ONWI-416

The Quaternary Geology of Rayburn's Salt Dome: North Louisiana Salt Dome Basin

Technical Report

February 1983

Charles R. Kolb
Joseph C. Holmes

Institute for Environmental Studies
Louisiana State University
Baton Rouge, LA 70803

ONWI
Office of Nuclear Waste Isolation

BATTELLE Project Management Division

BIBLIOGRAPHIC DATA

Kolb, C. R. and J. C. Holmes, 1983. *The Quaternary Geology of Rayburn's Salt Dome: North Louisiana Salt Dome Basin,* ONWI-416, prepared by the Institute for Environmental Studies, Louisiana State University for the Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

NOTICE

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A08
Microfiche copy: A01

ONWI-416
Distribution Category UC-70

The Quaternary Geology of Rayburn's Salt Dome: North Louisiana Salt Dome Basin

Technical Report

February 1983

Charles R. Kolb
Joseph C. Holmes

Institute for Environmental Studies
Louisiana State University
Baton Rouge, LA 70803

The content of this report was effective as of January 1982. This report was prepared by the Institute for Environmental Studies, Louisiana State University under Subcontract E512-08000 with Battelle Project Management Division, Office of Nuclear Waste Isolation under Contract No. DE-AC06-76RLO1830 and DE-AC02-83CH10140 with the U.S. Department of Energy. This contract was administered by the Battelle Office of Nuclear Waste Isolation.

Acknowledgements

Numerous individuals have helped in the collection, analyses and presentation of the data summarized in this report. Some worked full time on the project as research associates and others worked part-time as graduate assistants, student workers, and consultants. Thomas Avgikos, Elizabeth Clark, Rick Erickson, Joe Holmes, James McNees, Donald Mohr, Donald Nemeth, David O'Brian, John Parker, and Glenn Smith were or are research associates. Young Choi, Clifton Dixon, Robb Eidemiller, Glen Fredlund, Michael Harris, Randy Hilding, Margaret Kress, and James Rehage were or are part-time graduate assistants. Mark Betts, Mark Gaby, Greg Gasperecz, Nazarin Goodarzi, Linda C. Gordon, Monica Hill, Peter Hirlihy, Mike LeBlanc, Barbara Lowery, Matthew Mathers, Patti Phillips, Linda Rice, David Ryan, Frank Sagona, Upal Sengupta, Victor Sittig, and Zia Tammami were or are student workers.

Professor J. Joseph Alford, University of Western Illinois, acted as geomorphological consultant. Professor David Krinsley, Arizona State University, conducted grain-surface and texture analyses. Professor Robert Ehrlich, Mary Ann Langford and Carlene Sexton, University of South Carolina, conducted Fourier grain-size analyses. Professor Anthony J. Lewis, formerly with LSU, helped in interpreting remotely sensed data. Professor Fred Wiseman, Department of Geography and Anthropology, LSU, provided guidance in our pollen studies.

Avgikos, Betts, Dixon, Erickson, Harris, Hirlihy, Holmes, McNees, Nemeth, Parker, Ryan, and Smith acted as field geologists accompanying the drilling rigs. Avgikos, Choi, Holmes, LeBlanc, Mathes, Nemeth, O'Brian, Parker, Sagona and Sittig processed core samples in the Quaternary Studies lab at LSU-IES and compiled these data in subsurface sections under the supervision of Nemeth.

Hill, Holmes, O'Brian, Parker, and, in particular, Choi were responsible for drafting the numerous charts and figures needed in this and other reports. Field surveys were conducted by Avgikos, Choi, Dixon, Holmes, LeBlanc, Smith, and Parker. Air photo interpretation was performed by Holmes, Parker, and Phillips.

Smith was responsible for setting up the ^{14}C dating facility in the LSU-IES Quaternary lab with the aid of Professor F. A. Iddings, Nuclear Science Center, LSU. Smith also conducted the isotope studies on the boulder zone materials to determine their origin. Fredlund processed, extracted, and analyzed samples for the palynological studies.

Special thanks are due Joseph D. Martinez, former director of LSU-IES, who provided guidance during much of the research effort. He served as an informed and constructive sounding board for some of the hypotheses advanced in this report.

Recognition and appreciation are due the staffs and personnel of the following companies who operated the drilling rigs and obtained requested samples: Servitron Inc., of Baton Rouge; McClelland Engineers, Little Rock, Arkansas; Fowler Drilling Company, Newton, Texas; Doak Boring Company, Magnolia, Arkansas; and J. L. Gatz Exploration, Inc., Vicksburg, Mississippi. Additionally, the authors would like to acknowledge professional services of James R. McCoy and Associates, Monroe, and Greswald Engineering, Bossier City, for location surveys; Harding-Lawson Associates, San Rafael, California, for seismic refraction surveys; Law Engineering Testing Company, Marietta, Georgia, for electrical resistivity surveys; and Beta Analytic, Inc., Boca Raton, Florida, University of Arizona at Tucson, Laboratory of Isotopic Geochemistry, for radiocarbon dates. The cooperation and support of Continental Forest Industries and their representatives, W. C. Postle and Andrew Schaar, are greatly appreciated.

The authors are grateful for the efforts of the office staff of LSU-IES, particularly Ellie Jeansonne, Patsy Benoit, Marie Champagne, Laura Jolley and Cathy Scivicque, and for the editorial guidance of Jami Donley.

ABSTRACT

Investigation of the Quaternary sediments above Rayburn's salt dome was undertaken as part of the study of the utility of Gulf Coast salt domes for the storage of radioactive wastes. The areal and vertical distribution of the coarse-grained gravelly Quaternary sediments was delineated with shallow cored borings. The relationship of the Quaternary sediments to the older Tertiary and Cretaceous sediments, and to a zone of calcite boulders found above the caprock was analyzed through the use of stratigraphic, paleontologic, petrographic, palynologic, isotopic, and geochronologic methods. Investigations of the Quaternary deposits above the dome indicate that:

(1) A 20-to 100-foot sequence of fine sediments with increasing amounts of sand and chert gravel with depth underlies a topographic low above the salt dome. These deposits are of Quaternary (specifically late Quaternary) age.

(2) A "boulder zone" consisting of water-worn calcite boulders and cobbles in a matrix of dark gray and tan sandy clay and clayey sand is present beneath these gravel-bearing Quaternary deposits and above the anhydrite-gypsum caprock.

(3) Isotopic studies have identified the boulder zone as the remnant of a once continuous calcite caprock cover that was subjected to subaerial erosion in the geologic past. Radiocarbon dating of organic deposits in the boulder zone has provided dates of approximately 19,000 and 21,000 years. However, the pollen contained in the boulder zone suggests that the material may have formed at an earlier date, perhaps between Oligocene and late Pliocene time.

(4) Generally speaking, the anhydrite-gypsum caprock is closer to the surface near the center of the topographic low over the salt dome and slopes down toward the outer limits of this low. However, the caprock surface rises again very abruptly and very steeply at the extreme edges of the low, suggesting that an underground ridge of caprock, sometimes only 15 feet below the surface, completely encircles the outer boundaries of the low. Thus, if uncovered, the caprock over the center of the dome would look like a bowl with a high center.

(5) The only outlet to the central topographic low that could have drained it during Quaternary time is to the south along Fouse Creek, now filled with Quaternary alluvium only 10 to 12 feet deep. Thus, the 100-foot thickness of gravel-bearing Quaternary that underlies the low can be accounted for only by dissolution of the underlying salt and subsidence of the Quaternary.

(6) Radiocarbon dates from samples of wood found in the gravel-bearing (the surficial) Quaternary above the dome range from about 13,500 to 19,500 years BP. Based on the assumptions made, the rates of dissolution and subsidence of the surficial Quaternary during the past 20,000 years range between 1.0 and 3.0 feet per 1,000 years. If radiocarbon dates from two organic samples from the boulder zone are correct (about 19,000 to 21,000 years BP), dissolution and subsidence during the past 20,000 years range between 1.5 and 5.0 feet per 1,000 years.

TABLE OF CONTENTS

List of Plates

List of Figures

List of Tables

Introduction

The investigation of Quaternary age deposits at Rayburn's salt dome is part of the research by the Institute for Environmental Studies, Louisiana State University (LSU-IES) on the utility of Gulf Coast salt domes for the storage or disposal of radioactive wastes. Geologic descriptions and field reconnaissance by LSU-IES personnel during the early phase of the project indicated the presence of such Quaternary age deposits above Rayburn's dome. It was reasoned that if there were Quaternary sediments of sufficient vertical and lateral extent above the dome to warrant a detailed study, they might provide important clues in evaluating movement of the dome since these strata were deposited, i.e., the past million years or so. Specifically, the study concerned four objectives:

a. To determine whether the Quaternary has been lifted out of place above the dome by upward movement of the salt since the deposition of these sediments.

b. To provide insights concerning the hydrologic stability of the upper portions of the dome as evidenced by dissolution and subsidence and/or collapse during Quaternary time.

c. To estimate the effects of erosion above the dome during the next 250,000 years.

d. To utilize field mapping, borings, trenching and related techniques to determine the stratigraphy and structure of the Quaternary and the pre-Quaternary deposits above and immediately flanking the dome.

Location and Geologic Setting

Located in Bienville Parish, Rayburn's salt dome is one of nineteen domes in the North Louisiana Salt Dome Basin. Twelve of these domes, including Vacherie and Rayburn's, lie beneath topographic depressions, most of which are underlain by variable thicknesses of Quaternary deposits. Initial introduction of these sediments into the study area is thought to have occurred in late Pliocene or early Pleistocene times. They represent the first wave of coarse sedimentation known to have affected the area in Cenozoic and late Mesozoic times. They contain chert gravels probably originating in the mid-continent and are disposed as alluvial terraces along almost all of the creeks and rivers of the Gulf Coastal Plain. Only small remnants of the oldest and highest of these former terraces are found in the hills surrounding the study area. These remnants, together with early Tertiary and occasional upper Cretaceous sediments, are the source materials for the Quaternary deposits that now lie above the dome.

The surficial Quaternary* of the Rayburn's area is characterized by a mixture of clay, silt, sand and chert gravels. These materials are generally tan to red-brown indicating a considerable degree of oxidation. They rest principally over the central part of the dome, but they are also scattered irregularly above the Tertiary and Cretaceous deposits that flank the dome. These older sediments are characteristically unoxidized and contain no chert gravels or granular materials coarser than medium sand. In addition, they dip at significant angles. Thus, distinction between Quaternary and pre-Quaternary deposits in borings, or in trenches and other exposures, is relatively simple.

---

* See page 47 for a definition of surficial Quaternary as used in this report.

The topography at Rayburn's is that of a typical breached dome or anticline. Surface expression of the dome is that of a topographic low with a central saline surrounded by a ring of low hills. The low covers an area of approximately one and one-half square miles. The ring of low surrounding hills consists chiefly of Early Eocene strata: the Sparta, the Cane River, and the Wilcox Formations. Paleocene age Midway clay or shale lies at shallow depths, particularly off the southern flank of the dome. A classic outcrop of fossiliferous chalk, limestone and marl of Upper Cretaceous age is present off the eastern flank of the dome close to the central marshy area. This outcrop has served as a quarry for agricultural lime, and the exposed stratigraphy has been greatly disturbed by earth-moving equipment.

Fouse Creek drains the central topographic low through a gap in the low hills on the southern edge of the dome. This stream drains into the Dugdemona River, a tributary of the Little River which empties into Catahoula Lake and eventually into the Red River. Thus, the Fouse Creek drainage system is small, a tributary to a tributary to a tributary, and is hardly a prime candidate for formation and preservation of fluviatile terraces associated with waning glaciation and regional uplift. The terrace sequence as described by Fisk (1938, 1939) is at best poorly defined within the topographic low above Rayburn's and is probably only partially present in this region. As mentioned above only small remnants of Quaternary deposits are found in the hills surrounding the dome.

Methods of Investigation

Literature Review/Historical Activity

A literature search provided early geological and geographical descriptions of the site. Early maps located geological outcrops and identified areas where historical mining activity occurred.

Soil*/Rock Borings

Methods of sampling the Quaternary and Tertiary deposits from the Rayburn's dome study area included:

a. Auger borings. These were used primarily during the first season of field work. This sampling technique recovers a disturbed sample useful in providing a gross view of the lateral and vertical extent of Quaternary deposits.

b. Cored borings. Obtained by pushing or turning a 3-inch diameter Shelby Tube two feet into the sediments and extracting the contained material as a two-foot core. This method proved to be very successful as it was the least disruptive to the sediments, i.e., stratification and/or bedding planes, where present, were discernible. In all, some 119 cored borings were completed, producing several thousand feet of core.

c. Calyx borings. Samples are obtained with a bucket auger which produces a 24-inch diameter hole up to 60 feet deep. Material is removed in two-foot deep "bites." This technique proved most useful in obtaining samples from a layer of water-worn calcite boulders present beneath surficial Quaternary deposits and above the anhydrite-gypsum caprock.

Other Methods of Study

a. Remotely Sensed Imagery. Radar, color infrared, satellite imagery, and aerial photography were analyzed to detect lineations indicative of possible faults above and surrounding the dome (Martinez and others, 1977). Additional study of aerial photography helped in mapping early mining activities, roads, railways, and drilling activities.

* Soil is used here in the engineering geological sense, i.e., all unconsolidated materials above bedrock.

b. Geophysical Studies. Seismic refraction and electrical resistivity traverses were run and profiles produced in an attempt to determine the depth of the surficial Quaternary deposits and the depth to the boulder zone and caprock surfaces. (Harding-Lawson, 1977; LETCo, 1978).

c. Palynological Studies. Pollen studies were initiated as an aid to differentiate between Quaternary and pre-Quaternary sediments. Additionally, determinations of diagnostic pollen suites present within some samples proved useful in determining paleoclimates indicative of glacial and interglacial stages (Kolb and Fredlund, 1981).

d. Micropaleontological Studies. Select cores were examined for micropaleontological evidence of the geologic age of the strata being examined. A preliminary geologic map of the area was prepared based largely on these determinations.

e. Isotopic Studies. Isotopic analyses of boulder zone materials were performed to determine the mineralogic composition and possible origin of the boulder zone (Smith and Kolb, 1981; see Appendix C).

f. Geochronological Studies. Radiometric dating of organic material recovered from borings and surface excavations was used to provide absolute age determination of the sediments.

Literature Survey - History of Mining

Published Accounts

The earliest geologic account which mentions Rayburn's dome (Hilgard, 1869) noted the numerous deserted pits and furnaces in the extensive flat above the dome resulting from salt mining activity during the Civil War. The Federal blockade made the commercial production of salt from the Rayburn's

"Lick" profitable, and the small operation, started in the early 1840's by Mr. Foust, the owner of the land, expanded to produce a thousand bushels a day. Hilgard reported an interesting stratigraphic profile based largely on surface observations.

0-6 feet	Whitish mud of the lick, with ferruginous spots and at base frequently bearing balls of pyrite.
6-12 feet	Siliceous gravel, often cemented into conglomerate by crystallized calcite.
12-18 feet	Grayish or white crystalline limestone, horizontally banded, fragile, often covered with 5-6 inches crystallized aggregate of calcite, on a dark, banded base of the same.
18-20 feet	Dense, banded gypsum, pure.

Hilgard further reported that the dense, pure, banded gypsum was only reached in the pits located on the southeast side of the lick. Just where the above sequence was located is unknown.

A later observer (Hopkins, 1871) described the Rayburn's salt lick as resembling "the bottom of a dried up pond with a saline efflorescence... covering the lick." He also noted the numerous wells and described the stratigraphy as laminated sand resting on pebbly sand and that on a gypseous clay. One observation of particular interest reported by Hopkins was that mastodon bones had been found in the laminated sand. He also reported an outcrop of gypsum, suggesting that caprock was at the surface in 1871.

Lerch (1893) counted 80 wells which averaged 15-20 feet deep. Also, he recognized Exogyra costata, identifying the limestone and chalk which cropped out at the dome as Cretaceous.

The first detailed map and best description of the Rayburn's site was published by Harris and Veatch in 1900 (Figure 1). They observed old salt furnaces and wells covering an area of about 40 acres. They also

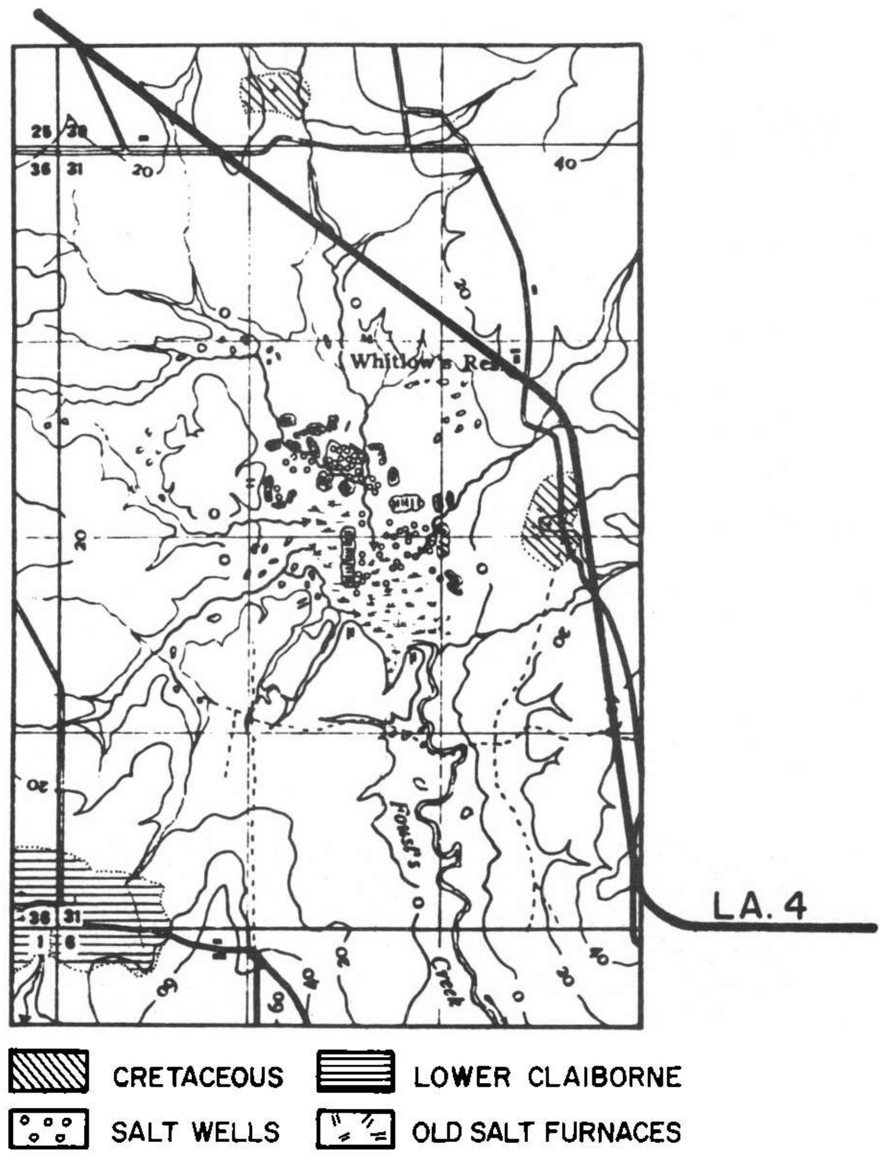

Figure 1. Sketch map of Rayburn's salt works, from Harris and Veatch (1900). Present location of La. Hwy 4 added.

noted around the edges of the depression a series of circular mounds about 60 feet in diameter and 3 to 4 feet high, similar to the "pimple mounds" common in many parts of Louisiana.*

Harris and Veatch recorded the depths of the wells as 15 to 20 feet and commented on the abundant quartz and chert gravels, and the dark gray and yellow crystalline limestone and gypsum present in the dump heaps around the wells. Their map locates salt wells and furnace sites, the Cretaceous outcrop, and the early roads.

Veatch (1902), in his report "The Salines of North Louisiana," described the site. He noted that the natural mounds were utilized as furnace sites and that near the center of the lick, where the natural mounds were absent, artificial mounds of ferruginous sandstone were built to support the large boilers used to concentrate the brine. Additionally, his report discussed the economic importance of the salt works during the Civil War, the Cretaceous outcrop, and the fossils collected.

Spooner (1926) recounted the earlier descriptions of the "lick," its economic importance, fossils present in the Cretaceous outcrop, and noted the strike and dip of the exposures at the outcrop. His map located wells drilled in 1910 and 1923 and gave depths to caprock and salt. Butler and Jones (1957) identified the Cretaceous outcrop as the equivalent to the Saratoga formation of Arkansas based on the presence of fossil ostracods.

Among the observations contained in these historical accounts were the following items pertinent to our study:

(a) Cretaceous sediments, some of the oldest exposed strata in Louisiana, have been brought to the surface by the Rayburn's salt dome.

---

* Pimple mounds, although not restricted exclusively to Pleistocene deposits, are common on these surfaces west of the Mississippi River in Louisiana.

(b) The shallow depth to anhydrite-gypsum caprock and to the underlying salt was recognized by even the early observers. Caprock may have been exposed prior to extensive salt mining that began in the area in the 1840's.

(c) The presence of chert gravels and mastodon remains in the dump heaps (described by early observers) identify the alluvium above the caprock as being of Quaternary age.

(d) The use of ferruginous sandstone for furnace foundations--some hauled in from quarries several miles from the saline--explains the presence of the abundant ironstone fragments scattered about the site. The dark, burnt and ashy soils encountered during our investigations identify locations of former furnace sites where brine was concentrated to commercially usable salt.

(e) The numerous pits, spoil piles and furnace sites that remain from the abandoned salt works have thoroughly disturbed the stratigraphy over limited portions of the dome.

Oral Accounts and Field Observations

Cultural disturbances of the "salt lick," the low, marshy saline above Rayburn's dome, are readily observable in the field. Some of the more obvious of these are the shallow pits or wells made to exploit the underlying salty groundwater. Timbers were sunk to depths of 20 feet or more to support walls of excavations 8 to 10 feet across, and some of these timbers are still in place. Stereoscopic examination of aerial photography revealed numerous shallow lows marking the locations of these former shafts. Figure 2 shows locations excerpted from available maps as well as others inferred from aerial photography.

Brine was also pumped from the dome in the 1940's and used by Southern Paper Company, a predecessor of Continental Forest Industries, the current owners. The location of wells or pipelines constructed by this company is uncertain. However, Figure 2 shows the general area where these two brine wells were located. Oral accounts tell of a pipeline which brought brine from the central saline to the highway east of the quarry where water trucks were loaded with the brine. A cement chimney said to have been constructed as part of Southern Paper Company's operation is located as shown on Figure 2.

Operational data on the quarry are meager, except that it was operated for some years as a source of agricultural lime. Lineations detected on the photo imagery were identified as former rail lines associated with the lime quarry in the early 1940's. The location of these lines is shown on Figure 2. Also shown on Figure 2 is a drainage outlet, still essentially intact, which was dug in the late 1950's and which drained water from the quarry into the low-lying saline. Recent (1981) shallow pits, dug with a bulldozer, by Continental Forest Industries, uncovered a continuation of the limestone rock in the quarry. The rock continues toward the south and dips about 70^0 toward the east.

Soil/Rock Boring Program

Lines of Borings

After a series of auger borings had been made to verify the existence, the general lithology, and thickness of the surficial Quaternary deposits above the dome, two major lines of fairly continuously cored borings, spaced at 200-foot intervals, were made crossing the dome at roughly right angles. One line, designated the X-Line, runs generally northwest to southeast. Beginning upslope in the northwest, the line runs across the topographic low over the central part of the dome, then parallels the course of Fouse Creek through the gap in the encircling Tertiary hills on the southeastern flank of the dome. The second line of borings, the A-Line, was drilled

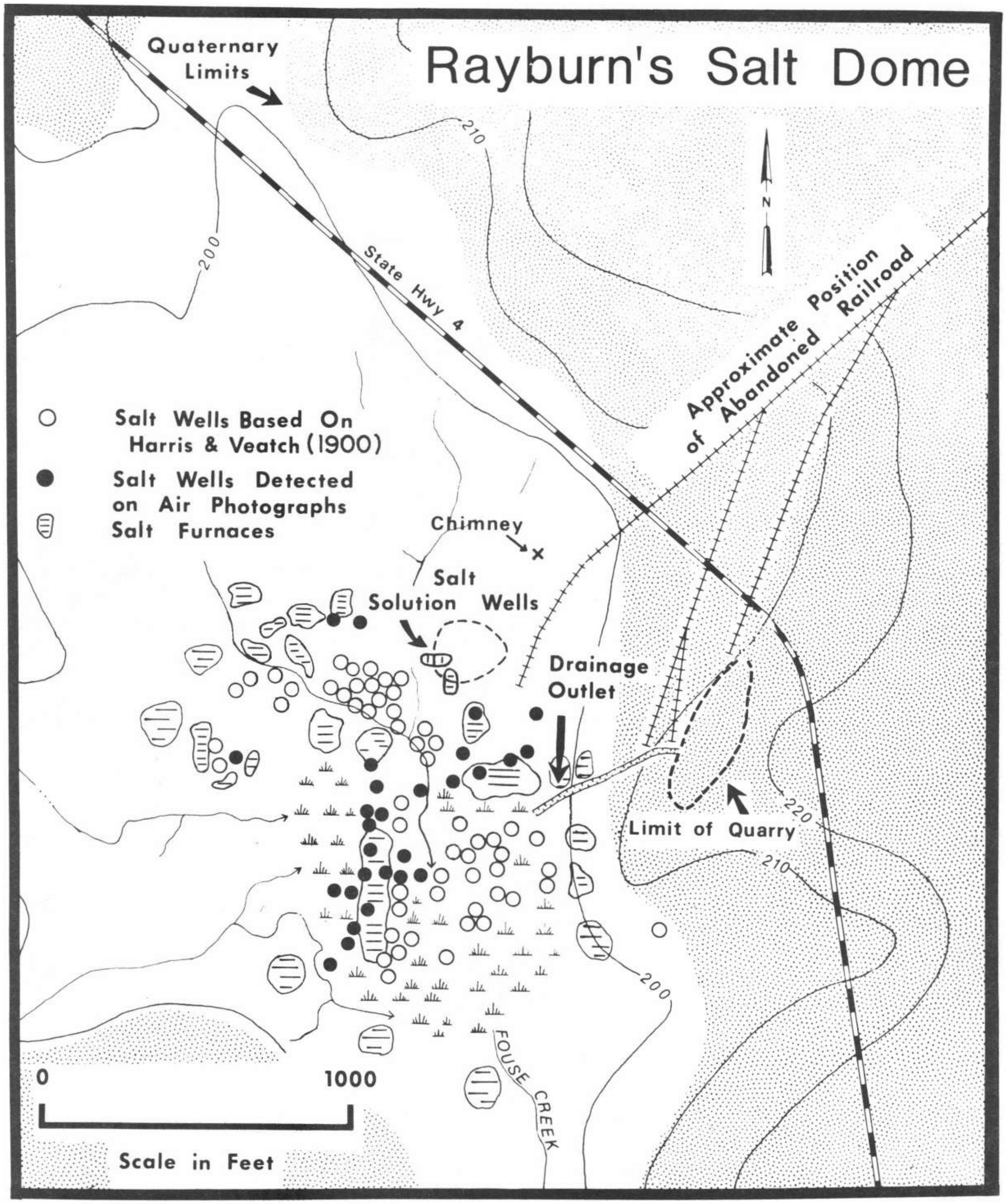

Figure 2. Location of salt wells and other features at Rayburn's dome.

with an east-west orientation, intersecting the X-Line near the center of the topographic low and extending upslope to the higher elevations on either side (Plate 1). A short third line was added which crossed the valley of Fouse Creek as it passes through the Tertiary hills on the southern margin of the dome. These borings are labeled "Y" on Plate 1. The results of this boring effort posed a number of problems that had to be resolved and, as a consequence, a series of borings were made around the topographic low which overlies the dome. The reasons for these borings will be discussed later, but this circumferential line of borings included the Y borings.

Additional borings were drilled to extend the ends of the original lines, obtain additional samples from particular locales, deepen previously drilled holes, explore the nature of the boulder zone, and compare the caprock surface as determined by borings with the results of seismic interpretations.

The A- and X- Lines

Preliminary results based on the early X- and A-Line borings indicated that the caprock was present at very shallow depths, i.e., 35 feet or less, near the central portions of the dome. Quaternary deposits with moderate amounts of chert gravels in this central area overlie a stratum of boulders and cobbles of hard, dark limestone, which was tentatively identified as the result of the weathering of a once continuous calcite caprock cover. These boulders and cobbles were in a matrix of dark gray to tan sandy clay and clayey sand. Obtaining samples from this stratum proved difficult using normal sampling techniques. A core barrel with a diamond or tungsten-carbide bit usually yielded only a foot or so of biscuit-shaped wafers of limestone per five feet of coring attempted. This zone, eventually identified as bouldery material, was encountered at the base of surficial Quaternary deposits in borings A-2 through A-16 (Plate 2) and X-2 through X-19 (Plate 3) over the central depression. In at least two of these borings, A-10 and X-14, anhydrite was encountered after passing through the bouldery stratum.

Only a few of these initial borings penetrated the boulder zone into the underlying intact anhydrite-gypsum caprock. Interestingly, when anhydrite chips began to appear in cuttings being flushed uphole in the borings, indicating that the base of the boulder zone had been reached, the drilling mud would often drain out of the hole and circulation of the drilling fluid would be lost. Sometimes this was accompanied by a drop in the drill pipe of several inches to a foot. Apparently the contact between the calcite boulder zone and the underlying anhydrite-gypsum caprock is characterized by a fractured or "mushy" zone. Later borings drilled to investigate the caprock experienced this same phenomenon.

The lateral extent, thickness, nature and age of the boulder zone, as well as its relationship to the known Quaternary deposits above it, were pursued in subsequent boring programs. As noted above, samples of the material were difficult to obtain. Shelby tube and split-spoon samplers retrieved only small amounts of the matrix within which the boulders and cobbles occurred. Rock-coring samplers retrieved fragmented portions of the calcite boulders and cobbles, but the sand, silt and clay of the matrix were lost completely in the coring operation. The boring method found to be most successful in sampling the boulder zone was the use of a bucket auger which produced a 24-inch diameter calyx hole. The depth of the hole depended on the depth to water table and the cohesiveness of the sediment penetrated. Water table depths in the topographic low over the central part of the dome varied from one to eight feet, and, in some instances, cohesive, relatively impermeable soils extended to depths of 25 feet. When permeable sands and gravels were encountered, water in the calyx hole would rise abruptly to the height of the piezometric level, and sampling would become more and more difficult. The sides of the hole, particularly at depth, would tend to slough in. However, sampling could usually be continued to caprock so that we could document the nature of the material encountered. The size of boulders that could be obtained was, of course, limited by the size of the openings at the bottom of the toothed bucket auger. These openings prevented boulders larger than a foot in diameter from entering the bucket. Samples were dumped on the ground, or on plastic or plywood sheets for field examination. Intact chunks of the dark gray sandy clay matrix, some with small calcite cobbles or gravels included, could be selected from the bucket dump for detailed examination and analysis in the laboratory. Additional sampling of the boulder zone, particularly in an exploratory pit made by T. L. James (See Appendix A) excavated boulders up to 26 inches in diameter. Photographs of this large boulder and other boulders that were sliced for detailed examination in the laboratory are shown in Figures 3 and 4. Boulders of much larger dimensions probably occur within the boulder zone.

Six borings were made using the bucket auger, all at locations that had previously been cored and sampled with more conventional small-diameter rigs. Such borings are indicated by a letter "C" prefixing the boring numbers on the X- and A-Lines (Plates 1, 2, and 3). The materials recovered in the calyx borings were fragments of dark gray hard limestone or calcite. The fragments were subrounded to subangular and appeared to be waterworn. Thin-section analyses of these boulders suggested that they were calcite caprock. It was hypothesized that the zone represented waterworn fragments of a once continuous calcite cover that was exposed to subaerial erosion in past geologic time. The most durable and water-resistant

Figure 3. Photographs of boulders retrieved with a bucket auger from the boulder zone at Rayburn's dome. Note that one fragment has been sliced so that it could be thin sectioned for petrographic study.

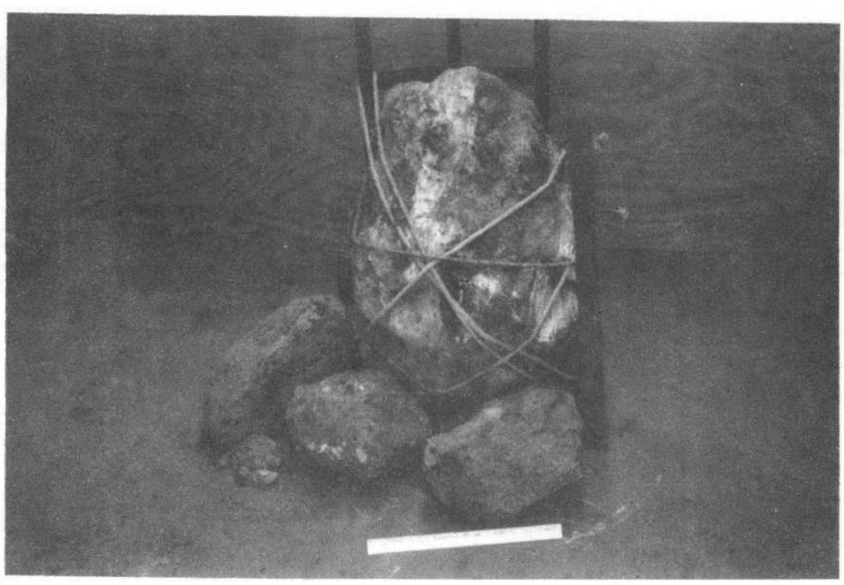

Figure 4. The largest boulder and several of the smaller boulders extracted from the boulder zone. Cardboard scale at right is two feet long.

fragments of the caprock were assumed to have been let down on top of the dome as a bouldery cover.

Further studies, to be discussed later, have substantiated this hypothesis and have gone a long way toward determining the time when the boulder zone was formed.

<u>Circumferential Borings (the C- and Y-Lines)</u>

One of the more puzzling aspects of the drilling program is illustrated on Plate 3, the X-line of borings. Surficial Quaternary deposits containing chert gravel along this line reached depths as great as 50 feet. Along the A-Line, gravel bearing Quaternary deposits reached depths of 80 feet. It had been anticipated that Quaternary sediments had once drained southward along Fouse Creek and, consequently, that a thick sequence of Quaternary would be found along the creek. The thickness of such Quaternary sediments would have to be commensurate with that of the thickest Quaternary found within the basin, that is, on the order of 80 or 90 feet. It was surprising, therefore, to find only from 10 to 12 feet of Quaternary deposits underlying Fouse Creek (that segment of the X-Line extending from X-20 to X-30 on Plate 3). These borings penetrated compact, dark gray to black clays, of probable Midway age, at very shallow depths.

The absence of a sufficiently entrenched outlet along Fouse Creek to account for the thick deposits of known Quaternary within the topographic low which the creek drains could be explained in two ways: (1) that an outlet had existed sometime during the Pleistocene which had drained in a different direction--that Fouse Creek was a path followed by only the most recent drainage outlet; or (2) that dissolution of the underlying salt and subsidence had caused Quaternary deposits to be displaced downward over the central part of the dome.

To explore the former possibility, borings were drilled which eventually formed a circumferential ring surrounding the surficial Quaternary present within the topographic low above the salt dome (Plates 4 and 5). These borings incorporate the Y-Line of borings which crossed Fouse Creek to the south of the central topographic depression. The circumferential borings were made in topographic dips, or saddles, in the surrounding hills along what were considered the most likely avenues for a previous Quaternary drainage outlet. Where Quaternary deposits were encountered, additional borings were positioned to determine the extent and general direction of Quaternary deposition. For example, see Borings C-9, C-16, C-22, and C-22W on Plate 1. Additional borings were subsequently positioned between these prime locations to close the gaps. No Quaternary outlet other than Fouse Creek was found. The only Quaternary deposits found along this profile were at Borings R-1, C-1, C-2, C-3, Y-1, and Y-2, and these proved to be less than 20 feet thick. All borings encountered pre-Quaternary deposits at elevations far above those flooring a possible erosional trench that might have drained the topographic low in former times.

Elsewhere along the circumferential profile, Tertiary or Cretaceous deposits were encountered at or slightly below the surface beneath a thin cover of residual soil. Although usually oxidized to a tan or brownish color like the Quaternary, residual soils developed on the pre-Quaternary are denser, normally consist of finer grained materials, and often retain vestiges of dipping bedding planes. None contained the chert gravel and coarse sand usually associated with the Quaternary, and few such soils were oxidized to depths of more than 2 or 3 feet before assuming a black to gray color where Eocene deposits were encountered, or a cream to gray color where Cretaceous chalks or limestones were encountered. Many of the samples were examined for microfauna, and the geologic age of the pre-Quaternary deposits was determined wherever possible. Determinations of age based on microfaunal evidence are shown, where appropriate, on most of the subsurface sections included as plates.

As no Quaternary outlet other than the one along Fouse Creek was found, the only feasible explanation for the deep gravelly Quaternary deposits filling the topographic low above the dome is dissolution of the salt and subsidence of the overlying Quaternary sediments. Moreover, since Quaternary deposits are displaced, dissolution and subsidence can be dated as having occurred during Quaternary time. This and related data will be discussed more fully in later sections of this report.

Data from the soil/rock boring program form the nucleus for determining the stratigraphy of the geologic units which form the top 200 feet of sediment in the Rayburn's area. These geologic units are described in the discussion which follows, from oldest to youngest: (a) the Cretaceous and Tertiary sediments, (b) the salt, (c) the anhydrite-gypsum caprock, (d) the boulder zone, and (e) the surficial Quaternary.

Cretaceous and Tertiary

One objective of the study was to use the data obtained from the Quaternary studies to map the Cretaceous and Tertiary sediments which form the surface above or flanking the dome or which underlie a thin cover of Quaternary deposits. Whenever possible, the Quaternary borings were extended 10 or more feet into underlying Cretaceous and Tertiary deposits, and several hundred feet of such cored samples are stored at Louisiana State University. As time and funds permitted, small portions of these samples were washed through fine-mesh sieves and the residue examined for stratigraphically diagnostic microfauna. Results of these micropaleontologic studies are shown on all the subsurface sections included as plates in this report. Microfaunally barren samples are shown with appropriate symbology on these plates. Those which contained microfauna were identified, where possible, and those containing fauna characteristic of Cretaceous strata labeled with a "k," those identified as Midway with an "m," and those identified as Wilcox with a "w."

As mentioned previously, some of the oldest strata in Louisiana have been lifted to the surface over the southeastern edge of Rayburn's dome. Steeply dipping limestone and chalk have long been quarried at the site, and early geologists (Lerch, 1893) reported the occurrence of *Exogyra costata* identifying the sediments as Upper Cretaceous. Butler and Jones (1957) refined the stratigraphy exposed at the quarry based on examination of microfauna (ostracods) from a number of cores. They concluded that the Cretaceous exposures at Rayburn's dome are "the equivalent of the Saratoga Formation of Arkansas." The Saratoga is the oldest formation of the Navarro Group (Table 1). Butler and Jones also identified steeply dipping Tertiary strata (Midway) near the eastern edge of the quarry. Durham and White (1960) described the contact between Tertiary and Cretaceous in strata exposed at the eastern edge of the quarry as containing borings of marine organisms backfilled with phosphatic materials, a typical situation at erosional surfaces inundated by marine deposition.

Figure 5 assembles data from which microfaunal or related stratigraphic determinations have been made. Locations of the shallow borings made in the quarry area by Butler and Jones are shown as small closed triangles. A well drilled by Hodge-Hunt in 1957 in the northwest corner of the figure (Boring HH3CC) encountered Midway shales above the caprock. Harris and Veatch (1900) identified Lower Claiborne (Cane River) sediments in the area so designated at the bottom left of the figure. The closed

Table 1. General thickness and lithology of pre-Quaternary sediments at Rayburn's salt dome.

	Series	Group	Formation	Average Thickness	Lithology
TERTIARY	Eocene	Claiborne	Sparta	200 ft	Massive quartz sands; occasional silt or clay lenses.
			Cane River	100-150 ft	Clay, minor glauconite and thin interbeds of silt and sandy silt. Glauconitic, fossiliferous marl. Interbedded khaki-colored silts and clays, calcareous, glauconitic and fossiliferous
		Wilcox	Undiffer-entiated	500-1300 ft	Interbedded fine to medium grained quartz sands interbedded with silts and shales...glauconite common
	Paleocene	Midway	Undiffer-entiated	600-800 ft	Dark gray to black, calcareous, fossiliferous shales; interbedded yellowish brown, fossiliferous calcareous shale, and white fossiliferous chalk
CRETACEOUS	Gulf	Navarro	Arkadelphia*		Predominantly a chalky marl with large amounts of interbedded shales and clays
			Nacatoch*		Massive, glauconitic, calcareous quartz sands with interbeds of shale, marls, and chalky marls
			Saratoga	150 ft	White to gray, slightly arenaceous and clayey, fossiliferous, glauconitic chalk
		Taylor	Marlbrook	?	Fossiliferous marly shales
	*Formations have not been recognized at Rayburn's.				

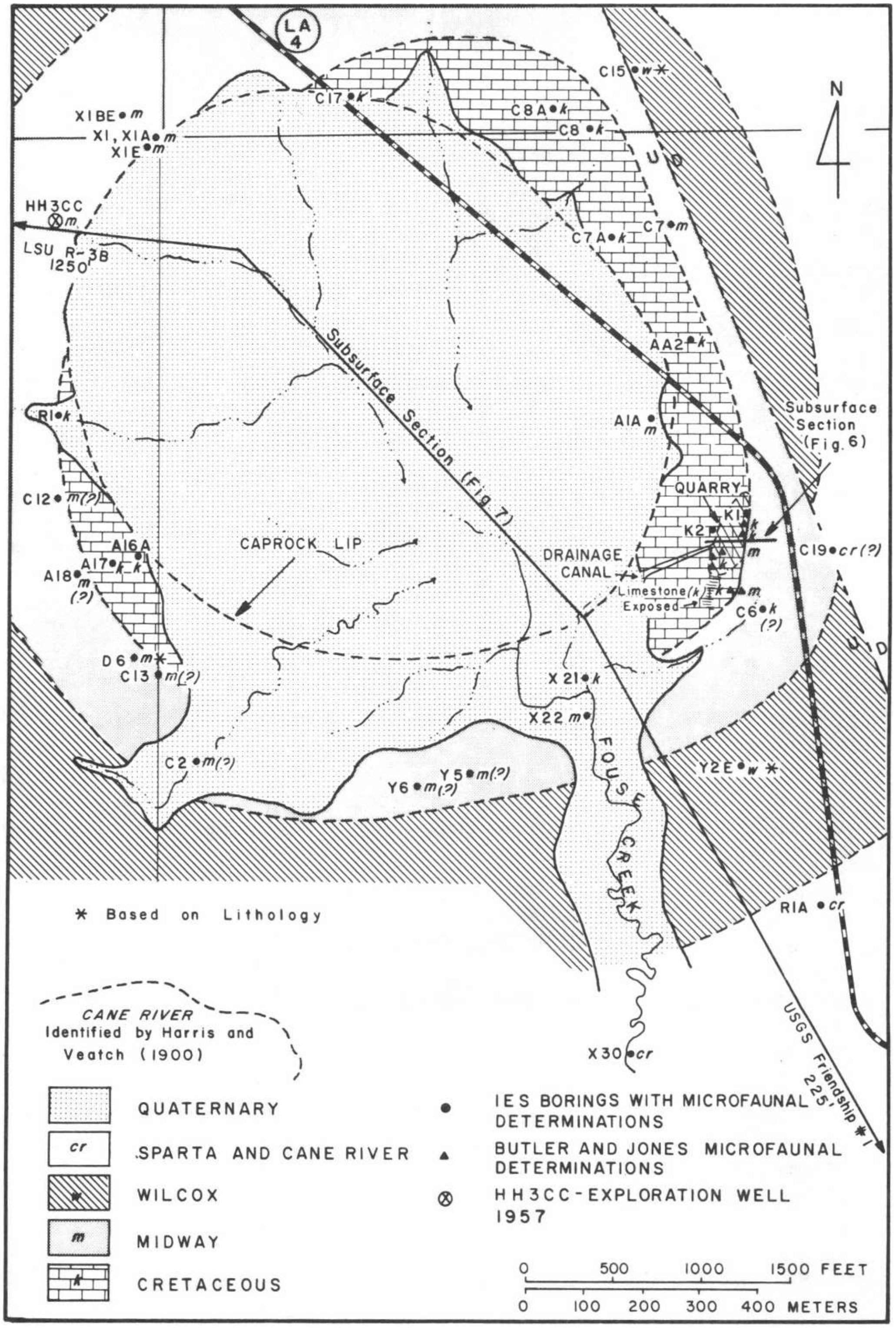

Figure 5. Preliminary map of surface geology at Rayburn's dome.

circles on the figure are locations of borings made for this study from which samples were obtained which contained stratigraphically diagnostic fauna. The geologic unit identified is shown beside the boring in each instance, e.g., "m," "k," or "w." The depth at which the identification was made can be determined from the subsurface sections, Plates 2 through 11. Also note, in examining these plates, that many samples were barren of microfauna or contained microfauna which were not stratigraphically significant.

Figure 5 is a preliminary map of the surface geology at Rayburn's and interprets the stratigraphic data discussed above. Contacts between the various geologic units shown on the map are largely inferred except for portions of the contact between the Cretaceous and the Midway, where exposures and faunal interpretations are fairly well supported by available data and the well-defined contact between the surficial Quaternary and the pre-Quaternary. A number of points should be kept in mind. Boring C-6 is shown on the map in an area mapped as Midway. Cretaceous fauna were identified in a sample taken from this boring; however, the sample was from a depth of more than 40 feet. The lithology penetrated suggests that dark gray Midway shales overlie the Cretaceous at this point and that the identified sample came from below the contact. Cretaceous forms were also identified in Borings X-21 and in the bottom of X22E (at a depth of 103 feet) despite the fact that they were collected in cores of black to dark gray shales characteristic of the Midway.

A possible fault has been included on Figure 5 trending northwest-southeast at the right edge of the figure. A fault in essentially the same position was mapped by Echols (1970) in an unpublished report. An anomalous situation, probably due to radial faulting, occurs at Boring A-1. Here, Midway shale was identified where Cretaceous should normally underlie the Quaternary. Future studies will undoubtedly uncover more anomalies such as this and locate many more faults if the situation at Rayburn's parallels the complex structural conditions prevalent over most salt domes.

Figure 6 is a section drawn from recent (1981) field exposures. It begins at the head of an old channel which was dug more than 20 years ago to drain the quarry, extends across the quarry, and ends near the highway where Butler and Jones (1957) and Durham and White (1960) identified the erosional contact between the Cretaceous and the Midway. Dips of the strata vary from 45 to 75 degrees to the east and southeast. Note that much of the eastern portion of the section is obscured by rubble over the old quarry. It is assumed that the rubble is underlain by chalk and limestone mined in the past for agricultural lime. Butler and Jones have identified the chalk and limestone layer as the Saratoga Formation of the Navarro Group. The older deposits on the western side of the section have not been definitely identified. Echols (1970) suggests that these beds belong to the Marlbrook Formation of the underlying Taylor Group since Exogyra ponderosa, a marker for the Taylor, has been tentatively identified from them. He also notes that Mumma (a student colleague) recognized ostracods in this unit, labeled "older Cretaceous deposits" on Figure 6, and that Howe (Echols, 1970) identified them as of Taylor age.

A subsurface section across the dome in a northwest-southeast direction is shown on Figure 7. Boring R-1A is a water well made for LSU-IES geohydrologic studies. Interpretation of cuttings and of geophysical down-hole logs suggested that a fault cut this boring at a depth of 260 feet. However, data on this possible stratigraphic displacement are too sparse to warrant showing this fault on Figure 7 or in plan on Figure 5. Note that in

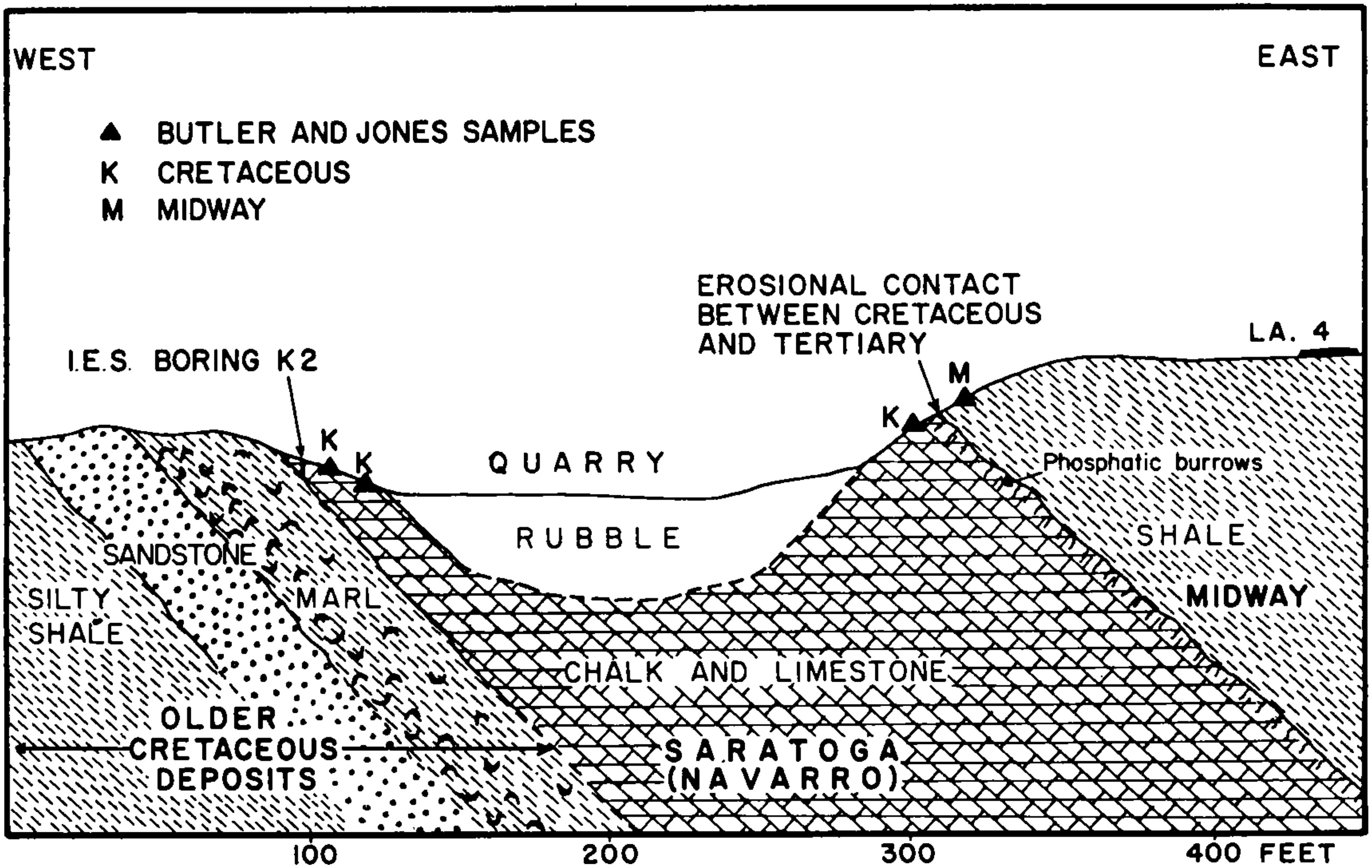

Figure 6. Generalized section at Rayburn's quarry.

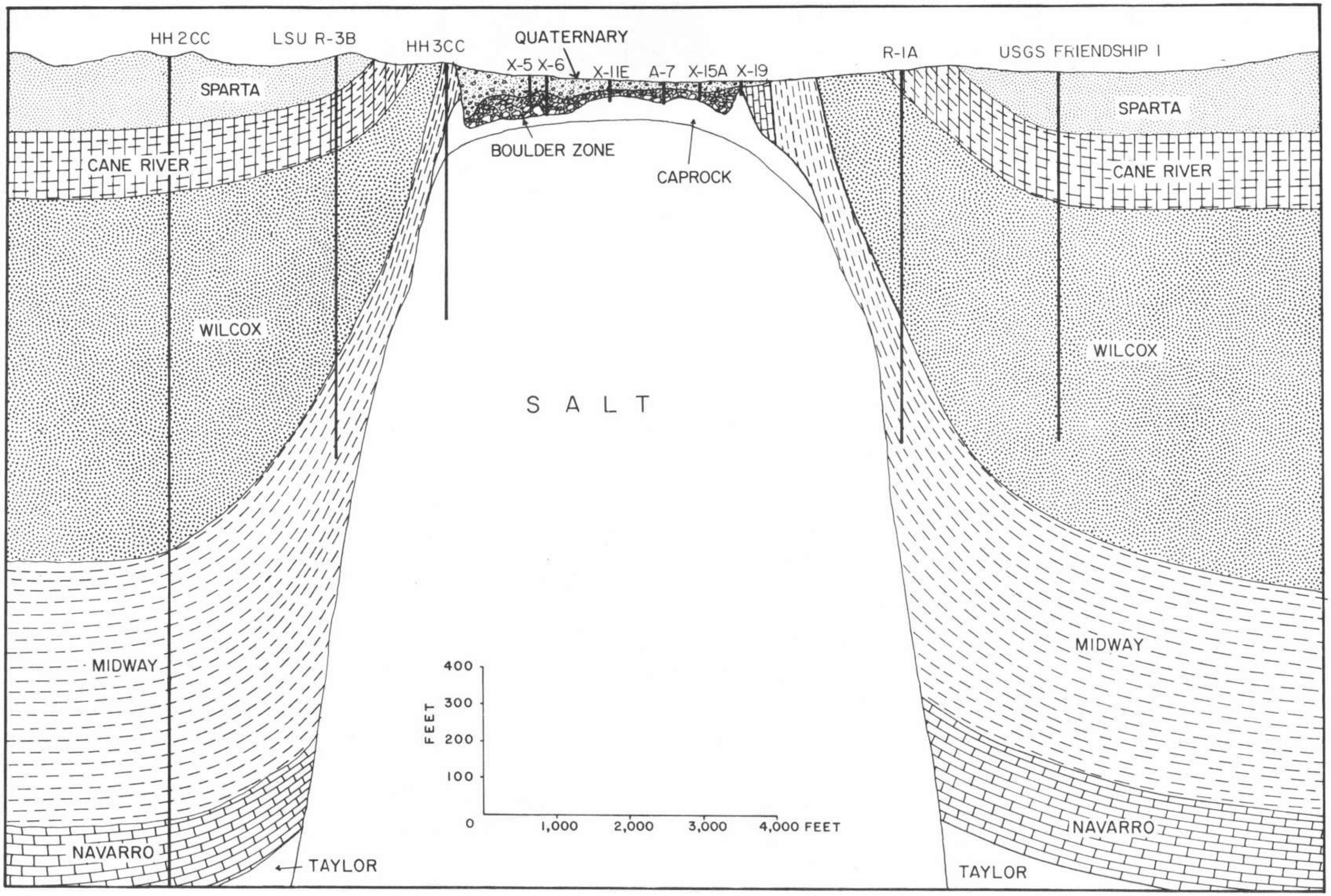

Figure 7. Northwest-southeast section across dome.

addition to the Cretaceous and the Tertiary, the section shows the salt, the gypsum-anhydrite caprock, the boulder zone, and the surficial Quaternary. Each is discussed in varying detail below.

Salt

The salt at Rayburn's is very shallow. One boring made for the Quaternary studies, C-9A on Plates 9 and 11, entered salt at or only inches below the boulder zone. The corehole also penetrated salt at the base of what is interpreted as the boulder zone or a two- to three-foot zone of gypsum sand beneath the boulder zone and above the salt contact. That the salt may directly underlie permeable Quaternary or pre-Quaternary materials in a significant number of instances is suggested by the high salinity of the groundwater pool above the central part of the dome. The brine, as previously discussed, was the source of a sizeable salt industry for many years. Analyses of samples of water from the T. L. James Pit (see Plate 3 and Appendix C) provided salinity values of 65,000 ppm.

Two shallow brine wells were reported to have been made in the area so designated on Figure 2. Just how deep these wells were and what size cavity they may have produced in the underlying salt are not known. One resident who lived in the area at the time has reported a surface collapse which involved a drill rig or a similar structure in the general vicinity of these wells. It is possible that the gradually enlarging salt cavern beneath the brine wells eventually collapsed and that this resulted in surface failure and abandonment of the wells.

The following is a list of borings that penetrated salt (see Figure 2 and Plate 1 for locations):

Borings	Depth to salt	Date
IES C9A	130 ft	1979
IES Corehole	138 ft	1978
HH3CC	253 ft	1957
HH3FEE	115 ft	1923
2 Southern Paper Co. brine wells	unknown	1940's (?)

Anhydrite-Gypsum Caprock

The thickness of the caprock at Rayburn's has been tested in only two known instances: Hodge-Hunt Boring HH3CC penetrated 85 feet of caprock above salt, and Boring HH3FEE penetrated 30 feet of caprock above salt (see Plate 1 for locations). The LSU-IES corehole encountered what was thought to be five feet of caprock above salt; however, the cored results could as easily be interpreted as boulder zone material. The first core from the LSU-IES corehole was attempted at depths of between 109 and 133 feet. Only 1.5 feet of limestone fragments were recovered in this 24-foot run. The second run was from 133 to 138 feet. At 137 feet, the bit dropped between eight inches and one foot into a "mushy" zone, and circulation was lost. Approximately 150 barrels of mud were pumped into the hole before circulation could be regained (Hawkins, 1978). This situation is very similar to that encountered at the base of the boulder zone in our small diameter borings made for Quaternary Studies (discussed previously under "The A- and X-Lines").

Cores of intact caprock were obtained from a number of the Quaternary Studies borings. Examples include cores from the bottoms of Borings A-16A, A-7E, A-4E, X-1E, X-19E, and PS-2 (Plates 2, 3, 7, and 13). Some of the cores retrieved were 4 inches in diameter and many were thin-sectioned to determine their anhydrite-gypsum content. Gypsum, anhydrite, and calcite content, based on thin section analyses, were as follows:

Boring	Sample depth	Gypsum content	Anydrite content	Calcite content
X-19E	22'	99.9%		trace
	26'		99.9%	trace
	29'	45%	55%	trace
	32'		99%	trace
	37'		99%	trace
A-7E	44'	99%	trace	trace
	46'	50%	50%	
X-1E	72'	99.9%		trace
	77'	99.9%		trace
	80'	99%	trace	trace

Note that the gypsum content is highest at the contact and decreases with depth. Note also that the caprock changes from gypsum to anhydrite at a shallow depth in Borings X-19E and A-7E where it is covered by boulder zone material. In Boring X-1E, on the other hand, the caprock is covered by Tertiary deposits, and the entire eight feet of caprock consists of gypsum.

As more and more data from above the dome became available, particularly through the completion of borings or extensions of borings that had been previously made, an unusual configuration of the buried caprock surface began to evolve. Early borings suggested a shallow depth of caprock near the central part of the topographic low above the dome and progressively greater depths to caprock toward the north, east, and west. The central, high knob of caprock appeared to be progressively more shallow to the south until, at Boring X-19 (Plate 3), the caprock was found at only 15 feet below the surface. Boring X-20, only 200 feet farther south, encountered only early Tertiary shales. In an effort to further define the shape of the caprock surface, a number of borings were extended to greater depths; X-20, for example, was deepened to 95 feet (Boring X-20E) without encountering caprock or salt. Boring X-18, about 200 feet to the north, was deepened

(Boring X-18E) to 95 feet before encountering caprock. As shown on Plate 3, the configuration of the caprock surface between Borings X-19 and X-15AE is that of a high central knob. A depression filled with bouldery material occurs between Borings X-16 and X-18E, and a second, even higher knob of anhydrite, occurs at the extreme southern edge of the caprock (Boring X-19E) before it plunges steeply beneath the Tertiary and Cretaceous sediments to the south.

On the northern end of the X-Line (Plate 3), Borings X-1B, X-1 and X-2 were deepened to determine if a similar situation might prevail there. As shown on the section, here too, a prominent ridge of caprock separates boulder zone material from Tertiary and Cretaceous deposits. The abruptness of the bounding knob or ridge of caprock at the outer edges of the dome is visually accentuated on Plates 2 and 3 because of the vertical-to-horizontal scale distortion on these two plates. In order to present the situation and the complex lithology encountered in the borings more adequately, a number of sections were prepared at the true horizontal-to-vertical scale at the dome edges. Plates 6 and 7 illustrate conditions at the eastern and western ends of the A-Line, and Plates 8 and 9 detail conditions at the edge of the dome on the X-Line. One section (Plate 10) was prepared from borings that were made along the northern side of the dome. Plate 11 is a true-to-scale version of that portion of the section shown on Plate 10 that crosses the northern edge of the dome. Comments on these plates are summarized below.

Plate 6

This section, at the western end of the A-Line, illustrates a convention used in presenting these true horizontal-to-vertical data. The approximate slope of the caprock surface is shown as being about 45^{o} to the west at the outer edge of the dome. This is based on the depth at which the caprock was encountered in Boring A-16A and the fact that the caprock was not encountered in Boring A-17E. The caprock surface is extended a short distance to the east of A-16A because of the good probability that the caprock comes even closer to the surface than the depth at which it was penetrated in Boring A-16A. The assumption in all the sections is that the minimum depth of the caprock is somewhat less than that fortuitously tested with a boring.

Plate 7

The true-scale section shown on Plate 7 does much to alleviate the impression of precipitousness of the caprock knob or ridge on the eastern end of the A-Line as shown on Plate 2. However, in this instance there is a wedge of what is interpreted as Tertiary strata between the caprock ridge and the surficial Quaternary and boulder zone deposits. As shown on this plate, Midway and possible Wilcox fauna were identified in Boring A-1A. The interpretation may be in error or faulting may have distorted the stratigraphy. Quaternary erosion may have carried nearby ancient fauna into the depression. In any event, in this one instance, boulder zone and Quaternary sediments do not immediately flank the high caprock knob at the edge of the dome.

Plates 8 and 9

The true scale sections shown here are obviously more easily visualized than the distorted situation shown on Plate 3. However, the borings, i.e., the data points, are widely spaced, and much steeper and more irregular contacts than those shown could, of course, be drawn between them. Regardless, the characteristic high knob or ridge of caprock at the outer limits of the dome is well illustrated.

Plates 10 and 11

Plate 10, and the detail shown in Plate 11, illustrate the stratigraphy along a short section at the northern flank of the dome (See Plate 1 for location). Here again, the precipitous wall of caprock at the dome edge is well illustrated. Boring C-9BE penetrated a caprock sequence at a depth of 23 feet while Boring C-9, only 100 feet away, did not reach caprock at all and had to be abandoned at a depth of 130 feet.

Discussion

The important point here is that in every instance where boring data are available, the caprock was found to rise to elevations very close to the surface at the outer limits of the dome. To summarize, the anhydrite-gypsum caprock surface is consistently high near the center of the topographic low above the salt dome, and slopes downward toward the outer limits of this low. However, the caprock surface rises again very abruptly and steeply at the extreme edges of the low, suggesting that an underground ridge of caprock, sometimes only 15 feet below the surface, completely encircles the outer boundary of the dome. Thus, if uncovered, the caprock over the center of the dome would look like a bowl with a high center. The edges of the bowl would rise to elevations perhaps 20 to 30 feet above the high center of the bowl.

The mechanism for forming such a surface is beyond the scope of this report. However, certain conclusions can be drawn and will be discussed later concerning the significance of the caprock surface from the standpoint of the history of domal dissolution. Plate 12 is a contour map of the caprock surface. A roughly circular ridge of caprock is shown surrounding the top of the dome. It should be stressed that we have tested the existence of such an encircling ridge of caprock in only five instances.

However, the fact that it occurs in every instance tested warrants construction of the contours as shown on the plate. Figure 8a is a simplified version of the configuration of the caprock surface based on the contours shown on Plate 12. Figure 8b is a computer-generated three-dimensional sketch of this surface.

Boulder Zone

The nature, origin, and age of the bouldery stratum that lies between surficial Quaternary deposits and the gypsum-anhydrite caprock at Rayburn's have received considerable attention in this study. The boulder zone is, in many ways, the key to the history of the exposure, dissolution, and subsidence of the caprock and the underlying salt, to the time when such dissolution occurred, and to the rate of dissolution.

Nature of the Boulder Zone

As previously discussed under the heading "Soil/Rock Borings," standard coring methods were entirely unsuccessful in sampling the bouldery material. It was only through the sinking of 6 large diameter calyx borings that the nature of the material comprising the zone could be determined. The 2-foot bucket auger used to make these borings retrieved calcite boulders up to 12 inches in diameter. It also retrieved rounded to subrounded calcite fragments of cobble- and gravel-size fragments in a matrix of tan to dark gray clayey sand or sandy clay. Two calyx holes were made on the A-Line: CA-11 to a depth of 44 feet and CA-5 to a depth of 45 feet (Plate 2). Four calyx holes were made on the X-Line: CX-9, CX-13, and CX-19 and CX-23 (Plate 3). Although samples were retrieved using our standard small-diameter coring methods at the depths shown on the X- and A-Lines, most of the samples were short cores or fragments of calcite--obviously bits of calcite cobbles or boulders. Thus, only the samples obtained with the bucket auger were considered indicative of actual

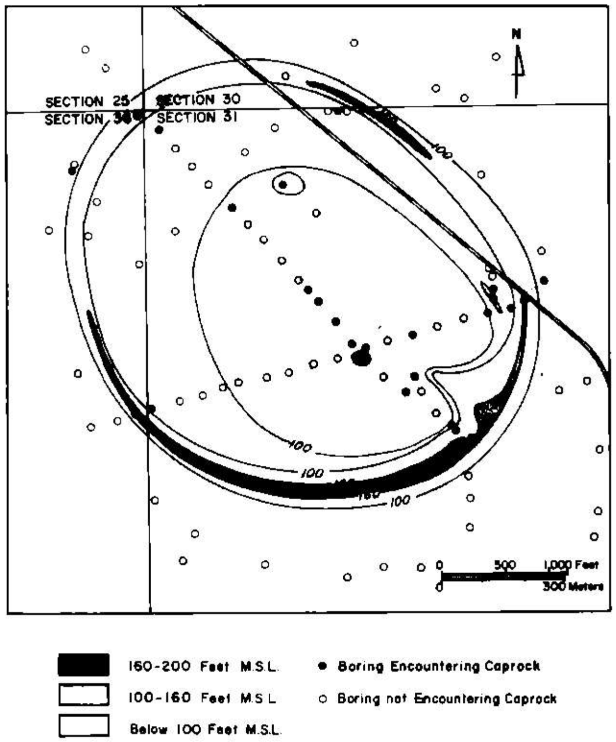

Figure 8a. Generalized contour map of caprock surface. (See Plate 12 for detail.)

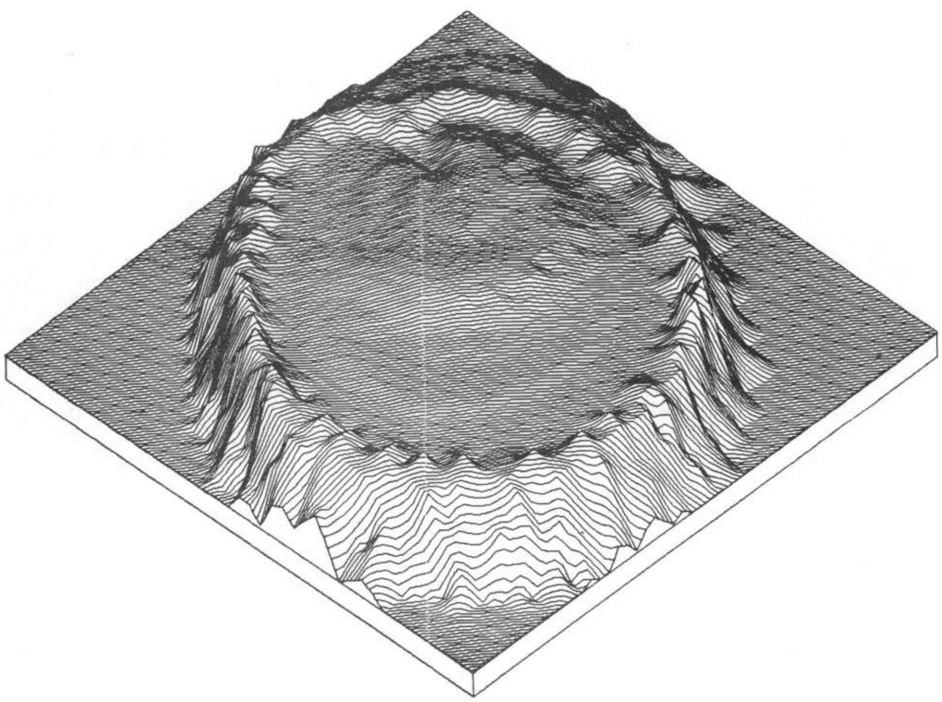

Figure 8b. A computer graphics rendition of the caprock surfact at Rayburn's dome to a depth of -200 msl based on Figure 12. The view is at 45° above horizontal and toward the southeast at 135°. (Prepared by Philip Larimore, Department of Geography and Anthropology, LSU, Baton Rouge, La.)

conditions within the boulder zone, and a generalized log of the lithology within the boulder zone is shown opposite each of the calyx borings on Plates 2 and 3.

As shown symbolically on our plates, the boulder zone is thought to contain boulders and cobbles throughout. There is also a suggestion on these plates that the size and number of calcitic fragments increase with depth. Logs of the six calyx holes and samples obtained from them suggest this; however, the T. L. James Pit (Appendix A) excavated between Borings X-14 and X-15 ran into what appeared to be a very sandy, almost boulderless zone beneath the surficial Quaternary. Unfortunately, the huge backhoe used to excavate the pit was working well below the water table when it penetrated the upper part of the boulder zone. Sandy Quaternary material was sloughing into the pit from the pit sides as it was being dug, and it is quite possible that the material being brought to the surface by the backhoe was not at all characteristic of what was being penetrated.

Sandy, essentially boulderless, strata were also penetrated in a few instances by our small-diameter borings. Some of these penetrated layers of sand with no boulder-, cobble-, or gravel-sized fragments. Sand or sand-silt stringers ranged from 6 to 30 inches thick and were detected by an abrupt change in drilling speed and the "feel" of the bit. Generally speaking, however, there is good reason to believe that at least half of the volume of the boulder zone consists of cobble (4-inch) to boulder size (a foot or more across) fragments of hard calcite. In most instances, the small-diameter fish-tail or core-barrel bits used to test the thickness and sample the zone bounced about alarmingly as they slowly penetrated the loose, bouldery material. The use of diamond bits on the core barrel was quickly abandoned when diamonds were dislodged from the metal matrix at the end of the bit.

In comparing the depth to caprock as interpreted from seismic refraction returns with the actual depth to caprock as determined from borings, it was found that seismic refraction results were incorrect more than half the time. Plate 1 shows the grid of seismic refraction traverses that were run at the site to try to determine depth to caprock. Had the effort been successful, a much more complete picture of shallow subsurface conditions would have been possible at a fraction of the cost. However, the results were disappointing. Note the considerable disparity between depth to caprock as determined by seismic refraction and as determined by borings on the A- and X-Lines (Plates 2 and 3). A series of six closely spaced borings were made in 1980 to further check the results of the seismic refraction survey (Plate 13). Results confirmed the conclusion that shallow seismic refraction surveys should be used with caution above Rayburn's dome particularly as they define the depth to caprock. Electrical resistivity surveys were even more disappointing. Appendix B elaborates the results of the shallow geophysical surveys made at the dome.

An important point: a contour map was drawn on the caprock surface based on the result of six seismic refraction traverses across the dome. It is shown as Figure B2 in Appendix B. Note that, in the southern part of the study area, these traverses detect a rise of the caprock surface that agrees fairly well with the position of the caprock "lip" as determined from borings, although the depth to the lip is only in fair agreement. The point is that the seismic returns tend to increase our confidence in assuming that the high lip at the outer limits of the Quaternary bowl is essentially continuous as shown in Figure 8a and 8b.

Origin of the Boulder Zone

The nature of the boulder zone--rounded to subangular fragments of hard calcite in a sandy clay or clayey sand matrix--suggested that this material is a remnant of a once continuous calcite caprock cover which was brecciated by collapse or subsidence and probably was subjected to subaerial erosion (Martinez and others, 1979). However, other origins were possible. Examination of thin sections of the calcite fragments suggested a caprock origin to one investigator, but suggested to another investigator marine limestone of possible Cretaceous age carried up with the salt as it intruded the overlying formations. The fragments were also considered to be the possible remnants of an algal reef that grew above the dome in post-Cretaceous, perhaps Oligogene, time, a not uncommon occurrence on salt domes in the present offshore areas of the Gulf Coast.

Arguing against a marine origin of the boulders was the fact that no marine organisms were recognizable in the samples, either with the unaided eye or microscopically. However, a more conclusive identification--whether marine or caprock--was sought. Furthermore, efforts to determine whether or not the boulder zone had been exposed in a subaerial environment during past geologic time were, at first, inconclusive. The existence of pollen at a depth within the boulder zone where it could not have been contaminated by the overlying surficial Quaternary deposits would have been conclusive evidence of subaerial erosion. However, pollen was scarce and, as later was found to be the case, where it did occur was often covered with a black hydrocarbon residue that prevented easy recognition.

Previous studies (Feely and Kulp, 1957) had shown that the calcite caprock of Gulf Coast salt domes is formed by a process greatly different from that of marine or freshwater limestones. Calcite caprock was found to have a distinctive isotopic composition reflecting this origin. These studies produced convincing geochemical, mineralogical, and isotopic evidence that calcite caprock is the product of the breakdown of hydrocarbons by bacteria in the subsurface environment yielding CH_4 and CO_2 which is eventually oxidized to form the carbonate radical, CO_3. Thus, compelling evidence for the organic origin of caprock carbonate is the isotopic composition of the carbon and oxygen present in these limestones.

An unpublished study by Smith and Kolb (Appendix C) presents evidence that calcite fragments in the Rayburn's boulder zone originated as caprock. Some of the more pertinent results of the study are summarized on Figure 9, which is adapted from this study. Figure 9 plots the δ-$^{13}C_{PDB}$ and the δ-$^{18}O_{PDB}$ values obtained for six samples of calcite caprock from Vacherie dome and compares these with the results from 14 samples of calcite fragments from the Rayburn's boulder zone. The mean δ-$^{13}C_{PDB}$ value and the typical range of values for marine limestones is shown at the lower left corner of the figure. Values range between +2 and -2. Sample K-2 was taken at a depth of 22 feet in the Cretaceous limestone at the quarry above Rayburn's. The values obtained for this sample are what one would expect. Obviously, the values obtained for the Rayburns's boulder zone calcites identify it as something other than a marine limestone; however, the rather broad scatter of the Rayburn's samples and the fact that many of the samples are more enriched in ^{13}C and ^{18}O than the Vacherie calcite caprock requires an explanation.

Note that five of the Rayburn's samples have values that lie generally within the range of values obtained from the Vacherie calcite caprock. The remaining nine, however, are significantly dissimilar. Work by others (Gross, 1964) has shown that changes in isotopic composition result from

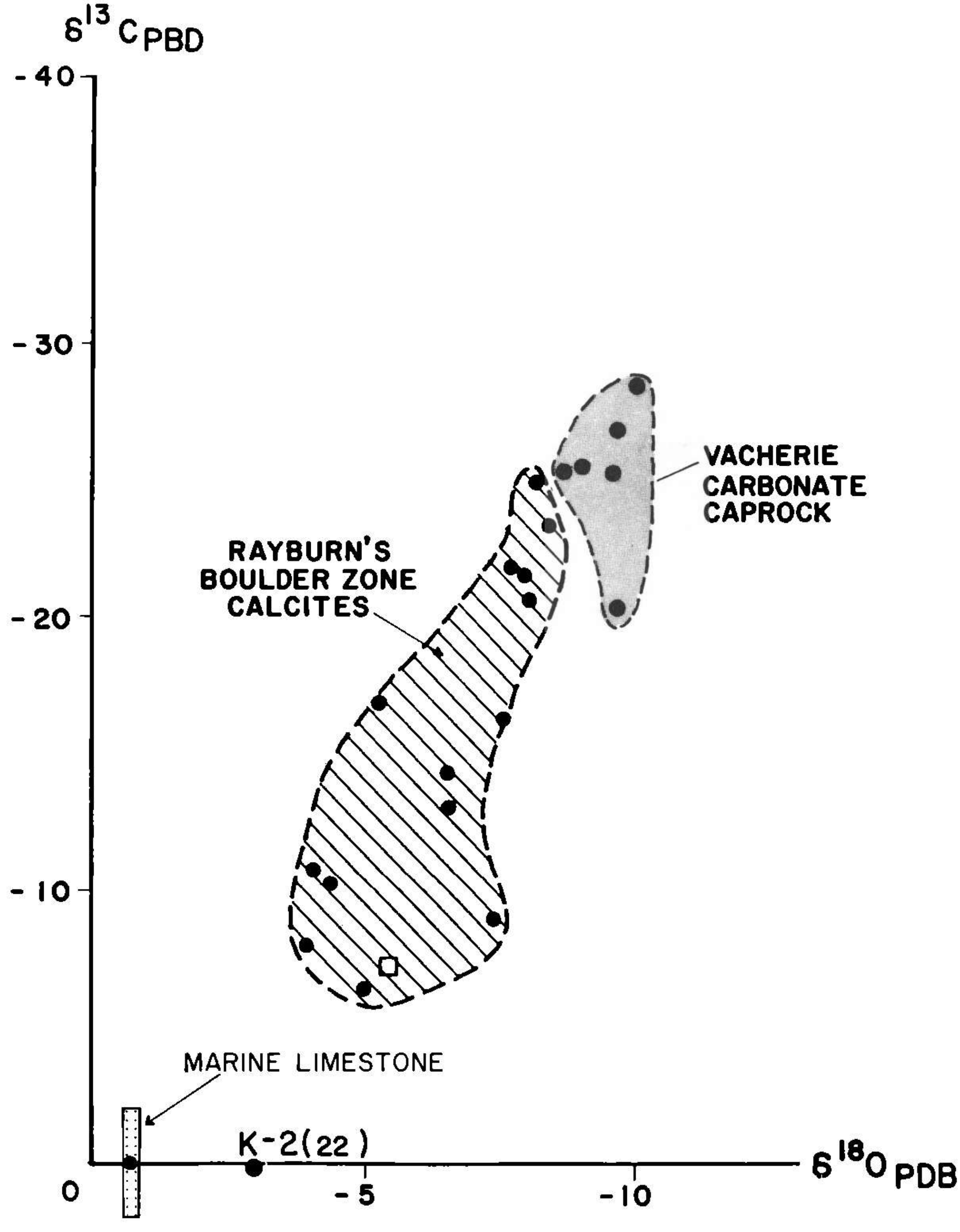

Figure 9. δ-$^{13}C_{PDB}$ and δ-$^{18}O_{PDB}$ values for Vacherie caprock and Rayburn's boulder zone. See text for explanation of other values plotted.

diagenesis due to the effect of groundwater bicarbonates. In Appendix C we concluded that the limit of isotopic alteration of the caprock due to such diagenesis at Rayburn's approach the values

$$\delta\text{-}^{13}C_{PDB} = 6.5 \text{ and } \delta\text{-}^{18}O_{PDB} = 5.4.$$

These data are plotted as a square symbol on Figure 9 for easy comparison with the boulder zone and Vacherie calcite. The square represents the limit of isotopic enrichment for Rayburn's dome calcite due to groundwater contamination. It was concluded that Rayburn's dome originally produced calcite caprock isotopically like that at Vacherie dome and that the Rayburn's calcite has undergone partial re-equilibration with near surface groundwater and groundwater bicarbonate. From these considerations and due to the general stratigraphic relationship of the boulder zone to the surrounding formation, it was concluded, further, that the boulder zone is highly weathered calcite caprock associated with the Rayburn's salt dome.

That the boulder zone was subjected to subaerial weathering in the geologic past was amply demonstrated by a rather comprehensive palynological study of Rayburn's samples (Kolb and Fredlund, 1981). Pollen was not nearly as prevalent as it was in the overlying surficial Quaternary sediments. However, of the 56 samples of boulder zone material examined, 14 contained pollen in moderate amounts. Some samples were taken from a considerable depth below the surficial Quaternary-boulder zone contact, and contamination from the younger upper zone is highly improbable.

Of the possible sequence of events suggested by the disposition of strata above and flanking Rayburn's dome, the events shown on Figure 10 are considered most likely. The stratigraphy in Sketch 10a of this figure is developed principally from the many borings along the X-Line (Plate 3) supplemented by deeper borings shown on Figure 7. The many borings used

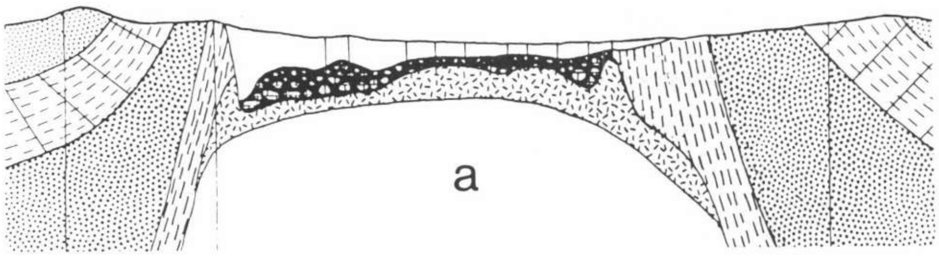

Figure 10a. Hypothetical subsurface section based on current data (see Plate 3 and Figure 7).

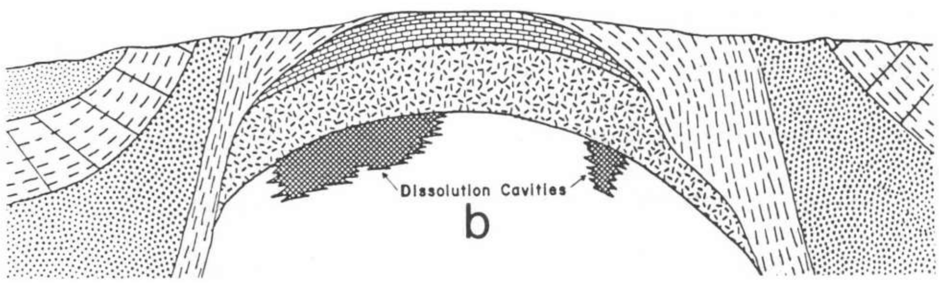

Figure 10b. Dissolution of the salt at anhydrite captrock/salt contact as salt column approches surface and zone of meteoric water.

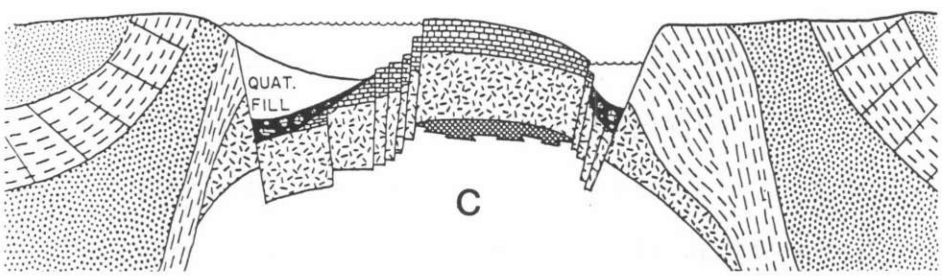

Figure 10c. Formation of surficial lakes resulting from failure and collapse of calcite and anhydrite caprock over area where greatest amounts of subsidence are noted today. Impounded water would hasten the deterioration of the calcite caprock, the anhydrite caprock, and the underlying salt.

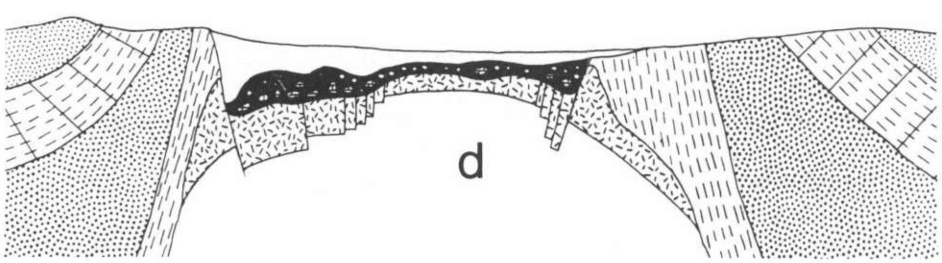

Figure 10d. Hypothetical irregular caprock/salt contact if process depicted in stages b and c is correct.

to delineate the well-defined contact between the known Quaternary and the boulder zone are not shown (see Plate 3 for this detail). Borings which penetrated to or through the contact between the boulder zone and the caprock along this line of section are shown on Figure 10a. Note that only one boring tests the thickness of the caprock, that is, penetrates the caprock-salt contact. Thus, this contact as shown on Figure 10a is largely conjectural. This is pointed out because, in the hypothesis that follows, the anhydrite caprock is pictured as having failed as a series of intact units or, alternatively, as a fractured and fragmented unit which has become recemented with time, leaving an irregular salt-caprock contact as indicated on Figure 10d.

Dissolution of the top of the salt column may have begun or may have accelerated markedly as the column neared the surface and the zone of meteoric water. As the salt dissolved, cavities of various sizes may have formed, but eventually these cavities would have collapsed under the weight of the overlying sediments. Figure 10b illustrates a situation that may have existed when the calcite caprock was in place. Dissolution of the salt at the contact between the salt and the anhydrite is postulated beneath those areas where the most significant subsidence occurred. With time, the situation illustrated in Figure 10c could have developed, with the extreme outer edges of the anhydrite caprock remaining in place, and blocks or wedges of calcite and anhydrite caprock subsiding into the cavernous salt below. Surficial lakes, such as those shown in Figure 10c, would have formed in the depressions caused by subsidence, impounding precipitation and drainage and hastening the breakdown of, first, the calcite caprock and then the underlying anhydrite caprock.

If the hypothesis in Figure 10 is correct, the situation as it exists today would not be the one shown on 10a but rather that shown on 10d. The high caprock lip at the present edge of the bowl would have remained essentially in place, supported to some extent by the sheath of caprock extending down the sides of the dome. The calcite caprock would have been completely weathered by subaerial erosion so that now only the boulder zone would remain. The underlying anhydrite caprock would have subsided slightly near the center of the bowl, more significantly toward the northern and southern limits of the bowl, and possibly not at all at the extreme limits of this line of section. It is doubtful if such a process of subsidence into a cavernous area would have left the anhydrite unfractured. It is likely that the anhydrite in such a situation would have become fractured and partially fragmented, then recemented or resealed in such a way that comparison of cores from the unaffected caprock at the bowl edges (such as cores from Boring X-19) and those from the subsided areas would contain detectable differences.

Additionally, there should be a thickening and thinning of the anhydrite caprock commensurate with the degree of subsidence. The anhydrite caprock should occur at lower elevations in areas of more subsidence and at higher elevations near the center of the bowl where there is less subsidence. This should be true whether the caprock was fractured and recemented, or failed as discrete faulted blocks and wedges as shown in Figures 10c and 10d. Regardless, the general thesis that the anhydrite-salt contact would be at greater depths beneath areas of maximum subsidence is considered valid. This would, of course, be true at Vacherie as well as at Rayburn's. It would be interesting to test the validity of this thesis at Rayburn's where a relatively shallow and inexpensive boring program to test such a hypothesis would be required.

Age of the Boulder Zone and Rate of Dissolution

The age of the boulder zone is of considerable consequence in trying to determine the rate of dissolution and subsidence of Rayburn's dome: the younger its age, the more rapid the rate of dissolution. The most obvious and direct method is to date organic material found within the zone. Organic material was observed in the returns from some of the fish-tail and cored borings made into and through the boulder zone; however, most of this material was brought to the surface in the drilling fluid used in advancing the bit and was considered suspect. Such material could easily be contaminated by organic debris from the surficial Quaternary which lies above the boulder zone. Hence, we were gratified to extract organic samples from the returns brought up by the bucket auger in Borings CA-11 and CA-5. Both samples (see Plate 2) were well down in the boulder zone sequence, only a few feet above the boulder zone-caprock contact. The sample from CA-11 was extracted at about 155 feet msl; the sample from CA-5 was taken from an elevation of about 148 feet msl--an average elevation of say 150 feet msl. Radiocarbon dates for these two samples were 19,265 ± 605 BP and 21,100 ± 900 BP, respectively, say 20,000 years BP. Note (Plate 2) that both of these samples were taken from the high central caprock knob in the center of the caprock "bowl."

Whether such an age is valid for the entire boulder zone is debatable. The much deeper boulder material beneath Borings A-2E and A-16E, for example, may have been formed during earlier periods of dissolution and subsidence. Use of the bucket auger in these deep boulder zone areas might well produce organic samples that could be used for dating. But, without such samples, it is prudent (in order to arrive at a maximum rate of dissolution) to assume that 20,000 years may be a valid date for the entire boulder zone. Note that the lowest elevation of the boulder zone (Boring A-16E) is at about 80 feet msl. Thus, the range of elevation differences of the base of the zone is between 80 feet msl and about 150 feet msl over the central "knob" where the radiocarbon dates apply. If the deepest part of the entrenched Fouse Creek outlet is 180 feet msl (see Plate 3), this would represent a range of 30 to 100 feet of subsidence of the boulder zone in 20,000 years, or a range of a nominal 1.5 to a significant 5.0 feet per 1,000 years of dissolution and subsidence of the top of the dome during the last 20,000 years. Figure 11 shows the amount of subsidence over the dome based on the elevation of the base of the boulder zone. Values of subsidence are derived by subtracting the contoured elevation of the base of the boulder zone from the elevation of the entrenched Fouse Creek, i.e., 180 feet msl.

It should be stressed that the youthful ^{14}C dates obtained for the two organic samples retrieved from the boulder zone were surprising and unexpected. A much older age had been anticipated. Kolb and Fredlund (1981) examined the pollen within the zone and concluded, on the basis of the microflora, that the age of the boulder zone probably ranged between Oligocene and late Pliocene in age. Although the conclusions were admittedly tentative, other lines of reasoning suggested that the boulder zone was of pre-Quaternary age; the most compelling of these was the fact that none of the samples retrieved from the boulder zone during the boring program contained chert gravels.* This suggests that the coarse siliceous sands and gravels associated with the Quaternary had not yet been deposited in the area and, thus, had not been incorporated in the boulder zone as the

* A few chert gravels were found adhering to calcite boulders retrieved from the T. L. James pit (see Appendix A and discussion under the heading "Surficial Quaternary").

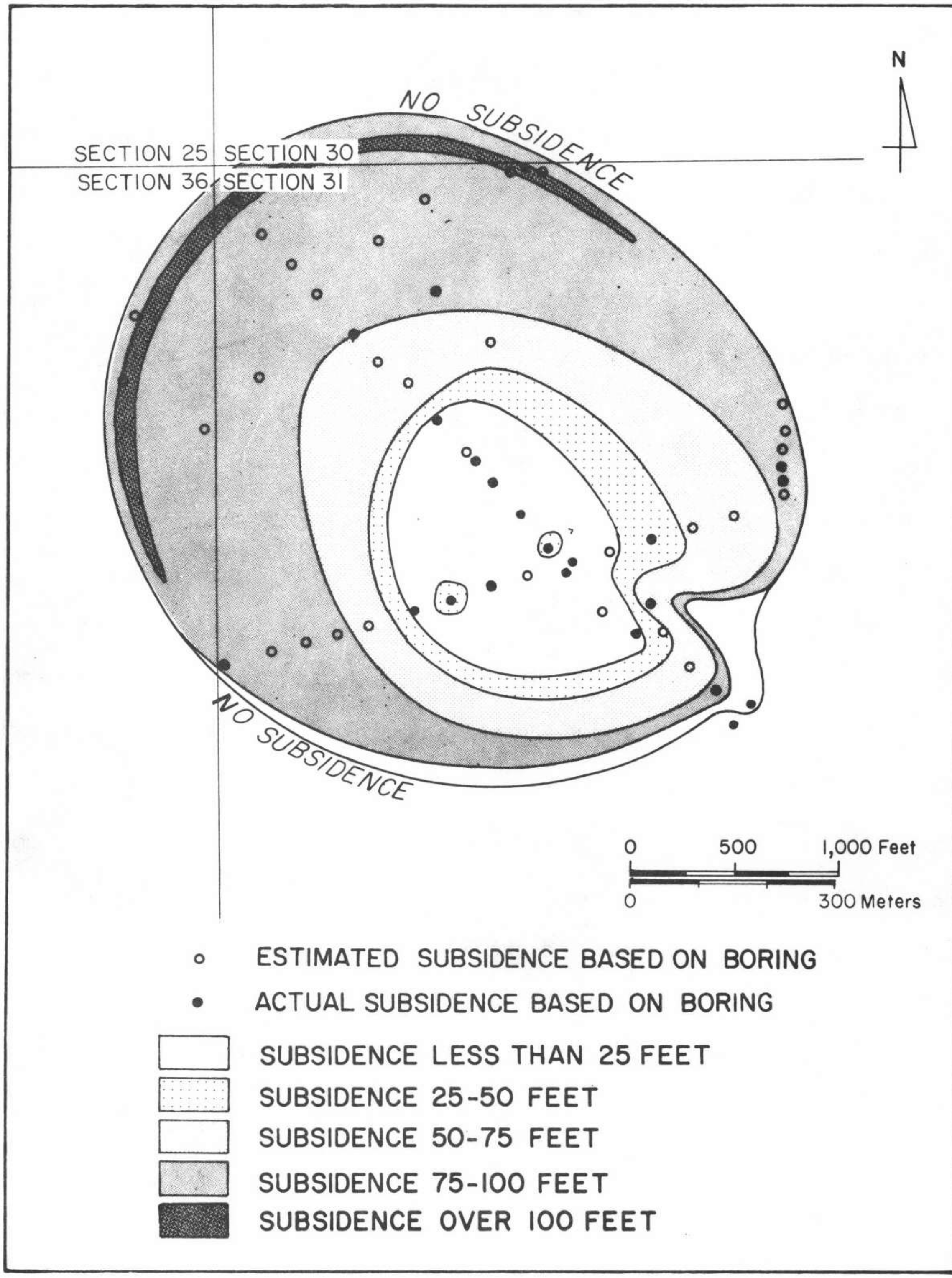

Figure 11. Subsidence over Rayburn's dome estimated from the elevation of the base of the boulder zone.

calcite caprock weathered above the dome. However, the ^{14}C dates indicate that the boulder zone is not only Quaternary in age, but very late Quaternary.

It could, of course, be argued that the number of samples obtained from the boulder zone was relatively small and, if a fairly large number of samples had been retrieved, chert gravels would have been found. Another intriguing possibility is that the very recent age of the boulder zone suggests a reason for the lack of chert gravels within it. As previously mentioned, Pleistocene terraces are absent or very poorly represented in the low hills that flank the Rayburn's depression. It is only directly over the central low above the dome that a well-defined sequence of Quaternary deposits with a diagnostic and ubiquitous suite of chert gravels is found. Even here the amount of chert gravels at Rayburn's is relatively small when compared with most of the Quaternary of north Louisiana.

A possible sequence of events: suppose the calcite caprock was actually in place and that the Rayburn's area rose as a low mound above the level of whatever minor amounts of coarse deposition were associated with the early and middle Pleistocene. Weathering of the calcite caprock may have begun at this time. Suppose further that at the beginning of the Late Wisconsinan glaciation and the drop in sea level (27,000 years ago), dissolution of the underlying salt had advanced to the point that collapse and subsidence of the caprock formed a topographic depression for the first time above the dome. It was only after the depression formed that chert gravels from the surrounding area could have been carried into the depression and deposited above the boulder zone. This might account for the fact that so few chert gravels were found in the boulder zone. It might also account for the relatively small amounts of chert gravel in the Quaternary above Rayburn's dome when compared with the much more gravelly Quaternary above Vacherie dome.

To summarize, it is very likely that an age of 20,000 years, based on radiocarbon dating of two samples, is appropriate for the boulder zone. This age may apply to only that portion of the boulder zone over the central caprock "knob," but it also may apply to the entire boulder zone. Thus, dissolution of the salt and subsidence of the boulder zone could range from a nominal 1.5 feet per 1,000 years to 5.0 feet per 1,000 years during the last 20,000 years.

Surficial Quaternary

During the early phases of this study the Quaternary over Rayburn's dome, which contains chert gravels, was referred to as the Quaternary and the underlying boulder zone as the boulder zone. When it became obvious that the boulder zone might also be of Quaternary age, the chert gravel-bearing Quaternary in our published reports on Rayburn's (Martinez and others, 1977, 1978, 1979) was referred to as the "known Quaternary" to distinguish it from the boulder zone of probable Quaternary age. Now that we have good reason to believe that the boulder zone is also of Quaternary age, probably of very late Quaternary age as discussed in the preceding paragraphs, it became necessary to add a suitably descriptive adjective to the chert gravel-bearing Quaternary. Thus, the term "surficial Quaternary" is used in this report to distinguish it from the Quaternary-age boulder zone. It should also be pointed out that wherever the term "Quaternary" is used on figures and plates (and occasionally in the text) that accompany this report, it refers to the surficial Quaternary.

The nature of the surficial Quaternary has been alluded to throughout this report. Its most distinguishing and ubiquitous characteristic from a lithologic standpoint is that it contains chert gravels, a uniquely diagnostic feature of the Quaternary in north Louisiana. The surficial

Quaternary is generally oxidized a tan or red-brown color and grades erratically downward from silts and clays at the surface to successively coarser materials with depth. Unlike most chert-bearing Quaternary deposits in north Louisiana, the amount of chert gravels in the Rayburn's surficial Quaternary is surprisingly small. As shown on the detailed sections on Plates 2 and 3, it is only at the very base of the surficial Quaternary--at its contact with the underlying boulder zone--that gravels making up more than 50% of the deposit are found. Gravelly sands, with gravel sizes making up less than 50% of the deposit, are found more frequently but still make up only a small proportion of the deposit. As can be seen on Plates 2 and 3, lithology in the surficial Quaternary consists principally of sand, clayey sand, and silty sand. Silts and clays occur in erratic lenses and, expectably, are particularly prevalent where the unit abuts caprock or Cretaceous and Tertiary sediments at its borders. An unsuccessful attempt was made to trace individual strata. Colors, whether cored returns were stratified or consisted of massive mottled sequences, or whether a sequence of coarse-grained sand could be traced from boring to boring, were the types of lithologic factors that were considered. However, individual units could not be traced in the surficial Quaternary deposits. As discussed below, we were more successful in tracing geologic units within these deposits based on pollen content.

Contacts between the oxidized surficial Quaternary deposits and the underlying Cretaceous and Tertiary deposits were easily determined in borings. Characteristically compact, dark gray shales or cream-colored or gray chalks or marls underlie orange surficial Quaternary sands. The contact between the surficial Quaternary and the boulder zone is equally abrupt and distinctive. The hard calcite boulders and cobbles effectively halt normal coring methods, e.g., Shelby tubes, split-spoon samplers. Only rock core bits or fish-tail bits could successfully penetrate the boulder zone.

One very useful happening during our studies was the excavation of an exploratory pit near the center of the basin. In July 1980, T. L. James Company dug a shallow pit close to Boring X-14 (Plate 3) to explore the possible utility of the shallow caprock or the calcite boulder zone as a source of aggregate. A large backhoe was used to dig the pit to a depth of 25 to 30 feet. The water table in the area is within a few feet of the surface, and the pumps used could not lower water levels in the pit to more than 18 feet. However, they succeeded in exposing a significant portion of the surficial Quaternary for detailed examination. An unpublished report on what was exposed in the pit is included as Appendix A.

Figure 12, taken from this report, shows the stratigraphy exposed in the pit. The top unit, Unit D, is identified as the original surface of the saline, covered in some places and mixed in others by spoil left by the miners who exploited the area for salt. Fire pits left by these activities form distinctive burnt and blackened zones within the unit. Fairly marshy conditions, such as those occurring at the present time, are believed to have prevailed during deposition. Unit C, about 3 feet thick, is oxidized but contains gray mottling. The upper contact of this unit is an erosion surface with a well-developed paleosol. Unit C is thought to have been deposited during a dry period, perhaps during the Altithermal some 7,000 years ago. Unit B consists of a massive gray clay separated from a sand unit by a thin organic layer. The organic layer has been dated radiometrically at about 13,500 years BP, a time when sea level had just begun to rise in response to the retreat of the last continental ice sheet. Partially reducing, ponded conditions probably existed in the area at the

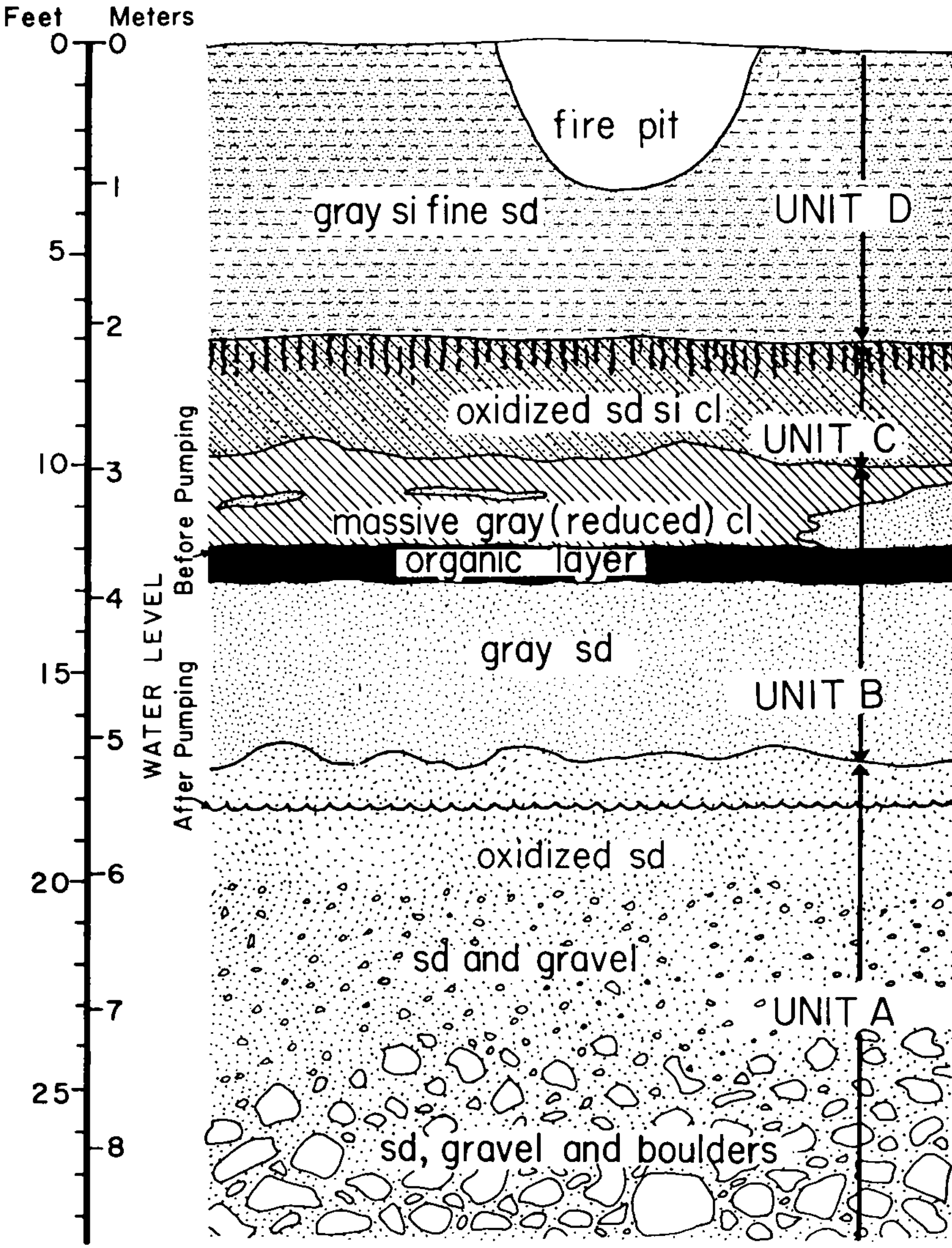

Figure 12. Generalized stratigraphy of T. L. James pit at Rayburn's dome.

time of deposition. Spruce pollen, a common cold weather flora, is characteristic of the unit.

Unit A was only poorly exposed by the fluctuating water level in the pit. However, it appeared to be separated from Unit B by an erosion surface. It consisted of oxidized sand with some chert gravel that graded downward into sand that, as far as could be determined, contained only calcite gravel. At a largely undetermined depth below the water level in the pit, the unit coarsened appreciably and the backhoe began to pick up boulders and cobbles of calcite. Of special interest was that several of these boulders, one from a depth of as much as 25 feet, had a few chert gravels clinging to their oxidized surfaces.

At the time the pit was excavated, the general concensus was that the boulder zone was of possible pre-Quaternary age. Association of chert gravel with 2 or 3 of the boulders excavated from some depth were rationalized (see Appendix A) as having worked their way downward from chert-bearing units above. The chert gravel in the top part of Unit A was thought to be from an earlier Pleistocene, possibly Prairie, horizon. When radiocarbon dates of 19,000 to 21,000 years were obtained from two organic samples taken from the boulder zone, it was conceded that the boulder zone as well as the surficial Quaternary deposits might be of very late Quaternary age. Our present position is that the most convincing data available to us support a very recent age for the boulder zone (19,000 to 21,000 years BP) as well as for the overlying surficial Quaternary.

Kolb and Fredlund (1981) studied the pollen content in a number of samples from borings made in the surficial Quaternary. They were able to subdivide this unit into three zones. The basal zone (Zone A) consisted of a spruce/pine assemblage. *Picea* (spruce) is an important cold weather indicator not found in the region today. Zone B (spruce/herbaceous) showed a significant increase in the occurrence of herbaceous and cooler weather arboreal pollen and a decrease in the relative frequency of pine pollen. These trends are most pronounced at the top of the zone where spruce becomes the dominant arboreal pollen taxon comprising up to 15% of the pollen sum. Tamarack and alder also occur, indicating a cooler climate than at present. Zone C (pine/oak forest) extends to the surface and contains a pollen suite characteristic of the region today.

Figure 13 is reproduced from Kolb and Fredlund's report and shows the distribution of these pollen zones along the A- and X-Lines. It is obvious from the above discussion that Zone B and, to a lesser extent, Zone A contain cold weather species characteristic of Pleistocene glacial times. Zone C contains warm weather species typical of the final stages of sea level rise and interglacial conditions prevalent today. Pollen Zone C corresponds to Units C and D observed in the T. L. James pit (Figure 12). Pollen Zone B corresponds to Unit B, and Pollen Zone A appears to correspond with the upper part of Unit A.

The subsurface sections shown on Figure 13 provide useful insights concerning the possible rates of dissolution of the underlying salt as reflected in the thickening of Pollen Zones B and C. As indicated, Zone B has been radiometrically dated as ranging from 13,520 to 14,340 years in age. The mean sea level elevation of the bottom of the Fouse Creek outlet which drained the Quaternary basin to the south during the last glacial maximum averages about 180 feet msl, and the base of Zone B in Boring A-1 (Section A-A') is at 170 feet msl. Thus, allowing for a reasonable gradient for flow from the basin and through the entrenched creek during the last glacial maximum, subsidence of about 15 feet is a reasonable estimate for this zone. Using a maximum age of 15,000 years for

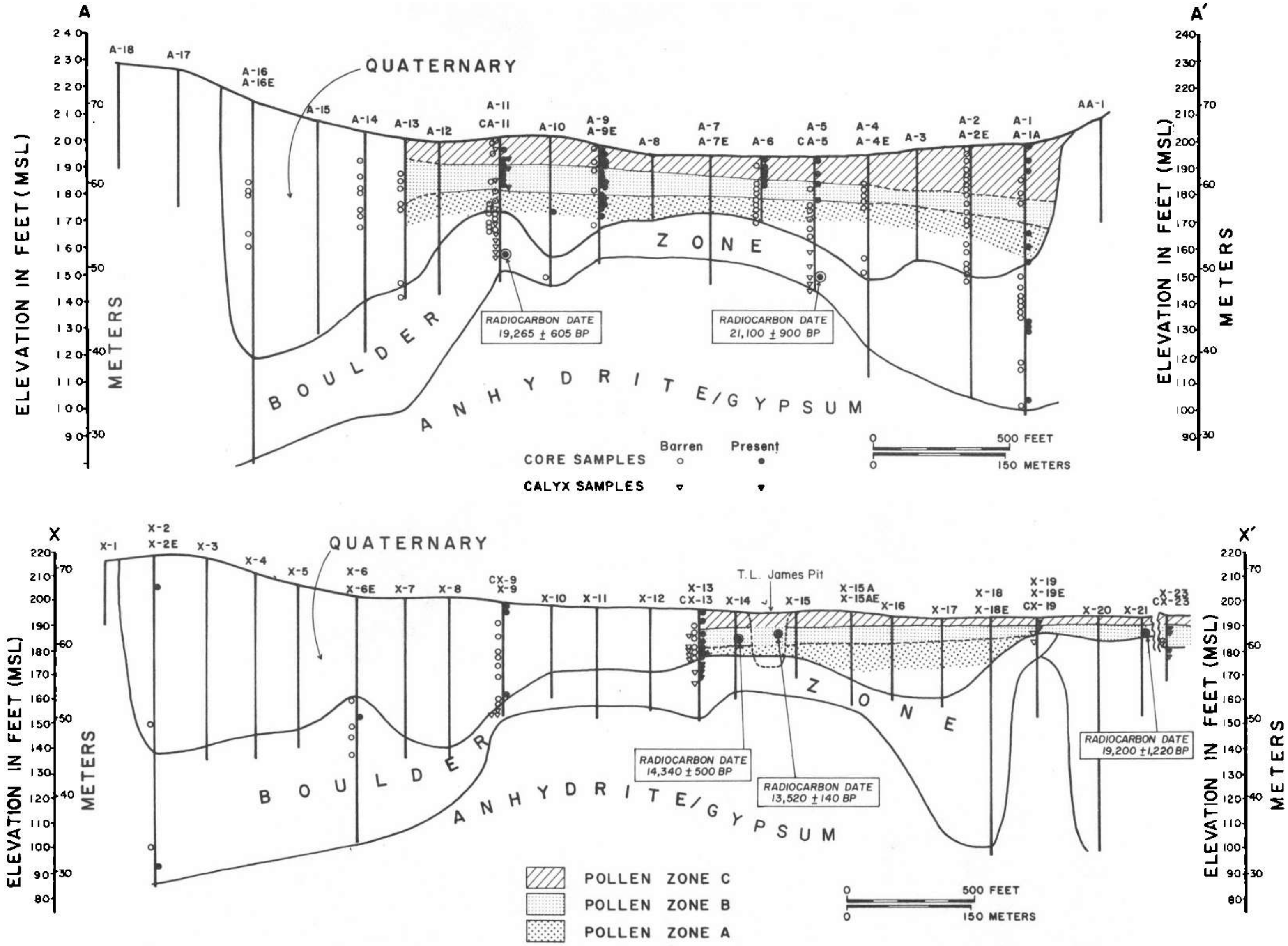

Figure 13. Subsurface sections above Rayburn's dome showing locations and depths of pollen samples. Pollen zones A and B correspond to Units A and B on Figure 12. Pollen zone C corresponds to Units C and D on Figure 12.

Zone B, therefore, a rate of dissolution of the salt and consequent subsidence of the zone would be about 1 foot per 1,000 years.

By using the data from the T. L. James pit (Figure 12) and estimated dates, the average rate of sedimentation for the exposed strata is as follows:

Unit	Sedimentation Rate
D	7 ft/7,000 yrs = 1.0 ft/1000 yrs
Surface To Organic Layer	13 ft/13,500 yrs = 1.1 ft/1000 yrs
B, C & D	17 ft/15,000 yrs = 1.1 ft/1000 yrs

Note that the sedimentation rate of 1 ft/1000 years is consistent throughout this 15,000-year span of time and compares very well with the rate of subsidence arrived at above. This, of course, is as it should be. Sediment is normally flushed from the basin through Fouse Creek. It is only through subsidence that additional space becomes available in the basin above the dome for continued deposition of sediment (discounting a minor amount of compaction).

Another approach to estimating the amount of dissolution and subsidence that affected the surficial Quaternary is to follow the line of reasoning used in our previous discussion of subsidence of the boulder zone. The deepest surficial Quaternary penetrated during our study was at A-16E where the base of the deposit was found at 120 ft msl. Using the value of 180 feet msl as the average depth of entrenchment of the Fouse Creek outlet during the glacial maximum results in a subsidence value of 60 feet. If 20,000 years is accepted as a maximum age of the surficial Quaternary (19,200 years was obtained from a sample in Fouse Creek), a value of 3 feet of subsidence per 1,000 years is obtained. Figure 14 shows subsidence values of the surficial Quaternary within the Quaternary basin above the dome.

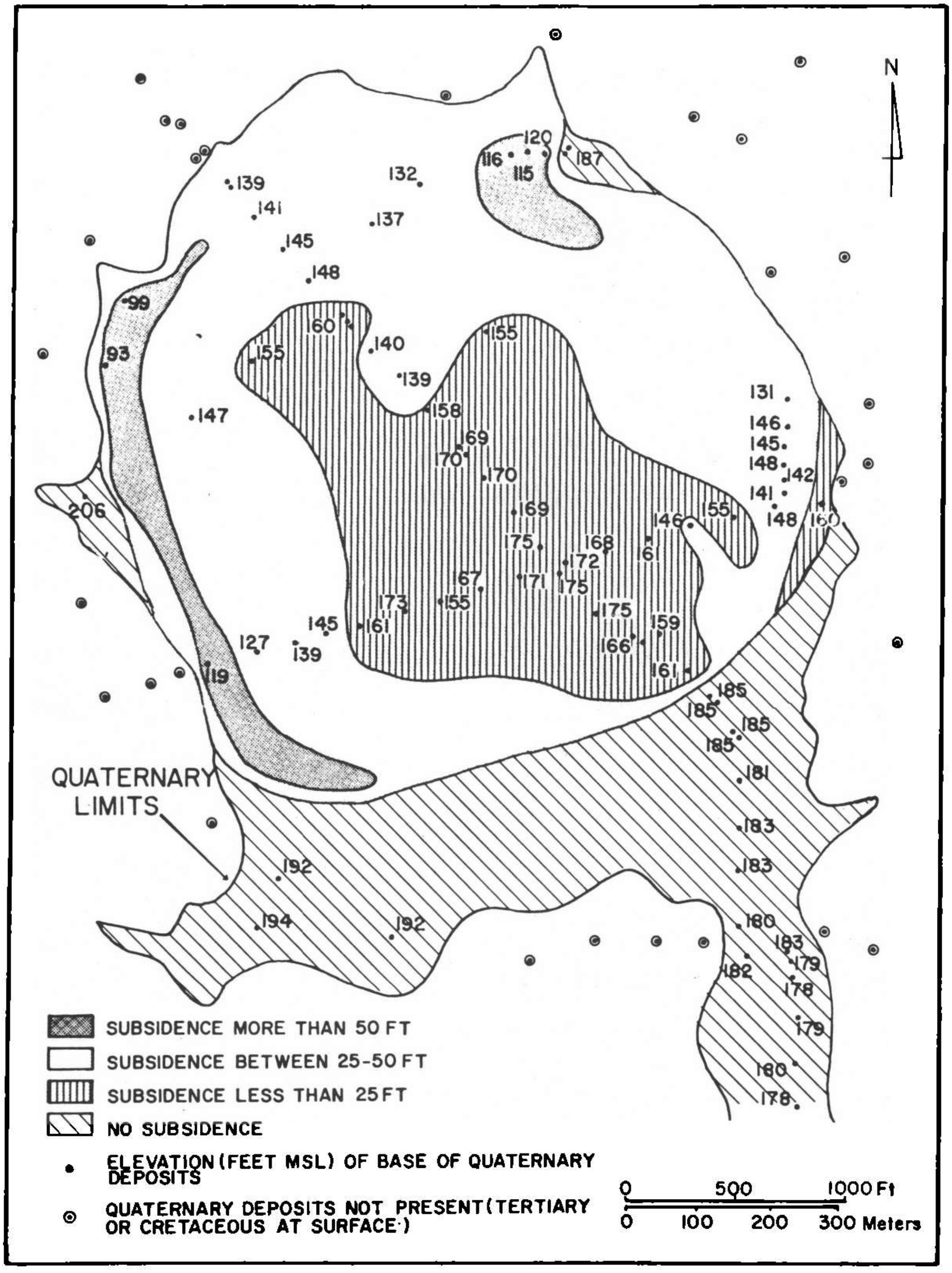

Figure 14. Subsidence over Rayburn's dome estimated from elevation of the base of the surficial Quaternary deposits.

Paralleling our discussion of the boulder zone, the chert-bearing Quaternary may, in some places, be much older than indicated by our ^{14}C dates. Maximum subsidence (Figures 13 and 14) was in the western portions of the A-Line and the northern part of the X-Line. It was in these portions of the sections, in addition, that pollen data could not be used to subdivide the surficial Quaternary into zones, suggesting that an older and different Quaternary sequence--older than 20,000 years--may lie beneath the northern and western portions of the basin. If only the surficial Quaternary, delineated between Borings A-13 and A-1 and between X-13 and X-19 (Figure 13), is used to arrive at a subsidence value, maximum subsidence would be to an elevation of 150 feet msl. This would result in a subsidence value of 30 feet, or 1.5 feet of dissolution and subsidence per 1,000 years.

Thus, dissolution values at Rayburn's, based on subsidence of the surficial Quaternary, range from (a) 1 foot per 1,000 years based on pollen studies, to (b) 1.5 feet per 1,000 years if only the eastern and southern portions of the basin are considered, to be 20,000 years old, to (c) 3 feet per 1,000 years if the surficial Quaternary of the northern and western portions of the basin is also assumed to be 20,000 years old.

Study Objectives

Four objectives were listed in the introduction to this report. Briefly they concerned the significance of Quaternary studies at Rayburn's in evaluating (a) hydrologic stability of the dome, (b) tectonic stability of the dome, (c) erosional effects during the next 250,000 years at the site, and (d) pre-Quaternary stratigraphy and structure at the site.

Hydrologic Stability

The greater part of this report deals with the significance of the Quaternary deposits in evaluating the hydrologic stability of Rayburn's dome. Other studies at LSU-IES of hydrologic stability of north Louisiana salt domes are approaching the problem by determining the existence of and the possible time of formation of saline plumes in the groundwater on the down-dip sides of the domes (Martinez and others, 1976, 1977, 1978, 1979). If no saline plumes are detectable it could be concluded with some validity that no dissolution of the salt column is occurring at the present time or has occurred in the immediate geologic past. A problem involved in reaching this conclusion is the rate at which such a saline plume can be dissipated by normal groundwater flow. A saline plume formed in the distant geologic past and no longer an indicator of hydrologic instability might well be trapped on the down-dip side of the dome. Conversely, a plume might be dissipated so rapidly by groundwater flow that the fact that one does not exist might be of little consequence in determining hydrological stability. Thus, determining whether or not dissolution has occurred and arriving at a reasonable rate of dissolution within a given time frame involves interactions of such parameters as the size of the plume, the distribution of salinity within it, and the groundwater flow conditions which affect it.

The Quaternary sediments above the dome complement this approach. They permit a reasonable estimate of the amount of salt that has been dissolved above the dome in order to account for the subsidence that has occurred. Moreover, where the age of these Quaternary sediments is datable, they permit an estimate of the amount of salt that has been dissolved within a given span of time.

Actual volumes of salt dissolved at Rayburn's could be calculated based on Figures 11 and 14. However, the accuracy of the data hardly warrants more than the general range of values listed below. These are essentially rates of dissolution of the salt column based on the parameters listed.

(a) Based on downwarping of pollen zones, 1 foot/1,000 years for the last 15,000 years.

(b) Based on radiocarbon dating of the surficial Quaternary over the southern and eastern portions of the dome, 1.5 feet/1,000 years for the last 20,000 years.

(c) Assuming that all the surficial Quaternary is 20,000 years old or less, 3.0 feet/1,000 years for the last 20,000 years.

(d) Assuming that the boulder zone over the central part of the dome is 20,000 years old or less, 1.5 feet/1,000 years for the last 20,000 years.

(e) Assuming that all the boulder zone is 20,000 years old or less, 5.0 feet/1,000 years for the last 20,000 years.

Thus, the values range between a nominal 1 foot/1,000 years to a fairly significant 5 feet/1,000 years during the last 20,000 years. If dissolution of salt continues at this rate, from 250 to 1,250 feet of salt could possibly be removed from the top of the dome in the next 250,000 years. It is far more likely, however, that as the salt column is dissolved and becomes more deeply buried under surficial rubble, the influence of meteoric water and the rate of dissolution will decrease considerably. The maximum figure of 1,250 feet cited above is considered very unlikely.

Tectonic Stability

Fieldwork concerned with the recognition and mapping of Pleistocene terraces in the gently rolling hills surrounding the Rayburn's topographic low has been minimal. However, it is apparent from preliminary field surveys that if such terraces exist or have existed in the past, too little remains of these surfaces to be of value in assessing the tectonic stability of the dome.

Indeed, our work to date suggests that during most of the Pleistocene the Rayburn's area may have formed a mound which rose above the general level of the surrounding terrain. It may have been only during the latest glacial interval beginning about 27,000 years ago that enough salt was dissolved from the top of the column to permit subsidence and disintegration of a former calcite caprock cover, the formation of the boulder zone, and the development of a topographic depression above the dome.

The only conclusion warranted would be that if the dome is still rising, it is rising at a rate slower than its rate of dissolution or, very obviously, no topographic low could form above the dome, a low filled with material of late Pleistocene and Holocene age.

Effects of Erosion

Erosional effects above the dome during the next 250,000 years at Rayburn's should be essentially the same as those above Vacherie dome. This has been discussed by Kolb in Martinez and others (1978). Briefly, it was reasoned that the maximum erosion that could affect the Vacherie-Rayburn's area would be during some future glacial stage, perhaps 200,000 to 250,000 years from now, when erosional processes would entrench the valleys above the domes. Added to this would be the regional uplift that is affecting the area as indicated by the various terrace levels that rise above the drainage systems.

At Vacherie an average entrenchment of the valleys in the area is 50 feet. Regional uplift can be estimated if one assumes that the lowest level along Bashaway Creek over Vacherie dome is Deweyville in age (about 25,000 years) and the upper level is Prairie in age (about 75,000 years).

The Holocene surface is at about 180 feet msl, the Deweyville at 190 feet msl, and the Prairie at 210 feet msl. This results in uplift values of 10 feet in 25,000 years between Holocene and Deweyville times and of 30 feet in 75,000 years between Holocene and Prairie times; or an average regional uplift of 1 foot per 2,500 years. Thus, in 250,000 years we can expect regional uplift to have raised the area 100 feet, a figure that agrees fairly well with uplift data on terraces which flank the Red River some 30 miles to the west (Martinez and others, 1978, p. 276-283). Add to these uplift values entrenchment of 50 feet during a glacial period 200,000 years or more from now, and one arrives at a maximum erosion of 150 feet.

If there is no continued dissolution of the top of Rayburn's dome, which is improbable, erosion of this magnitude would, of course, expose the anhydrite caprock and the salt to subaerial erosion at Rayburn's. Just how serious such exposure would be to the integrity of a repository at a depth of 3,000 feet is problematic. However, it is felt, intuitively, that it would be of little consequence.

Pre-Quaternary Geology

Figure 5 is the latest geologic map of the Rayburn's area based on microfaunal and lithologic data and on published and unpublished sources discussed under "Cretaceous and Tertiary."

REFERENCES

Butler, E. A., and D. E. Jones, 1957. Cretaceous Ostracoda of Prothro and Rayburn's Salt Domes, Bienville Parish, Louisiana, Louisiana Geologic Survey Bulletin 32.

Durham, C. O., Jr., and W. S. White, Jr., 1960. "A Guided Geological Tour through North and Central Louisiana, in 1960 Spring Field Trip, Shreveport Geological Society, pp. 83-147.

Echols, J., 1970. Geology of Bienville Parish, Louisiana Geologic Survey Bulletin 43. (unpublished).

Feely, H. W., and J. L. Kulp, 1957. "Origin of Gulf Coast Salt-Dome Sulphur Deposits", American Association of Petroleum Geologists, Vol. 41, No. 8, pp. 1802-1853.

Fisk, H. N., 1938. Geology of Grant and LaSalle Parishes, Louisiana Geologic Survey Bulletin 10.

Fisk, H. N., 1939. "Depositional Terrace Slopes in Louisiana", Journal of Geomorphology, Vol. 2, pp. 188-199.

Gross, M. G., 1964. "Variations in the O^{18}/O^{16} and C^{13}/C^{12} Ratios of Diagenetically Altered Limestones in the Bermuda Islands", Journal of Geology, Vol. 72, pp. 170-194.

Harding-Lawson Associates, 1977. Seismic Refraction Survey, Rayburn's Salt Dome, Bienville Parish, Louisiana, Harding-Lawson Associates, San Rafael, California (unpublished).

Harris, G. D., and A. C. Veatch, 1900. A Preliminary Report on the Geology of Louisiana, Geologic Survey of Louisiana, Report of 1899, pp. 52-55.

Hawkins, M. F., Jr., 1978. An Engineering Report of the Coreholes at Vacherie and Rayburn's Salt Domes--North Louisiana Salt Dome Basin, Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.

Hilgard, E. W., 1869. Supplementary and Final Report of a Geological Reconnaissance of the State of Louisiana, New Orleans Academy of Sciences and the Bureau of Immigration of the State of Louisiana, pp. 29-30.

Hopkins, F. V., 1871. Second Annual Report of the Geological Survey of Louisiana to the General Assembly, pp. 5-6, Geological Survey of Louisiana.

Kolb, C. R., and G. G. Fredlund, 1981. Palynological Studies, Vacherie and Rayburn's Domes, North Louisiana Salt Dome Basin, Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.

Lerch, O. 1893. Geology and Agriculture, A Preliminary Report upon the Hills of Louisiana, North of the Vicksburg, Shreveport and Pacific Railroad, State Experiment Station, pp. 13-14.

LETCo, 1978. Preliminary Report, Electrical Resistivity Survey at Rayburn's Salt Dome, Law Engineering Testing Company, Marietta, Georgia (unpublished).

Office of Nuclear Waste Isolation, 1980. Technical Progress Report for the Quarter 1 July - 30 September, 1980, ONWI-9(80-4), Battelle Memorial Institute, Columbus, OH.

Martinez, J. D., R. L. Thoms, D. H. Kupfer, C. G. Smith, Jr., C. R. Kolb, E. J. Newchurch, R. E. Wilcox, T. A. Manning, Jr., M. Romberg, A. J. Lewis, and J. E. Rovik, 1976. An Investigation of the Utility of Gulf Coast Salt Domes for the Storage or Disposal of Radioactive Wastes, ORNL-Sub-4112-25, Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.

Martinez, J. D., R. L. Thoms, C. G. Smith, Jr., C. R. Kolb, E. J. Newchurch, and R. E. Wilcox, 1977. An Investigation of the Utility of Gulf Coast Salt Domes for the Storage or Disposal of Radioactive Wastes, Y/OWI/SUB-4112/37, Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.

Martinez, J. D., R. L. Thoms, C. R. Kolb, M. B. Kumar, R. E. Wilcox, and E. J. Newchurch, 1978. An Investigation of the Utility of Gulf Coast Salt Domes for the Storage and Disposal of Radioactive Wastes, EW-78-C-05-5941/53, Volumes 1 and 2, Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.

Martinez, J. D., R. L. Thoms, C. R. Kolb, M. B. Kumar, R. E. Wilcox, and E. J. Newchurch, 1979. An Investigation of the Utility of Gulf Coast Salt Domes for the Storage or Disposal of Radioactive Wastes, Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.

Smith, G., and C. R. Kolb, 1981. Isotopic Evidence for the Origin of the Rayburn's Boulder Zone of North Louisiana, Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.

Spooner, W. C., 1926. "Interior Salt Domes of Louisiana", American Association of Petroleum Geologists Bulletin, Vol. 10, pp. 260-265.

Veatch, A. C., 1902. The Salines of North Louisiana, Geological Survey of Louisiana Special Report No. 11, pp. 71-75.

APPENDIX A

STRATIGRAPHY EXPOSED IN PIT AT RAYBURN'S SALT DOME

Table of Contents

Abstract

An excavation at Rayburn's salt dome in July, 1980, exposed the stratigraphy over the central part of the dome. Four geologic units were exposed in the top 18 to 20 feet. The top unit consists of essentially modern soils mixed together with spoil from salt mining operations that began in the 1840's. The unit below appears to have been introduced during a dry phase, perhaps during the Altithermal period some 7,000 years ago. The next unit contains an organic horizon which has been radiometrically dated at about 14,000 years BP, the time that sea level had just begun to rise in response to a major retreat of the continental ice sheet. Spruce pollen is characteristic of this unit. The bottom unit exposed, or partially exposed, a possible chert-bearing sand gravel that graded downward into the boulder zone, from which boulders weighing 300 lbs or more were brought to the surface.

Introduction

Recent excavations by T. L. James, Inc., an engineering firm from Ruston, Louisiana, (not part of the LSU-IES salt dome contract) have provided an opportunity for LSU-IES personnel to examine the stratigraphy over the central portion of Rayburn's salt dome. Two small test pits and one large excavation were opened during the period July 24 to July 30, 1980 to determine if "boulder zone" and/or caprock material above the salt dome were present in sufficient quantities and at shallow enough depths to establish an open pit rock quarry to mine this material.

The excavations were situated in the SE 1/4 NW 1/4 Section 31, T15N, R5W adjacent to and southwest of the intersection of the A-and X-Lines of shallow cored borings made for the Quaternary Studies Group of LSU-IES. The two small pits had been opened and filled before LSU-IES personnel arrived, and their exact locations were obscured by spoil. It is believed that one pit was at the location of Boring X15 and the other near the site of Boring X14 (Figure A1).

The pit viewed by LSU-IES personnel was a large rectangular excavation oriented roughly north-south with that side being 130 to 150 feet in length. The east-west dimension was 40 to 50 feet, and the depth sloped from about eight feet in the southern end to about twelve feet in the northern end. Located in the northwestern floor of the excavation, a deeper pit, about 25 x 25 feet, was excavated to a depth of about 40 feet. The water level in the pit rose to within 12 feet of the surface, and only with two pumps operating could the water level be lowered below that level. Samples were taken of an organic layer at the water surface.

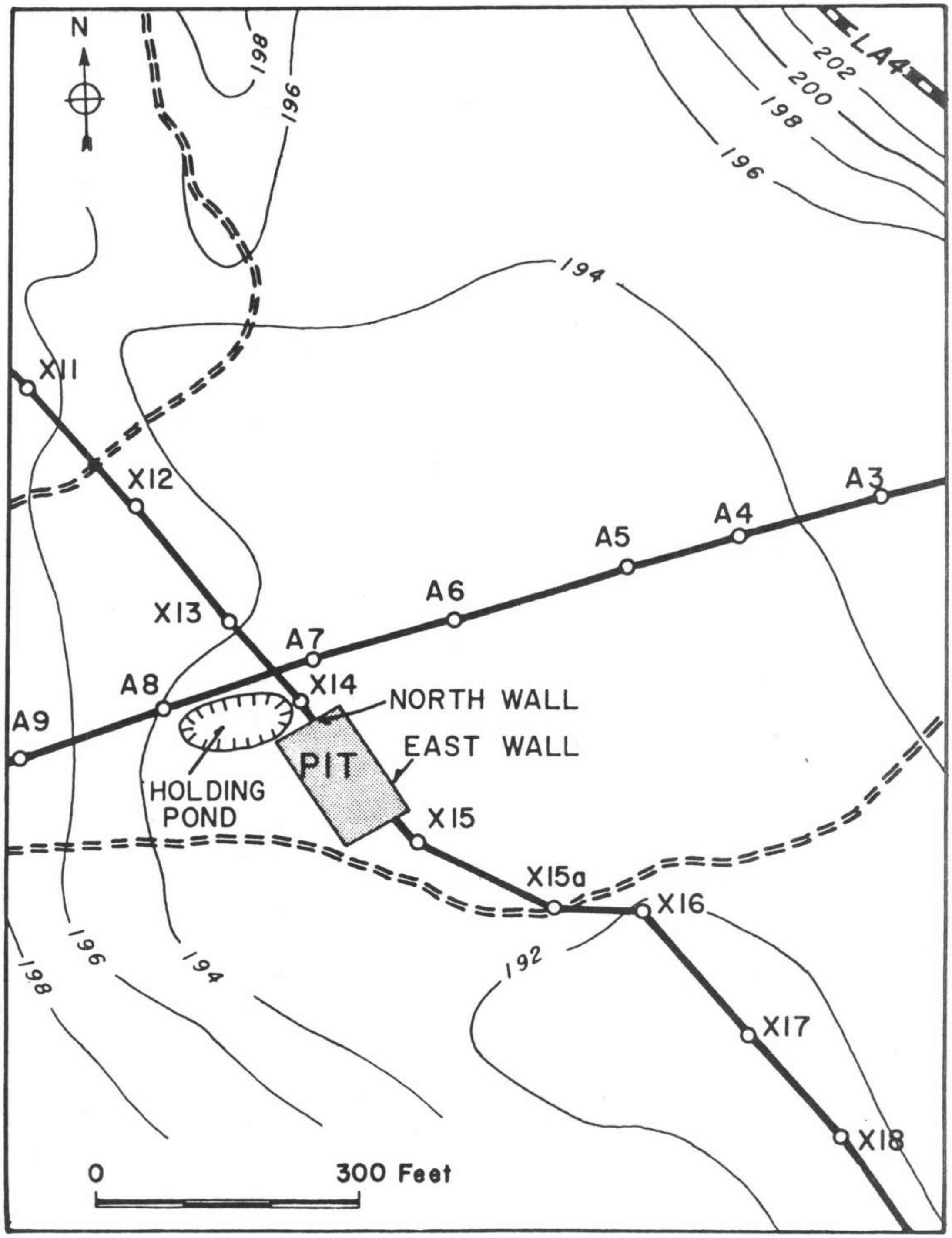

Figure A1. Location of exploratory pit dig by T. L. James, Inc. over the central part of Rayburn's dome. Circles labeled X13, A8, etc. are soils borings, most of which extend to anhydrite caprock.

Samples were also taken at one-foot intervals from the eastern wall, approximately in the center of its length, for textural analysis.

Sketches of the north, west, and east walls of the pit are shown on Figure A2. Selected photographs of the pit and the walls are shown on Figures A3 through A8. Specific portions of individual walls pictured in these photographs are shown on Figure A2, as well as the general location of the soil samples taken.

The excavation was filled in and abandoned by T. L. James, Inc. on July 30 after they determined that mineable material was too deep and that the saline groundwater presented too great a disposal problem for the venture to be profitable.

Stratigraphy

As digging progressed, four distinct units were exposed. Unit A, the lowest unit (Figure A9), is made up of sand, silt, gravels composed of chert, ironstone, and calcite, and cobbles and boulders consisting, as far as could be determined, only of calcite. The largest boulder brought to the surface by the backhoe used in the excavations measured about two feet across and weighed several hundred pounds (see Figure A8). The surfaces of most of the boulders were oxidized or were plastered with oxidized sand and silt. Of interest were occasional chert gravels clinging to the surface of boulders extracted from depths as much as 25 feet below the top of the pit.

The top of Unit A is an erosion surface that is about 17 feet below the present surface. The pumps were unable to lower the water table to a depth of more than about 18 feet below the surface, so the lithology shown on Figure A9 below this depth is largely conjectural. The base of Unit A, presumably anhydrite caprock, could not be reached by the backhoe. (The

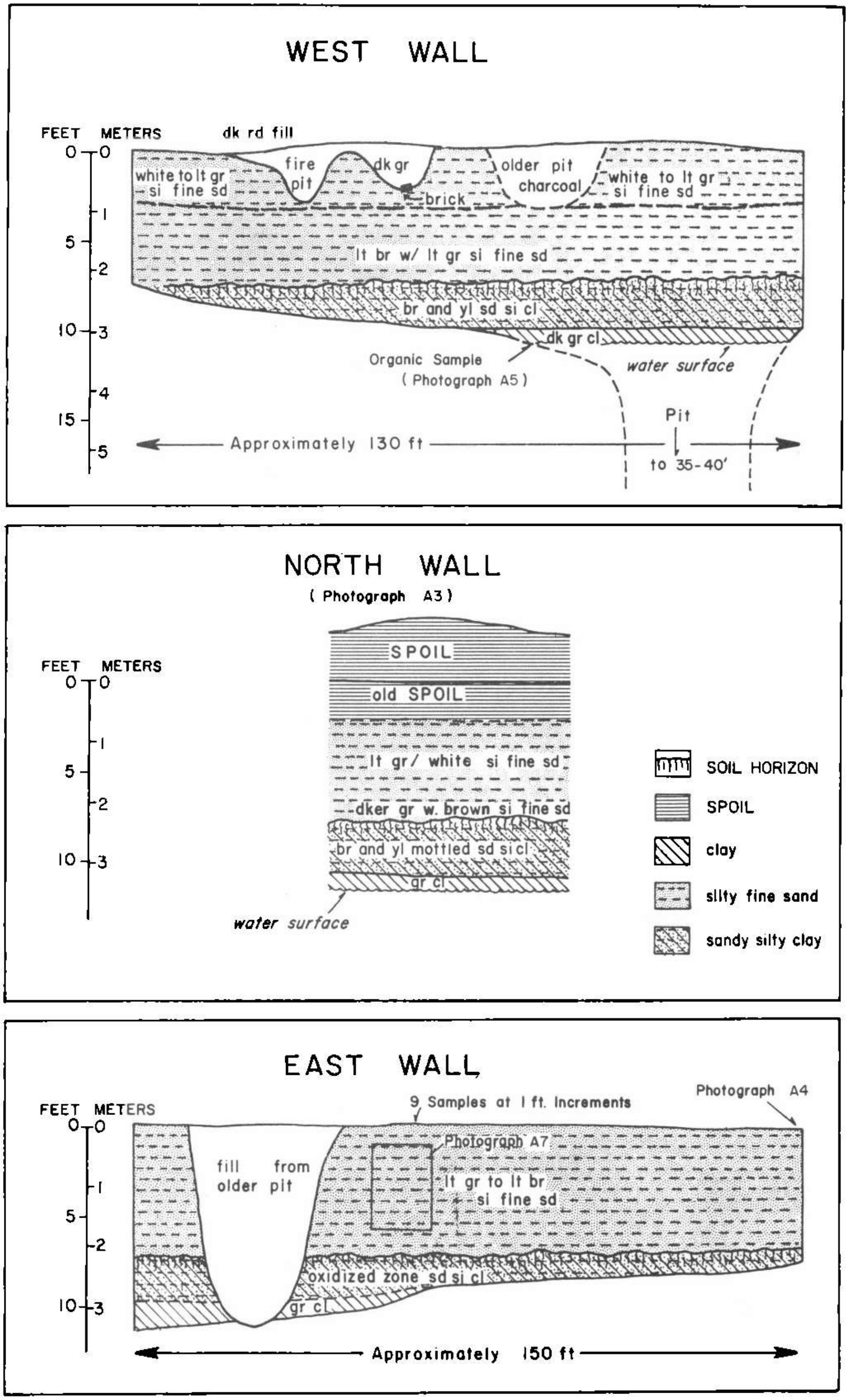

Figure A2. West, north, and east walls of pit.

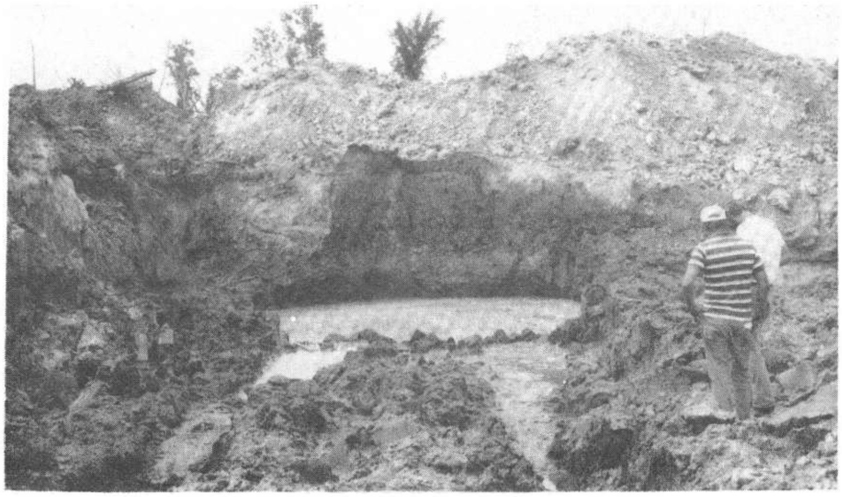

Figure A3. North wall of excavation. A pit about 50 x 150 feet was excavated to a depth of about 10 feet. A smaller pit, about 25 x 25 feet was then excavated to a depth of about 35 to 40 feet with a large backhoe. Water rose rapidly to the level shown (about 12 feet below surface) when the backhoe reached a depth of about 20 feet. Organic layer visible just above water level.

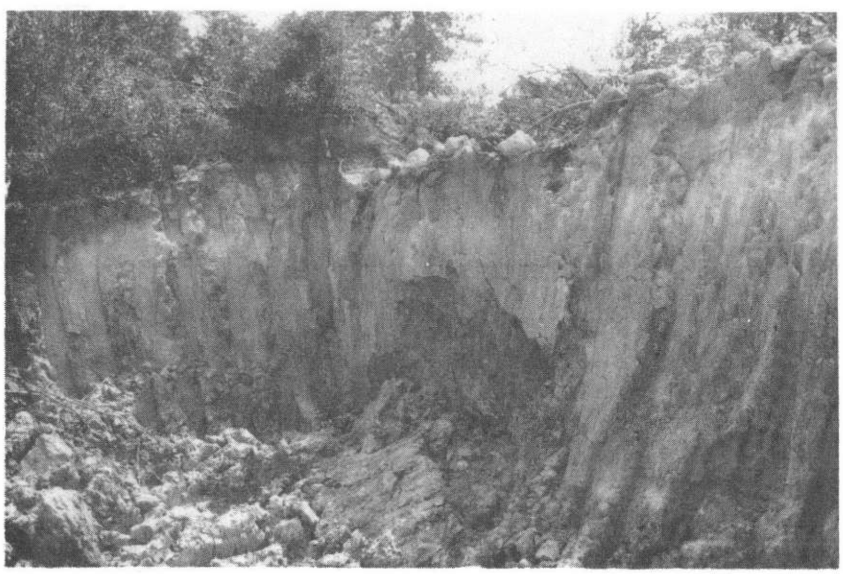

Figure A4. Southeast corner of pit. Oxidized zone at the top of Unit C forms pit bottom in this area.

Figure A5. Obtaining samples from organic layer at about 12 feet. Organic layer right at water line.

Figure A6. West wall of pit. Backhoe capable of reaching depths of 35 to 40 feet seen on left. Two pumps were used to lower the water table, but they could lower the water table only to a depth of 17 or 18 feet.

Figure A7. Detail of a portion of the east wall of the excavation. See Figure A2 for location.

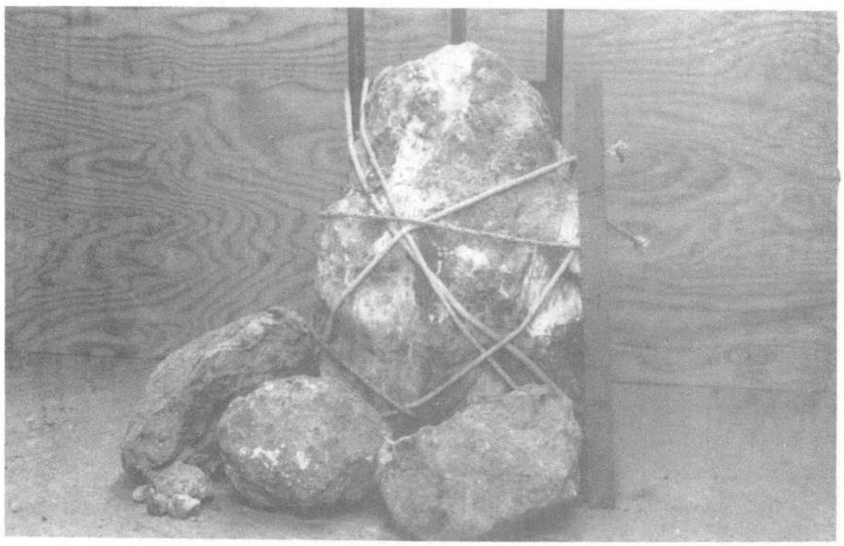

Figure A8. The largest boulder and several of the smaller boulders extracted from the boulder zone. These rounded and surficially oxidized rocks consist of hard calcite thought to be the eroded remnants of a former calcite caprock. The boulders shown were actually taken from the small test pit made at about the location of Boring X-15 (see Figure A1). Cardboard scale is two feet long.

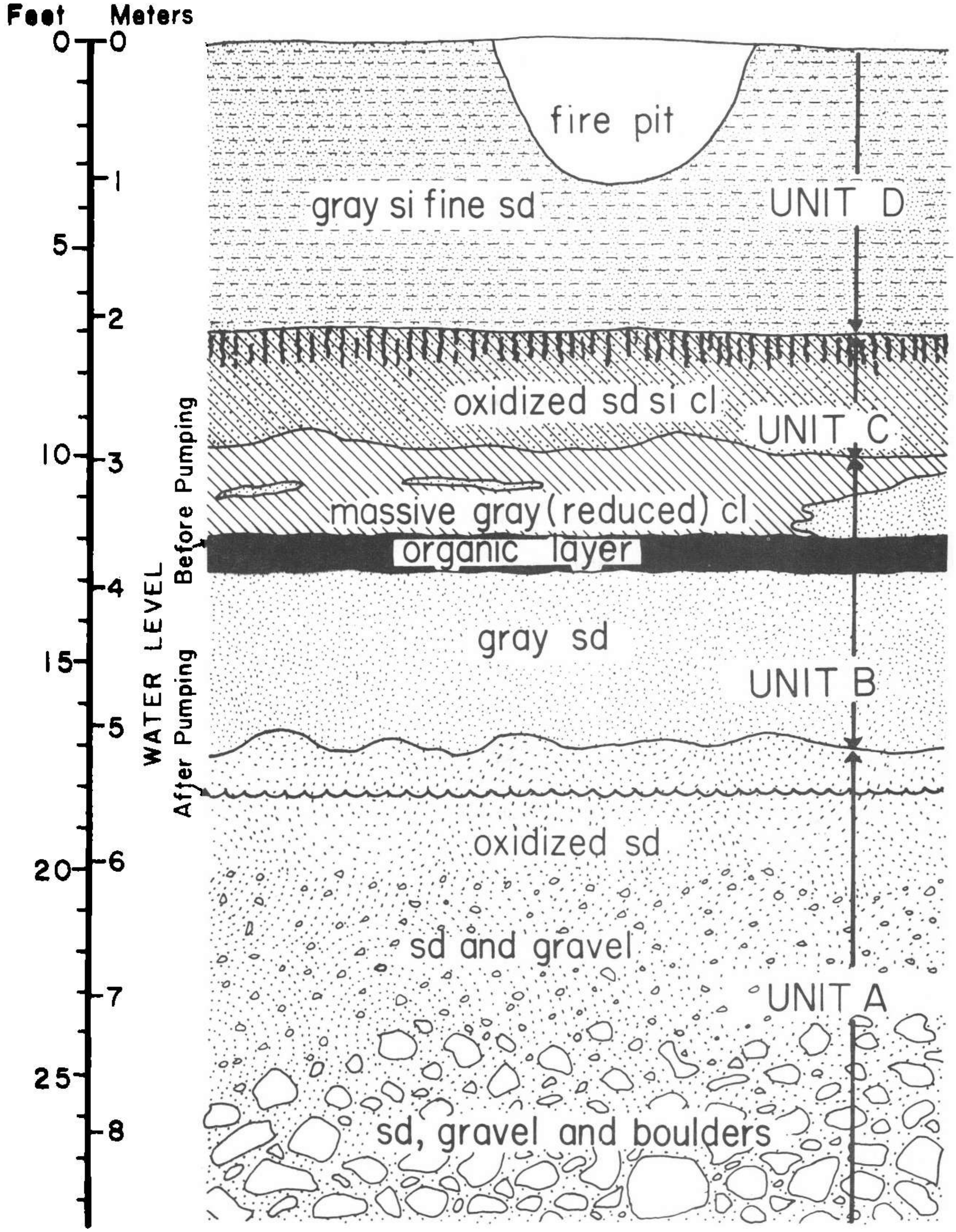

Figure A9. Generalized stratigraphy of James Pit. Vertical lines at the top of Unit C indicate a soil horizon.

backhoe's reach was approximately 35 to 40 feet below the present surface.) Boring X14, just north of the pit, encountered anhydrite beneath the boulder zone at a depth of 32 feet. Whether boulders were encountered to the entire depth reached by the backhoe is uncertain. Boulders may have been concentrated within the central part of Unit A.

Unit A makes an uneven contact with overlying Unit B. Unit B is about 7 to 8 feet thick and is characterized by gray colors indicating highly reduced conditions. The lower portion of the unit is dominated by sands while the upper portion is mostly a massive clay with stringers of sand. A rather continuous, but thin (4 to 8 inches), organic layer was observed and sampled from a level located about 2.5 feet from the top of this unit. Logs and sticks were observed in the lower portion of Unit B but were not sampled because of the unstable character of the pit walls.

Unit B makes a sharp contact with overlying Unit C. However, in this case it is not clear that an erosional episode is involved. At the contact, Unit B appears involuted. Small flame structures are common, suggesting features that occur when heavier material abruptly overrides saturated, semi-viscous sediments.

Unit C, which is about three feet thick, presents an oxidized appearance with some gray mottling. Texturally, the unit is characterized by fine sand, silt, and clay. The upper contact is an erosion surface that supports a well-developed paleosol.

The uppermost unit, Unit D, varies in thickness from about 6.5 feet at the north end of the pit to a measured 5 feet along the east wall of the pit. The original surface is marred by fire pits used by 19th century miners to boil brine. In the northeast corner of the pit, the cast of an old well was clearly visible in the wall. Spoil from the various diggings was intermixed with in situ soil and was scattered irregularly on the natural surface.

Despite these disturbances, the main characteristics of Unit D are easily discernible. The unit is massive in appearance and consists of silt and fine sand. It is ash gray in color and, where the original surface is intact, it supports a distinctly developed soil. Unit D has a well-defined contact with the paleosol that caps Unit C.

Discussion

The deposits exposed by the T. L. James exploratory pit provide the basis for a tentative reconstruction of Quaternary events over Rayburn's dome. The boulder zone is, obviously, the oldest unit observed, possibly pre-Quaternary in age. Various palynological, grain-shape, and related studies presently underway will, hopefully, help in determining its age. It could have been formed at any time from Tertiary to late Pleistocene through weathering of a calcite caprock, but evidence to date suggests that it is of pre-Pleistocene age. The chert gravels (previously mentioned) found together with boulders, perhaps as deep as 10 feet within the boulder zone, reopen the possibility that the zone may be of Pleistocene age. However, the occurrence of these chert gravels may, instead, indicate a long period of subaerial erosion and oxidation of the boulder stratum, during which time gravels introduced later in Pleistocene times worked their way downward within the zone.

To what age the upper sands and gravels of Unit A can be assigned is as conjectural as the age of the boulder zone. The overlying unit, Unit B, has been radiometrically dated, and it is logical to assume that the erosion surface at the top of Unit A was formed during the last low stand of sea level, some 17,000 years ago. This would make the sand and gravel forming the top six feet of Unit A Prairie in age or older. To date, no radiocarbon datable material has been found in this unit.

The gray, highly reduced sediments of Unit B reflect poorly drained, probably ponded conditions. Samples were taken from the organic layer, which occurs at about 12 feet, for future ^{14}C dating. An organic sample from about this same depth was previously dated from Boring X14 (see Figure A1 for location). The date obtained was approximately 14,000 years BP. Thus, the unit was deposited when sea level was still at a relatively low stand. Ponding could have been an essentially local phenomenon caused by slides or other minor topographic irregularities in this particular area. Alternatively, ponding could have been in response to more widespread conditions, such as subsidence over the dome or a pluvial cycle which radically affected the hydrologic regimen of the area over the dome. It is probable that heavy precipitation associated with a pluvial cycle might have choked off the narrow outlet to the basin south along Fouse Creek, leaving behind a shallow lake that filled in gradually with Unit B material over the central part of the basin.

The sediments (Unit C) overlying Unit B abruptly terminate the marshy environment within which Unit B was deposited. What triggered the influx of this material is unknown. It is clear that Unit C was subjected to an episode of erosion after which a period of surface stability allowed a well-oxidized paleosol to form. The drier conditions implied by these features might be associated with the mid-Holocene drought conditions of the Altithermal, postulated as having occurred about 7,000 years ago.

Finally, in late Holocene times, there was a return to wetter conditions, somewhat similar to those occurring at the present time. Top-lying Unit D presents the reduced appearance that one would expect to find beneath a present day marsh. Careful examination of this unit failed to produce any organic material that could be used for radiometric age determination. We can only estimate that Unit D is late Holocene in age.

Conclusions

1. The sand and gravel in the top part of Unit A represent the first Pleistocene sand and gravel introduced into the area above the dome and could range in age from early to late Pleistocene.

2. The erosional contact of the top of Unit A was probably formed during maximum lowering of sea level about 17,000 years ago; it strongly supports the argument that headward erosion was effective and incised even such minor tributary valleys as Fouse Creek during this short-lived drop in sea level.

3. The organic horizon in Unit B has been dated radiometrically at 14,000 years BP, a time when sea level had just begun to rise in response to a major retreat of the continental ice sheet. Spruce pollen found in this unit tends to substantiate this date. The gray, reduced nature of the unit suggests ponded conditions in the area at the time of deposition.

4. Unit C is a somewhat anomalous stratum that appears to have been introduced during a dry phase, perhaps during the Altithermal period some 7,000 years ago.

5. Unit D consists of essentially modern soils deposited in the fairly marshy conditions existing in the area at the present time. There is a good possibility that much of this unit consists of spoil spread out over the area as a result of salt mining operations that began in the 1840's.

APPENDIX B

AN EVALUATION OF SHALLOW GEOPHYSICAL SURVEYS AT RAYBURN'S DOME

Table of Contents

Abstract

Shallow seismic refraction and electrical resistivity surveys were made of the area over Rayburn's dome. One important objective was to determine the depth of the shallow anhydrite caprock. Both methods were disappointing in this regard. The general configuration of the caprock, however--a high central knob, sloping downward in all directions from the knob but culminating in a high outer rim--was suggested by the seismic refraction survey. It is also possible that what is interpreted as top of caprock in the electrical resistivity survey is actually top of salt.

Introduction

The program of cored borings conducted by the Quaternary Studies Group of LSU-IES during the summer of 1977 had established the presence of Quaternary deposits resting on a zone of calcite boulders within a clayey sand to sandy clay matrix. This "boulder zone" was encountered in the majority of cored borings and was initially thought to be the top of the caprock. Because of this interpretation and the difficulty of boring into and retrieving samples from this zone, borings were often halted when the boulder zone was reached. Little material identified as being of Tertiary or Cretaceous age was encountered except at the ends of the lines of cored borings.

Shallow geophysical surveys were initiated in September 1977 to determine if seismic refraction or electrical resistivity surveys could be used to advantage in lieu of, or in addition to, more expensive and time-consuming cored borings, auger borings, or large-diameter calyx borings. We hoped such surveys might determine the following geologic data: (1) the thickness and extent of the Quaternary; (2) major lithologic discontinuities in the Tertiary or Cretaceous, suggestive of stratigraphic changes or faulting; (3) the top of the boulder zone; (4) the top of caprock; and (5) the top of salt. Seismic refraction surveys by Harding-Lawson Associates, San Rafael, California, were made with a Nimbus ES-1200 seismograph. Electrical resistivity measurements were made by Law Engineering Testing Company, Marietta, Georgia (LETCo) using an ABEM Terrameter cycled DC resistivity unit. Previous work at Vacherie indicated that electrical resistivity was unreliable in detecting the Quaternary-Tertiary boundary but might be used in detecting the caprock surface at Rayburn's.

Shallow Seismic Refraction Surveys

1977 Seismic Survey

Shallow seismic refraction surveys were conducted along an extensive network of traverses at Rayburn's as shown on Plate 1. The energy source used was a two-pound charge of Nitramon, and a variety of geophone spacings were tried. Borings were available in many instances to check the results (Plates 2 and 3). Results were poor to fair. The base of the Quaternary was sometimes detected, but more often a horizon within the Quaternary proved to be a better reflector, such as the top of a gravel bed, a clay lense, or a thin layer of ironstone fragments. It was concluded that the method was too uncertain to be used with confidence to determine either the lateral limits or the depth of the Quaternary.

It was hoped that the method would be much more effective in determining the depth of caprock at Rayburn's considering the shallow depth of the caprock. Seismic velocities in the caprock are on the order of 12,900 feet/second (fps), considerably more than in the Tertiary and Quaternary which lie above it. Data from the seismic refraction surveys were computerized, and an example of a small portion of the computer printout which resulted is shown on Figure B1. Note that three seismic units are delineated on the computer printout: an upper unit, which we had hoped would correspond with the Quaternary, with velocities averaging 4,100 fps; a middle unit corresponding, we thought at the time, with the boulder zone or Tertiary and Cretaceous deposits, with velocities around 6,000 fps; and a basal unit, the caprock, with a velocity of 12,900 fps. We were sufficiently convinced at the time the survey was made that the high-velocity boundary defined the caprock surface. Consequently, these data were used to prepare the preliminary map of the caprock surface shown on Figure B2.

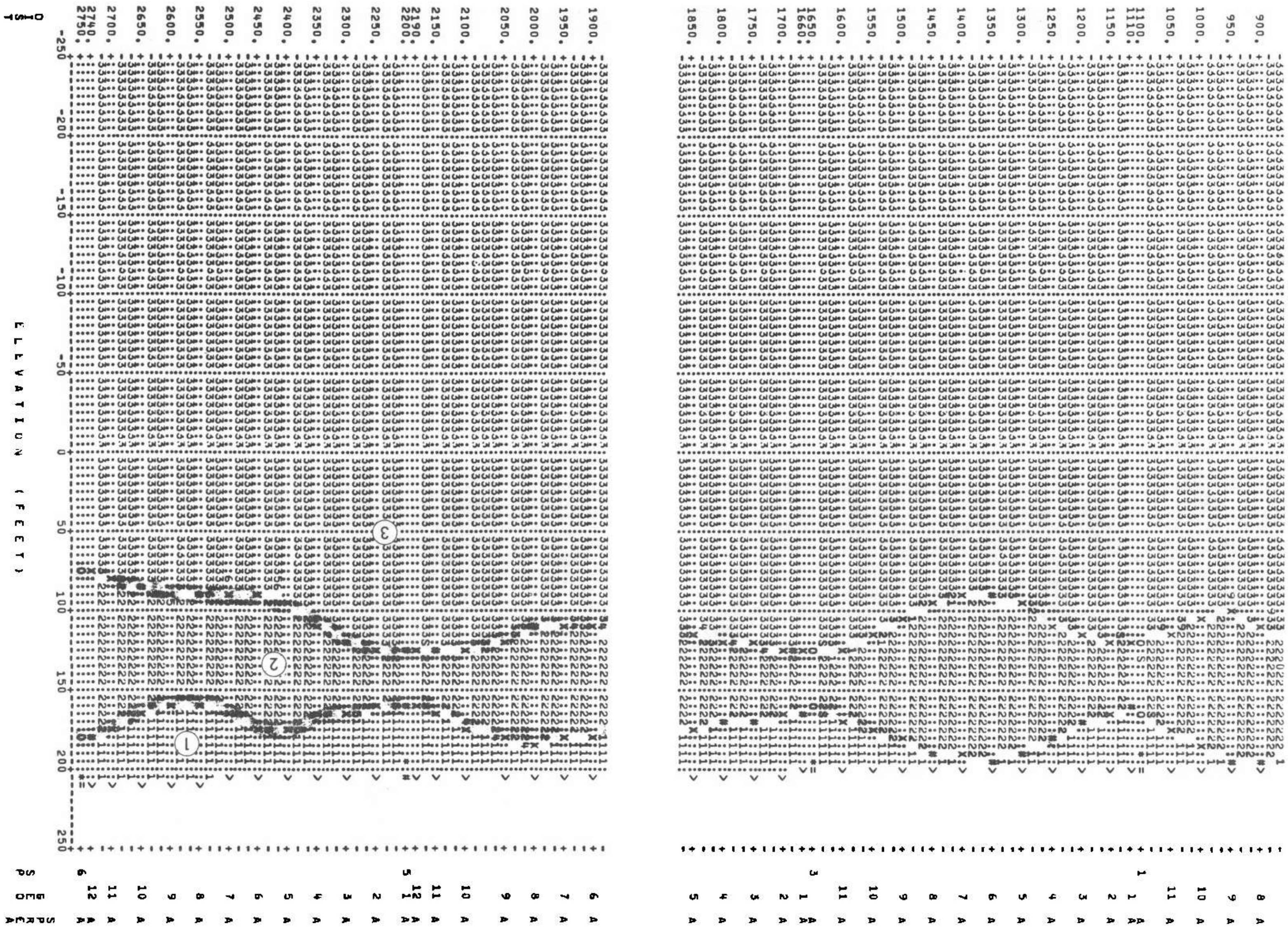

Figure B1. Computer printout of seismic refraction survey at Rayburn's dome.

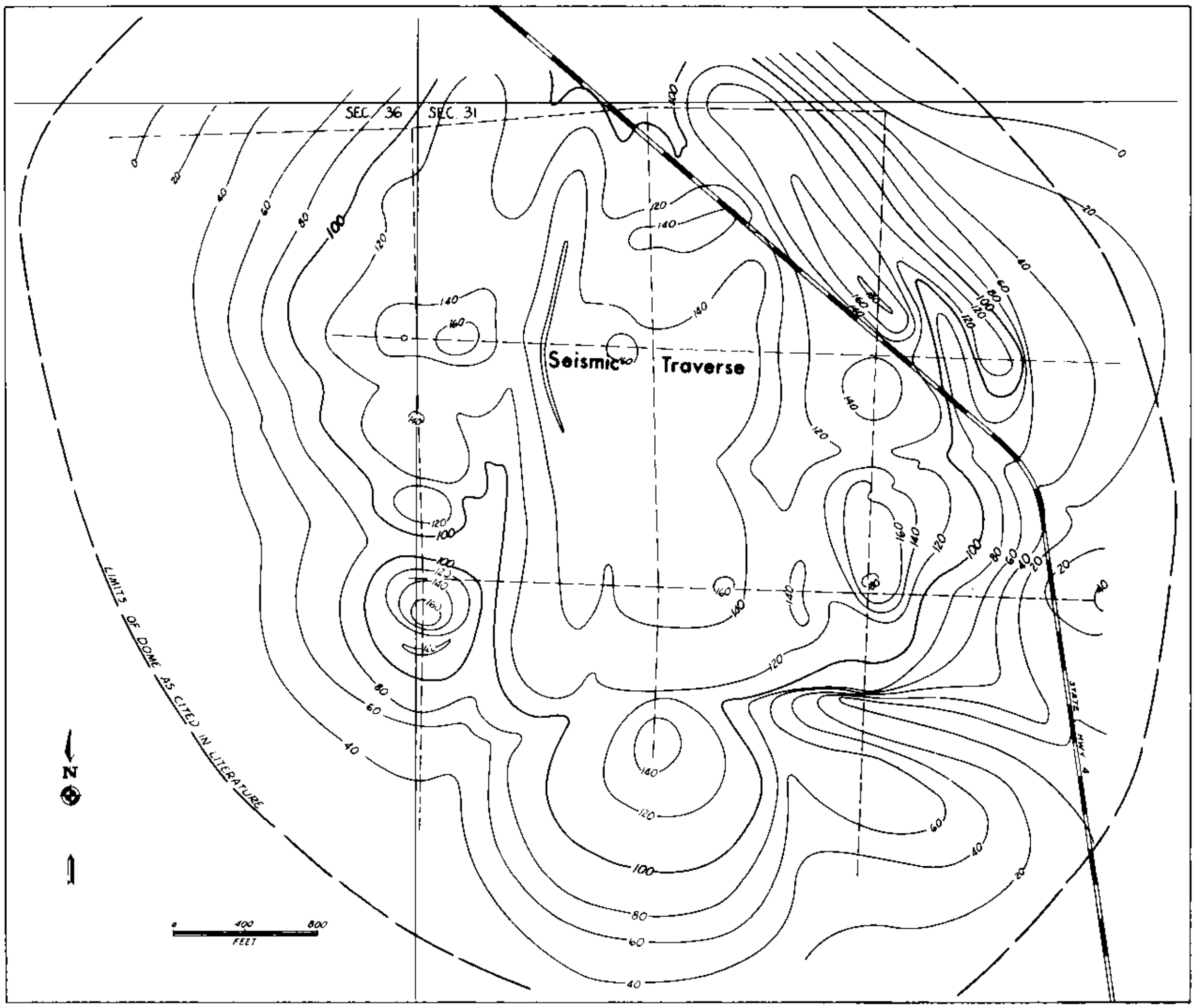

Figure B2. Preliminary map of caprock surface at Rayburn's dome based on seismic refraction surveys in feet msl.

Utilizing this contour map, the profile of the caprock was interpolated along the lines of cored borings, and the result is shown on Plates 2 and 3 and on Figures B3 and B4.

Subsequent cored and calyx borings have yielded much more information as to the depth and extent of the boulder zone, the Quaternary, the Tertiary and Cretaceous deposits, and the depth to and the nature of the caprock. Using these additional borings, a contour map of the caprock surface was prepared (Plate 12) as discussed on page 31. A comparison of this contour map with Figure B2, based on seismic returns, is interesting in that the general configuration of the caprock surface on Figure B2 and Plate 12 is similar. The central high knob is common to both maps, and in both instances the caprock surface slopes downward from this central knob in all directions. The existence of the high outer ridge of caprock that includes the dome is suggested by a series of discontinuous highs in roughly the same position as this ridge is shown on Plate 12. In many instances, however, the shape of the caprock surface developed from the seismic surveys varies significantly from that shown on Plate 12, and the depth to this surface is almost always in error.

In all, 32 borings have encountered the caprock. In only two of these (A10 and X13) did the depth to the caprock as interpreted from the Harding-Lawson survey coincide with the caprock as encountered in the cored borings. In eight borings the depth to caprock was observed to be within ten feet higher or lower than was interpreted from the seismic survey. In the remaining 22 borings the caprock was encountered as much as 30 feet above or 40 feet below the elevation predicted by the seismic work.

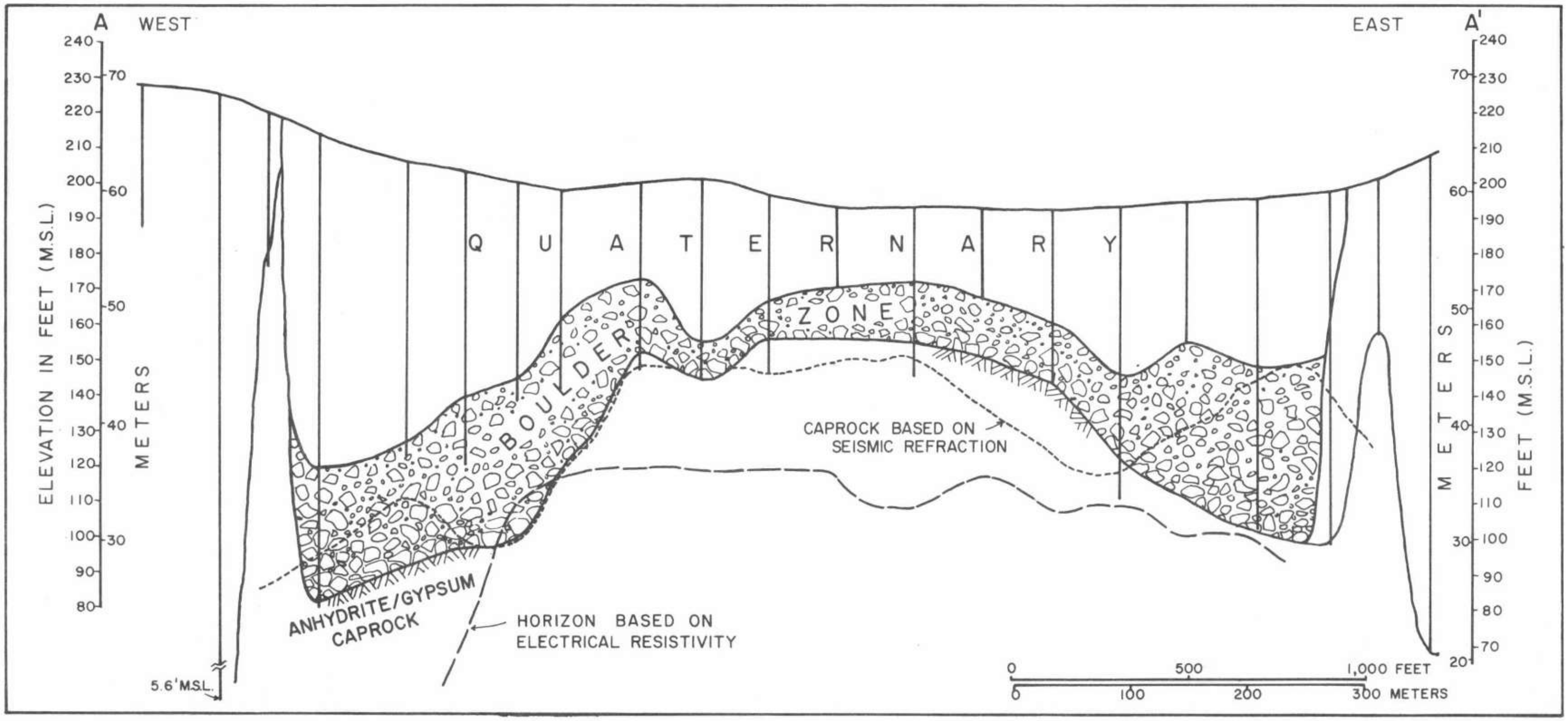

Figure B3. Subsurface profile along the A-Line showing caprock surface as interpreted from seismic refraction and electrical resistivity surveys.

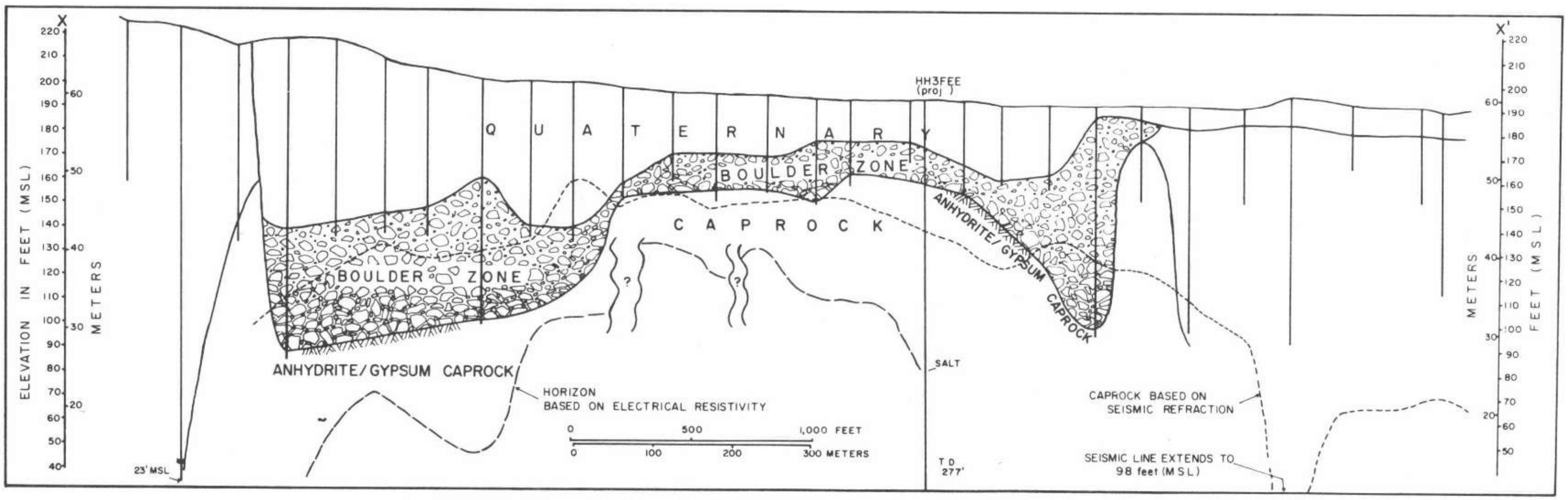

Figure B4. Subsurface profile along the X-Line showing caprock surface as interpreted from seismic refraction and electrical resistivity surveys.

One possible explanation for the disparity between the detected seismic elevations and actual elevations lies in the averaging nature of the seismic refraction survey technique. The apparent discrepancies might be explained by the supposition that the seismograph and computer processing techniques tend to establish a mean along the refracted seismic echoes and produce a smoother than actual seismic horizon. Another explanation for the unreliable nature of the seismically generated caprock elevations might be that the profiles as depicted on the X-Line and the A-Line were derived from the contour map produced from the grid pattern of the seismic lines rather than from refraction profiles along the lines of core borings.

1980 Check of Seismic Line "G"

Part of the FY80 boring program was designed to investigate the discrepancies outlined above and to carefully check depths to geologic horizons with cored borings along a specific seismic traverse. The seismic traverse chosen for the study was line "G" of the Harding-Lawson survey, the most eastern of the north-south seismic lines (see Plate 1). Six cored borings, PS0 through PS6 (no PS5 was drilled), spaced at intervals of 60 to 120 feet, were made along a 420-foot segment of this line.

The profile generated by the seismic survey is shown on Plate 13. The uppermost layer had a seismic velocity of 500 to 1,800 fps with a thickness of approximately 12 feet in this segment of the seismic traverse. The layer was theorized as consisting of clays and silts. Beneath this layer was a second layer having a seismic velocity of 6,000 fps which extended to depths ranging from 45 to 74 feet below the ground surface. This layer had a thickness which varied from 34 to 63 feet in this segment of seismic line "G" and was theorized as consisting of "pre-Quaternary limestone, chalk and shale of the Sparta, Cane River, and Wilcox formations"

(Harding-Lawson, 1977). Beneath this layer, a high velocity layer of 12,900 fps was identified. This layer was recognized along all seismic traverses made at the site and was interpreted by Harding-Lawson as representing "the caprock sequence which overlies the salt dome." Based on seismic returns the depth of caprock along the line being studied was expected to range between 48 and 74 feet below the surface.

The actual lithologic conditions along this line as determined by the six core borings (Plate 13) were quite different. In core boring PS-1 the caprock seismic horizon and the actual depth to caprock vary by 23 feet. In Boring PS-4, the actual depth to caprock is 64 feet lower than is indicated by seismic data. Clearly a discrepancy of 64 feet at a depth of only 110 feet is much too large an error to accept. It was noted that what had been interpreted from the seismic data as the top of caprock corresponds to some extent with the top of the boulder zone as determined by our borings. Perhaps, it was argued, the top of the boulder zone was being detected by the refraction seismic surveys and being interpreted as the top of caprock. However, this is hardly the case when comparing boring-seismic results on the A- and X-Lines (Plates 2 and 3 and Figures B3 and B4). On these profiles the caprock surface as interpreted from seismic results is seldom at the top of the boulder zone but usually within the zone or below it.

In summary, the results of the shallow seismic refraction survey at Rayburn's dome should be used with care. The most reliable contours available on the caprock surface are believed to be those shown on Plate 12, based entirely on borings. However, contours on the caprock surface, based on shallow seismic refraction data, are shown on Figure B2 for comparison. As can be seen, depths to the seismically generated caprock surface are in error in many instances, when compared with actual depth, based on boring data. However, the general configuration of the surface shown in Figure B2 and Plate 12 are similar. As previously stated, the high knob of caprock over the center of the dome was detected seismically. So also was the fact that the surface slopes away from this knob on all sides. Of particular interest is the observation that discontinuous seismic highs on Figure B2 correspond, in a general way, with the position of the continuous high outer rim of caprock shown on Plate 12.

Shallow Electrical Resistivity Survey

In 1978 an attempt was made to map the depth to caprock using the electrical resistivity method. An ABEM Terrameter cycled DC resistivity unit was used for data collection. Work was done by Law Engineering Testing Company, Marietta, Georgia. An interpretation of the data is contained in their unpublished report (LETCo, 1978). Twelve vertical depth soundings were conducted over the survey area, seven along the A-Line between borings A-16 and A-2, and five along the X-Line between borings X-1 and X-14 (see Figures B3 and B4, also Plates 1, 2, and 3). They ranged in depth of investigation from 100 feet to 250 feet. The general spacing between soundings was 600 feet. The Wenner array was used for both profiling and sounding.

The depth soundings were interpreted by the inverse slope method and curve matching techniques. Both methods gave compatible results. The results as they apply to the horizon, tentatively interpreted in the LETCo report as the top of caprock, are shown on Figures B3 and B4. Note that the depth to caprock as determined by the electrical resistivity method is consistently below the known depth to caprock along the A- and X-Lines as determined by borings.

A possibility is that the horizon interpreted from the electrical resistivity survey as the top of caprock may be the top of salt. We have one boring, HH3FEE, made in 1923, which was located as shown on Plate 1. We have projected this boring into the profile shown on Figure B4. Although the electrical resistivity line ends a few tens of feet short of the location of this boring, the depth to salt as reported in Boring HH3FEE is remarkably close to that determined in the survey. If the electrical resistivity survey lines shown on Figures B3 and B4 do, indeed, delineate the top of the salt, they would tend to support the sequence of events depicted on Figure 10 (see page 40) where we postulate a rise in the elevation of the salt where the caprock is high and a drop in the salt surface in those areas above the dome where dissolution has lowered the caprock surface and the base of the boulder zone.

Two-Foot Contour Interval Map

While the profiles generated by the seismic refraction and the electrical resistivity surveys were disappointing in many ways, surface elevation data gathered in these surveys, as well as for boring locations, provided the basis for a detailed 2-foot-contour-interval map of the Rayburn's site. The result is shown on Plate 14. Such a map would be particularly valuable should future efforts be made in the area to delineate possible Quaternary terrace sequences above the dome.

APPENDIX C

ISOTOPIC EVIDENCE FOR THE ORIGIN OF THE RAYBURN'S BOULDER ZONE OF NORTH LOUISIANA

Table of Contents

Abstract

A calcitic boulder zone overlies anhydrite caprock at Rayburn's dome in north Louisiana. It has been postulated that this zone is the result of the weathering of a former calcite caprock which once lay above anhydrite caprock. However, Cretaceous and Tertiary limestone is found in the normal sedimentary sequence which flanks and partly overlies the dome. Thus, the boulder zone could be the result of the weathering of a sedimentary limestone sequence which once overlay the dome.

One method of determining the origin of the calcite boulders is their carbon and oxygen isotopic composition. The present study has conclusively shown that the Rayburn's boulders are weathered or altered remnants of a former calcite caprock cover.

PART I. Introduction

The following report summarizes the results of carbon and oxygen isotope analyses of samples from the boulder zone which overlies anhydrite caprock at Rayburn's dome in north Louisiana. Partial results were presented in the July 1980 IES Quarterly Report. Additional results and final conclusions are presented here.

Due to the configuration of the boulder zone and its stratigraphic relationship to the anhydrite caprock of Rayburn's salt dome and to the overlying veneer of Quaternary alluvium, it was initially hypothesized that the boulder zone represents residuum formed by the weathering of calcite caprock during Quaternary time (Figures C1a and C1b, modified from Kolb in Martinez et al., 1979). Until the present, efforts to verify this hypothesis have been inconclusive. Examination of thin-sections of limestone boulders by Martinez and Rovik (Martinez et al., 1979) led to disagreement as to the origin of the limestone. Rovik suggested that the boulders represent marine limestone carried up with the salt as it intruded the overlying formations. Martinez concluded that the boulders are probably caprock, though unlike caprock specimens he had previously examined. Furthermore, efforts to test whether or not the boulder zone had been exposed in the subaerial environment during past geologic time were conducted by the IES palynology staff, but the results were inconclusive. Examination of 28 boulder zone samples during FY 79 yielded no significant pollen, indicating either that this lithologic unit had not been exposed at the surface or that any pollen

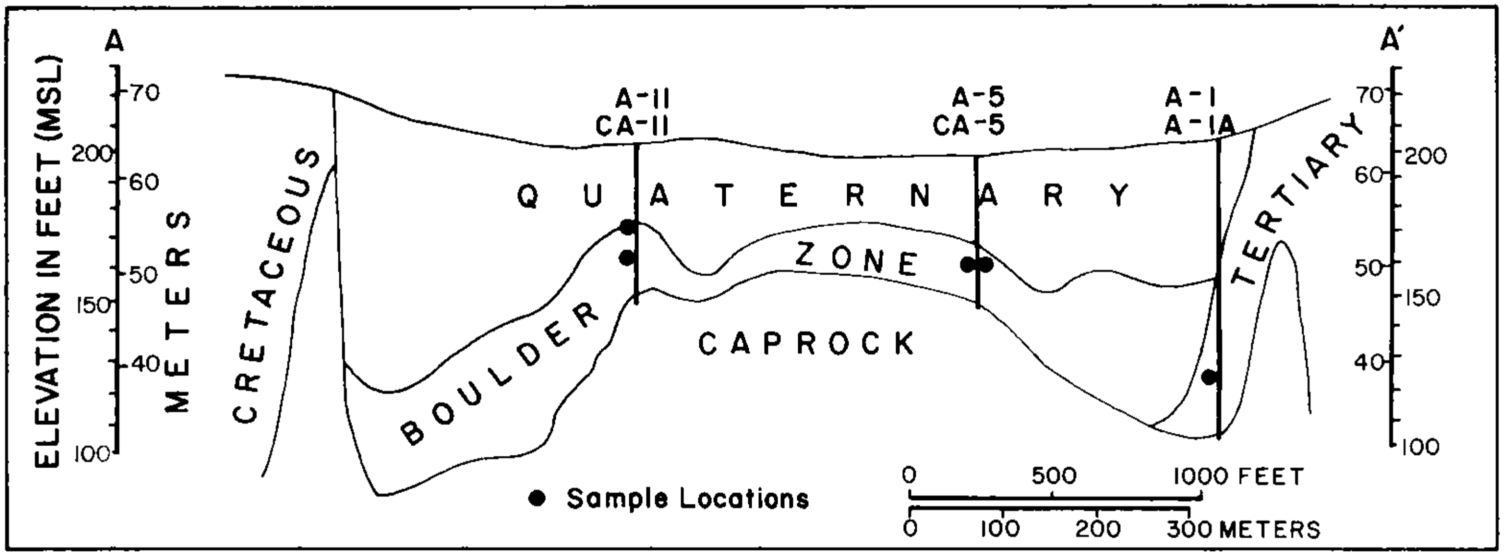

Figure Cla. Rayburn's dome, section A-A' showing locations of samples selected for isotope analyses.

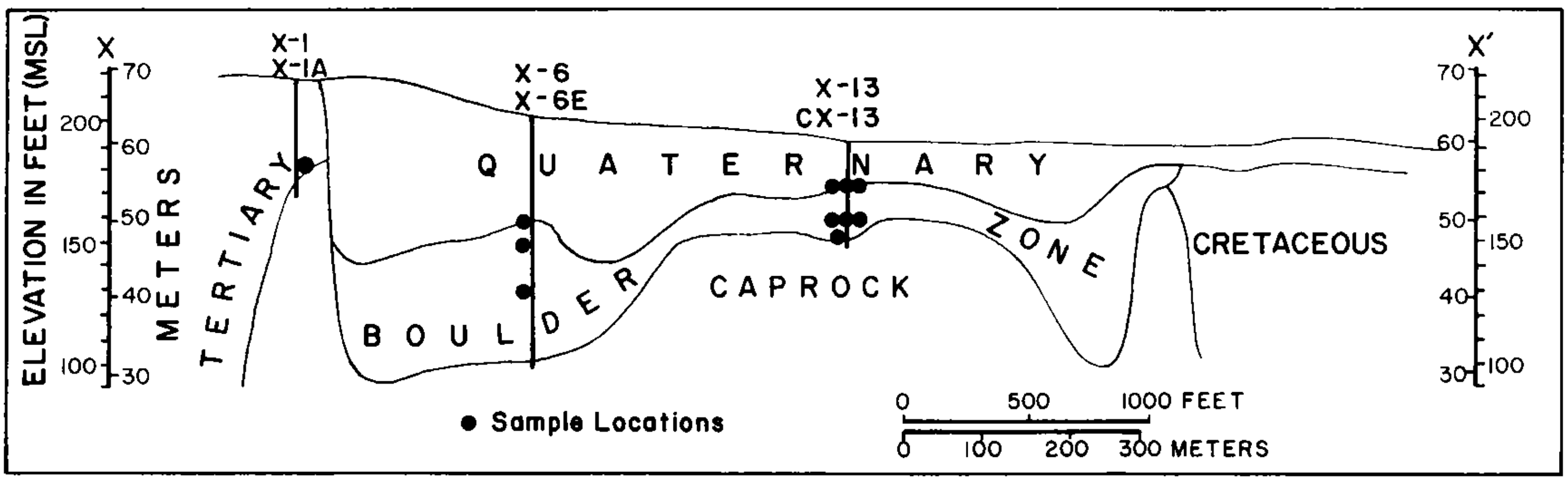

Figure Clb. Rayburn's dome, section X-X' showing locations of samples selected for isotope analyses.

that had been deposited had been subsequently destroyed due to unfavorable geochemical conditions. In order to further pursue this question, a new direction of study was sought.

Previous isotopic studies of caprock by Thode, Wanless, and Wallouch (1954), Feely and Kulp (1957), and Cheney and Jensen (1967) have shown that the calcite caprock of Gulf Coast salt domes is formed by a process greatly different from that of marine or freshwater limestone; consequently, calcite has a distinct isotopic composition reflecting this origin. Working independently, these authors have presented convincing geochemical, mineralogic, geologic, and isotopic evidence that calcite caprock is the product of the breakdown of petroleum hydrocarbons by bacteria in the subsurface environment yielding CH_4 and CO_2 which is finally oxidized to form the carbonate radical, CO_3. The most compelling evidence for the organic origin of caprock carbonate is the isotopic composition of the carbon and oxygen present in these limestones.

Results of the isotopic composition of the carbon present in 20 samples of calcite were reported in 1980. In order to assemble all data involving the subject under one convenient cover, the information reported in 1980 is repeated here with appropriate modifications as Part II. Part III summarizes these data and reports the isotopic composition of the oxygen present in the samples. In addition, recently acquired results on three additional samples are reported as well as the results of the pretreatment of selected samples with sodium hypochlorite to determine the possible effects of hydrocarbons and other organic materials on the sample results.

PART II. Carbon Isotopes

$\delta\text{-}^{13}C_{PDB}$

The parameter $\delta\text{-}^{13}C_{PDB}$ is used to define the isotopic composition of carbon present in limestone. For geochemical purposes, this parameter is not measured directly to yield a result of, say, 98.89897% ^{12}C and 1.10103% ^{13}C. Instead, each sample that is to be analyzed is converted to CO_2 and compared, using a mass spectrometer, to CO_2 used as a standard. The experimental data are converted to the parameter $\delta\text{-}^{13}C_{PDB}$ using the formula

$$\delta\text{-}^{13}C_{PDB} = \frac{(^{13}C/^{12}C)\text{sample} - (^{13}C/^{12}C)\text{PDB}}{(^{13}C/^{12}C)_{PDB}} \quad 1000 \text{ per mil}$$

where $^{13}C/^{12}C$ is a value based on the ratio between the two isotopes of a given sample and where PDB stands for CO_2 derived from Cretaceous-aged belemenites of the Peedee Formation of South Carolina. Examination of this formula shows that any sample having relatively more ^{13}C than the standard will have a positive value for $\delta\text{-}^{13}C_{PDB}$. These differences are expressed in parts per thousand.

Figure C2 compares $\delta\text{-}^{13}C_{PDB}$ values of various limestones to other sources of organic and inorganic carbon. Note that the standard used (PDB) has a $\delta\text{-}^{13}C_{PDB}$ value of zero and all of the $\delta\text{-}^{13}C_{PDB}$ values for other geologic materials are plotted relative to this standard. It can be seen that the compiled $\delta\text{-}^{13}C_{PDB}$ values for calcite caprock do not overlap with those values measured for marine or freshwater limestones. The $\delta\text{-}^{13}C_{PDB}$ values of calcite caprock overlap with those measured for petroleum and methane, which is strong evidence that caprock limestone is derived from these organic materials. Marine limestones, on the other hand, have $\delta\text{-}^{13}C_{PDB}$ values which compare favorably with marine HCO_3 from which this kind of carbonate rock forms.

Sample Processing

As shown on Table C1, 14 samples of calcite from the Rayburn's boulder zone were studied and compared with six samples from calcite caprock from the deep corehole made at Vacherie Dome.

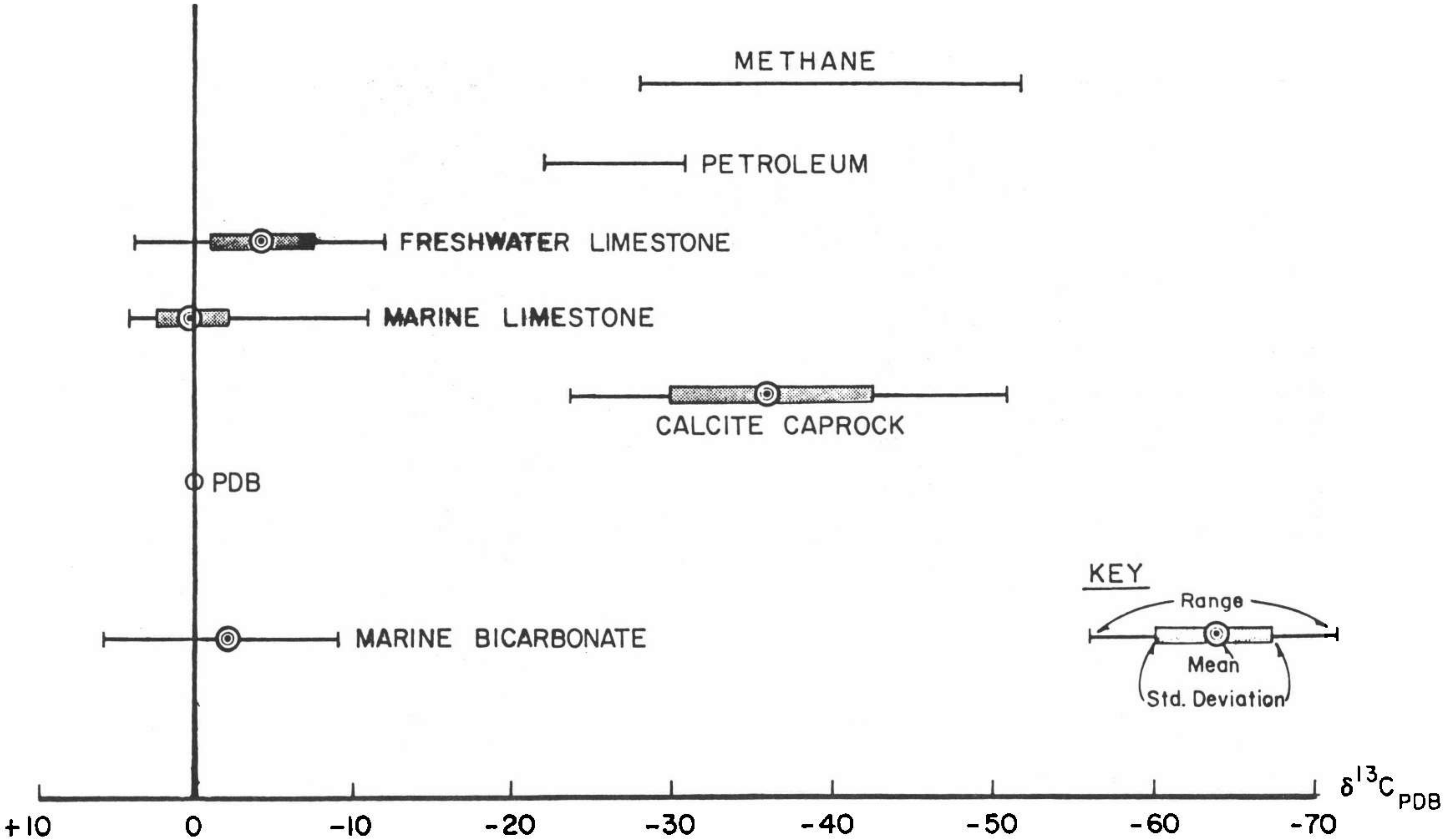

Figure C2. δ-$^{13}C_{PDB}$ values for selected limestones and the carbonaceous materials from which they are derived.

TABLE C1. ISOTOPIC DATA ON THE CARBON CONTENT OF SAMPLES FROM VACHERIE AND RAYBURN'S DOMES

Sample Boring No. (depth)	δ-$^{13}C_{PDB}$
VACHERIE DOME	
VC(543.5)	-28.4
VC(552.5)	-26.9
VC(555.5)	-25.2
VC(556.5)	-25.4
VC(559.0)	-25.2
VC(563.0)	-20.1
RAYBURN'S BOULDER ZONE	
X-6E (41)	-16.9
X-6E (53)	-23.4
X-6E (71.5)	-20.4
CA-11 (27)	-12.9
CA-11 (39)	-16.1
CX-13 (19a)	-10.3
CX-13 (19b)	- 8.0
CX-13 (19c)	- 6.2
CX-13 (32a)	-21.6
CX-13 (32b)	-14.4
CX-13 (32c)	- 9.0
CX-13 (41)	-10.8
CA-5 (37a)	-21.7
CA-5 (37b)	-24.9

Samples were washed with distilled water and oven dried prior to grinding in a stainless steel ball and mill. The ball and mill components were washed with 1.0 N HCl, rinsed with distilled water and dried between sample grindings to prevent cross-contamination of the samples. All samples were ground to pass through a 200-mesh sieve. Mass spectrometric analyses were contracted through Carbon Systems, 1287 Main Street, Baton Rouge, Louisiana. Carbon dioxide for isotopic analysis was extracted by reacting the carbonates with 100 percent phosphoric acid using the methods developed by McCrea (1950). Mass spectrometric analyses of the carbon dioxide were performed using laboratory techniques and data reduction methods as outlined by Craig (1957).

Results

Figure C3 compares measured δ-$^{13}C_{PDB}$ values for six samples of Vacherie calcite caprock and 14 samples of Rayburn's boulder zone limestone to δ-$^{13}C_{PDB}$ values obtained for other kinds of limestones. The deep corehole at Vacherie penetrated 22 feet of calcite caprock; the six samples used in the isotopic analyses were taken from continuous, 4-inch core returns at depths 543.5 ft, 552.5 ft, 555.5 ft, 556,5 ft, 559.0 ft and 563.0 ft. The mean δ-$^{13}C_{PDB}$ value for the six Vacherie samples equals -25.4 per mil, which is considerably enriched in ^{13}C, compared to the mean δ-$^{13}C_{PDB}$ value of -36.2 per mil that was observed for the 35 Gulf Coast salt dome caprock samples reported by Cheney and Jensen (1967). It is interesting to note that the mean δ-$^{13}C_{PDB}$ value for the Vacherie calcite caprock is very close to that observed for typical petroleums, as shown on Figure C2 indicating perhaps that methane, which is believed to be the precursor of strongly ^{13}C depleted calcite caprock, was not present during oxidizing conditions.

The results of the δ-$^{13}C_{PDB}$ measurements obtained for the 14 Rayburn's

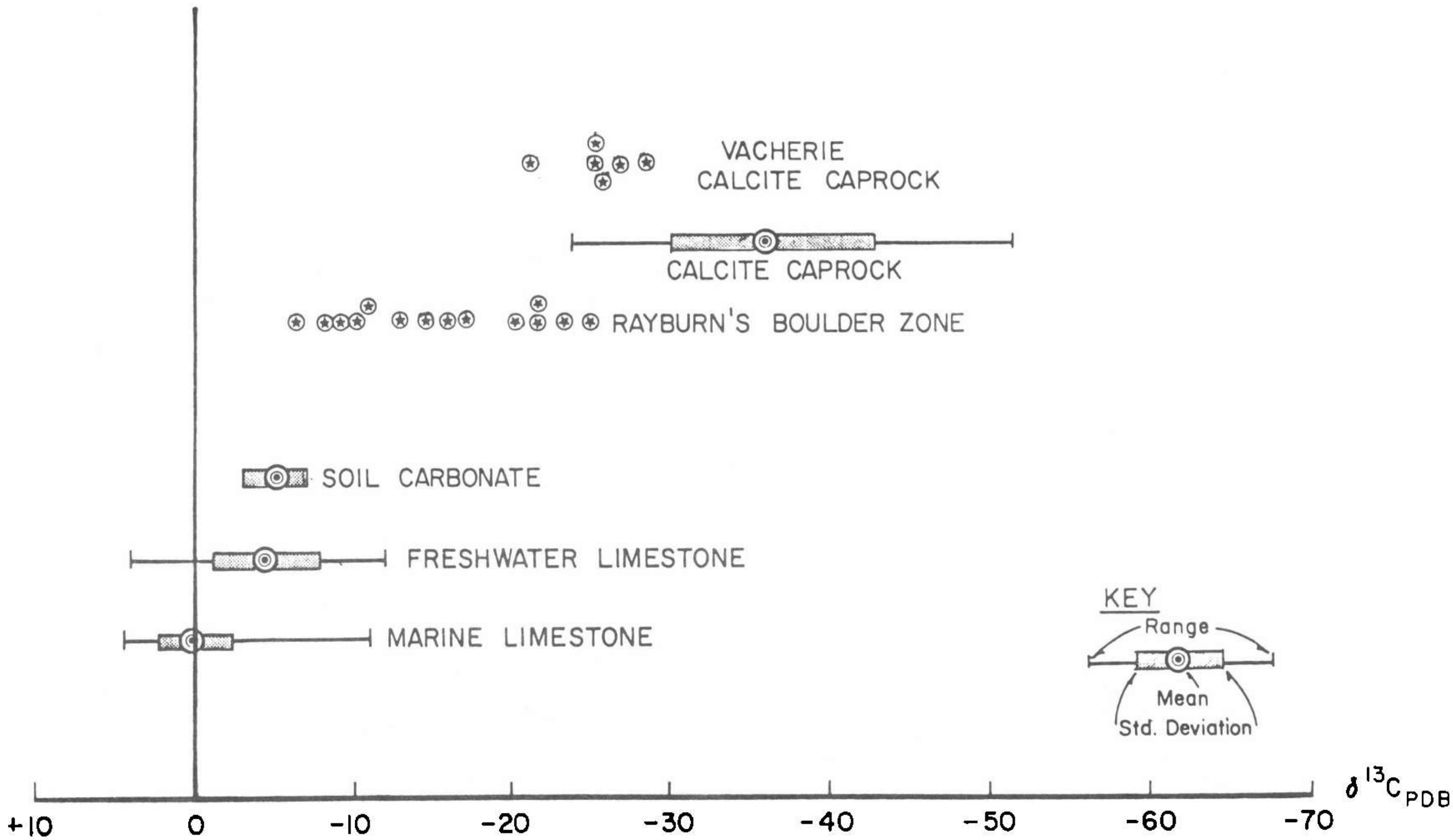

Figure C3. δ-$^{13}C_{PDB}$ values of 20 samples selected from the Vacherie calcite caprock and Rayburn's boulder zone limestone.

boulder zone samples are greatly different from that observed for the six Vacherie calcite caprock samples. The boulder zone δ-$^{13}C_{PDB}$ values range between -6.2 and -24.9 per mil and average -15.5 per mil. Considered as a single lithologic unit, the boulder zone data are distinctly different from both δ-$^{13}C_{PDB}$ values expected for marine limestones or terrestrial carbonates and the δ-$^{13}C_{PDB}$ values measured for calcite caprock. Fortunately, we have evidence that several generations of calcite are present in the boulder zone limestone fragments and our isotopic measurements show that the less altered primary calcite has δ-$^{13}C_{PDB}$ values that are more "caprock-like" than the younger secondary calcite veins and cement.

An example of this relationship was observed in many of the calcite boulders and attempts were made in sample selection to choose two or three small fragments from a single boulder for analysis: one fragment from what appeared to be an unaltered or unweathered portion and one or more from portions of the boulder that appeared altered or that contained veined intrusions. On Table C1 these are shown as samples from the same depth but with differing subscripts; e.g. samples CA-5(37a) and CA-5(37b). The sample with the greatest range of δ-$^{13}C_{PDB}$ values was from Boring CX-13 at a depth of 32 feet. This boulder was about 11 inches in its long dimension as shown on Figure C4 and contained what appeared to be three principal types of material: an amber non-porous calcite, a light tan porous limestone, and a dark amber calcite vein. These samples are designated on Table C1 as CX-13(32a), CX-13(32b), and CX-13(32c) respectively and have δ-$^{13}C_{PDB}$ values of -21.6, -14.4, and -9.0 per mil. This striking range of values is thought due to progressively greater introduction of soil carbonates derived from groundwater. The value -9 per mil is similar to δ-$^{13}C_{PDB}$ values measured for soil carbonates derived from groundwater.

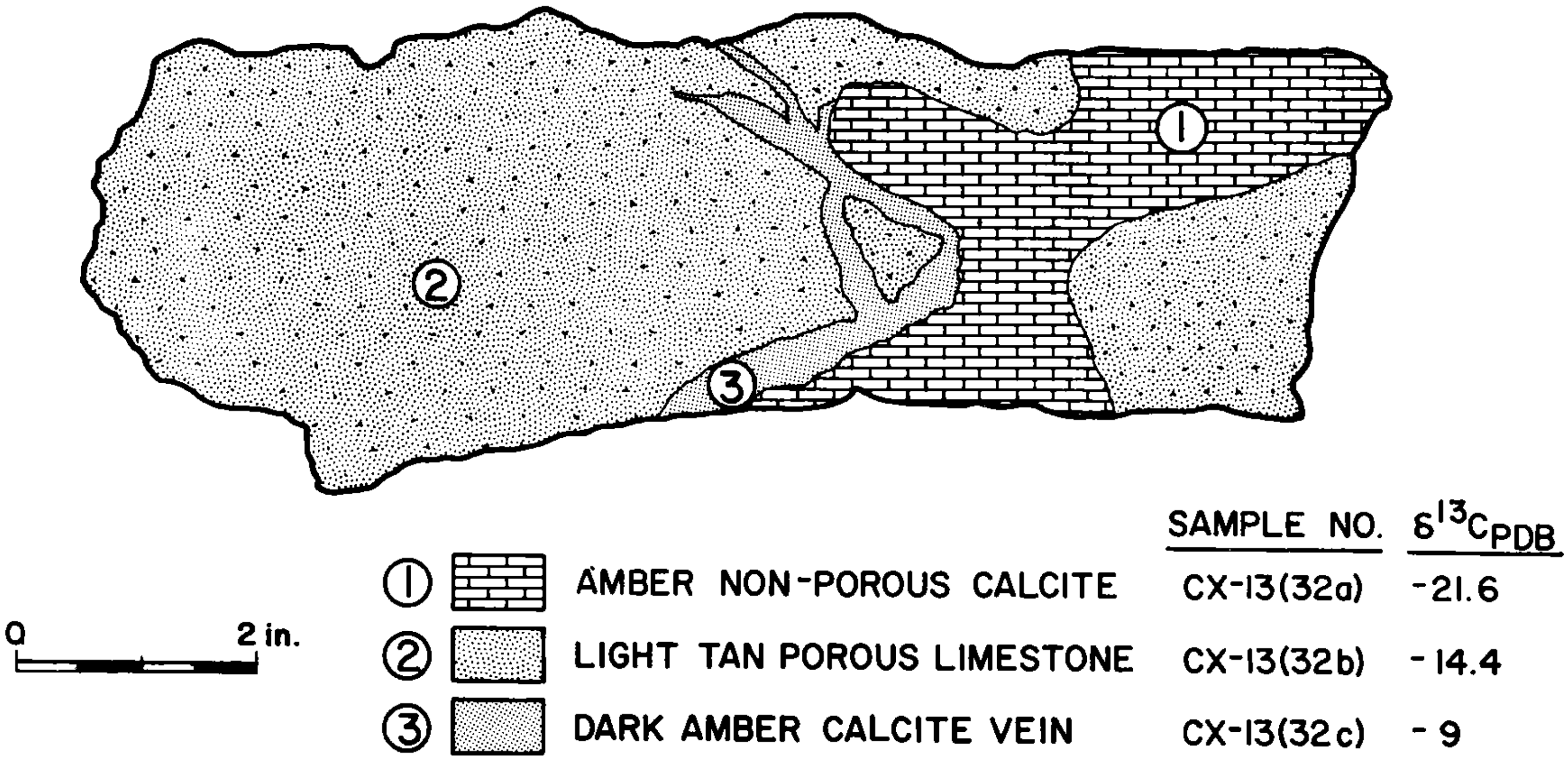

Figure C4. Composite drawing of cross section of limestone builder from CX-13 (32 ft) showing areas selected for isotopic analysis.

Thus, it appears that the boulder zone is caprock with an isotopic composition which has been altered by introduction of carbon from groundwater.

PART III. Oxygen Isotopes and Related Data

As reported in Part II, the isotopic composition of carbon in Rayburn's boulder zone calcites indicates that these rocks are highly weathered calcite caprock. Considered as a distinct group the boulder zone calcites have a distinctive suite of δ-$^{13}C_{PDB}$ values (mean = -15.5 permil; range =-6.2 permil thru -24.9 permil) which sets them apart from any other carbonate rocks reported in the literature. Furthermore, the range of isotopic composition within a single handsample [CX-13(32)] was found to be as great as 12.6 permil indicating that several generations of calcite are present in this lithologic unit.

To further these initial findings the isotopic composition of oxygen present in the boulder zone calcites are reported below. Also since the boulder zone calcites are rich in organic material the validity of the reported data has been tested for the deleterious effect organic material sometimes has on the isotopic analysis of carbonate rocks.

Data

The carbon and oxygen isotope data in Table C2 are presented in four groups: 6 samples of Vacherie caprock, 14 samples of Rayburn's boulder zone calcite, 3 miscellaneous carbonate samples, and Vacherie and Rayburn's samples which were rerun following treatment with sodium hypochlorite to remove organic material.

The δ-$^{13}C_{PDB}$ and δ-$^{18}O_{PDB}$ data pairs for the Vacherie and Rayburn's carbonate samples plot on the PDB scale as shown in Figure C5. Examination of this figure shows that the Vacherie and Rayburn's carbon and oxygen stable isotope data plot in two distinct fields which do not overlap.

TABLE C2. ISOTOPIC DATA ON SAMPLES FROM VACHERIE AND RAYBURN'S DOMES

VACHERIE DOME

Sample No. Boring (depth)	δ-$^{13}C_{PDB}$	δ-$^{18}O_{PDB}$
VC(543.5)	-28.4	-10.0
VC(552.5)	-26.9	- 9.6
VC(555.5)	-25.2	- 8.6
VC(556.5)	-25.4	- 8.9
VC(559.0)	-25.2	- 9.6
VC(563.0)	-20.1	- 9.6
RAYBURN'S BOULDER ZONE		
X-6E (41)	-16.9	- 5.2
X-6E (53)	-23.4	- 8.3
X-6E (71.5)	-20.4	- 8.0
CA-11 (27)	-12.9	- 6.5
CA-11 (39)	-16.1	- 7.5
CX-13 (19a)	-10.3	- 4.4
CX-13 (19b)	- 8.0	- 3.9
CX-13 (19c)	- 6.2	- 5.0
CX-13 (32a)	-21.6	- 7.9
CX-13 (32b)	-14.4	- 6.5
CX-13 (32c)	- 9.0	- 7.3
CX-13 (41)	-10.8	- 4.1
CA-5 (37a)	-21.7	- 7.7
CA-5 (37b)	-24.9	- 8.1
OTHER SAMPLES FROM RAYBURN'S		
*K-2 (22)	+ 0.3	- 3.0
X-1a (32)	-13.2	- 9.3
A-1a (78)	- 9.7	- 9.4

SAMPLES PRETREATED WITH SODIUM HYPOCHLORITE

	No Treatment		Sodium Hypochlorite Pretreatment	
Sample	δ-$^{13}C_{PDB}$	δ-$^{18}O_{PDB}$	δ-$^{13}C_{PDB}$	δ-$^{18}O_{PDB}$
VC(543.5)	-28.4	-10.0	-28.3	-9.7
X-6E(53)	-23.4	- 8.3	-23.1	-8.2
CA-11(39)	-16.1	- 7.5	-16.0	-7.4
CX-13(19)	-10.3	- 4.4	-10.2	-4.2

* Cretaceous limestone from Rayburn's quarry.

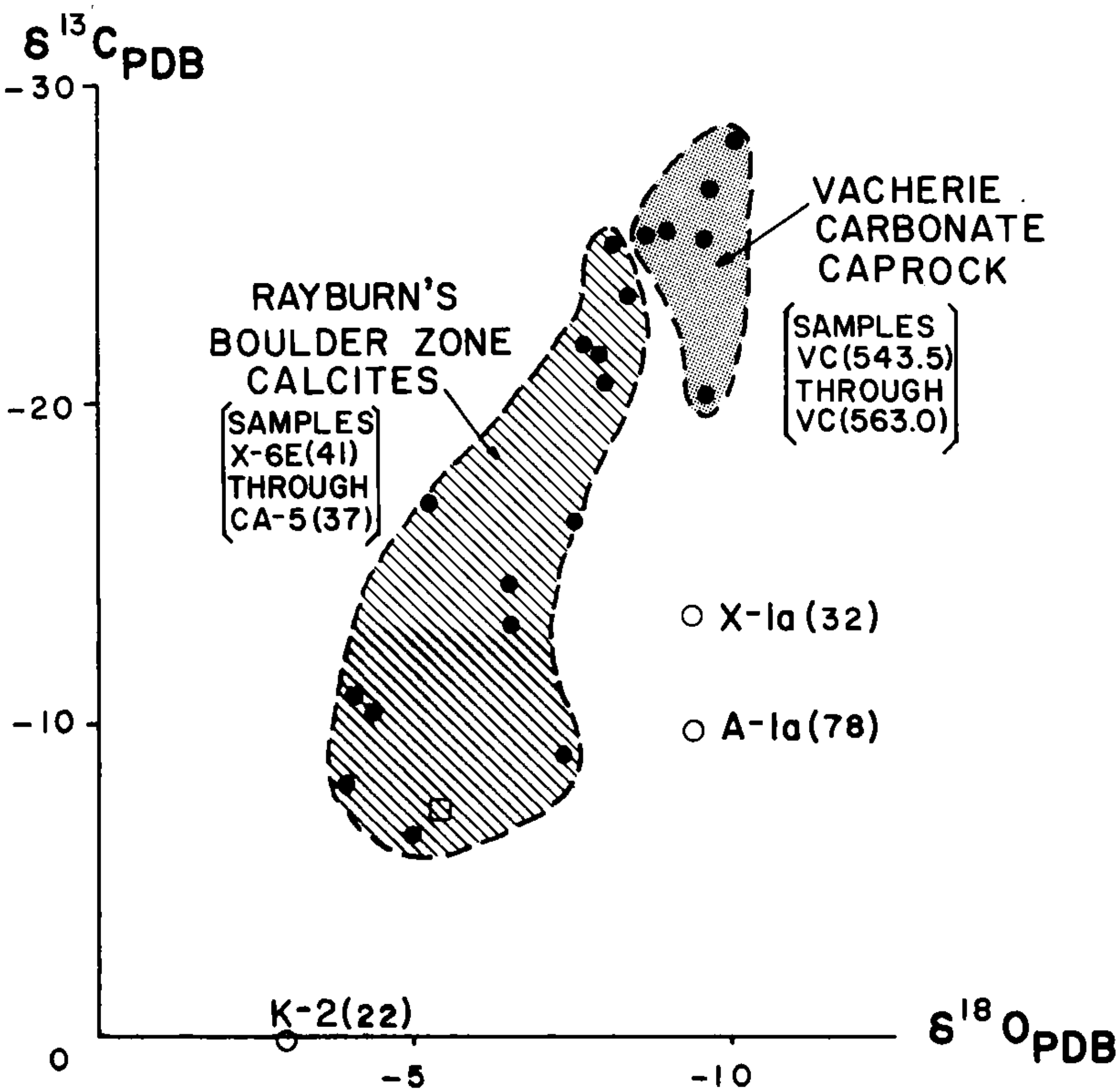

Figure C5. δ-$^{13}C_{PDB}$ and δ-$^{18}O_{PDB}$ values for Vacherie caprock, Rayburn's boulder zone, and miscellaneous samples.

These same $\delta\text{-}^{13}C_{PDB}$ values were reported in Part II and compared with $\delta\text{-}^{13}C_{PDB}$ values for other carbonate rocks. The $\delta\text{-}^{18}O_{PDB}$ values are reported here for the first time.

Vacherie Caprock

The $\delta\text{-}^{13}C_{PDB}$ values for Vacherie caprock average -25.4 permil (range = -20.1 thru -28.4 permil) and the $\delta\text{-}^{18}O_{PDB}$ values average -9.7 permil (range =-8.6 thru -10.0 permil). As far as we were able to determine these are the only $\delta\text{-}^{18}O_{PDB}$ values ever reported for calcite caprock associated with Gulf Coast salt domes. The calcites used for these analyses were taken from the deep Vacherie corehole which penetrated 22 feet of carbonate caprock. Figure C6 shows, side by side, the core positions from which isotope samples were taken and the positions from which Rovik (Martinez et al., 1978) sampled material for thin-sectioning. Thin section numbers and numbers given by those who did the isotopic analysis (last two columns) are also shown for cross-reference purposes.

The mineralogy of the carbonate section of the core is complex and calcite occurs as both a major and minor mineral component of the rock. For instance, thin-section V-la reveals fine and coarse textured calcites with traces of pyrite while the section of core from which thin-section V-3 was prepared is predominately anhydrite and gypsum with only traces of calcite. No relationship between the isotopic composition of the calcite and mineralogy of each particular core position can be assigned from these data. For the purposes of this report the carbon and oxygen stable isotope values of the Vacherie calcite caprock will be used as typical of "normal" unaltered caprock.

Rayburn's Boulder Zone Calcites

The $\delta\text{-}^{13}C_{PDB}$ values for boulder zone calcites average -15.5 permil (range = -6.2 thru -24.9 permil) and the $\delta\text{-}^{18}O_{PDB}$ values average -6.5

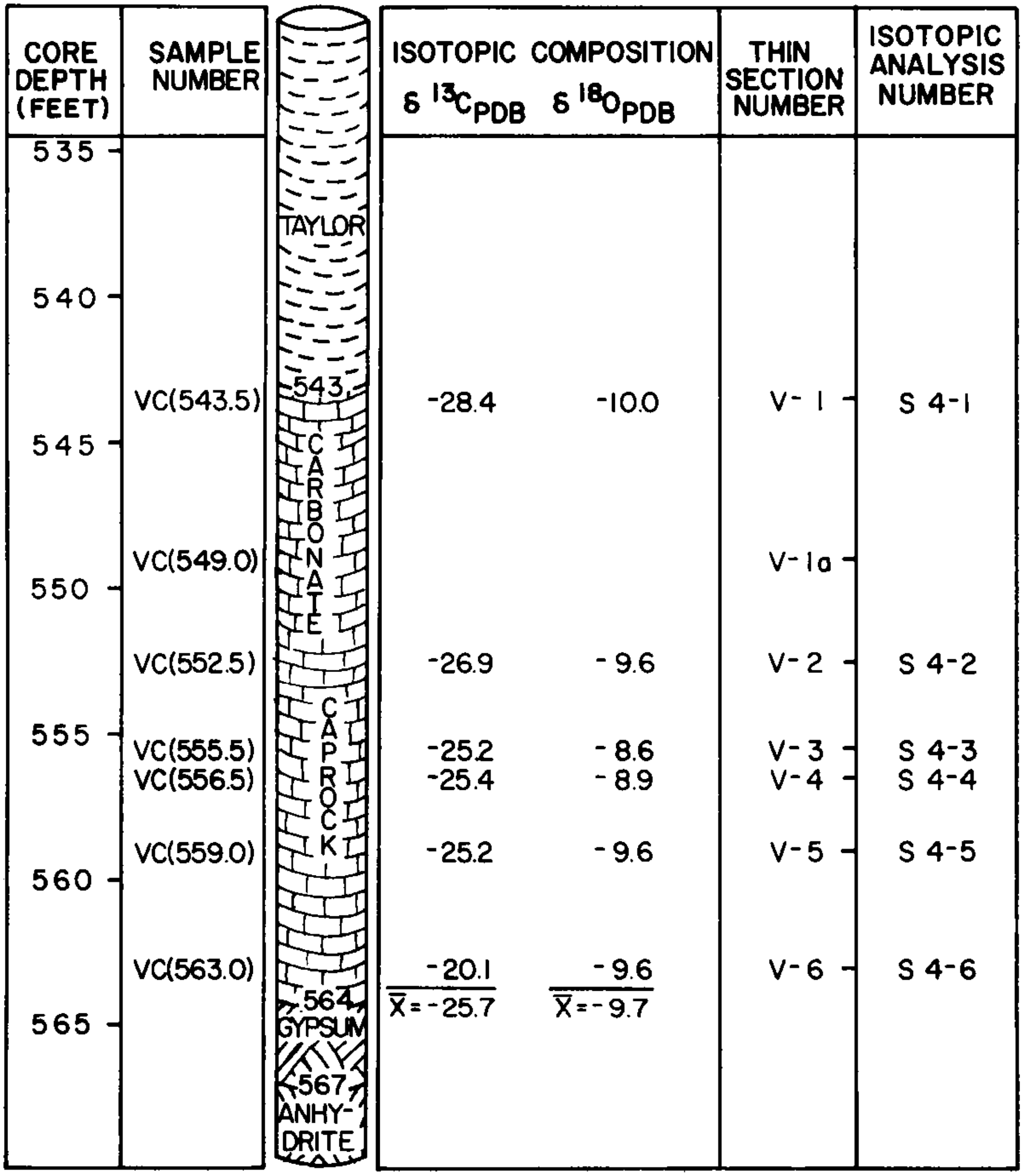

Figure C6. Vacherie carbonate caprock.

permil (range = -3.9 thru -8.3 permil). Examination of Figure C5 reveals that 5 of these data pairs have $\delta\text{-}^{13}C_{PDB}$ values which overlap those determined for Vacherie caprock while the $\delta\text{-}^{18}O_{PDB}$ values for these same samples are slightly more enriched in ^{18}O yet fall within 2.0 permil of the mean $\delta\text{-}^{18}O_{PDB}$ value of Vacherie caprock. The remainder of the boulder zone calcites have isotopic values which are progressively more enriched in ^{13}C and ^{18}O than the Vacherie caprock, the most extreme $\delta\text{-}^{13}C_{PDB}$ and $\delta\text{-}^{18}O_{PDB}$ values being enriched in the heavier isotope by 19.2 permil and 5.8 permil respectively than the mean Vacherie caprock isotope values. If the boulder zone is weathered calcite caprock as has been previously suggested the magnitude of isotopic alteration must be explained.

Discussion

A large body of research pertinent to the present study has been conducted on the diagenesis of carbonate rocks in the sub-aerial environment. The majority of the papers as exemplified by the work of Friedman (1964), Gross (1964), Land (1967) and Land et al., (1967) deal with the lithification and diagenesis of aragonitic sediment in the presence of meteoric groundwaters producing changes in both the fabrics and the initial isotopic composition of the unaltered sediment. Though the mineralogy and isotopic composition of the sediments and rocks examined by these authors are greatly different from that of calcite caprock, the diagenetic processes revealed by this body of research are applicable to the problem of the boulder zone.

Gross (1964) examined the relationship of the isotopic composition of aragonitic sediments undergoing diagenesis to the $\delta\text{-}^{13}C_{PDB}$ and $\delta\text{-}^{18}O_{PDB}$ values of groundwater bicarbonate and meteoric and groundwaters present in the diagenetic environment. He concluded ". . .changes in the $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios of the diagenetically altered limestone are shown to be the result of precipitation of secondary calcite as cement, veins, and casts in the limestones, as well as alteration of the individual constituent grains." In many instances the rock fabric showed little effect of isotopic re-equilibration.

To apply this same approach to the interpretation of the boulder zone carbon and oxygen isotope data we need reliable estimates of the isotopic composition of the groundwater bicarbonate and groundwater present at the Rayburn's site during diagenesis. The model of equilibrium precipitation presented by Gross (1964) suggests that the $\delta\text{-}^{13}C_{PDB}$ values of these calcites should range between -3.0 and -11.0 permil. $\delta\text{-}^{13}C_{PDB}$ values reported by Stuiver and Polach (1977) for soil carbonate agree with this estimate. Thus for the purposes of this report a value of -6.5 permil will be used as an estimate of the average $\delta\text{-}^{13}C_{PDB}$ value of a calcite in equilibrium with groundwater bicarbonate at the Rayburn's site. Knauth et al., (1980) measured the oxygen isotope composition of well water from a depth of 476-486 feet in well V-4 over the Vacherie salt dome and reported a value of $\delta\text{-}^{18}O_{PDB}$ -5.4 permil (SMOW)*. It will be assumed that the groundwater at the Rayburn's site has a similar value.

If the boulder zone calcites have undergone diagenesis in a manner consistent with the model proposed by Gross (1964) for Bermudan limestones, the limit of isotopic alteration of the caprock at the Rayburn's site should approach the values $\delta\text{-}^{13}C_{PDB}$ = -6.5 permil and $\delta\text{-}^{18}O_{PDB}$ = -5.4 permil. This data pair is plotted on Figure C5 as a square symbol for easy comparison with the boulder zone calcite and Vacherie carbon and oxygen data.

* SMOW: Standard Mean Ocean Water

The carbon and oxygen isotope values of boulder zone calcites form a linear trend between two endpoints: the isotopically light Vacherie carbonate caprock and the heavier hypothetical Rayburn's soil carbonate. Thus, it appears that Rayburn's dome produced calcite caprock isotopically like that at the Vacherie dome and that the Rayburn's calcite caprock has undergone partial re-equilibration with near surface groundwater and groundwater bicarbonate. From these considerations and due to the general stratigraphic relationship of the boulder zone to the surrounding formations, we conclude that the boulder zone is highly weathered calcite caprock associated with the Rayburn's salt stock.

Miscellaneous Samples

Three additional samples were selected from core returns of Rayburn's boreholes. Sample K-2(22) was taken from a Cretaceous limestone which crops out in a quarry above the dome. It has an isotopic value of $\delta\text{-}^{13}C_{PDB}$ = +0.3 permil and $\delta\text{-}^{18}O_{PDB}$ = -3.0 permil (Figure C5). Keith and Weber (1964) reported the values $\delta\text{-}^{13}C_{PDB}$ = +0.56 and $\delta\text{-}^{18}O_{PDB}$ = -5.25 permil as average values for selected normal marine limestones. Thus, sample K-2(22) produced values within the expected range of normal marine limestones.

Samples X-1a(32) and A-1a(78) were from calcitic fragments retrieved from cores at the extreme edges of the Quaternary basin above the dome (Figures C1a and C1b). It was difficult to determine from the sample return and from the lithologic sequence penetrated by these borings whether these fragments were from marine limestones, from possible in-place calcitic caprock, or from the boulder zone. It was thought that isotopic analysis of these fragments would help in making these stratigraphic decisions. The isotopic results are plotted on Figure C5 and, as can be seen, the results are ambiguous. They are atypical of the boulder zone suite of isotopic values. They are too light to be normal marine carbonates, and too heavy to be in-place calcitic caprock.

Sodium Hypochlorite Pretreatment

Samples VC(543.5), X-6E(53), CA-11(39), and CX-13(19) were prepared in the same manner as those described in Part II and then treated with 5.25 percent sodium hypochlorite solution (Clorox) for 24 hours at room temperature to remove organic material, rinsed repeatedly with distilled water and oven dried. Portions of these samples had been previously analyzed without sodium hypochlorite pretreatment.

The effect of bleaching organic material out of these samples upon subsequent isotopic analysis is minimal as is shown in Figure C7. The δ-$^{13}C_{PDB}$ value of the bleached aliquots was 0.12 permil more enriched in ^{13}C than the previously run unbleached samples and the δ-$^{18}O_{PDB}$ values were 0.17 permil more enriched in ^{18}O. It is possible that this small effect is due not to the sodium hypochlorite treatment but due to systematic machine drift as each batch of samples was run months apart. In any case, these data show that organic material incorporated in the boulder zone calcites has not greatly affected their isotopic analysis.

PART IV. Conclusions

1. Based on δ-$^{13}C_{PDB}$ and δ-$^{18}O_{PDB}$ values, it is concluded that the boulder zone is highly weathered calcite caprock associated with the Rayburn's salt stock.

2. The calcite caprock has undergone partial re-equilibration due to the introduction of groundwater and groundwater bicarbonate and has increased in both ^{13}C and ^{18}O content. The heaviest oxygen isotopic values approach those obtained from groundwater samples at Vacherie dome. The lightest carbon and oxygen isotopic values approach or equal those obtained from calcite caprock at Vacherie dome.

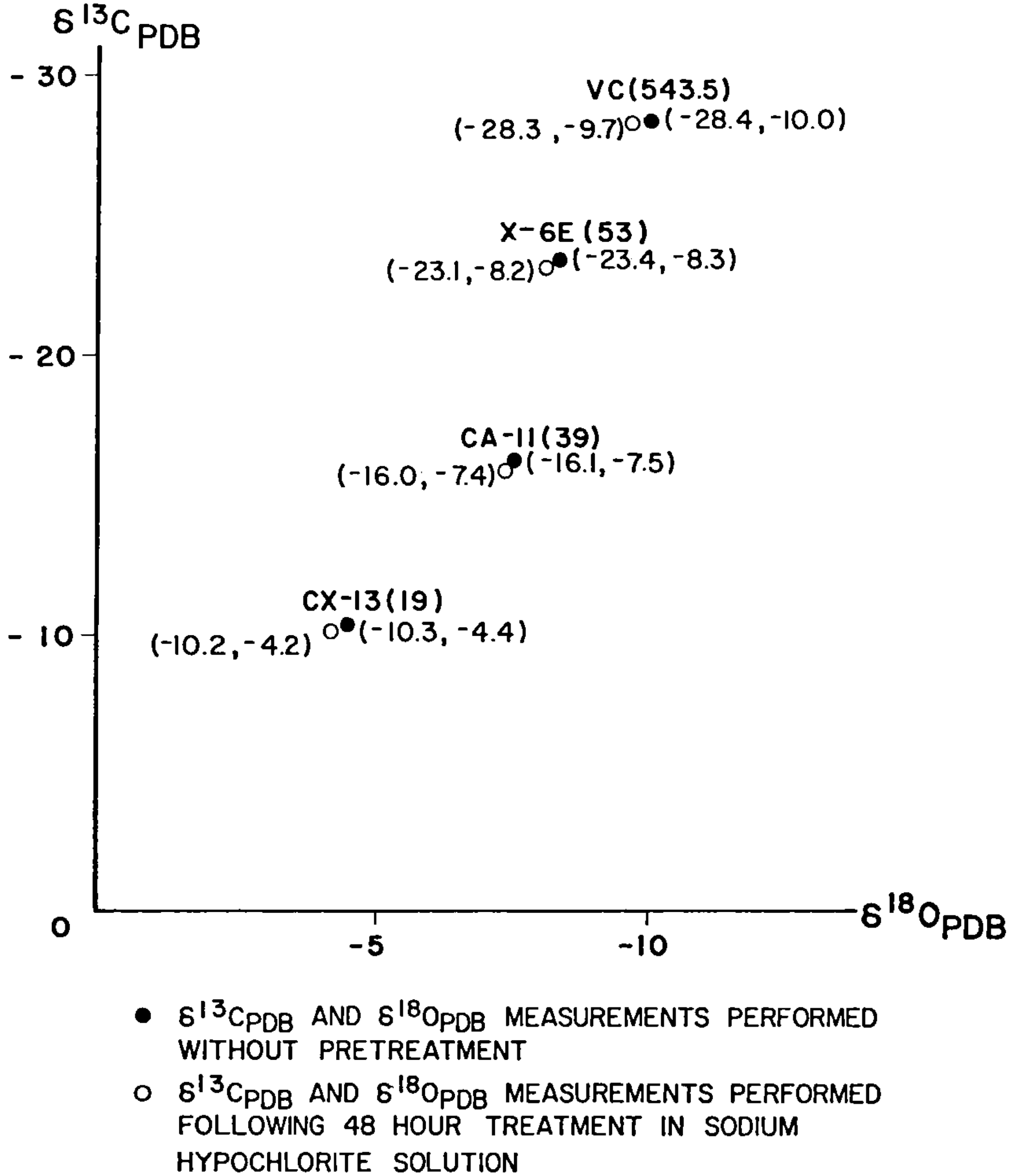

Figure C7. Effect of bleach pretreatment on measurement of stable carbon and isotope ratios of impure calcite.

3. The effect on δ-$^{13}C_{PDB}$ and δ-$^{18}O_{PDB}$ values of hydrocarbons and other organic material incorporated with the boulder zone calcites is negligible.

REFERENCES

Cheney, E. S., and M. L. Jensen, 1967. "Corrections to Carbon Isotopic Data of Gulf Coast Salt-Dome Caprock", Geochimica et Cosmochimica Acta, Vol. 31, pp. 1345-1346.

Craig, H., 1957. "Isotopic Standards for Carbon and Oxygen and Correction Factor for Mass-Spectrometric Analysis of Carbon Dioxide", Geochimica et Cosmochimica Acta, Vol. 2, Nos. 1/2, pp. 133-149.

Feely, H. W., and J. L. Kulp, 1957. "Origin of Gulf Coast Salt-Dome Sulphur Deposits", American Association of Petroleum Geologists Bull., Vol. 41, No. 8, pp. 1802-1853.

Friedman, G. M., 1964. "Early Diagenesis and Lithification in Carbonate Sediments", Journal of Sedimentary Petrology, Vol. 34, pp. 777-813.

Gross, M. G., 1964. "Variations in the O^{18}/O^{16} and C^{13}/C^{12} Ratios of Diagenetically Altered Limestones in the Bermuda Islands", Journal of Geology, Vol. 72, pp. 170-194.

Keith, M. L., and J. N. Weber, 1964. "Carbon and Oxygen Isotopic Composition of Selected Limestones and Fossils", Geochimica et Cosmochimica Acta, Vol. 28, pp. 1787-1816.

Knauth, L. P., M. B. Kumar, and J. D. Martinez, 1980. "Isotope Geochemistry of Water in Gulf Coast Salt Domes", Journal of Geophysical Research, Vol. 85, pp. 4863-4871.

Land, L. S., 1967. "Diagenesis of Skeletal Carbonates", Journal of Sedimentary Petrology, Vol. 37, pp. 914-930.

Land, L. S., F. T. Mackenzie, and S. J. Gould, 1967. "Pleistocene History of Bermuda", Geological Society of America Bulletin, Vol. 78, pp. 993-1006.

Martinez, J. D., R. L. Thoms, C. R. Kolb, M. B. Kumar, R. E. Wilcox, and E. J. Newchurch, 1978. An Investigation of the Utility of Gulf Coast Salt Domes for the Storage or Disposal of Radioactive Wastes, EW-78-C-05-5941/53, Volumes 1 and 2, Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.

Martinez, J. D., R. L. Thoms, C. R. Kolb, M. B. Kumar, R. E. Wilcox, and E. J. Newchurch, 1979. An Investigation of the Utility of Gulf Coast Salt Domes for the Storage or Disposal of Radioactive Wastes, E511-02500-A-1, Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.

McCrea, J. M., 1950. "On the Isotopic Chemistry of Carbonates and a Paleo-Temperature Scale", Journal of Chemical Physics, Vol. 18, pp. 949-860.

Stuvier, M., and H. A. Polach, 1977. Reporting of C-14 Data--Discussion, Radiocarbon, Vol. 19, No. 3, pp. 355-363.

Thode, H. G., R. K. Wanless, and R. Wallouch, 1954. "The Origin of Native Sulphur Deposits from Isotope Fractionation Studies", Geochimica et Cosmochimica Acta, Vol. 5, pp. 286-298.

DISTRIBUTION LIST

ACRES AMERICAN INC
R. STRUBLE
ALABAMA DEPT OF ENERGY
CAMERON MCDONALD
ALABAMA STATE GEOLOGICAL SURVEY
THORNTON L. NEATHERY
AMERICAN FRIENDS SERVICE COMMITTEE
WILLIAM REYNOLDS
AMERICAN NUCLEAR INSURERS
DOTTIE SHERMAN
APPLIED MECHANICS INC
JOHN R. WILLIAMS
ARINC RESEARCH CORP
H. P. HIMPLER
ARIZONA STATE UNIVERSITY
PAUL KNAUTH
ARKANSAS GEOLOGICAL COMMISSION
WILLIAM V. BUSH
NORMAN F. WILLIAMS
ARTHUR D. LITTLE INC
AVIVA BRECHER
CHARLES R. HADLOCK
BABCOCK & WILCOX
INFORMATION SERVICES
BALL ASSOCIATES LTD
DOUGLAS BALL
BILL GRAHAM
CHARLES A. JONES
JOHN C. PACER
BLACK & VEATCH
M. JOHN ROBINSON
BRENK SYSTEMPLANUNG
H. D. BRENK
BROOKHAVEN NATIONAL LABORATORY
P. W. LEVY
PETER SOO
HELEN TODOSOW (2)
BUNDESANSTALT FUR GEOWISSENSCHAFTEN UND ROHSTOFFE
HELMUT VENZLAFF
BUNDESMINISTERIUM FUR FORSCHUNG
ROLF-PETER RANDL
BUREAU DE RECHERCHES GEOLOGIQUES ET MINIERES
PIERRE F. PEAUDECERF
CANYONLANDS NATIONAL PARK
PETER L. PARRY
CAPITAL AREA GROUND WATER CONSERVATION COMMISSION
A. N. TURCAN JR.
CAYUGA LAKE CONSERVATION ASSOCIATION INC
D. S. KIEFER
CENTRAL WASHINGTON UNIVERSITY
J.R. HINTHORNE
CGS INC
E. DONALD MCKAY, III
CITIZENS ASSOCIATION FOR SOUND ENERGY
JUANITA ELLIS
COASTAL ENVIRONMENTS INC
ROD E. EMMER
COLORADO GEOLOGICAL SURVEY
JOHN W. ROLD
COLORADO SCHOOL OF MINES
DONALD LANGMUIR
CORNELL UNIVERSITY
JOHN BIRD
ARTHUR L. BLOOM
FRED H. KULHAWY
ROBERT POHL
COUNCIL ON ECONOMIC PRIORITIES
MARVIN RESNIKOFF
D.R.E.
KARL J. ANANIA
DALTON, DALTON & NEWPORT
MARIA R. EIGERMAN
DAMES & MOORE
RON KEAR
CHARLES R. LEWIS
DAPPOLONIA CONSULTING ENGINEERS INC
LISA K. DONOHUE
ABBY FORREST
AMIRA HAMDY
PETER C. KELSALL
CARL E. SCHUBERT
DRAVO ENGINEERS AND CONSTRUCTORS
KEN BEALL
DUKE UNIVERSITY
THOMAS DAVIS
DYNATECH R/D COMPANY
STEPHEN E. SMITH
E.L.H. PUBLICATIONS - THE RADIOACTIVE EXCHANGE
EDWARD L. HELMINSKI
EARTH RESOURCE ASSOCIATES INC
SERGE GONZALES
EARTH SCIENCE AND ENGINEERING INC
LOU BLANCK
EARTH TECHNOLOGY CORP
KENNETH L. WILSON
EBASCO SERVICES INC
ZUBAIR SALEEM
ECOLOGY & ENVIRONMENT INC
MICHAEL BENNER
ECOLOGY CENTER OF LOUISIANA
ROSS VINCENT
ELSAM
A. V. JOSHI
ARNE PEDERSEN
ENERGY FUELS NUCLEAR INC
DON M. PILLMORE
ENERGY INC
ENVIRONMENTAL POLICY INSTITUTE
DAVID M. BERICK
FRED MILLAR
ENVIRONMENTAL RESEARCH GROUP INC
PETER G. COLLINS
ENVIROSPHERE COMPANY
BOB HAINES
ERTEC WESTERN INC
MATT WERNER
KENNETH WILSON
FENIX & SCISSON INC
JOSE A. MACHADO
CHARLENE SPARKMAN
FLORIDA DEPT OF ENVIRONMENTAL REGULATION
HAMILTON OVEN
FLORIDA STATE UNIVERSITY
JOSEPH F. DONOGHUE
FLUOR ADVANCED TECHNOLOGY DIVISION
JOAN V. MCCURRY
FORD, BACON & DAVIS UTAH INC
PRESTON H. HUNTER
FOSTER-MILLER ASSOCIATES INC
NORBERT PAAS
FREESTONE COUNTY COURTHOUSE
SAM BOURNIAS
FREIE UNIVERSITAET BERLIN
HANSKARL BRUEHL
GENERAL ATOMIC COMPANY
ROBERT J. CAMPANA
GEO/RESOURCE CONSULTANTS INC
ALVIN K. JOE, JR.
GEOLOGICAL SURVEY OF CANADA
LIBRARY
GEOLOGICAL SURVEY OF DENMARK
L. F. ANDERSEN
GEOLOGICAL SURVEY OF NORWAY
SIGURD HUSEBY
GEORGIA INSTITUTE OF TECHNOLOGY
CHARLES E. WEAVER
GEOTECHNICAL ENGINEERS INC
RICHARD W. TURNBULL
GEOTHERMAL ENERGY INSTITUTE
DONALD F. X. FINN
GEOTRONS
JAMES MERCER
GERMANTOWN FRIENDS SCHOOL
HERB BASSOW
GESELLSCHAFT F. STRAHLEN U. UMWELTFORSCHUNG M.B.H.
H. MOSER
GIBBS & HILL INC
ROBERT PRIETO
GOLDER ASSOCIATES
ELIZABETH EISENHOOD
LAWRENCE A. WHITE
GRIMCO
DONALD H. KUPFER
GTC GEOLOGIC TESTING CONSULTANTS LTD
JOHN F. PICKENS
GULF STATES UTILITIES COMPANY
JOHN E. BARRY
HAHN-MEITNER-INSTITUT FUR KERNFORSCHUNG BERLIN
KLAUS ECKART MAASS
HALEY AND ALDRICH INC
JAMES R. LAMBRECHTS
HARDING LAWSON ASSOCIATES
FRANK C. KRESSE
HARVARD UNIVERSITY
RAYMOND SIEVER
HOUGH-NORWOOD HEALTH CARE CENTER
GEORGE H. BROWN, M.D.
IDAHO BUREAU OF MINES AND GEOLOGY
EARL H. BENNETT
ILLINOIS STATE GEOLOGICAL SURVEY
KEROS CARTWRIGHT
IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY
B. K. ATKINSON
NEVILLE J. PRICE
INDIANA UNIVERSITY
HAYDN H. MURRAY
INSTITUT FUR TIEFLAGERUNG
KLAUS KUHN
E. R. SOLTER
PETER UERPMANN
INSTITUTE OF GEOLOGICAL SCIENCES
STEPHEN THOMAS HORSEMAN
INTERA ENVIRONMENTAL CONSULTANTS INC
LARRY RICKERTSEN
ROBERT WILEMS
INTERNATIONAL ENGINEERING COMPANY INC
TERRY L. STEINBORN
MAX ZASLAWSKY

INTERNATIONAL RESEARCH AND EVALUATION
R. DANFORD
INTERNATIONAL SALT COMPANY
LEWIS P. BUSH
JOHN VOIGHT
IRT CORP
J. STOKES
JACKSON STATE UNIVERSITY
ESTUS SMITH
JACOBY AND COMPANY
CHARLES H. JACOBY
JOHNS HOPKINS UNIVERSITY
JARED L. COHON
KANSAS DEPT OF HEALTH AND ENVIRONMENT
GERALD W. ALLEN
KANSAS STATE GEOLOGICAL SURVEY
WILLIAM W. HAMBLETON
KBS
LARS B. NILSSON
KERNFORSCHUNGSZENTRUM KARLSRUHE GMBH
K. D. CLOSS
KIHN ASSOCIATES
HARRY KIHN
KILLGORES INC
CHARLES KILLGORE
LAW ENGINEERING TESTING COMPANY
JAMES L. GRANT
LAWRENCE BERKELEY LABORATORY
JOHN A. APPS
THOMAS DOE
BRIAN KANEHIRO
ROBIN SPENCER
J. WANG
HAROLD WOLLENBERG
LAWRENCE LIVERMORE NATIONAL LABORATORY
HUGH HEARD
LAWRENCE D. RAMSPOTT (2)
LEHIGH UNIVERSITY
D. R. SIMPSON
LOS ALAMOS TECHNICAL ASSOCIATES INC
R. J. KINGSBURY
LOUISIANA DEPT OF NATURAL RESOURCES
B. JIM PORTER
FRANK SIMONEAUX
LOUISIANA DEPT OF TRANSPORTATION & DEVELOPMENT
GEORGE H. CRAMER, II
LOUISIANA GEOLOGICAL SURVEY
CHARLES G. GROAT
SYED HAQUE
LEE W. JENNINGS
LOUISIANA NUCLEAR ENERGY DIVISION
L. HALL BOHLINGER (3)
LOUISIANA STATE UNIVERSITY
JEFFREY S. HANOR
EDWIN J. NEWCHURCH
ROBERT L. THOMS
LOUISIANA TECH UNIVERSITY
LIBRARY
LOUISIANA TECHNICAL NUCLEAR CENTER
R. H. THOMPSON
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
JOHN DEUTCH
MCMASTER UNIVERSITY
L. W. SHEMILT
MELLEN GEOLOGICAL ASSOCIATES INC
FREDERIC F. MELLEN
MEMBERS OF THE GENERAL PUBLIC
MORRIS A. BALDERMAN
W. VON BLACK
DAVID H. BOLTZ
JAMES BOYD
STEPHEN S. BRIGGS
DANNELLE D. DUDEK
RICHARD L. FOUKE
CARL A. GIESE
SHIRLEY M. GIFFORD
DARYL GLAMANN
C. F. HAJEK
ARLIE HOWELL
HAROLD L. JAMES
KENNETH S. JOHNSON
GRANT W. LAPIER
DAVID LYLE
MAX MCDOWELL
A. ALAN MOGHISSI
ALAN D. PASTERNAK
SHAILER S. PHILBRICK
HARRY W. SMEDES
NORM C. SMITH
A. E. WASSERBACH
JIMMY L. WHITE
MICHIGAN DEPT OF PUBLIC HEALTH
DON VAN FAROWE
MICHIGAN GOVERNORS OFFICE
WILLIAM C. TAYLOR
MICHIGAN PUBLIC SERVICE COMMISSION
RON CALLEN
MICHIGAN TECHNOLOGICAL UNIVERSITY
GARY L. DOWNEY
MINERALOGICAL SOCIETY OF AMERICA
EDWIN ROEDDER
MINNESOTA ENERGY AGENCY
MIKE MURPHY
MISSISSIPPI ATTORNEY GENERALS OFFICE
MACK CAMERON
MISSISSIPPI BUREAU OF GEOLOGY
MICHAEL B. E. BOGRAD
MISSISSIPPI CITIZENS AGAINST NUCLEAR DISPOSAL
STANLEY DEAN FLINT
MISSISSIPPI DEPT OF ENERGY AND TRANSPORTATION
JOHN W. GREEN (3)
MISSISSIPPI DEPT OF NATURAL RESOURCES
ALVIN R. BICKER, JR.
CHARLES L. BLALOCK
CURTIS W. STOVER
MISSISSIPPI DEPT OF WILDLIFE CONSERVATION
JOSEPH W. JACOB, JR.
MISSISSIPPI EMERGENCY MANAGEMENT AGENCY
JAMES E. MAHER
MISSISSIPPI LIBRARY COMMISSION
SARA TUBB
MISSISSIPPI MINERAL RESOURCES INSTITUTE
MISSISSIPPI POWER & LIGHT
ROBERT SHADDIX
MISSISSIPPI STATE BOARD OF HEALTH
EDDIE S. FUENTE
J. WARREN GREEN
MISSISSIPPI STATE HOUSE OF REPRESENTATIVES
TERRELL BRELAND
E. FRED DOBBINS
JERRY OKEEFE
MISSISSIPPI STATE SENATE
MARTIN T. SMITH
MISSISSIPPI STATE UNIVERSITY
TROY J. LASWELL
MITRE CORP
LESTER A. ETTLINGER
NASA JOHNSON SPACE CENTER
MICHAEL R. HELFERT
NATIONAL ACADEMY OF SCIENCES
JOHN T. HOLLOWAY
PETER B. MYERS
NATIONAL ATOMIC MUSEUM
GWEN SCHREINER
NATIONAL BUREAU OF STANDARDS
LEWIS H. GEVANTMAN
NATIONAL OCEANOGRAPHIC AND ATMOSPHERIC ADMINISTRATION
JACK SCHUMAN
NATURAL RESOURCES DEFENSE COUNCIL
THOMAS B. COCHRAN
NEW JERSEY DEPT OF ENVIRONMENTAL PROTECTION
JEANETTE ENG
NEW YORK DEPT OF HEALTH
DAVID AXELROD,M.D.
NEW YORK STATE GEOLOGICAL SURVEY
ROBERT H. FAKUNDINY
NEW YORK STATE PUBLIC SERVICE COMMISSION
FRED HAAG
NIEDERSACHSISCHES SOZIALMINISTERIUM
HORST SCHNEIDER
NORTH CAROLINA STATE UNIVERSITY
M. KIMBERLEY
NORTHWESTERN UNIVERSITY
BERNARD J. WOOD
NTR GOVERNMENT SERVICES
THOMAS V. REYNOLDS
NUCLEAR INFORMATION AND RESOURCE SERVICE
GARY HZKOWITZ
NUCLEAR WASTE WATCHERS
HELEN LETARTE
NUS CORP
W. G. BELTER
JOSEPH J. DINUNNO
OAK RIDGE NATIONAL LABORATORY
J. O. BLOMEKE
LESLIE R. DOLE
JOHN T. ENSMINGER
CATHY S. FORE
ARTHUR J. SHOR
ELLEN D. SMITH
STEPHEN S. STOW
OFFICE OF NWTS INTEGRATION
ROBERT E. HEINEMAN
OHIO STATE UNIVERSITY
M. A. CORNWELL
OKLAHOMA GEOLOGICAL SURVEY
CHARLES J. MANKIN
OPEN EARTH
PETER J. SMITH
ORANGE COUNTY COMMUNITY COLLEGE
LAWRENCE E. OBRIEN
ORGANIZATION FOR ECONOMIC COOPERATION AND DEVELOPMENT
J. P. OLIVIER
OTHA INC
JOSEPH A. LIEBERMAN
PACIFIC NORTHWEST LABORATORY
DON J. BRADLEY

PARSONS, BRINCKERHOFF, QUADE, & DOUGLAS, INC.
T. C. CHEN
T. R. KUESEL
PB-KBB INC
JUDITH G. HACKNEY
DILIP K. PAUL
MARK E. STEINER
PENNSYLVANIA GEOLOGICAL SURVEY
ARTHUR A. SOCOLOW
PENNSYLVANIA STATE UNIVERSITY
WILLIAM B. WHITE
PERRY COUNTY BOARD OF SUPERVISORS
PAUL D. JOHNSTON, SR.
PERRY COUNTY CITIZENS AGAINST NUCLEAR WASTE DISPOSAL
WARREN STRICKLAND
PETTIS WALLEY
PERRY COUNTY SCHOOLS
MANIEL A. COCHRAN
PHYSIKALISCH-TECHNISCHE BUNDESANSTALT
PETER BRENNECKE
PRESQUE ISLE COURTHOUSE
PRINCETON UNIVERSITY
PETER MONTAGUE
PUBLIC LAW UTILITIES GROUP
DORIS FALKENHEINER
PUBLIC SERVICE INDIANA
ROBERT S. WEGENG
R.J. SHLEMON AND ASSOCIATES INC
R. J. SHLEMON
RADIAN CORP
BARBARA MAXEY
RE/SPEC INC
WILLIAM C. MCCLAIN
RICHTON CITY HALL
R. RAHAIM
ROCKWELL HANFORD OPERATIONS
R. A. DEJU
K. THIRUMALAI
ROGERS AND GOLDEN
JACK A. HALPERN
S.E. LOGAN & ASSOCIATES INC
STANLEY E. LOGAN
SANCANA INC
RALPH L. HOPKINS
SANDIA NATIONAL LABORATORIES
R. W. LYNCH
ANTHONY MULLER
RICHARD E. PEPPING
ALLAN R. SATTLER
A. W. SNYDER
WOLFGANG WAWERSIK
SAVANNAH RIVER LABORATORY
S. W. OREAR SR
SCIENCE APPLICATIONS INC
JEFFREY ARBITAL
RONALD HOFMANN
JOHN E. MOSIER
HOWARD PRATT
SHANNON & WILSON INC
HARVEY W. PARKER
SHIMIZU CONSTRUCTION COMPANY LTD
JUNJI TAKAGI
SIERRA CLUB - MISSISSIPPI CHAPTER
SIERRA CLUB - RADIOACTIVE WASTE CAMPAIGN
MINA HAMILTON
SIERRA GEOPHYSICS INC
STEPHEN L. GILLETT
SOUTH CAROLINA GEOLOGICAL SURVEY
NORMAN K. OLSON
SOUTHWEST RESEARCH AND INFORMATION CENTER
DON HANCOCK
ALISON P. MONROE
ST MARTIN HIGH SCHOOL
RAYMOND J. WERTHNER
STANFORD UNIVERSITY
KONRAD B. KRAUSKOPF
IRWIN REMSON
STATE UNIVERSITY OF NEW YORK AT BINGHAMTON
FRANCIS T. WU
STONE & WEBSTER ENGINEERING CORP
PATRICIA ANN OCONNELL
J. PECK
ARLENE C. POST
EVERETT N. WASHER
STUDIO GEOLOGICO FOMAR
A. MARTORANA
SUMMIT COUNTY ENVIRONMENTAL SERVICES
JAMES T. KING
SYSTEMS SCIENCE AND SOFTWARE
PETER LAGUS
T.M. GATES INC
TODD M. GATES
TECHNICAL INFORMATION PROJECT
DONALD PAY
TECHNICAL RESEARCH CENTRE OF FINLAND
SILJA RUMMUKAINEN
TEKNEKRON RESEARCH INC
ANTHONY F. MOSCATI
TERRA TEK INC
NICK BARTON
TEXAS A&M UNIVERSITY
P. DOMENICO
JOHN HANDIN
ROY W. HANN, JR.
STEVE MURDOCK
GARY ROBBINS
JAMES E. RUSSELL
TEXAS BUREAU OF RADIATION CONTROL
DONALD G. ANDERSON
TEXAS DEPT OF HEALTH
DAVID K. LACKER
TEXAS DEPT OF WATER RESOURCES
C. R. BASKIN
TEXAS ENERGY & NATURAL RESOURCES ADVISORY COUNCIL
TERRY BARRON
CAROL KING
ROBERT D. SMITH
TEXAS HOUSE OF REPRESENTATIVES
PETE LANEY
THE ANALYTIC SCIENCES CORP
J. W. VOSS
THE CLARION-LEDGER
MARK SCHLEIFSTEIN
U.K. DEPT. OF THE ENVIRONMENT
RADIOACTIVE WASTE MANAGEMENT DIVISION
U.S. ARMY CORPS OF ENGINEERS
ALAN BUCK
U.S. BUREAU OF LAND MANAGEMENT
EDWARD R. SCHERICK
U.S. BUREAU OF MINES
GEORGE E. NIEWIADOMSKI
U.S. DEPT OF ENERGY - ALBUQUERQUE OPERATIONS OFFICE
R. LOWERY
JOSEPH M. MCGOUGH
U.S. DEPT OF ENERGY - ASSISTANT GENERAL COUNSEL FOR ENVIRONMENT
S. H. GREENLEIGH
U.S. DEPT OF ENERGY - CHICAGO OPERATIONS OFFICE
PAUL KEARNS
PUBLIC READING ROOM
R. SELBY
U.S. DEPT OF ENERGY - DIVISION OF WASTE REPOSITORY DEPLOYMENT
W. WADE BALLARD, JR.
J. W. BENNETT
CRITZ H. GEORGE
THOMAS P. LONGO
JEFF SMILEY
RALPH STEIN
U.S. DEPT OF ENERGY - HEADQUARTERS
PUBLIC READING ROOM
U.S. DEPT OF ENERGY - IDAHO OPERATIONS OFFICE
PUBLIC READING ROOM
U.S. DEPT OF ENERGY - NEVADA OPERATIONS OFFICE
M.P. KUNICH
PUBLIC READING ROOM
U.S. DEPT OF ENERGY - NWTS PROGRAM OFFICE
T. BAILLIEUL
M. BLANCHARD
L. A. CASEY
R. LAHOTI
L. K. MCCLAIN
J. O. NEFF
K. K. WU
R. C. WUNDERLICH
U.S. DEPT OF ENERGY - OAK RIDGE OPERATIONS OFFICE
PUBLIC READING ROOM
U.S. DEPT OF ENERGY - OFFICE OF NUCLEAR FUEL CYCLE
O. P. GORMLEY
U.S. DEPT OF ENERGY - OFFICE OF WASTE ISOLATION
JOSEPH A. LEARY
JANIE SHAHEEN
U.S. DEPT OF ENERGY - RICHLAND OPERATIONS OFFICE
O. L. OLSON
PUBLIC READING ROOM
U.S. DEPT OF ENERGY - SAN FRANCISCO OPERATIONS OFFICE
ENERGY RESOURCES CENTER
PUBLIC READING ROOM
U.S. DEPT OF ENERGY - SAVANNAH RIVER OPERATIONS OFFICE
REGINA T. HARRIS
U.S. DEPT OF ENERGY - TECHNICAL INFORMATION CENTER (27)
U.S. DEPT OF ENERGY - WIPP PROGRAM
LAWRENCE H. HARMON
U.S. DEPT OF LABOR
ALEX G. SCIULLI
KELVIN K. WU
U.S. ENVIRONMENTAL PROTECTION AGENCY
DIVISION OF CRITERIA & STANDARDS
JAMES NEIHEISEL
U.S. FOREST SERVICE
JOSEPH E. CLAYTON
U.S. GEOLOGICAL SURVEY
RUDOLPH W. KOPF

U.S. GEOLOGICAL SURVEY - ALEXANDRIA
G. N. RYALS
U.S. GEOLOGICAL SURVEY - BATON ROUGE
DARWIN KNOCHENMUS
U.S. GEOLOGICAL SURVEY - COLUMBUS
A. M. LA SALA, JR.
U.S. GEOLOGICAL SURVEY - DENVER
M. S. BEDINGER
RAYMOND D. WATTS
U.S. GEOLOGICAL SURVEY - JACKSON
GARALD G. PARKER, JR.
U.S. GEOLOGICAL SURVEY - MENLO PARK
MICHAEL CLYNNE
U.S. GEOLOGICAL SURVEY - RESTON
I-MING CHOU
JOHN ROBERTSON
EUGENE H. ROSEBOOM JR
PETER R. STEVENS
DAVID B. STEWART
U.S. HOUSE SUBCOMMITTEE ON ENERGY AND THE ENVIRONMENT
MORRIS K. UDALL
U.S. NUCLEAR REGULATORY COMMISSION
ENRICO F. CONTI
MICHAEL C. CULLINGFORD
J. J. DAVIS
HIGH-LEVEL WASTE LICENSING BRANCH
HIGH-LEVEL WASTE TECHNICAL
ROBERT JOHNSON
PHILIP S. JUSTUS
H. E. LEFEVRE
LINDA L. LEHMAN
LIBRARY
JOHN B. MARTIN (3)
HUBERT MILLER
THOMAS J. NICKOLSON
EDWARD ODONNELL
JAY E. RHODERICK
U.S. SENATE COMMITTEE ON ENERGY AND NATURAL RESOURCES
WILLIS D. SMITH
UNION CARBIDE CORP
JOHN D. SHERMAN
UNION OF CONCERNED SCIENTISTS
MICHAEL FADEN
UNIVERSITY OF AKRON
R. G. CORBETT
UNIVERSITY OF ALBERTA
F.W. SCHWARTZ
UNIVERSITY OF ARIZONA
STANLEY N. DAVIS
UNIVERSITY OF CALIFORNIA AT RIVERSIDE
LEWIS COHEN
UNIVERSITY OF CINCINNATI
ATTILA KILINC
UNIVERSITY OF DELAWARE
ROBERT R. JORDAN
UNIVERSITY OF FLORIDA
DOLORES C. JENKINS
UNIVERSITY OF HAWAII AT MANOA
DAVID EPP
UNIVERSITY OF ILLINOIS AT URBANA - CHAMPAIGN
MAGDI RAGHEB
UNIVERSITY OF LOWELL
JAMES R. SHEFF
UNIVERSITY OF MISSOURI AT COLUMBIA
W.D. KELLER
UNIVERSITY OF MISSOURI AT KANSAS CITY
EDWIN D. GOEBEL
UNIVERSITY OF MISSOURI AT ROLLA
ALLEN W. HATHEWAY
UNIVERSITY OF NEVADA AT RENO
RODNEY J. WEICK
UNIVERSITY OF NEW MEXICO
DOUGLAS G. BROOKINS
RODNEY C. EWING
UNIVERSITY OF SOUTHERN MISSISSIPPI
CHARLES R. BRENT
ROBERT E. BURKS
FREDDIE G. HOWELL
JAMES W. PINSON
DANIEL A. SUNDEEN
GARY L. WILDMAN
UNIVERSITY OF TENNESSEE AT KNOXVILLE
DON W. BYERLY
J.B. FUSSELL
UNIVERSITY OF TEXAS AT AUSTIN
BUREAU OF ECONOMIC GEOLOGY
MARTIN P. A. JACKSON
JOE D. LEDBETTER
DOUGLAS C. RATCLIFF
E. G. WERMUND
UNIVERSITY OF TEXAS AT SAN ANTONIO
DONALD R. LEWIS
UNIVERSITY OF TORONTO
R. M. STESKY
UNIVERSITY OF UTAH RESEARCH INSTITUTE
LIBRARY
HOWARD P. ROSS
UNIVERSITY OF WESTERN ONTARIO
WILLIAM S. FYLE
UNIVERSITY OF WISCONSIN
B. C. HAIMSON
UNIVERSITY OF WISCONSIN AT MILWAUKEE
HOWARD PINCUS
URS/JOHN A. BLUME & ASSOCIATES, ENGINEERS
ANDREW B. CUNNINGHAM
UTAH BUREAU OF RADIATION CONTROL
DARRELL M. WARREN
UTAH GEOLOGICAL AND MINERAL SURVEY
GENEVIEVE ATWOOD
MAGE YONETANI
UTAH SOUTHEASTERN DISTRICT HEALTH DEPARTMENT
ROBERT L. FURLOW
UTAH STATE UNIVERSITY
DEPT OF GEOLOGY
VANDERBILT UNIVERSITY
FRANK L. PARKER
WATTLAB
BOB E. WATT
WBAI-FM
WARREN LIEBOLD
WEST DADE REGIONAL LIBRARY
LOURDES BLANCO LOPEZ
WESTINGHOUSE ELECTRIC CORP
D. NEWBY
WESTINGHOUSE WIPP PROJECT
WESTINGHOUSE ELECTRIC CORPORATION
WISCONSIN DEPT OF LOCAL AFFAIRS AND DEVELOPMENT
DAVID WOODBURY
WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY
MEREDITH E. OSTROM
WOODWARD-CLYDE CONSULTANTS
ASHOK PATWARDHAN
WRIGHT STATE UNIVERSITY
A. A. BAKR
WYOMING GEOLOGICAL SURVEY
DANIEL N. MILLER
YALE UNIVERSITY
BRIAN SKINNER

☆ U.S. GOVERNMENT PRINTING OFFICE: 1983 -659-102/1369

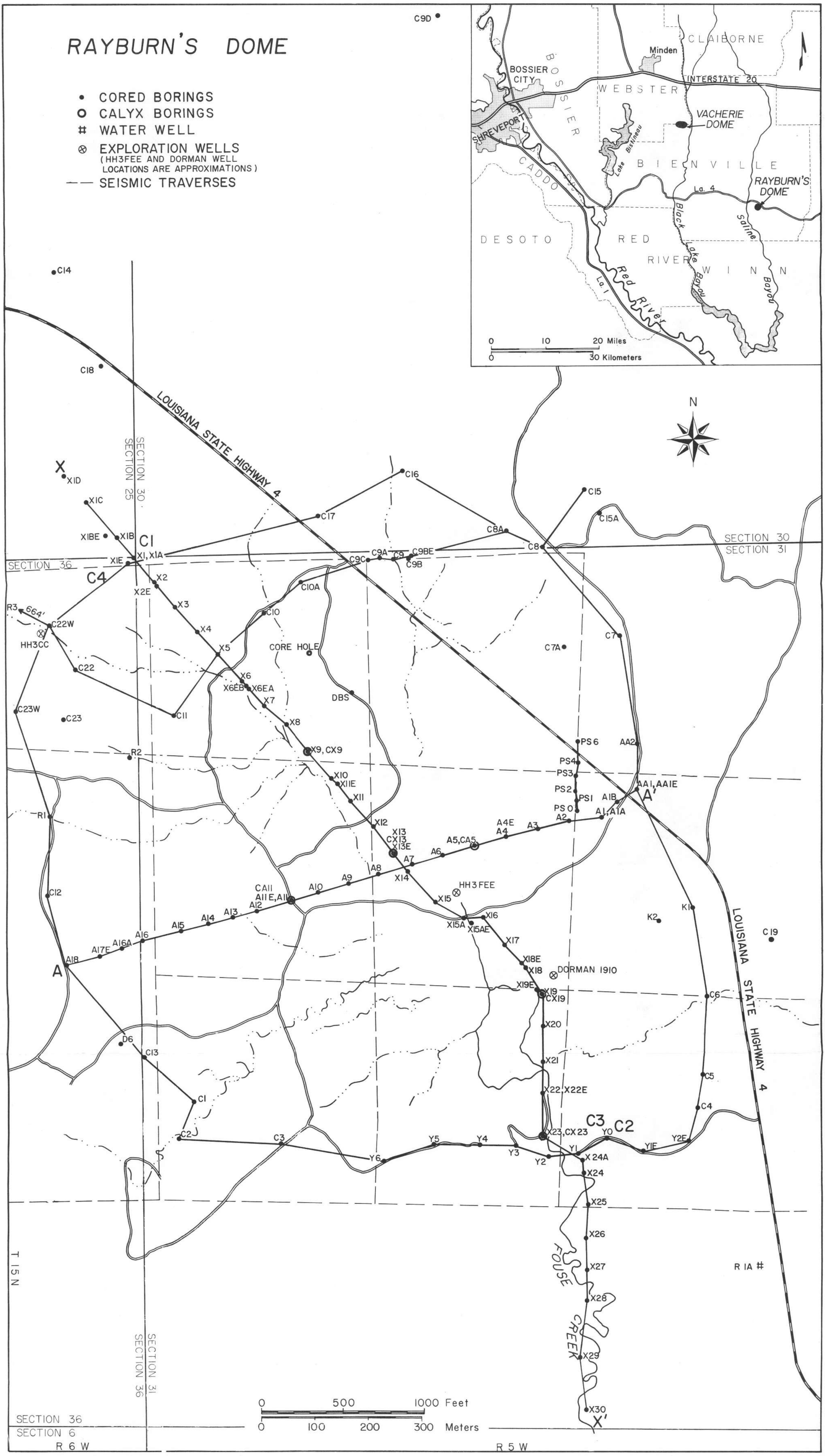

Plate 1. General location map.

Plate 1.

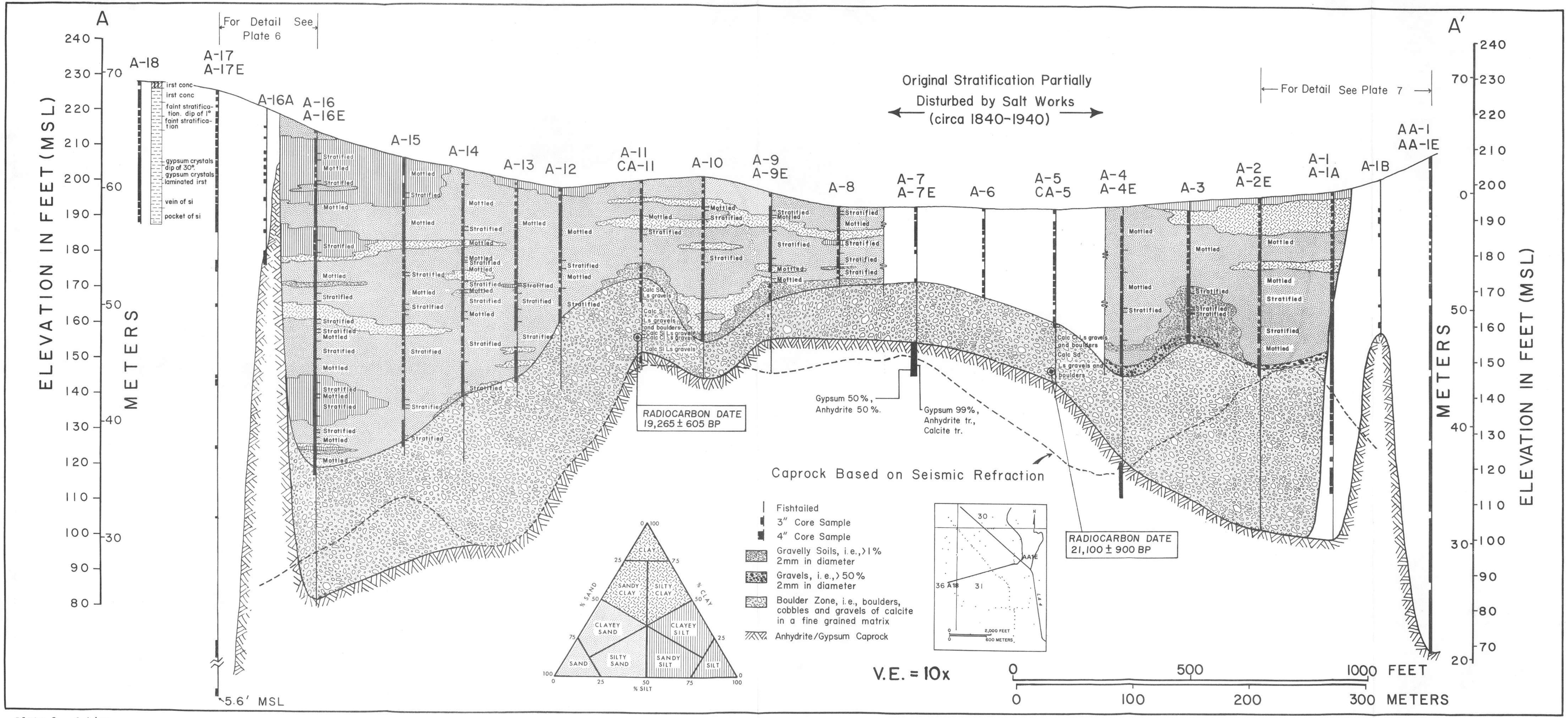

Plate 2. A-Line.

Plate 3. X-Line.

Plate 4. C1-C2 Line.

Plate 4.


C3
C4
ELEVATION IN FEET (MSL)
METERS
670'
560'
670'
YO
Y-1
Y-2
Y-3
Y-4
Y-5
Y-6
C-3
C-2
C-1
C-13
A-18
C-12
R-1
C-23W
C-22W
X-1
X-1E
scattered irst conc.
si layer
organic specks
dip of 45°
dip of 60°
stratified sd
irst conc cross bedding
lignitic
gypsum xls
x-bedding
vein of sd
brecciated appearance
irst conc
stratified irst
x-bedding
Barren
Midway
scattered irst conc
irst conc
pyrite and marcasite conc
dip of 70°
charcoal seam of si
dip of 45°
stratification
dip of 60°
gypsum xls
dip of 30°
pocket of si
pyrite conc
K
Mn staining
indurate sdsi
dip of 20°
dip of 45°
calcareous cl
dip of 30°-45°
abundant pyrite
vein of gypsum
V.E. = 10x
0 200 400 600 800 1000 FEET
0 100 200 300 METERS
※ All dips are apparent.
► PALEONTOLOGICAL ANALYSIS
K CRETACEOUS
▻ BARREN
% SAND
% CLAY
% SILT
Clay
Sandy Clay
Silty Clay
Clayey Sand
Clayey Silt
Sand
Silty Sand
Sandy Silt
Silt
si
sicl
sd
clsi
sdcl
lignite
sdsi
clsd
sisd
shale
limestone
30
36
31
C4
C3
Scale in Miles

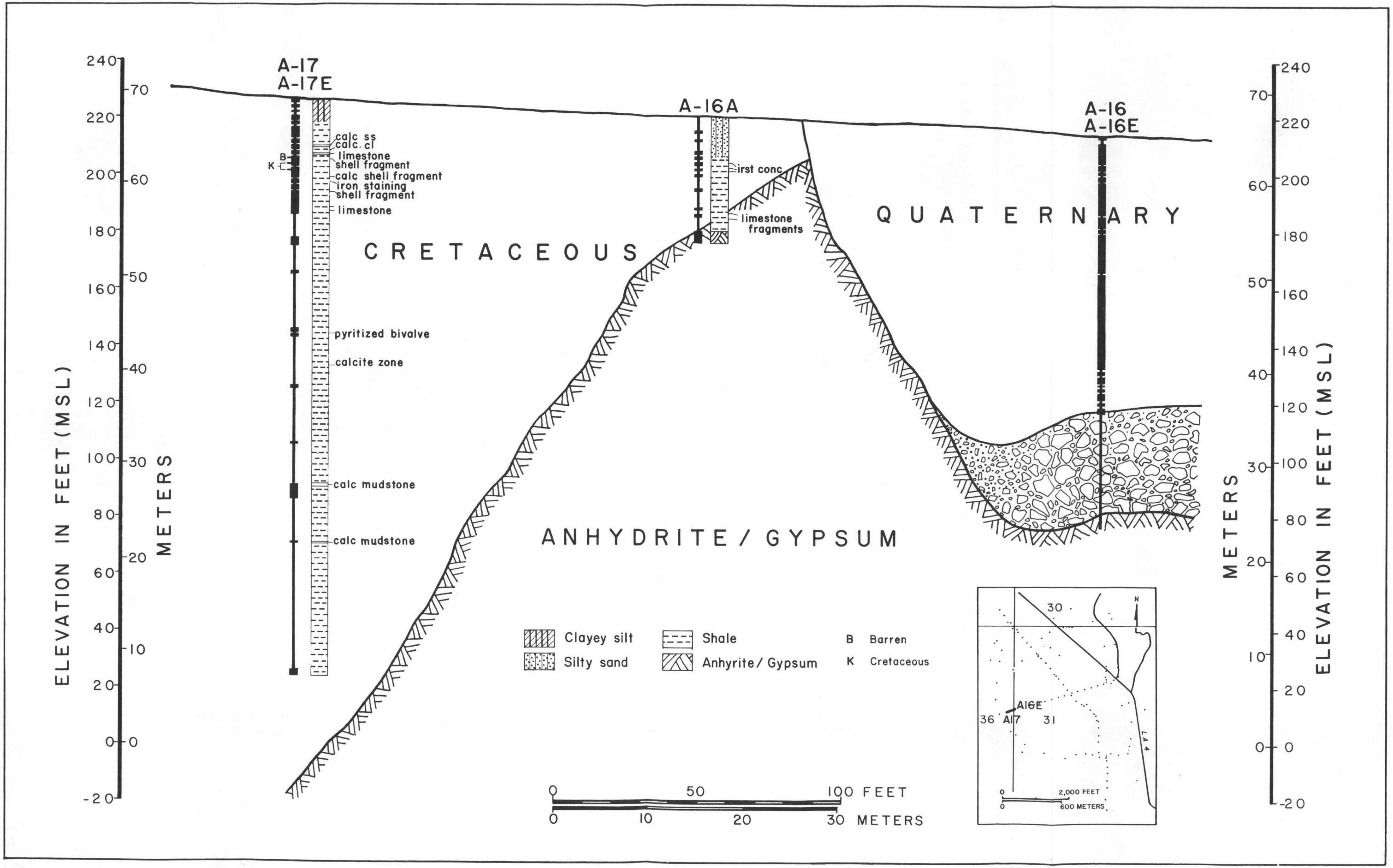

Plate 6. West end of A-Line (true scale).

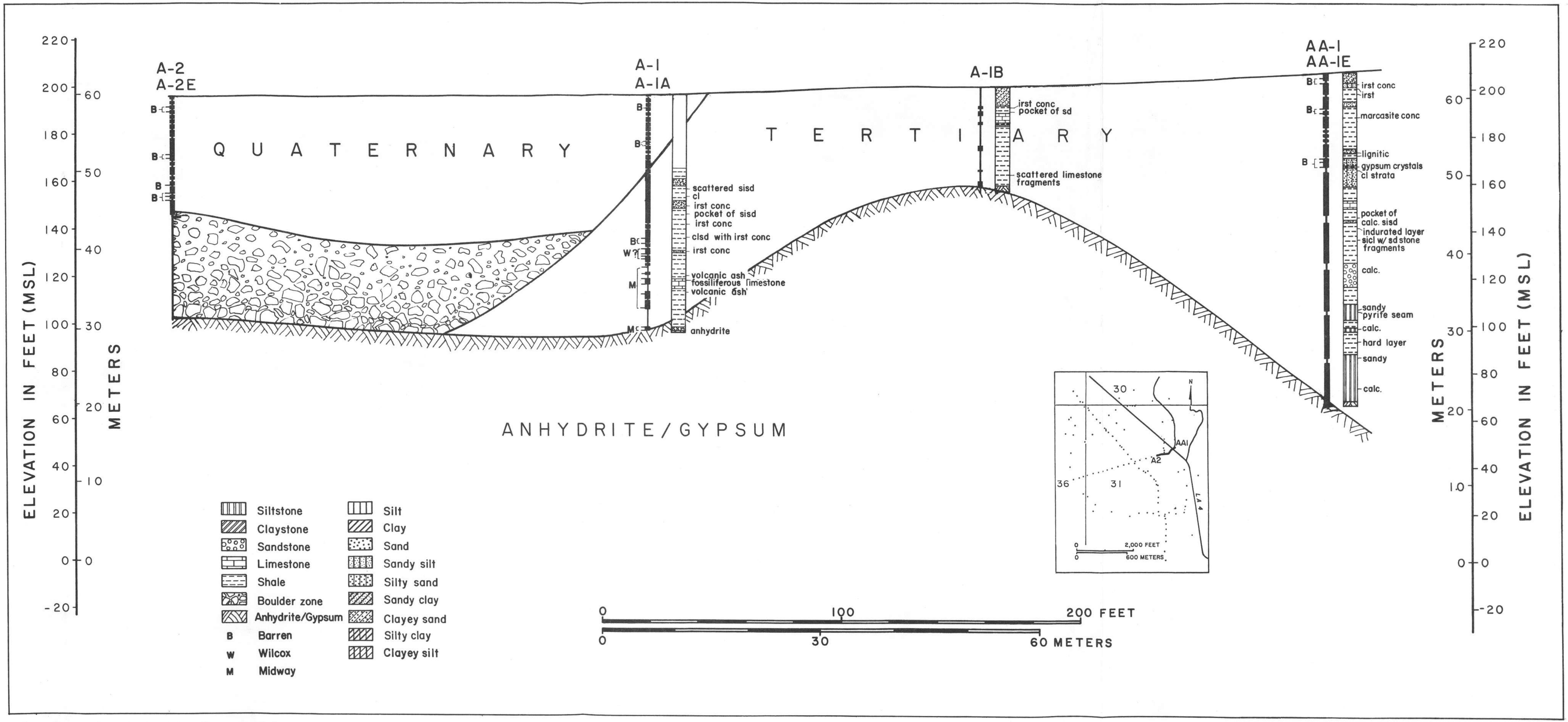

Plate 7. East end of A-Line (true scale).

ate 7.

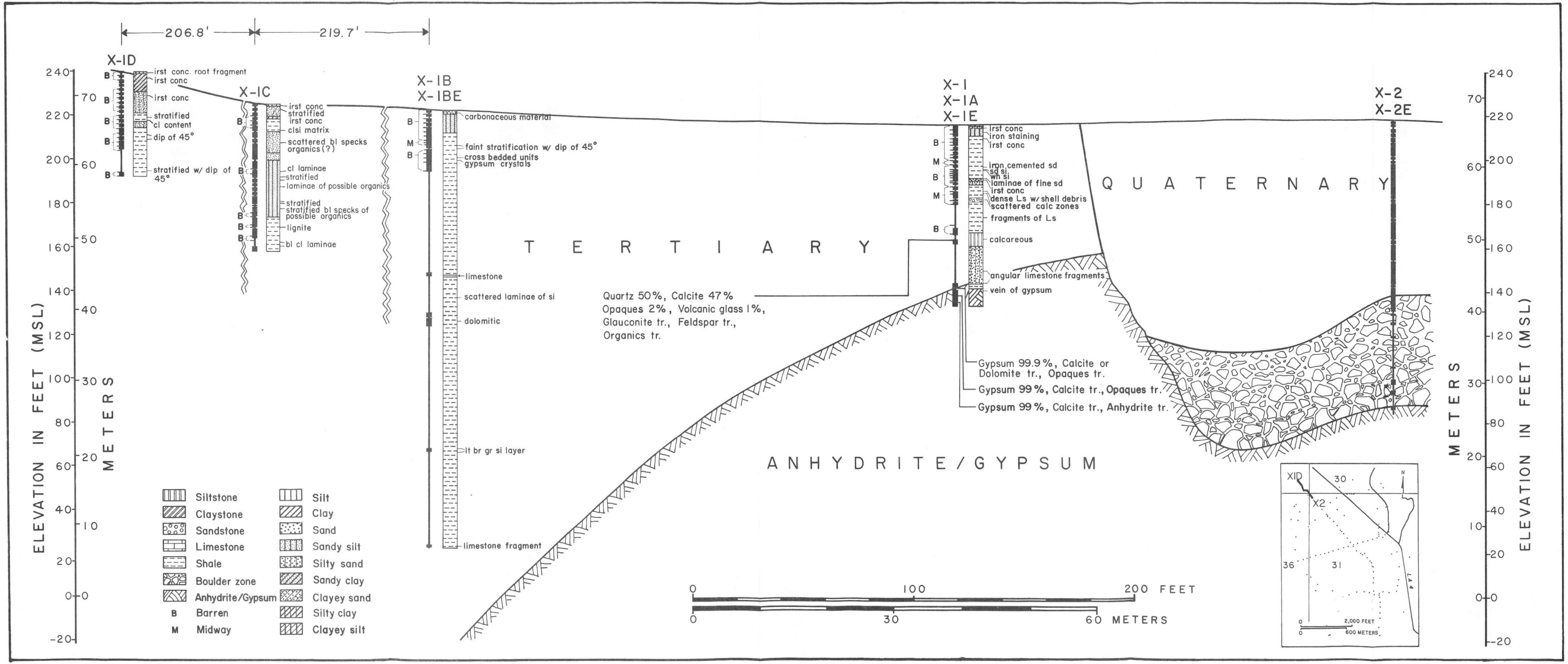

Plate 8. North end of X-Line (true scale).

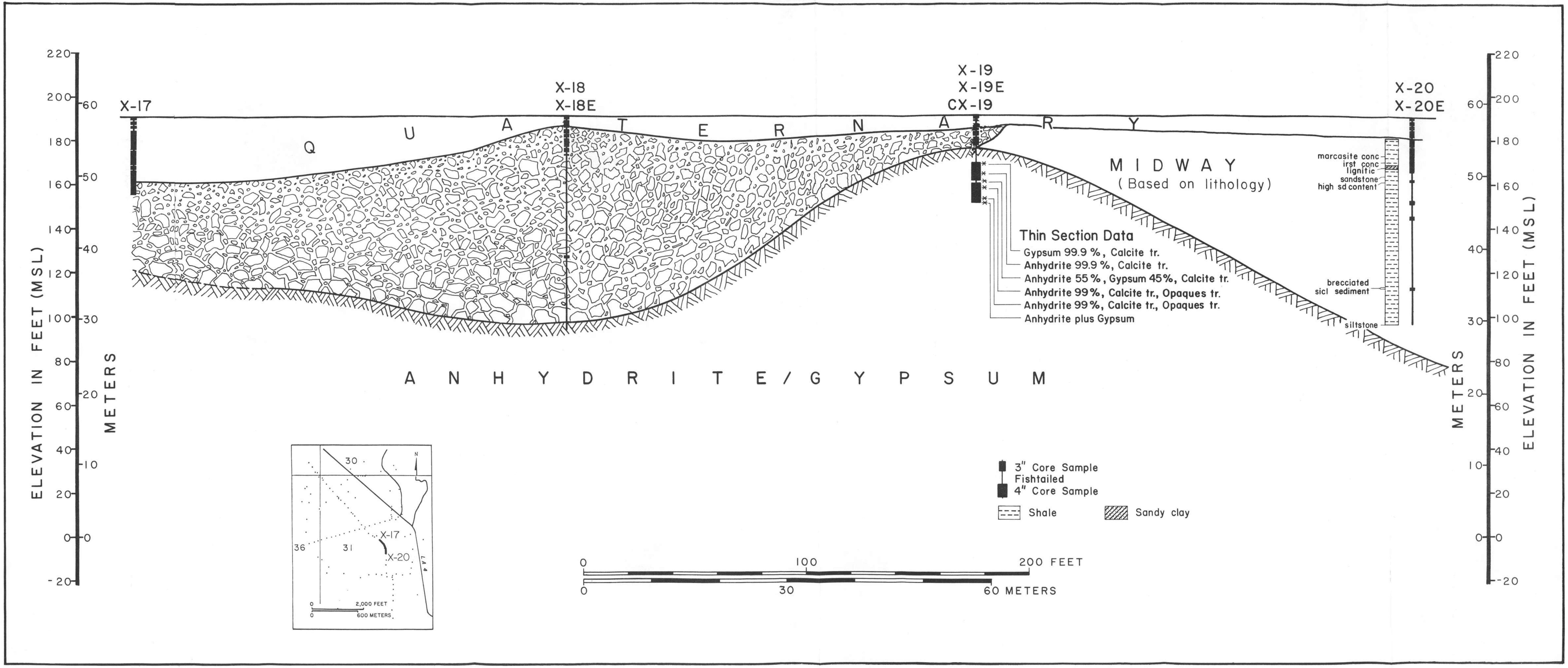

Plate 9. Southern portion of f X-Line (true scale).

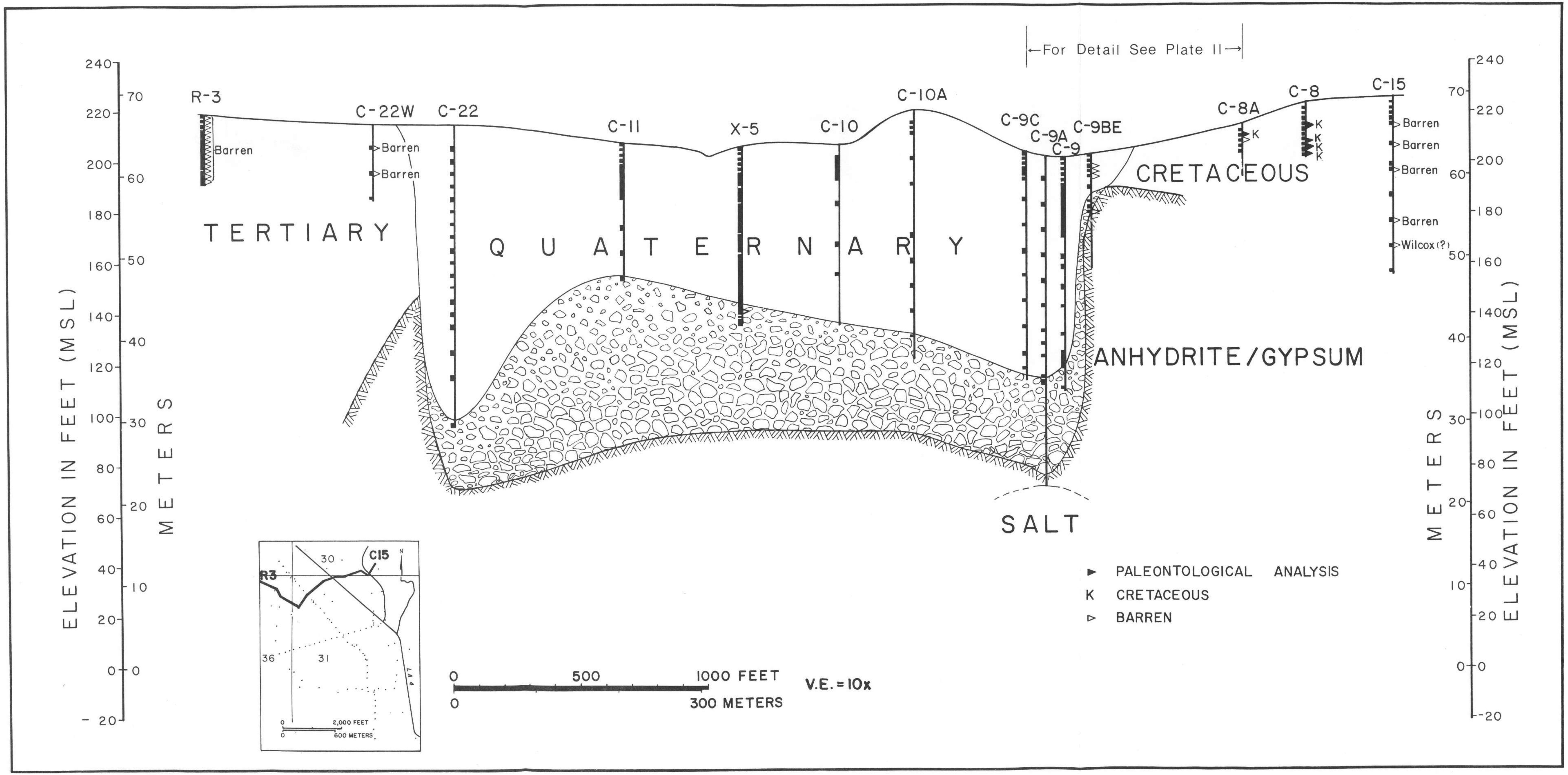

Plate 10. R-3 to C-15 Line.

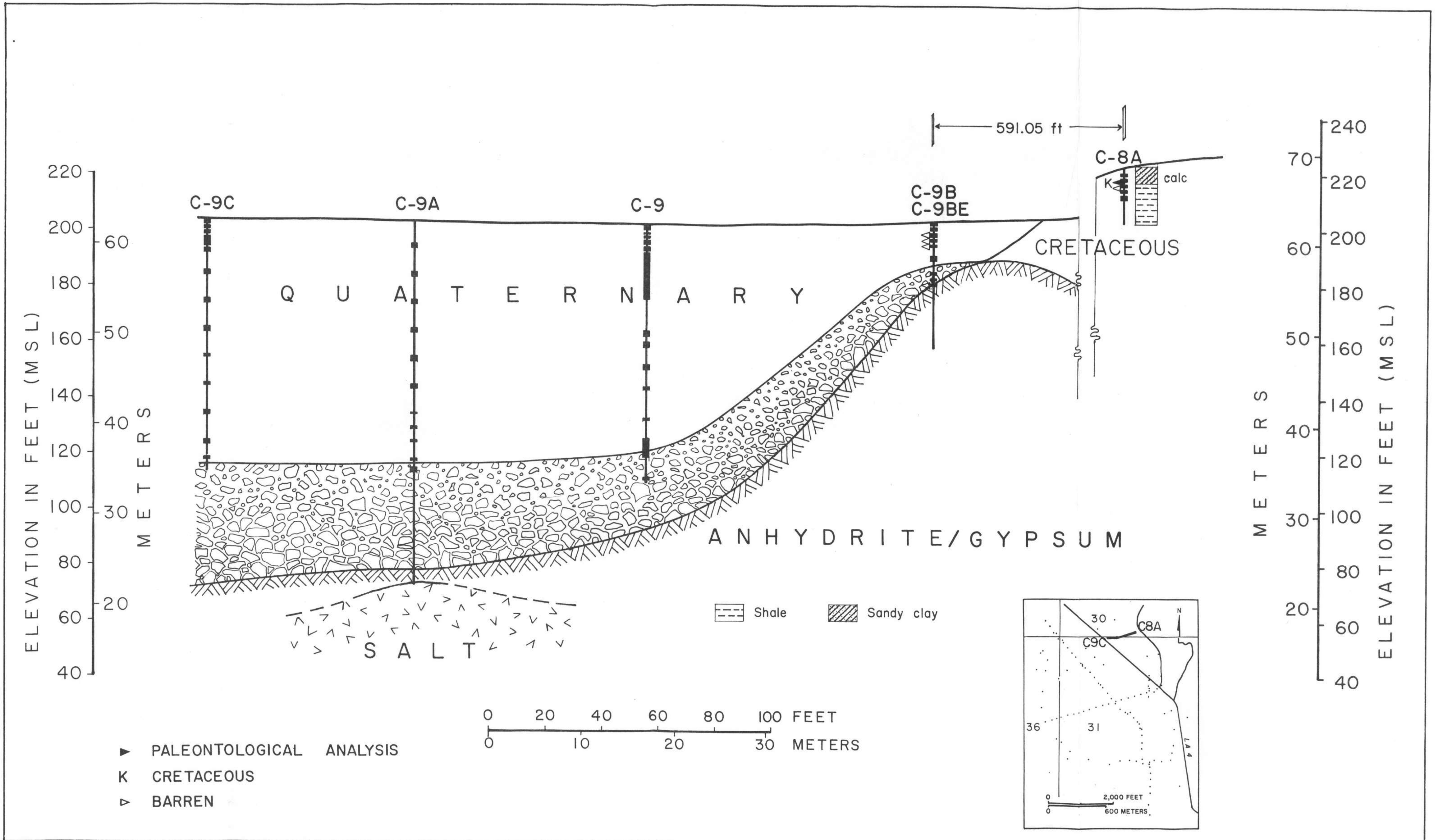

Plate 11. C-9C to C-8A (true scale).

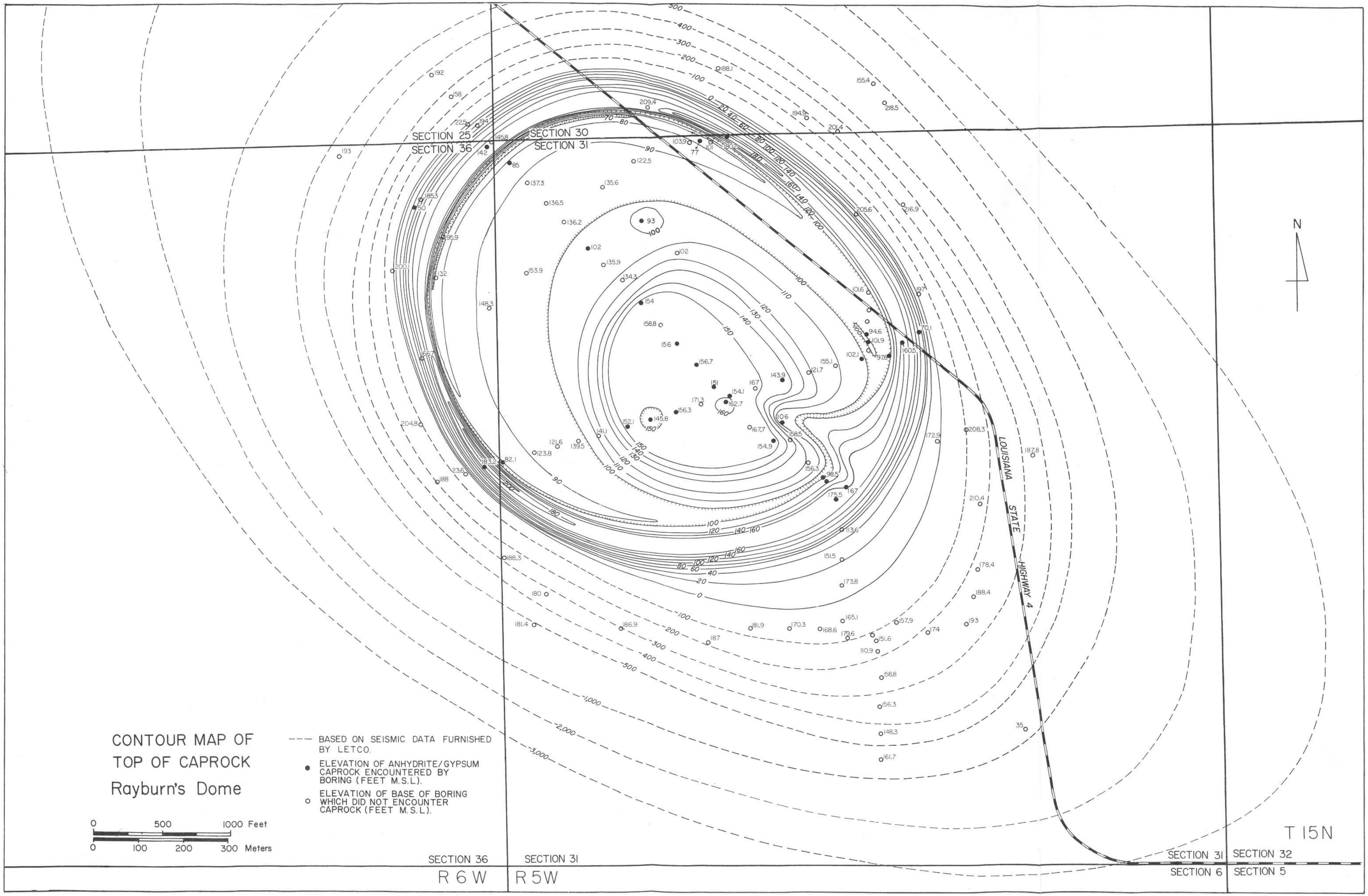

Plate 12. Contour map of top of caprock at Rayburn's dome based principally on borings.

Plate 12.

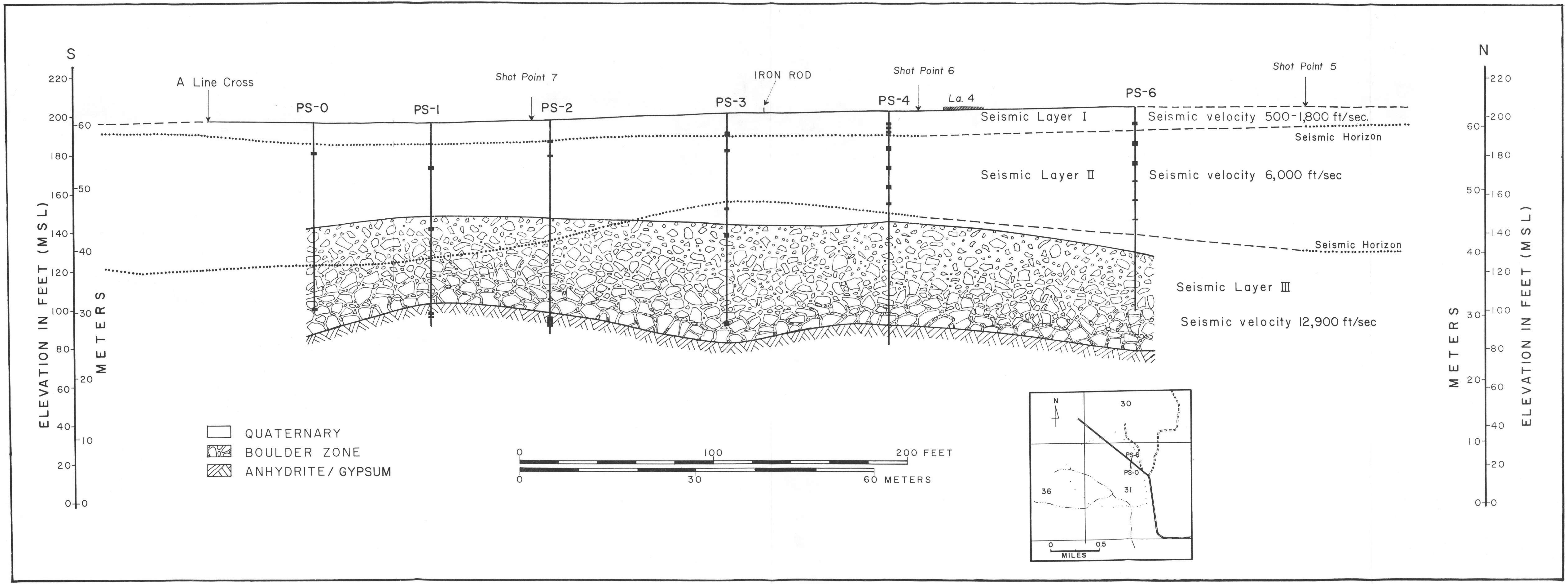

Plate 13. PS-0 to PS-6 Line.

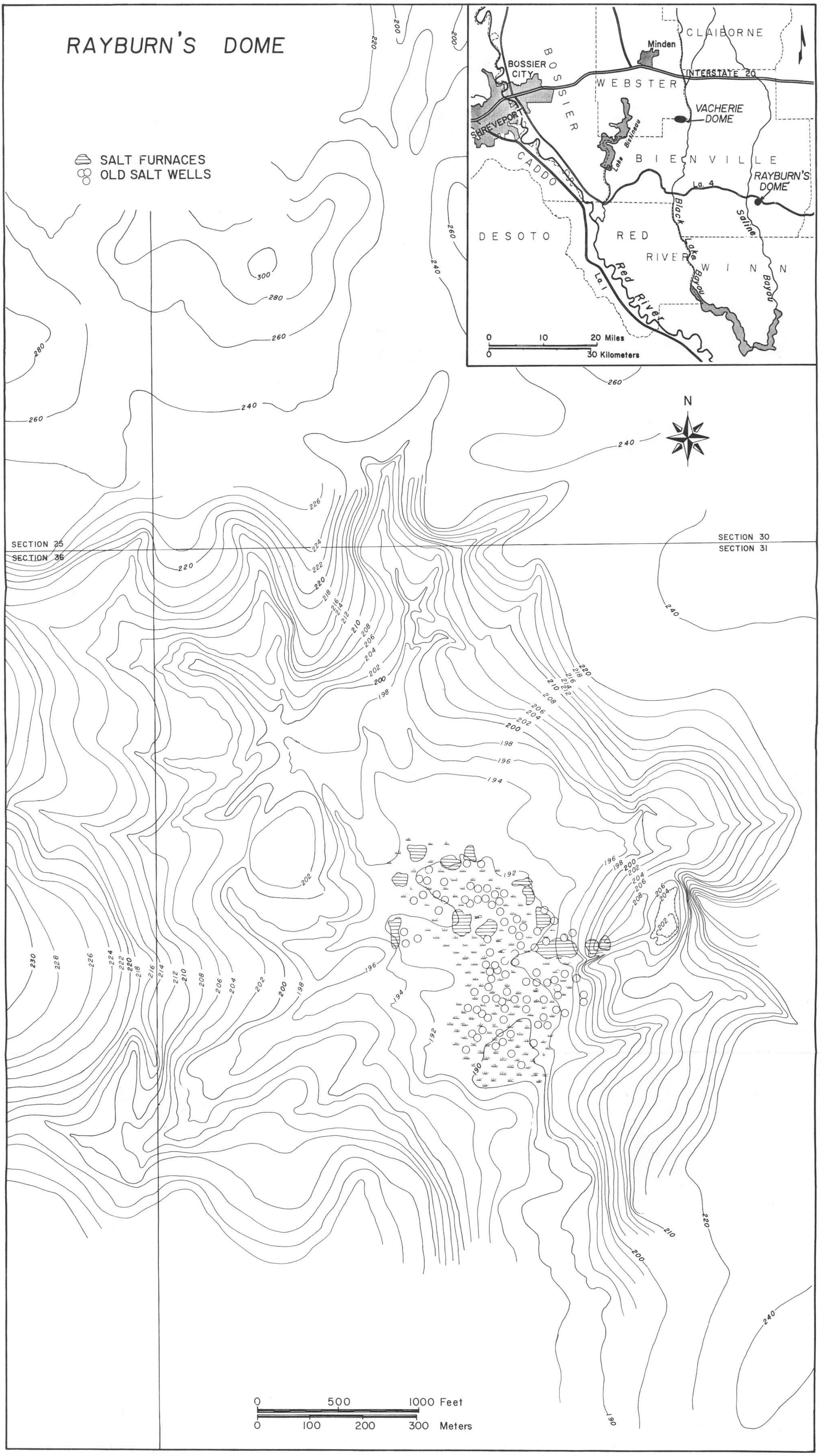

Plate 14. Topographic map of Rayburn's dome area.

Plate 14.

ONWI

Office of Nuclear Waste Isolation

BATTELLE Project Management Division
505 King Avenue
Columbus, Ohio 43201