) to confirm the presence of a saline plume as indicated by electric logs.

3) Provide sites to monitor water quality and water level changes in the future, possibly during aquifer performance tests.

The hydrologic data from these wells presently is limited to water samples and a few water level measurements on each well.

A thorough study of the chemistry of the water samples has not yet begun. Laboratory analyses of the first samples from the wells (Table IV-B-3) appeared to contain excessive amounts of drilling fluids indicating the wells had not been adequately developed. Consequently, additional development and pumping was done on wells V-4, V-5 and V-6. The USGS is currently collecting new samples from these wells. The chemical analyses will be published at a later date.

Well V-7 is a special case because it was not completed in a normal aquifer. This well is screened in the narrow interval (3 to 5 ft thick) between the base of the caprock and the underlying salt stock. The exact nature of the interval is not known. Indications are that this zone contains loose sediments, probably anhydrite grains dissolved from the salt but not yet solidified into caprock. The caliper log shows a maximum reading here, indicating the drill hole dissolved or "washed-out" the interval.

A section of stainless steel screen 10 ft long was set between 797 and 807 ft and the well was pumped using a submersible pump set at 500 ft below the surface. After three days of intermittent pumping, the well had produced about 300 gallons of brine. Samples from the first day contained a maximum of 180,000 ppm Cl^- . The poor performance of the well may be due to one or a combination of the following factors:

Table IV-B-3. Water quality analyses of Vacherie test wells.
 [LSU results are expressed in ppm; USGS results are expressed in mg/l]

Well Number ¹	LSU	USGS	LSU	USGS	LSU	USGS
	V-4 ²	Wb-373 ³	V-5 ²	Bi-181 ³	V-6 ⁴	Bi-180 ³
Calcium as Ca	15	16.0	45.4	44.0	1041.0	1000
Magnesium as Mg	6	5.6	14.3	13.0	83.9	84.0
Iron as Fe	0.97	---	0.77	0.043	0.1	0.110
Manganese as Mn	0.006	0.11	0.06	0.05	0.1	0.240
Sodium as Na	370	390	1520	1600	4297.0	4100
Carbonate as CO ₃	---	0.0	---	0.0	0.0	0.0
Bicarbonate as HCO ₃	214	220	185	286	356	369
Sulphate as SO ₄	2	12	2	8.8	2668.	2700
Chloride as Cl	504	540	2993	2330	6539.0	6300
as NaCl	831	---	---	---	---	---
Fluoride as F	---	0.2	---	0.3	0.8	0.7
Nitrate as NO ₃	1.06	0.3	---	0.08	0.0	00.0
Phenolphthalein alkalinity as CaCO ₃	---	---	---	---	0.0	---
Total alkalinity as CaCO ₃	---	---	---	---	292.0	---
Total hardness as CaCO ₃	62.	---	1172	---	2945.0	---
Dissolved residue, calculated	1067	1110	4706	4140	14986.3	14400
Specific conductance, micromhos/cm	1620	2070	6520	7460	21000	21800
pH	7.25	6.8	8.42	7.7	7.0	7.3
Total iron	---	---	---	---	0.6	---
Potassium as K	8.4	8.1	15.4	15.0		55.0
Silica as SiO ₂	1.0	20.0	5.4	12.0		24.0
Date of sample						
Date of analysis		3-22-77 4-12-77		4-12-77 5-3-77		7-22-77

¹Each LSU well has been assigned a number by the USGS. For example, V-4 is USGS well Wb-373.

²Analysis by Barrow-Agee Laboratories.

³Analysis by USGS.

⁴Analysis by Pope Testing Laboratories.

- 1) The completion zone is only slightly permeable.
- 2) The well was not properly developed and the completion zone is plugged by drilling mud behind the gravel pack.
- 3) The permeability of the screened zone may be reduced by a natural accumulation of crude oil which was produced during water sampling.

In a final attempt to develop the well and obtain a water sample, an oil field "swab" truck was brought in to swab the well. This operation involves placing a 2 inch diameter pipe in the casing to the bottom of the well and lifting water out of the well beginning at the bottom of the pipe. A hoist truck lowers and lifts a weight fitted with flexible "cups" which provide a tight seal against the 2 inch tubing as the cable is raised, lifting the water out of the well. Several trips of the "swab" emptied the well. The well was swabbed again several hours later and on the following day. At neither time had the well fully recovered, i.e., the water level was below static level. Swabbing did not improve the yield of the well.

A small amount of crude oil was produced when the well was pumped and when it was swabbed. Although the oil appears to be economically insignificant, an understanding of how it became trapped beneath the caprock may clarify certain aspects of the geohydrology of the dome. For example, it is likely the oil originated and migrated from some unknown depth down the flank of the dome to its present position. This implies a hydraulic connection, present or past, between the caprock/salt interface and the surrounding hydrocarbon source. If oil could find its way updip along the dome to the crest of the salt plug, ground water capable of dissolving salt could also have migrated from deeper sediments to a

shallower position at the top of the dome in the direction of decreasing hydraulic head. The fact that a minor amount of oil was trapped near well V-7 suggests the overlying caprock may be nearly impermeable. Further investigation may show that the caprock at V-7 prevents escape of water from the surface of the salt at that point. If the permeable caprock/salt interface encountered at V-7 is a result of salt being dissolved by ground water, the flow path of the water is not known.

In the near future continuous water level recorders will be installed on the wells by the USGS. Changes in water levels will be analyzed in an attempt to determine if ground-water flow patterns, recharge or discharge areas, and aquifer continuity between wells are suggested. Presently, results obtained from the wells can be separated into two categories: (1) ground-water salinity distributions, and (2) hydraulic head measurements.

a. Salinity distribution. During the first year of the current study of Gulf Coast salt domes, the salinity in the Wilcox sands was mapped at Vacherie dome using a technique involving the "SP" curve recorded on electric logs of oil and gas wells. A saline anomaly was found in the basal sands of the Wilcox group east of the dome. Subsequently, the same logs were reevaluated using a preferred alternative method based on electric log resistivity. As a result, the original estimate of salinity was determined to be too high. Instead of a maximum of 12,500 ppm of NaCl, the new method indicated the saline "plume" contained water having a maximum concentration of 4000 ppm total dissolved solids (TDS) as shown in Figure IV-B-5. The plume extends eastward from the dome and appears to decrease in salinity gradually.

FIG. IV-B-5

Leases for test wells were not available east of the dome during the year so no wells were drilled to obtain water samples or water levels in the vicinity of the plume. However, the western area of the plume was tested with wells V-4, V-5 and V-6. These wells were planned to intercept the plume near its apparent origin as determined in the early studies. The total dissolved solids content of waters pumped from the basal sands of the Wilcox in wells V-4 and V-5 is shown in Figure IV-B-5 along with estimates of dissolved solids content from available electric logs. The basal Wilcox sands were tested because the denser saline water tends to occupy the lowest parts of this aquifer. The decrease in resistivity with increasing depth recorded in well logs near the base of the sand confirms this relationship.

The first estimates of ground-water salinity in the north Louisiana Salt Dome Basin reported for this study (Martinez, et al., 1975) used the technique presented in Turcan (1966). This method uses a "field formation resistivity factor" (F_f) to estimate the dissolved solids content of ground water from the long-normal resistivity curve recorded on electrical logs. Turcan derived field formation factors for various aquifers empirically using the following equation:

$$F_f = \frac{R_o}{R_w}$$

where: F_f = the field formation resistivity factor

R_o = resistivity of the long-normal curve of the electric log

R_w = resistivity of the water in the formation

The electric logs and results of water analyses from the two Wilcox sand wells at Vacherie (V-4 and V-5) were evaluated to determine F_f for

the Wilcox sands at Vacherie and to compare this value with the F_f supplied by Turcan. The calculated field formation factors were 3.0 for V-4 and 4.6 for V-5 for an average value of 3.8. The F_f determined by Turcan for the Wilcox in an area west of Vacherie dome was 2.4.

An F_f value of 3.8 and the relationship between dissolved solids and resistivity developed by Payne (1975) were used to determine the dissolved solids content as shown in Figure IV-B-5. The dissolved solids contents shown in the map are maximum estimates because a F_f value of 3.8 was used instead of Turcan's value of 2.4. The highest TDS value, and thus the highest salinity, is found in well V-6, completed at the base of the Wilcox in the supposed top of the caprock. The salinity decreases rapidly with distance from this well and no other logs or water samples in the Wilcox have TDS values above 5000 ppm. Hence, the saline plume has a maximum salinity at the crest of the eastern end of Vacherie. The plume is elongated to the east, suggesting this is the direction of ground-water flow.

The revised estimate of maximum ground-water salinity east of the dome produces a lower net salt removal than estimated in Martinez, et al., (1975). The estimated salinity of the plume has been reduced to approximately 1/3 of the original estimate. Hence, the amount of salt calculated to be removed during a 100,000 year period is reduced from 150 ft to 50 ft. If this rate is correct, then only about 125 ft of salt would be removed from the top of the dome in 250,000 years if the current assumed conditions are maintained. Although the calculated rate of salt dissolution is small, it must be emphasized that the calculations used in deriving this number include numerous assumptions which must be verified with data from either present or future wells. However, it appears

the saline plume in the Wilcox sand does not represent a salt dissolution rate large enough to eliminate Vacherie dome from further consideration for nuclear waste storage. Additional geohydrologic testing is needed. Continuing geohydrologic studies, coupled with an improved understanding of the structure above the dome related to salt dissolution and caprock formation, should provide adequate data for assessing the present hydrologic stability of the dome.

b. Hydraulic head measurements. Two wells, V-4 and V-5, are screened in basal Wilcox sands on the north and south flanks of the dome, respectively. Well V-6 is thought to be screened at the interface between caprock and salt. Water level measurements made in these wells by the USGS are shown in Figure IV-B-5. Because each well contains water of a different salinity, the true hydraulic head at each well must be determined by multiplying observed water level by the density of the water in the well. For instance, V-7 had a measured water level of approximately 95 ft above sea level in July 1977. Although the well did not produce enough water to provide a pure water sample suitable for a complete analysis, analyses of water from V-7 were made during well development. The highest field measurement of Cl^- was 180,000 ppm. Thus, the water from the top of the salt is at or near saturation with respect to NaCl, and therefore has a relative density of 1.1972 at 20° C. If the column of water in the well were fresh, the water level (L) would be:

$$L = h \times 1.1972$$

where h is the height of water in the well above the top of the screen. In the case of V-7, the corrected head is 124 ft above sea level. The corrected hydraulic heads for each well are shown in Figure IV-B-6.

WELL	TOTAL DISSOLVED SOLIDS (PPM)	CALCULATED DENSITY
V-4	1,067	1.001
V-5	4,706	1.0047
V-6	14,986	1.015
V-7	277,000 (est.)	1.191 (est.)

OBSERVED WATER LEVELS AND
CALCULATED HYDRAULIC HEAD
OF TEST WELLS AT VACHERIE DOME

The significance of the hydraulic heads depicted in Figure IV-B-6 is that ground water will flow from the area of highest head in the caprock wells (V-6 and V-7) to areas of lower head, perhaps to the Wilcox sands (wells V-4 and V-5) if a permeable connection exists between the two areas. Hence, it is possible the saline plume mapped in the Wilcox east of the dome is supplied by saline water from the caprock.

Darcy's law could be used to establish the volume of water that could move under the observed hydraulic gradient from the caprock to the surrounding aquifers if the permeability and area of any interconnections were known. At present, the values of these two components of the equations may only be guessed at. New wells and aquifer tests will be necessary to solve this problem.

It is too early to establish the source of the relatively high hydraulic head in wells V-6 and V-7. However, the pressures in the observation wells may already be offering clues to the answer. In wells V-6 and V-7 the heads are near hydrostatic. That is, the ratio of the weight of water standing in the well above the screened zone divided by the weight of overburden above the screen (1 lb/ft) is calculated to be approximately 0.43. The heads in wells V-4 and V-5 are below hydrostatic, being approximately 0.37. Three possible reasons for the anomalously low pressures in the Wilcox wells near the dome are as follows.

- 1) Ground water is being pumped from the aquifer nearby, thus lowering the head.
- 2) The Wilcox aquifer could be discharging water into a shallow aquifer, perhaps the Quaternary sands and gravels or sparta sands in the stream valley crossing the dome.
- 3) The relatively fresh water of the Wilcox sands is being drawn out of the aquifer by an osmotic potential created by the separation of

fresh water in the aquifer from salt water (near the salt core) by a semipermeable membrane of clay.

The first possibility is unlikely. Local Wilcox wells are few and used only for domestic use. The Wilcox sands may be discharging water into the alluvium in the valley crossing Vacherie dome. The heads measured in the Wilcox wells are about 195 ft above sea level. Bashaway Creek has an elevation of 180 to 200 ft in the valley at Vacherie dome. The correspondence of aquifer head and valley elevation may reveal a hydraulic connection between the aquifer and stream. Shallow wells completed in the valley sands above the dome are needed to make this determination.

Osmosis is a third mechanism which could produce the head distribution observed at Vacherie dome. An osmotic pressure gradient occurs where a semipermeable membrane separates waters of two different concentrations. As a result, water flows through the membrane from the more dilute solution into the more concentrated solution. At Vacherie dome a semipermeable membrane may be created by the Midway group clays separating relatively fresh water in the Wilcox sands from brines in the caprock. In response to the osmotic gradient, fresh water would flow from the Wilcox into the caprock. Hydraulic head would increase in the caprock and decrease in the Wilcox.

The hydrostatic conditions in the caprock wells indicate that if osmosis is active, the caprock is not hydraulically isolated from shallower aquifers because the pressure is not abnormally high. Perhaps the inflow of fresh water is offset by an out-flow of brine from the caprock to adjacent aquifers of lower head--perhaps the Wilcox group.

IV-C. GEOHYDROLOGIC STUDIES OF RAYBURN'S DOME

C. G. Smith, Jr., R. A. Barlow, and B. Hoda

1. Introduction

Four pairs of wells have been planned for Rayburn's dome. The location of each well is shown in Figure IV-C-1. In each case, one well was expected to penetrate sediments off the flank of the dome and one well was expected to drill through the shallow sediments and caprock over the top of the dome. To date (September 1977), three of the eight wells planned have been completed at this dome. All of these wells are located off the dome.

One purpose of the wells planned at Rayburn's dome is to investigate the nature of the strata near the flank of the dome; i. e., the contact between the salt stock and the surrounding aquifers and clays. In addition, water samples and measurements of the potentiometric surface will be made to determine the direction of ground-water movement at the dome. Finally, some information should be gained regarding the geohydrology of the sediments above the dome, possibly in the caprock, and near the salt.

The geohydrologic setting at Rayburn's dome presently appears rather simple. The salt plug has penetrated through the Wilcox group to within 100 ft of the surface. In at least one locale on the eastern portion of the top of the dome, Cretaceous limes and chalks have been raised to the surface. The center of the dome is a low marshy area long known for its saline springs and shallow saline waters. Rollo (1960) used well logs of oil and gas tests in the area of the dome to show that the Wilcox group sands are not contaminated with salt water even though they have been pierced by the dome. Instead, they contain an anomalously deep occurrence of fresh ground water (-1100 ft). The fact that no salt water has been

**RAYBURN'S SALT DOME
WELL LOCATION MAP**

- OBSERVATION WELLS COMPLETED
- OBSERVATION WELLS PLANNED
- △ EXISTING WELLS — INTO SALT
- ▲ EXISTING WELLS — OFF DOME

detected in the Wilcox sands at Rayburn's dome suggests this aquifer is separated from the dome, possibly by clays of the Midway group. Hopefully, the presence and hydrologic significance of a shale (clay) sheath enveloping the salt stock at Rayburn's can be verified and studied by the test wells planned.

The well locations shown in Figure IV-C-1 were selected using a combination of gravity data and topography to indicate the edge of the top of the salt stock. Only two of the oil and gas test wells in the area have been drilled to salt on top of the dome. Hence, the limits of salt are not well established. Shallow seismic surveys being performed in the field should help to establish the boundaries of shallow salt and the irregularities at the top of the salt. Before well drilling resumes in fiscal year 1978, well sites will be reevaluated in light of the new seismic data to allow for more precise placement.

2. Results of Drilling

The three wells that have been completed at Rayburn's dome are drilled to depths greater than 1100 ft along the flanks of the dome and none of the three reached caprock or salt. Preliminary indications are that in each well the stratigraphic section appears to be normal, although each of the rock units was encountered shallower than in existing wells further from the dome.

Wells R-2B and R-3B (Figure IV-C-1) were intended to be located on the flank of the dome and were not expected to hit salt. Well R-1A was expected to bottom in salt within 300 ft of the surface. However, drilling was halted when R-1A reached 1130 ft in Midway shales and did not encounter salt. The southeastern edge of the salt, therefore, must be located further north than expected. R-1B will be relocated north of R-1A, hopefully within

the boundaries of the top of the upper salt surface. Although the details of the geologic structure of the sediments abutting the dome at well R-1A have not been fully studied, the electric logs of the well are only slightly different from the log of an earlier USGS test well located 0.25 miles to the south. A dipmeter survey of R-1A indicates the Wilcox group sands dip to the south and southeast at angles between approximately 30 and 45 degrees. A more complete analysis of the geophysical logs of all wells drilled at Rayburn's will be presented in a future report.

Presently, no water samples have been analyzed from the wells. Electric logs indicate fresh water is present nearly to the base of the Wilcox group. There are no indications that salt water is moving from the salt stock into the local ground water system.

3. Acknowledgements

The U.S. Geological Survey has played a major role in the success of the water well drilling programs at Vacherie and Rayburn's domes. With the cooperation of G. T. Cardwell of the USGS Water Resources Branch in Baton Rouge, R. L. Hosman and G. Ryals of the Baton Rouge and Alexandria offices, respectively, collected water samples for complete analyses, made on-site chemical analyses and have initiated a program of continuing water level measurements for all observation wells. Their suggestions led to important changes in well development procedures to improve the quality of native ground-water samples. Additionally, their help has saved many miles of travel and many hours of travel time.

IV-D. GEOHYDROLOGIC STUDIES OF MISSISSIPPI SALT DOMES

B. Hoda and R. A. Barlow

1. Introduction

Anderson and others (1973) named 14 salt domes in the Mississippi Salt Dome Basin as potentially suitable for waste emplacement. Numerous criteria were used to judge the site suitability, including depth to the dome and the geohydrologic conditions surrounding the dome. The purpose of the research reported here is to investigate more fully the hydrologic stability of these domes based on interpretations of ground-water salinity distributions near the domes. The same approach has already been applied to the Texas and Louisiana Salt Dome Basins (Martinez, et al., 1975, 1976).

Three of the Mississippi domes were studied and reported in Martinez, et al., (1976). Of the remaining 11 domes, 8 are included in this report. The three domes omitted from the study: Hazlehurst, Cypress Creek and Arm, did not have sufficient data to merit study. The eight domes reported in this study are Byrd, Bruinsburg, County Line, Crowville, Gilbert, Leedo, Richmond and Sardis Church (Figure IV-D-1). Crowville and Gilbert domes are located in Franklin Parish, Louisiana and the others are located in Mississippi.

The evaluation of the geology and hydrology of the salt domes is limited by the paucity of subsurface information. With the possible exception of Crowville, these domes have not been intensely explored; consequently there are few drill holes around them. Of the 8 domes studied, only Gilbert, Crowville and Leedo had enough well control for a complete cross section across the dome. None of the domes had enough drill hole data to allow mapping of the areal distribution of any possible saline

FIG. IV-D-1 MAP SHOWING LOCATION OF SALT DOMES
 IN THE MISSISSIPPI SALT DOME BASIN

plumes in fresh water aquifers. However, the study was continued where possible to check for any evidence of salinity anomalies which might indicate dissolution of salt by fresh ground water.

Most of the shallow domes of the Mississippi Salt Dome Basin are roughly cylindrical in shape and about one mile in diameter and have very steep sides. The beds overlying the domes appear to be complexly faulted in those domes where sufficient well control is available (Karges, 1975). The structural interpretation included in the accompanying cross sections (Figures IV-D-2 through IV-D-10) are a result of the most rudimentary interpretation of limited data. However, as the focus of the study is the hydrologic stability of the salt domes as determined from salinity variation of the ground water, this preliminary structural interpretation should not have substantial effect on the conclusions discussed below.

The salinities in the deeper saline aquifers--Cockfield formation, Sparta formation and Wilcox group--were also studied. However, although rises in the salinities in these aquifers near the dome were noted, these were not considered determining factors in establishing the hydrologic stability of the dome.

2. Procedure

The main source of data for the geohydrologic sections are electric logs of oil and gas wells. Electric logs of the drill holes located within a radius of 5 miles of the presumed center of the salt domes were used. The aquifers were correlated, salinity of the ground water determined, and cross sections drawn (see Table IV-D-1 at end of Section for well lists).

The salinity of the formation water where the salinity was low was determined from the resistivity of the formations as indicated by long-normal curves on the electric logs. This method has been described in

detail by Jones and Buford (1951), Guyod (1954), Turcan(1966), and Alger (1966). The empirical relationship between the resistivity of formation and ground-water salinity of the Mississippi aquifers as determined by Newcome (1975) was used. Where the salinity was high (greater than 20,000 ppm TDS), NaCl content of the ground water was calculated from the spontaneous potential reading. These methods, though commonly used in ground water and petroleum investigations, give only an estimate of the water salinity. Because the assumptions discussed below must be made, there are some limitations to the use of these methods.

1) In the resistivity method, an average value of the formation factor of the aquifer is used. However, the formation factor of an aquifer is related to its water salinity, porosity, cementation and hydraulic conductivity. These properties may change over short distances creating errors in salinity estimates.

2) The relationship between the resistivity and salinity of the water as expressed in total dissolved solids content depends on the species of ions in solution. This relationship is empirically derived and is based on the average ionic composition of the ground water of the area. In fresh water aquifers NaCl is usually not the dominant ion in solution, and so the addition of NaCl by salt dissolution will alter the relative composition and thus the empirical salinity - resistivity relationship. The calculated salinity of water in which NaCl is the predominant ion will be lower than the true salinity.

3) These methods of salinity determination are useful only in sand aquifers. In Mississippi many of the aquifers are calcareous and the presence of lime, which could not be detected on electric logs, may also have contributed to some error.

As a result of these considerations, any conclusions based on the results presented below should be considered tentative. Actual sampling of the aquifers is required in order to firmly establish the salinity of the ground water around salt domes.

Dissolution of the salt domes, if it occurs, is presumed to occur mainly in the fresh water aquifers. Anderson, et al. (1973) report that the saline water is generally conceded to be stationary and, therefore, cannot be participating in important salt dissolution after it becomes a saturated brine in contact with salt mass. For this reason, work was concentrated on the salinity variation in the fresh water aquifers. In Mississippi, strata of Miocene age serve as the main fresh water aquifers. The base of the fresh water (less than 1,000 ppm TDS), except around Sardis Church dome, coincides with the base of the Catahoula formation (Miocene). Any abnormal rise in the depth to the base of the fresh water around a dome is assumed to indicate dissolution and apparent hydrologic instability of the dome.

3. Discussion

a. Bruinsburg Dome. Bruinsburg salt dome is located in the southwestern corner of Claiborne County, Mississippi. The well drilled on top of the dome encountered limestone caprock at a depth of 1802 ft, and salt at 2020 ft, at shallowest.

The structure of the beds overlying the dome is complex, and beds are cut by numerous faults (Karges, 1975). These faults have produced a small structural trap where gas accumulated. Over 500 million cubic feet (MCF) of gas was produced from this field before abandonment (Karges, 1975).

The number of well logs available for the cross section is sparse, and

therefore, the structural interpretation presented in Figure IV-D-2 is, of necessity, very simple.

Catahoula formation (Miocene) is the most widespread of all fresh water aquifers in Claiborne County, and serves as its most important source of ground water. It is also the deepest fresh water aquifer. The water in deeper aquifers is generally saline (Bicker, et al., 1966). Salinity of the water in Catahoula formation around the dome could not be determined from the available data. The available logs either start from the base of the Catahoula or below it (Figure IV-D-2). In the cross section, deeper aquifers appear to be saline with salinity generally increasing with depth. The ground water in the Cockfield formation and Wilcox group also shows an increase in salinity near the salt dome. The highest salinity in the Cockfield formation in well No. 2 is about 22,000 ppm; while in well No. 3, it is about 14,000 ppm. The salinity of the water in well No. 1 could not be determined because of the absence of any thick sand. The salinity of the water in the Wilcox group is about 81,000 ppm at a depth of approximately 4100 ft in well No. 2, while it is about 47,000 ppm at an equivalent depth in well No. 3.

The Sparta formation, however, shows an increase in salinity away from the salt dome. The highest salinities in this aquifer are 23,000 ppm, 42,000 ppm and 50,000 ppm in wells Nos. 1, 2 and 3, respectively.

On the basis of these conflicting data and because only two wells yield salinity estimates for the Cockfield and Wilcox sands, no conclusion about the hydrologic stability of the dome has been reached.

b. Sardis Church Dome. Sardis Church dome is located approximately 5.5 miles southeast of the town of Hazlehurst in Copiah County, Mississippi.

VERTICAL EXAGGERATION: x 11.2
1 INCH = 1.6 MILES

GROUNDWATER QUALITY.
DISSOLVED SOLIDS IN PPM

BRUINSBURG SALT DOME
CLAIBORNE COUNTY, MISSISSIPPI

FIG. IV-D-2

It has been incompletely studied and little geophysical work has been done. Consequently, the size and the shape of the dome are not well known.

A few wells have penetrated the salt dome indicating that the shallowest depth to the caprock is 1440 ft from the surface. None of the wells have reached the salt, so the thickness of the caprock is not known. However, it has been reported to be at least 400 ft thick (Anderson, et al., 1973).

Catahoula and Hattiesburg formations are the principal fresh water aquifers in Covich County. Although Sparta and Cockfield formations also contain fresh water, they are not used for water supply because of their lower transmissivity (Bicker, et al., 1969). However, the cross section of the area shows an anomalous situation of alternating zones of fresh and brackish water to the base of the Sparta formation in the 2 wells about 2.5 miles southwest of the dome (Figure IV-D-3). The salinity of the ground water in the two wells on the dome could not be determined because of the poor quality of the logs. Two possible reasons can account for this apparent anomaly:

- 1) The lower resistivity of some sand units may have been due to their higher clay content, rather than higher salinity of the ground water.

- 2) This vertical salinity distribution may be due to difference in permeability values of the sand units. Since the salinity of the ground water is a function of its residence time in the aquifer (Bicker, et al., 1969), any change in the permeability of the sand should affect the velocity and thus the salinity of the ground water. Lower permeability units will contain water with higher salinity than more permeable units subject to active circulation.

VERTICAL EXAGGERATION: x 6.6
1 INCH = 0.88 MILE

GROUNDWATER QUALITY.
DISSOLVED SOLIDS IN PPM

SARDIS CHURCH SALT DOME
COPIAH COUNTY, MISSISSIPPI

FIG. IV-D-3

Although the effect of shale may have contributed to some error, this vertical salinity distribution is most probably due to differences in permeability values of sand units. Giving credence to this theory is the observation by Bicker, et al., (1969) that the water from wells screened in more permeable sand have lower salinity than those screened in less permeable sand, provided they were at the same depth.

Though the cross section indicates fresh water below the top of the dome, the stability of the dome cannot be established from the available data. The control wells are all located on one side of the dome, and the absence of a saline plume could not be established by such sparse well coverage.

c. Gilbert Dome. This dome is named after the town of Gilbert, Louisiana and is located approximately 3 miles to the southwest of the town. The depth to the anhydrite caprock has been reported by Anderson, et al., (1973) as 1425 ft, with depth to the salt at 1770 ft below surface. The dome probably penetrates the Midway group and is in contact with the Wilcox group (Figure IV-D-4).

Surficial geology and hydrology of the fresh water aquifers of the area in the vicinity of the dome are not well known. The depth to the base of the fresh water could not be determined from the available logs as they all start below it. The deeper, saline aquifers show no increase in salinity around the dome (Figure IV-D-4). The highest salinity in the Sparta formation in wells Nos. 2, 4 and 5 varies approximately between 30,000 ppm and 36,000 ppm. In the Wilcox formation, except for well No. 4 located 2.5 miles south of the dome, the highest salinity is approximately the same (50,000 ppm) in all the wells. The highest salinity in well No. 4 is slightly lower (43,000 ppm). Salinities in well No. 3 on the flank of the dome could not be determined due to the poor quality of the log.

VERTICAL EXAGGERATION: $\times 13.2$
1 INCH = 2.4 MILES

GILBERT SALT DOME FRANKLIN PARISH, LOUISIANA

GROUNDWATER QUALITY.
DISSOLVED SOLIDS IN PPM

FIG. IV-D-4

Although no salinity anomaly was found in the cross section, the hydrologic stability of the dome cannot be established with any degree of certainty. More control wells are needed, especially to the east and west of the dome, to establish water quality variations in these areas.

d. Crowville Dome. Crowville dome, located in Franklin Parish, Louisiana, is the shallowest of the domes studied. Two wells have been drilled over the dome and one of these encountered limestone caprock at a depth of 511 ft from the surface. The other well encountered anhydrite caprock at a depth of 2977 ft. The depth to the salt is not known as neither of the two wells penetrated the salt. However, Anderson, et al., (1973) contend that the salt mass may be considerably deeper than 2000 ft and less than 1 mile in diameter.

The base of fresh water could not be determined from the available logs as they all start below it. It probably lies in the unconsolidated alluvial deposits within 175 ft from the surface (Anderson, et al., 1973).

The saline aquifers show an increase in salinity near the dome (Figure IV-D-5). The highest salinity in the Sparta formation occurs in wells 5 and 3 close to the dome and is approximately 64,000 ppm. In other wells the salinity varies between 38,000 ppm and 17,000 ppm, being generally higher towards the northeast. The salinity of the ground water in the Wilcox group also increases to 69,000 ppm and 76,000 ppm in wells 5 and 3, respectively, from the highs of 44,000 ppm and 50,000 ppm in the adjacent wells 6 and 2. This rise in salinity indicates a possible dissolution of the salt dome. Boatner (1975) also mapped a saline plume around Crowville salt dome. Well No. 9 also shows an anomalous increase in salinity to a high of above 70,000 ppm in the Wilcox group. This increase may be due to some reason other than dissolution of the salt dome because of the distance of this well from the dome.

FIG. IV-D-5

The rate of flow of ground water in the deeper aquifers of the Mississippi Salt Dome Basin is not known, so the rate of dissolution of any dome cannot be estimated. Although the data indicate possible dissolution of salt at Crowville dome, the degree of hydrologic instability cannot be calculated.

e. County Line Dome. Depth to the caprock of County Line Dome in Greene County, Mississippi has been reported by Anderson, et al., (1973) to be 1230 ft below the surface and by Halbouty (1967) to be 1288 ft. However, the two wells drilled over the dome encountered caprock at a depth of 1300 ft and salt at 2169 ft, at the shallowest. Only two well logs were available for analysis and therefore no conclusions regarding hydrologic stability were made. However, the cross section indicates (Figure IV-D-6):

- 1) The base of fresh water is located at the base of the Catahoula formation.

- 2) Few thick sands are present below the Catahoula formation and these are generally shaley.

- 3) The salinity of the deep saline aquifers around County Line dome is lower than around other domes. In well No. 2, the highest salinity in the Cockfield formation, Sparta formation and Wilcox group is 6,000 ppm, 8,000 ppm and 11,000 ppm, respectively. The salinity in well No. 1 could not be determined because of the absence of thick sands below the Catahoula.

The hydrologic stability of the dome could not be ascertained from the available data, apart from the observation that the shale of the deep aquifers may contribute to the hydrologic stability of the dome.

VERTICAL EXAGGERATION: x 12.4
1 INCH = 1.76 MILES

GROUNDWATER QUALITY.
DISSOLVED SOLIDS IN PPM

COUNTY LINE SALT DOME
GREENE COUNTY, MISSISSIPPI

FIG. IV-D-6

f. Byrd Dome. Only three logs in the area around Byrd dome in Greene County, Mississippi could be obtained, and none of these penetrates the dome. They are located south and southeast of the dome (Figure IV-D-7). However, Hawkins and Jirik (1966) have reported the depth to the anhydrite caprock as 1483 ft, with depth to the salt as not greater than 2,058 ft below the surface. The dome probably terminates in the Claiborne group. Some domal and flank faults are associated with the dome (Karges, 1975).

The depth to the base of the fresh water is uniform and is located at the base of Catahoula formation (Figure IV-D-7). The deeper aquifers are predominately shaley sands so no reliable salinity determinations of these aquifers could be obtained. However, in the few thick sands present, no trend is discernible in the salinity variation in Cockfield and Sparta formations. The salinity is highest in well No. 2. In the Wilcox group, the salinity decreases towards the dome from a high of about 72,000 ppm in well No. 1 to 20,000 in well No. 3.

The hydrologic stability of the dome cannot be established on the basis of such sparse data and the absence of any trend in the salinity variations around the dome. However, the absence of sand in deeper aquifers may restrict active circulation of ground water around the dome and prevent dissolution of salt. The shale of these aquifers could contribute to the hydrologic stability of the dome.

g. Leedo Dome. Leedo dome is located in the southeast corner of Jefferson County, Mississippi. The shallowest recorded depth to caprock and salt is 1405 (?) ft and 2065 ft (subsurface) respectively. Estimates based on limited drill hole data place the size of the dome at one mile in diameter at 2600 ft subsurface (2100 ft below sea level; Anderson, et al., 1973).

The surface strata over Leedo dome consist of clays and sands of the Pascagoula and Hattiesburg formations (Miocene) locally overlain by Pliocene sands and gravels (Anderson, et al., 1973). In the subsurface the dome is in contact with interbedded sands and clays of the Sparta formation and Wilcox group (?).

Problems exist in the interpretation of the subsurface geology of Leedo dome. As previously noted, salt was encountered at a depth of 2065 ft subsurface in well No. 1 (Figures IV-D-8 and -9). The drilling record and electric log for this well, however, fail to indicate the presence of normal caprock. However, less than 0.5 mile south of well No. 1, well No. 2 encountered caprock at either 1847 ft subsurface (scout card interpretation) or 1405 ft subsurface (D. H. Eargle interpretation of electric log data; see Anderson et al., 1973). Thus either caprock thicknesses vary greatly over the dome or else the caprock character varies over the dome. If well No. 1 actually contains an appreciable thickness of caprock, then its electric log characteristic is quite different from the electric log characteristic of caprock in well No. 2.

The cross sections in Figures IV-D-8 and -9 illustrate a simple structural interpretation of the subsurface geology, using well No. 1 as the center of the dome. A more precise location and configuration for Leedo dome could necessitate a reinterpretation of the subsurface structure.

The base of fresh water over Leedo dome is about 550 ft below surface and extends down to between 960 ft and 1160 ft subsurface in wells north, east, and west of the dome. Calculations indicate the depth to the base of fresh water south of the dome (well No. 8) is 1530 ft below the surface. The base of fresh water in all the wells exists near the lower section of

GROUNDWATER QUALITY.
DISSOLVED SOLIDS IN PPM

LEEDO SALT DOME
JEFFERSON COUNTY, MISSISSIPPI
CROSS SECTION A-A'

FIG. IV-D-8

GROUNDWATER QUALITY.
DISSOLVED SOLIDS IN PPM

VERTICAL EXAGGERATION: x 6.6

LEEDO SALT DOME
JEFFERSON COUNTY, MISSISSIPPI
CROSS SECTION B-B'

FIG. IV-D-9

the undifferentiated Miocene deposits. Salinities at the base of the Miocene deposits generally reach greater than 3000 ppm.

Salinities of aquifers within the Cockfield and uppermost Sparta formations are significantly higher in wells west and southwest of Leedo dome. The precise cause of these increased salinities cannot be determined by the present study. However, since the regional ground-water flow direction is southwesterly, the increase in ground-water salinity southwest of the dome suggests that salt dissolution from Leedo dome may be a cause. For this reason Leedo dome may be hydrologically unstable.

h. Richmond dome. Richmond dome is located in the southeast corner of Covington county, Mississippi. The discovery well, drilled in 1944, encountered caprock at a depth of 1609 ft and was terminated in anhydrite at a total depth of 1740 ft subsurface. A second well, located approximately 0.3 miles north of the discovery well, entered salt at 1954 ft. Anderson, et al., (1973) speculate that depth to salt in the vicinity of the discovery well may be on the order of 200 ft less than that encountered to date.

The surface strata over the dome are mainly clayey members of the Pascagoula and Hattiesburg formations of Miocene age (Anderson, et al., 1973). Fresh water sands and limestones of lower Miocene and Oligocene age comprise a large portion of the sediments below the surface clays, extending to a depth of about 1200 ft. Beyond 1200 ft, clays of the Yazoo formation, sands and clays of the Cockfield formation, and clays of the upper Cook Mountain formations (all of Eocene age) serve to separate the salt from the principal fresh water aquifers.

The limited amount of well control for the areas immediately surrounding the dome severely limits structural interpretations. Three wells located

on top of the dome (Figure IV-B-10) suggest a normal domal uplift for the overlying sediments. The degree of sediment disturbance beyond simple domal uplift cannot be estimated with the existing data.

Water quality determined from electric logs indicates the base of fresh water over Richmond dome at about 660 ft below surface (within an aquifer of undifferentiated Miocene rocks). Both well No. 3, located on the north end of the dome, and well No. 4, located about 6 miles north of the dome, indicate the presence of fresh water at a depth of approximately 800 ft subsurface (Figure IV-D-10). Generally the geometry for the base of fresh water conforms with the geometry for the base of Miocene deposits over the dome.

The lack of sufficient ground-water salinity data precludes assessment of the hydrologic stability of this dome. However, the separation of fresh water aquifers from the salt by more than 400 ft of predominately clayey sediment, provides an unknown degree of isolation of the salt from dissolution by fresh water.

VERTICAL EXAGGERATION: x 8.8

**GROUNDWATER QUALITY.
DISSOLVED SOLIDS IN PPM**

**RICHMOND SALT DOME
COVINGTON COUNTY, MISSISSIPPI**

FIG. IV-D-10

Table IV-D-1. List of electric well logs used in the Mississippi Salt Dome Basin salt dome cross sections.

BRUINSBURG SALT DOME

(Fig. IV-D-2)

Well No.	Name	Total depth (feet)	Elevation (feet)
1	Freeport Sulphur Co. #4 W. R. Hammett	1830	85
2	Barnett Serio-Justiss-Mears #1 Alex Wilson	6504	203
3	Lyle Cashion McAmis #1	6515	160

SARDIS CHURCH SALT DOME

(Fig. IV-D-3)

1	Geo. Koch-Vasser Drilg. Co. W. W. Broome #	6709	410
2	Ze-Nae Oil Corp. #1 W. W. Broome	2888	335
3	Freeport Sulphur Co. #1 So. Package Co.	2186	414
4	Freeport Sulphur Co. #1 Allen - E. Hazlehurst	1452	387

GILBERT SALT DOME

(Fig. IV-D-4)

1	Monsanto Chem. Co. Leila #1	6525	85
2	Jett Drilg. Co., Inc. et al. #1 J. B. Eley	7115	84

Table IV-D-1, continued.

Well No.	Name	Total depth (feet)	Elevation (feet)
3	Continental Oil Co. L. T. Carroll #1	3957	80
4	Crown Central Pet. Womble #1	4502	74
5	Johnson, Smith & Cameron Archie Eezell #1	7505	79

CROWVILLE SALT DOME

(Fig. IV-D-5)

1	J. C. Maxwell Alice Donnel #1	5394	95
2	Trice Prod. Co. N. L. Hower #1	5266	94
3	Gulf Refining Co. George Washington #2-A	3129	82
4	Gulf Refining Co. George Washington #1-A	911	85.5
5	Murphy-Sun Oil Co. J. E. Holt # E-4	5012	85
6	Murphy-Sun Oil Co. J. E. Holt # D-29	4814	86
7	Murphy-Sun Oil Co. J. E. Holt # D-30	4603	85
8	Robert F. Roberts McFarland #1	4113	87
9	Murphy-Sun Oil Co. J. E. Holt # D-16	3902	88

BYRD SALT DOME

(Fig. IV-D-6)

1	Humble Oil and Refining Co. Green Co. Bd. of Sup. #2	7128	200
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Table IV-D-1, continued.

Well No.	Name	Total depth (feet)	Elevation (feet)
2	Humble Oil and Refining Co. B. Stover #3	8767	256
3	A. R. Temple-Crawford Drilg.Co.	8500	159.5

COUNTY LINE SALT DOME

(Fig. IV-D-7)

1	Sun Oil Company David Gaines #2	1342	140
2	Pan American Pet. Corp. M. S. Gatlin #1	14737	235

LEEDO SALT DOME

(Figs. IV-D-8 & IV-D-9)

1	Gulf Refining Co. #1 S. V. Cupit	2070	478
2	Exploro Corp. John T. Cupid #1	2108	521
3	Gulf Refining Co. #2 Ella M. Cato	7908	486
5	Shortridge, Webster & Williams #1 Shelton	6511	323
6	Shortridge, Webster & Williams #1 Crosby Lumber Company	6575	428
7	Tide Water Assn. Oil Co. #1 B. F. Buie	10754	436
8	Allied Producing Co., Durham & Lazard & Victor P. Smith #1 U.S. Lumber Central	6422	434
11	Ray-Mac Petroleum Co. #1 U.S. Lumber et al.	6418	479
12	Ray-Mac Petroleum Co. #1 Sidney Smith	6421	465

Table IV-D-1, continued.

Well No.	Name	Total depth (feet)	Elevation (feet)
RICHMOND SALT DOME			
(Fig. IV-D-10)			
1	Freeport Sulphur Beasley #1	1624	240
2	Freeport Sulphur Co. J. W. Watts #1	1719	222
3	Freeport Sulphur Co. Mrs. P. Scarborough #1	1910	272
4	Cities Services Oil Co. #1 R. Aultman	9708	293

IV-E. CAPROCK STUDIES

J. D. Martinez and J. E. Rovik

A major thrust in our caprock study has been an effort to develop an understanding of the genesis of caprock through a petrographic investigation of both the caprock and salt near the interface. It is hoped that some basis can be established for determining from an examination of a core and/or other subsurface data whether active dissolution is in process at a particular location on the upper surface of the salt in a dome. For example, a zone of loose anhydrite sand or poorly consolidated anhydrite caprock would suggest recent or active dissolution. A "pile of brick" fabric of the anhydrite caprock, with little cementation, would also be suggestive of this condition.

Conversely, a sharp line of demarkation between completely recrystallized anhydrite and salt would suggest lack of active dissolution at the point from which the core was obtained.

Our petrographic studies are designed to help us understand the process which occurs in this initial stage of caprock formation. It would be useful to develop definitive evidence indicating whether or not caprock is indeed developed by a residual accumulation of anhydrite. Although this process has been questioned by Walker (1972), it is the most generally accepted explanation. We are proceeding on the basis that caprock does indeed form from the residual accumulation of anhydrite resulting from salt dissolution.

This study has been hampered by the lack of availability of suitable cores adjacent to the interface between caprock and salt. A few appropriate cores have been found. The results obtained from certain of these were described in the 1976 report (Martinez, et al., 1976).

During the 1977 fiscal year, cores were obtained from the Gibbsland salt dome in north Louisiana and the Moss Bluff dome in Texas.

Information furnished us on the Moss Bluff cores indicates that they were taken near the caprock/salt interface. Seven thin sections were prepared from 5 core samples. A weak clustering of anhydrite crystals was noted in the salt samples. These clusters are characterized by brick-shaped anhydrite crystals which are preferentially oriented at angles to the horizontal which are less than 45° . In the anhydrite above the salt there is very little indication of preferential crystal orientation. The samples furnished to us did not permit an assessment of any possible change in orientation of anhydrite at greater distance from the interface.

Core samples from the caprock/salt interface of the Gibbsland dome in north Louisiana which were furnished to us by H. B. Gibbsland of the Hercules Petroleum Company, have provided us with new evidence of anhydrite-salt relations in the salt near the contact which may ultimately provide a better understanding of processes in this region and may be of value to our investigations.

Three thin sections were prepared from the anhydrite caprock approximately 9 cm above the salt/caprock interface. These sections showed this portion of the caprock to consist of more than 99 per cent anhydrite with traces of dolomite. No gradational changes were noted. Larger crystals of anhydrite are more numerous in the caprock than in the salt, which suggests some recrystallization near the contact.

Three thin sections were prepared from the salt from 3 cm to 9 cm below the caprock/salt interface. These sections provided us with new insights into the petrology of this part of the salt. In the interval from 4 to 9 cm below the contact, there is a concentration of anhydrite grains in trails of crystals along salt crystal boundaries (Figure IV-E-1).

Figure IV-E-1. Concentration and orientation of anhydrite crystals along salt crystal boundaries.

In these trails, elongate axes of anhydrite crystals are preferentially aligned along the salt/crystal boundaries. The anhydrite ranges from brick- to block-shaped crystals and varies between 0.1 mm and 0.3 mm in size. Although a few anhydrite crystals in this region are included in salt crystals, their density increases at the salt crystal boundaries. It is reasonable to conclude that these crystals migrated to the boundary positions in their present form. This movement may have occurred by salt dissolution and recrystallization causing the original crystals to reject the anhydrite; or, it may have developed by movement of the anhydrite out of the salt in some form of solid state process. It is

premature at this time to speculate further on this process, but it is possible that some entirely new concepts may develop from this observation. The movement of liquid bubbles through salt along heat gradients may possibly provide a model to explain this observed movement of anhydrite crystals.

These anhydrite trails are wider and contain more crystals near the caprock/salt interface. Three centimeters below the contact, as much as 80 per cent anhydrite is concentrated in elongate zones roughly parallel to the salt contact. These zones or layers are separated by salt containing very little anhydrite.

Our work thus far confirms the idea of salt dome caprock forming by residual accumulation of anhydrite, and supports the thesis that conditions at the caprock/salt interface may be used to indicate whether active dissolution is in progress. Much more data are needed from cores to proceed with this work, although such cores are difficult to find. We believe that we can develop much more information from a relatively inexpensive, continuing, study of salt dome caprock of this kind.

IV-F. HYDROLOGIC ISOLATION OF MINED OPENINGS IN SALT DOMES

J. D. Martinez and R. L. Thoms

1. Introduction

This investigation, which was initiated in January 1976, is still in progress. Reported and observed conditions in some mines underscore the need to continue this study. Thus far we have determined that the Grand Saline and Hockley mines are dry and that the mine in the Cote Blanche dome is essentially so, with only a few traces of water which are probably connate. We continue to be severely hampered by lack of access to mines in the Jefferson Island and Avery Island domes. We have not yet visited the Belle Isle mine which has been reported to be a wet mine; but according to a preliminary unofficial discussion with a representative of mine management, only connate water has been encountered. The Weeks Island mine has been inspected and provides a contrasting set of conditions to those which have been found to be dry. Although Weeks Island mine is not considered by the management to have water leaks of serious consequence to mining, it is not now considered to be a dry mine from the standpoint of long range isolation of radioactive wastes. Therefore, we do have data of sufficient contrast to begin to develop a strategy for prediction of potential internal hydrologic problems in domes prior to development of underground space.

The approach to this problem must go much deeper than observation and case history analysis. It requires the accumulation of much more data and information and thorough assessment of the internal structure of Gulf Coast salt domes and theories of their development particularly bearing on potential avenues for internal fluid movement. Figure IV-F-1 represents our updated plan for this mine hydrology investigation. We have only begun

FIG. IV-F-1 PLAN FOR MINE HYDROLOGY INVESTIGATION

to follow the sequence of steps involving petrological and geochemical studies. These appear to be a very important approach in our drive to develop meaningful conclusions. The evaluation of explanations of water inflow into mined openings in domal salt is very important and involves an appraisal of published hypotheses which have been proposed to describe and explain mechanisms of growth and adjustment to growth of salt domes. For example, the "spines of movement" hypothesis, which has been developed by implication from Balk's work (1949) by Muehlberger (1960), and later elaborated on by Kupfer (1974, 1976), has been used both by Muehlberger and Kupfer to account for the presence of included sediments in domal salt. Kupfer (1976b) has proposed shear zones between older spines of movement which may provide avenues for water movement along inclusions of sediments. This explanation may well be correct and, if it is, would suggest the possibility of encountering leaks in openings made deep in the salt stock. However, the mine in the Grand Saline dome, which presumably gave birth to the spines of movement suggestion by Balk and "pediatric care" by Muehlberger, is dry.

On the other hand, the possibility should be evaluated that inclusions have been incorporated into the salt by other mechanisms and that major shear zones in salt, if indeed present, may be ephemeral features that do not persist deep into the stock but represent only local adjustments to growth near the advancing front of the salt mass. Such an alternative might make it appear more feasible to locate leak-free areas in salt domes for waste isolation.

The Jefferson Island dome has been cited as an example of a dome with a "spine" (Kupfer, 1974; Muehlberger, 1960). If a cross section of

Jefferson Island salt stocks is depicted without vertical exaggeration as in Figure IV-F-2, the dome could be more aptly described as possessing a surface "knob." Furthermore, the presence of caprock only on the lower bench could be interpreted as evidence that the entire stock moved as one entity with dissolution occurring only over that part of the surface now covered by caprock. In any event, much more consideration must be given to the mechanism by which sediments are infolded into the salt.

2. Comparison of Gulf Coast Salt Mines

As our study has progressed we have become increasingly aware of the diversity between Gulf Coast domes as well as internal differences in individual domes. For this part of our overall study, comparisons of mine conditions are complicated by the fact that some of the mines are in the interior basins and some are in the coastal domes. Attention has been directed in our earlier reports as well as in the current one to the differences between these two groups of domes.

Bearing the above comments in mind, it has appeared useful to examine certain critical domal-mine configurations for possible explanations of differences in mine hydrology and/or suggested avenues of further study. The data accumulated for this purpose are displayed in Figure IV-F-3. Although it is considered accurate enough for this use, we are still in the process of updating and confirming data from some mines. Therefore the exact figures should be considered somewhat tentative.

The general diversity of domal conditions is confirmed by these data. In addition, mine depths vary considerably. These two general parameters provide some basis for speculation. For example, the Cote Blanche mine, which is dry, is one of the deepest and also has the greatest separation

FIG. IV-F-2 KNOB ON JEFFERSON ISLAND DOME

FIG. IV-F-3 CONFIGURATIONS OF VARIOUS GULF COAST SALT DOME MINES

from the upper surface of the salt without any intervening mined levels. These two conditions also apply to the Hockley mine which is also dry. The Grand Saline mine, a dry mine, does not fit this pattern. It is neither a deep mine nor is the thickness of salt over the mine as great as it is for Cote Blanche or Hockley. However, it does appear to provide somewhat more isolation than is the case for mines which experience water problems.

Hockley is seen to have a caprock thickness of about 1000 ft. This contrasts starkly with the Five Island domes and is evidence of dissolution of perhaps two or more miles from the rising salt column. This suggests the possibility of different physical properties of salt from those encountered in domes showing no evidence of dissolution. Perhaps dry conditions in the Hockley mine may be in some way related to this observable condition. On the other hand, the only other dome under consideration with a thick caprock is Winnfield. The mine in that dome has been flooded.

Reflection on these and other differences give rise to another conjecture. The Five Island domes exhibit impressive positive relief in coastal areas, with depth to salt being least for Avery Island and Weeks Island--the two with greatest surface elevation. Furthermore, only the Belle Isle dome has any caprock over its highest point, and that is relatively thin. Caprock is not present over the "knob" of Jefferson Island dome, but does occur on a lower bench. One may, therefore, surmise that these domes are rising relatively rapidly; too fast for caprock to form. This might suggest a different state of stress in the domal material that could influence movement of water through the stock and into mined openings.

It is emphasized that these suggestions are extremely tentative and designed to open new avenues for thought and study that may lead to firmer conclusions. The following subsections of this report provide direct

observational evidence of hydrologic conditions within certain Gulf Coast domes.

3. Mine Hydrology - Weeks Island

In order to continue our evaluation of the problem of leaks in salt mines, we sought and received permission to visit the Weeks Island salt mine. Operating personnel of the Morton Salt Company were very helpful and cooperative in arranging two thorough visits of the mine. J. D. Martinez, C. G. Smith, and R. A. Barlow of the Institute for Environmental Studies and W. V. Jones of the LSU Physics Department were led on the first inspection of the mine on February 10 by Bob Fiedler, Mine Superintendent, and Mahmood B. Mirza, Assistant Manager.

Prior to the trip underground we were briefed by John E. Goodbrake, Mine Manager, who was especially interested in discussing mine conditions with us. He considers the mine to be essentially dry and from an operating point of view to be unaffected by any water leaks or seeps. He called our attention to one small leak that he believes to be now inactive.

The visit to the mine was informative and instructive. Pertinent evidence was noted and representative samples were collected. It was obvious that a second visit would be required for a more careful sampling and detailed photography of points of interest. Our second visit for this purpose was made on March 14, 1977. Once again we were graciously received by the mine operators and given all the assistance we required to complete our observations and records.

LSU scientists on this second trip included Martinez, Barlow and graduate assistant, R. Brown. Messrs. Mirza and Derise took us through the mine on this occasion. Our combined observations for both of these mine

visits are consolidated and discussed below. Items of interest are located on a mine map (Figure IV-F-4) on which Kupfer (1976) has indicated generalized layering and postulated shear zones. Features noted, which will be described, include presence of water, and evidence of former presence of water such as salt stalactites, hydrocarbon seeps, "chimneys" or large blowouts of salt at a blasted face, included sediments, impure salt, and lenses of recrystallized salt. The locations of these features are identified by location number on the Weeks Mine plan (Figure IV-F-4) and listed in Table IV-F-1. The word "room" as used in the text denotes either intersections of corridors or short sections of corridors.

A water leak (Figure IV-F-5) has been definitely identified at location 6 on Figure IV-F-4. This leak was initiated by an undercut for mining a new face about two years ago. A pool of water which formed at that time is said to be diminishing in volume and this has been considered evidence for cessation of flow. However, as can be seen in the photograph of Figure IV-F-5, perhaps 100 square feet of the floor is still covered with water. Also, an intermittent gurgling sound can be heard from the undercut. It would seem that this is more likely to be caused by some kind of gas rather than water flow. It is also reported that there was some seepage of water from a shot hole 5 ft above the undercut before undercutting.

In Room 14-V there is a small oil and gas seep, possibly including water, which was encountered about 6 months ago. Gas was observed to be bubbling through an accumulation of oil on the floor of the mine and through oil in the bottom of an inclined drill hole extending about 2 ft into the salt. Directly over the pool an area several feet square was noted to be covered with a light colored deposit from which a salt stalactite was suspended. This stalactite which was collected for analysis is hollow with thin walls and oily.

FIG. IV-F-4 MINE PLAN, GENERALIZED LAYERING, AND
LOCATION OF SPECIAL FEATURES, WEEKS MINE
(AFTER FEA, 1976a; KUPFER, 1962)

Table IV-F-1. List of locations of special features, Weeks Island salt mine.

[Figure IV-F-4]

Location No.	Feature
1	Horizontal Chimney
2	Vertical Chimney
3	Large crystals of salt
4	Stalactites
5	Vertical vein of large salt crystals
6	Water seep from undercut
7	Pod of included sedimentary rock
8	White efflorescence on walls and ceiling
9	White efflorescence on walls (oil sample collected)
10	Pool of water reportedly a result of condensation, collected water and grease samples
11	Mass of large crystals of salt cutting banding
12	Highly folded layers of black (impure) salt
13	Stalactites and stalagmites (stalagmite samples collected)
14	Stalactites
15	Clusters of stalactites

Fig. IV-F-5. Water seep from undercut, Weeks Mine.
(Location 6, Fig. IV-F-4.)

Large pools of water exist on corridor floors on the east edge of the mine. These accumulations of water are considered by operating personnel of the mine to result from condensation. Evidence cited for this explanation is the observation that more water collects during summer months when warmer air is brought into the mine by the ventilation system. The pools occur along the main air passageway. Unfortunately, the coincidence of this passageway with the postulated shear zone introduces some element of uncertainty. At location 10, coalescing pools of water up to about 20 ft in diameter (Figure IV-F-6), are typical of this condition. Small bubbles rise to the water surface in one area here. A pool of water was also seen at location 11 and at location 8. A white efflorescence (Figure IV-F-7) covers much of the wall and ceilings near rock bolts, suggesting former general water seepage or condensation. There is no evidence of water on the walls or ceilings at this time, which indicates: (1) that if the efflorescence resulted from seepage, then that flow has ceased; or (2) that the water which caused this phenomenon was indeed condensation. This same white material is extremely common on the walls at location 9 (Figure IV-F-8); and on the ceiling, rock bolts, and walls at location 10 and to a lesser extent at location 11.

Another type of evidence of former water drips are stalactites and stalagmites. This dripping water, which has now disappeared, may have been due to temporary seeps of connate water or possibly condensation. They are to some extent, but not entirely, associated with rock bolts. Stalactites (Figure IV-F-9) were noted at location 4, location 14, and most abundantly at location 15 (Figure IV-F-10). Stalactites and stalagmites (Figure IV-F-11) were observed and the latter collected at location

Fig. IV-F-6. Coalescing pools of water reportedly due to condensation, Weeks Mine. (Location 10, Fig. IV-F-4.)

Fig. IV-F-7. Efflorescence on walls, Weeks Mine.
(Location 8, Fig. IV-F-4.)

Fig. IV-F-8. Efflorescence on walls, Weeks Mine.
(Location 9, Fig. IV-F-4.)

Fig. IV-F-9. Stalactites, Weeks Mine.
(Location 4, Fig. IV-F-4.)

Fig. IV-F-10. Clusters of stalactites, Weeks Mine.
(Location 15, Fig. IV-F-4.)

Fig. IV-F-11. Stalagmites, Weeks Mine.
(Location 13, Fig. IV-F-4.)

13. This room was mined about six years ago. Iron stains are noted on ceilings where stalactites exist and elsewhere as well. There seems to be some association with rock bolts although this is not completely conclusive. An observation in Room X between 14 & 15 suggests that these features may indeed have resulted from seeps of connate water which have since dried up. Rock bolts had been emplaced in this room about two days before our visit. Circles of moisture about one foot in diameter had already appeared around these rock bolts and water was slowly dripping to the floor from the bolts. Presumably this will eventually cease. It seems likely that the rock bolts had intercepted interstitial water in cracks formed by the bolting. Openings about them are serving as conduits for release of connate water.

Both oil and grease were falling from the ceiling near the "Boundary Shear Zone." Heavy grease seeps were noted at location 8 and oil seeps were noted at location 9.

An interesting feature which has been noted in this mine, but said to be less common in other mines, is large blowouts of salt in the ceiling and walls of a blasted face at the time of blasting. These are called chimneys because they commonly, although not always, project upward into the ceiling. Figure IV-F-12 shows a nearly vertical chimney at a blasted face at location 2. At location 1, a large and unusual horizontal chimney in the blasted face itself is shown in Figure IV-F-13. These features have generally been considered a result of gas pockets. However, the fact that they normally extend upward and rarely, if ever, downward on the floor suggests an alternative explanation. They may represent an explosive release of stress caused by the blast. If due to gas pockets they might be expected to occasionally form in the floor. Both factors may be involved. This is discussed in the following section on the Cote Blanche Mine.

Fig. IV-F-12. Vertical chimney, Weeks Mine.
(Location 2, Fig. IV-F-4.)

Fig. IV-F-13. Horizontal chimney in blasted face, Weeks Mine.
(Location 1, Fig. IV-F-4.)

Large salt crystals (Figure IV-F-14) were observed at location 3. A vertical "vein" of large crystals (Figure IV-F-15) was noted at location 5. The photograph shows that the salt is whiter than normal and that there is a dark band on the one border of this material. Notice the vaguely banded salt on one side of the "vein" and the dark unbanded salt on the other side. The dark band represents an accumulation of anhydrite (Figure IV-F-16) perhaps derived from the coarsely crystalline "clear" salt vein. Further study is planned of this feature.

There are enclosed sediments of somewhat unusual appearance found along the eastern boundary of the mine, called a "Boundary Shear Zone" by Kupfer (1976b). These have been sampled for detailed petrographic analysis. Figure IV-F-17 shows a pod of sediment suggestive of a breccia, but with rounded rather than angular fragments. This sediment mass occurs at location 7. Figure IV-F-18 is a photomicrograph of a sample of this inclusion. A shale sample was collected at location 10. A highly fractured sandstone layer (Figure IV-F-19) infilled with salt was also collected from the mine. The texture of this inclusion is shown on the photomicrograph of Figure IV-F-20.

R. Brown, a geochemistry graduate assistant working with R. E. Ferrell, collected water, oil, and stalagmite samples for trace element and other analysis. This data will be evaluated for relevance to this problem after an analysis and report by Dr. Ferrell is completed. Excellent exposures of highly folded layers of black (impure) salt (Figures IV-F-21 & IV-F-22) may be seen at location 12. Our observations coincide in part with those described by Kupfer (1976) in a recent Guidebook which was used for a visit to the Weeks Island Mine.

Fig. IV-F-14. Large salt crystals, Weeks Mine.
(Location 3, Fig. IV-F-4.)

Fig. IV-F-15. Vein of large crystals, Weeks Mine.
(Location 5, Fig. IV-F-4.)

a. with out crossed nichols

b. with crossed nichols

Fig. IV-F-16. Photomicrograph of anhydrite band.
(Location 5, Fig. IV-F-23.)

Fig. IV-F-17. Pod of sediment inclusion of brown (buff) sandstone, Weeks Mine. (Location 7, Fig. IV-F-4.)

a. without crossed nichols

b. with crossed nichols

Fig IV-F-18. Photomicrograph of sediment inclusion, Weeks Mine.
(Location 7, Fig. IV-F-23.)

Fig. IV-F-19. Sample of highly fractured sandstone inclusion infilled with salt, Weeks Mine.

Fig. IV-F-20. Photomicrograph showing texture of sandstone inclusion, Weeks Mine.

Fig. IV-F-21. Highly folded layers of black (impure) salt, Weeks Mine.
(Location 12, Fig. IV-F-4.)

Fig. IV-F-22. Additional view of highly folded layers of black (impure) salt, Weeks Mine. (Location 12, Fig. IV-F-4.)

4. Mine Hydrology - Cote Blanche

The Cote Blanche salt mine which is owned and operated by Domtar Chemicals, Inc. was visited on June 8, 1977 in connection with mine hydrology studies. Members of the project team inspecting the mine included J. D. Martinez, R. L. Thoms, E. J. Newchurch and graduate assistant, C. P. Smith. The plan of the Cote Blanche mine is shown on the map in Figure IV-F-23 which was published by the Federal Energy Administration in 1976 (FEA, 1976). The locations of special features are indicated on the map and listed in Table IV-F-2. The mine has been historically, and is presently, essentially dry. In fact, it is quite hot and dusty. Jack Tufts, the mine manager, told us that only three minor occurrences of water intrusion into the mine had been experienced. In all instances the water was considered to be connate because the flow had stopped.

In one instance, water was encountered in drill holes in the floor in one room (location 1, Figure IV-F-23). The face of the room was wet at the time, April 1973, but no water collected on the floor. Water is still standing at depth in a 50 foot drill hole at that location. Water was also noted in another floor hole at location 4 in late 1974. After removal of the salt, there was no longer any indication of water. At location 3, water dripped from the roof in January 1974. The drip lasted for about 6 weeks and stopped. It is reasonable to conclude that the water encountered in all three of these instances was connate (trapped water).

With the three minor exceptions noted above, the mine was found to be dry. There was some standing water found in a sump pit near the ventilation shaft. This water is believed to have collected in the shaft from condensation. The shaft is approximately 8 ft in diameter and accommodates an air intake of 130,000 CFM. Below the cemented section which

FIG. IV-F-23 MINE PLAN AND LOCATION OF SPECIAL FEATURES—
COTE BLANCHE MINE. (AFTER FEA, 1976b)

Table IV-F-2. List of locations of special features, Cote Blanche salt mine.

[Figure IV-F-23]

Location No.	Feature
1	Water in drill holes in floor; vertical blowout
2	Rock bolts installed without discoloration of salt
3	Water drips from roof
4	Water in floor hole
5	Intensely fractured, fine grained salt
6	Chimney in ceiling; string of chimneys; nose of fold in ceiling; well-aligned blowouts

extends into the salt, dissolution has enlarged the shaft opening. Near the base of the shaft, the opposite condition has occurred. Precipitation of salt narrows the opening and salt must periodically be removed to permit easy passage of the hoist. No water was noted anywhere else in the mine. Where rockbolts were installed, as at location 2, there was no discoloring of the salt by iron oxide (Figure IV-F-24).

Several "chimneys" or blowouts were observed. All but one, which was in a mine face, were in the ceiling. The vertical blowout at location 1 is shown in Figure IV-F-25. A typical chimney in the ceiling at location 6 is shown in Figure IV-F-26. It appears to be controlled by the banding in the salt. The effect becomes more pronounced in Figure IV-F-27 from the same location which shows two of several blowouts which are very well aligned. All of these features seem to be in the core of the fold, the nose of which is shown in Figure IV-F-28. Whether the blowouts were due to pressure of enclosed gas or whether they were due to relief of stress with consequent release of gas, it is quite clear that the presence of gas in the salt is strong evidence of impermeability. This is reinforced by the obvious relation of the blowouts to the banding in the salt. Inasmuch as the banding very likely represents relict bedding, there is some possibility that the gas was trapped during diagenesis. However, this would not follow if the blowouts are purely a stress release feature.

Included sediments were only seen at one location, but the mine manager indicated that they were more extensive. A variety of salt types occurs in the mine, including salt which crackled when placed in water due to release of gas. One very interesting rock type is shown in Figure IV-F-29, location 5. This salt is fine grained and intensely fractured. An open cavity is reported at this location but we did not observe it.

Fig. IV-F-24. Salt showing no discoloration from oxidation of rock bolts, Cote Blanche Mine.
(Location 2, Fig. IV-F-23.)

Fig. IV-F-25. Vertical blowout, Cote Blanche Mine.
(Location 1, Fig. IV-F-23.)

Fig. IV-F-26. Typical chimney in ceiling, Cote Blanche Mine.
(Location 6, Fig. IV-F-23.)

Fig. IV-F-27. String of chimneys in line along ceiling, Cote Blanche Mine.
(Location 6, Fig. IV-F-23.)

Fig. IV-F-28. Nose of fold in banding of salt, Cote Blanche Mine
(Location 6, Fig. IV-F-23.)

Fig. IV-F-29. Fine grained, intensely fractured salt, Cote Blanche Mine.
(Location 5, Fig. IV-F-23.)

The contrasting nature of hydrological conditions in this mine with those in the other domes of the Five Island group is significant to this study.

5. Gas Intrusion in Solution-Mined Cavities

The occurrence of hydrocarbons, both oil and gas, has been observed in a number of salt domes according to Francis Falcon (personal communication, 1977) in a Shell Oil Company Report. Those included: Avery Island, Choctaw, Cote Blanche, Darrow, East Hackberry, Eugene Island Block 188, Garden Island Bay, Jefferson Island, Lake Hermitage, Lake Washington, Sulphur, Venice, Weeks Island, White Castle, and Winnfield. The development of solution-mined storage cavities in the Sorrento salt dome in Ascension Parish, Louisiana has provided valuable background information on the nature of the occurrence of gaseous hydrocarbons in that dome. Mr. Falcon of Shell has made his report available for our use and William F. Sporleder of Shell has also provided valuable data and insights. The following information is summarized from these sources.

Salt cores from the first LPG storage well at Sorrento contained small bubbles filled with oil and gas. The release of these fluids with a popping noise upon splitting or dissolution indicated that they were under pressure.

The second well drilled by Shell into the salt at Sorrento was abandoned due to "overpressure". It was found that the weight of the mud could not be increased sufficiently to prevent it being "cut" by the gas. Their fifth well had to be abandoned for the use of storage of ethylene because of contamination by methane. It is now filled with saturated brine and being monitored for flow of methane. The daily flow at this time is about 100 MCF of gas, primarily methane, at surface conditions (60°F and 60 psi).

Inasmuch as the cavity is filled with saturated brine, it is not reasonable to conclude that the gas is released from dissolution of the salt. There are three possible explanations: (1) the gas may be entering the cavity from some kind of casing leak; (2) the gas is following permeability channels through the salt stock from the surrounding sediments; and/or (3) the gas is moving into the cavity through permeability channels in the salt stock from concentrations in the salt itself. In view of the fact that gas was noted in other wells, the first explanation is unlikely. Interconnection with surrounding sediments is a distinct possibility. It is also conceivable that overpressuring in testing or brining activities could have induced fracturing sufficient to allow inflow of gas.

Therefore, we are presented with two different kinds of evidence from this dome. The presence of trapped gas under pressure in the salt cores strongly suggests impermeability. On the other hand, the movement of gas into a cavity filled with saturated brine is a very good indication of the presence of permeability channels in the stock. Further study must be devoted to this paradoxical problem.

Mr. Falcon concluded that the gas in the salt was derived from inclusions of hydrocarbon sediments trapped in the salt as it intruded upward. He supports this explanation by the Oligocene age, probably younger than Vicksburg, which was assessed to a clay band in the Sorrento salt. The age was determined through a paleontological study by Charles L. Trotter (1961).

6. Conclusion

It is still premature to evaluate conclusively the significance of observed mine leaks in salt dome mines to the utilization of salt domes for radioactive waste isolation. However, it becomes increasingly clear

that this is a problem that will have to be reckoned with in the future. Current information indicates that water leaks occur in some Gulf Coast salt dome mines and not in others. This raises two questions. First, to what extent would leaks of different magnitude condemn a particular site? Second, what is the source of such leaks and why do they occur in some mines and not in others? Leaks of water and/or hydrocarbons have been found to be associated with anomalous occurrences of included sediments, impure salt and particular types of structure shown by banding of the salt (Kupfer, 1976b). He and others have advanced the hypothesis that these are shear zones (Kupfer, 1976b). On the other hand these may represent sediments infolded by other mechanisms. If these are shear zones they might be expected to extend deeply into the salt. If not, then they may occur only near the top. In this eventuality, and perhaps for shear zones as well, long time dissolution of salt (evidenced by thick caprock) may have eroded the salt down below these included impurities. Martinez (1974) reviews other tectonic implications of caprock. Countering this possibility is another proposal by Escher and Kuenen (1929) that salt becomes more impure with depth. We simply do not know which, if any, of these ideas is correct, and we must continue to search for a better understanding of salt dome genesis which may take a long time to develop, if ever.

The one thing that does seem to be a reality is the variability of salt domes on a basinal as well as an individual basis. Therefore, exploration by drill and/or shaft and mine is the only positive test of a salt dome, in the final analyses, for internal hydrologic isolation.

In the further conduct of this study, we propose to complete our inspection and development of mine hydrology history of Gulf Coast salt mines. We further intend to conduct petrological and geochemical studies

of the type already discussed in order to determine sources of mine waters and conditions which permit their movement into the mines. We strongly recommend close cooperation with current Department of Energy (formerly Federal Energy Administration) studies bearing on crude oil storage in salt mines. The vast amount of data developed by scientific groups involved in that effort should be transferable to our problem and may prove especially helpful. In this connection we would strongly recommend permeability measurements of the included sediments as well as the salt itself.

IV-G. FINDINGS AND RECOMMENDATIONS

C. G. Smith, Jr.

1. Findings

1) Electric logs from the new observation wells drilled at Vacherie dome indicate a subsidence structure exists over the center of the dome. The Cane River formation previously thought to have been eroded from the top of the dome was found more than 300 ft below the surface. A likely cause of the subsidence is extensive salt dissolution at the top of the dome occurring subsequent to Cane River deposition. This finding may be a key to the rate of salt dissolution during the last 48 million years and the consequent rate of caprock formation during the same time period.

2) Water samples taken from the four test wells at Vacherie dome indicate that, as expected, water in the caprock and near the salt is saline and water in the Wilcox sands surrounding the dome is fresh to saline. The relationship between electric log resistivity and water quality that was used to map the saline ground water east of the dome (Martinez, et al., 1976) was confirmed by the logs of the Wilcox observation wells and analyses of water obtained from these wells. The higher potential (hydraulic head) of the caprock wells, as compared to the Wilcox sands, reveals a possible source for the saline water found in the "plume" east of the dome. If permeable connections exist between the caprock and the Wilcox aquifer (and they probably do) water will flow from the caprock into the shallower sands. Additional data is needed on local ground-water flow rates and aquifer characteristics to satisfactorily estimate the degree of hydrologic instability represented by this feature.

3) The drilling program at Rayburn's dome was concluded at the end of fiscal year 1977 and no firm conclusions have yet been reached regarding the hydrologic data from these wells. However, these wells have helped to define the limits of salt, and have not revealed saline water conditions in the Wilcox aquifer that are at variance with the original conclusions regarding the distribution of water quality around this dome (as reported in Martinez, et al., 1975). No new evidence of salt dissolution is suggested.

4) Efforts to map saline anomalies in the ground water around Mississippi salt domes met with limited success due to the relative lack of exploration of the Mississippi domes. Electric log availability around most of the domes (reported as "unrejected" by Anderson, et al., 1973) was inadequate to satisfactorially determine the distribution of water salinity around the domes. No evidence of saline ground-water anomalies was found either in fresh-water or saline-water aquifers of Tertiary age, with the exception of Crowville and Leedo domes. The increase in salinity in the Sparta and Wilcox sands at these domes indicates the potential hydrologic instability.

5) Visits were made to several salt mines in Gulf Coast domes. Grand Saline and Hockley domes in northeast Texas and Cote Blanche dome in south Louisiana were essentially dry. Weeks Island dome, although essentially dry for current mining operations, was determined to represent a mine with sufficient inflow of water to possibly jeopardize long term isolation of waste. Of the remaining mines, Jefferson Island, Belle Isle, and Avery Island have not been visited. A variety of anomalous features noted in both wet and dry mines deserve further study in order to assess the internal hydrologic conditions of salt domes. These features include oil, gas and water seeps, areas of large crystals which

may suggest past salt dissolution, and recrystallization and blow-outs which occur during salt mining.

6) Petrographic examination of salt and caprock from Gibsland (Louisiana) and Moss Bluff (Texas) domes reveal no consistent trends in anhydrite concentration near the salt/caprock interface. However, in Gibsland dome samples show an unusual feature not yet reported. Euhedral (well developed faces) crystals of anhydrite concentrate along and orient with salt crystal boundaries. In other areas and in other samples the anhydrite is distributed throughout the salt crystals. In contrast here, the anhydrite appears to have moved through the salt mass. It is reasonable to conclude that these crystals migrated to the boundary positions in their present form. This movement may have occurred by salt dissolution and recrystallization causing the original crystals to reject the anhydrite; or, it may have developed by movement of the anhydrite out of the salt in some form of solid state process.

2. Recommendations

1) Additional drilling is required at Vacherie salt dome to determine ground-water flow rates and directions, and to determine aquifer characteristics for the Wilcox group sands. Of particular interest is the eastern end of the dome in the vicinity of the saline plume. The evaluation of the geohydrology of the dome will depend also on new data from shallower borings designed to study Quaternary and Tertiary sediment structure over the dome. A minimum of two observation wells is required at the west end of the dome where data on water quality is lacking.

2) A study of the geochemical significance of variations in water quality observed in the water samples collected from the wells at Vacherie and Rayburn's domes is recommended. Of particular interest is: 1) the

relationship between caprock (and false caprock) formation and the chemistry of the native water; and 2) possible correlations between brackish to saline water in the Wilcox sands and saline water in the caprock.

3) A thermal infrared survey is recommended over salt dome sites of interest in north Louisiana and Texas. Such surveys have been useful in detecting soil moisture differences along lineations. In the case of salt domes, this survey may locate lineations and faults which are areas of ground-water discharge. Lineations and reported "mineral springs" on Vacherie dome are primary targets.

4) Petrographic studies of salt and caprock formation and mechanisms of salt dissolution near the caprock/salt interface should continue. Further studies are planned to sample areas of interest in Weeks Island dome, and caprock and salt cores from the proposed test holes at Vacherie and Rayburn's domes.

5) The inspection of hydrologic conditions in Gulf Coast salt dome mines should continue. Petrological and geochemical studies which may aid in determining sources of mine waters and conditions which permit water movement into the mines will continue. Close cooperation between current Department of Energy studies of salt domes for crude oil storage and our investigations should prove beneficial to both efforts.

V. REGIONAL GEOLOGY

- A. General
- B. Computerized Mapping
- C. Growth Rates of Salt Domes of the North Louisiana Salt Basin
- D. Seismic Studies of Vacheire Salt Dome
- E. Gravity Investigations of North Louisiana Salt Domes
- F. Geochemistry
- G. Mineral Resource Maps of Vacherie and Rayburn's Salt Dome Areas
- H. Findings and Recommendations

V-A. GENERAL

R. E. Wilcox

Several geological, geophysical, and geochemical investigations were undertaken during the 1977 fiscal year in order to more fully understand the structural and stratigraphic characteristics of the North Louisiana Salt Dome Basin and to expand continuing detailed studies of Vacherie and Rayburn's salt domes. Geological studies included: (1) completion of a series of computer-generated trend and residual maps of various stratigraphic horizons and intervals begun in fiscal year 1975; (2) calculation of growth rates for selected salt domes in northern Louisiana and the preparation of diagrammatic models of dome growth; (3) compilation of mineral resources maps for the Vacherie and Rayburn's areas; and (4) preliminary work on mapping the pre-Quaternary formations around Vacherie and Rayburn's salt domes. Geophysical studies comprised: (1) completion of processing and interpretation of seismic lines in the Vacherie area acquired from a petroleum company, and reinterpretation of one such line plus the two LSU lines shot in 1975; (2) acquisition, compilation and interpretation of gravity data for Vacherie, Rayburn's, and Prothro salt domes; and (3) initial inquiries into obtaining magnetic data for the North Louisiana Salt Dome Basin. Geochemical studies were initiated with analyses of salt-dome salt from two mines. The studies will be expanded in the next two fiscal years to include salt cores from Vacherie and Rayburn's domes, additional salt-mine samples, selected sedimentary rocks, ground waters, and surface waters, and soils from the dome areas.

For this salt dome project, the methods applied to the studies of regional geology, geophysics, and geochemistry have been, and will continue to be, those established by successful applications to similar problems. Relatively new computer techniques were utilized in constructing trend and residual maps and in processing geophysical data. Standard analytical techniques and instrumentation were used in the geochemical work. Additional information on methods and techniques of study are included in the following sections.

Over 500 structural and stratigraphic maps have been generated by the use of several computer programs utilizing elevation and thickness data from about 950 wells in Webster, Bienville, and Winn Parishes (Counties), Louisiana. The maps are produced by fitting polynomial trend surfaces to the subsurface data using least-squares criteria. First order polynomial surfaces are planes that give mathematically precise "regional dip" (for structural data) or "regional rate and direction of thickening" (for thickness data; i.e., isopachs). Second order polynomial surfaces are undulating and thus, for structural data, depict anticlines and synclines. Third and higher order surfaces are more irregularly undulating and show more complex patterns. First to third order trend surfaces (maps) were prepared. Accompanying residual maps were generated from most of these by subtracting from the trend-surface values the original data-point values (elevations or thicknesses).

Estimated growth rates of salt domes in north Louisiana have been calculated from the limited structural and stratigraphic data around the domes coupled with data from the regional trend maps. In most cases, two methods have been used, separately or in combination, namely: (1) stratigraphic thinning assumed to be related to dome growth during deposition;

and (2) structural relief caused by arching of strata as the salt domes rose. A series of hypothetical cases of salt-dome growth are presented diagrammatically, some simple and others more complex. Well control is sparse near most north Louisiana salt domes. Therefore, many assumptions and consequent uncertainties are involved in calculating the growth rates, so they should be viewed with some caution.

Seismic studies consisted of reprocessing four seismic lines over Vacherie salt dome that were donated earlier by Atlantic Richfield Co., and preliminary interpretation of these and three other lines that were processed in fiscal year 1976. The seismic data provide constraints on the general size and shape of Vacherie salt dome, but the data are not adequate for determining the detailed configuration of the salt stock. For that reason additional seismic surveys of Vacherie salt dome and an initial set of seismic lines over Rayburn's salt dome have been proposed for fiscal year 1978.

Gravity investigations of the North Louisiana Salt Dome Basin benefitted from donations of data by Cities Service Co., Atlantic Richfield Co., Texaco, Inc., and Continental Oil Co. These data were used to make composite complete Bouguer anomaly maps over Vacherie, Rayburn's, and Prothro domes. Additional detailed gravity data were obtained by an LSU survey over Vacherie dome.

Geochemical investigations of salt-dome salt and associated sedimentary rocks and fluids were initiated in fiscal year 1977. Most of the efforts were directed toward standardization and calibration of techniques for the analysis of salt, especially mineralogical analyses by scanning electron microscopy and chemical-element determinations by atomic absorption spectroscopy and colorimetry. Groups of salt samples were collected

from mines in Weeks Island and Cote Blanche domes in south Louisiana, and analyses of these samples are underway.

Maps were prepared for the Vacherie and Rayburn's salt dome areas to show the following mineral resources: oil and gas, ground water, gravel, and (potentially) lignite. Portions of seven oil and gas fields are shown; three near Vacherie and four near Rayburn's. Various water wells and sand and gravel pits are indicated.

V-B. COMPUTERIZED MAPPING

M. B. Kumar

1. Background

For a regional synthesis of subsurface data, the computerized trend and residual mapping of the North Louisiana Salt Dome Basin was started in 1975. The computer mapping is useful as an adjunct to the previous geological reconnaissance studies of the deep structure of the basin. The sources of data and the general character of the resulting map types are described in the last annual report on the LSU salt dome study (Martinez, et al., 1976).

The computerized maps comprise trend maps and residual maps of the structures and isopach intervals. The trend maps are intended to emphasize the regional trends of the structure or the thickness variations of mapped stratigraphic units, as the case may be. On the other hand, the residual maps, which are based on the departures of the observed values from the computed trend values, bring out the local anomalies in the structure and thickness variations of stratigraphic units of the basin. It is, however, noteworthy that the distinction between "local" and "regional" trends is subjective and is influenced considerably by factors such as the size of the geologic feature expected or mapped, the scale of mapping, and the distribution of control points.

2. Stages of Mapping

At the outset of the computer mapping program, the North Louisiana Salt Dome Basin was divided into three sub-areas. Data and maps for these

sub-areas were compiled by different individuals under the direction of D. H. Kupfer of the LSU Geology Department. (See Martinez, et al., 1975, 1976.) The three sub-areas of the basin encompass approximately Webster, Bienville, and Winn Parishes (Counties), respectively. For each of the sub-areas, trend and residual maps of up to third order were generated on the computer on-line printer. Each stratigraphic unit or horizon mapped is identified with a computer-formatted nomenclature; for example, WMDWX for the "the top of the Midway to the top of the Wilcox." The resulting maps are listed in Tables V-B-1 through V-B-3 for the three sub-areas. Each map title in the lists actually represents a set of five maps that comprise three trend maps and two residual maps (first and third order). A total of over four hundred maps have been computer-generated. These maps are available in the office of the Institute for Environmental Studies at LSU. They are supplementary to those constructed by Crowe (1975), Hessenbruch (1975), and Reese (1977).

During the later phase of the computer mapping, isopach data were employed for mapping the thickness variations of stratigraphic units of the total area representing the North Louisiana Salt Dome Basin. Trend and residual maps were generated for the fifteen stratigraphic units listed in Table V-B-4. For each stratigraphic unit, trend maps of first order and third order were prepared and are described in the last annual report (Martinez, et al., 1976).

It is only toward the end of fiscal year 1977 that the residual mapping of the total area was completed. The resulting residual maps for each stratigraphic unit (Table V-B-4) are of first and third order. Each such type is represented by a set of three maps, which separately depict positive residuals, negative residuals, and both residuals (composite). Thus a total of ninety residual maps have been computer-generated.

Table V-B-1. List of computer trend maps of the North Louisiana Salt Dome Basin: Webster Parish and vicinity.

[Map Nos. 1-15 refer to isopach trends and residual maps.
 Map Nos. 16-28 refer to structure trends and residual maps.]

<u>Map Series No.</u>	<u>Computer Nomenclature</u>	<u>Geologic Title</u>
1	WBSSL	Black Shale to Top Sligo
2	WSLBT	Top Sligo to Base Tuscaloosa
3	WB TAK	Base Tuscaloosa to Top Arkadelphia
4	WBSHO	Black Shale to Top Hosston
5	WTUOZ	Top Tuscaloosa to Top Ozan
6	WBSCU	Black Shale to Top Cotton Valley
7	WCUHO	Top Cotton Valley to Top Hosston
8	WHOSL	Top Hosston to Top Sligo
9	WSLPJ	Top Sligo to Top Pine Island
10	WPIJA	Top Pine Island to Top James Limestone
11	WJARD	Top James Limestone to Top Rodessa
12	WRDFL	Top Rodessa to Top Ferry Lake
13	WFLMP	Top Ferry Lake to Top Mooringsport
14	WMPBT	Top Mooringsport to Base Tuscaloosa
15	WBTTU	Base Tuscaloosa to Top Tuscaloosa
16	WTUBN	Top Tuscaloosa to Top Brownstown
17	WBNOZ	Top Brownstown to Top Ozan
18	WOZAN	Top Ozan to Top Annona
19	WANAK	Top Annona to Top Arkadelphia
20	WAKMD	Top Arkadelphia to Top Midway
*21	WMDWX	Top Midway to Top Wilcox
22	WHOKB	Structure on top of the Hosston
23	WSLKB	Structure on top of the Sligo
24	WFLKB	Structure on top of the Ferry Lake
25	WTUKB	Structure on top of the Tuscaloosa
26	WOZKB	Structure on top of the Ozan
27	WMDKB	Structure on top of the Midway
28	WWXKB	Structure on top of the Wilcox

*Data too limited for mapping.

Table V-B-2. List of computer trend maps of the North Louisiana Salt Dome Basin: Bienville Parish and vicinity.

[Maps Nos. 1-24 refer to isopach trends and residual maps.
 Maps Nos. 25-30 refer to structure trends and residual maps.]

<u>Map Series No.</u>	<u>Computer Nomenclature</u>	<u>Geologic Title</u>
1	BBSSL	Black Shale to Top Sligo
2	BSLBT	Black Shale to Base Tuscaloosa
3	BBTAK	Base Tuscaloosa to Top Arkadelphia
4	BBSHO	Black Shale to Top Hosston
5	BCUHO	Top Cotton Valley to Top Hosston
6	BTVOZ	Top Tuscaloosa to Top Ozan
7	BBSCU	Black Shale to Top Cotton Valley
8	BCULL	Top Cotton Valley to Lower Lime (Hosston)
9	BLLUL	Lower Lime to Upper Lime (Hosston)
10	BULHO	Upper Lime (Hosston) to top Hosston
11	BHOSL	Top Hosston to Top Sligo
12	BSLPI	Top Sligo to Top Pine Island
13	BPIJA	Top Pine Island to Top James Limestone
14	BJARD	Top James Limestone to Top Rodessa
15	BRDFL	Top Rodessa to Top Ferry Lake
16	BFLMP	Top Ferry Lake to Top Mooringsport
17	BMPBT	Top Mooringsport to Base Tuscaloosa
18	BBTTV	Base Tuscaloosa to Top Tuscaloosa
19	BTVBN	Top Tuscaloosa to Top Brownstown
20	BBNPZ	Top Brownstown to Top Ozan
21	BOZAN	Top Ozan to Top Annona
22	BANAK	Top Annona to Top Arkadelphia
23	BAKMD	Top Arkadelphia to Top Midway
*24	BMDWX	Top Midway to Top Wilcox
25	BHODF	Structure on top of the Hosston
26	BSLDF	Structure on top of the Sligo
27	BFLDF	Structure on top of the Ferry Lake
28	BTVDF	Structure on top of the Tuscaloosa
29	BOZDF	Structure on top of the Ozan
30	BMDDF	Structure on top of the Midway

*Data too limited for mapping.

Table V-B-3. List of computer trend maps of the North Louisiana Salt Dome Basin: Winn Parish and vicinity.

[Maps Nos. 1-18 refer to isopach trends and residuals
 Maps Nos. 19-26 refer to structure trends and residuals]

<u>Map Series No.</u>	<u>Computer Nomenclature</u>	<u>Geologic Title</u>
1	JSLBT	Top Sligo to Base Tuscaloosa
2	JBTUK	Base Tuscaloosa to Top Arkadelphia
3	JFLBT	Top Ferry Lake to Base Tuscaloosa
4	JTUOZ	Top Tuscaloosa to Top Ozan
5	JHOSL	Top Hosston to Top Sligo
6	JSLPI	Top Sligo to Top Pine Island
7	JPIJA	Top Pine Island to Top James Limestone
8	JJARD	Top James Limestone to Top Rodessa
9	JRDFL	Top Rodessa to Top Ferry Lake
10	JFLMP	Top Ferry Lake to Top Mooringsport
11	JMPBT	Top Mooringsport to Base Tuscaloosa
12	JBTU	Base Tuscaloosa to Top Tuscaloosa
13	JTUBN	Top Tuscaloosa to Top Brownstown
14	JBNOZ	Top Brownstown to Top Ozan
15	JOZAN	Top Ozan to Top Annona
16	JANUK	Top Annona to Top Arkadelphia
17	JUKMD	Top Arkadelphia to Top Midway
18	JMDWX	Top Midway to Top Wilcox
19	JHOKB	Structure on top of the Hosston
20	JSLKB	Structure on top of the Sligo
21	JRDKB	Structure on top of the Rodessa
22	JFLKB	Structure on top of the Ferry Lake
23	JTUKB	Structure on top of the Tuscaloosa
24	JOZKB	Structure on top of the Ozan
25	JMDKB	Structure on top of the Midway
26	JWXXB	Structure on top of the Wilcox

Table V-B-4. List of Computer maps of the North Louisiana Salt Dome Basin: isopach trend and residuals maps.

Map Series No.	Geologic Title
1	Midway
2	Top of Arkadelphia to Top Annona
3	Annona
4	Ozan
5	Top Brownstown to Top Tuscaloosa
6	Tuscaloosa
7	Base Tuscaloosa to Top Mooringsport
8	Mooringsport
9	Ferry Lake
10	Top Rodessa to Top James Limestone
11	James Limestone
12	Pine Island Shale
13	Sligo
14	Gulfian Series
15	Comanchean Series

3. Interpretation of Computer Maps

Since the computer-generated maps have a different appearance from conventional (geologic) contour maps, and are based on certain mathematical models, they have to be interpreted in terms of geologic features. Such geologic interpretations of computer maps entail a careful consideration of various factors related to the mechanics of the computerized mapping process and the known and unknown geologic possibilities. Thus, this phase of computer mapping is a time consuming task. An analysis of the computer-generated residual maps has been started. At this time (September 1977) the appraisal of maps is incomplete and inconclusive.

V-C. GROWTH RATES OF SALT DOMES OF THE
NORTH LOUISIANA SALT BASIN

M. B. Kumar

1. Introduction

The growth of a salt dome implies a vertical elongation of the body of salt, although this really involves three-dimensional changes in the original approximately horizontal, tabular shape of the salt mass. During the growth of a salt dome, the salt movement is initially mostly horizontal and subsequently mostly vertical (Figure V-C-1). In the context of the nuclear waste storage problem, it is the vertical movement that is critical. Therefore, the growth rate of a salt dome is considered in this report to imply the rate of uplift of the top of the salt. In order to determine the growth rate, it is necessary to measure or estimate the magnitude and the duration of the uplift. The units commonly used for expressing the growth rates are feet/million years (ft/my) and millimeters/year (mm/yr).

2. Approach

The various growth phases of a salt dome are reflected in the structure and stratigraphy of sedimentary layers over the dome and in the geometry of the rim synclines adjacent to the salt dome--both of which have changed through geologic time. In addition, the character of the caprock of the dome can provide useful evidence as to its growth history. (See Section IV-E in this report.) The choice of approach to the quantification of salt-dome growth depends on the nature of the available basic data. Several possible approaches are briefly reviewed below.

SURFACE

FIG. V-C-1. THREE STAGES IN THE EVOLUTION OF A SIMPLE SALT STOCK OF LOUISIANA

a. Volume or rim syncline. As Kupfer (1977a) correctly observed, volume calculations give the best control on rate of salt movement with time, because they include both vertical and horizontal movements. The data required for this approach can be obtained mainly from isopach maps of various stratigraphic units on which the geometry of rim synclines and salt withdrawal basins can be quantitatively worked out. Computations can be performed along the line originally suggested by Nettleton (1934). This procedure involves measurements on radii of rim synclines, the salt stock, and the thickness of the original salt bed. Kupfer (1977a) attempted a similar approach (a variation of the method employed by Sannemann, 1968, and Trusheim, 1960) using the sparse data available for the Vacherie salt dome; but because of the lack of sufficient data, the final results are inconclusive. This approach was not applied to other domes for which the available data are even less adequate than for the Vacherie dome.

b. Caprock thickness. Martinez (1974) suggested the possibility that thickness of caprock is related to rate of growth. In this regard, Muehlberger (1976) indicated that the relationship between the thickness of caprock and the amount (thickness) of salt dissolved from a salt stock could be useful for the estimation of the growth rate of a salt dome. This is based on the premise that if the anhydrite-to-salt ratio in the salt dome is the same as that of sea water, then each foot of caprock (anhydrite) represents approximately 30 ft of dissolved salt. Muehlberger found that this hypothesis holds for the northeast Texas domes. The quantification of growth rates by this approach requires data on thickness of caprock and its chemistry. Since no sufficiently precise data on these aspects of the domes are available, this approach was not attempted.

c. Domal thinning. As Murray (1961) observed, stratigraphic thinning is commonly associated with arching of strata close to and over a salt structure. In some cases, thinning may amount to more than half the thickness of an individual sequence some distance away from the dome. For an appraisal of the thickness variations in the sediments deposited over an active salt dome, the idealized situation of Figure V-C-2 is considered. Here, through the cycle of sedimentation, the horizontal surface of deposition is maintained while the salt is rising from the original horizontal bed. The thickness of sediments accumulated is minimal at the crest of the dome and gradually increases down the flanks to a maximum (normal) thickness away from the dome. Considering the geometry of the sedimentary layers and the salt pillow, the salt uplift (H) can be calculated using:

$$H = T_n - T_c$$

where T_n is the normal (maximum) thickness, and T_c is the sediment thickness (minimum) at the crest. Thus, the stratigraphic thinning over the dome is basically a measure of the salt uplift during the deposition of the stratigraphic unit considered. It is this approach that has been adopted here in conjunction with the structural relief approach discussed below.

d. Structural relief. Another approach is to assume that as a salt dome grows it arches up or uplifts the overlying strata without thinning. In the idealized case represented in Figure V-C-3, the stratigraphic unit overlying the salt mass is uniform in thickness, signifying that there was no growth of the dome during its deposition. The stratigraphic

FIG. V-C-2. ILLUSTRATION OF THE DOMAL THINNING APPROACH FOR ESTIMATING THE DOME GROWTH

FIG. V-C-3. ILLUSTRATION OF THE STRUCTURAL RELIEF APPROACH FOR ESTIMATING THE DOME GROWTH

(lithologic) unit was arched up as a result of the post-depositional salt uplift. From the configuration of the salt pillow and the deformed overlying lithologic unit, the structural relief (R) on the top of the beds can be equated to the total vertical rise (H) of the salt. Thus, the structural relief is a measure of post-depositional salt uplift.

During dome growth, each deformation is added to all earlier deformations. As in the case of Vacherie dome (Crowe, 1975), structural dips at the margins of the salt stock increase with increasing depth or age. This may not always be true, however, particularly if the salt stock diminishes in cross section during the later phases of diapirism as illustrated in Figure V-C-4 (after Nettleton, 1934). The structure of the sedimentary layers adjacent to a salt stock is also considerably modified during the course of development of rim synclines.

In view of the preceding considerations, the structural relief of the sedimentary layers associated with a salt dome may not be a reliable indicator of salt dome growth. However, the structural relief of the shallowest stratigraphic marker bed can be employed for estimating the amount of dome growth since the deposition of the marker bed.

3. Problems in Estimation of Growth Rates

After defining the approach in the previous section, it is appropriate to bring into focus the various assumptions and consequent uncertainties that are built into the computation of growth rates of salt domes. In order to do this, several simple and complex cases are presented below.

Case 1. Figure V-C-5 illustrates a stratigraphic unit arched up over a salt dome, the stratum being thinner over the top of the dome.

Note: The diagrams indicate a possibility of thinning of a salt stock during the final phase of diapirism. Beyond stage 3, when the supply of salt is cut off by the peripheral sink, the cross-section of the salt decreases inducing a collapse of the sediments around the dome.

(AFTER NETTLETON, 1934)

FIG. V-C-4. EVOLUTIONARY STAGES OF A DOME
AS PER THE FLUID MECHANICAL HYPOTHESIS

SALT UPLIFT DURING THE DEPOSITION OF
THE STRATIGRAPHIC UNIT = Δt_g

THINNING OF STRATA:

Δt_g DUE TO DOME GROWTH DURING SEDIMENTATION

Δt_c DUE TO DIFFERENTIAL COMPACTION

Δt_s DUE TO TENSIONAL STRETCHING

THE STRATIGRAPHIC THINNING, ΔT

$$= T_n - T_c$$

$$= \Delta t_g + \Delta t_c + \Delta t_s$$

$$= \Delta t_g, \text{ ASSUMING } \Delta t_c = 0 \text{ AND } \Delta t_s = 0$$

(BY NEGLECTING Δt_c AND Δt_s THE ESTIMATE
OF Δt_g IS MAXIMIZED.)

THE TOTAL UPLIFT AS MANIFESTED IN THE
ARCHED-UP STRATIGRAPHIC UNIT

= STRATIGRAPHIC THINNING + STRUCTURAL
RELIEF ON THE TOP OF THE STRATUM

$$= \Delta T + \Delta H$$

FIG. V-C-5. SALT GROWTH EXPRESSED IN STRATIGRAPHIC
THINNING AND STRUCTURAL RELIEF

The observed stratigraphic thinning is due to salt uplift during sedimentation, subsequent differential compaction of the sediments, and the stretching of the bed over the rising salt. Since possible thinning due to the last two factors is considered negligible, the amount of observed thinning is a maximal estimate of the uplift during the deposition of the stratigraphic unit. The total uplift as manifested in the arched-up thinned stratigraphic unit can be represented by the sum of its stratigraphic thinning and the structural relief on the top of the sedimentary unit.

Case 2. Figure V-C-6 presents a simple case of a stratigraphic unit pierced by a salt stock. By neglecting the effects of differential compaction and tensional stretching of the up-turned beds, the stratigraphic thinning on the dome flank next to the dome represents a maximal estimate of the salt uplift during the deposition of the beds. The total uplift (S) of the salt dome can be estimated by:

$$S = \Delta t + T_f + \Delta H + \Delta R$$

where: Δt = the stratigraphic thinning on the dome flank
 T_f = the thickness of the stratum penetrated at the flank
 ΔH = the structural relief on the top of the stratum
 ΔR = the relief on the top of the salt plug beyond the highest level of rupture of the stratum

Case 3. From Figure V-C-7 it is evident that a piercement salt dome could be the result of: (1) slow salt uplift during the sedimentation of several stratigraphic units and salt intrusion at the end of their deposition; or (2) salt intrusion at the end of deposition of the several stratigraphic units; or (3) a combination of the two situations. Without adequate data on the age of a salt uplift and the mode of salt intrusion, the amount of dome growth for a particular time interval cannot be determined.

SALT UPLIFT DURING THE DEPOSITION OF
 THE STRATIGRAPHIC UNIT = Δt_g
 THE STRATIGRAPHIC THINNING, Δt
 $= T_n - T_f$
 $= \Delta t_g + \Delta t_s + \Delta t_c$ (FROM FIG. V-C-5)
 $= \Delta t_g$, ASSUMING $\Delta t_s = 0$ AND $\Delta t_c = 0$
 (BY NEGLECTING THESE TWO TERMS,
 THE ESTIMATE OF Δt_g IS MAXIMIZED)

THE TOTAL UPLIFT (GROWTH) OF THE
 SALT DOME
 $=$ STRATIGRAPHIC THINNING + THICKNESS
 OF BEDS PENETRATED + STRUCTURAL
 RELIEF ON TOP OF THE STRAT. UNIT
 + RELIEF OF SALT TOP BEYOND THE
 LEVEL OF RUPTURE OF THE SEDIMEN-
 TARY UNIT
 $= \Delta t + T_f + \Delta H + \Delta R$

FIG. V-C-6. SALT GROWTH EXPRESSED IN TERMS OF STRATIGRAPHIC THINNING, MAGNITUDE OF PIERCEMENT AND STRUCTURAL RELIEF

FIG. V-C-7. SOME ALTERNATIVE INTERPRETATIONS OF THE GEOLOGIC HISTORY OF A PIERCEMENT DOME

FIG. V-C-8. AN EXAMPLE OF PIERCEMENT DOME WITH PERTINENT DATA FOR THE COMPUTATION OF GROWTH RATES

Case 4. With the aid of Figure V-C-8, it is demonstrated numerically that the mode and age of salt intrusion influence the computation of growth rates.

For simplicity of computation, the following assumptions are made:

- 1) At the end of deposition of each stratigraphic unit, there is no relief of the salt plug above the surface of deposition, (i.e., $\Delta R = 0$).
- 2) The relief of the top surface of each stratigraphic unit due to salt intrusion is 100 ft, (i.e., $\Delta H = 100$).
- 3) The growth of the salt dome during the deposition of unit D is negligible, (i.e., $S_D = 0$).

Two examples with different modes and ages of salt intrusions are considered below, although numerous variations or combinations of the cases are possible. In both situations the total growth of the salt dome is the same, since the end result of the different geologic events is the same as that shown in Figure V-C-8. (The notations used in Example 1 and Example 2 are the same as those used for Case 2 above).

Example 1. Salt is judged to have intruded each stratigraphic unit just between the end of its deposition and the start of deposition of the next overlying unit. Also, the salt dome grew during the deposition of each of units A, B, and C.

$$\begin{aligned}\text{For Unit A: salt dome growth, } S_A &= \Delta t_A + T_{fA} + \Delta H_A + \Delta R_A \\ &= (400 - 200) + 200 + 100 + 0 \\ &= 500 \text{ ft;} \end{aligned}$$

$$\text{duration of deposition, } \Delta T_A = 130 - 100 = 30 \text{ my}$$

$$\begin{aligned}\text{Therefore, growth rate, } \frac{S_A}{\Delta T_A} &= \frac{500}{30} = \underline{16.65 \text{ ft/my}} \\ &= \underline{0.005 \text{ mm/yr}} \end{aligned}$$

For Unit B: $S_B = (600 - 300) + 300 + 100 + 0 = 700 \text{ ft}$

$$\Delta T_B = 100 - 65 = 35 \text{ my}$$

$$\frac{S_B}{\Delta T_B} = \frac{700}{35} = \underline{20.00 \text{ ft/my}} = \underline{0.006 \text{ mm/yr}}$$

For Unit C: $S_C = (500 - 300) + 300 + 100 + 0 = 600 \text{ ft}$

$$\Delta T_C = 65 - 40 = 25 \text{ my}$$

$$\frac{S_C}{\Delta T_C} = \frac{600}{25} = \underline{24.00 \text{ ft/my}} = \underline{0.007 \text{ mm/yr}}$$

For Unit D: From the assumption, $S_D = 0$

Total growth (uplift) of the salt dome:

$$\begin{aligned} \Sigma S &= S_A + S_B + S_C + S_D \\ &= 500 + 700 + 600 + 0 \\ &= 1800 \text{ ft} \end{aligned}$$

Overall growth rate:

$$\begin{aligned} &= \frac{\Sigma S}{\Delta T_A + \Delta T_B + \Delta T_C} = \frac{1800 \text{ ft}}{(30 + 35 + 25) \text{ my}} \\ &= \underline{20.00 \text{ ft/my}} = \underline{0.006 \text{ mm/yr}} \end{aligned}$$

Example 2. Salt is judged to have intruded the sedimentary layers only once just between the end of deposition of units A, B and C, and the start of deposition of unit D. The salt dome also grew during the deposition of units A, B and C.

$$S_A = \Delta t_A = 400 - 200 = 200 \text{ ft}$$

$$\frac{S_A}{\Delta T_A} = \frac{200}{30} = \underline{6.67 \text{ ft/my}} = \underline{0.002 \text{ mm/yr}}$$

$$S_B = \Delta t_B = 600 - 300 = 300 \text{ ft}$$

$$\frac{S_B}{T_B} = \frac{300}{35} = \underline{8.57 \text{ ft/my}} = \underline{0.003 \text{ mm/yr}}$$

$$S_C = \Delta t_C + \Sigma t_f + \Sigma \Delta H + \Delta R$$

$$= (500 - 300) + (200 + 300 + 300) + (100 + 100 + 100) + 0$$

$$= 1300 \text{ ft}$$

$$\frac{S_C}{T_C} = \frac{1300}{25} = \underline{52 \text{ ft/my}} = \underline{0.016 \text{ mm/yr}}$$

$$S_D = 0 \text{ (from the assumption)}$$

Total growth of the salt dome:

$$\Sigma S = S_A + S_B + S_C + S_D$$

$$= 200 + 300 + 1300 + 0$$

$$= 1800 \text{ ft}$$

Overall growth rate:

$$= \frac{1800 \text{ ft}}{(30 + 35 + 25)_{\text{my}}} = \underline{20.00 \text{ ft/my}} = \underline{0.006 \text{ mm/yr}}$$

A comparison of the growth rates for the stratigraphic intervals of the above two examples reveals that for units A and B the growth rates of Example 1 are much greater than those of Example 2, whereas for unit C the growth rate of Example 1 is much less than that of Example 2. Similarly, more cases representing variations of these two situations can be examined which lead to the conclusion that the age and mode of salt intrusion may make a significant difference in the estimate of growth rate for individual stratigraphic intervals.

Case 5. In Figure V-C-9, two different examples of identical stratigraphic units have been presented. Referring to Example 1 in the figure, the horizontal and uniformly thick units, D, E and F overlying the deformed beds, A, B and C indicate that the salt dome growth has terminated prior to the deposition of unit D. Example 2 reflects two stages of salt growth, the later stage having affected all the units. In both the examples, assuming the same stratigraphic thinning of 800 ft for units A, B and C combined, the overall growth rate is $800/(58-50) = 100 \text{ ft/my} = 0.031 \text{ mm/yr}$. In Example 1 the growth rate during the time intervals of D, E, F, and post-F is zero. In example 2 the top surface of the youngest unit F has a relief, say, of 400 feet, while there is not variation in the thickness of units, D, E, and F. The growth rate during the time intervals of D, E, and F is zero as in Example 1, but the growth rate for the post-F interval is indeterminate without the information on the age of the uplift causing the 400-foot relief on unit F. At this stage of computation, different figures are obtained using various assumptions. For example, if the uplift has been continuing at a uniform rate since the end of deposition of unit F, the growth rate $= 400/20 = 20 \text{ ft/my} (= 0.006 \text{ mm/yr})$. The growth rate estimate changes to $40 \text{ ft/my} (= 0.012 \text{ mm/yr})$ if duration of the uplift is assumed to be 10 my. Similarly, for a shorter duration of uplift, such as 1 my, the growth rate works out to be $400 \text{ ft/my} (= 0.12 \text{ mm/yr})$. This is illustrative of the problem in estimating growth rates for the Tertiary in particular.

Case 6. Figure V-C-10 emphasizes the point that the age of post-Tertiary uplift cannot be determined, unequivocally, solely on the basis of thickness data since the thinning over the dome may or may not be the result of salt uplift. Even without any salt dome uplift during the post-Tertiary

EXAMPLE I

EXAMPLE II

FIG. V-C-9. TWO DIFFERENT SITUATIONS OF IDENTICAL STRATIGRAPHIC UNITS

FIG. V-C-10. A DIAGRAM ILLUSTRATIVE OF THE PROBLEM OF DATING AND ESTIMATING THE POST-TERTIARY UPLIFT ON THE BASIS OF THICKNESS DATA ONLY

time, a thinner strata of sediment is likely to have formed over the dome in the process of in-filling of a sedimentary basin.

Case 7. In Figure V-C-11 it is indicated that the estimate of growth rate based on inadequate well control data may not be realistic. From the illustration it is evident that without the data from Well 6 the estimated growth rate will be significantly lower than the actual. This is because the configuration of the top surface of a salt stock may be highly irregular, and this might have appreciably affected the thickness of the overlying sediments during their deposition.

Case 8. The effects of dissolution of salt from the upper part of a salt stock in a circulating fresh water zone could be considerable. The resulting subsidence of strata over the dome diminishes original structural relief caused by salt uplift. Because of lack of pertinent data, the estimated values of the growth rates will probably be lower than the actual.

The salt domes of the North Louisiana Salt Basin represent various combinations of the situations just discussed. Therefore, the results of the computations of growth rates of these domes should be used with caution. The validity of the resulting estimated figures on growth should be judged in light of the purpose for which they are intended to be used.

4. Bases of Computations

The computations of growth rates of the salt domes of the North Louisiana Salt Basin are based on the domal thinning of strata and structural relief on the youngest known stratigraphic marker (e.g. a Tertiary formation top).

FIG. V-C-II. A DIAGRAM ILLUSTRATIVE OF AN UNREALISTIC ESTIMATE OF GROWTH RATE WITHOUT A CRITICAL WELL CONTROL

The important assumptions inherent in the calculations are as follows:

- 1) The surface of deposition of each stratigraphic unit considered has been horizontal throughout the period of its deposition.
- 2) The effects of differential compaction of sediments and tensional stretching of the up-turned sedimentary layers associated with a salt stock are not significant.
- 3) The thinning of a stratigraphic unit due to an unconformity and thickening of beds due to growth faulting (indeterminable for lack of data) are negligible.
- 4) The structural relief on the shallowest known stratigraphic marker bed is due to salt uplift continued at a uniform rate ever since the marker bed was deposited.
- 5) The effects of dissolution collapse of the strata close to the top of the salt stock are considered to be negligible.

The basic data employed for the present study were taken from the M. S. theses of C. T. Crowe (1975), J. M. Hessenbruch (1975), and R. J. Reese (1977). The isopach maps, structure contour maps, geologic cross sections, and tables from these papers were used. For regional or normal trends of stratigraphic thickness and structures, the computer (trend) maps of M. B. Kumar were consulted. Some electric-log well sections of C. G. Smith (Martinez, et al., 1975), were used. In addition, the following documents were referred to: Martin, et al., 1954 for Minden dome; G. T. Worley's thesis (1962) for Arcadia dome; W. T. Cook's thesis (1969) for Minden dome. The numerical ages of the stratigraphic units used in the calculations are based on Kupfer's work (Figure IV-C-13, Martinez, et al., 1976). The basic data and computations for growth

rates of the north Louisiana salt domes are summarized in Table V-C-4, which is included at the end of this Section.

5. Results and Conclusions

The stratigraphic information available for the present study is, by and large, fragmentary. The control wells are sporadically distributed and not deep enough to provide adequate vertical and lateral controls. The deep-well data pertaining to the Cretaceous (mostly the Upper Cretaceous) which are available, are for Vacherie, Winnfield, Drake's, Milams, Chester, Packton, Sikes, King's and Rayburn's domes. As regards the Tertiary, the shallowest horizons on which stratigraphic information exists are indicated below.

Shallowest Tertiary Unit

Cook Mountain Formation

Sparta Formation

Cane River Formation

Wilcox Group

Midway Group

Salt Domes

Packton, Caster Creek,
Winnfield, Coochie Brake

Cedar Creek, Minden

Arcadia, Vacherie, Price's

Drake's, Milams, Chester,
Sikes, Chestnut

Prothro, Bistineau, Rayburn's

Of the nineteen salt domes of the North Louisiana Salt Basin, eighteen were considered for the present study. The dome excluded is Gibsland for which no quantitative stratigraphic data are available. The growth rates of the eighteen domes are presented in Table V-C-1. The ranges of growth rates are summarized in Table V-C-2.

Table V-C-1. Growth rates of salt domes of the North Louisiana Basin (in mm/yr).

Geologic Period	(m.y.)	Stratigraphic Unit	Name of Dome:	Vacherie	Rayburn's	Prothro	King's	Winnfield	Drakes	Milams	Chester	Packton	Sikes	Minden	Chestnut	Coochie Brake	Cedar Creek	Price's	Castor Creek	Arcadia	Bistineau
QUATERNARY	-2																				
	-42		---	***			---	---				0.001				0.003			---		---
		Cockfield	---				---	---				0.001		0.004		0.001	0.001		---		---
	-44.5	Cook Mt.	---	0.006	0.002		---	0.008?	0.002	0.002	0.001	---	0.004		0.001	Neg.		0.001	Neg.	0.006	---
	-48	Sparta	---				---	0.019				0.006		0.011		0.006	Neg.		Neg.		---
	-50	Cane River	Neg.**				---	0.023						Neg.		0.011	0.015	0.008	Neg.	Neg.	---
	-58	Wilcox	---				---	0.020	---	0.016	0.008	0.003	0.015	0.023	0.014	0.027	---	---	---	---	---
	-65	Midway	0.027	0.030?	0.002	---	0.016	0.015	0.003	0.004	0.003	0.015	0.026				---	---	---	---	0.004
		(Overall rate for Cenozoic)	(0.007)	(0.009?)	(0.002)	(0.006)	(0.009)	(---	(0.003)	(0.002)	(0.002)	(0.007)	(0.009)	(0.004)	(0.009)	(---	(---	(---	(---	(---	(---
UPPER CRETACEOUS	-65	Arkadelphia	Neg.		---	---															
	-66	Nacatoch	Neg.		---																
	-70	Saratoga	Neg.	Neg.	---	0.006	0.003	0.002			0.002	0.001									
	-71	Marlbrook	Neg.		---																
	-73	Annona	Neg.	Neg.	---	---															
	-76	Ozan	Neg.	Neg.	---	---															
	-79	Brownstown	0.006		---	---	0.019	0.011	0.014	0.002											
	-81	Tokio + Eagle Ford	0.004	Neg.	---	---															
	-92	Tuscaloosa	0.002	0.006	---	---	0.009	0.006	0.001	0.013?	---	0.006									
	-99	(Overall rate for U. Cret.)	(0.002)	(---	(---	(---	(0.013)	(0.007)	(0.008)	(---	(---	(---									
LOWER CRETACEOUS	-99	(Erosion)																			
	-100	Washita-Frdbg.	---	---	---	---	---	Neg.	0.019	---	---	---									
	-104	Paluxy	---	---	---	---	---	---	---	---	---	---									
	-105	Rusk	0.350?	---	---	---	---	0.030	0.061	---	---	---									
	-106	Ferry Lake	0.043	---	---	---	---	---	---	---	---	---									
	-107	Rodessa + James	0.067	---	---	---	---	---	---	---	---	---									
	-111	Pine Island	0.050	---	---	---	---	---	---	---	---	---									
	-113	Sligo	0.011	---	---	---	---	---	---	---	---	---									
	-120	Hosston	---	---	---	---	---	---	---	---	---	---									
	-132	(Erosion)																			
	-135	(Overall rate for L. Cret.)	(0.042)	(---	(0.009)	(0.013)	(---	(---	(---	(---	(---	(---									

*No data

**Negligible

***Arrow indicates average value for time span shown

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Table V-C-2. Range of growth rates (mm/yr) of salt domes of the North Louisiana Basin

Stratigraphic Interval	Range of Average Growth Rates mm/yr	
	(Minimum)	(Maximum)
Cenozoic	0.001 (Chester)	- 0.027 (Vacherie)
Upper Cretaceous	0.001 (Sikes)	- 0.019 (Winnfield)
Lower Cretaceous	0.009 (Prothro)	- 0.042 (Vacherie)

With reference to the Cenozoic growth rates, it is emphasized that the estimated figures represent minimal growth rates, because the structural relief on the shallowest Tertiary horizon used for estimating the growth rates is assumed to be due to the salt uplift occurring at a uniform rate throughout the time since the formation of that horizon.

From the results of this study, it is apparent that: (1) the growth rates of these salt domes are variable throughout geologic time; and (2) for the same stratigraphic interval there is a wide range of variation from dome to dome. Similar conclusions can be drawn from the results of study on the growth rates of salt domes on the northeast Texas salt dome basin by Netherland, Sewell and Associates, Inc. (1976) who adopted a similar approach for estimating the growth rates. Their results are summarized in Table V-C-3 for a comparison with the north Louisiana salt domes.

Table V-C-3. Range of growth rates (mm/yr) of northeast Texas domes.

Stratigraphic Interval	Range of Average Growth Rate
	mm/yr
Tertiary	0.003 - 0.043
Upper Cretaceous	0.014 - 0.029
Lower Cretaceous	0.026 - 0.054

The wide variation in the estimates of growth rates of the Louisiana domes is attributed to some or all of the following important factors:

- 1) Non-uniformity of the thickness of the mother salt bed.
- 2) Variation in the density differential between the salt and the surrounding sediments.
- 3) Variation in the critical thickness of overburden due to its variable strength and thickness with time and locale.
- 4) Variable validity of the assumptions underlying the computation of the growth rate.

From the estimated figures on the growth rates of the domes, no consistent pattern of variation in space and time could be derived. This may be partly due to the fact that the study is based on sporadic well control and fragmentary stratigraphic information. The present study is indeed considered to be preliminary at this time and should be continued in the light of new data as they become available, particularly in the near future from the Quaternary boreholes. Tertiary core-holes and deep seismic work in the areas of interest, as proposed for the

next fiscal year, constitute additional important sources of new data. A reasonably complete investigation of the Cenozoic growth rates, which are of immediate concern to the storage problem, will have to await the conclusion of the Quaternary studies and the Tertiary drilling and seismic survey in the area.

Table V-C-4. Growth rates of salt domes of the North Louisiana Basin: basic data and computations.

The well numbers referred to in the following sections correspond to the identification numbers of the control wells which appear on the maps of C. T. Crowe (1975), J. M. Hessenbruch (1975), and R. J. Reese (1977). The computer maps of M. B. Kumar are discussed and listed in Section V-B of this report.

VACHERIE DOME

Sources of Data

Basic data are from electric logs of L.S.U. wells, Tables 7 and 8 of Crowe (1975) and Kumar's computer maps. Among the control wells used, eight are located over the dome; 14 wells are near or on the flank. For some of the wells there are only drillers logs with no stratigraphic information.

Growth Rates

Cenozoic

Cane River (2 my):

No significant thinning observed. Hence, growth rate is negligible.

Wilcox (8 my):

No reliable information is available.

Midway (7 my):

Minimum thickness (Well 1) = 70 ft
 Normal thickness = 700 ft
 Stratigraphic thickness = 630 ft
 Growth rate = 90.0 ft/my = 0.027 mm/yr

Post-Midway (58 my):

Structural relief on top of the Midway = 820 ft (Wells 2 and 3)
 Growth rate = 14.2 ft/my = 0.004 mm/yr

Overall Cenozoic Growth rate = $(620 + 820)/65$
 = 22.3 ft/my = 0.007 mm/yr

Upper Cretaceous

Arkadelphia (1 my)
 Nacatoch (4 my)
 Saratoga (1 my)
 Marlbrook (2 my)
 Annona (3 my)
 Ozan (3 my)

No significant stratigraphic thinning observed. Hence, growth rate is negligible.

Table V-C-4, continued.

Brownstown (2 my):

Minimum thickness (Well 7) = 216 ft
 Normal thickness = 256 ft
 Stratigraphic thinning = 40 ft
 Growth rate = 20.0 ft/my = 0.006 mm/yr

Tokio & Eagle Ford (11 my):

Minimum thickness (Well 21) = 630 ft
 Normal thickness = 760 ft
 Stratigraphic thinning = 130 ft
 Growth rate (locally close to the flank) = 11.8 ft/my = 0.004 mm/yr

Tuscaloosa (7 my):

Minimum thickness (Well 17) = 160 ft
 Normal thickness = 200 ft
 Stratigraphic thinning = 40 ft
 Growth rate = 5.7 ft/my = 0.002 mm/yr

Overall growth rate for the Upper Cretaceous = 6.3 ft/my = 0.002 mm/yr

Lower Cretaceous

Rusk (Mooringsport, ?0.5 my):

Minimum thickness (Well 7) = 209 ft x 0.97 (15° dip) = 203 ft
 Normal thickness = 778 ft
 Stratigraphic thinning = 575 ft
 Growth rate = 1150 ft/my (?) = 0.350 mm/yr (?)

Ferry Lake (1 my):

Minimum thickness (Well 17) = 152 x 0.94 (20° dip) = 143 ft
 Normal thickness = 285 ft
 Stratigraphic thinning = 142 ft
 Growth rate = 142 ft/my = 0.043 mm/yr

Rodessa and James (4 my):

Minimum thickness (Well 17) = 317 x 0.91 (25° dip) = 288 ft
 Normal thickness = 1162 ft
 Stratigraphic thinning = 874 ft
 Growth rate = 218.5 ft/my = 218.5 ft/my = 0.067 mm/yr

Pine Island (2 my):

Minimum thickness (Well 27) = 69 ft x 0.87 (30° dip) = 60 ft
 Normal thickness = 224 ft
 Stratigraphic thinning = 164 ft
 Growth rate = 82.0 ft/my = 0.050 mm/yr

Sligo (7 my):

Minimum thickness (Well 27) = 235 x 0.82 (35° dip) = 193 ft
 Normal thickness = 448 ft
 Stratigraphic thinning = 255 ft
 Growth rate = 36.4 ft/my = 0.011 mm/yr

Table V-C-4, continued.

Overall growth rate for the Lower Cretaceous = $2010/14.5 = 138.6 \text{ ft/my}$
 = 0.042 mm/yr

RAYBURN'S DOME

Sources of data

Basic data are from Reese (1977), Kumar's computer maps and Smith's Figure IV-B-3 (Martinez, et al., 1975). Among the well controls used, six are located over and around the dome. Two wells (157 and 228 on Reese's maps) have penetrated salt. There is no stratigraphic data on Wells 156, 157 and 228. None of the other wells have penetrated below the Rusk formation (Lower Cretaceous Comanchean Series). Wells 153, 154, 155, and 156 used for computations are located on or close to the flank of the dome.

Growth RatesCenozoic

Post-Midway (58 my):

Structural relief on top of the Midway = 1200 ft (Smith's Figure)
 Growth rate = 20.7 ft/my = 0.006 mm/yr

Midway (7 my):

Stratigraphic thinning (Smith's Figure) = ?700 ft
 Growth rate = ?100 ft/my = $?0.030 \text{ mm/yr}$

Overall Cenozoic growth rate = $?0.009 \text{ mm/yr}$

Upper Cretaceous

Arkadelphia

+Nacatoch

(8 my)

+Saratoga

+Marlbrook

Annona

(3 my)

Ozan

(3 my)

Brownstown

+Tokio

(13 my)

+Eagle Ford

No significant stratigraphic thinning observed. Hence, growth rate for these stratigraphic intervals is negligible.

Tuscaloosa (7 my):

Minimum thickness (Wells 153 & 154) = 170 ft
 Normal thickness = 300 ft
 Stratigraphic thinning = 130 ft
 Growth rate = 18.6 ft/my = 0.006 mm/yr

Table V-C-4, continued.

Lower Cretaceous

No reliable information is available.

PROTHRO DOME

Sources of Data

Basic data are from Reese (1977) and Kumar's computer maps. Among the control wells available, one has penetrated salt but no stratigraphic information exists; only one other well (159 on Reese's map) is located on the southern flank of the dome. This well has penetrated into the upper Trinity (Lower Cretaceous).

Growth RatesCenozoic

Post-Midway (58 my):

Structural relief on top of the Midway = $1120 - 680$ (Well 159) = 440 ft
 Growth rate = 7.6 ft/my = 0.002 mm/yr

Midway (7 my):

Minimum thickness (Well 159) = 670 ft
 Normal thickness = 720 ft
 Stratigraphic thinning = 50 ft
 Growth rate = 7.1 ft/my = 0.002 mm/yr

Overall Cenozoic growth rate = 7.5 ft/my = 0.002 mm/yr

Upper Cretaceous

The hand-drawn maps (Reese, 1977) and computer trend maps (Kumar) suggest no thinning in the Well 159 area, although a pronounced thickening around the dome is indicated.

Lower Cretaceous

No well control is available. However, on Figure 19 of Reese's thesis, a thinning of the order of 1000 ft is indicated on the southern flank of the dome. Thus, for the Lower Cretaceous (35 my) the overall (speculative) growth rate = 28.6 ft/my = 0.009 mm/yr.

KING'S DOME

Sources of Data

Basic data are from Reese (1977). Among the control wells, four (136, 138, 139 and 140 on Reese's maps) are drilled into salt with no strati-

Table V-C-4, continued.

graphic information available. Another three wells (59, 141 and 200) located within three miles of the dome are used here as additional controls for computations.

Growth Rates

Cenozoic

Structural relief on top of the Arkadelphia (Figure 30 of Reese, 1977) = 1300 ft (approximately). Overall growth rate since the end of the Arkadelphia time = $20.0 \text{ ft/my} = \underline{0.006 \text{ mm/yr}}$.

Upper Cretaceous

Nacatoch & Saratoga (5 my)

Minimum thickness (Well 139) =	100 ft
Normal thickness =	200 ft
Stratigraphic thinning =	100 ft
Growth rate = 200 ft/my =	$\underline{0.006 \text{ mm/yr}}$

For the rest of the Upper Cretaceous no pertinent well controls exist.

Lower Cretaceous

No well control is available. However, Reese's Figure 19 suggests a thinning of about 1500 ft over the flank of the dome. Hence, the overall (speculative) growth rate = $42.9 \text{ ft/my} = \underline{0.013 \text{ mm/yr}}$

WINNFIELD DOME

Sources of Data

Basic data are from Hessenbruch (1975), Kumar's computer maps and Smith's Figure IV-B-7 (Martinez, et al., 1975). Thirty-seven control wells are drilled on or adjacent to the dome. Most of these are extremely shallow and bottomed in either caprock or salt. Six flank wells (102, 104, 105, 106, 107 and 108 on Hessenbruch's maps) have penetrated most of the Lower Tertiary and all of the Upper Cretaceous section; one of these (Well 102) has encountered the entire Lower Cretaceous Comanche section.

Growth Rates

Cenozoic

Cook Mountain (2 my):

Stratigraphic thinning (Smith's Figure) =	$125 - ?75 = ?50 \text{ ft}$
Growth rate = $?25 \text{ ft/my}$ =	$\underline{?0.008 \text{ mm/yr}}$

Table V-C-4, continued.

Sparta (3.5 my):

Stratigraphic thinning (Smith's Figure) = $500 - 275 = 225$ ft
 Growth rate = 64.3 ft/my = 0.019 mm/yr

Cane River (2 my):

Stratigraphic thinning (Smith's Figure) = $275 - 125 = 150$ ft
 Growth rate = 75 ft/my = 0.023 mm/yr

Post-Wilcox (50 my):

Structural relief on top of the Wilcox (Hessenbruch's Table 3, Figures 11 & 17 and Kumar's computer maps) = 1000 ft

Growth rate = 20.0 ft/my = 0.006 mm/yr

Wilcox & Midway (15 my):

Minimum thickness (Well 107) = 1638 ft
 Normal thickness = 2550 ft
 Stratigraphic thinning = 912 ft
 Growth rate = 60.8 ft/my = 0.018 mm/yr

Midway (7 my):

Minimum thickness (Well 107) = 350 ft
 Normal thickness = 725 ft
 Stratigraphic thinning = 375 ft
 Growth rate = 53.6 ft/my = 0.016 mm/yr

Wilcox (8 my):

Stratigraphic thinning (from the above) = $912 - 375 = 537$ ft
 Growth rate = 67.1 ft/my = 0.020 mm/yr

Overall Cenozoic growth rate = 29.4 ft/my = 0.009 mm/yr

Upper Cretaceous

Arkadelphia - Annona (11 my):

Minimum thickness (Well 108) = 215 ft
 Normal thickness = 425 ft
 Stratigraphic thinning = 210 ft
 Growth rate = 19.1 ft/my = 0.006 mm/yr

Ozan - Eagle Ford (16 my):

Minimum thickness (Well 107) = 200 ft
 Normal thickness = 1200 ft
 Stratigraphic thinning = 1000 ft
 Growth rate = 62.5 ft/my = 0.019 mm/yr

Tuscaloosa (7 my):

Minimum thickness (Well 108) = 200 ft
 Normal thickness = 400 ft
 Stratigraphic thinning = 200 ft
 Growth rate = 28.6 ft/my = 0.009 mm/yr

Table V-C-4, continued.

Overall Upper Cretaceous growth rate = 41.5 ft/my = 0.013 mm/yr

Lower Cretaceous

No adequate well control is available for an estimation of growth rate.

DRAKE'S DOME

Sources of Data

Basic data are from Hessenbruch (1975) and Kumar's computer maps. Out of nine wells drilled in the area of the dome, stratigraphic information is available only on five. Two of the wells (402 and 403 on Hessenbruch's maps) are located on or near the flank; the other wells (147, 148 and 149) are over the dome.

Growth Rates

Cenozoic

Post-Wilcox (50 my):

Structural relief on top of the Wilcox (Hessenbruch's Table 3) = 400 ft

Growth rate = 8 ft/my = 0.002 mm/yr

Midway (7 my):

Minimum thickness (Well 147) = 370 ft

Normal thickness = 725 ft

Stratigraphic thinning = 355 ft

Growth rate = 50.7 ft/my = 0.015 mm/yr

Upper Cretaceous

Arkadelphia - Annona (11 my):

Minimum thickness (Well 147) = 325 ft

Normal thickness = 440 ft

Stratigraphic thinning = 115 ft

Growth rate = 10.4 ft/my = 0.003 mm/yr

Ozan - Eagle Ford (16 my):

Minimum thickness (Well 147) = 690 ft

Normal thickness = 1260 ft

Stratigraphic thinning = 570 ft

Growth rate = 35.6 ft/my = 0.011 mm/yr

Tuscaloosa (7 my):

Minimum thickness (Well 147) = 215 ft

Normal thickness = 350 ft

Stratigraphic thinning = 135 ft

Growth rate = 19.3 ft/my = 0.006 mm/yr

Overall Upper Cretaceous growth rate = 24.1 ft/my = 0.007 mm/yr

Table V-C-4, continued.

Lower Cretaceous

No adequate well control is available for an estimation of growth rate.

MILAMS DOME

Sources of Data

Basic data are from Hessenbruch (1975) and Kumar's computer maps. Among available control wells, two wells (199 and 401 on Hessenbruch's maps) are located on the southern flank; one well (200) is in the northern rim syncline.

Growth RatesCenozoic

Post-Wilcox (50 my):

Highest structural elevation of the top Wilcox (Well 199)	= -509 ft
Regional normal elevation on top of the Wilcox	= -810 ft
Structural relief	= 300 ft
Growth rate = 6 ft/my	= <u>0.002 mm/yr</u>

Wilcox & Midway (15 my):

Minimum thickness (Well 199)	= 1685 ft
Normal thickness	= 2050 ft
Stratigraphic thinning	= 365 ft
Growth rate = 24.3 ft/my	= <u>0.007 mm/yr</u>

Midway (7 my):

Minimum thickness (Well 199)	= 800 ft
Normal thickness	= 730 ft
Stratigraphic thinning	= 70 ft
Growth rate = 10.0 ft/my	= <u>0.003 mm/yr</u>

Wilcox (8 my):

Minimum thickness (Well 199)	= 1685 - 800 = 885 ft (from the above)
Normal thickness	= 2050 - 730 = 1320 ft
Stratigraphic thinning	= 435 ft
Growth rate = 54.4 ft/my	= <u>0.016 mm/yr</u>

Overall Cenozoic growth rate = 10.2 ft/my = 0.003 mm/yr

Upper Cretaceous

Arkadelphia - Annona (11 my):

Minimum thickness (Well 199)	= 366 ft
Normal thickness	= 430 ft
Stratigraphic thinning	= 64 ft
Growth rate = 5.8 ft/my	= <u>0.002 mm/yr</u>

Table V-C-4, continued.

Ozan & Eagle Ford (16 my):

Minimum thickness (Well 199) = 400 ft
 Normal thickness = 1150 ft
 Stratigraphic thinning = 750 ft
 Growth rate = 46.9 ft/my = 0.014 mm/yr

Tuscaloosa (7 my):

Minimum thickness (Well 199) = 328 ft
 Normal thickness = 360 ft
 Stratigraphic thinning = 32 ft
 Growth rate = 4.6 ft/my = 0.001 mm/yr

Overall growth rate for the Upper Cretaceous = 24.9 ft/my = 0.008 mm/yr

Lower Cretaceous

Washita - Fredericksburg (4 my):

Minimum thickness (Well 401) = 348 ft
 Normal thickness = 350 ft
 No significant stratigraphic thinning.
 Growth rate is negligible.

Rusk (1 my):

Minimum thickness (Well 199) = 1800 ft
 Normal thickness = 1900 ft
 Stratigraphic thinning = 100 ft
 Growth rate = 100 ft/my = 0.030 mm/yr

CHESTER DOME

Sources of Data

Basic data are from Hessenbruch (1975) and Kumar's maps. Out of only three control wells, two wells (221 and 222 on Hessenbruch's maps) are bottomed in caprock and salt, respectively; one well (220) provides control through the Upper Cretaceous and Lower Tertiary intervals.

Growth RatesCenozoic

Post-Wilcox (50 my):

Structural relief on top of the Wilcox = 80 ft
 Growth rate = 1.6 ft/my = 0.001 mm/yr

Wilcox & Midway (15 my):

Minimum thickness (Well 222) = 1850 ft
 Normal thickness = 2150 ft
 Stratigraphic thinning = 300 ft
 Growth rate = 20 ft/my = 0.006 mm/yr

Table V-C-4, continued.

Wilcox (8 my):

Minimum thickness (Well 222) = 1250 ft
 Normal thickness = 1450 ft
 Stratigraphic thinning = 200 ft
 Growth rate = 25 ft/my = 0.008 mm/yr

Midway (7 my):

Minimum thickness (Well 222) = 600 ft
 Normal thickness = 700 ft
 Stratigraphic thinning = 100 ft
 Growth rate = 14.3 ft/my = 0.004 mm/yr

Overall rate of uplift for the Cenozoic = 5.8 ft/my = 0.002 mm/yr

Upper Cretaceous

Arkadelphia - Annona (11 my):

Minimum thickness (reconstructed for Well 221) = 427 ft
 Normal thickness = 370 ft
 No stratigraphic thinning; growth rate indeterminate.

Ozan - Eagle Ford (16 my):

Minimum thickness (Well 221) = 900 ft
 Normal thickness = 1000 ft
 Stratigraphic thinning = 100 ft
 Growth rate = 6.6 ft/my = 0.002 mm/yr

Tuscaloosa (7 my):

Minimum thickness (Well 222) = ?150 ft
 Normal thickness = 450 ft
 Stratigraphic thinning = 300 ft
 Growth rate = ?42.9 ft/my = ?0.013 mm/yr

Lower Cretaceous

Washita-Fredericksburg (4 my):

Minimum thickness (Well 221) = 295 ft
 Normal thickness = 550 ft
 Stratigraphic thinning = 255 ft
 Growth rate = 63.7 ft/my = 0.019 mm/yr

Rusk (1 my):

Minimum thickness (reconstructed for Well 221) = 1700 ft
 Normal thickness = 1900 ft
 Stratigraphic thinning = 200 ft
 Growth rate = 200 ft/my = 0.061 mm/yr

Table V-C-4, continued.

PACKTON DOME

Sources of Data

Basic data are from Hessenbruch (1975) and Kumar's computer maps. Out of the available control wells, six wells (60, 61, 62, 66, 256 and 267 on Hessenbruch's maps) encountered the Lower Tertiary Wilcox; only two wells (61 and 66) have penetrated the Upper Cretaceous section.

Growth RatesCenozoic

Post-Cook Mountain (42.5 my):

Structural relief on top of the Cook Mountain = 357 (Well 62) - 232 (Well 60)
= 125 ft

Growth rate = 2.94 ft/my = 0.001 mm/yr

Sparta & Cane River (5.5 my):

Minimum thickness (Well 62) = 593 ft

Normal thickness = 700 ft

Stratigraphic thinning = 107 ft

Growth rate = 19.45 ft/my = 0.006 mm/yr

Wilcox & Midway (15 my):

Minimum thickness (reconstructed for Well 66) = 2798 ft

Normal thickness = 2950 ft

Stratigraphic thinning = 152 ft

Growth rate = 10.13 ft/my = 0.003 mm/yr

Wilcox (8 my):

Stratigraphic thinning = 152 (Wilcox & Midway) - 74 (Midway) = 78 ft

Growth rate = 9.7 ft/my = 0.003 mm/yr

Post-Wilcox (50 my):

Growth = Cook Mountain relief + Cook Mountain thinning + thinning
of Sparta and Cane River = 125 + 8 + 107 = 240 ft

Growth rate = 4.8 ft/my = 0.001 mm/yr

Midway (7 my):

Minimum thickness (Well 66) = 666 ft

Normal thickness = 740 ft

Stratigraphic thinning = 74 ft

Growth rate = 10.57 ft/my = 0.003 mm/yr

Overall Cenozoic growth rate = 6.0 ft/my = 0.002 mm/yr

Upper Cretaceous

Arkadelphia - Annona (11 my):

Minimum thickness (Well 66) = 390 ft

Normal thickness = 450 ft

Stratigraphic thinning = 60 ft

Growth rate = 5.45 ft/my = 0.002 mm/yr

Table V-C-4, continued.

Ozan - Eagle Ford (16 my):

?Minimum thickness (reconstructed for Well 61) = 1395 ft

Normal thickness = 1240 ft

No stratigraphic thinning.

Growth rate indeterminate.

Tuscaloosa (7 my):

?Minimum thickness (Well 61) = 471 ft

Normal thickness = 450 ft

No stratigraphic thinning.

Growth rate indeterminate.

SIKES DOMES

Sources of Data

Basic data are from Hessenbruch (1975) and Kumar's computer maps. Among the control wells, seven wells (171, 174, 174A, 174B, 174C, 174D, and 174E on Hessenbruch's maps) provide information on the Lower Tertiary; only two wells (171 and 174) have penetrated the Gulfian section of the Upper Cretaceous.

Growth RatesCenozoic

Post-Wilcox (50 my):

Structural relief on top of Wilcox = 900 - 232 (Well 174A) = 668 ft

Growth rate = 13.4 ft/my = 0.004 mm/yr

Wilcox & Midway (15 my):

Minimum thickness (Well 174D) = 1502 ft

Normal thickness = 2350 ft

Stratigraphic thinning = 848 ft

Growth rate = 56.5 ft/my = 0.017 mm/yr

Wilcox (8 my):

Stratigraphic thinning = 848 - 340 (Midway) = 408 ft

Growth rate = 51.0 ft/my = 0.015 mm/yr

Midway (7 my):

Minimum thickness (Well 174C) = 380 ft

Normal thickness = 720 ft

Stratigraphic thinning = 340 ft

Growth rate = 48.6 ft/my = 0.015 mm/yr

Overall Cenozoic growth rate = 23.3 ft/my = 0.007 mm/yr

Table V-C-4, continued.

Upper Cretaceous

Arkadelphia - Annona (11 my):

Minimum thickness (Well 174C) = 440 ft
 Normal thickness = 480 ft
 Stratigraphic thinning = 40 ft
 Growth rate = 3.6 ft/my = 0.001 mm/yr

Ozan - Eagle Ford (16 my):

?Minimum thickness (Well 174C) = 1420 ft
 Normal thickness = 1150 ft
 No stratigraphic thinning; growth rate indeterminate.

Tuscaloosa (7 my):

Minimum thickness (Well 174C) = 250 ft
 Normal thickness = 400 ft
 Stratigraphic thinning = 150 ft
 Growth rate = 21.4 ft/my = 0.006 mm/yr

Lower Cretaceous

No data are available for an estimation of growth rate.

MINDEN DOME

Sources of Data

Basic data are from the work of J. L. Martin, et al., (1954) and W. T. Cook (1969). Computations of growth rates are based on geologic sections in Figure 8 of Martin, et al., and Figures 3, 11, and 15 of Cook.

Growth RatesCenozoic

Post-Sparta (44.5 my):

Structural relief on top of the Sparta = 540 ft
 Growth rate = 12.1 ft/my = 0.004 mm/yr

Sparta (3.5 my):

Stratigraphic thinning = 130 ft
 Growth rate = 37.1 ft/my = 0.011 mm/yr

Cane River (2 my):

No significant stratigraphic thinning observed.
 Growth rate is negligible.

Wilcox (8 my):

Stratigraphic thinning = 600 ft
 Growth rate = 75 ft/my = 0.023 mm/yr

Table V-C-4, continued.

Midway (7 my):

Total growth since the start of the Midway time
 = structural relief on the base of the Midway = 1860 ft
 = growth during the Midway and growth during the Wilcox and
 growth during the Cane River and growth during the Sparta and
 Post-Sparta growth.
 = growth during the Midway + 600 + 0 + 130 + 540
 Hence, Midway growth = 1860 - 1270 = 590 ft
 Growth rate for the Midway = 84.3 ft/my = 0.026 mm/yr

Post-Wilcox (50 my):

Growth rate = (540 + 130 + 0)/50
 = 13.4 ft/my = 0.004 mm/yr

Wilcox and Midway (15 my):

Growth rate = (600 + 590)/15
 = 79.3 ft/my = 0.009 mm/yr

Overall Cenozoic growth rate = 28.6 ft/my = 0.009 mm/yr

Cretaceous

No adequate information is available for an estimation of growth rate.

CHESTNUT DOME

Sources of Data

Basic data are from Hessenbruch (1975) and Kumar's computer maps. Out of four control wells, data on only three wells (336, 404, and 405 on Hessenbruch's maps) are available. Well 404 is bottomed in salt. Only Well 336 has penetrated the entire Upper Cretaceous section; others have encountered the Lower Tertiary section.

Growth RatesCenozoic

Post-Wilcox (50 my):

Structural relief on top of the Wilcox (Wells 404 & 405) = 250 ft
 Growth rate = 5 ft/my = 0.001 mm/yr

Wilcox & Midway (15 my):

Minimum thickness (Well 404) = 1312 ft
 Normal thickness = 2000 ft
 Stratigraphic thinning = 688 ft
 Growth rate = 45.9 ft/my = 0.014 mm/yr

Overall Cenozoic growth rate = 14.4 ft/my = 0.004 mm/yr

Cretaceous

No data are available for an estimation of growth rate.

COOCHIE BRAKE DOME

Sources of Data

Basic data are from Smith's Figure IV-B-5, (Martinez, et al., 1975), Hessenbruch (1975) and Kumar's computer maps. Ten wells are located along the flank of the dome, providing controls mostly for the Lower Tertiary Claiborne. Only Well 44 (Hessenbruch's maps) penetrated the top of the Upper Cretaceous.

Growth RatesCenozoic

Cook Mountain (2 my):

No significant stratigraphic thinning (Smith's Figure)
Growth rate is negligible.

Sparta (3.5 my):

Stratigraphic thinning (Smith's Figure) = $450 - 375 = 75$ ft
Growth rate = 21.4 ft/my = 0.006 mm/yr

Cane River (2 my):

Stratigraphic thinning (Smith's Figure) = $200 - 125 = 75$ ft
Growth rate = 37.5 ft/my = 0.011 mm/yr

Wilcox & Midway (15 my):

Minimum thickness (Well 44) = 1660 ft
Normal thickness = 3000 ft
Stratigraphic thinning = 1340 ft
Growth rate = 89.3 ft/my = 0.027 mm/yr

Post-Wilcox (50 my):

Structural relief on top of the Wilcox = 600 ft
Growth rate = 12 ft/my = 0.004 mm/yr

Post-Cook Mountain (41.5 my):

Total growth = Post-Wilcox uplift - uplift during the Cane River,
Sparta and Cook Mountain time
= $600 - (75 + 75 + 0)$
= 450 ft

Growth rate = 10.8 ft/my = 0.003 mm/yr

Overall Cenozoic growth rate = 29.8 ft/my = 0.009 mm/yr

Cretaceous

No data are available for an estimation of growth rate.

Table V-C-4, continued.

CEDAR CREEK DOME

Sources of Data

Basic data are from Smith's Figure IV-B-13, (Martinez, et al., 1975), Hessenbruch (1975) and Kumar's computer maps. Eight wells are drilled along the flank of the dome. However, only two wells (112 and 113 on Hessenbruch's maps) provide controls for the lower Tertiary Wilcox; only one well (113-D) penetrated the top of the Upper Cretaceous.

Growth RatesCenozoic

Sparta (3.5 my):

No stratigraphic thinning observed (Smith's Figure)
Growth rate is negligible.

Cane River (2 my):

Stratigraphic thinning (Smith's Figure) = $275 - 175 = 100$ ft
Growth rate = 50 ft/my = 0.015 mm/yr

Post-Wilcox (50 my):

Structural relief on top of the Wilcox = 300 ft (Wells 112 & 113)
Growth rate = 6 ft/my = 0.002 mm/yr

Post-Sparta (44.5 my):

Total growth = Post-Wilcox uplift - uplift during the Cane River
and Sparta time
= $300 - (100 + 0) = 200$ ft

Growth rate = 4.5 ft/my = 0.001 mm/yr

Cretaceous

No data are available for an estimation of growth rate.

PRICE'S DOME

Sources of Data

Basic data are from Smith's Figure IV-B-12 (Martinez, et al., 1975), Hessenbruch (1975) and Kumar's computer maps. Three wells (191, 192, and 251 on Hessenbruch's maps) are drilled on the dome. Stratigraphic information only on the lower Tertiary are available.

Growth RatesCenozoic

Cane River (2 my):

Stratigraphic thinning (Smith's Figure) = 50 ft
Growth rate = 25 ft/my = 0.008 mm/yr

Table V-C-4, continued.

Post-Wilcox (50 my):

Structural relief on top of the Wilcox (Well 191) = 200 ft
 Growth rate = 4 ft/my = 0.001 mm/yr

Post-Cane River (48 my):

Growth rate = $(200 - 50)/48$
 = 3.1 ft/my = 0.001 mm/yr

Midway:

No data are available for an estimation of growth rate.

Cretaceous

No data are available for an estimation of growth rate.

CASTER CREEK DOME

Sources of Data

Basic data are from Hessenbruch (1975) and Kumar's computer maps. A number of wells are located in the area, providing controls for the lower Tertiary.

Growth RatesCenozoic

Cook Mountain (2 my)
 Sparta (3.5 my)
 Cane River (2 my)

No significant stratigraphic thinning. Hence, uplift rate negligible.

Post-Wilcox (50 my):

Structural relief on top of the Wilcox (Well 86) = 30 ft
 Growth rate = 0.6 ft/my = 0.0002 mm/yr (negligible).

Cretaceous

No well control is available for an estimation of growth rate.

ARCADIA DOME

Sources of Data

Basic data are from the thesis of Worely (1962).

Growth RatesCenozoic

Post-Cane River (48 my):

Structural relief = 900 ft
 Growth rate = 18.7 ft/my = 0.006 mm/yr

Table V-C-4, continued.

Cane River (2 my):

No significant thinning.

Hence, growth rate is negligible.

BISTINEAU DOME

Sources of Data

Basic data are from Smith's Figure IV-B-5 (Martinez, et al., 1975).

Growth Rates

Cenozoic

Midway (7 my):

Stratigraphic thinning = 100 ft

Hence, the Midway growth rate = $14.3 \text{ ft/my} = \underline{0.004 \text{ mm/yr}}$

No data are available for other stratigraphic intervals.

V-D. SEISMIC STUDIES OF VACHERIE SALT DOME

R. H. Pilger, Jr.

1. Background

Seismic profiling provides two related kinds of information pertinent to the goals of this project. First, it constrains the configuration and size of the dome; second, it provides an image of the structure of flanking sedimentary rocks which is helpful in reconstructing the tectonic history of the salt.

In last year's report (Martinez, et al., 1976), the results of a seismic survey over Vacherie by Petty-Ray, under contract to LSU, were presented by Newchurch and Romberg. In addition, one line (line 40) of a reprocessed older survey obtained from Atlantic Richfield Company was presented. These data confirmed the generally elliptical shape of Vacherie, as previously inferred from geologic mapping, second-hand gravity surveys, topographic expression, and limited well control. In addition, flanking rim synclines and several faults were identified on the profiles. The rim synclines appear to overlie horizontal reflections at depth, suggesting thinning of an intervening salt layer, from which the salt of Vacherie dome was derived. As a corollary, the profiles can provide an estimate of the depth to the "mother" (Louann) salt, if accurate velocity information is available.

It was noted in the 1976 report that the depth to mother salt near Vacherie must be greater than the depth of the deepest well in the vicinity--approximately 14,500 ft below sea level (BSL). It was suggested that the depth of salt lies between 16,000 and 18,500 ft BSL.

The 1976 report recommended that other seismic data obtained from Atlantic Richfield be processed in a manner similar to that of Line 40.

The following sections present interpretations of each of the ARCO profiles together with the Petty-Ray profiles described in last year's report. Since the reprocessed data were received late in fiscal year 1977 from the processing company (Geophysical Data Processing, Inc., of Houston, Texas), only preliminary conclusions can be presented at this time. Nevertheless, based on the data, some significant results have been obtained.

2. Processing of the Data

The location of the ARCO seismic lines is shown in Figure V-D-1. The processing techniques applied to the ARCO paper records from lines A-2, A-6, 9, and 39 were virtually the same as those previously applied to ARCO line 40, as described in last year's report (Martinez, et al., 1976). Digital deconvolution was not applied, however. Lines A-2, A-6, 9, and 39 were plotted, and line 40 replotted, so as to preserve a nearly constant horizontal scale. As the digitized records are recorded on magnetic tape, further manipulation of the records in the future will be possible.

3. Results

The reprocessed ARCO seismic lines A-2, A-6, 9, 39, and 40 are presented in Figures V-D-2a, -3a, -4a, -5a, and -6a. Preliminary interpretations of the lines are shown in Figures V-D-2b, -3b, -4b, -5b, and -6b. As mentioned above, the potential contribution of seismic profiling to the project involves delineation of the location and configuration of the salt dome and definition of the structure of the sedimentary rocks flanking the dome.

a. Configuration of the dome. With respect to the first goal, the 1976 report (Martinez, et al., 1976) noted that the Petty-Ray and ARCO seismic lines provide constraints on the location of the flanks of Vacherie dome,

FIG. V-D-1. LOCATION OF SEISMIC LINES OVER VACHERIE DOME

FIG. V-D-2a
SEISMIC SECTION, LINE A-2

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AREA <h3 style="margin: 0;">MINDEN</h3>	LINE NO <div style="border: 1px solid black; border-radius: 50%; width: 40px; height: 40px; display: flex; align-items: center; justify-content: center; margin: 0 auto;"> A-2 </div>																																										
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4/002/506--4112/67

INTERPRETED SEISMIC SECTION
ARCO LINE A-2
VACHERIE SALT DOME AREA

FIG. V-D-2 b

9 Low Sub-works

WEST

EAST

SEISMIC SECTION, LINE A-6

FIG. V-D-3a

LOUISIANA STATE
UNIVERSITY

AREA

MINDEN

LINE NO.

A-6

LOCATION

BIENVILLE & WEBSTER
Phs., LOUISIANA

DIGITAL PROCESS

100 %

RECORDING INFORMATION

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Geophysical Data
Processing Center, inc.

DATE

PROCESSING INFORMATION

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2 TRUE AMPLITUDE RECOVERY
3 VERTICAL SUM RECORDS
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6 CONSTANT VELOCITY SCANS
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13 DECON AFTER STACK OPER MS PREDICTION DIST MS
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15 FILTER
16 0 TO 3.0 SEC 20/45 HZ TO SEC HZ
TO SEC HZ TO SEC HZ
17 TRACE EQUALIZATION
18 AGC
19 MANUAL STATIC EDIT

REMARKS

FIG. V-D-3b

SOUTH

NORTH

283

FIG. V-D-4a
SEISMIC SECTION, LINE 9

LOUISIANA STATE UNIVERSITY

AREA

MINDEN

LINE NO

9

LOCATION

BIENVILLE & WEBSTER
Phs., LOUISIANA

DIGITAL PROCESS

100 %

RECORDING INFORMATION

SHOT BY ATLANTIC REFINING CO. DATE RECORDED 12/46
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Processing Center, inc.

DATE

PROCESSING INFORMATION

1 REFORMAT SAMPLE RATE 4 MS
TRUE AMPLITUDE RECOVERY
VERTICAL SUM RECORDS
3 PRIMARY STATICS DATUM 0' VC 6000' /SEC
VELOCITY SPECTRUM
CONSTANT VELOCITY SCANS
DECONVOLUTION OPER MS PREDICTION DIST MS
DESIGN WINDOW 1 TO SEC 2 TO SEC
4 NMO CORRECTION
MUTE
AUTOMATIC STATICS WINDOW 1 TO SEC
2 TO SEC
STACK FOLD
DECON AFTER STACK OPER MS PREDICTION DIST MS
DESIGN WINDOWS 1 TO SEC 3 TO SEC
2 TO SEC 4 TO SEC
5 FILTER
0 TO 3.0 SEC 20/40 HZ TO SEC HZ
TO SEC HZ TO SEC HZ
7 TRACE EQUALIZATION
8 AGC
6 MANUAL STATIC EDIT

REMARKS

9/0051506-4112/32

INTERPRETED SEISMIC SECTION
ARCO LINE 9
VACHERIE SALT DOME AREA

FIG. V-D-4b

4/600E/506 - 4/2/39

LOUISIANA STATE UNIVERSITY

AREA

MINDEN

LINE NO

39

LOCATION

BIENVILLE & WEBSTER
Phs., LOUISIANA

DIGITAL PROCESS

100 %

RECORDING INFORMATION

SHOT BY ATLANTIC REFINING CO. DATE RECORDED 12/46
CREW 15 SOURCE DYNAMITE
LENGTH 3.9 SEC. SWEEP FREQUENCY
GAIN AGC INSTRUMENTS
FORMAT ANALOG ANALOG ☒ DIGITAL ☐
SAMPLE RATE MARINE ☐ LAND ☒
RECORDING FILTER RECORD LENGTH 3.9 SEC.
GEO/STA STA INT VARIABLE
SP INT VARIABLE NEAR TRACE
FAR TRACE DISTANCE TRACE OF SP

PROCESSED BY

Geo physical Data
Processing Center, Inc.

DATE

PROCESSING INFORMATION

1 REFORMAT SAMPLE RATE 4 MS
2 TRUE AMPLITUDE RECOVERY
3 VERTICAL SUM RECORDS
4 PRIMARY STATICS DATUM 0' VC 6000' / SEC
5 VELOCITY SPECTRUM
6 CONSTANT VELOCITY SCANS
7 DECONVOLUTION OPER MS PREDICTION DIST MS
8 DESIGN WINDOW 1 TO SEC 2 TO SEC
9 NMO CORRECTION
10 MUTE
11 AUTOMATIC STATICS WINDOW 1 TO SEC
2 TO SEC
12 STACK FOLD
13 DECON AFTER STACK OPER MS PREDICTION DIST MS
14 DESIGN WINDOWS 1 TO SEC 3 TO SEC
2 TO SEC 4 TO SEC
15 FILTER
16 0 TO 3.0 SEC 20/42 HZ TO SEC HZ
TO SEC HZ TO SEC HZ
17 TRACE EQUALIZATION
18 AGC
19 MANUAL STATIC EDIT

REMARKS

WEST

EAST

LINE 3

260-9600
350-0000
500-9100
800-10000
1000-10500
2300-12000

LINE 40

SEISMIC SECTION, LINE 39

FIG. V-D-5a

9/0001506-40237

INTERPRETED SEISMIC SECTION
ARCO LINE 39
VACHERIE SALT DOME AREA

FIG. V-D-5b

AREA MINDEN		LINE NO 40
LOCATION BIENVILLE & WEBSTER Phs., LOUISIANA		
DIGITAL PROCESS 100 %		
RECORDING INFORMATION		
SHOT BY ATLANTIC REFINING CO. DATE RECORDED 12/46		
CREW 15	SOURCE DYNAMITE	
LENGTH 3.9 SEC.	SWEEP FREQUENCY	
GAIN AGC	INSTRUMENTS	
FORMAT ANALOG	ANALOG ☒ DIGITAL ☐	
SAMPLE RATE	MARINE ☐ LAND ☒	
RECORDING FILTER	RECORD LENGTH 3.9 SEC.	
GEO/STA	STA INT VARIABLE	
SP INT VARIABLE	NEAR TRACE DISTANCE	
FAR TRACE DISTANCE	TRACE OF SP	
PROCESSED BY physical Data Processing Center, Inc.		
DATE		
PROCESSING INFORMATION		
1. FORMAT	SAMPLE RATE 4 MS	
THIN AMPLITUDE RECOVERY		
VERTICAL SUM RECORDS		
3 PRIMARY STATICS DATUM 0' VI 6000' / SEC		
VELOCITY SPECTRUM		
CONSTANT VELOCITY SLANS		
5. DECONVOLUTION OPER 120 MS PREDICTION DIST 32 MS		
DESIGN WINDOW 1 300 TO 2.8 SEC 2 TO SEC		
4 NMO CORRECTION		
MUTE		
AUTOMATIC STATICS WINDOW 1 TO SEC		
2 TO SEC		
STACK FOLD		
DECON AFTER STACK OPER MS PREDICTION DIST MS		
DESIGN WINDOWS 1 TO SEC 3 TO SEC		
2 TO SEC 4 TO SEC		
6. FILTER		
0 TO 3.9 SEC 12/36 HZ TO SEC HZ		
TO SEC HZ TO SEC HZ		
TRACE EQUALIZATION		
2.0 AGC		
7. MANUAL STATIC EDIT		
REMARKS		

FIG. V-D-6a
SEISMIC SECTION, LINE 40

9/0002/2006-0002/37

FIG. V-D-6b

4/0011506-41123)

but do not provide precise, direct estimates of its shape. The reason for this seems to be that deformation of the sedimentary rocks adjacent to the dome disrupts the stratification to such a degree that coherent reflections are not readily observed in the data as presently available. However, an indirect observation from the seismic profiles seems to be of significant value for constraining the location of the flanks of the dome--namely, recognition of a probable sub-salt reflector. In addition, appropriate interpretation of this reflector provides an estimate of the depth of the base of the mother salt.

At about 2.3 seconds (two-way travel time) on ARCO profiles 39 and 40 (Figures V-D-5a, and -6a) and on Petty-Ray profiles A and B (c.f., Figures IV-E-2 and IV-E-3 in Martinez, et al., 1976, p. 199 and 201), the top of a convex upward set of reflections (reflector D in Figures V-D-5b and -6b) is observed beneath the core of the salt stock. The reflections appear to correlate with reflections at about 2.6 seconds in the sedimentary rocks flanking the dome. These are the only distinctive reflections occurring in or beneath the otherwise effectively transparent salt; thus, it seems reasonable to suggest that reflector D and those below represent sedimentary beds below the salt, as suggested by Kupfer (Martinez, et al., 1976).

The apparent deformation of the reflectors could either represent tectonic deformation of the sub-salt rocks, or it could be a velocity effect. Since the velocity of salt is generally higher than most sedimentary rocks, the apparent deformation could represent a velocity "pull-up" such that the shape of reflector D beneath the salt is actually an image of the top of the salt dome. The higher velocity of the salt would result in faster travel times than those of raypaths entirely within the flanking sedimentary rocks.

In order to test the velocity pull-up hypothesis, depth calculations of reflector D beneath the dome and beneath the flanking sedimentary strata were made using published estimates of average salt velocity and velocity information derived from the Petty-Ray seismic survey.

Estimates of average salt velocity range from 13,000 - 15,500 ft/sec (Gardner, et al., 1974), although 15,000 ft/sec is the value usually used in seismic refraction prospecting (e.g., Musgrave, et al., 1960). Allowing for 600 ft of sedimentary rocks above the crest of Vacherie dome, with an average velocity between 5500 and 7500 ft/sec (as taken from the Petty-Ray velocity measurements in Martinez, et al., 1976), the depth of reflector D (2.3 seconds, two-way travel time) is likely to be in the range 14,100 - 18,400 ft BSL. The preferred value is 16,650 ft (salt velocity = 15,000 ft/sec; sediment velocity (above dome) = 7500 ft/sec).

The average velocity in flanking sedimentary rocks as calculated by Petty-Ray appears to be in the range 12,000 - 14,000 ft/sec (Figure V-D-7). While higher velocities are reported, they are obtained from either within the dome itself or along its immediate flanks. For reflector D at 2.6 seconds, this gives a depth range of 15,600 - 18,200 ft BSL. For an average velocity of 13,000 ft/sec the estimated depth is 16,900 ft BSL. Last year's report noted that the sediment velocities calculated from the seismic section might be too high, in which case the estimated depth ranges are too great.

This limited analysis suggests that reflector D occurs at the base of the salt dome and may originate from a nearly horizontal horizon. (The further significance of reflector D is discussed below in the section on structure of the sedimentary rocks flanking Vacherie salt dome.) The interpretation of reflector D as a horizontal, sub-salt horizon is similar

FIG. V-D-7
VELOCITY-DEPTH RELATIONS

to that of a horizon on a seismic profile across Hainesville salt dome in northeast Texas, as reported by Dobrin (1976). Dobrin suggests that a deep reflecting horizon beneath the dome is deformed on the seismic time section as a result of velocity effects. As the quality of the Hainesville Profile, particularly at depth, is better than that of any of the LSU profiles, correlation of the sub-salt reflectors with sub-sediment reflectors is well defined on the Hainesville profile.

If the distortion of reflector D is due to velocity effects, then its shape is an image of the top of Vacherie dome. Even without sophisticated ray-tracing techniques, it is possible to use the shape as an estimate of the configuration of the top of the dome, assuming a minimum depth of salt (or caprock) of 400 ft BSL and constant salt velocity of 15,000 ft/sec. This estimate of the shape of the top of the dome is included in Figures V-D-5b and -6b and in the reinterpreted Petty-Ray profiles (Figures V-D-8 and -9). An important additional consequence of this analysis is that the upper portion of Vacherie dome is attached to and continuous with deeper salt, just above reflector D. It seems unlikely that the coherence of reflector D would be maintained if the upper portion of the dome were detached from deeper salt. Further, the success of the hypothesis that reflector D is continuous and horizontal also suggests that the salt is continuous from approximately 17,000 ft to 400 ft below sea level. The inferred configuration of the top of Vacherie dome (Figure V-D-10) also incorporates this interpretation of reflector D.

b. Deformation of flanking sedimentary rocks. In last year's report (Martinez, et al., 1976), it was noted that rim synclines were apparent at depth on Petty-Ray profile B and on ARCO line 40. Major rim-syncline formation on Petty-Ray line B and Arco line 40 appears to be confined to horizons well below reflector B, which was inferred to correspond with the top of

REINTERPRETED SEISMIC SECTION
PETTY-RAY LINE A
VACHERIE SALT DOME AREA

FIG. V-D-8

FIG. V-D-9

9/6000/506--411/37

VACHERIE SALT DOME
STRUCTURE CONTOUR MAP
BASED ON SEISMIC PROFILES,
TOP OF CAPROCK OR SALT
(FEET BELOW SEA LEVEL)

FIG. V-D-10

Y/lowe/Isob-4112/37

the Sligo formation (Martinez, et al., 1976). Reflector B is also recognized on ARCO lines A-2 and 9 (Figures V-D-2b and -4b, respectively). However major synclinal deformation to the north of Vacherie (line 9) occurs at a much shallower depth than to the south (line A-2). Further to the north, on line 9, the Minden syncline (Kupfer in Martinez, et al., 1976) clearly involves strata above reflector B. These combined observations indicate that major synclinal formation, presumably synchronous with salt withdrawal, occurred in a time-transgressive manner, terminating well before Sligo time on the south, just before Sligo time to the north of Vacherie, and much later farther north--south of Minden dome.

The 1976 report did indicate minor synclinal deformation of horizons B and also A (correlated with the top of the Annona formation) on the north, south, and west flanks of Vacherie dome. This pattern is also apparent on ARCO profiles A-6 and 40 (Figures V-D-3a, -3b, -6a, and -6b). As reflections shallower than reflector A are poorly resolved, further determination of the deformation history of the sedimentary rocks, on the basis of the seismic profiles is limited.

As noted in the previous section, reflector D may well represent a near horizontal reflector beneath Vacherie salt dome. However, velocity pull-ups are not restricted to sub-salt positions. Pull-ups appear to occur under the flanking sediments as well (see Figures V-D-1a, -1b, -4a, and -6b). Beneath the flanking sediments, reflector D appears to occur at 2.4 - 2.5 seconds (two-way travel time). The region above this segment of reflector D is characterized by incoherent reflections and numerous diffractions while more coherent reflections occur farther from the dome. As the velocity analyses from the Petty-Ray survey seem to be somewhat higher along these dome flanks, the stepped configuration of reflector D might be caused by higher velocities in deformed sediments adjacent to the dome. Thus the velocity

pull-ups of reflector D appear to occur in two stages: beneath denser, higher velocity sediments; and beneath even higher velocity salt. Alternatively, the zone of incoherent reflections could represent a deep shoulder of salt on the south flank of the dome. That the flanking sedimentary rocks might be more dense and have a higher seismic velocity is supported by studies by Crosby (1964), who showed that gravity anomalies over some salt domes seem to require higher density sediments immediately adjacent to the domes than off the flanks.

Further to the south, on ARCO profiles A-2 and 40, reflector D appears to be continuous with a reflector which is anticlinally deformed. An obvious interpretation is that the anticlinal structure is a salt pillow. Such an interpretation would require, however, that reflector D is underlain by more salt, at least to the south of Vacherie dome. There is no indication of a similar situation to the north of Vacherie. Either the inferred continuation of reflector D is invalid, or a second salt horizon exists below reflector D. The latter interpretation would have significant bearing on the sedimentary history of the Jurassic salt beds.

4. Future Work

It is planned that future work on these existing seismic profiles will involve additional processing of the Petty-Ray profiles involving migration and further velocity analysis. In addition, characteristic reflections on the ARCO profiles will be digitized and migrated as well. In order to further test the velocity pull-up model of reflector D, ray tracing mathematical models are planned in an effort to reproduce the time sections by varying the shape of the dome and the velocity structure of the overlying sedimentary rocks.

Attempts to obtain additional seismic data such as that obtained from

ARCO will be made. If such attempts are successful, reprocessing of the new data will be undertaken in a similar manner.

It is felt that the main goals of this aspect of the project will require the acquisition of new seismic data. In order to more precisely outline the configuration of the dome, a refraction survey with geophones in a corehole in the salt is planned. In addition, it is highly desirable to obtain short, high resolution seismic profiles over the flanks of the target domes in order to delineate the shallow structure of the flanking sedimentary rocks and the shape of the top boundaries of the dome.

A regional seismic survey linking two or more target domes is also desirable. Such a survey would be aimed at definition of the deeper structure of the sedimentary basin separating, for example, Vacherie and Rayburn's domes. The regional survey would provide valuable control on the estimate of the movement history of the salt, volumes of salt, and deformation of the overlying sedimentary rocks. It could also provide additional tests of the velocity pull-up hypothesis versus suggestions of sub-mother salt structural involvement.

Together with the gravity data, the existing and proposed seismic data should provide accurate and precise estimates of the shape and size of the target domes. In addition, coordination with well log studies will give an excellent historical perspective on the development of the domes prior to middle Cenozoic time.

5. Acknowledgements

M. Romberg, consultant to the LSU project, lent his expertise to supervision of the processing of the ARCO lines, and assisted in interpretation of the seismic profiles at an earlier stage.

V-E. GRAVITY INVESTIGATIONS OF NORTH LOUISIANA SALT DOMES

R. H. Pilger, Jr.

1. Background

The goals of the LSU salt dome project require accurate and precise knowledge of not only the geographic location, but also the sizes, depths, and shapes of the target salt domes. In addition, a knowledge of the nature of the flanking sedimentary rocks is desirable. From various sources, a rough idea of the locations and depths to the tops of Vacherie and Rayburn's domes has been developed, based on oil well and second-hand gravity data (summarized in Martinez, et al., 1975, 1976).

Traditionally, gravity surveys have been viewed as reconnaissance tools for the location of density anomalies (such as salt domes) in the subsurface. By analysis of the shapes of reduced anomalies, using simple mathematical models such as spheres, cylinders, and cones, rough estimates of the depth of anomalous masses can be obtained (e.g., Nettleton, 1976). Several iterative techniques have also been applied to simple problems involving assumptions of constant density contrast between an anomalous mass and the surrounding material (e.g., Cordell and Henderson, 1968). Such techniques suffer from simple assumptions, such as constant density, and from the absence of suitable geologic constraints. Through the application of basic geologic assumptions (e.g., Dorman, 1975) and constraints derived from other sources (e.g., well logs; Burkhard and Jackson, 1976) it appears possible to derive more sophisticated estimates of the variations in density contrast with depth and of the shape of the anomalous mass as well. Alternatively, it might be desirable to derive the density contrast

of each element of a three-dimensional grid whereby the boundaries of an anomalous mass could be defined on the basis of changes in density contrast.

2. Data Acquisition

Detailed gravity data over Vacherie dome were collected in May 1977, and the mathematical techniques described above will be applied to these data in an effort to define the configuration of the dome. Using a LaCoste-Romberg gravity meter, approximately 200 stations were occupied at close spacing over the inferred northeast, southeast, and western flanks of the dome. Relative elevations and locations of the stations were determined by alidade and plane table and were tied to new precise-leveling survey bench marks erected by the National Geodetic Survey (see Section III-B). Complete reduction of the data has been delayed, awaiting receipt of elevations of the bench marks from the NGS.

In addition to gravity data collected directly by LSU personnel, all major oil companies were contacted and requests for additional gravity data in the areas of interest were made. The response to these requests was most gratifying. Cities Service, Atlantic Richfield, Texaco, and Conoco provided copies of complete Bouguer anomaly maps which include individual station locations and readings. Examinations of the maps indicates that the data sets, while independently derived, are compatible although base values differ. Composite complete Bouguer anomaly maps over Vacherie, Rayburn's, and Prothro domes have been constructed from the Cities Service and Atlantic Richfield data (Figures V-E-1 and -2). More detailed evaluation of the data will involve computer techniques.

FIG. V-E-1

FIG.V-E-2

3. Results

From the Bouguer gravity maps (Figures V-E-1 and -2) several observations are apparent. The anomaly shape over Vacherie is highly elliptical as is also reflected in the topography, seismic profiles, and limited well data available (Martinez, et al., 1975, 1976). In contrast, the Rayburn's and Prothro anomalies are much more circular. Further, the magnitude of the anomaly associated with Vacherie is much greater than those associated with Rayburn's and Prothro domes (15 milligals over Vacherie, versus approximately 4 milligals for Rayburn's and Prothro). These observations provide additional support for inferences that Vacherie is a much larger dome than either Rayburn's or Prothro. Further, both Rayburn's and Prothro domes show distinct asymmetries in their gravity anomalies.

The east flank of the Rayburn's anomaly shows a slight concavity to the east, indicating a relative mass excess on the east flank. Such a mass excess could be an indication of a shallow overhang of salt over sedimentary rocks on the east flank; sedimentary rocks might be partially surrounded by salt on the northeast, east, and southeast flanks of the dome.

A similar, though less pronounced, asymmetry in the Prothro anomaly is also suggestive of a mass excess. The concavity indicated in the 24.5 milligal contour suggests either a shallow overhang at depth, or a morphologic depression in the salt, such that the top of Prothro dome might be somewhat horseshoe-shaped.

4. Future Work

In order to utilize the data from the LSU surveys and those received from the oil and contracting companies more completely, mathematical models have been developed which will produce "best-fit" configurations of the

domes to the gravity data. As is well known, such modeling techniques are of little value in the absence of suitable constraints. The seismic profiles and well data from Vacherie, and the engineering seismic data from Rayburn's will provide the necessary constraints when combined with geologically reasonable estimates of the density variations of the sedimentary rocks of northern Louisiana. As the models being derived also compute regional effects, estimates of the sizes and shapes of neighboring domes must also be taken into account. Fortunately, the neighboring domes are far enough away from the domes of interest that only rough estimates of geometry and location are needed.

The amount of data available combined with more detailed surveys should provide valuable control on the size, shape, and density contrast of the domes. This facet of the project seems well able to achieve its goals.

It is proposed that additional, highly detailed gravity surveys be undertaken over the flanks of Vacherie and Rayburn's domes. The spacing of the stations should be on the order of 100 feet or less. As detailed gravity surveys require accurate and precise elevation information, it is further proposed that detailed leveling surveys be undertaken prior to the gravity surveys. The leveling surveys could be easily coordinated with surveys of boreholes, water wells, and engineering seismic refraction studies.

5. Acknowledgements

L. Lakin and J. Lucas, students in the LSU Geology Department, assisted in the acquisition of the field gravity data over Vacherie Dome. In addition Mr. Lakin assisted in reduction of the gravity data obtained from oil companies.

V-F. GEOCHEMISTRY

R. E. Ferrell, Jr.

1. Background

A geochemical investigation of salt-dome salt was initiated in January 1977. The purpose of the study was to collect and analyze chemical data on salt in pursuit of the general goals of the investigation of the utility of Gulf Coast salt domes for the storage or disposal of radioactive wastes. This program is designed to provide results which can be used to assess the tectonic and hydrologic stability of salt domes. The results of the current year's activities in geochemistry are presented in this report. Most of the work effort was devoted to the standardization and calibration of techniques for the analysis of salt, including mineralogical analysis by scanning electron microscopy and chemical-element determinations by atomic absorption spectroscopy and colorimetry.

The geochemical studies are expected to be most useful in assessing the hydrologic stability of salt domes. The findings will directly assist other investigators in this project who are studying mine hydrology, groundwater movement, caprock formation, salt petrology and the mechanics of salt deformation. The geochemical program should also establish a baseline data set which can be used to assess which geochemical parameters or techniques should be included in any detailed, site specific studies which may follow. However, at the present time, only preliminary results of the laboratory-techniques studies are available.

2. Scanning Electron Microscope (SEM) Techniques

The scanning electron microscope is an extremely useful analytical instrument for the study of the size and shape of mineral grains. When

these microscopes are equipped with an energy dispersive X-ray analysis system, their utility is expanded further. The morphology and chemical composition of individual grains as small as a micrometer in diameter can be examined with such a system.

The mineral grains examined in this study were the water insoluble minerals in salt samples from the domes at Weeks Island and Cote Blanche. They were collected by dissolving the bulk salt in distilled water at room temperature and then filtering the solution through a 0.45 μm membrane. The residues were mounted on 1-inch aluminum or brass sample stubs as bulk grain mounts or individual hand-picked grains. In most cases, these specimens were coated with a thin carbon film in a vacuum evaporator in order to provide the surface electrical conductivity required to form secondary electron images in the SEM. The carbon film is also fairly transparent to X-rays which are generated in the sample by the microscope's electron beam. A few samples were coated with a gold film in order to obtain better quality, high magnification photomicrographs.

In the microscope, all bulk samples were scanned at variable magnifications and representative areas were photographed on Polaroid P/N 55 type film at relatively low magnification settings (60 - 300 times enlargement). Individual grains were also photographed at low magnifications, and their chemical compositions were determined by the X-ray analyzer. Typical results of these procedures are presented below. The instrument used was the JEOL JSM-2 microscope with an ORTEC Model 6100 X-ray system in the LSU Department of Geology.

3. Atomic Absorption Spectroscopy (AAS)

Atomic absorption spectroscopy is a very versatile analytical chemistry technique. With standard equipment, one can measure trace concen-

trations of elements in aqueous solutions or major elements in solid samples after dissolution and dilution of the samples with distilled water. In this study, the AAS system has been used to obtain quantitative determinations of the water soluble potassium, calcium, magnesium, strontium, and sodium in salt samples from Cote Blanche and Weeks Island salt domes.

A representative 2 gram sample of the dry, crushed salt was dissolved in about 80 ml of distilled water and filtered through a 0.45 μ m membrane to remove the insoluble mineral grains. The filtrate was collected in a volumetric flask and adjusted to a volume of exactly 100 ml. Additional 10x, 100x, or 1000x dilutions of this stock solution were also made in order to reduce the concentrations of the dissolved species to the working ranges commonly used in AAS analyses. The samples were analyzed with the instrumental parameters recommended in the Perkin-Elmer Handbook.

The analytical results were calibrated with known solutions of potassium, magnesium, calcium, strontium, and sodium by the method of standard additions. The measured values were then multiplied by the appropriate factors in order to calculate the elemental concentrations in the original sample. The final results are expressed on a weight basis as parts-per-million. The instrument used for these determinations was a Perkin-Elmer Model 370A Atomic Absorption Spectrophotometer in the LSU Institute for Environmental Studies.

4. Colorimetric Procedures

Several colorimetric, titrimetric, or turbidimetric procedures have been investigated for the determination of the water soluble chloride, iodide, bromide, and sulfate concentrations in salt. Only the chloride and sulfate techniques have produced satisfactory results at the present time.

Chloride in salt was determined by the Mohr method using silver nitrate to titrate the diluted samples to the desired end point. The silver nitrate solution utilized was approximately 0.013 N and the reagents required in the analysis were the prepackaged powders supplied by the Hach Chemical Co.

Sulfate was determined by a turbidimetric procedure. The Sulfate IV reagent powders prepared by Hach Chemical Co. were used in this analysis because they yielded more reproducible results than the reagents prepared in the LSU laboratory.

5. Salt Samples

Samples of salt used in this initial phase of the geochemical study were collected from the Morton Salt Company mine at Weeks Island and the Domtar Company mine at Cote Blanche. Blocks of salt with a volume of approximately 2000 cm^3 were broken from the walls with a geological hammer, placed in cloth sample bags, and returned to the laboratory for analysis.

Ten locations were sampled from the 800 foot level in the Weeks Island mine. Most of the sample locations were on the east side of the mine near the shear zone as identified by Kupfer, personal communication, 1977 B. The mine level coordinates of the pillars from which the samples were taken are listed in Table V-F-1. The salt samples were generally pure salt with occasional dark bands of anhydrite. In sample 18-19-V (DB), a very pronounced 1 cm thick band was evident which contained approximately 50 per cent by weight anhydrite.

Several samples were collected from 8 locations at the 1320 ft level in the Cote Blanche mine. The coordinates of the pillars which were sampled are also listed in Table V-F-1. Blending of light colored salt with darker colored streaks of anhydrite and salt was very evident in all these samples. An effort was made in the laboratory to restrict the

sampling to single light or dark bands. These samples are identified by additional numbers following the mine location designation. For example, the sample 21-L-N-3-1A refers to the first run (A) of the first bank (1) in the third sample (3) collected at 21 and L corridors in the northern (N) part of the Cote Blanche mine.

Table V-F-1. Mine level coordinates of salt samples collected at Weeks Island salt mine and Cote Blanche mine.

<u>Weeks Island</u>	<u>Cote Blanche</u>
14 between X and W	20-K-North
14-V	21-L-North
between 17 & 18	25-G-North
between 18 & 19	25-L-South
19 between S & T	29-K-South
20-O-East	21-M-South
21-J-East	21-N-South
23-H	18-I-South
23-G	
21-D	

6. Results of SEM Studies

The photomicrographs of the water insoluble minerals in the salt samples from Weeks Island dome have produced some interesting preliminary results as illustrated in Figures V-F-1, -2, and -3. The water insoluble mineral grains are predominantly anhydrite in the very fine sand to coarse silt size range. Most of the particles are blocky with smooth surfaces. In some samples the surfaces are marked with striations and features which may be related to dissolution or precipitation. The sizes and shapes of the grains as well as the surface irregularities appear to vary with sample location. The anhydrite grains may also be associated with other minerals such as pyrite, dolomite, magnesite, quartz and others which contain the common trace elements in salt--zinc and nickel. The relationships between

the occurrences of the minerals and the variability of their morphology with respect to diagenetic processes is one of the future studies which we hope will have a direct bearing on the assessment of the reaction between domal salt and the surrounding sediments.

The scanning electron photomicrographs in Figure V-F-1 exhibit the typical features of the mineral grains in the water insoluble residue from the dark band in sample 18-19-V (DB). In the general views of the sample (A and B in Figure V-F-1) the blocky to slightly tabular, 0.1 to 0.2 mm grains of anhydrite are dominant. In photo B, the anhydrite grain in the center of the field of view partially encloses two quartz grains with distinct pyramidal crystal terminations. At higher magnifications (photos C and D), two types of parallel features may be observed on certain anhydrite grains. The striations in photo C are the result of crystal growth. In photo D, the more irregular parallel ridges and grooves are more difficult to interpret. They may have originated as dissolution features produced by etching in brines which were undersaturated with respect to anhydrite, or alternatively, they may have resulted from crystal growth.

In Figure V-F-2, additional photomicrographs illustrate the morphological variability of mineral grains in 4 other samples of salt from Weeks Island. Photomicrographs A and B in this Figure are from the 17-18-W and 21-J-East locations, respectively. Larger particles are apparent in both, and the grain-size distribution frequency appears bimodal. Many particles are about 0.4 - 0.5 mm in size, while others are closer to 0.1 mm in average length. The irregular surface features appear to be more common in photo B of this figure. In a sample (18-19-V (WC)) that contained large halite crystals (in Figure V-F-2), the anhydrite grains are more irregular

Figure V-F-1. Scanning electron photomicrographs (SEM) illustrating the morphological variability in a simple sample of the water insoluble residue from a Weeks Island salt sample.

Figure V-F-2. SEM photomicrographs illustrating the morphological variability of four water insoluble residues from Weeks Island salt.

in shape than the ones discussed above. The most irregularly shaped anhydrite grains were present in sample 20-K-North (photo D in Figure V-F-2).

Sample 20-G-East (photo A in Figure V-F-3) contained anhydrite grains with the most corroded appearance of the samples observed. In the other scanning electron photomicrographs of Figure V-F-3, clay mineral rich residues from 21-J-East may be observed in B, fractured anhydrite is dominant in C from sample 18-K-North, and very platy anhydrite from sample 20-O-East is present in D. The central mineral grain in the last photo is a crystal of hematite (iron oxide) or limonite (iron hydroxide). Additional scanning electron microscope studies are underway which should make it possible to determine whether the morphological changes illustrated in this figure and the previous ones are the result of original depositional conditions, or produced by shearing forces during domal growth or interactions of the salt with the surrounding sediments.

Examples of individual mineral grains (other than anhydrite) are illustrated in Figure V-F-4. A rhombohedral dolomite crystal is the largest crystal present in photo A of this figure. Two smaller rhombohedra of the same material form interpenetrating twins near the center of the photomicrograph. The large dolomite crystal appears to engulf 2 smaller quartz crystals (photo A, upper right and lower left) and a pyrite crystal (photo A, lower right). A mixed aluminum and magnesium phase, which may be a gibbsite and brucite intergrowth, is present in photo B in Figure V-F-4. Pyrite (photo C) and magnesite (photo D) are common in many samples. Identification of these crystals is helping to interpret the chemical history of the salt, especially the distribution of trace elements.

Figure V-F-3. SEM photomicrographs of anhydrite grains and other minerals in the water insoluble residue from salt samples

Figure V-F-4. SEM photomicrographs of hand picked grains from the water insoluble residue of salt: A) dolomite; B) gibbsite and brucite; C) pyrite; and D) magnesite.

Table V-F-2. Results of chemical analyses of salt from Weeks Island and Cote Blanche salt mines.

[Values are tabulated as parts per million]

Sample Location	Sequence Number	Sodium	Potassium	Magnesium	Calcium	Strontium	Chloride	Sulfate
Weeks Island salt mine								
18-19-V (WC)	A	384,000	500	26	370	0	- -	1,262
	B	330,000	499	18	465	0	- -	- -
18-19-V (DB)	A	- - *	418	13	12,700	3.3	- -	33,100
	B	- -	443	17	17,000	2.7	- -	46,800
20-0-E	A	380,000	81	6	8,220	1.7	- -	27,450
	B	372,000	75	10	8,600	1.7	- -	26,950
H-23	A	- -	111	3	23	0	- -	- -
	B	341,000	103	2	15	0	- -	- -
17-18-W	A	- -	401	43	4,060	1.7	- -	8,970
	B	390,000	396	51	3,720	1.3	- -	8,150
21-J-E	A	- -	12	3	2,520	0.4	- -	6,200
	B	- -	8	4	26	0.4	- -	4,950
Cote Blanche salt mine								
21-M-S	A	- -	183	4	3,240	0.4	- -	7,400
	B	- -	180	4	3,460	0.5	- -	7,950
20-K-N	A	- -	760	285	3,930	0.9	- -	9,900
	B	- -	818	389	4,150	0.5	- -	9,300
18-I-S	A	- -	8,060	422	519	1.2	- -	15,300
	B	- -	9,390	445	4,790	1.0	- -	11,250
21-L-N	1-1A	321,000	60	8	619	10.0	650,000	8,518
	1-1B	- -	60	9	697	7.0	667,000	8,930
	1-2A	299,000	80	- -	- -	15.0	649,000	7,290
	1-2B	307,000	65	- -	5,480	0	639,000	7,380
	1-3A	374,000	50	7	6,280	10.0	621,000	10,160
	1-3B	379,000	45	7	- -	13.0	649,000	11,204
	1-4A	345,000	60	6	6,990	10.0	669,000	8,260
	1-4B	344,000	50	6	7,080	8.0	640,000	9,990
	1-5A	343,000	55	7	21,600	24.0	621,000	24,820
	1-5B	347,000	56	7	20,400	23.0	602,000	25,230

* Analysis not completed.

Table V-F-2, continued.

Sample Location	Sequence Number	Sodium	Potassium	Magnesium	Calcium	Strontium	Choloride	Sulfate
Cote Blanche salt mine								
21-L-N	1-6A	368,000	55	6	160	3.6	604,000	2,540
	1-6B	353,000	52	6	204	6.5	622,000	2,120
	1-7A	335,000	61	15	139	5.6	664,000	2,030
	1-7B	342,000	60	15	139	3.7	667,000	2,360
	1-8A	- - *	62	15	3,460	5.5	636,000	12,430
	1-8B	- -	61	13	4,000	6.5	623,000	11,890
	1-9A	- -	56	5	339	2.0	668,000	- -
	1-9B	- -	- -	8	398	2.0	649,000	2,120
	1-10A	487,000	40	7	3,990	5.0	621,000	10,680
	1-10B	476,000	40	7	3,980	4.0	619,000	10,920
	1-11A	409,000	37	7	3,060	5.6	667,000	- -
	1-11B	407,000	37	6	3,120	1.8	642,000	- -
	1-12A	399,000	60	6	1,300	2.0	659,000	- -
	1-12B	392,000	40	6	1,400	2.0	640,000	- -
	1-13A	- -	20	8	3,590	9.0	640,000	- -
	1-13B	- -	19	7	2,170	3.8	631,000	- -
	1-14A	- -	40	9	2,400	4.5	641,000	- -
	1-14B	- -	20	8	2,200	3.0	640,000	- -
	3-1A	- -	30	5	2,200	0	622,000	3,150
	3-1B	- -	30	5	2,100	0	630,000	3,060
	3-2A	- -	35	5	1,900	0	650,000	3,140
	3-2B	- -	40	8	3,190	0	- -	5,400
	3-3A	- -	50	6	2,390	0	621,000	6,180
	3-3B	- -	45	5	2,290	0	640,000	6,690
	3-4A	- -	30	4	2,400	0	621,000	4,270
	3-4B	- -	30	6	2,700	0	650,000	4,700
	I4-1A	- -	- -	- -	2,200	- -	660,000	4,320
	I4-1B	- -	- -	- -	2,310	- -	619,000	3,950
	I4-2A	- -	- -	- -	2,120	- -	- -	5,620
	I4-2B	- -	- -	- -	195	- -	- -	5,520

* Analysis not completed.

Table V-F-2, continued.

Sample Location	Sequence Number	Sodium	Potassium	Magnesium	Calcium	Strontium	Choloride	Sulfate
Cote Blanche salt mine								
21-L-N	I4-3A	- - *	- -	- -	2,120	- -	- -	3,860
	I4-3B	- -	- -	- -	2,200	- -	- -	3,780
	I4-4A	- -	- -	- -	1,990	- -	- -	2,970
	I4-4B	- -	- -	- -	1,790	- -	- -	2,710
	II4-1A	- -	- -	- -	2,700	- -	- -	4,010
	II4-1B	- -	- -	- -	2,790	- -	- -	4,010
	II4-2A	- -	- -	- -	- -	- -	- -	2,970
	II4-2B	- -	- -	- -	- -	- -	- -	3,140
	II4-3A	- -	- -	- -	- -	- -	- -	4,750
	II4-3B	- -	- -	- -	- -	- -	- -	4,800
	II4-4A	- -	- -	- -	- -	- -	- -	9,200
	II4-4B	- -	- -	- -	- -	- -	- -	9,450
	5-1A	- -	- -	- -	- -	- -	- -	- -
	5-1B	- -	- -	- -	- -	- -	- -	- -
	5-2A	- -	- -	- -	- -	- -	- -	- -
	5-2B	- -	- -	- -	- -	- -	- -	- -
	5-3A	- -	- -	- -	- -	- -	- -	- -
	5-3B	- -	- -	- -	- -	- -	- -	1,280
	5-4A	- -	- -	- -	- -	- -	- -	8,400
	5-4B	- -	- -	- -	- -	- -	- -	7,160
	5-5A	- -	- -	- -	- -	- -	- -	6,960
	5-5B	- -	- -	- -	- -	- -	- -	7,250
21-N-S	1-1A	- -	- -	- -	- -	- -	- -	5,880
	1-1B	- -	- -	- -	- -	- -	- -	5,200
	1-2A	- -	- -	- -	- -	- -	- -	- -
	1-2B	- -	- -	- -	- -	- -	- -	- -
	1-3A	- -	- -	- -	- -	- -	- -	- -
	1-3B	- -	- -	- -	- -	- -	- -	- -
	1-4A	- -	- -	- -	- -	- -	- -	8,700
	1-4B	- -	- -	- -	- -	- -	- -	9,040

* Analysis not completed.

Table 2, continued.

Sample Location	Sequence Number	Sodium	Potassium	Magnesium	Calcium	Strontium	Choloride	Sulfate
Cote Blanche salt mine								
21-N-S	2-1A	- - *	- -	- -	- -	- -	- -	5,140
	2-1B	- -	- -	- -	- -	- -	- -	5,050
	2-2A	- -	- -	- -	- -	- -	- -	18,700
	2-2B	- -	- -	- -	- -	- -	- -	17,500
	2-3A	- -	- -	- -	- -	- -	- -	22,800
	2-3B	- -	- -	- -	- -	- -	- -	28,200
	2-4A	- -	- -	- -	- -	- -	- -	17,900
	2-4B	- -	- -	- -	- -	- -	- -	17,900
	2-5A	- -	- -	- -	- -	- -	- -	6,820
	2-5B	- -	- -	- -	- -	- -	- -	6,850
	2-6A	- -	- -	- -	- -	- -	- -	3,110
	2-6B	- -	- -	- -	- -	- -	- -	- -
	2-7A	- -	- -	- -	- -	- -	- -	26,600
	2-7B	- -	- -	- -	- -	- -	- -	19,600
	3-1A	- -	- -	- -	- -	- -	- -	- -
	3-1B	- -	- -	- -	- -	- -	- -	- -
	3-2A	- -	- -	- -	- -	- -	- -	- -
	3-2B	- -	- -	- -	- -	- -	- -	- -
	3-3A	- -	- -	- -	- -	- -	- -	4,360
	3-3B	- -	- -	- -	- -	- -	- -	4,170
	3-4A	- -	- -	- -	- -	- -	- -	10,000
	3-4B	- -	- -	- -	- -	- -	- -	10,800
	3-5A	- -	- -	- -	- -	- -	- -	20,100
	3-5B	- -	- -	- -	- -	- -	- -	23,900
	3-6A	- -	- -	- -	- -	- -	- -	17,800
	3-6B	- -	- -	- -	- -	- -	- -	15,300

* Analysis not completed.

7. Results of Chemical Determinations

Partial chemical analyses of approximately 60 salt samples are shown in Table V-F-2. Ranges of values for the chemical constituents analyzed are shown in Table V-F-3. These determinations form the initial baseline data on the chemical variability of Gulf Coast salt and brines generated from the salt. The method of standard additions was necessary in all the atomic absorption analyses because of the reasons discussed below.

Table V-F-3. Range of values detected in quantitative chemical analyses of salt sample from Weeks Island and Cote Blanche mines.

<u>Chemical Constituent</u>	<u>Range (ppm)</u>
Sodium	299,000 - 487,100
Strontium	0.0 - 24.0
Potassium	8.0 - 9390
Calcium	15.0 - 21,600
Magnesium	2.2 - 445
Chloride	602,000 - 668,000
Sulfate	46.0 - 15,300

The results of atomic absorption analyses must be calibrated with solutions containing known concentrations of the elements to be determined. In most cases this can be accomplished by dissolving a known weight of the pure element in a fixed volume of distilled water and then relating the measured absorbance to the prepared concentration. The relationship is usually linear with a zero intercept and variable slope depending on a number of operating conditions.

Occasionally, the samples being analyzed may exhibit a tendency to produce incorrect results by this technique because of a variety of interferences which are generally referred to as "matrix" effects. This problem

can be overcome in many cases by adding multiple increments of the element being determined to separate aliquots of the sample being analyzed (standard additions).

In the determination of the potassium, calcium, magnesium, and strontium concentrations in the salt samples reported in Table V-F-2, a large difference was detected in the slopes of the equations relating absorbance to concentration. These equations are tabulated for comparison in Table V-F-4.

Table V-F-4. Equations used to calibrate elemental determinations by atomic absorption spectroscopy.

Element	Distilled Water Standards	Standard Additions
Potassium	$\text{ppm} = 0.12 + 20.9 (\text{abs.})^*$	$\text{ppm} = 0.12 + 10.1 (\text{abs.})$
Calcium	$\text{ppm} = 0.10 + 18.2 (\text{abs.})$	$\text{ppm} = 14.2 (\text{abs.})$
Magnesium	$\text{ppm} = 1.50 (\text{abs.})$	$\text{ppm} = 1.75 (\text{abs.})$
Strontium	$\text{ppm} = 30.0 (\text{abs.})$	$\text{ppm} = 38.6 (\text{abs.})$
Sodium	$\text{ppm} = 5440 (\text{abs.})$	$\text{ppm} = 5400 (\text{abs.})$

* abs. = absorbance

For calcium and potassium, a small positive intercept was included in the calculations involving distilled water standards. For standard additions, only the line representing the potassium calibration curve failed to go through zero. This effect is probably related to the ionization interference between sodium and potassium. Sodium was also determined by the additions method even though the differences in the test results were

negligible. Observing these precautions will help guarantee the reliability and reproducibility of the analytical results.

The results of the chemical determinations are shown in Table V-F-2. A rigorous evaluation of the changes detected was not attempted at this time because the results are not complete for all samples and the data are only from a few locations at this time.

8. Summary and Recommendations

The geochemical investigation has begun to produce interesting results on the mineralogy and chemical composition of Gulf Coast salt. The laboratory techniques have been established after rigorous testing. Changes in the characteristics of the water insoluble minerals in the salt have been observed and many of the trace elements in the salt have been assigned to specific mineral phases. However, all the results obtained to date must be tested with more samples from various field locations and specific analyses of salt and associated materials in the vicinity of Vacherie and Rayburn's domes. Plans to analyze these samples and additional chemical tests have been proposed for fiscal years 1978 and 1979.

The results obtained by these additional tests and new samples must then be interpreted to assess their overall applicability to the solution of the project goals. When this is completed, we should have first hand geochemical information on the origin of brines associated with aquifers near salt domes. Such information will be an important input in our assessment of whether the salt in the domal masses is stable hydrologically.

9. Acknowledgements

The work was carried out with the assistance of several undergraduate and graduate assistants including: Richard Brown, Paul Carpenter, Lori

Governale, Clark Hanna, Patti Harper, Robert Hixon, Patti Phillips, Becky Robertson and Cleason Smith.

V-G. MINERAL RESOURCE MAPS OF
VACHERIE AND RAYBURN'S SALT DOME AREAS

R. A. Barlow and J. K. Whisman

Two maps were prepared showing the location of important mineral resource developments at Vacherie and Rayburn's salt dome areas (Figures V-G-1, and V-G-2, respectively). These resources include oil and gas, ground water, gravel, and (potentially) lignite. Ground water and oil and gas are by far the most abundant and most thoroughly developed resources. One large active gravel pit is located north of Vacherie dome and, as yet, lignite resources are in a preliminary stage of evaluation. Well locations and depths are listed in Table V-G-1 (Vacherie area) and Table V-G-2 (Rayburn's area).

1. Oil and Gas

Vacherie area. Portions of three oil and gas fields are shown on the Vacherie map (Sibley, Ada, and Sailes) as well as wildcat wells. The closest production is approximately two miles northeast of the dome (Ada field). The depths of these wells range from 5400 to 7400 ft.

Rayburn's area. Portions of four oil and gas fields are shown on the Rayburn's map (Lucky, Liberty Hill, Danville, Saline) as well as wildcat wells. The closest production is just over two miles southeast of the dome (Danville field). Depths for these wells range from 8800 to 9800 ft.

2. Ground Water

Ground water is a valuable resource in north Louisiana. The two major producing aquifers in the area are the Sparta (Eocene) and

Wilcox (Eocene - Paleocene). The nearest commercial or public wells to the domes (ignoring small domestic wells) are as follows:

Vacherie: Central School well--1.5 miles northwest

Gravel Pit wells--2.0 miles north

Rayburn's: Wells #W-(Bi)100--0.2 miles southeast
#W-(Bi)165

Friendship wells--1.75 miles east

3. Gravel

Because permits are not required for gravel pit operations in Louisiana, there are no official records of active gravel pit locations. However, investigations of aerial photographs of the dome areas indicate that the only active commercial interest of any significance is the "silica mine" in Sparta sands approximately two miles north of Vacherie dome. This pit is operated by Dresser Industries.

4. Lignite

Nearly the entire area shown on the maps is leased either to Phillips Petroleum or Shell Oil Companies for exploration purposes. At this time no specific data as to present or planned test holes are available. Various LSU drilling operations have encountered some lignite deposits. However, the findings are insufficient to anticipate possible economic potentials.

5. Data Sources

a. Oil and gas wells. Data sources for oil and gas wells are as follows:

- 1) Commercial oil and gas map of north Louisiana, marketed by Globe Co., Shreveport, Louisiana.

2) Oil and gas map supplied by a major oil company as base information for C. Crowe's Masters Thesis on Vacherie dome (Crowe, 1975).

3) Continually updated oil and gas map maintained by the Louisiana Department of Natural Resources.

Where the various maps did not agree on well status and/or location, the information contained on the Louisiana Department of Natural Resources maps was used.

b. Water Wells. Information regarding all water wells was obtained from the records of the U. S. Geological Survey Water Resources Branch, Baton Rouge, Louisiana.

c. Gravel Pits. Because these operations are not recorded by state agencies, color aerial photographs were used to locate operating gravel pits.

6. Acknowledgement

This work was done under the direction of C. G. Smith, who provided guidance and background information.

Table V-G-1. Existing wells, Vacherie dome area.

VACHERIE DOME AREA - OIL AND GAS WELLS											
Township	Range	Section	Well #	Name	Total Depth (ft.)	Township	Range	Section	Well #	Name	Total Depth (ft.)
18N	9W	22	1	Atlantic Dant #1	4,019	18N	9W	35	1	N. A.	8,995
			23	Arlda Wereberrin #1	8,612				2	Wilson Crichton C-1	6,735
		24	2	S. W. Nat. Prod. Frazier-Wilscout #1	7,155				3	Wilson A-1	N. A.
			1	N. A.	9,045				4	N. A.	5,800
			2	Delta Burson #1	6,795				5	Wilson Bodcaw B-1	6,810
		25	3	Delta Glass B-1	8,940				6	Sklar et al Kennon	6,810
			1	Steward B-1	N. A.				7	Crichton Fitt & Perritt	N. A.
			2	Frank et al. Crichton #1	7,251				8	J. P. Evans Aichton #1	N. A.
			3	Atlantic R. Connell #2	6,931				9	Wilson Roberts #1	5,736
			4	N. A.	N. A.				10	Ray Burson #1	5,818
			5	Halsey Circleton #1	5,700			36	1	Atlantic Balton A-1	8,521
			6	Atlantic Glass #1	5,872				2	Franks et al. Crichton	N. A.
			7	Atlantic Vice #1	5,866				3	Ambrose Connell #1	5,875
			8	Atlantic Vice #2	6,705				4	J. P. Evans Crichton #1	N. A.
		26	1	Dods Pet. R. V. Smith #1	6,975				5	N. A.	N. A.
			2	Atlantic Halley #1	10,863				6	Sklar Balton #1	6,812
			3	N. A.	7,612	18N	8W	19	1	Delta Gibbs #1	6,615
		27	1	Evans Burson #1	3,515				2	N. A.	8,700
			2	S. W. Nat. Burson #1	N. A.				1	Regan #1	N. A.
			3	Atlantic Cooke #1	5,040				2	Ducole Woodward #1	2,418
			4	N. A.	9,462				3	Harry W. Boss #1	7,125
			5	Grigsby Cooke #1	4,916				4	Atlantic Harvey #1	7,229
		28	1	N. A.	7,300			21	1	Doran Perryman #1	10,625
			33	Brooks Burson #3	4,875				2	N. A.	N. A.
			2	Franks Reed #5	5,812			22	1	N. A.	2,755
		34	3	Delta Caribbeau Reed #1	7,112				2	Carter Johnson #1	6,690
			1	Brooks Burson #1	5,104			23	1	Marion Eates #1	6,571
			2	Atlantic Burson #1	4,950				2	A. W. Woodward	8,980
		35	3	Atlantic Roberts #2	N. A.				3	J. S. Rushing Mason #1	7,436
			4	Atlantic Roberts #1	4,383			24	1	Barnwell Mason # 1	7,677
			5	Dode Pet. Roberts #1	7,150				2	Monsauto Bert #1	8,775
			6	Evans Olrich #1	6,935			25	1	Carter Walker #2	8,005
			7	Atlantic Burton	14,252				2	Rushing Mattie #1	7,687
			8	Olrich #7	N. A.				3	Humble (Carter O. Co) Woodward #1	8,175
			9	Crichton #1	N. A.			26	1	Carter Bates #1	5,722
			10	Wilson	N. A.				2	Carter Gleason #1	4,448
			11	Crichton B-1	N. A.				3	Carter Woodward #1	8,968
		36	12	Duncan Beatly #1	5,760			27	4	N. A.	4,475
									5	N. A.	N. A.
									1	Carter Davis #1	6,646
		37						28	2	Mon. #2	4,433
									3	Carter Davis #3	4,465

Table V-G-1, continued.

VACHERIE DOME AREA - OIL AND GAS WELLS														
Township	Range	Section	Well #	Name	Total Depth (ft.)	Township	Range	Section	Well #	Name	Total Depth (ft.)			
18N (cont.)	8W	27	4	Kean #1	2,445	18N (cont.)	7W	32	1	N. A.	8,200			
			5	Carter Davis #2	5,702				2	N. A.	10,009			
			6	Crow Davis #1	4,435				3	F. Whitader A. F. White #1	8,955			
			7	N. A.	5,534				4	S. W. Nat. Prod. White #1	7,643			
			8	N. A.	3,008				5	Atlantic W. L. Horne #2	N. A.			
		28	1	Rushing Carter #1	7,755				6	Atlantic Mc Caudlish	5,950			
			2	Harvey	5,707				33	1	N. A.	N. A.		
			3	N. A.	7,062					2	S. W. N. P. Smith #1	8,515		
			4	N. A.	5,955					3	S. W. Nat. White A-1	8,452		
			5	Archie Davis #1	6,841					4	Hunt Neba Fee #1	8,260		
		29	1	N. A.	6,078			5		N. A.	4,125			
			2	Tillman #1	7,850			6		Atlantic #1	5,917			
			3	Crow #1	5,534			7		N. A.	5,940			
			4	Carter #1	5,855			8		N. A.	7,627			
			5	N. A.	7,470			9		N. A.	7,918			
		30	1	N. A.	8,450			10		N. A.	5,915			
			2	Atlantic Nicholson#1	7,100			17N	9W	2	1	S. O. Co. Franks	8,936	
			3	Union P. Walker B-1	10,383						2	Methodist	4,781	
		31	1	N. A.	N. A.						3	N. A.	7,202	
			33	1	Carter Johnson						7,840	4	Moffitt-Perrett Fuducker	5,729
				2	Carter Davis #1						7,259	1	Gray West Unit # 1	6,360
				3	N. A.						7,317	2	Atlantic Recg. #1	5,777
		34		1	Carter Feldman #1					5,323	3	Franks Sims #1	9,400	
			2	N. A.	4,463					4	Wilson Goodwill	5,750		
			3	N. A.	4,465					5	Placid Starts	8,660		
			4	N. A.	4,460					6	N. A.	6,685		
			5	N. A.	14,146					7	N. A.	5,760		
			6	N. A.	6,460					8	Placid Starra #1	5,759		
			7	N. A.	5,855					9	N. A.	6,639		
			8	N. A.	4,448					1	Franks et al Read #1	6,729		
			9	Rushing et al. Butler #1	5,753					2	N. A.	8,615		
			10	N. A.	9,450					3	N. A.	4,154		
		35	1	N. A.	4,450					4	4	Atlantic R. A. Reed #1	5,902	
			2	Hope Woodward Walker #2	5,776						5	N. A.	6,710	
			3	Humble (Carter)	10,192						6	Atlantic Dreit #2	N. A.	
			36	1	N. A.						N. A.	7	Atlantic Dreit #1	5,925
				2	Carter Francis #1						8,070	8	N. A.	5,905
		3		Carter Woodware #1	6,673						9	Lehman	2,287	
		4		Carter W. Morris #1	N. A.						1	N. A.	N. A.	
		5		Carter A. Walker	7,588					2	Brooks L. L. Morgan #1	5,694		
18N	7W	19	1	Franks Ogysum #1	8,700	9	3			Brooks J. D. Hait #1	5,861			
			1	Brown Evans J.J. Miles #1	2,915		1			N. A.	9,035			
		28	1	Arkla Exp. Jackson #1	9,020		10			2	N. A.	5,772		
			29	1	S.W. Nat Prod Broodwill #1					8,411	3	Skelly T. O. Ramsey #1	5,738	
				2	N. A.					9,020				
		30	1	Carter Oil Meiritt #1	8,046									
			31	1	Humble Walker A-1			7,500						
		2		Carter Smith #1	7,323									
		3		N. A.	9,016									

Table V-G-1, continued.

VACHERIE DOME AREA - OIL AND GAS WELLS													
Township	Range	Section	Well #	Name	Total Depth (ft.)	Township	Range	Section	Well #	Name	Total Depth (ft.)		
17N (cont.)	9W	10	4	Z. Brooks Felts #1	5,945	17N (Cont.)	8W	16	5	S. O. Co. R. Jordan #1	897		
			11	1	N. A.				N. A.	18	1	Shuler et al Moore #1	5,320
			2	W. C. Feazel Tillman #1	6,075				20	1	Pan Am. E. J. Smith #1	5,417	
		14	1	J. K. Wadley J. M. Pearch et al #1	3,350				21	1	Standard Scott #1	2,558	
			16	1	N. A.			9,914			2	S. O. Co. L. Stephens #1	798
		24	1	Midway O. & G. W. M. Coleman #1	1,420				22	1	Lion O. Co. Woodward #1	1,843	
			2	S. A. Lane M. Miles #1	1,469					23	1	Garfield et al Woodward et al #1	5,414
		34	1	N. A.	N. A.				28		1	Amerada (Barnwell) Connell #1	10,006
			36	1	Petra Jones #1			5,935			31	1	Norton Oil Co. Reeve #1
		2		Tridant Ward #1	6,705				32			N. A.	N. A.
17N	8W	1	1	Carter O. Co. Walker #1	5,702		34	1	Tesora Lawhon #1	7,201			
			2	Carter O. Co. B. Woodward #1	6,870			17N	7W	4	1	N. A.	5,920
			3	N. A.	5,706						2	N. A.	9,224
		2	1	Carter O. Co. Bates et al	5,407		3				Cardinal Kendrick #1	5,925	
			2	Carter O. Co. H. Walker	5,425		4			N. A.	7,663		
		3	1	N. A.	5,404		5			1	Atlantic Youngblood #1	9,513	
			4	Carter O. Co. E. Stark #1	5,785					2	Atlantic Hammer #1	7,536	
		5	1	N. A.	N. A.		3			1	N. A.	N. A.	
			6	Carter Edwards	5,698					3	Atlantic Courtney Gas #1	5,804	
		7	1	N. A.	5,453		4			1	Leonard Courtney #1	7,324	
			8	Sam Skiar et al P. Mott	7,103					6	1	Carter J. W. Baker #1	6,939
		9	1	J. Rushing Woodward #1	5,680		2				N. A.	5,255	
			10	1	Carter O. Co. Woodward #1	6,850				3	N. A.	5,750	
		3		1	Hope Prod. Co. M. A. Davis	5,667				4	Butler Johnson (Carter Oil)	8,520	
			2	1	Carter O. Co. R. Calbert-Davis #1	5,469				9	1	Phillips Petrofunds #1	10,016
		9		1	H. H. Temple #1	1,872					16	1	Phillips Baker #1
			2	1	Woodward & Walker Stewart #1	3,626				17		1	Phillips Baker
		10		1	Pan Amer. Pet. B. F. Rowland #1	8,955					2	Wegman Stewart et al	3,705
			11	1	Carter Oil A. Walker #1	7,400				19	1	Union Prod. Woodward-Walker #1	6,313
		2		1	Carter Oil A. Walker #2	7,300		2	Carter-Jones Woodward-Walker #1		7,318		
			3	1	Carter Oil J. Johnson #1	5,841		28	1	Franks Woodward-Walker #1	10,220		
		14		1	N. A.	7,580			29	1	Wheless Drig. Cole #1	8,244	
			2	1	Coulsin Walker #1	5,828		2		N. A.	7,492		
		3		1	D. D. Montgomery Woodward & Walker	4,289		30	1	Franks et al Brown et al #1	10,488		
			15	1	Shuler et al Scott #1	5,367			31	1	W. F. Hyde J. S. Cole et al #1	6,929	
		16		1	Stewart Oil #1 Test Hole	1,107		2		N. A.			
			2	1	S. O. Co. J. C. Woodward #1	1,872		3	Arlda et al Page #1	9,217			
		3		1	Crow & Ford #1	960		4	1	Ohio O. Co. Woodward-Walker #1	7,010		
			4	1	C. S. Clarke T. J. Jordan #1	603			32	1	Ohio O. Co. Crow #1	7,698	
							2	Franks et al. Sallies #1		10,237			
								3	Ark. Fuel O. Co. Woodward-Walker #1	6,875			

Table V-G-1, continued.

VACHERIE DOME AREA - OIL AND GAS WELLS						VACHERIE DOME AREA - WATER WELLS								
Township	Range	Section	Well #	Name	Total Depth (ft.)	Township	Range	Section	Well # (USGS)	Well Depth(ft.)	Aquifer			
17N (cont.)	7W	32	4	Kinsey et al Woodward	7,700	18N	9W	21	Wb-342	no well made				
				Wb-216	200				Sparta					
				Wb-217	144				Sparta					
	Wb-218	170	Sparta											
	Wb-247	107	Sparta											
	Wb-347	113	Sparta											
16N	9W	1	1	Franks et al Ryan #1	5,910			22	Wb- 63	95				
				Wb-263	185				Sparta					
				Wb-219	136				Sparta					
			Wb-343	no well made										
		11	1	Crow Drill. et al Scott	N. A.			24	Wb-258	test hole	Sparta			
				Wb-252	174				Sparta					
			Wb- 58	210										
			Wb-221	132	Sparta									
		12	1	Bond Davis #1	6,807			28	Wb-345	92	Sparta			
				Wb-344	84				Pleistocene					
			Wb-134	94	Pleistocene									
16N	8W	1	1	Franks et al Smith #1	9,849			18N	8W	33	Wb- 50	14	Sparta	
		3	1	Madden Lowery #1	3,005	19	Wb-253			90	Sparta			
				Wb-259	233		Sparta							
			Wb-271	220	Sparta									
		20	Wb-254	72	Sparta									
			30	Wb-329 A,B	140,490	Sparta, Wilcox								
		34		Wb-213	110	Sparta								
				Wb-214	110	Sparta								
		17N	9W	No water wells in this portion of T & R						14	Wb-249	438	(Wilcox)	
					Wb-250	458	Wilcox							
					Wb-167	175	Sparta							
					Wb- 65	100								
					Wb- 39	102								
				22	Wb-290	178	Wilcox							
					Wb-334	277	Wilcox							
				26	Wb-332	no well made								
					27	Wb-296	342				Wilcox			
				35		Wb-333	no well made							
		17N	8W		5	Wb-314	230	Sparta						
				Wb-315		190	Sparta							
				7	Wb-281	462	Wilcox							
					15	LSU-4	754	Wilcox						
				17		LSU-7	849							
					22	LSU-6	643	Wilcox						
						LSU-5	815							
				34	Bi-70	255								
					29	Bi- 68	180							
16N	9W			3		Bi-143 A,B	210,351	Wilcox						
		no water wells												
16N	8W	no water wells												
		16N	7W	no water wells										

RAYBURN'S DOME AREA - OIL AND GAS WELLS

Township	Range	Section	Number	Well Name	Total Depth (ft.)	Township	Range	Section	Number	Well Name	Total Depth (ft.)
T14N	R5W	1	1	Sohio Caston	10,000	T14N	R5W	30	1	Bodcaw Co. Fee 5	9,716
			2	Franks & Petrofunds Robertson	8,683				2	Bodcaw Co. Fee 1	8,686
			3	E. K. Oil Company Tardo 1	8,719				3	Union Hunt Bodcaw 1	7,784
		2	1	Petrofunds Franks G-1	8,729	T14N	R6W	1	1	N. A.	2,572
		4	1	G. E. Buddecke Barron 1	9,066			8	1	Frank Vuci O. Co. Evans 1	1,058
		8	1	Franks & Petrofunds Prey 1	9,320				2	Frank Vuci O. Co. Woodard Walker 1	4,000
		9	1	Franks & Petrofunds Williamette B-1	9,014			11	1	N. A.	8,390
		10	1	Franks & Petrofunds Cont'l Can 1	9,050			13	1	N. A.	9,805
		11	1	Petrofunds & SunnySouth Pardee 1	8,708			14	1	Discovery Union Producing Co. Frazier 1	6,840
			2	Petrofunds Hass 1	9,000				2	Frank L. Vuci Evans	11,330
			3	N. A.	8,818			15	1	N. A.	N. A.
		12	1	N. A.	8,538			18	1	LaGrange Fair 1	5,016
		13	1	N. A.	N. A.			23	1	Union & Pure Barbers 1	6,800
			2	Petrofunds Crowley 1	8,709				2	N. A.	10,700
			3	N. A.	N. A.			24	1	N. A.	9,805
		14	1	Petrofunds Blankenship 1	9,012				2	Bodcaw Franks Texaco Harper	12,631
			2	N. A.	8,818			25	1	N. A.	8,830
		15	1	Franks & Petrofunds Davis 1	8,900			26	1	N. A.	9,807
			2	Franks & Petrofunds C. C. Company	9,009			27	1	Saline Dr. Co. Pardee	3,819
		16	1	N. A.	8,900			28	1	Planters Oil Co. Enlow	2,945
			2	Texaco K. D. Johnson 1	7,531	T15N	R5W	3	1	N. A.	9,010
		17	1	Franks & Petrofunds C. C. Company Inc.	8,894			4	1	Smith & Cameron Smitherman	8,618
		18	1	Petrofunds Hoss 1	9,814			5	1	Franks Gilster Allison 1	8,900
		19	1	Bodcaw Company Fee 2	8,818				2	Union P. Co. Allison 1	8,300
			2	Bodcaw Company Fee 3	11,700			6	1	Placid Sou. Adv. 3	8,600
		20	1	N. A.	8,916			7	1	Placid S. Adv. B-1	8,503
			2	Franks & Petrofunds Hoss B-1	8,914				2	N. A.	N. A.
		21	1	N. A.	8,830			8	1	Placid S. Adv. B. & P. 1	8,875
		22	1	Franks & Petrofunds C. C. Company T-1	8,915				2	Hodge Hunt	3,000
			2	Texaco Inc. Talmadgeiad 1	2,030			9	1	Placid Oil Co. So. Adv. B. & P. B-1	6,800
		23	1	N. A.	8,774			18	1	R. J. Carraway Cont'l Can 1	8,882
			2	N. A.	8,815			19	1	Hodge Hunt C. C. Co. A-1	4,310
		24	1	Petrofunds Cont'l Can Co. L-1	8,782			22	1	Harvey Broyles Cont'l Can Co. A-1	9,056
			2	N. A.	10,160			25	1	Ark. La. G. C. C. Co. 1	9,317
		25	1	N. A.	8,810			29	1	Hodge Hunt Cont'l Can 1	4,120
		26	1	N. A.	8,800				2	Hodge Hunt Fee	3,003
		27	1	N. A.	8,900			31	1	Hodge Hunt Fee	272
		28	1	Franks & Petrofunds C. C. Co. V-1	9,014			36	1	Evans & Copeland Flowers 1	8,816
		29	1	Bodcaw 6	8,915				2	Ark. La. G. Cont. Co. 2	10,220
			2	N. A.	8,816						

Table V-G-2, continued.

RAYBURN'S DOME AREA - OIL AND GAS WELLS						RAYBURN'S DOME AREA - OIL AND GAS WELLS					
Township	Range	Section	Number	Well Name	Total Depth (ft.)	Township	Range	Section	Number	Well Name	Total Depth (ft.)
T15N	R6W	1	1	J. C. Trahan C. C. C. 1	7,900	T16N	R6W	35	2	Franks Gilster Harrison 1	8,108
			2	Robt. F. Roberts Cont'l Can Co. 1	8,530				3	Placid S. Adv. Bag.	8,610
		2	1	Placid I. V. Watson	8,345	36	1	John Franks Martin 1	7,911		
			3	1	Placid Nebo			N. A.			
		2			Placid S. A. B. &P. Co.	8,008					
			4	1	Placid O. Co. 1	8,031					
		5			1	Placid O. Co. Nebo A-2	8,303				
			6	1		Placid Wood 2	13,576				
		2				Placid Nebo 1	N. A.				
			3		Placid O. Co. E. N. Wood 1-A	3,735					
		7		1	Placid Nebo A-9	3,715					
			2			Placid V. Miller 1	N. A.				
		8		1	Penrod Drlg. Co. W. J. Sprawls	N. A.					
			9		1	Placid Wise 1	8,222				
		10		1		Placid Whitney 1	8,102				
			11		1	Placid Watson 1	8,325				
		12		1		Placid Harrison 1	8,529				
			13		1	Bright & Schiff Kemp 1	8,770				
		14		1		David Crow Lybrens 1	8,500				
			15		1	Placid O. Co. Sou. Adv. 2	8,377				
		16		1		Placid O. Co. Sou. Adv. A-4	8,113				
			17		1	Placid Nebo	N. A.				
		2				Benedum & Trees Sprawles	5,005				
			18	1	Placid O. Co. Nebo O. Co. A-3	11,250					
		21			1	N. A.	N. A.				
			22	1		Monsanto Ch. Co. Hunt 1	8,806				
		36			1	Hodge Hunt Cont'l Can 2	4,045				
			2			Hodge Hunt Cont'l Can 3	709				
		3			Hodge Hunt Continental Can 7	4,237					
			31	1	Franks Gilster Cont'l Can	8,180					
		32			1	Wheless Drig. Roden	8,245				
			31	1		Placid O. Co. Nebo O. Co. 6A	8,206				
		32			1	Hunt May 1	N. A.				
			33	1		L. Hunt Cummings 1	8,004				
		34			1	Placid Wilson 1	8,162				
			35	1		Lyonsier O. A. Butler 1	7,975				
RAYBURN'S DOME AREA WATER WELLS											
Township	Range	Section	USGS Number	Well Depth(ft.)	Aquifer						
T14N	R5W	2	Bi-97 Bi-99	312 261	Sparta Sparta						
			6	Bi-100 Bi-165	90 836	Sparta Wilcox					
		12		Bi-102 A Bi-102 B	181 292	Sparta Sparta					
			14	Bi-190	N. A.	N. A.					
		21		Bi-189	N. A.	N. A.					
			22	Bi-188	N. A.	N. A.					
		23		Bi-64	214	N. A.					
			5	Bi-21	106	N. A.					
		27		Bi-95 A Bi-95 B Bi-16	258 718 83	Wilcox Wilcox Sparta					
			28	Bi-96	690	Wilcox					
		T15N		R5W	1	Bi-172 Bi-173 Bi-174 Bi-175 Bi-176	no well made 430 530 no well made 500	Sparta Sparta Sparta Sparta			
			10			Bi-121	342	Sparta			
11	Bi-117 Bi-118 Bi-119 Bi-169 Bi-171				416 382 314 440 430	Sparta Sparta Sparta Sparta Sparta					
	13		Bi-120		403	Sparta					
14			Bi-109 Bi-110 Bi-115		410 336 416	Sparta Sparta Sparta					
	15		Bi-111 Bi-113 Bi-114 Bi-168 Bi-170		376 325 321 410 no well made	Sparta Sparta Sparta Sparta Sparta					
16			Bi-112		348	Sparta					
	22		Bi-116		392	Sparta					
33			Bi-167 A Bi-167 B Bi-11 Bi-171		120 234 195 430	Sparta Sparta Sparta Sparta					
	16		Bi-122		402	Sparta					
26			Bi-77		126	N. A.					
	29		Bi-151		156	Sparta					

V-H. FINDINGS AND RECOMMENDATIONS

R. E. Wilcox

1. Findings

1) A set of over 500 structural and stratigraphic maps of the north Louisiana basin, which were prepared using computer compilation and plotting methods, have been completed and are on file at the Institute for Environmental Studies at LSU.

2) Growth rates for salt domes in the North Louisiana Salt Dome Basin have been calculated using stratigraphic and structural data from sparse well control and computer trend maps. The growth rates must be used with considerable caution because of many uncertainties in the data and in the assumptions used in the calculations. Growth rates for the north Louisiana salt domes, thus derived, are less than 0.1 mm/yr, and average growth rates over long periods of time are less than 0.05 mm/yr. For three such periods, the maximum inferred rates for any dome in the basin are as follows: Cenozoic, 0.03 mm/yr; Upper Cretaceous, 0.02 mm/yr; and Lower Cretaceous, 0.04 mm/yr.

3) Four additional seismic lines in the Vacherie dome area (acquired from the Atlantic Richfield Company) were processed, and preliminary interpretations of these and three other lines were made. The base of the salt layer to which Vacherie salt dome is connected probably lies at a depth of between 16,000 and 17,000 ft below sea level. Some tentative modifications of the contour map of the shape of Vacherie salt dome were made.

4) Bouguer gravity maps for Vacherie and for Rayburn's and Prothro salt domes were prepared using data acquired from industry. Preliminary interpretations support the elliptical shape of Vacherie and the more circular shapes of Rayburn's and Prothro inferred from previous work. Asymmetries in the gravity anomalies of the latter two domes suggest irregular shapes of the salt stocks near the surface.

5) Results of the geochemical work initiated in fiscal year 1977 have produced interesting preliminary data on the mineralogy and chemical composition of Gulf Coast salt-dome salt. Rigorous testing has established a set of analytical techniques. Salt samples from two south Louisiana domes (Weeks Island and Cote Blanche) have been analyzed, and differences in morphology of water-insoluble minerals (mostly anhydrite) have been noted. Also, certain trace elements in the salt have been assigned to specific mineral phases.

6) Mineral resources maps were prepared for Vacherie and Rayburn's salt dome areas.

2. Recommendations

1) Analysis of the computer generated structural and stratigraphic maps of the North Louisiana Salt Dome Basin is in progress and should be completed during the first half of fiscal year 1978.

2) As additional well data and seismic data become available for Vacherie and Rayburn's domes, the growth histories of the domes and their growth rates should be revised.

3) Further seismic surveys of Vacherie and Rayburn's salt domes have been proposed for fiscal year 1978. They are designed to obtain: (a) detailed data on deformation over and around the domes down to 5,000 ft;

(b) similar data to depths of 20,000 ft to aid in developing the growth histories of the domes; (c) profiling of the domes down to 5,000 ft utilizing coreholes in the domes for geophone emplacement; and (d) a regional line through that portion of the basin lying between Vacherie and Rayburn's domes. In addition, more reprocessing of existing data will be attempted using migration techniques and other computer methods.

4) Additional gravity data from north Louisiana purchased from industry sources in late fiscal year 1977 should be compiled and analyzed. Detailed gravity surveys of Vacherie and Rayburn's salt domes have been proposed for fiscal year 1978 in order to further elucidate the exact shape and form of the uppermost portions of the salt stock and any caprock present.

5) Geochemical analysis of salt and other minerals, brines, gases, and hydrocarbons from Gulf Coast salt domes should continue so as to build a set of baseline data. A major effort in geochemistry during fiscal year 1978 will be the detailed analyses of salt cores from Vacherie and Rayburn's domes. Comparison and interpretation of these data will depend heavily upon the baseline studies of samples from salt mines in Gulf Coast domes.

6) Salt cores to be obtained in fiscal year 1978 from Vacherie and Rayburn's domes will be examined by a variety of petrologic and structural methods in addition to the geochemical analyses. As an adjunct to this work, it has been proposed that LSU should build a collection of salt cores and salt samples from mines in Gulf Coast salt domes to be used for comparative studies of the nature and physical properties of salt.

7) In order to prepare detailed geologic maps of the Vacherie and Rayburn's salt dome areas, extensive boring and selected coring programs should be undertaken during the next two fiscal years. Those studies

would provide basic data on the detailed structural and stratigraphic relationships within the Cenozoic and Mesozoic rocks which enclose the salt stocks. All other geological, geophysical, geochemical, hydrological, and pedological studies of these two domes would be enhanced by utilization of such information.

VI. QUATERNARY STUDIES

- A. General
- B. Quaternary Deposits above Vacherie and Rayburn's Domes
- C. Lineations on Vacherie and Rayburn's Domes
- D. Pedologic Investigations
- E. Nature of Quaternary Warping above Domes
- F. Terrace Levels
- G. Topographic Lows above Domes
- H. Drainage Basin Analysis
- I. Erosional Effects during next 250,000 Years
- J. Findings and Recommendations

VI-A. GENERAL

C. R. Kolb

Investigations conducted in fiscal year 1976 concluded that Quaternary deposits of sufficient thickness and lateral extent occurred over Vacherie and Rayburn's domes to warrant an in-depth investigation of their nature and their possible disturbance due to movement of the underlying salt. The age of the Quaternary deposits above both domes is believed to vary from 200,000 years to the present. Thus the history of the stability, or the possible instability, of these two domes may well be recorded in these deposits during this critical span of time.

Consequently it was decided that, where possible, continuously sampled borings would be made at both sites so that the stratification within the Quaternary could be carefully examined for discontinuities or warping--warping which would suggest uplift, or conversely, downward collapse due to dissolution of the underlying salt. Because of the expense involved in studying the Quaternary deposits in sufficient detail above and adjacent to these domes solely by using continuously sampled borings, shallow seismic refraction and related seismic methods were used to obtain a greater sampling of data points at less expense. At the time this report was written (September, 1977) the boring program for Vacherie had been completed in those areas where access rights had been obtained from the property owners, and the boring program at Rayburn's was underway. A shallow seismic refraction survey is underway at Rayburn's and is being planned for Vacherie.

The status of the boring program at both domes, the status of the seismic exploratory program, preliminary results based on the available

boring and seismic data, and the thrust of the boring and seismic programs in the immediate future are outlined in the following section entitled "Quaternary Deposits above Vacherie and Rayburn's Domes".

Companion studies which consider the effects of tectonic and hydrologic instability of the domes on the areal distribution of landforms and the soil sequences associated with them are subsequently covered under appropriate headings. Some of these studies, e.g., remote sensing of lineations over and adjacent to the domes, and the pedologic studies of residual and colluvial soils in the domal areas, are currently underway. Others are in the planning stages. Finally, a summary section is devoted to preliminary findings and recommendations.

VI-B. QUATERNARY DEPOSITS ABOVE VACHERIE AND RAYBURN'S DOMES

C. R. Kolb

1. Pleistocene-Holocene Deposition

The general limits of the deposits laid down during Quaternary time over Vacherie and Rayburn's domes are shown in Figures VI-B-1 and VI-B-2. As more field data are gathered these maps may be modified slightly, but present indications are that the limits as shown in these figures are essentially correct. Preliminary maps of the surface distribution of Tertiary and Cretaceous deposits are shown in Figures IV-B-1 and IV-B-2 of the 1976 report on the study (Martinez, et al., 1976). As boring and related data are being gathered, it becomes evident that fairly extensive changes will be necessary in the mapped distribution of these pre-Quaternary deposits. Such changes could affect the conclusions reached in the Quaternary studies. Certainly they will be helpful in reconstructing the history of tectonism, faulting, and possible dissolution and collapse, in the long hiatus between the deposition of the youngest Tertiary deposits over each dome and the deposition of the Quaternary sediments over these domes. In the case of Rayburn's dome, this time interval amounts to approximately 55 million years and at Vacherie, approximately 50 million years.

Basically, the Quaternary deposits in north Louisiana are those associated with the waxing and waning of the ice sheets during Pleistocene and Holocene times. Quaternary deposits are significantly coarser than, and otherwise lithologically dissimilar to, the early Tertiary and late Cretaceous deposits which form the surface and shallow subsurface materials over Vacherie and Rayburn's domes. Perhaps the most important lithologic distinction between the two is the characteristic occurrence of

Fig. VI-B-1. Index map of lines of borings and seismic refraction traverses made at Vacherie dome.

Fig. VI-B-2. Index map of lines of borings and seismic refraction traverses made at Rayburn's dome.

chert gravels in the Quaternary, and the absence of such gravels in the early Tertiary and late Cretaceous--a reflection of the increased local relief and the erosive power of streams during the Quaternary and the difference in source beds during these two periods of geologic time. Quaternary and pre-Quaternary lithology is described more fully in Section IV-B (Martinez, et al., 1976).

2. Status of Boring and Seismic Programs at Vacherie Dome

Eighty-one borings were made during the 1977 fiscal year at Vacherie dome in order to sample, as continuously as possible, the Quaternary deposits and the upper portions of the underlying Tertiary deposits. The soil samples and cores are being logged on an inch-by-inch basis in the Quaternary Studies laboratory at LSU at this time (September 1977). Some of the samples are being subjected to chemical tests in the Pedologic laboratory at LSU, and others are being analyzed for grain-size distribution in the Soil Mechanics laboratory. Color photographs are being taken of the cores for classification and record purposes. Preliminary visual classification of the soils sequence has been completed for approximately 75 per cent of these borings, and some of the results from the Soils Mechanics laboratory have been correlated with the visual results.

The results obtained to date are incorporated in the two subsurface sections, Figures VI-B-3 and VI-B-4. Downhole geophysical probes were made in most of the boreholes. Electrical resistivity, spontaneous potential, and natural gamma logs are available for as many as 75 per cent of the borings, and where correlations could be made, significant or diagnostic geophysical horizons are traced between adjacent borings. Much of these data--geophysical, laboratory analyses, etc.--have been incorporated in the subsurface section shown on Figure VI-B-3. Laboratory

FIG. VI-B-3

Fig. VI-B-4. Vacherie dome, section B-M (from cored borings).

testing of samples from the borings shown on Figure VI-B-4 is, as yet, incomplete and the results only partially analyzed. Revision of these figures, particularly Figure VI-B-4, is probable as additional data are processed. All data on the Vacherie borings, i.e., detailed visual classification, laboratory analyses, and downhole geophysical logs, will be condensed and reproduced as a Topical Report when the boring program and laboratory testing have been completed.

The boring plan at Vacherie was to complete two cross-creek lines of borings (labeled as M-line and S-line on Figure VI-B-1), and one northwest-southeast line of borings roughly paralleling Bashaway Creek (labeled as B-line on Figure VI-B-1). Access to some of the areas involved along the B-line was prohibited by the landowners during fiscal year 1977. As can be seen on the figure, there are significant gaps in the central part and at the southeast end in the B-line as indicated by dotted rather than solid lines. If and when access rights to the properties have been obtained, borings will be made along the dotted portions of the B-line and the line will be extended eastward beyond the limits of the dome for some 4000 ft.

Traverses, made with Nimbus ES1200 seismic refraction equipment, were run along portions of the two dirt roads which cross Vacherie dome (see dashed lines on Figure VI-B-1). In mid-September 1977, the equipment was used to explore the limits of three anomalous "lows" found along the subsurface section shown in Figure VI-B-4. Three 200-ft deep borings were made at these sites and a wave front analysis was to be made of the seismic shocks from explosives set off at varying depths in these borings. The general locations of these experiments are shown on Figure VI-B-1, but the results of these experiments were not available for inclusion in this report.

3. Results of Boring and Seismic Programs at Vacherie Dome

The subsurface section (Figure VI-B-3) shows the lithology of the Quaternary borings made along the S-line. Determining the depth at which each boring penetrated the Quaternary and entered the underlying Tertiary was fairly simple. The lithologic break between the two units is usually well-defined and can be determined within inches. Where soil samples were not available, the contact was determined from the downhole geophysical logs. The thickness of the Quaternary along the S-line is nominal, the deepest deposit occurring at boring C-1. Two well-defined levels of Quaternary exist, the lower level probably of Holocene or Deweyville age (0 to 30,000 years old); the upper level of Prairie Terrace age (80,000 to 110,000 years old). The Quaternary consists of a heterogeneously intercalated series of oxidized soils ranging from clay sizes through chert gravels two or more inches in diameter. No individual stratum could be traced laterally for any great distance within the two geologic units. This is reasonable considering the relief in the area and the natural heterogeneity of such alluvial deposits. It can be seen, however, that the coarse content of the deposits--sandy and gravelly soils--characteristically form the basal units of the two deposits, while the true gravels (i.e., where 50 or more per cent of the material is above 3/8ths inches in diameter) are common just above the contact with the Tertiary. Moreover, the entrenchment of the two units, as indicated by the Quaternary-Tertiary contact, is remarkably even. In addition, the base of the entrenched Prairie Terrace material is slightly above, and thus compatible with, the base of the Holocene-Deweyville material. It is evident from this data that no disturbance of the Quaternary, either through uplift or subsidence, has occurred along this section since the material was laid down as long as 100,000 or more years ago.

The stability of the Quaternary deposits since their deposition is even more convincingly illustrated at the undistorted scale used in Figure VI-B-5. In this figure the subsurface section shown on Figure VI-B-3 is reproduced at the same horizontal and vertical scale. The position of the underlying salt plug is based on the most recent seismic and boring data available. Water Well 6 (designated Well V-6 in Section IV, and Appendix B of this report) which reached the caprock, is shown on the figure. Had the salt beneath the section moved upward or downward to any extent during the Quaternary, the movement would most assuredly have been reflected in the thin, conspicuously level alluvial sequence at the surface.

The situation indicated by the borings made along the subsurface section shown on Figure VI-B-4 is decidedly different. As mentioned previously, much of the boring data was not completely analyzed when this report was written. Also, seismic refraction surveys were in the process of being obtained, and only a small part of the results was available for analysis. However, it is obvious from the interpretation shown on Figure VI-B-4 that the depth to what is considered Wilcox or other early Eocene formations varies greatly. At borings B-8 and B-9, at boring M-8, and at boring M-3, the depth to this horizon is from 180 to more than 200 ft. These anomalous lows along the section may well be the result of dissolution of the underlying salt and the collapse of the surficial material.

A very fine silty sand or sandy silt that appears to be homogeneous to great depths was encountered in these borings. The material begins at a depth as shallow as 12 ft in boring B-9, and as deep as 60 ft in boring M-3. The material is fairly dense and entirely unlike the Wilcox deposits

Fig. VI-B-5. Undistorted subsurface section showing thin Quaternary sequence along the S-line (Figure VI-B-3) above Vacherie dome.

that are characteristic of the Tertiary elsewhere along this section and in other areas over and adjacent to Vacherie dome. The Wilcox normally consists of dark gray, thinly and irregularly stratified silty clays and silty sands that are usually oxidized to depths of 3 or 4 ft and rarely more than 15 ft below the contact. Moreover, the dip in the Wilcox bedding as measured in the cores ranges between 15 and 60 degrees. The material in question, on the other hand, is white or tan or red--the tan or red colors indicating oxidation in samples taken from depths as great as 180 ft. Stratification in the few samples obtained is horizontal.

It should be stressed that only a few samples were taken in this material. Turning the sampling tube so disturbed the sample that it could not be retained in the tube with a core catcher. The samples from depths greater than 50 ft were obtained by driving a small ID split-spoon. Thirty minutes of pounding normally resulted in only six inches of the material being penetrated, and this sample was often lost as the sampler was withdrawn from the hole. However, the few samples that were obtained plus evidence from the down-hole geophysical logs, suggest a very homogeneous silty sand or sandy silt that is oxidized to great depths, contains no gravels, is fairly dense, and is horizontally stratified. Four possible explanations for these anomalous deposits have been suggested and are discussed below.

- 1) The material is of Wilcox age and is essentially in situ, the abrupt change in lithology in the lows compared with borings only 150 ft away being the result of highly variable deltaic deposition during Wilcox time. This hypothesis is very doubtful. Lateral lithologic changes of this magnitude in deltaic deposits is highly unlikely. Moreover, the material is oxidized and is horizontally stratified.

2) The material is of Sparta age and has been displaced downward because of faulting and/or collapse. This is a possible explanation. As yet we know relatively little about Sparta lithology in the Vacherie area. However, the fact that the deposits are oxidized to such a great depth and are horizontally stratified argues against their being of Sparta age. Careful sampling and comparison with known Sparta cores in the area would confirm or rule out this explanation.

3) The material is of Quaternary age. This seems unlikely. The samples obtained so far, the down-hole geophysical logs, the considerable density of the material, and above all, the lack of chert gravels, suggest that the material is not of Quaternary age. Careful sampling of the material to rule out the occurrence of chert gravels should eliminate this as a possibility.

4) The most probable explanation is that between post-early Eocene and Quaternary times (e.g., during Miocene or Pliocene times) uplift and graben formation, or more probably dissolution and collapse of the underlying salt, resulted in surface depressions over the dome into which the fine silty sands of the surrounding Wilcox, Cane River and Sparta formations were carried during rainstorms. This resulted in the generally horizontal bedding found in the samples and accounts for the fact that they were oxidized. Careful sampling might recover thin clay or silt strata from which pollen can be taken for analysis. If so, the assignment of the material to a specific geologic age may be possible. Attempts will be made to obtain continuous samples from the lows shown on Figure VI-B-4, and uphole seismic wavefront analyses will be used to further delineate the depth and lateral extent of these lows.

If we accept the thesis that these lows were caused by dissolution and collapse, what do they imply from the standpoint of hydrologic instability at Vacherie dome? If the situation outlined in case (1) above is correct, there would, of course, have been no displacement. If case (2) is true, we would be faced with a complex problem in determining when the faulting or dissolution and collapse occurred. If case (3) is correct, it would imply major dissolution and collapse in Quaternary time involving significant and perhaps serious hydrologic instability. If case (4), the most probable situation, is correct, it would be useful to know when the downward displacement occurred. Displacement and collapse during the Miocene, for example, would have been too far back in time to be of any consequence. Displacement during late Pliocene or early Pleistocene, on the other hand, might be considered more serious.

What is the significance of these lows from the standpoint of tectonic stability? If the silty sand and sandy silt in them prove to be of pre-Quaternary age, upward movement of the salt during Quaternary time would be essentially ruled out along the line of borings shown on Figure VI-B-4. Evidence from cored borings and from the downhole geophysical logs, as yet only partially analyzed, suggest that this is the case--that the line on this subsurface section labeled Quaternary-pre-Quaternary contact is, indeed, the base of the Quaternary. No chert gravels are known to exist below this contact. The thickness and distribution of the coarse versus fine alluvium within the unit considered Quaternary on Figure VI-B-4 is compatible with the data shown on Figure VI-B-3 and is good evidence that no uplift has occurred since this unit was deposited.

Figure VI-B-6 reproduces the major contacts shown on Figure VI-B-4 at an undistorted scale. Water Well 7 (designated Well V-7 in Section IV

Fig. VI-B-6. Undistorted subsurface section showing thin Quaternary sequence and possible pre-Quaternary lows along the B-M-line (Fig. VI-B-4) above Vacherie dome.

and Appendix B of this report) which penetrated the caprock and entered salt is shown in this figure. As was the case in Figure VI-B-5, the thin, horizontal disposition of the unit considered Quaternary, and its essentially undisturbed nature, are convincing evidence that no uplift has occurred since the Quaternary was deposited. However, even at this true scale, the anomalous lows filled with silty sand and sandy silt are conspicuous along the section. It is possible, if these features are due to dissolution and collapse of the underlying salt and caprock, that distinctive lows or collapse phenomena will be found in the dome directly beneath. Seismic surveys to explore this possibility are planned.

4. Status of Boring and Seismic Programs at Rayburn's Dome

Figure VI-B-2 introduced earlier illustrates the boring and seismic programs underway at Rayburn's dome at the time this report was prepared (September 1977). It is estimated that 60 borings will have been completed by the end of fiscal year 1977 and that an additional 20 borings will be made at the southern end of the X-line (dotted) in fiscal year 1978. Cores will not be opened and analyzed until fiscal year 1978. Traverses along which seismic refraction surveys are to be made are shown as dashed lines. Most of these were scheduled for completion in fiscal year 1977, but the resulting data were not available for this report.

5. Results of the Boring and Seismic Programs at Rayburn's Dome

Preliminary results at Rayburn's indicate that the caprock of the salt plug lies at very shallow depths, i.e., 35 ft or less near the central portions of the dome. Quaternary deposits with moderate amounts of chert gravel in this central area give way at depth to what appears to be a stratum of boulders and cobbles of hard, dark limestone, tentatively

identified as caprock. The boulders and cobbles are in a matrix of clay and obtaining samples from this type of deposit is nearly impossible with the small drill rigs used for the Quaternary studies. It is possible that the seismic refraction network of traverses will be able to detect the base of this bouldery stratum. The boulders and cobbles are interpreted as water-worn fragments of caprock (obviously once at a higher elevation) left behind by surface erosion in either Quaternary or pre-Quaternary time.

6. Summary

The cored boring program and the seismic investigations at Vacherie and Rayburn's domes were only partly completed when this report was written (September 1977) and results are preliminary. However some tentative conclusions are possible.

1) There is no evidence of irregularities in the Quaternary strata that would suggest tectonic instability along the two cross-valley lines of borings (Figures VI-B-3 and VI-B-4) that have been made and analyzed at Vacherie dome.

2) There are three anomalous zones along one of these sections (Figure VI-B-4) extending to depths of more than 200 ft that are incompatible with the lithology encountered in adjoining borings. These lows are tentatively interpreted as depressions caused by dissolution and collapse of the underlying salt and filled possibly in Miocene or Pliocene times with fine silty sands.

3) Caprock at Rayburn's dome was encountered at depths as shallow as 35 ft, but much of it appears to consist of large water-worn fragments in a matrix of clay.

7. Acknowledgements

The writer is indebted to numerous individuals who worked as research associates, graduate assistants, and student helpers on field mapping, the field supervision of borings, the seismic surveys, the laboratory analyses, data compilation, and the drafting of figures in this portion of the report. Among these are Thomas Avgikos, Linda Curro, Robb Eidemiller, Rick Erickson, Nazarin Goodarzi, Michael Harris, Randy Hilding, Monica Hill, Joseph Holmes, Rose Kress, Barbary Lowery, Matthew Mathes, James McNees, Don Nemeth and Frank Sagona.

VI-C. LINEATIONS ON VACHERIE AND RAYBURN'S DOMES

A. J. Lewis

1. General

During fiscal year 1977 the acquisition of remotely sensed data has greatly aided the mapping of lineations on a regional and local scale. Multiple look direction radar imagery (1/400,000) was acquired and preliminary evaluations of the imagery have been completed. Aerial photography, both black and white and color, have also been obtained at 1/10,000 scale for the color photographs and at 1/5,000 and 1/10,000 scale for the black and white photography.

Due to the writer's absence on sabbatical leave, other remote sensing specialists were asked to help evaluate and interpret the data. W. K. Dornbusch and J. R. May of the U.S. Army Corps of Engineers, Vicksburg, prepared a map of the regional lineation patterns using the radar imagery. Their findings are summarized in this report. F. Henderson, a visiting professor specializing in remote sensing, prepared a map of photo-lineations of Vacherie and Rayburn's domes from two sets of aerial photography, 1/120,000 color infrared photos and 1/10,000 color photos.

2. Methods

The radar lineaments were interpreted from four sets of images: near and far range west-look direction, and near and far range south-look direction. The advantage of orthogonal look directions is the enhancement of lineations oriented at right angles to the look directions; whereas, near and far range data increases detection by providing the interpreter with different oblique perspectives. Lineations compiled from four data

sets were depicted on one overlay. Emphasis was placed on Vacherie and Rayburn's domes as they were of particular importance to the overall study.

After examining the aerial photography (1/5,000 black and white, and 1/10,000 color and black and white) the 1/10,000 color was selected as the primary data base for lineations mapping. The high altitude color infrared photography was also used in the lineament analysis following its enlargement to 1/10,000.

The radar lineations and the photo lineations were compiled and transferred to a 1/10,000 topographic map indicating the approximate extent of the Quaternary on Vacherie and Rayburn's domes. Prior to data transfer, all of the lineations were evaluated as to their strength (i.e. length and the number of times a given lineation had been interpreted by different interpreters). All the lineation data from remotely sensed data were studied and only the very strongest lineations were transferred. The method of selection involved looking at the original data base along with the overlay of radar and photo lineations. Large numbers of linear features originally interpreted by Dr. Henderson were eliminated because they were very weak, i.e., were short in length, had very subtle tonal change, and had not been detected by other interpreters. On rare occasions new lineaments were added by the writer when the feature was prominent.

Field checking and image enhancement techniques were also incorporated in the interpretation. Several trips were made to Vacherie and Rayburn's domes to investigate prominent lineations and to confirm that these lineations were not historic or cultural features (old roads, railroad beds, property lines, fences, and survey lines). Limited access, either because of the terrain or lack of owner's permission, prohibited field checking all of the interpreted lineations. All of the lineations noted in the

field corresponded with topographic features, i.e., valleys of intermittent streams and scarps or breaks in slope.

Image enhancement techniques were employed to amplify and improve the radar imagery. Positive radar transparencies (1/400,000) were taken to the USGS User Data Facility (National Space Technology Lab) at Picayune, Mississippi, and electronically enhanced on the VP-8 image analyzer. Although the VP-8 color-coded image of tones provided some impressive color images, it was the isometric display that proved most valuable. This electronic display of the image is a series of density traces that can be rotated 360° and tilted 90° enabling the interpreter to manually control the viewing perspective of the scene. Anyone who has looked for lineations realizes the importance of such versatility.

3. Evaluation of Data Sets

An evaluation of the radar imagery was provided by Dornbusch and May. They emphasized the lack of control between imagery from adjacent passes. This made the construction of a radar mosaic difficult and the superpositioning of radar lineaments from different mosaics impossible. Radar distortions, although the system has a ground range presentation and therefore a semi-controlled image, appear to have resulted in objects occurring in erroneous geographic perspective. For example, Prothro dome appears north of Rayburn's dome on a radar mosaic whereas the opposite is true.

Of the three image scales (1/400,000, 1/200,000 and 1/50,000) used in this evaluation, the 1/200,000 was found to be the most convenient to work with and contained nearly the same level of information as the 1/50,000 imagery. The 1/50,000 imagery was used to spot check interpretations from the 1/200,000 scale data and to eliminate lineaments of cultural origin.

Although Dornbusch and May noted that the detection of lineations is look direction range position dependent, no single look direction range position seemed to offer any apparent overall advantage to the detection of lineaments or domal structures. General trends in radar lineations are evident in like-look direction passes; however, the exact location of individual lineaments could not always be accurately correlated.

The original radar image product (1/400,000) is too small scale for detailed interpretation; however, the superb quality of even the 2nd generation radar imagery permits enlargement of greater than 30X on an optical enlarger without the image breaking down. Areas are presently being selected for photographic enlargement to 1/10,000 in order to allow superpositioning of radar-derived data directly over the 1/10,000 aerial photos and vice versa. This should provide more accurate data transfer and correlation of radar and photo derived lineaments with each other as well as with 1/10,000 topographic data.

4. Results

Most of the effort during fiscal year 1977 was focused on the Vacherie and Rayburn's areas. Lineations around and transecting the domes were of particular importance, especially the lineations that extended partially through or across the Quaternary deposits that lie above each dome. Lineations within the Quaternary suggest upward or downward movement during Quaternary time that might result from tectonic instability or hydrologic instability of the underlying salt.

Figures VI-C-1 and VI-C-2 represent the combined radar and airphoto interpretations by six interpreters over the past year for Vacherie and Rayburn's domes, respectively. Lineations at Vacherie are found flanking the dome, extending from the Tertiary into the Quaternary which overlies

Fig. VI-C-1. Lineations over and adjacent to Vacherie dome based on interpretation of radar, black and white, and color imagery.

Fig. VI-C-2. Lineations over and adjacent to Rayburn's dome based on interpretation of radar, black and white, and color imagery.

the dome, and crossing the Quaternary. One particularly interesting set of lineations, labeled A and B on Figure VI-C-1, can be found in the upper reaches of Bashaway Creek. These lineations correspond remarkably well with the dissolution and collapse features interpreted on the subsurface section shown on Figure VI-B-4 at borings M-3 and M-7, respectively. It is stressed here that the mapping of lineaments was done entirely independently of the cored boring interpretations illustrated on Figure VI-B-4, and vice versa. Neither group had prior knowledge of the other's results. The coincidence of results is most encouraging.

Several other lineations which extend into or lie wholly within the Quaternary deposits need to be investigated in the field through the use of borings or seismic surveys. Of special interest are the curvilinear features on the eastern flank of Vacherie dome, labeled C on Figure VI-C-1. These correspond with the general shape of the dome at depth and, although they could be the result of dissolution and collapse phenomena as at A and B on Figure IV-C-1, they could also suggest tectonic instability. When access to the property has been obtained, these curvilinear features will be thoroughly explored in the field.

Although several lineations cross the Tertiary-Quaternary boundary, the pattern at Rayburn's dome is less organized or marked than it is at Vacherie. There is little evidence of major lineations paralleling Fouse Creek valley; however a pronounced northwest-southeast lineation, labeled D on Figure VI-C-2, runs parallel with the Quaternary-Tertiary boundary on the northwest side of Rayburn's and should be investigated.

The primary importance of the lineaments on both domes is that they suggest the possibility of movement and as such should be investigated. It should not be concluded at this stage of the investigation that they are faults.

5. Acknowledgements

In addition to acknowledgements made in the text of this section of the report, the writer is grateful for the help of research associate Joseph Holmes.

VI-D. PEDOLOGIC INVESTIGATIONS

B. J. Miller

Pedologic investigations of a limited nature were initiated in fiscal year 1977 to aid in evaluating tectonic and hydrologic stability in the Rayburn's and Vacherie salt dome areas. Studies of the kinds and distribution of soils and their characteristics in these areas can be informative for a number of reasons. Soil development and the processes of soil formation are unique to the zone at, and immediately beneath, the earth's surface. The various soils that develop constitute a continuum on the land surface that may include soils developed in a number of rock and/or time stratigraphic units. Consequently, the soil continuum (soil-stratigraphic unit) provides a useful reference for evaluating the nature and sequence of events that is quite independent of rock or time stratigraphic units in which the soils developed. The kinds of soils that form, and the degree of expression of their different characteristics, are dependent upon the combined effects of climate, parent material, organic influences, topography, and time of exposure at the land surface. Soils are thus products of their environment, and knowledge of their characteristics and distribution can furnish information concerning the nature of the pedogenic environment and the time of soil development. The processes of soil formation result in many irreversible changes, and, as a result, the characteristics of distribution of ancient buried soils (paleosols) provide a particularly useful key to earlier geomorphic and environmental conditions. For example, the characteristics and distribution of paleosols have been a major source of information for evaluating the events and environment of the Pleistocene in many areas.

The pedologic studies around Vacherie and Rayburn's domes were designed to provide information on the relationships between landscape stability and soil development on the different sediments, and to determine if there is chemical evidence that Na-bearing solutions have intruded the soils and sediments above the domes. The studies were designed to be conducted in three interdependent phases as follows:

1) Phase 1: field investigations to determine the kinds and distribution of soils, their thickness and morphologic characteristics, and their relationship to parent materials and geomorphology in the study areas. The investigations include detailed studies of core samples of Quaternary and Tertiary formations near the surface collected by other investigators with similar objectives with regard to any paleosols that can be identified.

2) Phase 2: the determination of cation exchange capacity and the distribution of certain exchangeable cations on samples selected on the basis of the field investigations and studies of the core samples. Here, emphasis is placed on determining the distribution of exchangeable Na with depth and identifying possible anomalies in distribution between adjacent stratigraphic units. The information obtained can be used to evaluate the approximate extent and time of intrusion of any Na-bearing waters. These studies can be especially useful in leached zones having low total soluble salt content as is typical of many of the sediments in the study areas. This phase of the investigations can be expanded to include other less mobile exchangeable cations, provided geochemical investigations of the salt body indicate a potential for additional information by such an approach.

3) Phase 3: thin section studies to determine the depths of weathering and expression of selected processes of soil formation in the

modern soils and in any paleosols that can be identified. Samples for investigation are selected on the basis of results obtained in the field investigations and studies of the core samples. Emphasis will be placed on evaluating the depth and extent of weathering and development of horizons in which secondary accumulations of translocated clay can be recognized. The studies also include samples from across, and on either side of, the interface zone of apparent discontinuities in which there is evidence of soil development. Studies of these samples will provide information concerning the continuity of pedogenic processes across these zones.

To date, most of the work has been field investigation aimed at inventorying the soils in the area, determining their characteristics, and evaluating their geomorphic and parent material relationships. This work is essential to the selection of soil areas for more detailed field investigation or for chemical and thin section studies.

Detailed field investigations were conducted during the period May-August, 1977, and a detailed soil survey has been completed for areas around Vacherie dome where access is permitted. The aerial coverage is approximately four square miles. Eighteen different soils were recognized and described in the area. The soils, together with certain of their characteristics are listed in Table VI-D-1. The soil names listed are tentative field names and, in some cases, may be changed after additional field investigations. The pre- and post-Pleistocene parent materials indicated in the table coincide with the formations described by Martinez, et al., (1976). The Pleistocene parent materials indications are based on that work and on results of this study. Standard field soil survey methods were used in conducting the survey. The soil parent material relationships, thickness of soil profiles, and soil textures are based

Table VI-D-1. The soils and their parent materials, landscape position and profile thickness in the Vacherie salt dome area.

Soil name	Soil parent material	Landscape position	Approximate minimum profile thickness in inches
Alaga	Tertiary (Sparta)	Upland	20
Beauregard	Pleistocene alluvium	Stream terrace	60
Bibb	Holocene alluvium	Floodplain	6
Bienville	Holocene alluvium	Floodplain	10
Cahaba*	Pleistocene? Holocene? alluvium	Stream terrace	36
Eustis	Tertiary (Sparta)	Upland	60
Guyton	Pleistocene? Holocene? alluvium	Stream terrace	50
Iuka	Holocene alluvium	Floodplain	6
Keithville**	Pleistocene alluvium	Upland	60
Kirvin	Tertiary (Cane River)	Upland	40
Lucy	Tertiary (Sparta)	Upland	60
Malbis	Pleistocene alluvium	Stream	60
Meth	Tertiary (Cane River)	Upland	60
Ocklockonee	Holocene alluvium	Floodplain	6
Ruston	Tertiary (Sparta)	Upland	60
Sacul	Tertiary (Wilcox)	Upland	40
Saucier**	Pleistocene alluvium	Upland	60
Smithdale	Tertiary (Sparta)	Upland	60

*Soils mapped as Cahaba also occur on footslope positions in the uplands.

**Soils identified as Keithville and Saucier developed in thin deposits of Pleistocene alluvium overlying clayey Cane River or Wilcox sediments.

on numerous observations of each soil by soil scientists in the field. The aerial distribution of the soils is shown on the soils map (Figure VI-D-1).

Eight of the soils developed in Tertiary sediments. Five of these (Alaga, Eustis, Lucy, Ruston, Smithdale) developed in the sandy sediments of the Sparta formation and are characterized by soil profiles that are approximately 60 inches or more in thickness. They are the least clayey of the soils developed in the Tertiary sediments and contain less than 35 per cent clay throughout the profile. Except for the Alaga, these soils all have distinct horizons of secondary accumulations of clay.

Two of the soils (Kirvin and Meth) developed in sediments of the Cane River formation, and one (Sacul) developed in Wilcox formation sediments. These are the most clayey soils in the area and are characterized by secondary horizons of clay accumulation containing 35-60 per cent clay. The Kirvin and Sacul soils are more clayey than the Meth and have profiles that are characteristically thicker than about 40 inches. The Meth soils have a minimum profile thickness of approximately 60 inches. Differences in the profile thicknesses of the different soils can be attributed largely to lower clay content and greater permeability with increased sand content in the parent materials. The sandy soils developed in the Sparta formation sediments typically occupy the steepest slopes and highest landscape positions in the interdrainage areas. The soils developed in the more clayey and less erosive sediments of the Cane River and Wilcox formations occupy lower landscape positions and more gently sloping areas. The flattening of the slope (Figures VI-D-2 and VI-D-3) in traversing from soils developed in the Sparta to those developed in the Cane River or Wilcox formations is characteristic of the entire area.

Fig. VI-D-1. Distribution of soil series in the Vacherie dome area.

FIG. VI-D-1

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Fig. VI-D-2. Soil section A-A' (see Fig. VI-D-1 for location) showing landscape position, surface stratigraphy and profile characteristics.

Fig. VI-D-3. Soil section B-B' (see Fig. VI-D-1 for location) showing landscape position, surface stratigraphy and profile characteristics.

Three of the soils (Keithville, Saucier and Beauregard) developed in areas where a thin mantle of Pleistocene (Prairie?) sediments apparently overlies clayey sediments of the Wilcox or Cane River formations. These soils are characterized by secondary horizons of clay accumulation with maximum clay contents of less than about 35 per cent. The total soil profile thicknesses are greater than about 60 inches and generally exceed the thicknesses of the soils developed entirely in the clayey Tertiary sediments. The field investigations indicate that the overlying Quaternary sediments may have been deposited on existing soils developed in the clayey Tertiary deposits. This could account for the thicker profiles compared to soils developed entirely in the clayey Tertiary sediments. The distribution of the soils (Figures VI-D-1, -2, and -3) and their characteristics suggest that the Pleistocene sediment component of their profiles is probably Prairie in age. The possibility that these and other soils have developed in more recent colluvial footslope accumulations from soils at higher landscape positions cannot be ruled out at this time.

The Malbis soils developed in Pleistocene deposits (Prairie? or Deweyville?) and occupy gently sloping areas intermediate between the Tertiary uplands and more recent stream terraces of Bashaway Creek (Figure VI-D-2). Malbis soils also occupy higher landscape positions (Figure VI-D-3) in the uplands and have developed in Pleistocene gully fill or footslope accumulations on the dissected pre-Quaternary surface. These soils developed in sandy sediments and are thought to be similar in age. They are characterized by secondary horizons of accumulation of clay with maximum clay contents of about 35 per cent and have profiles that are greater than about 60 inches thick.

The minimum profile thicknesses described in Table VI-D-1 show a general increase in thicknesses with increasing time of surface exposure

to pedogenic processes in soils developed in lithologically similar parent materials in the area around Vacherie dome. For this reason, it is thought that the Malbis soils have developed in an older Pleistocene formation (Prairie?) than the soils discussed in the following paragraphs, which characteristically have thinner profiles and typically occur at lower elevations.

Two of the soils (Cahaba and Guyton) developed in late Pleistocene (Deweyville?) or early Holocene deposits that form terraces adjacent to more recent stream deposits along Bashaway Creek. The Cahaba soil formed in the more sandy and better drained old natural levee deposits, whereas, the Guyton formed in sediments containing more silt and clay. Both soils are characterized by horizons of secondary accumulations of clay with maximum clay content of less than about 35 per cent. The Cahaba and Guyton have minimum profile thicknesses of about 36 and 50 inches, respectively. Along Bashaway Creek the Cahaba soils appear to conformably overlie Guyton-like soil profiles. This suggests that a cycle of stream aggradation followed by a soil-forming interval may postdate the Guyton soil and predate the recent alluvial deposits. The minimum thickness described for the Cahaba soil profiles may further indicate this possibility. Areas of Cahaba soils are also mapped in upland positions where they appear to have developed entirely in parent material comprised of footslope accumulations of colluvial material eroded from soils at higher elevations developed in the Sparta formation. The typical setting in this position is illustrated in Figure VI-D-2 where Cahaba soils occur in association with Ruston and Malbis soils. More detailed field studies are planned which should determine if the Cahaba does include units developed in parent material of different ages.

Four of the soils (Iuka, Bibb, Bienville, Ocklockonee) developed in recent (Holocene) floodplain deposits (Figure VI-D-1). They are sandy throughout with thin stratification evident at shallow depths (< 1 ft) in most areas. Profile development in these soils is largely limited to a 6-10 inch thick surface horizon characterized by an accumulation of organic matter. Typically, they are underlain at shallow depths by weathered surfaces that appear to include horizons of Cahaba-like or Guyton-like soils. In soil identified as Bienville, the depth to the underlying Guyton-like soil profile is characteristically less than three feet.

Additional field work is planned in the area for more detailed studies of the relationships between soils formed on the modern surface and those in buried surfaces. Tentative sites have been selected for detailed sampling of soils for chemical analyses and thin section studies. The objective in site selection for detailed studies has been: 1) to select soils developed in lithologically similar parent-materials of different ages; and/or, 2) to select soils that will allow for comparisons between soils on the modern surface and buried surfaces from the core samples. At this time, soils selected for additional studies are the Lucy, Saucier, Cahaba, Meth, Sacul, Keithville and Malbis.

Studies of the core sections collected from the Quaternary (Figures VI-B-3 and VI-B-4) have not been completed. The core samples collected along traverse S are being examined in detail for evidence of paleosols in the underlying Tertiary and within the Quaternary. Similar studies are also in progress on cores from traverses M and B. Unfortunately, segments of many cores were lost during sampling. In some cases, the appearance of subjacent samples indicate that these may have included buried soil horizons. The preliminary observations on the core samples lend support to interpretations based on the field studies and are providing

additional information concerning buried surfaces within the Quaternary and underlying Tertiary. For example, weathered Tertiary sediments that appear to contain pedogenic horizons underlie the Quaternary at some sites. In some cases, these surfaces appear to have characteristics somewhat similar to those of the modern surface. There is a minimum of two zones within the Quaternary containing weathered strata that appear to have preserved soil horizons. Organic materials have been sampled from some of the cores for attempts at dating by radioactive carbon techniques. Sections of cores from traverses have been tentatively selected for chemical analyses and thin section studies.

In continuing the investigations, emphasis will be placed on the study of any soils buried by Quaternary deposits as well as modern soils developed in Quaternary and older sediments. The study areas will be extended to include limited investigations at off-dome localities in order that more extensive and definitive comparisons can be made. This is essential to certain phases of the study such as establishing the norm for thicknesses of profiles of different soils. Studies limited to the dome areas proper allow only for comparisons among sites above the salt domes. Inherent to the study is the implicit assumption that conditions above the dome may differ from the norm as a result of tectonic instability and/or certain hydrologic phenomena.

The investigations should be expanded to include detailed pedologic and geomorphic studies in which comparisons are made between conditions in the dome areas and areas outside the possible influence of dome-related tectonic or hydrologic activity. Included in these studies would be investigations to determine the source of the older Quaternary sediments in the dome areas, and the extent to which these and younger sediments may be comprised of erosion products from the different deposits now

exposed in these areas. Dating of these deposits and reconstruction of events which led to the present landscape would yield important information regarding the tectonic history of the dome in the recent past. These investigations could also provide additional information concerning the rates of erosion over long time periods. The pedologic studies should complement the Quaternary and Tertiary geologic studies and thereby provide an additional method of evaluating and correlating possible lines of evidence bearing on the tectonic and hydrologic stability of the domes.

The writer is indebted for the help of graduate assistants Rose Kress and James Rehage on this section of the report. He is also grateful for suggestions and comments by J. Alford of Western Illinois University.

VI-E. NATURE OF QUATERNARY WARPING ABOVE DOMES

C. R. Kolb

One of the problems associated with the study of the Quaternary is that there is almost no published data concerning the distortion of Quaternary beds when they are warped upward above a salt dome or when they are displaced downward by faulting or collapse. Questions that arise because of this lack of data are numerous. For example, does uplift occur over a broad base lifting the Quaternary as an essentially unbroken stratum with the greatest uplift near the center of the dome? Does the uplift cease only short distances beyond the dome boundaries, or does uplift die out gradually with distance from the dome boundaries? Is the uplift highly irregular caused by sporadic upward movement of small portions of the salt plug? Alternatively, does the uplift result in a horst-and-graben effect, segmenting the Quaternary into blocks and slices? Answers to these questions would be exceedingly helpful in analyzing the results of our boring and seismic programs over north Louisiana salt domes.

There are excellent examples of the upwarping of the Quaternary above salt domes in south Louisiana and south Texas. The Five Islands of south Louisiana are cases in point. In each instance the Quaternary has been lifted upward above the level of the surrounding marsh and coastal plain. In some instances gravel once several hundred feet below sea level is now exposed at elevations tens of feet above sea level. No data are published, however, that indicate how regularly or irregularly this uplift has occurred. It is possible that oil and/or salt company files contain shallow subsurface data crossing certain of the coastal domes where the Quaternary has been lifted upward. A few acoustic subbottom profiles have been published which show the warping of Holocene and Pleistocene

strata above domes in the offshore areas of Louisiana and Texas. These show the Quaternary strata to have been lifted regularly and evenly with no apparent offsets due to faulting. More of this kind of information should be available from company files or from soils engineers involved in foundation studies for offshore drill rigs. German and Dutch investigators, as part of their nuclear waste storage research, have studies underway concerned with the warping of the Quaternary deposits above salt domes. Efforts will be made to assemble these kinds of data so that we can more properly interpret our boring and shallow seismic information as it develops.

VI-F. TERRACE LEVELS

C. R. Kolb

An approach to the study of possible uplift of the Quaternary above a salt dome is to map, identify, and compare the elevations of the various Quaternary surfaces or their remnants over the dome and in a broad area around the dome (C. R. Kolb in Martinez, et al., 1975). Delineation of these surfaces requires closely spaced contour maps or lengthy field traverses along which elevations are surveyed to the nearest foot. Quadrangle maps available over Vacherie and Rayburn's domes have 20 ft contour intervals and can only be used with caution. Moreover, both domes lie below minor creeks--creeks that are tributary to bayous which in turn are tributary to the larger streams along which the various Quaternary terraces have been mapped. Extending the mapping of these surfaces involves increasing complexities as one moves upstream to smaller and smaller tributaries. Thus, assigning a specific age to the various levels of the Quaternary that occur along, for example, Bashaway Creek and the valleys filled with Quaternary alluvium that surround it, is difficult and controversial.

Fortunately, from the point of view of this study, assigning a specific age to existing Quaternary levels, though desirable, is not absolutely necessary. Present thinking is that the lowest level along Bashaway Creek at Vacherie dome is of Holocene and Deweyville age and that there is a higher level that corresponds to the Prairie Terrace. Carbon-14 and other types of radiometric dating may permit the assignment of specific age to the two levels of deposits. It is highly significant that these same two surfaces can be traced downstream into the floodplain and bordering terrace along Black Lake Bayou and up into the

tributary valleys of Black Lake Bayou that flank Bashaway Creek on the north and the south.

Two lengthy seismic lines were run in June 1975 over Vacherie dome: one in a northeast-southwest direction, the other generally at right angles to the first, roughly paralleling Bashaway Creek. The location of the northeast-southwest line of shotholes made for this survey is shown in Figure VI-F-1. Returns from the shothole borings were logged from cuttings in the field, and although not entirely accurate from the standpoint of depths of the Quaternary, the identification of the Quaternary because of the occurrence of chert gravels was readily determinable. Results and the basic data from these shotholes are reported in Martinez, et al., 1976. Elevations along this line were carefully surveyed by the contractor, and gravelly Quaternary deposits in the valleys to the north and south of Bashaway Creek were encountered along this line at remarkably concordant levels. Moreover, two levels of Quaternary deposits were found in these adjacent levels that agree remarkably well with those known to occur along Bashaway. The terrace level is at elevation approximately 240 msl; the Holocene-Deweyville floodplain level is at about elevation approximately 220 msl. Both levels are entirely consistent with the same levels along Bashaway.

These data are shown in the subsurface section on Figure VI-F-1. The point here is that correlative levels of alluvial deposits occur in the valleys that flank Bashaway to the north and the south at distances far removed from the influence of the salt dome. Had uplift occurred since the deposition of these materials, it should be reflected in a definitely higher elevation of these features along Bashaway Creek. No such upward movement is apparent; the elevations in adjoining valleys are markedly concordant. It might be argued that had the seismic line

FROM FIG. IV B-1 (MARTINEZ ET AL. 1976)

BASED ON FIG. IV B-4 (MARTINEZ ET AL. 1976)

Fig. VI-F-1. Concordant levels of Quaternary deposits along Bashaway Creek with similar deposits in the valleys to the north and south.

been oriented more nearly north-south, the levels would not have been so nearly the same. This is true in theory; however, the general direction of the three stream valleys involved is toward the southeast. The seismic line is at right angles to this general trend and, thus, more accurately reflects comparable positions within each of the valleys.

The proof of this pudding, of course, is in carefully mapping the slopes of the two Quaternary surfaces along Bashaway, along Black Lake Bayou, and along the streams in surrounding valleys. Slopes within the valleys can then be correlated across the Tertiary divides with confidence. They can also be merged with the slopes along the stream to which they are tributary--Black Lake Bayou. Unfortunately, considerable field work and occasional borings would be required, as well as access rights to properties miles on either side of the dome. One alternative is to prepare maps at 5 or 2-1/2 ft contour intervals using air photos. This would, at least, provide the necessary elevation control, and such maps for Vacherie and Rayburn's have been proposed in the 1978 budget. Another method is to search for elevation data in the files of oil and/or geophysical companies. Gravity as well as seismic surveys require elevation control that may be available at a reasonable price, or even gratis.

In summary, the writer is impressed with the concordant elevations of Quaternary levels in Bashaway and the valleys to the north and to the south. He is convinced they are of the same age, and that if uplift of any reasonable magnitude has occurred since their deposition, it would have been reflected by remnants of these Quaternary units at significantly higher elevations along Bashaway Creek.

VI-G. TOPOGRAPHIC LOWS ABOVE DOMES

C. R. Kolb

An intriguing geomorphic fact about many of the north Louisiana salt domes is that they lie beneath well developed topographic lows which have formed above breached domes or anticlines. Vacherie (see Figure VI-G-1) and Rayburn's are examples. Many of the domes in south Louisiana, on the other hand, where tectonic uplift is thought to be still going on or to have ceased only in the recent geologic past, form topographic highs. The Five Islands of south Louisiana are good examples. A reasonable conclusion might be that domes overlain by topographic lows have long since ceased to be tectonically active and that those overlain by topographic highs are still active or have ceased to be active only recently.

This explanation is not necessarily true, however. Consider the effect on the surface topography of the upward movement of a salt dome (diagram "a" in Figure VI-G-2). If the uplift occurred beneath an existing stream at a moderate rate, the stream would merely entrench itself as the surface rose (diagram "b"). In such an instance, the presence of a topographic low above the dome today would be of no significance from the standpoint of the tectonic stability of the dome. The dome could have long since ceased moving upward or it could be moving upward today. What is difficult to accept, if we choose this model, is that the domes of north Louisiana have so often selected an existing stream to rise beneath.

On the other hand if the uplift occurred fairly rapidly, normal drainage would tend to be diverted around it, as in diagram "c". Because of the increased relief, radial drainage would tend to develop over the dome

Fig. VI-G-1. Topographic low occupying the breached anticline over Vacherie dome.
(Photograph of model.)

An undisturbed plain.

The situation where uplift is reasonably slow so that the existing stream can maintain itself in its former channel.

Uplift has been rapid enough to divert the stream to the right. This also illustrates the situation where no prior stream existed. Radial drainage develops over the top of the uplift.

The high basin that might form above the uplift as erosional processes strip an erosion-resistant stratum.

The formation of a well-developed valley above the dome due to faulting because of tensional stresses occurring during uplift.

Erosional processes have worn the uplifted area down considerably at which time dissolution and collapse of the underlying salt result in the formation of a valley above the dome.

Fig. VI-G-2. Block diagrams illustrating hypothetical origins of topographic lows over domes.

and erosive processes would begin to wear the topographic high down to the former level from which it originally was lifted. If the strata were largely homogeneous, erosion would continue to be active but the hill could hardly be eroded to an elevation lower than that of the surrounding terrain. This would be true whether the dome had ceased moving upward or was still tectonically active. If the surface moved upward at a faster rate than erosion wore it down, elevations of the topographic uplift would increase and there would even be less reason to expect a depression or a valley to form above the dome.

If the material composing the uplift were heterogeneous, as in diagram "d", erosion might eventually cut through the upper sandstone stratum and encounter a less resistant shale beneath. At this stage in the development, the sandstone might stand as a rim around a basin, but the basin would still be higher than the surrounding topography and the plain which was originally pushed upward by the rising salt dome. Again, cessation of upward movement would only shorten the time it would take to wear down the topographic knob, but there is no reason to believe that a topographic low could develop at a level below that of the surrounding plain.

To what, then, can we attribute the pronounced topographic lows that have developed above Vacherie and Rayburn's domes if we do not consider the highly coincidental situation where the uplift begins beneath an existing stream? The most obvious reasons are: (1) formation of faults/grabens above the dome due to tensional forces caused by the uplift; or, (2) depressions caused by dissolution and collapse of the underlying salt. The writer feels the latter is the more probable cause at Vacherie and Rayburn's.

Considering faulting and graben formation first, it is well known from studies of other domes that such features characteristically occur above

domes. Figure VI-G-3 shows the actual fault pattern over a deep-seated salt dome at the Heidelberg structure in Jasper County, Mississippi. Note the complexity of the faulting. Diagram "e" in Figure VI-G-2 sketches such a situation in simplified form. If the magnitude of downfaulting due to tectonic uplift is sufficiently great, the zone weakened by faulting could well become the path for surface drainage that could eventually develop into a valley such as the one which has formed above Vacherie.

A second method for producing a depression above a salt dome--one that can eventually develop into a significant valley--is through dissolution and collapse of the underlying salt. The potential for depression formation is considerably greater through this process. There is a decided and roughly calculable limit to the amount of downthrow that can occur because of faulting and relief of tensional stresses above a rising dome. The wedges of faulted strata are limited in their downward movement by the geometry of the uplift. It is apparent in Figure VI-G-3 that the amount of subsidence of individual wedges, particularly as this subsidence affects the near surface formations such as the Selma Chalk, is relatively small. If the amount of uplift is low, the amount and magnitude of faulting and graben formation is low. If the amount of uplift is high, the formation of a depression below the level of the surrounding unaffected terrain depends on large downward displacements of wedges of material which must have room to move downward.

Collapse due to dissolution of the underlying salt, however, is unrestricted by such factors. An area where uplift had occurred in the past but which had long since ceased to be tectonically active, would be particularly susceptible to depression formation due to collapse. Although some

Fig.VI-G-3. Actual fault pattern over a deep-seated salt dome at the Heidelberg structure in Jasper County, Mississippi (From Hughes, 1960).

residual relief due to the former uplift might remain, the relief would be low and even a minor amount of subsidence due to collapse could form a depression which, on draining, could become a valley of significant size and depth (diagram "f" in Figure VI-G-2).

In this regard one feature of the valleys above Vacherie and Rayburn's domes is pertinent. Both domes, and others in north Louisiana, are characterized by Quaternary deposits which broaden out in plan above the dome. Thus, the Quaternary alluvium flanking Bashaway Creek above Vacherie dome narrows markedly in plan just at the borders of the dome where the Bashaway Creek alluvium merges with the alluvium of Black Lake Bayou floodplain (Figures VI-B-1 and VI-G-1). Similarly, Fouse Creek at Rayburn's dome is flanked by a broad, roughly circular area of Quaternary alluvium above the dome and exits southward near the dome boundaries along a narrow corridor of alluvium (Figure VI-B-2).

The shape of these valleys suggests the formation of depressions over both domes compatible with the shape of the domes, and the exit of surface drainage at a low spillover point -- drainage which later developed into the narrow floodplains of Bashaway and Fouse creeks. A further point to be considered is that present topography in the area is largely the result of geomorphic processes active during Quaternary time. Given the present weight of evidence for tectonic stability of the domes during Quaternary times, it is more logical to assign responsibility for formation of the original depressions over the domes to collapse of the underlying salt.

In summary, the fact that Vacherie and Rayburn's domes lie in topographic depressions is considered to be of little significance from the standpoint of the tectonic stability of the salt. In considering processes which produced these depressions, it is important to note that the depressions

lie within deep valleys which have reached the base levels of the valleys to which they are tributary. The establishment of such drainage can be due to the existence of a through-flowing stream prior to uplift, major displacements caused by faulting due to tectonic uplift, or by dissolution and collapse of the underlying salt. The writer, at this stage of the investigation, believes that the topographic lows can be most logically explained as resulting from dissolution and collapse. A final point: if collapse is eventually determined to be the cause for the topographic lows above the domes, it is obvious that the domes must be considered tectonically stable; or that they are being dissolved at a faster rate than they are moving upward.

VI-H. DRAINAGE BASIN ANALYSIS

A. J. Lewis

The analysis of drainage pattern, form, and texture has long been used to help determine lithology, possible faults and fractures, soil texture, and topography (Strandberg, 1967). Drainage pattern form is a reflection of lithology, slope, and bedrock structure; whereas drainage pattern texture is related to soil properties such as texture and permeability. Offset and the alignment of offset streams are indications of faults and/or fractures. Several drainage pattern forms, such as barbed, asymmetrical, etc., indicate uplift; whereas others, such as contorted and rectangular patterns, suggest structural control.

The basic steps in drainage basin analysis include:

- 1) stream course delineation,
- 2) basin and sub-basin delineation,
- 3) drainage pattern and form analysis,
- 4) drainage texture analysis, and
- 5) basin shape vs age analysis.

Drainage basin shapes are genetically linked to the erosional processes of drainage systems and supply useful criteria for defining geomorphic regions of erosional origin. Drainage basin shapes may also act as independent variables in predicting the sediment discharge from these basins (McArthur and Ehrlich, 1977).

The feasibility of this approach for separating drainage basins formed on Pleistocene vs Tertiary surfaces has already been demonstrated in Louisiana by McArthur and Ehrlich. The approach may prove valuable in dating the drainage basins that are located in topographic lows over many of the north Louisiana salt domes, in determining their history, and

in determining if the lows are due to faulting and graben formation associated with uplift, or to dissolution and subsidence.

McArthur and Ehrlich suggest that drainage basin morphology may also help predict sediment discharge. If so, basin morphology could be used to supplement, corroborate, or differ with the estimate of erosion rates in north Louisiana based on variations in terrace levels. (A discussion of erosional effects is presented in the following section.)

VI-I. EROSIONAL EFFECTS DURING NEXT 250,000 YEARS

C. R. Kolb

One of the factors that must be critically examined at each site proposed for nuclear waste storage is the projected effect of erosional processes on the site during the 250,000 years that the waste will remain radioactive. Elevations at Vacherie and Rayburn's domes generally range from 200 to 250 ft msl. Under current conditions, and assuming there is no upward movement of the salt and the waste entombed in it, it is impossible for a repository at a depth of 3000 ft to be exposed by erosion. Erosion in today's climatic regimen could only strip the hill area at Vacherie and Rayburn's to local base level--at approximately 180 ft msl in both instances. Even given the outside chance that erosion would reduce the topography in the area to its ultimate base level, sea level, there would still be some 2800 ft of material above a 3000-ft-deep repository.

However, this simplified model is complicated by a number of factors. These include: (1) the normal tectonic rise in north Louisiana during the next 250,000 years; (2) an ice age or two in this time interval, a very probable occurrence; and, most important, (3) the effect on the integrity of the repository of exposing caprock and possibly underlying salt. The latter situation would hardly be a factor at Vacherie where caprock and salt are at considerable depth, but might possibly be a factor at Rayburn's where the salt is thought to be at depths of less than 100 ft. Certainly the situation should be considered in the engineering design of any salt repository where the salt is this close to the surface. Thoroughly grouting the caprock to provide a positive, erosion-resistant shield above the salt might be one way to circumvent the possible effects

of erosion on shallow salt domes. The following sections present a brief discussion of the other two factors listed above: (1) normal tectonic rise of the area; and (2) the effect of an ice age and the accompanying drop in sea level during the next 250,000 years.

1. Regional Tectonism

Fortunately, we have a fairly good measure of the overall tectonic rise in the north Louisiana area and the rate of rise during Pleistocene times. The base levels of major creeks and streams are preserved as terrace levels along these streams in a region that is rising tectonically. The highest terrace levels reflect the oldest base levels; the present floodplains of the creeks and streams measure today's base level. In north Louisiana there is a marked consistency in the levels of the terraces, the elevation differences between terraces, and the elevation difference between the highest and lowest terraces. Generally speaking, Figure VI-I-1 lists the approximate levels of the terraces and the names of the terraces that have been mapped in the Vacherie area. Those in the Rayburn's dome area are from 20 to 30 ft lower.

Fig. VI-I-1. Approximate msl elevations of the Quaternary levels in the vicinity of Vacherie dome area.

Regional tectonic uplift since Williana time, the earliest of the Pleistocene interglacials, is on the order of 110 ft. If 1.5 million years is assumed from Williana time to the present, this would amount to less than 20 ft in 250,000 years---a value too small to be of significance.

2. Glaciation

What is the possibility of an ice age occurring in the 250,000 year time span during which the waste will be radioactive, and what effect might an ice age have on hastening erosion of, or exposing the salt? Similarly, what is the possibility of the ice caps on Greenland and Antarctica melting in this time interval, and how might this affect the integrity of the nuclear waste repository? Geologists and climatologists conclude that one major ice age (the Wisconsin) and at least one minor ice age (the Late Wisconsin) have occurred during the past 100,000 years, and that at least three additional major ice ages occurred during the 1.5 million years that have resulted in the deposition of the Quaternary terraces in Figure VI-I-1. There is every reason to believe that we are currently living in an interglacial period and that the ice will advance again in the next 250,000 years.

What might such an advance mean in terms of increased erosion and the general stability of a shallow dome such as Rayburn's? The most obvious natural phenomenon associated with such an ice advance is the eustatic lowering of sea level. There is little reason to believe that an ice sheet might reach the latitude of north Louisiana; all previous Quaternary sheets in North America have reached no farther south than the latitude of St. Louis. Lowering of sea level, however, by as much as 450 ft (the generally accepted value for the Wisconsin glaciation) reduces the base levels of the major streams. In time the effect of this lowered base level is felt on even such minor tributaries as Bashaway and Fouse creeks at

Vacherie and Rayburn's domes. The change in base level and the amount of erosion that results is plainly evident along these creeks and can be estimated by measuring the thickness of the Quaternary fill, i.e., the depth of the entrenched valleys which contain the Quaternary fill. In the case of Bashaway Creek this amounts to about 50 ft; in the case of Fouse Creek, somewhat less.

Another effect of lowered base levels is the general lowering of water tables. Again this effect becomes less with distance from the Gulf and with distance from the major stream valleys. It is doubtful if water tables would drop significantly from their present levels in north Louisiana. There is good evidence that pluvial periods, periods of rainfall amounts much higher than those of the present, or distinctively arid periods occurred during both glacial and interglacial periods. Thus, periods of increased, as well as reduced, erosion due to climatic fluctuations should be expected many times during the next 250,000 years. But the overall effects of such fluctuations on water tables and on erosion rates should be minor. Their total effect is conveniently reflected in the differences in elevation of the terrace levels of north Louisiana.

A final consideration associated with glaciation is the possibility of the ice caps melting entirely. This is believed to have been the normal situation on our planet during the past billion years when climatologists estimate that average global temperatures stood close to 72° F. Today world temperatures average only about 59° F. Should we revert to more "normal" times in the next 250,000 years, and should the ice caps melt, it is estimated that sea level could rise as much as 200 ft. Thus the sea could conceivably cover Rayburn's and Vacherie domes. As the sea advanced over what is now land, base levels and water tables would

rise and first the major valleys and then their tributaries would begin to aggrade. This would be reflected in additional alluvial deposition above the domes and eventually if the sea actually covered the domes, by marine deposition. The effect of such an occurrence on a repository is conjectural. On the one hand, a rise in sea level would bury a waste repository even more deeply. On the other hand, a remote adverse possibility might be that additional sedimentation above the domes would reactivate upward movement of the dome. On balance, however, adverse effects should be minimal.

To summarize, the magnitude of the erosional and depositional processes predicted for the next 250,000 years is too small to be of any real consequence. The caprock on a shallow dome such as Rayburn's might become exposed or moderate changes in ground-water level might affect the salt in ways as yet unclear; but it is felt that such effects can be designed for should further study conclude they might be significant.

VI-J. FINDINGS AND RECOMMENDATIONS

C. R. Kolb

1. Findings

Originally the studies of the Quaternary had as their objective the determination of the tectonic stability of the salt domes. As the studies progress, however, it becomes apparent that they may also develop information useful in determining the hydrologic stability of the salt during Quaternary and pre-Quaternary time. Definitive conclusions concerning tectonic and hydrologic stability based on Quaternary studies are premature at this stage in the investigation, but several preliminary findings of importance are summarized below.

1) Detailed borings made at Vacherie have not been completely analyzed, but two subsurface sections crossing the dome at roughly right angles to its long axis (Figures VI-B-3, -4, -5, and -6) show no irregularities that can be attributed to uplift, i.e. tectonic instability.

2) The borings along the subsurface section at the western end of Vacherie dome (Figures VI-B-4 and -6) encountered three anomalous zones where oxidized fine sandy silts and silty sands reach depths of at least 200 ft. These are interpreted as lows caused by dissolution and collapse of the underlying salt in pre-Quaternary times, e.g. Miocene or Pliocene times.

3) Lineations detected on radar, color, and black and white imagery have been mapped (Figure VI-C-1) extending through two of the three anomalous zones mentioned above. Arcuate lineations in Quaternary deposits on the eastern flank of the dome in the floodplain of Black Lake Bayou suggest the only possibility found to date of upward movement of the salt during Quaternary time.

4) Concordant elevations of the Quaternary deposits flanking Bashaway Creek over Vacherie dome with the Quaternary deposits in the valleys to the north and south of Bashaway Creek are excellent evidence that no uplift due to salt movement has occurred in Quaternary time. Unfortunately only one sufficiently detailed topographic profile is available on which to base this conclusion (Figure VI-F-1).

5) Vacherie and Rayburn's domes lie in topographic depressions above breached structural domes or anticlines. The most probable reason for these topographic depressions is that they are due to dissolution and collapse of the underlying salt.

6) The magnitude of the erosional processes predicted for the next 250,000 years is too small to be of any real consequence. The caprock on a shallow dome such as Rayburn's might become exposed in this time period, but it is felt that this situation can be designed for should further study conclude that such exposure might cause problems.

2. Recommendations

Recommendations for further study are contained throughout the text of this section of the report. Much of the data already collected is only partly analyzed; other portions are currently being obtained. Some of the field work has been deferred until access rights are available to the areas in question. Office studies are continuing.

A summary of recommendations follows.

1) Continue cored boring program at Rayburn's and Vacherie and extend it, in fiscal year 1978, into areas where access was denied in fiscal year 1977.

2) Use seismic refraction methods for delineation of the contact between the Quaternary and pre-Quaternary wherever possible. Use selected borings or up-hole seismic methods where anomalous situations are found.

3) Determine the lateral extent of anomalous lows and through use of pollen analysis or possible radioactive dating, determine the age of the material in these lows. Attempt deeper penetration with seismic methods in order to locate collapse of caprock beneath surface lows.

4) Continue pedologic studies to determine their effectiveness in detecting irregularities that suggest warping of the soil profiles formed above the dome resulting from tectonic instability.

5) Study cases of known Quaternary warping above salt domes, e.g., Five Islands, German and Dutch domes, etc., in order to better interpret boring and seismic profiles at Vacherie and Rayburn's.

6) Continue studies of the significance of the topographic lows above north Louisiana domes. It is felt that drainage basin analysis as discussed in the text may prove an excellent and sophisticated tool to examine this problem.

7) Collect as much detailed elevation data as possible in a broad zone around both domes in order to map the extent and the elevation differences in the Quaternary surfaces. Correlation of corresponding levels away from the dome with those above the dome are considered an excellent method to determine tectonic stability.

8) Refine the preliminary conclusions presented here on erosional effects at Rayburn's and Vacherie during the next 250,000 years.

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VIII. APPENDICES

- A. Soundings and Borings: Vacherie Salt Dome
- B. Water Well Records: Vacherie Salt Dome

APPENDIX A

Soundings and Borings:

Vacherie Salt Dome

DEPTH, FT.	SYMBOL	SAMPLES	SOIL DESCRIPTION	SHEAR STRENGTH, TSF			* BLOWS/FT.	PLASTIC LIMIT			WATER CONTENT			LIQUID LIMIT		
				0.5	1.0	1.5		10	20	30	40	50	60			
			SURFACE ELEV.:													
			HARD TAN SILTY CLAY WITH SILT SEAMS AND LAYERS													
110		X						50/4"								
		X						98/10"								
120		X						50/6"								
		X														
130		X						55/5"								
		X														
140		X						50/4"								
150			TERMINATION DEPTH = 150'													
160																
170																
180																
190																
200																
COMPLETION DEPTH: 150'				*140 LB. HAMMER DROPPED 30 INCHES												
DATE: 8/12/77																
SEE SHEET 1 FOR LEGEND				LOG OF BORING NO. 1 VACHERIE SALT DOME DUBBERLY, LOUISIANA								FIG. A-1 (cont'd)				
				SHEET 2 OF 2

COMPLETION DEPTH: 175'

* 140 LB. HAMMER DROPPED 30 INCHES

DATE: 7/19/77

SEE SHEET 1 FOR
LEGENDLOG OF BORING NO. 2C3
VACHERIE SALT DOME
DUBBERLY, LOUISIANAFIG. A-3
(cont'd)

SHEET 2 OF 2

DEPTH, FT	SYMBOL	SAMPLES	SOIL DESCRIPTION	SHEAR STRENGTH, TSF			BLOWS/FT. *	PLASTIC LIMIT			WATER CONTENT			LIQUID LIMIT		
				0.5	1.0	1.5		+	---	+	+	---	+	+	---	+
			SURFACE ELEV.:													
			HARD GRAY SILTY CLAY				66									
110																
120							50/6"									
130																
140							50/6"									
150																
160			TERMINATION DEPTH = 160'													
170																
180																
190																
200																
COMPLETION DEPTH: 160'				*140 LB. HAMMER DROPPED 30 INCHES												
DATE: 8/23/77																
SEE SHEET 1 FOR LEGEND				LOG OF BORING NO. 3 VACHERIE SALT DOME DUBBERLY, LOUISIANA								FIG. A-4 (cont'd)				
				SHEET 2 OF 2

FUGRO GULF, INC.
Consulting Engineers and Geologists

PLATE

FUGRO GULF, INC.
Consulting Engineers and Geologists

PLATE

FUGRO GULF, INC.
Consulting Engineers and Geologists

FIG. A-13

FUGRO GULF, INC.
Consulting Engineers and Geologists

FIG. A-14

FUGRO GUIS, INC.
Consulting Engineers and Geologists

PLATE

PUBCO GULF, INC.
Consulting Engineers and Geologists

PLATE

FIG. A-21

APPENDIX B

Water Well Records:

Vacherie Salt Dome

Table B-1. Well completion description, Well V-4, Vacherie salt dome.

Log of Well for Louisiana State University Well No. V-4
 Address (City) Heflin (County) Webster State Louisiana
 Location of Well 6 miles East of Heflin, La. Made in Test Hole No. V-4

DRILLER'S LOG

TOTAL DEPTH	EACH STRATUM	FORMATION
	0-6	Red Clay
	6 - 16	Red Clay, Green Sand
	16 - 69	White Clay, Green Sand
	69 - 70	Lignite
	70 - 71	Rock
	71 - 90	Lignite
	90 - 112	Fine White Sand
	112 - 164	White Sand & Lignite
	164-165	Rock
	165-195	Pink Clay
	199-220	Sand, Clay, Boulder
	226-280	Clay
	280-233	Hard sandy Clay
	233-450	White Clay and Sand
	450-490	Hard Sand
	490-555	Hard Clay
	555-590	Hard Clay & Pyrite
	590-754	Hard Clay and Lime

STARTED WELL March 17, 19 77 AND COMPLETED March 28 19 77
 TOTAL DEPTH 487' ELEVATION _____ STATIC WATER LEVEL 60.7
 ALL MEASUREMENTS TAKEN FROM (GROUND) (TOP OF FOUNDATION) (TOP OF CASING) (TOP BASE PLATE)
 SURFACE CASING: SIZE _____ LENGTH _____ THICKNESS _____ T & C WELDED
 CEMENTED WITH _____ SACKS CEMENT OR PACKER TYPE _____ T & C X
 WELL CASING: SIZE 6" LENGTH 464' WEIGHT _____ WELDED
 CEMENTED WITH 110 SACKS CEMENT OR PACKER TYPE _____ T & C
 INNER CASING SIZE _____ LENGTH _____ TYPE MATERIAL _____ T & C WELDED
 WITH X (GUIDES LOCATED) _____ TYPE BACKOFF left hand
 SIZE SEAL 3 x 5 BACKPRESSURE VALVE none SIZE _____ LENGTH GUIDE _____
 WELL STRAINER: MAKE Johnson TYPE _____ SIZE 3 LENGTH 10 OPENING 020
 TYPE MATERIAL Stainless St. WITH T & C CONNECTIONS
 SIZE HOLE DRILLED FOR SURFACE CASING _____ WITH _____ BIT
 SIZE HOLE DRILLED FOR WELL CASING 8" -0 WITH Roller BIT
 SIZE HOLE DRILLED FOR STRAINER 4 7/8" WITH _____ REAMER
 YARDS OF GRAVEL USED _____ HOW PLACED _____ TYPE _____
 HOW WAS WELL DEVELOPED Air SAND? NO CLEAR? X
 FOUNDATION INSTALLED YES X DEPTH FEELING RODS X TOP OF WELL _____
 NOTES: _____
 RIG USED 1500 SUPT. _____ DRILLER Elgyn Smith

Table B-2. Well completion description, Well V-5, Vacherie salt dome.

Log of Well for Louisiana State University Well No. V-5
 Address (City) Heflin (County) Bienville State LA
 Location of Well 9 miles East of Heflin Made in Test Hole No. _____

DRILLER'S LOG

EACH STRATUM	FORMATION
0-18	Red Clay
18-20	Lignite
20-21	White Clay
21-26	Lignite
26-90	Pink Clay
90-115	Clay & Lignite
115-116	Rock
116-179	Clay & Lignite
179-207	Sandy Clay
207-208	Rock
208-214	Lignite
214-260	Clay
260-300	Lignite, Clay
300-365	Clay
365-395	Sandy
395-460	Clay
460-530	Hard Clay
460-530	Hard Clay strks., Pyrite
530-670	Hard Clay Lime
670-697	Lime, Shale
607-775	limestone
775-815	Rock

CONTRACT NO. CL-0385

STARTED WELL March 28 19 77 AND COMPLETED April 14 19 77
 TOTAL DEPTH 386' ELEVATION _____ STATIC WATER LEVEL 60.1
 ALL MEASUREMENTS TAKEN FROM (GROUND) (TOP OF FOUNDATION) (TOP OF CASING) (TOP BASE PLATE)
 SURFACE CASING: SIZE _____ LENGTH _____ THICKNESS _____ T & C WELDED
 CEMENTED WITH 100 SACKS CEMENT OR PACKER TYPE _____ T & C WELDED
 WELL CASING: SIZE 5" LENGTH 366' WEIGHT _____ T & C WELDED
 CEMENTED WITH _____ SACKS CEMENT OR PACKER TYPE _____ T & C WELDED
 INNER CASING SIZE _____ LENGTH _____ TYPE MATERIAL _____ T & C WELDED
 WITH X (GUIDES LOCATED) _____ TYPE BACKOFF L.H. Thread
 SIZE SEAL _____ BACKPRESSURE VALVE _____ SIZE _____ LENGTH GUIDE _____
 WELL STRAINER: MAKE Johnson TYPE _____ SIZE 3" LENGTH 10 OPENING 020
 TYPE MATERIAL Stainless St. WITH T & C CONNECTIONS _____
 SIZE HOLE DRILLED FOR SURFACE CASING _____ WITH _____ BIT
 SIZE HOLE DRILLED FOR WELL CASING 8" WITH Roller BIT
 SIZE HOLE DRILLED FOR STRAINER 4 7/8 WITH Bit REAMER
 YARDS OF GRAVEL USED _____ HOW PLACED _____ TYPE X
 HOW WAS WELL DEVELOPED Air SAND? _____ CLEAR? X
 FOUNDATION INSTALLED YES LINE _____ DEPTH FEELING RODS _____ TOP OF WELL _____
 NOTES: screen hole wash with spray nozzles
 RIG USED 1500 SUPT. _____ DRILLER Elgyn Smith

LAYNE CENTRAL DIVISION
 P. O. BOX 278
 CLEVELAND, MISS. 38732

Table B-3. Well completion description, Well V-6, Vacherie salt dome,

Lanford Drilling Company, Inc.

• P.O. Box 98 • Shreveport, La. • 71161

CUSTOMER	L.S.U. BOARD OF SUPERVISORS	WELL NO.	V-6
LOCATION	UNIVERSITY STATION	COMPLETED	April 1977
ADDRESS	BATON ROUGE, LOUISIANA 70803	PURCHASE ORDER NO.	
		CONTRACT NO.	139-774 BID NO. 2168-A

GROUND WATER OBSERVATION WELL
No. V-6 AT VACHERIE SALT DOME

Table B-4. Well completion description, Well V-7, Vacherie salt dome.

Lanford Drilling Company, Inc.

• P.O. Box 98 • Shreveport, La. • 71161

CUSTOMER	L.S.U. BOARD OF SUPERVISORS	WELL NO.	V-7
LOCATION	UNIVERSITY STATION	COMPLETED	April 1977
ADDRESS	BATON ROUGE, LOUISIANA 70803	PURCHASE ORDER NO.	
		CONTRACT NO.	139-774 BID NO. 2168-A

GROUND WATER OBSERVATION WELL No. 7
AT VACHERIE SALT DOME

Table B-5. Drill cuttings description, Well V-4, Vacherie salt dome.

WELL V-4

<u>Depth (feet)</u>	<u>Drill Cuttings Description</u>
30-70	Silt, clay, brown, glauconitic
70-74	Lignite, black
74-90	Silt, clay, streak of lignite
90-100	Silt, fine sand, light grey, grains subangular to subrounded
100-110	Silt, fine sand, gray, glauconitic, grains subangular to subrounded
110-120	Clay, grey
120-130	Clay, grey, silty, lignite
130-140	Clay, grey, silty
140-150	Silt, fine sand, grey, grains subangular to subrounded
150-160	Clay, grey, silty, streak of lignite
160-190	Clay, grey, silty
190-210	Clay, light-grey, silty, glauconitic, micaceous
210-230	Silt, fine sand, clay, light grey
230-240	Clay, light grey, silty
240-246	Lignite
246-276	Clay, light grey, silty
276-280	Lignite
280-294	Clay, light grey, silty
294-300	Lignite
300-310	Clay, light grey, silty
310-330	Clay, light grey, silty, streaks of lignite
330-345	Clay, light grey
345-430	Clay, light grey, silty
430-460	Silt, fine sand, light grey
460-482	Sand, fine grained, streaks of shale
482-754	Shale, grey

Table B-6. Drill cuttings description, Well V-5, Vacherie salt dome.

WELL V-5

<u>Depth (feet)</u>	<u>Drill Cuttings Description</u>
0-12	Silt, clay, red
12-22	Clay, light grey, silty
22-26	Lignite
26-42	Silt, clay, grey with minor red and buff clay
42-52	Silt, fine sand, grains subrounded to subangular, light grey, clayey
52-72	Fine sand, silt, grains subrounded to subangular, light brown, clayey
72-82	Silt, clay, grey
82-92	Clay, silt, grey
92-102	Clay, grey, silty
102-112	Clay, grey, silty
112-122	Clay, grey to blue grey, silty, lignite
122-132	Clay, grey to blue grey with minor red, silty
132-162	Clay, grey, silty
162-172	Silt and clay, grey
172-222	Fine sand and silt, grey, grains subrounded to subangular, clayey
222-245	Lignite
245-260	Clay, grey, silty
260-282	Silt and clay, grey
282-302	Clay, grey, silty to sandy, streaks of lignite
302-332	Silt clay, grey, calcareous
332-385	Fine sand, silt, clay, grey
385-525	Clay, grey, slightly calcareous
525-605	Clay, grey
605-615	Clay silt, grey, slightly calcareous
615-815	• Shale, calcareous, grey

Table B-7. Drill cuttings description, Well V-6, Vacherie salt dome.

WELL V-6

<u>Depth (feet)</u>	<u>Drill Cuttings Description</u>
10-20	Silt, shale, gravel, brown
20-30	Clay, brown, silty
30-40	Clay, dark grey
40-50	Clay silty, gravel, dark grey
50-60	Clay, grey, silty, lignitic
60-70	Silt and clay, grey
70-80	Silt and clay, grey, lignite
80-90	Silt and clay, grey, micaceous, lignite
90-100	Silt, grey, micaceous, clayey
100-110	Silt and clay, grey
110-120	Silt and clay, grey to black, lignite
120-140	Silt and clay, grey, micaceous
140-150	Silt and clay, grey, lignite
150-170	Silt and clay, grey, brown and green
170-230	Clay, grey, green silty
230-235	Silt and clay, grey
235-242	Lignite
242-248	Clay, grey, silty
248-255	Lignite
255-280	Clay, grey, silty
280-300	Clay, grey, silty, calcareous, glauconitic
300-420	Clay, grey, silty, calcareous, glauconitic
420-450	Silt and Clay, brown, slightly calcareous
450-490	Silt and Clay, light grey, slightly calcareous
490-510	Silt and clay, light grey, calcareous
510-610	Clay silty, limestone, light grey

Table B-8. Drill cuttings description, Well V-7, Vacherie salt dome.

WELL V-7

<u>Depth (feet)</u>	<u>Drill Cuttings Description</u>
0-20	Clay, red and white
20-30	Clay, tan to light red, silty, lignite
30-40	Silt, dark grey, clayey, micaceous
40-50	Clay, dark grey, silty, micaceous
50-60	Silt, dark grey, micaceous, lignite
60-80	Lignite, clay silty, dark grey
80-90	Fine sand, grey
90-100	Clay, light grey, silty
100-110	Clay, light grey, pyritic
110-120	Clay, light grey, silty
120-130	Silt, light grey, clayey
130-140	Silt, light grey
140-150	Silt, light grey, clayey
150-160	Fine sand, tan
160-170	Silt, grey, clayey, glauconitic
170-180	Fine sand, light brown
180-190	Fine sand, light brown, clayey
190-220	Fine sand, light brown
220-280	Fine sand, light red to brown, lignite (231-250), pyrite
280-300	Fine sand, grey, lignite
300-350	Fine sand, grey, clayey
350-370	Clay, red brown, silty
370-400	Clay, dark grey, calcareous
400-415	Clay, dark grey, very calcareous, glauconitic pyritic
415-535	Clay, grey green, very calcareous, limestone
535-570	Clay, slightly calcareous, less glauconitic
570-800	Anhydrite
800-850	Salt; no returns, no samples

FIG. B-1
WELL V-4
GEOPHYSICAL WELL LOGS

COMPANY LOUISIANA STATE UNIVERSITY
WELL VACHERIE SALT DOME WELL # 4
FIELD WILDCAT
COUNTY WEBSTER
STATE LOUISIANA

DATE 3-11-77
TIME 1:15 PM
LOGGERS J. H. B. & J. H. B.
GEOPHYSICIAN J. H. B.

LOGGING DEPTH 750
LOGGING RATE 1.5
LOGGING METHOD 1.5
LOGGING EQUIPMENT 1.5

LOGGING DATA
S.E. Log - ILM 6.4
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9

CHARLENE
WELL SURVEYING COMPANY
ELECTRIC LOG

COMPANY LOUISIANA STATE UNIVERSITY
WELL VACHERIE SALT DOME WELL # 4
FIELD WILDCAT
COUNTY WEBSTER
STATE LOUISIANA

DATE 3-11-77
TIME 1:15 PM
LOGGERS J. H. B. & J. H. B.
GEOPHYSICIAN J. H. B.

LOGGING DEPTH 750
LOGGING RATE 1.5
LOGGING METHOD 1.5
LOGGING EQUIPMENT 1.5

LOGGING DATA
S.E. Log - ILM 6.4
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9
S.E. Log - ILM 5.9

Compensated
Formation
Density Log

Borehole
Compensated
Sonic Log

4/601/506-4112/37

FIG. B-2
WELL V-5
GEOPHYSICAL WELL LOGS

**Compensated
Formation
Density Log**

**Borehole
Compensated
Sonic Log**

4/6001506-4112/37

SPONTANEOUS-POTENTIAL

$$\frac{5}{- \left| \text{---} \right| +}$$

MILLIVOLTS

CONDUCTIVITY

WILLIAMSONS M = $\frac{1000}{\text{OHMS M}^2 \text{ M}}$

3000	DEEP INDUCTION	1000
		2000
		1000
		0

RESISTIVITY

OHMS M²/M

0	DEEP INDUCTION	20
		200
	//////////	
	AVERAGED -SFL	
		20
		200
	//////////	
	AMP. AVE. - SFL	
		4

100
200
300
400
500

Borehole Compensated Sonic Log

4/000/sub-0112/57

GEOPHYSICAL WELL LOGS

4/low I/sub - 4112/37