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SUBSURFACE GEOLOGY AND POTENTIAL FOR

GEOPRESSURED-GEOTHERMAL ENERGY

IN THE TURTLE BAYOU FIELD-KENT

BAYOU FIELD AREA, TERREBONNE

PARISH, LOUISIANA

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ABSTRACT

SUBSURFACE GEOLOGY AND POTENTIAL FOR
GEOPRESSURED-GEOTHERMAL ENERGY
IN THE TURTLE BAYOU FIELD-KENT
BAYOU FIELD AREA, TERREBONNE
PARISH, LOUISIANA

Daniel R. Moore

A 216 square mile area approximately 65 miles southwest of New Orleans, Louisiana, has been geologically evaluated to determine its potential for geopressured-geothermal energy production. The structural and stratigraphic analyses were made with emphasis upon the Early and Middle Miocene age sediments which lie close to and within the geopressured section.

Stratigraphically the area exhibits a lithologic section which is typical of many areas in southeast Louisiana. The deepest sediments penetrated are within uppermost Lower Miocene. Paleontological evidence suggests that these sediments were deposited in transgressing environments. In contrast, the overlying Middle Miocene section was deposited during what appears to have been an overall regression of environments.

Structurally, the study area is bounded on the north and south by two relatively large, regional, northeast-southwest trending fault zones. A fault zone similar to these runs through the central part of the study area and marks the northern boundary of what has been termed the Houma embayment

(Sloane, 1966). Evidence from this study is consistent with that presented by Sloane (1966), and suggests that the Houma embayment was initiated in an outer shelf to slope edge environment at a time dating no later than the Cibicides opima zone. Embayment infilling was essentially complete by the end of Bigenerina humblei zone deposition.

Three geopressed sands, the Robulus (43) sand, Cibicides opima sand, and Cristellaria (I) sand, are evaluated for their potential of producing geothermal energy. Two of these sands, the Robulus (43) sand and the Cibicides opima sand, meet several of the United States Department of Energy's suggested minimum requirements for a prospective geopressed-geothermal energy reservoir.

INTRODUCTION

The Kent Bayou field-Turtle Bayou field study area is located along the northwestern border of Terrebonne Parish, Louisiana, approximately 65 miles southwest of New Orleans (Figure 1). The area extends northward to Ramos field, eastward to the western flanks of Gibson and Humphreys fields, and southward to the northern flanks of Bayou Penchant and Bayou Piquant fields. Geologically, the area lies within a prolific hydrocarbon-producing trend of Early and Middle Miocene age. This trend roughly parallels the present Gulf Coast shoreline.

The study was conducted under research contract DE-AS05-78ET27161 from the United States Department of Energy to evaluate subsurface geology and potential for geopressured-geothermal energy in South Louisiana. Several geopressured sandstone reservoirs are currently being tested in the Gulf Coast. Well bores penetrating these reservoirs are being evaluated for their production of geothermal waters and of methane gas contained within these waters.

Within this paper geopressure is defined and theories on its origin and maintenance, as they apply to the study area, are reviewed. Stratigraphic and structural evaluations

FIGURE 1. AREA OF STUDY LOCATION MAP.

of the study area are made with emphasis upon deeper horizons which are close to or within the geopressured section. In the final sections of this report three different sands are evaluated for their potentials as prospective geopressured-geothermal energy reservoirs.

REGIONAL GEOLOGIC SETTING

The study area lies within the uppermost Lower Miocene and Middle Miocene hydrocarbon-producing trend of southeast Louisiana. This trend roughly parallels the present Gulf Coast shoreline. The Miocene biostratigraphic zones, defined by marker foraminifera, are shown in Figure 2. Sediments in the Miocene trend were introduced to the Gulf Coast basin by large deltaic systems radiating out of the Mississippi embayment in southern Louisiana (Murray, 1957). Sand deposition predominated in the most proximal continental areas whereas shale predominated in the more distal, lower energy, deeper water marine areas.

The Middle Miocene sedimentation and subsidence rates appear to have been very high. Strata deposited during this stage represent a regressive megacycle. Study of electric log signatures indicates that an overall progradation of strata took place in the Middle Miocene trend. Marine shales and what appear to be density flow sand deposits are progressively overlain by sediments with a higher sand to shale ratio. This fact, combined with knowledge that the Miocene was a period of relative rising sea levels worldwide (Vail and others, 1977), supports the statement that

MIDDLE MIOCENE	BIGENERINA (2) TEXTULARIA (W) BIGENERINA HUMBLEI CRISTELLARIA (I) CIBICIDES OPIMA
LOWER MIOCENE	AMPHISTEGINA (B) ROBULUS (43) DISCORBIS (B) MARGINULINA (A) SIPHONINA DAVISI

FIGURE 2. BIOSTRATIGRAPHIC ZONES OF THE LOWER AND MIDDLE MIOCENE (MODIFIED AFTER THORSEN, 1964).

subsidence and sedimentation rates were high during the Middle Miocene.

The study area lies in and around the northwestern periphery of what Sloane (1966) has termed the "Houma embayment." This feature extends across the northern third of Terrebonne Parish, into the western edge of Lafourche Parish. The northern limit of this embayment is marked by a relatively large down-to-the-basin growth fault system. This fault system begins as one fault which extends from Deer Island field in the west, northeastward through the study area where it is joined by two smaller faults. The fault then makes an arcuate turn around the northern limits of Gibson field before bifurcating into smaller faults along the border of Terrebonne and Lafourche Parishes. The northern limit of the Houma embayment, and location of the study area in relation to the embayment, can be seen in Figure 3.

Sloane (1966) has used the term "embayment" to describe a structural/depositional setting where there was subsidence of a fault bounded area along the continental shelf and contemporaneous filling by marine and deltaic sediments. The term "embayment" has been used by Paine (1958), among others, to describe similar structural/depositional settings, i.e. the Camerina and Nodosaria embayments.

Sloane has constructed isopachous maps of certain sedimentary intervals in the Houma embayment. These maps

FIGURE 3. GEOGRAPHIC LOCATION OF THE HOUMA EMBAYMENT.

indicate that inception of embayment growth was no later than earliest Middle Miocene (Cibicides opima depositional time). Evidence from the current study is consistent with Sloane's conclusion. Within the study area, growth of the Cibicides opima interval is substantial. The exact amount of expansion which has taken place in this interval cannot be determined at this time, as no wells of the study area, within the embayment, penetrate the base of this zone.

According to Sloane's study, active subsidence of the embayment was essentially complete by the time the Bigenerina humblei zone had been deposited. Post-depositional (post-embayment) movement along the embayment fault zone is indicated by extension of the faults into sediments which are at least 1,000 feet above the latest occurrence of Bigenerina humblei. Visual inspection of cross-sections and individual logs indicate that growth within this 1,000 foot section, across the faults, is small. Actual timing of this later stage of faulting was not determined due to the loss of correlateable beds within the massive sand section.

There are no confirmed salt structures within the study area and the closest known salt-related structure is associated with Chacahoula field, approximately 15 miles north-northeast of Kent Bayou field. Sellars (1965) reports that there is a gravity anomaly associated with the Kent Bayou-Turtle Bayou-North Turtle Bayou field area which he believes

might indicate the presence of deep-seated salt.

GEOPRESSURE

The Gulf Coast basin contains one of the widest and thickest geopressured zones in the world. Not only is it one of the largest zones of its type, but it is also probably one of the most thoroughly studied. The following discussion is an overview of some of the most important aspects of the subject.

Some workers prefer to classify geopressure into two regimes, "soft" and "hard." The term soft geopressure is used when gradients are between 0.465 and 0.7 psi per foot of depth, and the term hard geopressure is used when gradients are 0.7 psi and greater. In this paper the term "geopressure" will refer to any stratum whose gradient is higher than 0.465 psi per foot of depth and only when the term "hard geopressure" is used, will the higher gradients be indicated.

In the Louisiana Gulf Coast, geopressure is commonly encountered in thick shale sequences which occur at the base of the sand-shale deltaic lithofacies. Regionally there is a tendency for the top of the geopressured horizon to become shallower with distance to the south (basinward). This overall decrease in depth of the geopressured horizon is related to the offlapping regressive depositional sequence present

in the Gulf Coast Middle and Upper Tertiary. Figure 4 illustrates this shallowing of geopressure towards the basin as well as the relative positions of the previously discussed hard and soft geopressured zones.

Causes for Geopressure

Normally-pressured sections can be thought of as open systems where the intergranular fluids are free to circulate, compensating for compaction and diagenesis. Geopressured zones, on the other hand, operate more like closed systems. During compaction and/or diagenesis, circulation of the intergranular fluids is restricted which leads to partial support of the solid overburden by the fluids. For this type of closed system to occur there must be some type of effective pressure seal.

Pressure seals have often been attributed to the simple dewatering and compaction of portions of relatively thick shale sections. The rapid rates of deposition in deltaic environments make it difficult for the dewatering of underlying marine shales to keep pace with sediment accumulation. When this happens, only upper strata (usually about 200 to 600 feet) of the shale section can dewater and compact. As the upper marine shales compact, their porosities decrease by as much as 85 percent, reducing total porosity to less than 15 percent (Mead, 1966). During this compaction stage,

Figure 4. Relationship of normal, "soft", and "hard" geopressure values to sedimentary facies and depth in the Gulf Coast basin (after Wallace and others, 1979).

permeability is steadily reduced until it appears to be negligible (Dickey and others, 1968). The expelled pore water is easily accepted by the overlying deltaic sands. With the reduced porosities and permeabilities, deeper shales are forced to retain their intergranular water.

Other factors may contribute to the formation of the geopressure seal besides simple compaction. Jones (1969) states that nonionized dissolved solids and gases such as silica, bicarbonate complexes, and carbon dioxide are able to move upward through clay beds with the escaping waters. In this process, carbonate and silica are precipitated in the uppermost clay beds. Jones believes that these precipitants may be the result of chemical reactions with exchangeable cations of clay minerals in the zone where pressure and temperature gradients are steep.

Pressure seals have also been attributed to osmotic pressures generated across clay barriers. White (1965) explains that these fine-grained sediments can behave as semipermeable membranes, thus permitting selective escape of water out of the underlying shale mass and allowing concentration of the remaining ionized dissolved solids within the membrane. For the process of osmosis to work there must be different concentrations of solutions on the opposite sides of a membrane. With continued upward flow of water through the semipermeable membrane, the formation waters in the

membrane become much more concentrated (saline), and those above become more dilute. An osmotic pressure gradient is built up with higher pressures in the direction of the more saline aquifer. Theoretically, with time, the osmotic pressure can sufficiently build up to stop any further outward flow of formation water.

In reality, it is doubtful that any of the above pressure sealing mechanisms ever reach equilibrium, where the seal becomes totally impermeable. Through geologic time the chemical and physical state of lithologies is constantly changing. The top of geopressure is known to have shifted and even today we can see direct evidence of fluid migration along fault zones which penetrate this geopressured section. This fluid migration is evidenced by the increase in depth of geopressure along some such zones.

Diagenesis plays a role in the initiation and maintenance of geopressured strata. Among the most important diagenetic processes active in geopressured lithologies is the conversion of montmorillonite to illite. This process is well described by Burst (1966). According to Burst (1966, p. 73), this conversion takes place ". . . in a relatively restricted, depth-dependent temperature zone . . ." of approximately 220°F, following the initial release of water from inter pore voids during compaction. During the conversion, montmorillonite releases fresh water from its crystal

lattice. The amount of water released is significant, being equal to approximately 10 to 15 percent of the compacted bulk volume of the clays. In sealed reservoirs this decrease in clay volume leads to an increase in the permeability and porosity of the surrounding sediments. This increase is accompanied by a decrease in the load-bearing strength of the clays. The intergranular water which cannot escape into the porous overlying units begins to partially support the overburden. This conversion of montmorillonite to illite is thought to be responsible for the large salinity differential that exists between normally pressured and geopressured reservoirs. With the release of fresh water into geopressured shale sections, saline pore fluids are diluted.

Development of Geopressure (in the Study Area)

There are several interesting features of geopressure development in the Kent Bayou-Turtle Bayou field study area. In the central and eastern area, geopressure is generally encountered in the shale section underlying sand development at the top of the Bigenerina humblei zone. This can be seen on cross-section A-A', Plate 2. It appears that Bigenerina humblei sands act as an open reservoir for dewatering of the underlying geopressured shale section. There is generally a transition from normal pressure gradients at the base of the

sands to hard geopressure some 300 to 600 feet below in the shale sequence. This situation is illustrated in Figure 5, which is a portion of the electric log from Quintana's F. H. Kuntz, well No. 1 (Sec. 41, T-17-S, R-15-E). It should be noticed in this figure that there is a relatively abrupt decrease in the electric log resistivity readings with the transition from normally pressured to geopressured strata. This decrease is the result of higher content of saline water and increased porosity within the geopressured section (Ham, 1966).

In many cases, when geopressured strata are cut by a fault there is a tendency for the top of the geopressured horizon to be anomalously deep. This is an indication that fluid migration has taken place along the fault zone. It should be noted that with Faults B, C, and D, which are just to the north of Kent Bayou and Turtle Bayou fields, this is the exception rather than the rule. As can be seen on cross-section B-B', there is a shallowing of the top of hard geopressure across this fault zone, from the downthrown side of Fault E to the upthrown side of Fault C. This is a clear indication that these are sealing-type faults. If the migration of fluids were taking place along the fault planes, the top of geopressure horizon would surely become more equalized than at present. The reason for increased depth of geopressure on the upthrown side of this fault zone is undetermined.

FIGURE 4. PORTION OF INDUCTION-ELECTRIC LOG SHOWING TRANSITION FROM A NORMAL PRESSURE GRADIENT TO HARD GEOPRESSURE.

Such an abrupt change in the top of geopressure horizon must be the result of relatively local factors. The most probable cause of this deepened zone is fluid escape along the north-east-southwest trending fault zone which cuts through Ramos field. This fault zone may have allowed the dewatering of Cristellaria (I) and Cibicides opima zone sands, causing the top of geopressure to migrate down-section to its present position.

STRATIGRAPHY

This study of the Kent Bayou field-Turtle Bayou field area is concerned with strata located in the uppermost Lower Miocene and Middle Miocene hydrocarbon-producing trend of Southeast Louisiana. Biostratigraphically, this trend is characterized by the occurrence of the Textularia (W), Bigererina humblei, Cristellaria (I), Cibicides opima, Amphistegina (B), and Robulus (43) faunal zones, youngest to oldest, respectively. The highest occurrence of Amphistegina (B) is generally taken as the break between Middle and Lower Miocene strata.

Characterization of this interval in the study area requires at least two type electric logs; one "updip" type log for the section as it is seen in the Ramos-North Turtle Bayou field region, and one "downdip" type log for the expanded section present south of the Houma embayment's bounding fault zone. Such a composite type section is illustrated on Plate 6. The Amerada, Avoca, Inc. No. 2 well (Sec. 47, T-16-S, R-13-E) was chosen to represent the updip section. This well appears to be free of any substantial faults and exhibits a section typical of Ramos field and those wells lying just north of the Houma embayment fault zone. No paleontological

information is available for this well. The laterally continuous nature of spontaneous potential and resistivity log signatures allowed for correlation of this information from adjacent wells. The Amoco, Continental Land and Fur No. E-1 well (Sec. 10, T-18-S, R-14-E) was chosen to represent the downdip section. This well lies in the south-central part of the study area and is representative of the lithologic section seen from Kent Bayou field, eastward to Gibson and Humphreys fields.

As stated in a previous section of this paper, development of the Houma embayment began no later than the time of Cibicides opima deposition. The embayment continued to subside through Bigenerina humblei zone deposition. Deposition, contemporaneous with this subsidence, buried the top of the Lower Miocene below the total depth of any wells within the embayment. In the northern part of the study area, on the upthrown side of the embayment fault zone, Lower Miocene sediments of the Amphistegina (B) and Robulus (43) faunal zones have been penetrated. This area is represented by Amerada, Avoca No. 2 well on the type section.

Lower Miocene

As stated in the previous section, the oldest sediments penetrated in the study area are found north of the Houma embayment and are identified by the presence of the Early

Miocene Robulus (43) faunal assemblage. The top of the Robulus (43) zone occurs at approximately 15,000 feet on the type section and corresponds with a sand body which has been termed the Robulus (43) sand. A net sand isopach map constructed on this sand (Plate 6) indicates that, locally, the unit has a general, undulating east-west isopachous trend which thickens from 50 feet on top of the structural high at Ramos field to at least 130 feet off of the southern flanks of this structure. The sand probably reaches a maximum thickness just south of the type log location before thinning again near the northern boundary of the Houma embayment. Although the distance and sparcity of wells make correlations rather conjectural, the Robulus (43) sand appears to "shale-out" to the southeast and southwest. Additional mapping is needed in adjacent areas before the origin of this sand can be determined with any certainty. A large fault zone along the northern flanks of Ramos field makes updip correlation of this sand body extremely difficult. The extensive displacement and expansion of section across the fault zone, of strata lying below the Bigenerina humblei faunal zone, daunted all attempts to make definite correlation of equivalent units.

Two deeper sand bodies seen on the "updip" type section, at approximately 15,300 feet and 16,100 feet, are similar in character to the Robulus (43) sand. Both are laterally

continuous through the Ramos field area and electric log signatures indicate that there are no abrupt changes in thickness or lithologic character.

Overlying the Robulus (43) faunal zone and marking the top of the Lower Miocene is the Amphistegina (B) faunal zone. On the updip type section this unit is approximately 1,000 feet thick and comprised primarily of shale. One poorly developed, rather shaley, 30 to 60-foot thick sand bed is present within this zone in the Ramos field area. This sand is present at approximately 14,200 feet on the type section. About four miles south of Ramos field this sand apparently thickens into a 300 to 600 foot shaley-sand sequence before being downfaulted by the Houma embayment boundary fault zone. These thicker shaley-sand sequences can be seen in the Austral, Continental Land and Fur No. 1 well (Sec. 11, T-17-S, R-13-E). Due to poor well control, any explanation for this increase in thickness would be speculative and it is even possible that these sands are not genetically related. The thicker southern sequence may have been deposited in an undetected eroded channel occurring south of and trending at an oblique angle to Ramos field. This could account for the increased sand thickness and would indicate that it is not genetically related to the northern sand.

Skinner (1972) states that Amphistegina (B) and its accompanying fauna in the Lower Miocene are indicative of

environments in which the water depth was no more than 300 feet. This should indicate that deposition took place in areas which were no more distal than the middle shelf (Tippword and others, 1966).

Middle Miocene

Overlying Amphistegina (B) is the Cibicides opima faunal zone which marks the beginning of Middle Miocene time. In the northern part of the study area (see updip type section) this zone is approximately 2,350 feet thick, while in the Houma embayment the base has not been penetrated by the well bore. The embayment section is greatly expanded due to active subsidence during this period.

According to Skinner (1972), Cibicides carstensi opima, the marker species for this zone, occurs in an outer shelf facies of sandy shale, shale, and lenticular sands which are believed to have been deposited in water depths greater than 300 feet. Assuming that Skinner's (1972) environmental interpretations are correct for Amphistegina (B) and Cibicides opima, it appears that there was a slight transgression during the transition from Early to Middle Miocene. This period represents a short reversal in the overall regressive Miocene sequence.

Several workers have reported the occurrence of a deep-water faunal assemblage in Houma embayment wells located

within the study area (Sellars, 1964; Ferguson, 1960; and Sloane, 1966). This assemblage occurs in the Cibicides opima zone and is present in the Shell, Continental Land and Fur No. E-2 well (Sec. 19, T-17-S, R-14-E) at a depth of 12,600 feet, approximately 400 feet below the top of the zone. Nowhere in the study area has this assemblage been reported north of the embayment. This indicates that the embayment fault zone was near, if not marking, the shelf-slope "hinge-line" during lowermost Middle Miocene time.

This deep-water faunal assemblage is known as the "Harang facies" which has been described in a regional context by many workers (i.e. Pope, 1955; Skinner, 1972; and Thorsen, 1964). Skinner states that the Cibicides opima fauna blends downdip into the Harang facies, which occurs throughout an arcuate area in southeastern Louisiana coastal parishes (Figure 6). The fauna and associated facies have a wedge-shaped distribution. In the northern area only a thin interval is found while downdip the fauna occurs in all of the Lower and Middle Miocene section (Skinner, 1972). According to Skinner this widespread occurrence indicates that the Harang is a type of magna facies; that is, the upper and lower limits of this shale wedge transgress established time lines. Presence of the Harang fauna indicates deep water environments (greater than 500 feet), from extreme outer shelf to upper continental slope (Skinner, 1972).

As can be seen on the type section, the Cibicides opima zone present in the study area is composed primarily of shale with a few interspersed thin, discontinuous sand beds. One sand bed, here termed the "Cibicides opima sand," appears to be continuous through the entire area. This unit's stratigraphic position indicates that it may be an equivalent facies to the sand termed "Hollywood" or "Southdown" in many Houma embayment field studies. The Cibicides opima sand is actually a shale/sand sequence which generally contains no more than 25 percent shale. This sequence is approximately 90 feet thick in the updip type section while in the downdip type section it has expanded to a thickness of 390 feet. South of the downdip type section, at the California Company, Continental Land and Fur No. 1 well (Sec. 23, T-18-S, R-14-E), this sand attains a recorded thickness of approximately 600 feet.

In the eastern and southeastern part of the study area, where deep well control is sufficient, a net sand isopach map was made on the Cibicides opima sand (Plate 7). In general, the pattern of sand deposition is rather smooth, showing few abrupt changes in the amount of sand deposited in any given area. The changes in thickness which are present are probably a result of predepositional topography on the sea floor (see section on structure and its effects on sedimentation).

It is believed that these shaley-sand sequences are the

result of turbidity flows which originated in shallower shelf areas, possibly within the Houma embayment. As the Cibicides opima sand is present updip from the Houma embayment, it must be assumed that initial flow of these turbidity currents occurred landward of the shelf edge. No well-defined channels were established for this sand in the eastern part of the study area but it does appear that there are linear areas of maximum deposition. These areas probably correspond with topographic lows which existed on the sea floor. As the turbidity flows fanned-out, these areas received the maximum amount of sediment before additional deposits were deflected off to adjacent sides.

It is interesting that such large deposits of sand would have accumulated in an area very close to or over the shelf edge. These areas generally have steeper than average neritic basinward slope gradients. One possible explanation for this shelf edge to upper slope deposition may be that during the time of embayment growth, subsidence along the bounding fault zone was so great that a decrease in regional dip occurred, or possibly even a dip reversal. Also, in the past several years, the work of Martin and Bouma (1978), Bouma, et al. (1978), Ewing and Antoine (1966), and others has shown that the Gulf Coast outer shelf and slope areas have been and are the site of numerous diapiric structures. These structures are known to create sites for deposition of sediments.

Logs from the few deep wells that penetrate below the Cibicides opima sand indicate the presence of another extensively shaley-sand sequence in the Cibicides opima zone which underlies the Cibicides opima sand. This sequence is shown on cross-section A-A" (Plate 2), where it has an average thickness of 600 feet and is very similar in character to the Cibicides opima sand. Further to the east, in the vicinity of the downdip type section, Amoco, Continental Land and Fur No. E-1 well, this sand is not present. Because of limited deep well control it is difficult to speculate on the equivalence of this sand in the northern Kent Bayou-Turtle Bayou field area. If an equivalent sand is present in this northern area, it is much thinner. According to the wells present in this northern area, the maximum thickness of any sand which could be stratigraphically equivalent is 200 feet.

Stratigraphically overlying Cibicides opima is the Cristellaria (I) faunal zone. As seen on the type section, this zone is approximately 1,000 feet thick in the northern area and expands to about 1,500 feet within the Houma embayment. Similar to the underlying strata, this zone is made up primarily of thick shale sequences separated by thin discontinuous sand beds. One sand to shaley-sand sequence, which occurs near the top of the Cristellaria (I) zone, can be traced throughout most of the northern and central parts of the study area. This sequence is here termed the "Cristellaria"

(I) sand." Although this appears to be a channel facies, there is generally a relatively thin accumulation of sand which corresponds with the channel-top throughout much of the study area. These deposits are probably the result of over-bank sediment flow, which would have occurred at about the time the channel had become filled.

The Cristellaria species occur in a range of environments, from inner to outer shelf, but their highest frequency is associated with the latter. Considering the framework of previously described sediments, an outer shelf environment seems most likely for the Cristellaria (I) zone strata in this area. It is possible that this zone may contain some sediments which were deposited in an even deeper water environment than that mentioned above. Sellars (1964) reports that there is a "Harang-like" deep water fauna present in the Shell, Continental Land and Fur No. 9 well (Sec. 33, T-17-S, R-14-E) at a depth of 11,490 feet, very close to the top of the Cristellaria (I) zone. As stated previously, the Harang fauna indicates deep water environments from extreme outer shelf to upper continental slope.

The Cristellaria (I) sand appears to have been deposited unconformably in an eroded channel bed. A cross-section study (Plate 5) of the deep Pennzoil wells in Sections 1, 2, and 3, T-18-S, R-13-E, indicates that as much as 600 feet of Cristellaria (I) zone shale was eroded to form one of these

channels which is just slightly over a mile wide. A net sand isopach map was made for this sand in the central part of the study area (Plate 7). Although well control is sparse in the northeastern part of Kent Bayou field, abundant deep well control to the north and south allows accurate definition of the channel facies. The apex of these linear sand bodies trends in an overall north to south direction. Significantly, these channels trend normal to and cut across the Houma embayment fault zone with no apparent change in character. This may indicate that erosion of the channels and subsequent deposition of sand within these channels and in overbank areas was rather rapid. Assuming that subsidence (displacement) was taking place along the fault zone during this period, any lengthy erosional and/or depositional event should be reflected by differences in channel depth and amount of sediment present on opposite sides of the faults.

These channels may originally have been cut into the outer shelf by turbidity currents which were initiated in locally unstable, updip areas. Although it is generally held that in marine environments turbidity currents occur and originate within submarine canyons (Klein, 1980), it seems that these canyons must also have tributaries which extend upslope and funnel turbidity currents from unstable shelf areas. It is in the latter context that the study area channels are viewed.

The channel associated sand sequences which are penetrated

by well bores range from thick and massive to extremely shaley, commonly being a combination of both, with no ordered arrangement of stratum. Considering the discontinuous nature of these sand sequences it seems probable that intermittent surges or flows of sediment were introduced into the area, and the bulk of sediment from each subsequent deposit settled out either updip or downdip, depending on density of flow and/or the established gradient.

Overlying Cristellaria (I) is the Bigenerina humblei faunal zone. The sediments in this zone were deposited in water depths of approximately 150 to 300 or more feet (Skinner, 1972). The top of this zone corresponds to a sand unit which is continuous throughout the central and eastern portions of the study area. This sand can be seen on the type section and has been termed the "Bigenerina humblei sand" by the writer. Correlation of this unit is rather difficult in the wells just north of the Houma embayment. Within these wells several small sand bodies are present in an area of approximate stratigraphic equivalence to the Bigenerina humblei embayment sand. Further updip, near Ramos field, there is only one sand within this zone, typical of that seen on the type section and marked as the Bigenerina humblei sand equivalent.

Thickness of this faunal zone averages about 350 feet in the northern, updip part of the area; within the Houma embayment this zone has expanded to about 750 feet. As was

stated earlier, development of the Houma embayment was essentially complete by the end of Bigenerina humblei time.

The last section of strata evaluated in this study lies within the Middle Miocene Textularia (W) faunal zone. Corresponding with the top of this zone is a 150 foot thick (average) sand bed which has been termed the "Textularia (W) sand." Although no geopressed sediments lie within this zone, the Textularia (W) sand, with its "blanketing" nature, serves as an excellent marker horizon within the study area. This sand is continuous throughout the study area and changes very little in character. Overall electric log configuration and paleontology in the area suggest that this sand is the first of, undoubted deltaic origin. The "blanketing" nature of this sand and the overlying alternating sand-shale sequence indicates the continuing progradation during the Middle Miocene.

STRUCTURAL GEOLOGY AND ITS EFFECT ON SEDIMENTATION

Structural evaluation of the study area is concentrated upon deeper horizons which contain geopressed strata. Because of the discontinuous nature of deeper sediments in the area, lack of sufficient deep well control in the central portion of the area, and fluctuation in the top of geopressure, it was necessary to change structural mapping horizons at two boundaries. One of these datum changes takes place between the Turtle Bayou-North Turtle Bayou-Kent Bayou field area and the Gibson-Humphreys field area (Plate 9). This datum change is from the Cristellaria (I) sand to the Cibicides opima sand. The second datum change is situated just north of the Houma embayment's bounding fault zone (Plate 9). North of this datum change a structure map was constructed on the Robulus (43) sand. These datum changes separate the study area into eastern-southeastern, central, and northern sections. Each of these sections will be discussed separately.

In addition to the three mapped horizons mentioned above, a Textularia (W) sand structure map (Plate 8) and three structural cross-sections were constructed. Plate 1 shows the area traversed by each of the above cross-sections and is labeled with their plate identification numbers. A report

by Sloane (1966) on the structural history of the Houma embayment was also useful in obtaining a feel for the regional geology of the area.

Dominant structural features within the study area are three regionally extensive fault zones. Two of these zones mark the northern and southern limits of evaluation and therefore received only minimal consideration. The central fault zone which, as stated earlier, marks the updip limit of the Houma embayment, is thought to have originated in a zone of weakness near the shelf edge. A Middle Miocene regression deposited great amounts of sediment in the Houma embayment. This sediment influx apparently exceeded the rate of subsidence leading to an outbuilding of the shelf edge. It is believed that sometime thereafter a new zone of weakness was established and the southernmost regional fault zone was initiated. Similar views on this fault zone have been expressed by Sloane (1966). Although beyond the scope of this study, it is believed that the most northern fault zone was established in a similar manner prior to initiation of the two southern fault zones.

One can only speculate as to the origin of anticlinal and domal features found in the study area. The closest known salt structure to the area is associated with Chacahoula field, approximately eight miles north of Gibson field. Sellars (1965, p. 106) states that there is a gravity anomaly

present under the Kent Bayou-Turtle Bayou-North Turtle Bayou field area which "indicates that these fields are underlain by salt." It seems just as likely that these areas could be underlain by diapiric shale masses. Diapiric shale has been well described by Bruce (1972), and Coleman and Prior (1980), among others. It is believed that the low-density of diapiric shale may also cause gravity anomalies.

Northern Area Structure

This area extends from the upthrown side of the Houma embayment fault zone, northward to Ramos field. Outside of Ramos field and North Turtle Bayou fields, well control is sparse. The few deep tests which have been made in the inter-field area make it possible to correlate between Ramos field and the high concentration of wells lying to the south.

The northern area is characterized by relatively low-angle regional dips, averaging 100 feet per mile in shallow horizons and steepening with depth to approximately 150 feet per mile at the top of the Robulus (43) faunal zone. As stated earlier, there is a large contemporaneous, down-to-the-basin regional fault which trends in a northeasterly direction through Ramos field. This fault is seen as Fault "A" on the Textularia (W) and Robulus (43) structure maps (Plates 8 and 9), and cross-section B-B' (Plate 3). Fault displacement averages approximately 450 feet at the Textularia (W) horizon

and is known locally to exceed 1,000 feet at depths below the Robulus (43) mapping horizon. Present at the Textularia (W) horizon, on the downthrown side of Fault "A", is a roll-over structure which extends through, and reaches a maximum high, just northeast of Ramos field. Only one other small fault cut has been detected in the Ramos field area at this horizon. This cut, present in the British American well in Section 21, is believed to be a down-to-the-west fault, trending normal to the previously mentioned rollover structure.

As Fault "A" migrates to the south with depth, the anti-clinal structure described above loses its definition. Both the structure and the fault described, in the British American well are absent at the Robulus (43) horizon. Although well control is limited at this depth, it appears that two structural highs are present: one rather flat-topped high in the central portion of Ramos field and one with much steeper flanks, just northeast of the field. Also detected at this horizon are two faults not seen in the shallowest mapped horizon. One of these faults, trending through Sections 23 and 24, is clearly a bifurcation of Fault "A". The easternmost and larger of the two faults is only detected in two closely-spaced wells which are approximately one mile away from Fault "A". Because of the limited well control for this fault, its trend north and south of the defining wells is highly subjective.

Further to the south at North Turtle Bayou and Bay Wallace fields, deeper horizons show the development of an anticlinal structure which is cut close to its crest by Fault "B" and its bifurcation, Fault "C". The shallower Textularia (W) horizon in this area seems to exhibit a structure which is unrelated to that at deeper horizons. This is evidenced by extremely low angle dips around North Turtle Bayou field and what appears to be a synclinal structure at Bay Wallace field.

Central Area Structure

The central part of the study area has been defined as lying south of and including the Houma embayment fault zone (Faults "B, C, D, and E") in the vicinity of Kent Bayou and Turtle Bayou fields. As discussed earlier, inception of embayment development (movement and contemporaneous deposition along Faults "B, C, D, and E") was no later than earliest Middle Miocene and was essentially complete by the end of Bigenerina humblei zone deposition. Post-depositional movement along this fault zone is indicated by displacement of much shallower sedimentary horizons.

In the northeastern corner of this area southwesterly trending Fault "B" bifurcates, forming Faults "C" and "E". Fault "E" makes a rather abrupt curve and trends off to the south-southwest where its throw decreases and it terminates

between Turtle Bayou and Kent Bayou fields. Fault "C" continues through the field area in a southwesterly direction before curving to the south around the periphery of Kent Bayou field. Interestingly, this fault shows much less post-embayment displacement than its two southern counterparts, Faults "D" and "E". At the Textularia (W) horizon, north of Kent Bayou and Turtle Bayou fields, this fault is all but nonexistent. There is no evidence of Fault "C" north of the Shell, Continental Land and Fur No. E-1 well (Sec. 19, T-17-S, R-14-E) while 550 feet below the Textularia (W) horizon, a 350 foot fault cut is present in this well. A common situation in this area, this indicates a rapid termination and burial of Fault "C".

Fault "D", observed at the Cristellaria (I) horizon (Plate 9), bifurcates at its northeastern end, the northern segment joining Fault "C" and the southern joining Fault "E". At shallower horizons the northern segment joining Faults "D" and "C" dies out, and displacement is maintained with the southern segment joining Fault "E" (Plate 8). Fault "D" trends subparallel to Fault "C" through the Turtle Bayou-Kent Bayou field area. West of these fields the faults curve and trend toward the south, marking the western edge of the Houma embayment depocenter. Two other faults were detected in the central part of the study area. These faults are both down-to-the-north and labeled "F" and "G" on the

relevant structure maps. The cause of these faults and their time of initiation are both significant questions. The faults may be antithetic (adjustment) type faults associated with the Houma embayment fault zone or they may be associated with the Kent Bayou-Turtle Bayou anticlinal structures which post-date major movements along the embayment fault zone. As neither Fault "F" nor "G" exhibits noticeable expansion on its downthrown side at any horizon, it is difficult to speculate on the time of origin. Further studies considering the time of structural uplift as well as the migration and trapping of hydrocarbons in the area might lend further insight to the problem.

The Kent Bayou-Turtle Bayou fields are situated on two anticlinal highs which trend in a northeast-southwest direction. These structures are fairly continuous with depth through the mapped horizons. The structures can be seen on the shallow Textularia (W) sand and deeper Cristellaria (I) sand structure maps (Plates 8 and 9, respectively). In comparison, the plates show a significant increase in dip with depth on the flanks of the anticlinal structures. This is as expected for any uplift of deep-seated origin.

Initiation of the Kent Bayou-Turtle Bayou structures postdated major periods of growth along the Houma embayment fault zone. As explained previously, embayment development started no later than Cibicides opima time and was

essentially complete by the end of Bigennerina humblei time. It is believed that the central area field structures could have been initiated no earlier than the end of Cristellaria (I) deposition. Evidence for the above statement lies in the fact that Cristellaria (I) channel sands traverse the crest of Kent Bayou field and Turtle Bayou field anticlinal highs. This situation can be seen on cross-section A-A' (Plate 2). It seems highly unlikely that flow in outer neritic environment channels would traverse the crest of an existing anticlinal structure.

Eastern-Southeastern Area Structure

The eastern-southeastern area of study is bounded on the north by Fault "B", on the west by a structural low, trending roughly north-south between Turtle Bayou and Gibson fields, and on the south by a regionally extensive fault zone (Fault "L"). There are many interesting structures in this area, most of which probably developed during subsidence of and sedimentation in the Houma embayment. Comparing the Textularia (W) sand and Cibicides opima sand structure maps (Plates 8 and 9) it can be seen that most of the central structures, Faults "H, I, and J", die out and are buried by the time of Textularia (W) deposition. A small down-to-the-south fault is seen at the Textularia (W) horizon and probably originated after the final stages of embayment development. The

structure may be related to late movement (uplift) of the Gibson field anticlinal structure. This fault has died out above the depth of the deeper mapping horizon.

Structural cross-section C-C' transects the eastern-southeastern area. This cross-section combined with the Cibicides opima sand structure map illustrates the structure which is present at depth in the area. A large down-to-the-north fault zone (Fault "H" and bifurcations "I and J") bisects the Houma embayment fairway in an east-west direction. This fault zone combined with a large regional fault to the north (Fault "B") and south (Fault "L") divides the embayment into a horst-graben structure. Centrally located within the graben is an anticlinal structure from which Gibson field produces, while on top of the horst is another anticlinal structure associated with Humphreys field. To the west, Faults "H, I, and J" are believed to die out along the flanks of the above mentioned anticlines.

Origin of Faults "H, I, and J" is probably related to the adjustment to large amounts of sediment being dumped into the Houma embayment as well as uplift of the anticlinal structure at Humphreys field. Initial timing of the above events can be dated as no later than that corresponding to Cibicides opima zone deposition. Evidence for this statement can be seen on cross-section C-C' (Plate 4). The Cibicides opima sand thins to approximately 175 feet near the crest of

Humphreys field while thicknesses of 500 to 600 feet are found in the graben structure to the north. This suggests that deposition of the above sand was being influenced by structures that were present during earliest Middle Miocene time.

Moving southwest, down-dip from Humphreys field and adjacent to regional Fault "L", an area with extremely low angle dips is encountered. Just west of this terrace-like structure a 200 foot fault cut is present in the Pure, Continental Land and Fur No. 2 well (see Fault "K" on cross-section C-C' and Cibicides opima sand structure map). This fault is believed to be a northern bifurcation of the regional Fault "L". As can be seen on cross-section C-C', substantial thinning of the Cibicides opima sand takes place on the downthrown side of Fault "K". An explanation for this differential thickness is questionable. It may have resulted from thinning of sediments on the crest of a rollover structure associated with Fault "K".

On the downthrown side of Fault "K", at the deepest mapped horizon, is a steep-sided syncline which trends in a north-west-southeast direction. The western flanks of this structure extend upward, cresting just west of Bayou Piquant field.

HYDROCARBON PRODUCTION

Hydrocarbon production in the study area comes from numerous sands, the shallowest of which is a 2,500-foot sand in Kent Bayou field, and the deepest of which is a 19,300-foot Lower Miocene sand in Ramos field. Within the studied horizons, production is related almost exclusively to structural traps. The traps are a result of several different processes, i.e., deep-seated uplifts causing structural closure, rollover development on the downthrown side of growth faults, and anticlines on the upthrown side of regional growth faults, the last of which is probably related to prefaulting structure.

As major field structures were described in the previous section, it is sufficient here to discuss only the main producing horizons in each of the study area fields.

Ramos field's main producing horizons lie within the Lower Miocene Robulus (43) zone. All horizons from which production has been obtained to date, lie below the Robulus (43) sand proper. The two Amerada, Avoca wells in southern Ramos field produce gas from horizons around 18,000 and 19,000 feet. The structure at these depths may be unrelated to that seen on the Robulus (43) sand structure map.

Gas and oil are currently produced from four main horizons at North Turtle Bayou field. These include two Cristellaria (I) zone sands, one Cibicides opima zone sand and the Bigenerina humblei sand. Production from the uppermost Cristellaria (I) zone sand may be partially stratigraphic, as it is a channel facies sand.

Hydrocarbons are being or have been produced from over 12 different horizons in the Kent Bayou-Turtle Bayou field area. Approximately 90 percent of this production is from Textularia (W) and Bigenerina humblei zone sands.

Production in the Gibson-Humphreys field area comes from as many as 20 different sands. The majority of these intervals are found on the crest of the Gibson field structure in Textularia (W) and overlying zones. Production records indicate that no well has been completed below the Cristellaria (I) zone in Gibson field. Humphreys field has been proven productive in a Cristellaria (I) zone sand as well as the Bigenerina humblei sand.

GEOPRESSURED-GEOTHERMAL ENERGY EVALUATION

The United States Department of Energy has been studying and sponsoring studies on geopressured-geothermal resources along the Gulf Coast since 1975. The primary objectives of their geopressured-geothermal program "are to define the geopressured fairways in the Gulf Coast and to delineate favorable areas which could be developed as test sites for long-duration testing." (Westhusing, 1981, p. 3) Several test wells are currently being evaluated for their productivity of methane and thermal energy.

After a general reconnaissance of South Louisiana, several areas with geopressured-geothermal energy potential were considered for this study. The area was chosen mainly because of a shallow geopressure horizon and abundant well log data for strata extending through this horizon. The latter can be a real problem in many areas of the Gulf Coast where in the past, operators have customarily stopped drilling when they reached the geopressured horizon. The primary reasons for this lie in the additional cost and risk of drilling into high-pressured strata. Previous workers such as Paine (1977) and Mumme (1979) who recognized the geopressured-geothermal

energy potential of the Middle Miocene trend just east of the present study area also influenced the choice of a specific site to study.

Parameters and Procedures

Among some of the most important factors to be considered in evaluating a subsurface horizon for potential energy are temperature, pressure, permeability, and reservoir volume. Concerning the above parameters, the Department of Energy has suggested the following (somewhat flexible) guidelines for potential energy reservoirs (Westhusing, 1981):

1. fluid temperatures of greater than 250°F,
2. pressure gradients of 0.7 psi per foot or greater,
3. at least one cubic mile of sand with a minimum of 100 essentially continuous net feet of 100 percent water-saturated sand,
4. water salinity of less than 75,000 ppm, and
5. minimum permeabilities of 20 millidarcys.

No specific data were incorporated into this study concerning the last two guidelines (numbers 4 and 5). The accuracy of these data when calculated from the common induction-electric log and/or sonic log is questionable (see Kurth, 1981, pp. 61 and 68) and determination from alternate sources of data would lead to poorly controlled interpretations. Previous field studies in the Houma embayment area report salinity

values for the geopressured section which tend to be rather high compared with the suggested maximum. Kusters (1981) states that salinity values in the field areas lying directly east of the current study area range from about 80,000 ppm to 130,000 ppm. Permeability of study area sands is, no doubt, highly variable, depending on factors such as clay content and diagenetic history. Sellars (1964) and Phillips (1965), who studied the productive histories of Kent Bayou-Turtle Bayou fields and Gibson field, respectively, state that permeability of all productive sands ranges from "average" to "good."

To evaluate the area for prospective geopressured-geothermal resources, a structure map was first made on a relatively shallow, laterally continuous, normally pressured horizon. This initial construction resulted in a general understanding of the stratigraphic and structural relationships in the area. Following this a structure map on top of the hard geopressured horizon and a 12,000 foot depth temperature map were constructed. It was hoped that combined observations of the above maps would help in finding sizable areas of relatively high temperatures and shallow geopressured zones with abundant well control; analyses of these maps are discussed in the following sections. Subsequently, three sands were chosen which lie within the geopressured section. Choice of these sands was based primarily on the thickness, lateral continuity, and amount of well control available. The next stage of

evaluation involved making structural and net sand isopach maps on these sands. These maps helped in determining the thickness, specific dimensions, and depositional origin of possible prospective sands. In following sections of this paper interpretations made from the temperature and pressure maps are discussed.

Temperature

Geothermal gradients along the Gulf Coast usually range between 1.4° to 2.4°F per 100 feet (Bebout and others, 1978), showing a slight gradient increase when going from the normally pressured zone into geopressured strata. This increase probably results from a slowdown in the upward flow of water that occurs in the geopressured strata (Jones, 1969). When the upward flow of water is restricted, so is the dissipation of heat.

The 12,000-foot horizon was chosen for mapping temperatures in the study area (Plate 10). This horizon was believed to be deep enough to reflect underlying structure within the geopressured section and yet shallow enough in most places to avoid the higher thermal gradients encountered in that section. Assuming a linear temperature gradient, the areas at the 12,000-foot horizon with high values and the areas with low values theoretically should correspond, in a relative way, with deeper horizons. It should be noted that the 12,000-

foot horizon did intersect geopressure thermal gradients on the crest of several field structures. Effects of this intersection will be discussed in a later paragraph.

The values used to construct the temperature map were obtained from bottom-hole temperatures recorded on sonic and induction-electric logs. As these values are consistently low because of the cooling effect of drilling mud on formations in the borehole, equilibrium corrections had to be made. These corrections were made by use of an empirical relationship developed by Kehle (1971). This relationship is based on a statistical study of a great number of wells over a wide area along the Gulf Coast. Using Kehle's relationship, Bebout et al. (1978) constructed a simple curve which shows temperature corrections for depths from 7,000 feet to 20,000 feet. This curve, depicted in Figure 7, was utilized in the present study.

Bottom-hole temperature recordings are generally taken at each casing point in the well bore. In obtaining data for the temperature map, the two bottom-hole (casing point) temperatures, lying above and below the 12,000-foot horizon, were corrected and then an interpolation was made to the mapping horizon, assuming a linear gradient. In some cases the lowermost temperature to be used for interpolation was within the geopressured zone. When this was the case, two shallower temperature recordings were used and an extrapolation was

Figure 7. Temperature corrections as a function of depth for adjusting well-log temperatures to approximate equilibrium temperatures (after Bebout and others, 1978).

made to the 12,000-foot horizon. This extrapolation was not made when the actual mapping horizon was within geopressure.

When the temperature map was being contoured it was obvious that some values were anomalously high or low, causing local "bulls-eye" contour patterns. As noncontinuous, abrupt changes in temperature seem highly unlikely, these values were ignored on the revised map and marked with an "x" subscript. Kurth (1981) explains at some length, the possible reason for these anomalous temperature values. Inaccuracy of instruments and poor control in measurements taken during drilling of earlier Gulf Coast wells seem to be the most likely reasons for anomalous readings.

The data presented on the contoured temperature map are interesting. Approximate locations of faults are also plotted on this map to help determine their effect upon temperature distribution. Inspection indicates that few generalities can be made relating structures to temperature highs and lows. Many workers (Harrison, 1980; and Gatenby, 1980) have stated that hot pore waters originating in the geopressured section often migrate up along fault zones creating temperature highs in these areas. This process appears to be the exception rather than the rule, within the study area. There are no linear temperature highs associated with the Houma embayment fault zone. In fact, some of the area temperature lows lie right within this zone, i.e. at North Turtle Bayou field.

This situation probably results from sealing at depth, along the fault plane. One linear temperature high which might be associated with a fault zone is found in and to the west of Humphreys field, on the upthrown side of Fault "H". Although the high is not centered directly over the fault trend, its linear nature, cutting across and away from the Humphreys field structure, suggests that it is fault controlled.

At Ramos, Bayou Piquant, Gibson and Humphreys fields, high temperature values appear to be related to the anticlinal structures. This association is probably indicative of the relationship between fluid migrations and stratigraphy; lateral fluid migration along bedding planes dominates over vertical fluid movement. The relationship at Turtle Bayou and Kent Bayou fields is not as easily explained. The anticlinal structures at these two fields are associated with temperature lows. Low temperatures on top of the Kent Bayou field structure are especially interesting because the geopressured zone intersects the 12,000-foot mapping horizon. This intersection of horizons normally gives temperature values higher than surrounding areas. It is probable that these low temperature areas are somehow related to deeper structures which cannot be seen on the Cristellaria (I) sand structure map.

Temperatures throughout the area, at the 12,000-foot horizon, have a fairly low variance. The temperatures range from about 200° to 240°F at this horizon, averaging

approximately 230°F. Deep geopressured sands which were evaluated had temperatures which ranged from about 220° to 275°F. Several of the temperature measurements on these sands can be seen on the temperature map, in parentheses, next to the 12,000-foot measurements. The Robulus (43) sand, evaluated in the northern part of the study area, had an average temperature of about 260°F. In the central part of the study area, where the Cristellaria (I) sand was evaluated temperatures were relatively low, ranging from 210° to 255°F and averaging about 230°F. The Cibicides opima sand which was studied in the eastern and southeastern areas has temperatures ranging between 225° and 270°F. Cibicides opima sand temperatures in the graben block between Faults "B" and "H" were generally higher than those on the horst block to the south, as expected. No single area had temperatures which were consistently above 250°F. The most prospective areas for geopressured-geothermal energy, in terms of water temperature, appear to be in the Ramos field area and north of Fault "H" in the Gibson field area.

Pressure

As stated earlier, fluid pressure gradients of 0.7 psi per foot or greater are desired in prospective energy reservoirs. These pressures are important because they control the primary driving forces which produce geothermal waters.

A pressure map (Plate 11) was constructed on the 0.7 psi per foot pressure gradient in the study area. The above pressure gradient has been defined as the top of hard geopressure (see section titled Geopressure) and occurs at the base of a transition zone from normally pressured strata. This transition zone is usually very easy to locate on electric logs, occurring where resistivity values (averaged in "clean" shale sections) are abruptly reduced. A typical electric log transition zone is illustrated in Figure 5. When the transition from normally-pressured strata to geopressured strata takes place over several hundred feet it is difficult to visually pick the top of hard geopressure. To assist in obtaining values for these cases and for general consistency of "picks" throughout the area, a Schlumberger resistivity-depth pressure prediction chart (in Ham, 1966) was used (Figure 8).

Comparison of the pressure map (Plate 11) and the deep structure map (Plate 9) indicates that the top of geopressure is greatly affected by structure. All anticlinal structures in the study area are associated with a relatively shallow occurrence of the 0.7 psi per foot pressure gradient. Also apparent from the two maps is the fact that at least one of the major fault zones is acting as a pressure seal between different geopressured horizons. This is especially well illustrated by the Houma embayment fault zone, north of Kent Bayou and Turtle Bayou fields. Although the other two

R_{SHALE} -DEPTH PRESSURE PREDICTION CHART

Figure 8. Chart for estimation of pore pressure from Louisiana Gulf Coast shale resistivities (modified after Schlumberger, in Ham, 1966).

regionally extensive faults, "A" and "L", certainly affect the top of geopressure horizon, without more extensive mapping it is difficult to say if they are acting as pressure seals between the horizons. Steep gradients associated with the above two fault zones may simply indicate a "leaking" of pressure along the structures, quite the opposite of sealing.

Prospect Evaluation

Considering the information presented within this report, it is possible to make some preliminary judgments on the study area's potential for producing geopressured-geothermal energy.

In the northern part of the study area around Ramos field and south to the Houma embayment fault zone, the Robulus (43) sand was evaluated. As is true of all other sands to be mentioned, it lies below the top of hard geopressure. Pore fluid temperatures, of the Robulus (43) sand, in Ramos field and to the south are among the highest found in the study area. They average approximately 260°F, 10° above the suggested prospect minimum. The Robulus (43) sand is relatively thin on top of the Ramos field structure, with some wells showing less than 50 feet of good "clean" continuous sand. Moving south, off of the field structure, a net sand isopach study (Plate 7) indicates a steady thickening of this sand. The southernmost wells in Ramos field show well over 100 feet of sand but it generally contains 3 or more thin shale beds, limiting the

amount of continuous sand to approximately 70 feet. This sand probably reaches its maximum thickness just south of Ramos field before thinning again along the Houma embayment fault zone.

The Cristellaria (I) sand was evaluated in the Kent Bayou-Turtle Bayou-North Turtle Bayou area. Of the three geopressed sands studied, the Cristellaria (I) sand is the least prospective. The average fluid temperature within this sand is about 230°F, 20° below the suggested prospect minimum for prospective sands. Although locally the sands are extremely thick and vertically continuous, the channel facies severely limits their lateral extent. Another deterrent to geothermal energy production is the fact that hydrocarbons are being produced out of this sand in North Turtle Bayou field.

In the eastern-southeastern part of the study area, the geopressed Cibicides opima sand was evaluated. Fluid temperatures within the Cibicides opima sand are highly variable. On the northern side of Fault "H", in the Gibson field graben block, temperatures average about 255°F which is higher than the 250°F suggested minimum. South and southeast of Fault "H", temperatures are much lower, averaging approximately 235°F. The net sand isopach map (Plate 7) indicates good accumulations of sand throughout the area, with the exception of a small area cresting the Humphreys field structure. Even with the presence of several thin shale lenses in many well

logs, there is generally over 100 feet of vertically continuous sand present.

I believe that, if further studies are made in the present study area on geopressured-geothermal energy potential, they should be concentrated around the southern Ramos field area and between Faults "B" and "H" in the vicinity of Gibson field. The geological investigations presented herein indicate that these areas have the highest potential for geothermal energy.

CONCLUSIONS

The Kent Bayou-Turtle Bayou field study area lies within a prolific hydrocarbon-producing trend of Early and Middle Miocene age which roughly parallels the present Gulf Coast shoreline. A northeast-southwest regionally trending fault zone is centrally located within this area and marks the northern limits of the Houma embayment. Cross-sections, isopach studies, and paleontological information indicate that inception of this embayment occurred in an outer shelf to slope edge environment during a period which can be dated no later than earliest Middle Miocene (Cibicides opima deposition). The embayment served as a depocenter for marine and deltaic sediments through Bigenerina humblei zone deposition. Continued deposition resulted in an outbuilding of the continental shelf. The southern boundary of the study area is marked by another large regionally-trending fault zone. This zone also may have been initiated in an outer shelf to slope edge environment during some period post-dating or near the end of Houma embayment deposition.

Several anticlinal-type structures have been identified within the study area. As no wells in the area have penetrated salt or diapiric shale, one can only speculate upon the

origin of the anticlines. Although time of uplift could not be determined for all the above structures, it is known that movement took place during at least two different periods. Geological evidence indicates that the Kent Bayou field and Turtle Bayou field structures were initiated much later than uplift of the Humphreys field structure.

The relatively shallow top of geopressure and abundance of deep (12,000+ feet) wells made it possible to evaluate several deep geopressured sand bodies within the study area. Three sands, the Robulus (43) sand, Cibicides opima sand, and the Cristellaria (I) sand, were selected and preliminarily evaluated for their potential in producing geopressured-geothermal energy. Two of these sands, the Robulus (43) sand and the Cibicides opima sand, in limited areas meet several of the Department of Energy's suggested minimum requirements for a prospective geopressured-geothermal energy reservoir. It is recommended that future geothermal energy investigations be concentrated in the following two areas: 1) on the Robulus (43) sand in an area just south of and on the southern flanks of Ramos field, and 2) on the Cibicides opima sand in the Gibson field area.

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Daniel R. Moore was born in Marlinton, West Virginia on March 19, 1957. Upon graduation from Asheville High School (Asheville, North Carolina) in 1975, he attended Appalachian State University in Boone, North Carolina, where he received his Bachelor of Science degree in Geology. In the fall of 1980 he entered Graduate School at the University of Southwestern Louisiana where he submitted this thesis for a Master of Science degree in Geology.

C66

A
WEST

A'
EAST

PLATE 2
KENT BAYOU-TURTLE BAYOU AREA
TERREBONNE PARISH, LOUISIANA
STRUCTURAL CROSS SECTION
GEOLOGY BY: DAN MOORE DRAFTED BY: HENRY R. HARRIS

PLATE 3
KENT BAYOU-TURTLE BAYOU AREA
TERREBONNE PARISH, LOUISIANA
STRUCTURAL CROSS SECTION
GEOLOGY BY: DAN MOORE DRAFTED BY: HENRY R. HARRIS

C
SOUTH

C'
NORTH

PLATE 4
KENT BAYOU-TURTLE BAYOU AREA
TERREBONNE PARISH, LOUISIANA
STRUCTURAL CROSS SECTION
GEOLOGY BY: DAN MOORE DRAFTED BY: HENRY R. HARRIS

PLATE 5
KENT BAYOU-TURTLE BAYOU AREA
TERREBONNE PARISH, LOUISIANA
STRATIGRAPHIC CROSS-SECTION D-D'
GEOLOGY BY: DAN MOORE DRAFTED BY: HENRY R. HARRIS

PLATE 6
TYPE SECTION
KENT BAYOU - TURTLE BAYOU AREA
TERREBONNE PARISH, LOUISIANA

C72

C73

C74

C75