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Annual Report

A PRELIMINARY ASSESSMENT OF HIGH-RESISTIVITY CAP ROCK SHALE IN THE FRIO FORMATION OF THE TEXAS GULF COAST

by

Robert J. Finley

Prepared for
U.S. Department of Energy
Division of Geothermal Energy

under Contract No. DE-AC08-79ET27111

Bureau of Economic Geology
The University of Texas at Austin
Austin, Texas 78712

W. L. Fisher, Director

May 1982

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title page

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assisted by

Susan L. Hallam and Stephen W. Speer

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ABSTRACT

Mapping of high resistivity cap rock shales in the Frio Formation of the Texas Gulf Coast shows that few areas of thin cap rock occur in the upper Texas Gulf Coast, and more extensive, thicker cap rock occurs in the lower Texas Gulf Coast. Increases in (1) maximum shale resistivity, (2) unstable minerals (volcanic rock fragments, detrital carbonate grains), and (3) authigenic cementation parallel the increase in cap rock from the upper to the lower Gulf Coast. Similarity in cap rock distribution in two major Frio deltaic depocenters is not evident.

Facies analysis of regional cross sections in the lower Texas Gulf Coast and of cross sections in Sarita East field, Kenedy County, shows preferential development of cap rock in the delta-front/slope facies of the Norias delta system. Sand content of the cap rock interval varies from 23 to 41 percent in part of Sarita East field, suggesting that if cap rock is due to authigenic cementation, such sands may act as fluid conduits during mineralization. Cap rock is rarely developed in the shale-rich prodelta and distal delta-front facies.

High resistivity cap rock shales have been considered a result of authigenic calcite cementation, but definite evidence for this origin is lacking. Preliminary mineralogic analyses of well cuttings have not yielded satisfactory results. Analysis of core through cap rock and non-cap rock intervals will be required to determine the mineralogic variability within each interval and to accurately assess any mineralogic control of the high resistivity log response.

INTRODUCTION

Present research efforts by the Bureau of Economic Geology to understand sandstone consolidation histories are focused on the mineralogy and chemistry of shales, especially high resistivity shales known as cap rock. The nature of cap rock, its distribution, and its relationship to the occurrence of deep secondary porosity are being evaluated. One aspect of this work has focused on the distribution of cap rock within the Frio Formation and its relationship to the genetic stratigraphy of deltaic and interdeltaic sedimentary environments. Regional mapping of cap rock intervals and peak resistivity was completed for the Frio Formation within the onshore Tertiary stratigraphic section in Texas. Cap rock occurrence was then related to stratigraphic facies by utilizing a set of dip-oriented regional cross sections (Dodge and Posey, 1981) and through more detailed study of Sarita East field, Kenedy County, Texas.

The Frio Formation

The Oligocene Frio Formation is one of the thickest progradational wedges within the Tertiary sedimentary section of the northwest Gulf of Mexico (Bebout and others, 1978). It is an important petroleum reservoir and has produced more than 16 billion barrels (oil and equivalent gas) of hydrocarbons (Galloway and others, in press). Furthermore, the Frio Formation has been extensively investigated and tested as part of the assessment of geopressured-geothermal energy resources (Bebout and others, 1978; Loucks and others, 1979; and Gregory and others, 1980). As part of the latter studies, detailed investigations of reservoir quality revealed complex diagenetic histories of Tertiary sandstones including the Frio Formation. Multiple episodes of precipitation and leaching of authigenic cements were noted, leading to a variable distribution of secondary porosity (Loucks and others, 1977; Loucks and others, 1980; Milliken and others, 1981).

Within the Frio Formation, reservoir quality depends on relationships among depositional environment, mineralogical composition, and the prior compaction, cementation, and leaching. Deeper Frio reservoirs display secondary porosity resulting from leaching of feldspars, volcanic rock fragments, and previous calcite cements. Secondary porosity is poorly developed in the lower Texas Gulf Coast, but improves toward the upper Texas Gulf Coast, in part because the mineralogy of the sandstones shifts toward a more quartzose and chemically stable assemblage. Also, fewer carbonate rock fragments are present in the Frio of the upper Texas Gulf Coast compared with the lower coastal area, where they are thought to act as nuclei for carbonate cementation (Lindquist, 1977; Loucks and others, 1977).

Cap Rock and Reservoir Quality

Because multiple episodes of calcite cementation and leaching are evident from the diagenetic history of the Frio, the search for indicators of good reservoir quality becomes significant. Any possible relationship between cap rock development and secondary porosity may lead to a useful indicator of reservoir conditions at greater depth (Kaiser and others, 1981). Cap rock shales are thought to be calcareous (Fertl, 1976; Magara, 1981), in which case carbonate minerals may be derived from leaching of cements at depth. It might then be expected that an inverse trend should exist between the development of cap rock and the development of secondary porosity. However a direct relationship between these parameters may exist if thick cap rock correlates with extensive authigenic cementation and, perhaps, an unstable mineral assemblage, as in the Frio Formation of the lower Gulf Coast. The latter situation appears to be true, at least in Texas.

Furthermore, detailed petrographic and geochemical studies of cap rock are incomplete and thus far have not positively identified increased quantities of authigenic carbonate minerals in the cap rock shale intervals under study

(Kaiser and others, 1981; K. L. Milliken, personal communication, 1981). This study shows that cap rock is best developed in the lower Texas Gulf Coast and that mineralogic analyses would best be shifted to that area, for example, to Kenedy and Kleberg Counties. Also, cap rock in the lower Texas Gulf Coast seems to be preferentially associated with the lowermost sands of a Frio deltaic system, thereby indicating that sand strata may be important conduits in fluid transport related to cap rock development.

CAP ROCK DELINEATION

In the assessment of entrained methane in geopressured reservoirs of the Gulf Coast (Gregory and others, 1980), formation fluid pressures were derived from shale resistivity data using the method of Hottmann and Johnson (1965). The amplified short normal resistivity curves from induction electrical logs were utilized to plot shale resistivity as a function of depth. Normal compaction curves were fitted by a least squares regression method, and a composite normal compaction curve was generated for most counties of the Texas Gulf Coast (Gregory and others, 1980). Cap rock is well to poorly defined as an interval of shale resistivity in excess of that predicted by the normal compaction curve (Fertl, 1976; Gregory and others, 1980).

Cap rock was mapped using a regional data base of approximately 350 wells for which shale resistivity versus depth had been hand-plotted by Gregory and others (1980). Continuous, digitized plots of shale resistivity were not useful for cap rock delineation because tight, silty or sandy shale cannot be differentiated from pure shale in presently available plotting routines. A typical shale resistivity plot includes the normal compaction curve, data on mud weight from the geophysical log, and calculated pressure values (fig. 1). Criteria were established for the recognition of cap rock from shale resistivity plots;

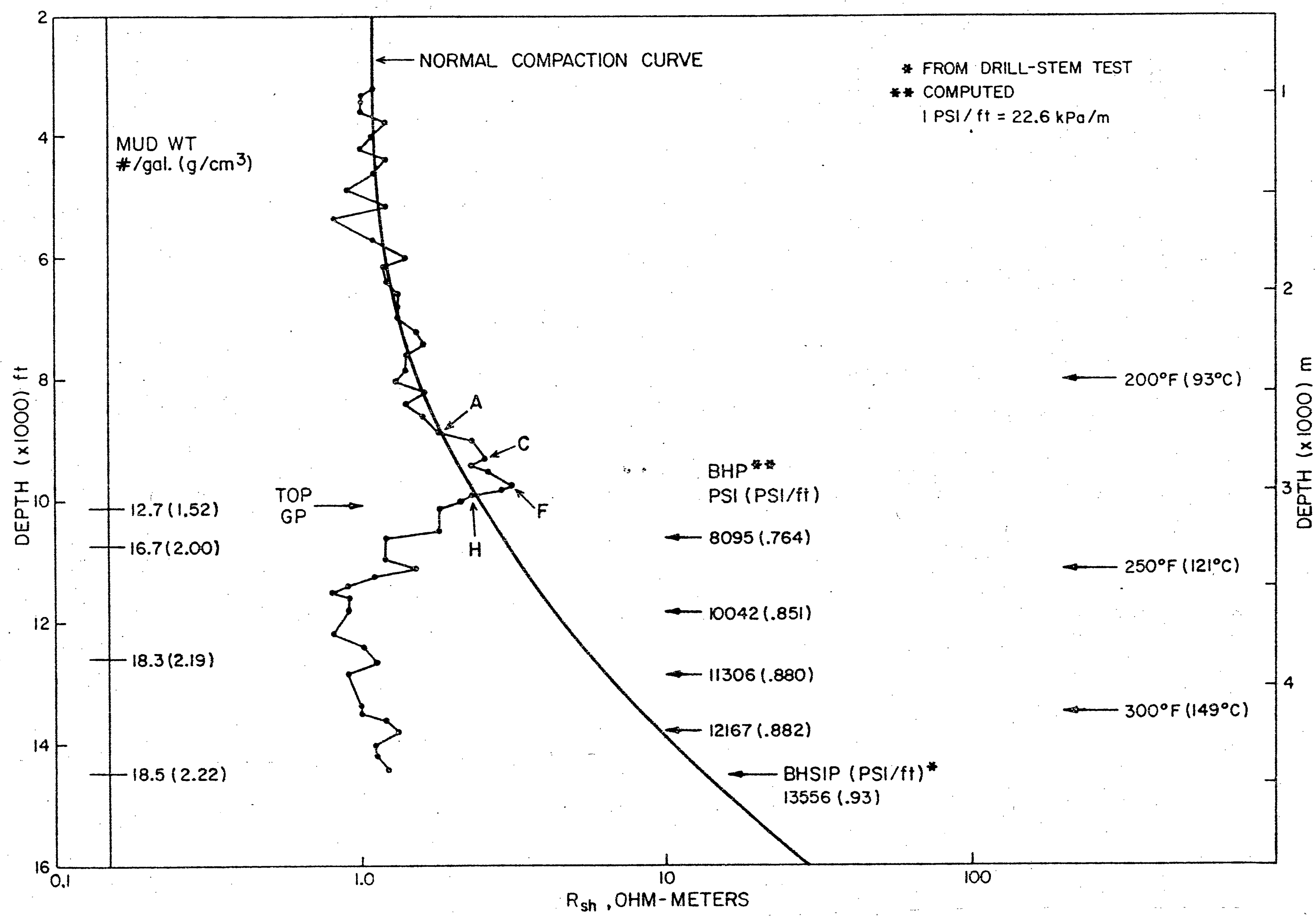

Figure 1. Shale resistivity plot for the Humble Oil and Refining Co., B-23 S. K. East well in Kenedy County, Texas.

anomalous plots were checked against the well log (table 1). That part of the shale resistivity plot representing the Frio Formation was determined from stratigraphic cross sections constructed by Dodge and Posey (1981) and modified by Galloway and others (in press).

Table 1. Criteria for defining cap rock; from shale resistivity plots derived from geophysical well logs.

(1) Shale intervals selected for reading of resistivity must show an SP response as close to baseline as possible and generally be 30 ft (9 m) thick. Thinner intervals may be utilized if necessary; resistivity is read from the amplified short normal trace of the induction electrical log.

(2) The distribution of shale resistivity vs. depth must be compared to the normal compaction curve based on resistivity of hydropressured shales in a given county (see Gregory and Backus, 1979).

(3) Two or more data points, which exceed the normal compaction curve on the shale resistivity plot, are considered necessary to define a cap rock interval. Single high values may be noted separately.

(4) Where irregular low amplitude SP deflection occurs within a resistive interval, a tight, silty, or sandy shale (or hydrocarbons) may be indicated. Such a zone will not be considered cap rock.

Each data point on figure 1 represents a shale interval generally at least 30 ft thick, although thinner intervals were utilized when necessary. Data points A through H define a cap rock interval approximately 800 ft (240 m) thick. This depth zone, as will be shown using data from Sarita East field, is not entirely shale and therefore will be termed the cap rock interval in this study. Sand content of the cap rock interval in Sarita East field, Kenedy County, will be illustrated.

REGIONAL CAP ROCK DISTRIBUTION

Thickness

Mapping of the cap rock interval within the Frio Formation shows few, small areas of cap rock in the upper and middle Texas Gulf Coast and larger areas and greater thicknesses in the lower Texas Gulf Coast (fig. 2). In the upper coastal region, concentrations of cap rock are found in scattered wells in Brazoria and Galveston Counties and in Jefferson County. However, only four wells have a cap rock interval more than 600 ft (180 m), and only one well contains as much as 900 ft (275 m). The Galveston/Brazoria County area and to a lesser extent the Jefferson County area show some spatially contiguous cap rock development in Miocene strata downdip of the Frio occurrences, but these are not included in figure 2.

In the lower Texas Gulf Coast, areas of cap rock are present where many wells contain intervals more than 700 ft (210 m) thick and some wells contain intervals of 1,100 to 1,400 ft (340 to 430 m) in thickness. The greatest areal extents of cap rock are in Kleberg and Kenedy Counties, Hidalgo County, and a coast-parallel trend in Cameron and southeastern Willacy Counties (fig. 2). No zero isopach is shown on figure 2 because wells outside the 300 ft (90 m) isopach may contain single intervals of high shale resistivity, and because interpretation of the shale resistivity plot is increasingly subjective in cases of poor cap rock development.

Peak Resistivity

Where Frio cap rock was found, the maximum resistivity occurs in the cap rock interval (fig. 1, point F). Even without cap rock development, resistivities within an individual well reach a maximum at the lowest point along the

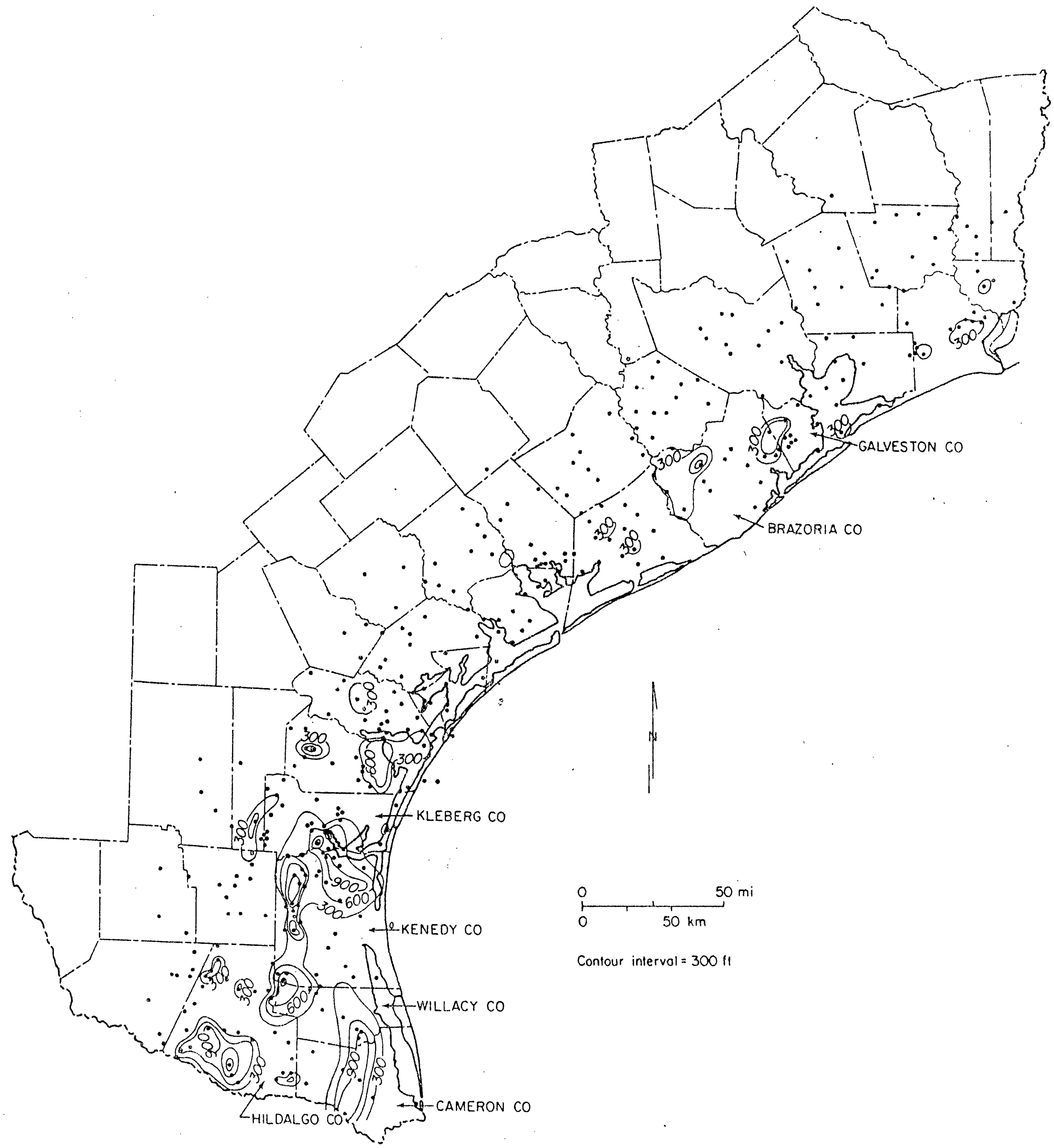

Figure 2. Thickness of cap rock intervals within the Frio Formation of the Texas Gulf Coast.

normal compaction curve just before encountering lower resistivities of undercompacted shales within the geopressured zone, if such a zone is present in a given well. The upper and middle Texas Gulf Coast are characterized by maximum Frio shale resistivities less than 2.0 ohm-meters except in the vicinity of limited cap rock development (fig. 3). The coastwide trend is one of increasing maximum shale resistivity from north to south, peak values being approximately 6.0 ohm-meters in wells both with and without cap rock in the lower Texas Gulf Coast (fig. 3).

The correlation of this trend having reduced sandstone reservoir quality owing to cementation and having more chemically unstable sandstone mineral assemblages (Loucks and others, 1977) suggests the possibility that mineralogic differences, including greater content of authigenically precipitated minerals, are responsible for the shale resistivity trend. However, Loucks and others (1980) found insufficient evidence, based on chemical analysis of shales in Brazoria and Hidalgo Counties, to determine whether or not the shales are an open chemical system with respect to associated sandstones. Trends in metal oxide content were most suggestive of an open pelitic system for CaO and K_2O, but data were insufficient to permit quantitative mass balance equations for sandstone-shale systems. When these data become available, potential mineralogic controls on shale resistivity may become more evident.

Cap Rock - Facies Relationships

The Frio Formation consists of four major depositional systems in the Texas Gulf Coast: (1) the Houston delta system of the upper coast, (2) a barrier-strandplain system of the middle coast, (3) a coastal lake/streamplain system of the middle coast, and (4) the Norias delta system of the lower coast (Galloway and others, in press). Six dip-oriented cross sections through the Tertiary

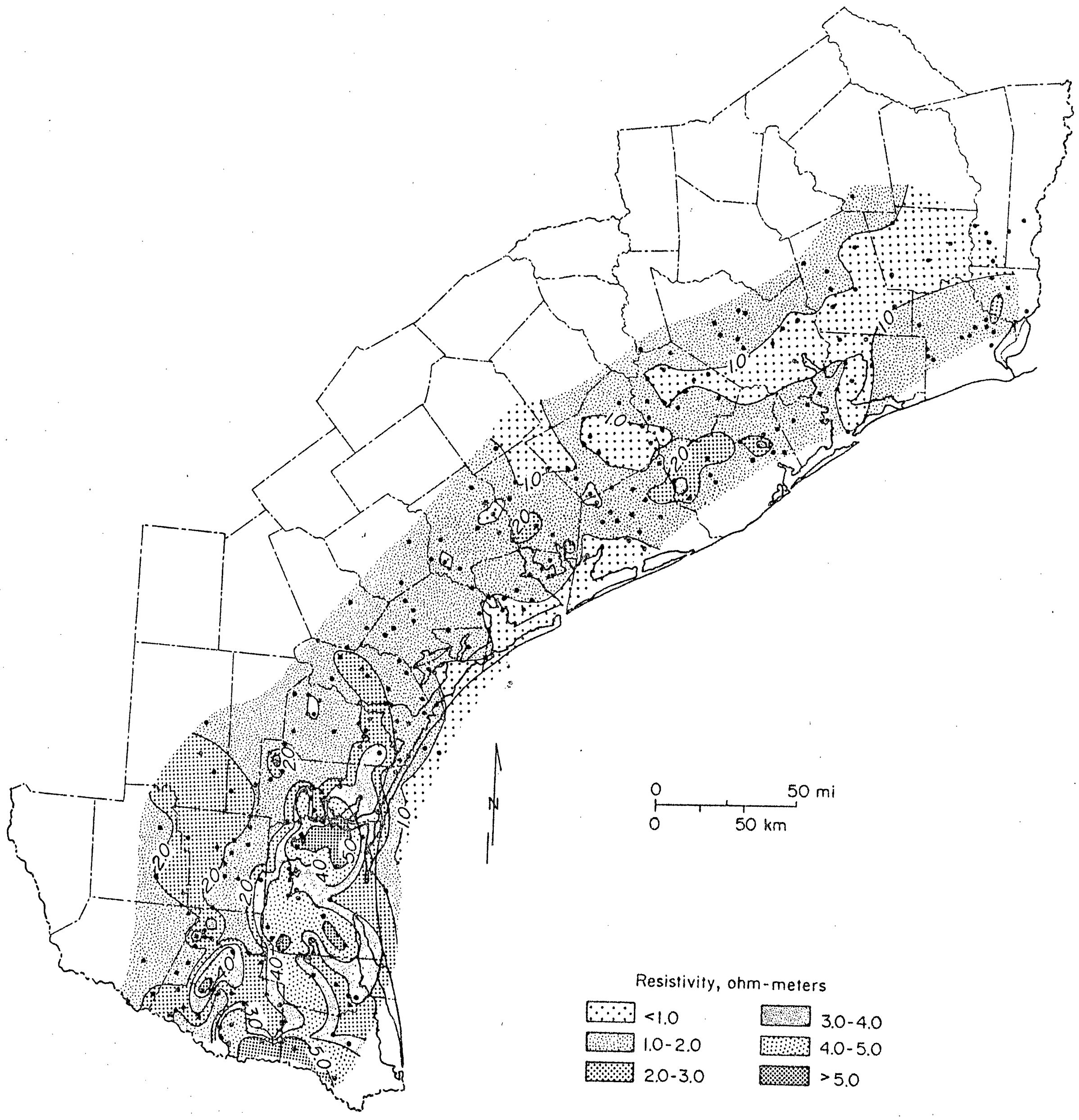

Figure 3. Maximum shale resistivity within the Frio Formation of the Texas Gulf Coast, including cap rock intervals.

section of the lower coast were selected for facies analysis to determine the relationship between cap rock and depositional environments (fig. 4).

Facies interpretations of the Frio Formation shown on sections 19-21 and 23-24 were prepared for this study on the basis of spontaneous potential (SP) and resistivity log patterns using principles outlined by Fisher (1969) and Fisher and others (1969). Galloway and others (in press) prepared a facies interpretation of section 22. These cross sections traverse the Norias delta system, which is the main Frio depocenter in the South Texas Coastal Plain. Component facies of this deltaic system, which resulted in progradation of the continental margin more than 60 mi (95 km) basinward, include delta plain, delta front, prodelta and slope, and reworked delta margin (Galloway and others, in press).

Section 19, which is typical of the 6 cross sections, illustrates the relative position of depositional environments, and shows a major offlapping episode of delta-front progradation overlain by mostly aggradational fluvial and delta-plain facies (fig. 5). Although the prodelta and distal delta-front facies contain the most shale, cap rock is primarily developed at the base of the sand-rich delta-front slope environment. This trend is maintained within the Frio Formation across the entire lower Texas Gulf Coast, wherein 66 percent of a total of 18,800 ft (5,740 m) of cap rock interval occurs within the delta-front slope facies (table 2). The preferential occurrence of cap rock within the delta-front facies suggests a need to examine an area containing abundant cap rock. Such an area was defined in Kenedy and Kleberg Counties (fig. 4). It includes wells sampled for mineral-formation water equilibria studies and local cross sections prepared in the course of defining prospective test areas for entrained methane resources (Weise and others, 1980).

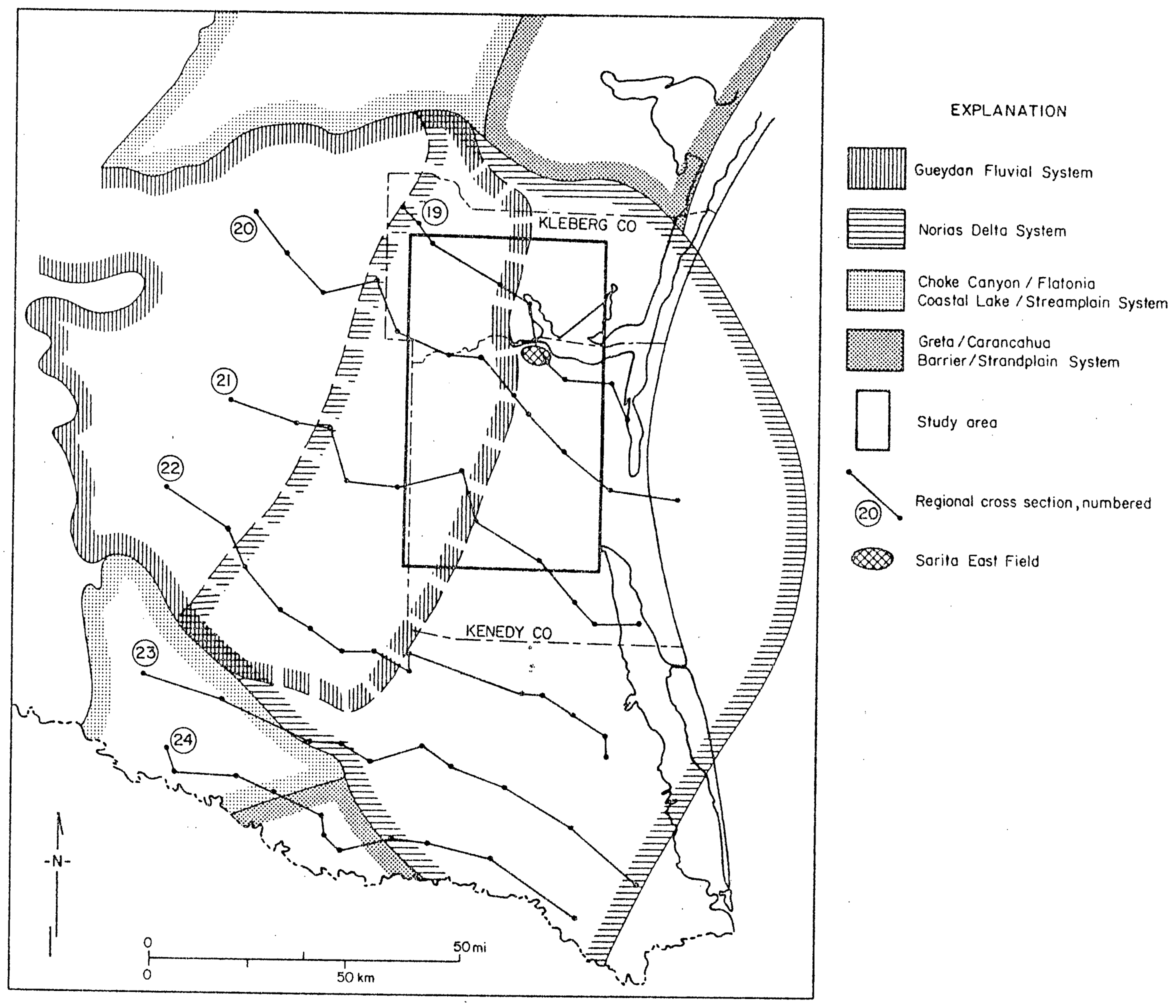

Figure 4. Major depositional systems of the Frio Formation in the lower Texas Gulf Coast, and location of regional cross sections of an area of more detailed study and of Sarita East field.

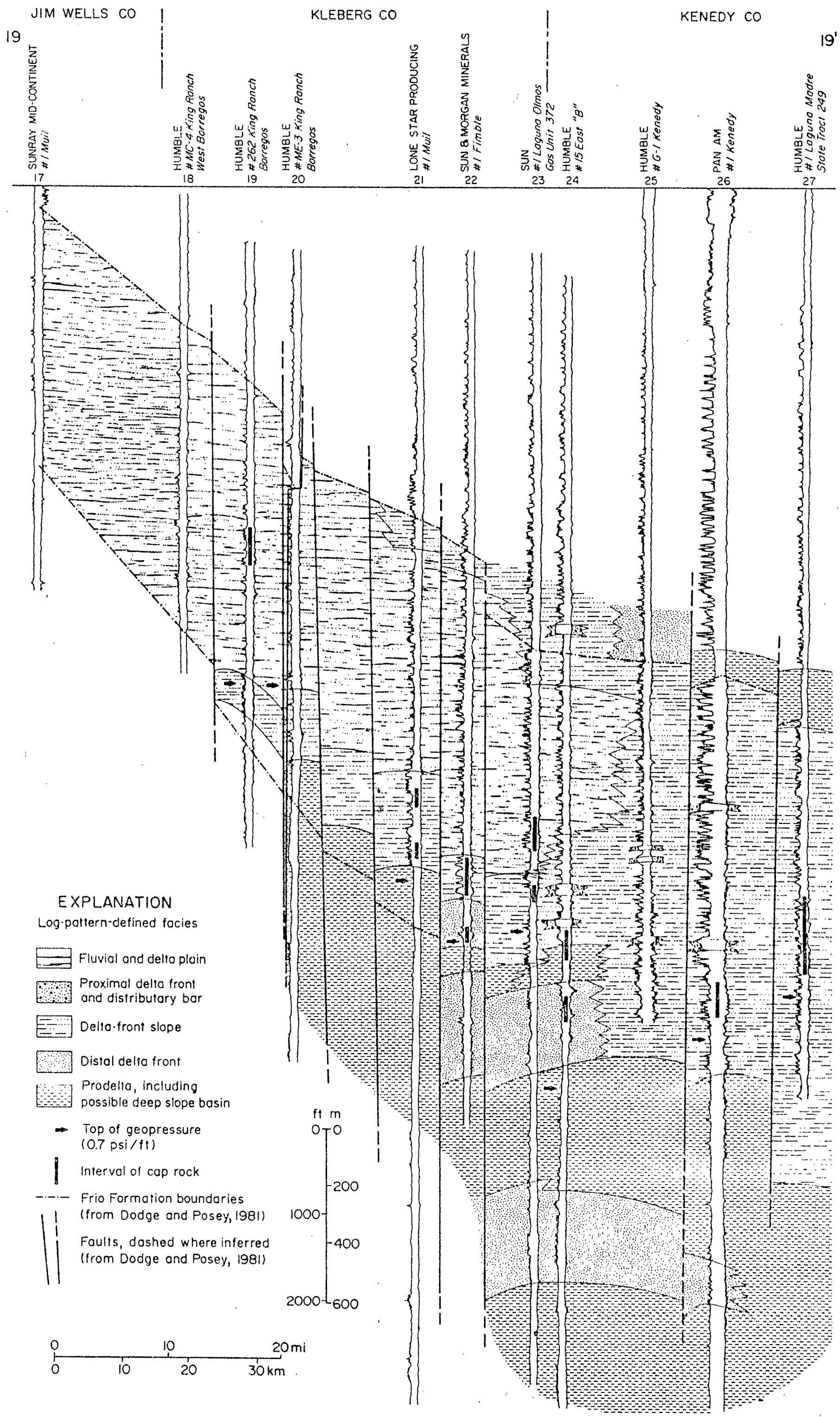

Figure 5. Facies interpretation of part of regional cross section 19, modified from Dodge and Posey (1981).

Table 2. Summary of cap rock intervals by depositional environment for regional dip sections 19-24.

thickness	prodelta	distal delta front	delta front slope	proximal delta front and distributary bar	fluvial and delta plain
ft	0	2,300	12,350	3,050	1,100
percent	0	12.2	65.7	16.2	5.9

KENEDY-KLEBERG COUNTY STUDY AREA

Cap Rock Distribution

The study area straddles the downdip limits of the fluvial system feeding the Norias delta, and includes extensive cap rock (fig. 2). Drilling for deep Frio gas to depths of 12,000-17,000 ft (3,700-5,200 m) provides excellent control on Frio depositional environments, from the shelf edge to the delta plain. Within the study area, deep well control is available for several fields including Sarita East (fig. 4), and initial work has centered on this field. Facies interpretations of Sarita East field were made for part of a cross section by Weise and others (1981) (B-B', fig. 6), and for section A-A' (fig. 6). These cross sections are tied to regional section 19 at well 24, which shows Sarita East located near the regional downdip limit of fluvial and delta plain sedimentation. Each cross section shows a deep, minor episode of prograding delta-front slope in the Lower Frio overlain by a major episode of progradation in the Middle and Upper Frio (figs. 7 and 8). Deep wells reaching the cap rock interval are lacking immediately updip of the field but are present to the northeast (fig. 6).

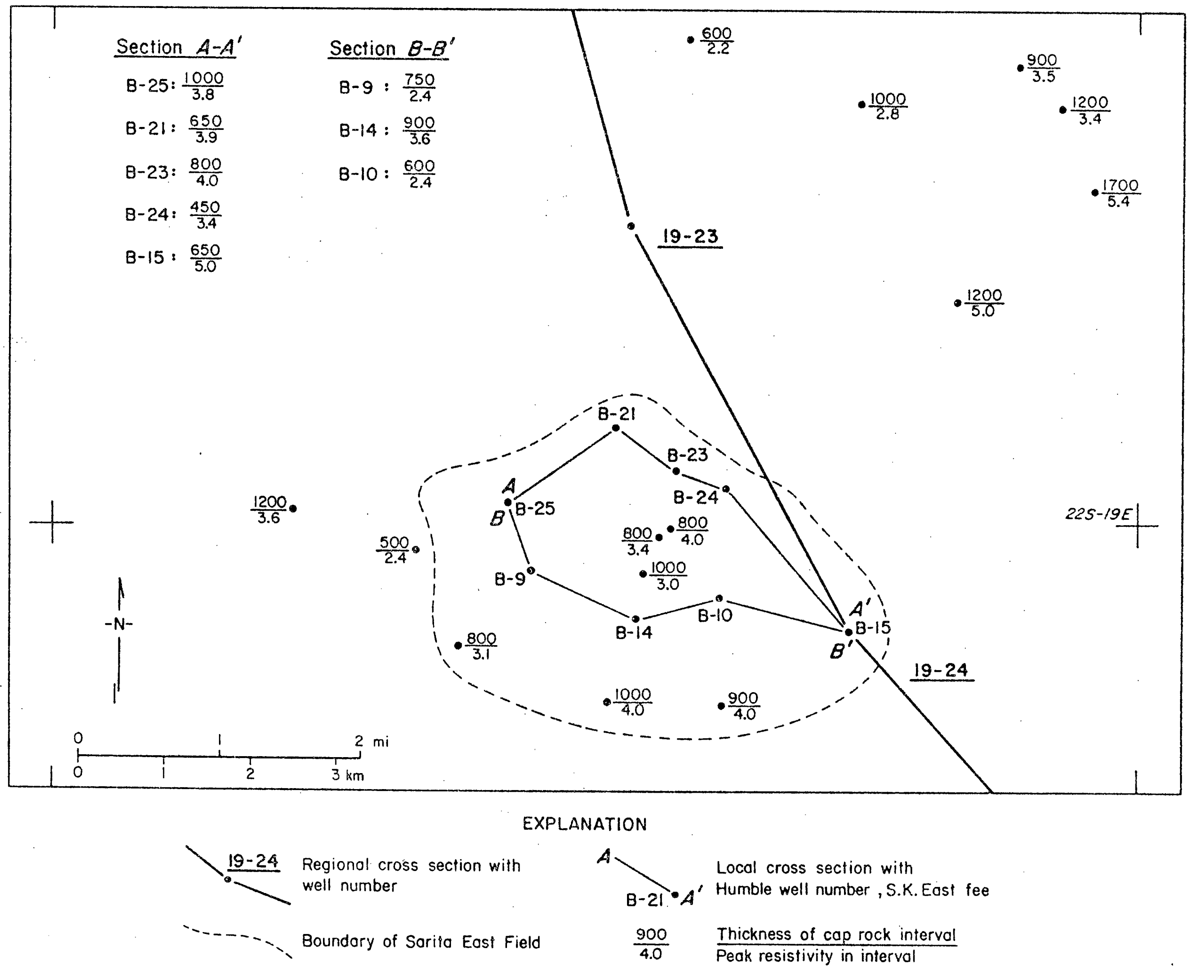

Figure 6. Index map of Sarita East field and vicinity with thickness and resistivity of cap rock intervals.

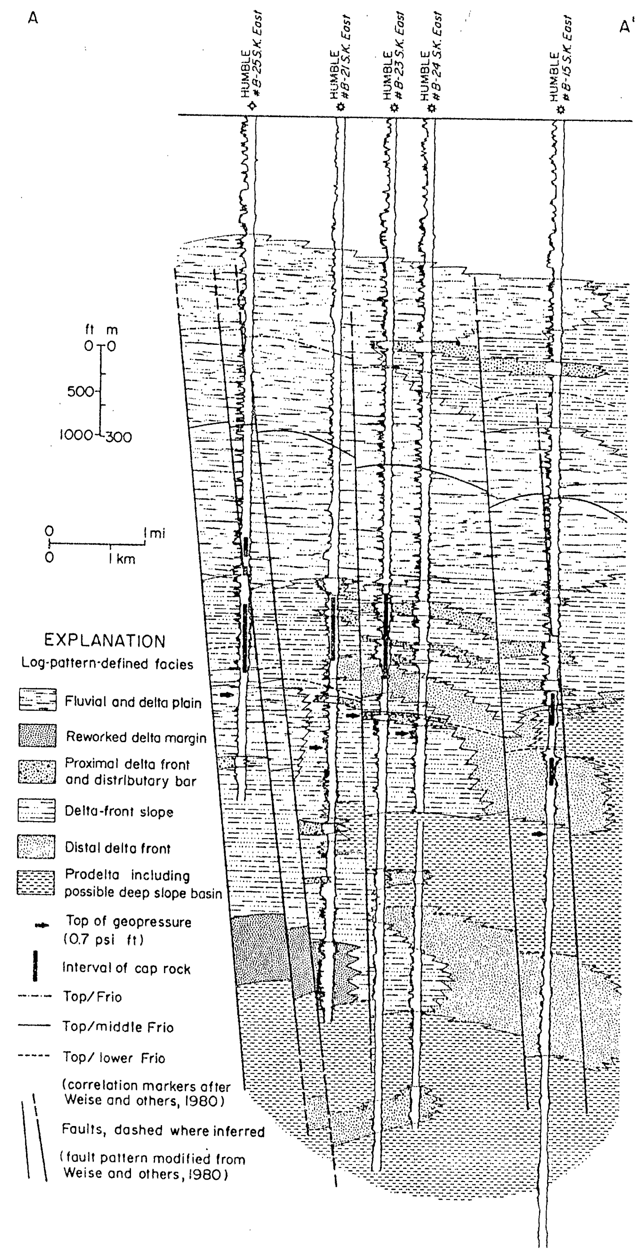

Figure 7. Structural cross section A-A' through northern Sarita East field; see figure 6 for location.

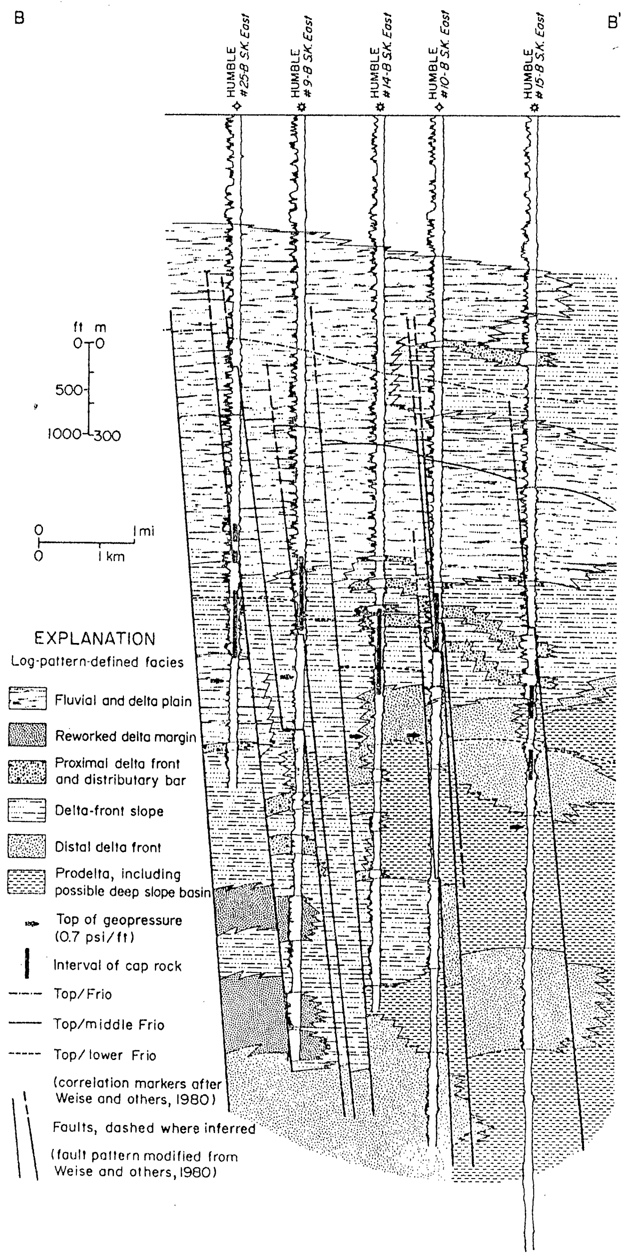

Figure 8. Structural cross section B-B' through central Sarita East field; see figure 6 for location.

As found within the Frio Formation throughout the lower Texas Gulf Coast, cap rock is poorly developed in the shaly prodelta and distal delta-front facies but occurs preferentially within the more sandy delta-front slope facies in Sarita East field (figs. 7 and 8). Within the field, 62 percent of the cap rock intervals delineated in eight wells occur in the delta front slope facies (table 3). Average cap rock thickness is 790 ft (240 m) for all wells within Sarita East field (fig. 6). Regionally (fig. 5) and locally (figs. 7 and 8) cap rock occurs several hundred to a thousand feet (100 to 300 m) above the top of the highly geopressured zone (defined as a pressure gradient of 0.7 psi/ft or 15.8 kPa/m). However, fluid pressure gradients within the cap rock interval are typically greater than hydrostatic (0.465 psi/ft, or 10.5 kPa/m), placing cap rock within the transition zone between pressure regimes. The occurrence of cap rock intervals generally follows the top of geopressure and the base of the more sandy deltaic facies, as the latter occurs from shallower to greater depths downdip (fig. 5). Yet the thickness of the stratigraphic section between the base of the cap rock interval and the top of geopressure may vary by a factor of 2 or 3 between adjacent wells (compare Humble B-25 and B-21, S. K. East, fig. 7).

Cap Rock Lithology

Cap rock defined from a shale resistivity plot is actually an interval containing sands and shales. For section A-A', the sand percent of cap-rock intervals varies from 23 to 41 percent and includes individual sand beds up to 50 ft (15 m) thick (fig. 9). The lettered shale intervals on the log of the Humble B-23 S. K. East well are those used to develop the shale resistivity plot, correspondingly lettered, of figure 1. Note that even relatively thin shales may

Table 3. Summary of cap rock intervals by depositional environment for cross sections A-A' and B-B' through Sarita East field, Kenedy County, Texas.

Section A-A'	prodelta	distal delta front	delta front slope	proximal delta front and distributary bar	fluvial and delta plain
ft	220	530	2,070	350	450
percent	6.1	14.6	57.2	9.7	12.4
	Total footage = 3,620				

Section B-B'	prodelta	distal delta front	delta front slope	proximal delta front and distributary bar	fluvial and delta plain
ft	0	80	1,560	400	200
percent	0	3.6	69.6	17.9	8.9
	Total footage = 2,240				
percent, both sections	3.7	10.4	61.9	12.9	11.1

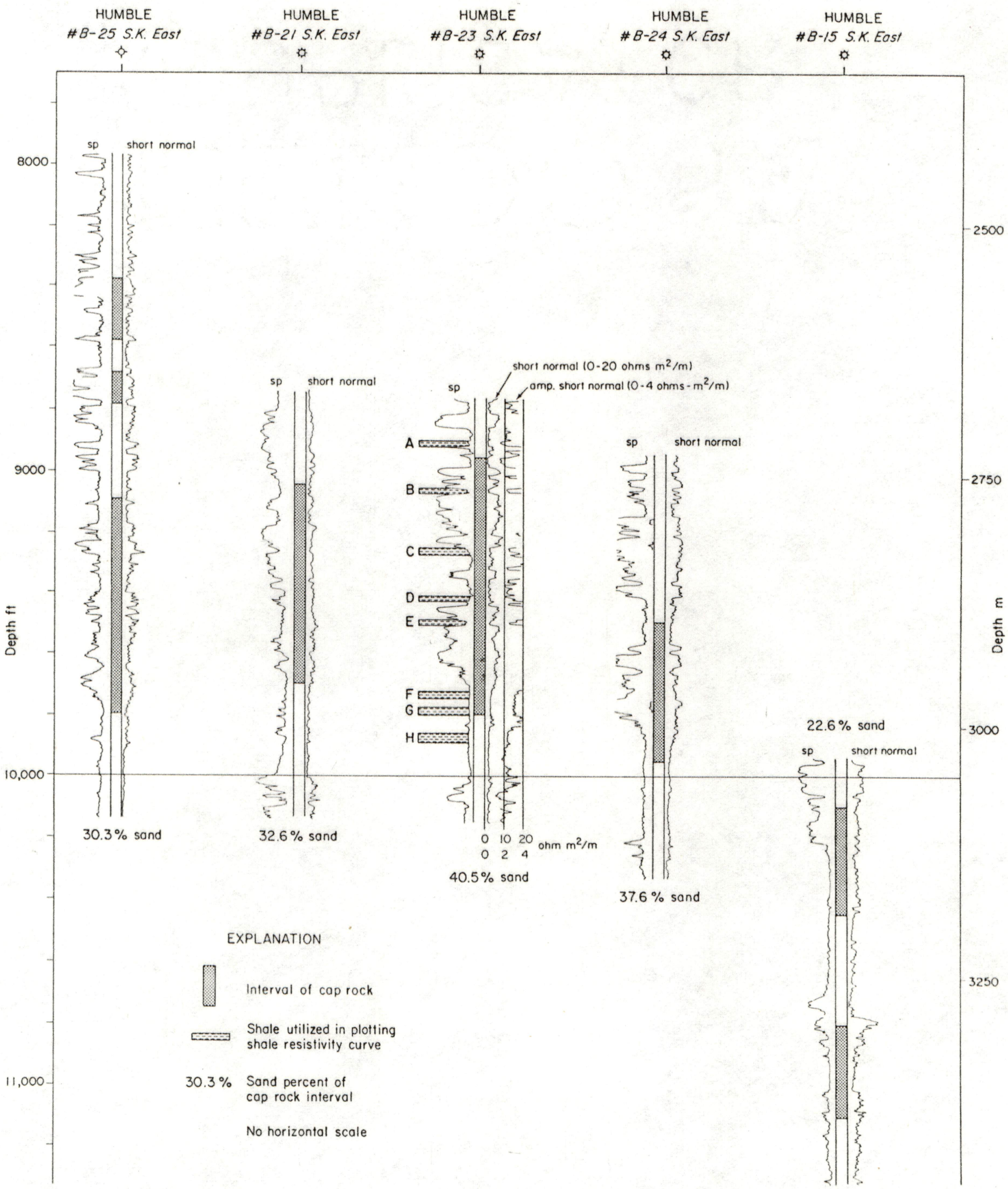

Figure 9. Detail of induction-electrical logs through cap rock intervals, section A-A' Sarita East field.

define the overall pattern of cap rock (B and E, fig. 9). Hence, cap rock thickness does not imply an equivalent thickness of shale.

Cap Rock Mineralogy

Cuttings were available from the cap rock intervals of two wells in the study area, the Humble B-21 S. K. East (fig. 6) and the Humble D-1 Kenedy (outside Sarita East field). Shales from cap rock and non-cap rock intervals in each well were examined under the binocular microscope and analyzed by X-ray powder diffraction. However, samples had been bagged at 30 ft (9 m) intervals; lithologic breaks corresponding to well log patterns were not well expressed, and confidence that samples picked were representative of the desired interval was only low to moderate. Testing of part of each hand-picked sample with dilute HCl gave the subjective impression that shales from the cap rock intervals were more calcareous. The degree of induration, subjectively tested with a steel probe on both wet and dry samples, varied randomly.

Three shale samples from each interval in each well were washed, ground to a uniform fineness, and mounted for X-ray diffraction analysis. The samples were run with $K\alpha$ (copper) radiation at a 2°/minute scan rate and at both 500 cps and 100 cps. The latter count rate should yield better peak height discrimination. Clays, calcite, and quartz are the major constituents, and the presence of minor albite suggests the presence of silt in most samples. Dolomite was detected as a trace constituent in the non-cap rock interval, and a trace of pyrite was noted in the cap rock interval of the Humble B-21 S. K. East well. The latter results were confirmed by scanning electron microscope (SEM) observation of dolomite rhombs and pyrite framboids in shales from the respective intervals.

Peak heights of calcite on X-ray diffraction patterns were compared for cap rock and non-cap rock intervals. The main calcite peak was always higher for the cap rock samples by ratios from 1.1/1.0 to 1.6/1.0. However, all patterns had a high level of background noise, and these results are only a qualitative indication that more calcite is present in the cap rock. Varying particle size and the degree of crystallinity of sample constituents affect peak height and width, making X-ray diffraction primarily a qualitative tool. Petrographic work will be necessary to distinguish carbonate skeletal debris from authigenic cement. From these considerations it is evident that core through cap rock and non-cap rock intervals will be required to determine the natural variability within each interval and to accurately assess any mineralogic control of log response.

DISCUSSION

Results thus far point to stratigraphic control of cap rock development within the delta-front slope facies of the Frio Formation. Cap rock is abundant in the lower Texas Gulf Coast but uncommon in the upper Texas Gulf Coast, although both areas were sites of major delta systems during deposition of the Frio Formation. Therefore, the less stable mineralogy of the lower Texas Gulf Coast may be the origin of authigenic minerals transmitted by fluid migration through delta-front slope sands to form the cap rock interval. The source of these fluids may be the overpressured stratigraphic section below the cap rock interval, and a geochemical control may exist on precipitation of minerals in the transition between hydropressured and geopressured zones, as in part suggested by Magara (1981). What has been established is the preference of cap rock for a relatively sandy facies, but the precise mineralogy of cap rock remains unclear. Magara's (1981) contention that cap rock is due to precipitation of authigenic calcite is a hypothesis that remains untested. Other diagenetic reactions, such as the change from mixed-layer smectite to mixed-layer illite with depth, must also be evaluated. Geochemical and petrographic analysis of core will be required to determine the mineralogy of cap rock shales and adjacent sandstones, as well as the balance of authigenic cement versus skeletal carbonate, if indeed carbonate is involved.

Previous studies (Lindquist, 1977; Loucks and others, 1977) reported that calcite cement is widely distributed in the Frio Formation of the lower Texas Gulf Coast. If so, is there a certain threshold of possible carbonate cementation beyond which a high resistivity log response becomes evident? Analyses of both cap rock and non-cap rock intervals will be necessary to answer these questions. Controls on fluid migration must also be evaluated. Comparison of cap rock distribution and regional faulting suggests that major faults bound thick cap rock intervals in the lower Texas Gulf Coast (fig. 10). More detailed cap rock mapping across these apparent boundaries will be required, especially where areas similar in facies and pressure regime to cap rock areas show only poor cap rock development.

Magara (1981) reviewed the maturation of organic matter to evolve CO_2 and the subsequent potential for acidic brines to dissolve calcite, thereby producing leached secondary porosity at depth and precipitation of calcareous cap rock in shallower stratigraphic intervals. This is probably a somewhat simplified viewpoint accounting for only one aspect of a complex history of burial diagenesis (Milliken and others, 1981). Furthermore, the abundance of cap rock within the Norias deltaic system and the lack of it within the Houston deltaic depocenter of the upper Texas Gulf Coast suggest that CO_2 evolution from herbaceous (type II) and woody (type III) organic matter (which would be abundant in deltaic environments) is not a primary control on cap rock formation.

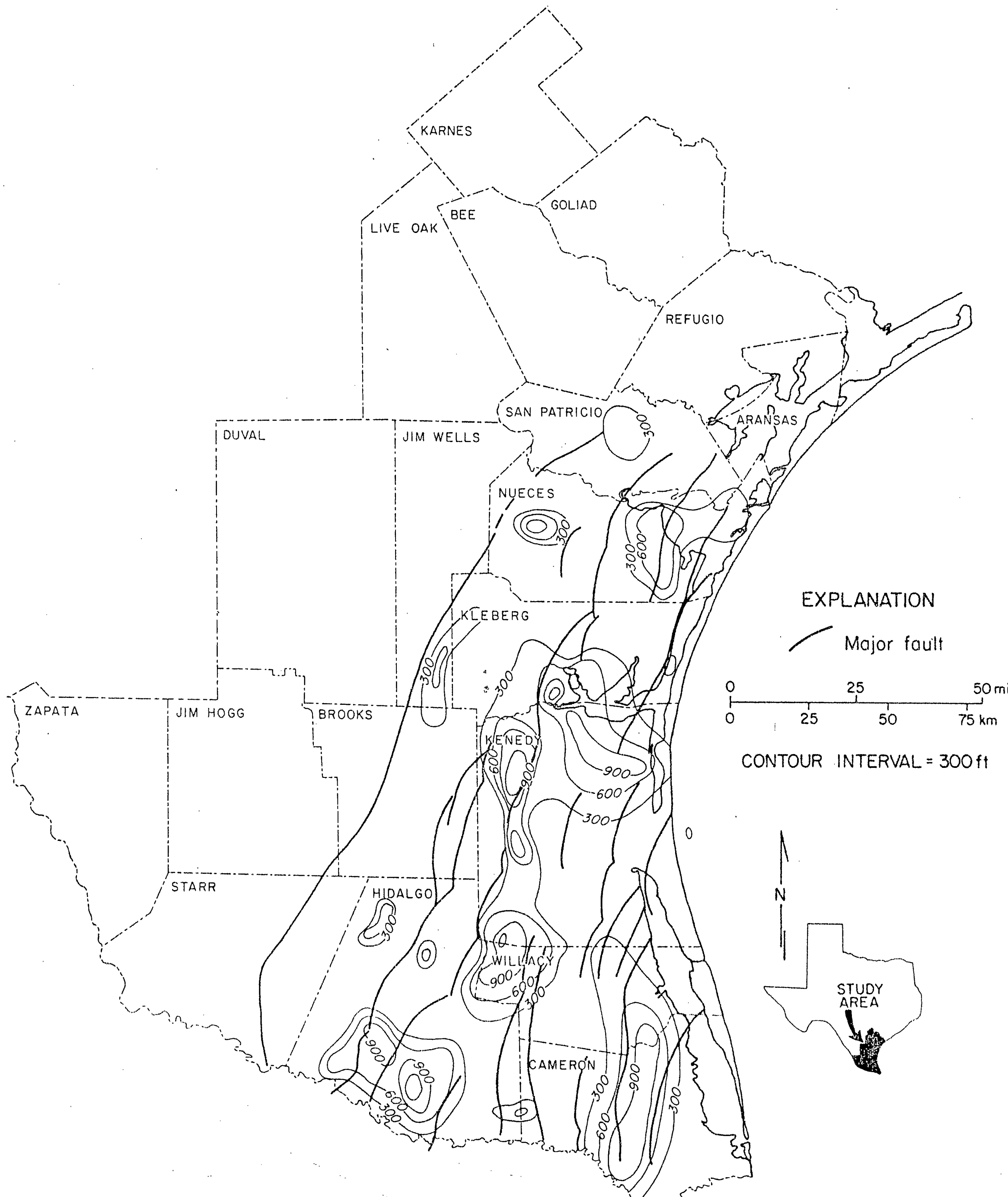

Figure 10. Cap rock interval thickness, Frio Formation, with fault pattern from Galloway and others (in press).

FUTURE WORK

Emphasis will continue on determining the origin of high resistivity shale cap rock. Geochemical and petrographic studies of suitable core will be required because the degree of natural variability in the system may obscure the cause(s) of cap rock development when only cuttings are examined. The quantity of any authigenic mineral rather than its absolute presence or non-presence may be a controlling factor. Also, the nature of sands adjacent to high resistivity shales must be examined for evidence of their role as a fluid conduit, and the relationship to secondary porosity in the geopressured zone must be determined. Simultaneously, other hypotheses on the origin of high resistivity shales may be examined, including the possibility of exsolved gases influencing log response and the relationship of cap rock to temperature as a control on diagenetic processes.

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