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SUBSURFACE EVALUATION OF THE GEOPRESSURED-
GEOHERMAL CHLOE PROSPECT
CALCASIEU PARISH
LOUISIANA

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December, 1981

MASTER

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INTRODUCTION

In the past ten years attention has been focused on the reservoirs of abnormally pressured hot water existing in the Gulf Coast region, and the feasibility of developing from this resource hydro-energy, geothermal energy, and dissolved methane. These reservoirs lie within the geopressured sediments that are common to this region. The sediments underlie a belt extending from approximately 100 miles inland out to the continental shelf that extends along the coast from the Rio Grande River to the Mississippi Delta (Bernard, 1978).

An abnormally high ratio of pore fluid pressure to depth of .7 psi/ft. or greater occurs within the geopressured sediments. The pressure is due largely to movement along growth faults, which trap interstitial water in the sediments by isolating them from porous updip aquifers (Dickey, 1968). When the water circulation is arrested, subsurface heat accumulates in the incompletely compacted and dewatered sediments, resulting in higher water temperatures. This hot, pressured water is presumed to be saturated with dissolved methane (Jones, 1975).

Estimates of the energy potential of the resource vary widely. In the Gulf Coast region the estimates of recoverable methane vary from 60 trillion mcf (Bernard, 1978) to

57 billion mcf (Hawkins, 1977). In a more conservative estimate of the reserves in Louisiana, Hawkins (1977) stated:

The geothermal geopressured potential of the Southern Louisiana Tertiary sands, in terms of technically recoverable energy, is estimated at 34.3 quadrillion BTU's or an equivalent of 6 billion barrels of oil. The technically recoverable natural gas from hot water alone is about 13.6 trillion cubic feet.

Within the range of expected reservoir temperatures, pressures, and salinities a typical well would be expected to produce between 30 and 50 standard cubic feet of methane per barrel of water (Bebout, 1978). Even at conservative estimates geopressured-geothermal energy represents a tremendous potential resource in the Gulf Coast region.

This report was conducted under research contract DE-AS05-78ET27161 for the Department of Energy to evaluate the geopressured-geothermal possibilities of the Chloe Prospect in Calcasieu Parish, Louisiana. The prospect was proposed by George Friedel (1978) in his ERDA study "Structure and Geothermal Relationships in the Lake Charles Area of Southwestern Louisiana." In the study Friedel concluded that the lower Hackberry sands of the Frio Formation were laterally continuous, thick sands within a pressured section that met the requirements for a nonelectrical geopressured-geothermal prospect. The purpose of the present study is to further refine the boundaries of the prospect, determine the reservoir parameters pertinent to production from the

reservoir, and relate them to the geologic structure and stratigraphy of the area.

The study area is located within the Oligocene Hackberry Embayment of the Gulf Coast Geosyncline (Figure 1). The three major structural features in the area are the Gillis-English Bayou Dome, Iowa Dome, and the Manchester Anticline. The geopressed reservoir in the study area is the Lower Hackberry "A" massive sands. The sands rest unconformably on older beds ranging from Lower Frio to Vicksburgian. Maps of the unconformable surface and geometry of the sands suggest the Hackberry sands were deposited as turbidites within a submarine channel (Paine, 1968; Benson, 1971).

The study was conducted using electric log and paleontologic data for structural cross sections and maps. Reservoir data were compiled from a variety of sources including well logs, cores, bottom hole pressure tests, and chemical analyses of formation water.

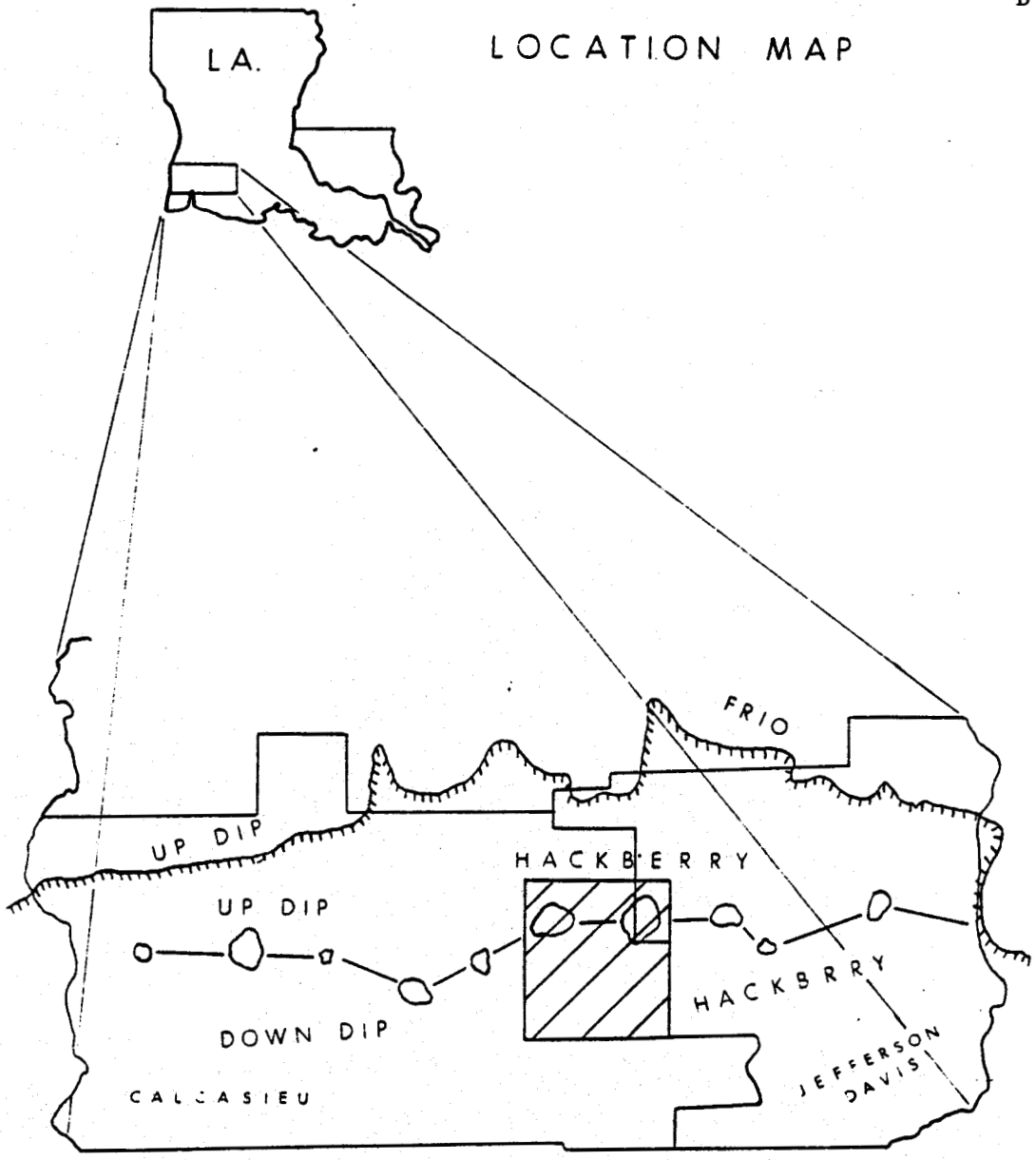


FIGURE 1

GEOPRESSURE

The normal overburden gradient for the Gulf Coast Tertiary sedimentary section is considered to be 1.0 psi/ft. (Fertl, 1975). The pressure is due to the combined weight of the sediments and their contained fluids on the underlying formation. The two components of this pressure are the lithostatic pressure (.535 psi/ft.) and fluid pressure (.465 psi/ft.). Normally lithostatic pressure is transmitted through rock by the mineral particles in contact, whereas fluid pressure is transmitted through the fluids that fill the pore spaces. Within normally compacting sediments water is free to escape as porosity is reduced during compaction.

In certain situations pore water is not free to escape. As the weight of overburden increases, pore space is reduced by compaction and the pore water partially supports the weight of the overlying rock. In this case the pore water is considered geopressured. Dickinson (1953) defines geopressure as "any pressure which exceeds the hydrostatic pressure of a column of water (extending from the stratum tapped by the well to the land surface) containing 80,000 mg./l. total solids." Therefore the geopressured zone is one of abnormally high pore fluid pressure within incompletely compacted and dewatered sediments, wherein the pore fluid partially

supports the weight of the rock overburden.

The prerequisites for a geopressured section are the presence of sealed sediments and a source of pressure. In the Gulf Coast Geosyncline rapid deposition of thick prodelta shales associated with contemporaneous faulting has formed much of the pressured sediments. Regional studies have shown that abnormal pressures generally occur within a major shale sequence (Dickinson, 1953). In the study area geopressure is encountered in the massive Hackberry Shale which acts as a pressure seal as well as a source of the geothermal waters found in the reservoir sand.

GEOPRESSURE SEALS

Three types of geopressure seals are commonly encountered in the Gulf Coast. These are: low electrical resistivity shale seals; osmotic seals; and limey sand and shale seals.

Low electrical resistivity shales have a low resistivity because they are undercompacted and contain more pore water than normally compacted, higher resistivity shales. Low resistivity shale seals are made up of fine grained shales composed of various clay types. Their sealing ability is due to their small grain size, which reduces permeability. Compaction with depth of burial rapidly reduces shale permeability. As little as 3 percent reduction in shale porosity reduces permeability by 30 percent. The nature of shale pore water

also influences permeability. The water adsorbed on clay particle surfaces is several hundred times more viscous than normal water (Grim, 1962). The net result is that in a massive shale section the effectiveness of the seal increases with depth as permeability decreases.

Gulf Coast shales contain a significant portion of montmorillonite. With burial montmorillonite is converted to illite due to the increase of temperature with depth. Illite tends to be less plastic than montmorillonite. With this conversion the shales tend to lose their plasticity and are more susceptible to fracturing. Fracturing can diminish the sealing ability of the shale. For this reason low electrical resistivity shale seals are more common in younger sediments. Low electrical resistivity shale seals are important early in the history of the formation of geopressure, but may be only a minor contributor to sealing in older sediments.

Osmotic pressure seals result from the property that clays can act as semipermeable membranes passing water but not ions. A difference in salinity on either side of a clay bed will cause water to flow to the more concentrated side due to osmotic pressure. In a compacting shale sequence more water is initially squeezed from the lower portion of the sequence, increasing its salinity. The released water migrates upward to decrease the salinity in the upper section of the shale. An osmotic gradient builds up until the pressure

gradient towards the lower shale seal equals the flow gradient of the underlying pressured strata. At this point the seal is complete and impermeable to fluid movement. The conversion of montmorillonite to illite with depth and increasing temperature destroys this type of seal. The conversion releases intercrystalline fresh water which disrupts the osmotic gradient. For this reason osmotic pressure seals are generally found in younger sediments.

Limey sand and shale seals form where calcium carbonate is deposited in the pore space of sediments, making them impermeable. Calcite within shales commonly is dissolved during diagenesis and is transported upward by released shale waters. It moves along fault planes and within beds to be precipitated in certain horizons. This process may form calcareous sands or limey streaks within shales. Calcareous concentrations may also form when an osmotic seal breaks down. In this case the calcite is deposited just above the previous osmotic shale seal. Limey sand and shale seals generally form early in the history of the geopressured formation and remain stable with increased depth of burial and temperature. This is the main type of seal responsible for the geopressure of the older Hackberry Shale in the study area.

CAUSES FOR GEOPRESSURE

With the continued deposition of overburden a point is reached where the sediments become sealed and pressure begins to build. Below the seal, water cannot escape, and further compaction is arrested. As a result the pore fluid begins to partially support the weight of overburden. Theoretically, the ratio of pore fluid pressure to depth would be 1.0 psi/ft. if the water supported the entire weight of overburden. In practice the seals are rarely 100 percent efficient and the matrix partially supports the overburden. In the Gulf Coast this ratio rarely exceeds .8 psi/ft. in the geopressed sections.

Abnormally high pore fluid pressures may result from a number of interrelated geologic processes. Pressure may be due to a combination of processes, with different processes dominating at different times in the history of the sediments. Causes for geopressure include compaction, clay mineral diagenesis, aquathermal pressuring, osmosis, and secondary precipitation.

Compaction, or more correctly lack of compaction, results from the inability of sealed sediments to expel pore water. The trapped water partially supports the weight of overburden, resulting in geopressure. The diagenetic conversion of montmorillonite to illite also causes geopressure.

At a temperature range of 200° to 230° F montmorillonite

starts to dehydrate to form illite, releasing intracrystalline water in the process (Burst, 1969). If the sediments are sealed the increased pore water volume produces geopressure. Aquathermal pressuring is caused by temperature-induced expansion of water within sealed sediments. Since the volume of the sediments is fixed, the expansion of pore water results in pressure. Osmosis can create geopressure as well as providing a sealing mechanism. Formation of the seal causes water to move below the seal, pressuring the formation. Secondary precipitation of cements such as calcium carbonate and silica within sealed sediments reduces pore space and hence may pressure a formation.

DEVELOPMENT OF GEOPRESSURE IN THE STUDY AREA

In the study area the rapid deposition of the upper Hackberry Shale provided the necessary conditions for the development of geopressure. This rapid deposition was accompanied by basin subsidence. As the weight of overburden and compaction increased, basinward slumping caused the formation of growth faults. The faults isolated the shale and enclosed sands from permeable updip strata. Water convection which normally would have dissipated heat was halted, causing higher than normal formation temperatures. Osmosis and compaction may have been important in the early history of the formation of a geopressured seal. As the temperature increased with depth of burial, montmorillonite was converted to illite and fresh water was released to pressure the section. Since this additional water was sealed in the sediments, it created and preserved higher than normal porosity by halting compaction.

The limey sands and shales of the Frio, and particularly the limey shales of the upper Hackberry, indicate that primary or secondary precipitation of calcite was important to the formation of the pressure seal. The other previously discussed sealing mechanisms tend to break down through time in relatively older sediments such as the Frio Formation. The

limey sections may have formed early in the depositional history or by secondary precipitation from waters escaping from the pressured section.

STRATIGRAPHY

The study area is located within the Anahuac-Frio trend of South Louisiana. Biostratigraphic divisions of this interval are based on the occurrence of benthonic foraminifera. The subdivisions of Warren (1957) were used for this report (Figure 2). The age of the Anahuac stage is shown as Oligocene-Miocene and has been in dispute for many years. The age of the Anahuac arbitrarily will be considered Oligocene in this report. The stratigraphic intervals of study, in ascending order, include the Vicksburg, Frio, and Anahuac stages of the Oligocene. Miocene or younger deposits are not considered in this study. Plate 2 is a type section showing the north-south stratigraphic relations of the area. On this section the terms "updip" and "downdip" refer only to the northern and southern portions, respectively, of the study area. The locations of the two type logs used are shown on Plate 1.

VICKSBURG STAGE

The strata above Bulimina jacksonensis and below Textularia seligi are generally recognized as Vicksburg. The Vicksburg consists of dark calcareous marine shale, marl, and lesser amounts of limestone (Paine, 1968). These strata were

Series	Terminology used in this paper	Generalized Zonal Terminology	Benthonic Index Foraminifera
MIOCENE	Post-Anahuac (lower section only)	Zones assume the names of the distinctive fossil	Amphistegina spp. Operculinoides sp. Discorbis bolivarensis Marginulina ascensionensis Siphonina davisii
OLIGOCENE-MIOCENE (controversial)	Anahuac Stage	Discorbis Zone	Lenticulina jeffersonensis Discorbis nomada Discorbis gravelli
		Heterostegina Zone	Heterostegina spp. Bolivina perca
		Marginulina Zone	Marginulina idiomorpha Marginulina vaginata Marginulina howei
OLIGOCENE	Frio Stage	Upper	Operculinoides sp. (Camerina sp. A) Miogypsina (Miogypsinoidea) sp. Cibicides hazzardi
		Middle	Marginulina texana Hackberry Assemblage
		Lower	Nonion struma Nodosaria blanpiedi Discorbis sp. Textularia seligi
	Vicksburg Stage		Cibicides mississippiensis Textularia warreni Textularia tumidula Anomalina bilateralis and others.

FIGURE 2. CORRELATION CHART FOR ANAHUAC AND FRIO SEDIMENTS, SOUTH LOUISIANA (WARREN, 1957).

deposited as shallow water marine sediments in a stable shelf environment (Benson, 1971). The Vicksburg stage represents a major period of transgression and is dominated by marine shales (Reedy, 1949). Vicksburg sediments were only encountered in the northern part of the study area. With the exception of salt, these are the oldest sediments encountered in the study area. The base of the Vicksburg was not encountered.

FRIO STAGE

The Frio Stage of Southwest Louisiana was divided by Paine (1968) into updip and downdip sections. The updip Frio section extends northward of the updip pinchout of the Hackberry sediments (Figure 1). South of this line the downdip Frio contains the Hackberry shale wedge. The downdip Frio is further subdivided into updip and downdip Hackberry. The boundary between these Hackberry divisions is the salt dome line (Figure 1). The study area is within the downdip Frio and contains both updip and downdip Hackberry. Within this framework, the subsurface Frio is divided into lower, middle, and upper zones.

Lower Frio

The strata above Cibicides mississippiensis and below the Hackberry Assemblage are recognized as Lower Frio. The

amount of section present and the character of the strata developed varies considerably in the study area. This variance is due in part to the two unconformities within the section. The northern type log (Plate 2) shows the stratigraphic position of the unconformities.

The lower unconformity, termed the Nodosaria-Vicksburg unconformity, is within a shale section below the beds containing Nodosaria blanpeidi. It cuts into the Lower Frio section and in some places into the top of the Vicksburg. The unconformity is best developed in the vicinity of the Gillis-English Bayou Dome. It may be a local unconformity. Evidence for the unconformity is twofold. First, numerous wells in the area are missing various amounts of section at about the same stratigraphic interval. Characteristic index foraminifera usually found below Nodosaria blanpeidi in other areas are missing. The unconformity is probably due to erosion.

The upper unconformity, or Hackberry unconformity, is found between the top of the Lower Frio section and the overlying Hackberry sediments of the Middle Frio. This unconformity is of major proportions. It was found in all wells in the study area drilled to a sufficient depth. Dipmeter logs show it to be an angular unconformity. The overlying Hackberry sediments have a regional dip of 1 to 5 degrees to the south. The underlying Lower Frio Section has higher dip

rates of 20 to 45 degrees in random directions, indicating a period of extreme folding and/or faulting (Benson, 1971). Paleontologic data also confirm the unconformity. The overlying Hackberry contains an outer shelf to lower slope fauna, while the underlying Lower Frio contains a shallow water middle to inner shelf fauna (Benson, 1971). There is no transition between faunas, but rather a sharp break.

A structural map of the top of the unconformity surface (Plate 3) and cross sections (Plates 9 through 13) show the nature of the unconformity surface. It can be seen that the surface is cut by channels running roughly in a north-south direction. Development of the unconformity and associated channels will be discussed later in terms of the development of the reservoir sands.

The Lower Frio section is composed of alternating sands and shales deposited in a middle to inner shelf environment. The development of sands within this section varies widely within the study area. Around the Gillis-English Bayou Dome area the section is thinnest. It is composed predominantly of shale, with minor sand lenses of 10 to 50 feet thickness each. In the Iowa Dome area the section is thicker. Massive sands dominate the section and alternate with thin shales. These appear to be localized shelf sands. In the southern portion of the study area the base of the Lower Frio has not been reached. In the wells in this area the Lower Frio is in

excess of 1,500 feet thick. In the Holmwood and Manchester Field areas the lower portion of the Lower Frio section is predominantly shale, with interbedded sand stringers. In the upper portion above the Nonion struma marker, a sequence referred to as the post-Nonion struma section is composed of sands separated by numerous thin shales. The thicker Lower Frio section in the southern part of the study area was deposited in slightly deeper water than its thinner northern counterpart.

Middle Frio

In Southwestern Louisiana the strata above Nonion struma and below Cibicides hazzardi are recognized as Middle Frio. In northern Calcasieu and Jefferson Davis Parishes an additional shale sequence occurs between the "normal" Upper and Middle Frio. Paine (1968) referred to this section as the Hackberry shale wedge. The name Hackberry was introduced by Garrett (1939) to designate the foraminiferal assemblage found in the shale section. Figure 1 shows the updip limit of the wedge north of the study area. From here the wedge thickens rapidly to the south across the salt dome line. Its thickness varies from 0 feet at the updip limit to more than 3,000 feet in the Plymouth Daughenbaugh No. 1 well, Sec. 29, T.10 S., R.7 W., in the southern portion of the study area.

In the study area the Hackberry shale wedge accounts for the entire Middle Frio section. Its base is marked by the Hackberry unconformity where it rests on beds from Lower Frio to Vicksburg. Its top is below Cibicides hazzardi and is generally placed at the top of the monotonous shale sequence characteristic of the upper Hackberry. The Hackberry wedge can be subdivided into upper and lower units. The lower unit contains a diagnostic "arenaceous fauna" which is distinctly different from the fauna in the upper unit (Garrett, 1939). Both sections contain pelagic shales with a deep water fauna (Hackberry Assemblage) indicating deposition at bathyal depths.

At its base the lower Hackberry shale wedge contains a massive sand section of varying thickness which lies just above the unconformity. The sand section grades upward into a pelagic shale which contains erratic sand lenses 10 to 30 feet thick. In the lower massive sand section the lithology changes abruptly both laterally and vertically between wells. This makes well to well correlations essentially impossible except for picking the top and base of the section. In the Manchester-Holmwood area picking the base is further complicated by the fact that the unconformity is in the middle of a massive sand sequence. In this sequence the Hackberry massive sands are above the unconformity and the post-Nonion struma section sands of the Lower Frio are below it. The

location of the unconformity was picked using the aid of paleontologic data, dipmeter logs, and electric log signature characteristics. Where these relations are not clear, particularly in the Manchester area, the unconformity picks of Benson (1971) were used.

The erratic nature of the massive sand section can be explained in terms of its genetic history and deposition environment. Based on core data, faunal relationships, and the geometry of the sand and underlying unconformity, numerous workers have concluded that the Hackberry sands are deep water turbidites (Paine, 1968, 1971; Benson, 1971; Kirst, 1977). The sands were deposited in a north-south trending channel in the northern portion of the study area. Around Manchester Field the channel branches out laterally into less confined subchannels. Here the sands were deposited in the subchannels and up against topographic highs of the unconformity surface (Plates 3 and 6). Sands are thickest and more massive in the axes of the channels. Away from the channel axes, sands are separated by shale intervals. This suggests the sands were formed by intermittent turbidite flows which produced stacked massive sands in the axes of channels and alternating sand and shale sequences along the channel margins. Sands first filled the channels, then spread out across the unconformable surface to lap out against highs. The sands have an increasing amount of interbedded shale with

increasing distance away from channels and topographic lows. For the purpose of this study the stacked sands will be considered as a single unit termed the Hackberry massive "A" sand. This sand unit is the reservoir of interest for possible production of geopressed-geothermal energy.

A conventional core from the Pan American Farmers Land and Canal No. A-4 well (Sec. 17, T.10 S., R.7 W.), was taken from the Hackberry "A" sand interval between the depths of 12,900 and 13,150 feet. Paine (1971) conducted a petrographic study of the core and concluded that the section was composed of turbidites. In his study he noted that:

. . . individual sandstone bodies range in thickness from a single 50 foot massive bed with small clay pellets to thinner beds of massive to laminated sandstone which average 3 to 5 feet. The thinner beds grade upward into siltstone and shale, many [of] which contain loadcasts and disturbed bedding. Although the cyclic nature of these sediments is less obvious (than the updip cycles), eleven cycles can be identified in the Manchester core. Some intervals . . . represent incomplete cycles in which a younger cycle has eroded the top of the next older cycle.

Figure 3 is a diagrammatic interpretation of a single complete turbidite cycle within this same core by Benson (1971).

Kirst (1977) conducted a petrographic study of the Hackberry "A" sand in the Manchester area using drill cuttings, sidewall cores, and conventional cores. Using the classification of Dott (1964), he classified the sands as feldspathic greywacke and subarkose. The sands are medium-

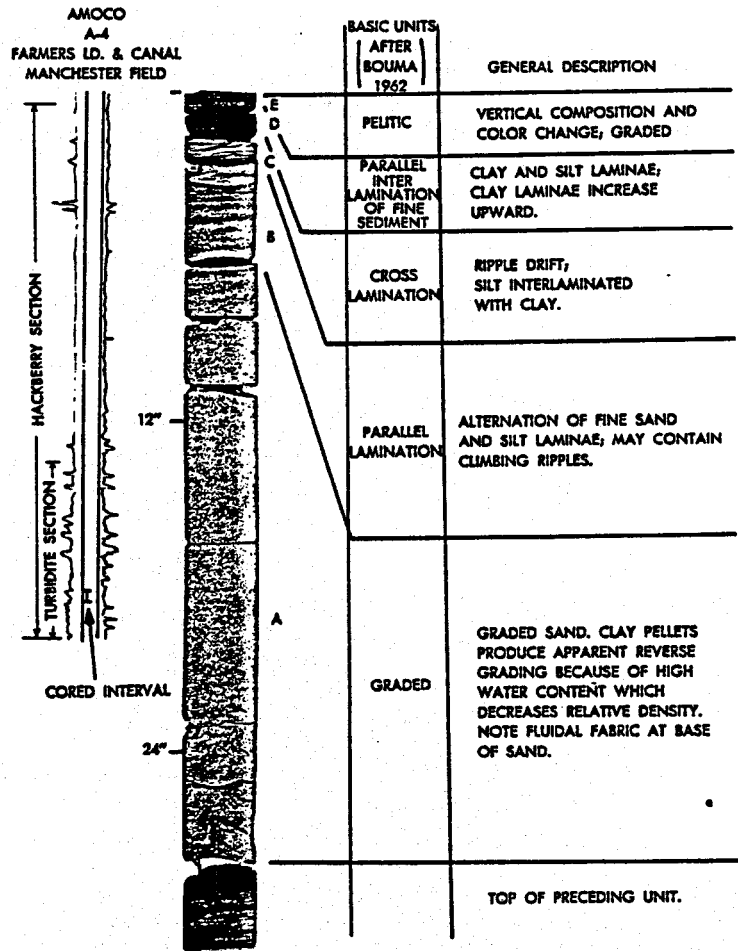


FIGURE 3. COMPLETE TURBIDITE SEQUENCE RECONSTRUCTED FROM CONVENTIONAL CORE IN AMOCO A-4 FARMERS LAND AND CANAL, MANCHESTER FIELD (BENSON, 1971).

to fine-grained and poorly sorted. Rock fragments are angular to subangular, with 50 percent of the fragments being shale. Kirst (1977) suggested that the shale fragments were torn from the channel bottom by the turbidity currents which deposited the sands. Plate 6 is a net sand map which shows the distribution of the Hackberry massive "A" sand. The sand produces hydrocarbons only at West and Southwest Manchester Fields where the strata pinch out against the unconformity against preexisting topographic highs.

The massive sand section grades upward into a pelagic shale sequence which contains sand lenses ranging from 10 to 30 feet in thickness. The thinner sands represent minor sporadic pulses of turbidity flows. Because the basin was partially filled and graded by the earlier massive sands, the younger thin sands are more widespread. Production has been established from these sands where they pinch out and where they have been draped by differential compaction over the underlying massive sands and adjacent shaley sections. The massive sand section and overlying shale and thin sands collectively form the lower unit of the Hackberry wedge.

The base of the overlying upper Hackberry wedge unit is defined by the last occurrence of the arenaceous fauna. Its top is below Cibicides hazzardi and is generally placed at the top of the monotonous shale sequence. The upper Hackberry wedge unit is predominantly dark gray palagic

shale with occasional thin sands and calcareous shales. Exceptions to this occur in the vicinities of Gillis-English Bayou, Iowa, and Holmwood Fields. In these areas the shale interval may contain several sandstone beds. The beds may be massive but are discontinuous. Locally they are economically important as hydrocarbon reservoirs. The upper Hackberry wedge unit was deposited in an outer shelf to slope environment.

Upper Frio

The base of the Upper Frio is placed above the occurrence of Marginulina texana. Its top is below the occurrence of Marginulina howei. The section is characterized by massive sands alternating with shales. The sands formed during inner neritic to deltaic deposition. The character of the section is relatively uniform within the study area.

The Hays sand is the first massive sand encountered above the Hackberry shale section. Above this is the Cibicides hazzardi marker sand. Plate 5 is a structural map of the top of this sand. At the top of the sand is a short shale section with a characteristic resistivity spike that was easily correlated in the study area. The next massive sands above, in ascending order, are the second Camerina and first Camerina sands. The first Camerina sand has a characteristic resistivity spike at its top due to a limey streak.

The massive sands of the Upper Frio are important hydrocarbon reservoirs in the study area.

ANAHUAC STAGE

The strata above Camerina sp. A and below Siphonina davisii are generally recognized as the Anahuac. Within the study area the top of the Anahuac is generally placed at the base of the massive Miocene sand section. The Anahuac is subdivided, in ascending order, into the Marginulina, Heterostegina, and Discorbis zones (Ellisor, 1944). The Marginulina zone consists of alternating calcareous sands and shales. The sands are massive, particularly in the northern portion of the study area. The Heterostegina zone contains calcareous shales with interbedded thin sands. The Heterostegina marker has a characteristic resistivity spike corresponding to a hard lime bed. The Discorbis zone consists of a shale section with three to four thin calcareous sands. The Anahuac sediments were deposited in an inner to outer neritic environment. The Anahuac sediments represent a major transgression in the study area. The transgression began during deposition of the Marginulina section and peaked during deposition of the Heterostegina section.

DEPOSITIONAL AND STRUCTURAL HISTORY

In the study area, the Middle Frio Hackberry wedge contains the geopressured-geothermal reservoir sand, as well as the shales responsible for the origin and sealing of the geopressured zone. For this reason the following discussion will focus mainly on the Hackberry wedge. The development of geopressure and distribution of the reservoir sand has resulted from a complex history of depositional and structural processes. The complicated stratigraphy of the Frio section was caused in part by a complex early Frio tectonic history and in part by depositional variations in the Hackberry section.

The first stage of the geologic history was the deposition of the Vicksburg sediments. In the study area, the Vicksburg represents a major period of transgression characterized by sedimentation in a shallow water sea. In the northern portion of the area, calcareous sands and shales were deposited in an inner neritic stable shelf environment. This environment changed little as the overlying Lower Frio section was deposited. The Lower Frio sediments have a more sandy character than the Vicksburg, possibly due to an increase in sedimentation rate or a change in source area.

Local uplift, particularly in the Gillis-English Bayou area,

resulted in the erosion which created the Nodosaria-Vicksburg unconformity.

After the unconformity was formed, deposition of the Lower Frio sediments continued in a middle to inner shelf environment. The sediments deposited were primarily shales with thin interbedded sands. An exception to this is the Iowa area where the equivalent sediments consist of localized massive shelf sands alternating with thin shales. The middle to inner shelf conditions prevailed up until about Nonion struma time, after which sedimentation became more sandy. The post-Nonion struma section was deposited and consisted of thick massive sands alternating with thin shales. A lower Middle Frio section was probably deposited above this but has been removed by the erosion which created the subsequent unconformity.

A major period of deformation followed the deposition of the Middle Frio section. This period was initiated by subsidence. Subsidence was rapid south of the salt dome line and less pronounced north of the line. Subsidence was probably related to salt tectonics. The area south of Gillis-English Bayou and Iowa Domes may have experienced salt withdrawal as salt mobilized in the early stages of the salt movements which formed the domes. South of the salt dome line rapid subsidence resulted in oversteepening of the slope, causing extensive slumping. Failure of large blocks in the

northern part of the area initiated turbidity currents which eroded a channel system. The pre-Hackberry sediments of the Middle and Lower Frio, and in places the Vicksburg, were removed by the turbidity currents. These sediments were probably transported through the area and deposited downdip.

North of the study area a shelf environment was established. Small, arcuate down-to-the-south faults formed near the shelf edge due to the tension formed during downdip subsidence. Sands supplied to the area moved across the shelf and were trapped in the shelf edge lows created by faulting (Paine, 1968). As downdip subsidence continued, progressive slumping at the channel heads resulted in headward erosion of the channels toward the shelf. When the channels reached the shelf edge, the thick sand accumulations at the shelf edge coupled with the oversteepened shelf to slope environment, initiated turbidity currents. These flows moved copious amounts of sand down the preexisting channels. Periodic turbidity currents deposited the lower Hackberry sands and shales. In the quiet periods between flows pelagic shales were deposited.

The areas of maximum erosion occurred in the northern portion of the study area where subsidence was less pronounced. Roughly south of the Manchester Field area the net effect of the turbidity currents was probably more depositional than erosional. Rapid subsidence resulted in the area being

topographically lower than the northern area, which helped to preserve more of the Lower Frio section. In the Manchester area the post-Nonion struma section of the Lower Frio appears to be the youngest remnant of the pre-unconformity sediments in the study area.

Deposition of the lower Hackberry massive sands was controlled by the unconformable surface. A comparison of the unconformity surface (Plate 3) and net sand distribution (Plate 6) shows the sands were deposited within channels and low areas between topographic highs. In the northern part of the area sand deposition is confined to a major channel developed between Gillis-English and Iowa Domes. The channel location, along with the observed thinning of Hackberry sediments approaching the domes, suggests the domes were positive features during the deposition of the Hackberry sediments. The presence of the channel close to the Gillis-English Dome indicates the dome was in an early stage of formation when the channel developed. Later growth of the dome has resulted in the channel being presently on the flank.

In the southern portion of the study area where the main channel branches out, sands have spread out laterally and were deposited in topographic lows. These areas subsided as sand accumulated, allowing for thicker deposits of sand. After initial lows were filled, the sands spread out across the unconformable surface to lap out against the Holmwood-South

Manchester, West Manchester, and Southwest Manchester anticlines. These anticlines remained as positive features during the deposition of the Hackberry as shown by the thinning of the Hackberry wedge over these areas.

After the deposition of the Hackberry massive sand section, the nature of the turbidity currents changed. The flows became less frequent, resulting in dominantly shale deposition. The flows were also of lesser magnitude, as shown by the thinner sands within the shale section. Deposition of the underlying massive sands had filled the channel areas and partially smoothed out the topography. For this reason later sporadic turbidites were progressively more widespread, producing blanket-like sands.

Towards the end of the period of lower Hackberry sedimentation, the frequency of sand deposition diminished. The upper section of the Hackberry wedge is predominantly deep water shale; very few sands are present. The end of the lower Hackberry deposition cycle was due either to a lowering of the flow gradient or a loss of the sand source. Gradual filling of the channels could have lowered the flow gradient to the point where channels could no longer keep themselves cleaned out (Friedel, 1978). In this case any additional sand would have been deposited further updip closer to the shelf edge. The sand source could have ended due to updip changes in the drainage system or the development of other depositional sites.

Deposition of the upper Hackberry shale continued to smooth out the topography. The only significant sands that were deposited within the shale sequence were in the vicinity of Iowa Dome. The faunal assemblage found in the shales shows they were deposited in an outer slope to abyssal environment (Paine, 1968).

The late Frio regression of the sea ended the deposition of deep water Hackberry shales. A shallow water shelf environment was established as the Upper Frio sediments prograded across the area. The Upper Frio and Anahuac sediments were deposited in a transitional period between the deep water sedimentation of the Hackberry and the shallow water deltaic sedimentation of the Miocene sediments. The uniformity of the massive sands within the Upper Frio and Anahuac suggests they were formed by the reworking of shelf sands. The major regression during the Miocene resulted in the progradation of the massive deltaic sand section which overlies the Anahuac.

The history of faulting in the area was controlled mainly by the development of salt domes, and to a lesser extent by depositional processes. Growth of the salt domes began during deposition of the Lower Frio and peaked in the Upper Frio. A second stage of salt movement at Iowa Dome renewed uplift in the Late Miocene to form the major down-to-the-north fault (fault "J", Plates 3, 4, and 5), which bisects the dome. Intrusion of the salt formed shallow graben faults

and radial faults near the crests of the domes. These faults created most of the structural traps associated with hydrocarbon production.

Faults "Q" and "J" (Plates 3, 4, and 5) are the only growth faults within the study area. Growth along these faults is related to Middle Frio to pre-Heterostegina deposition. The timing and development of faulting will be discussed in more detail in the following section.

STRUCTURE

Three structural maps and five cross sections were constructed to illustrate the structure of the study area. Two cross sections (Plates 9 and 10) trend north-south, while the others (Plates 11, 12, and 13) trend east-west. The horizons mapped, in ascending order, are the unconformity surface, top of geopressure, and top of the Cibicides hazzardi marker sand. Pertinent data on these horizons are shown in Table 1.

Table 1
Data for Structural Horizons Mapped

<u>Datum</u>	<u>Control Points</u>	<u>Min. Depth</u>	<u>Max. Depth</u>	<u>Relief</u>
unconformity	128	9,440'	13,497'	4,052'
geopressure	146	8,550'	11,440'	2,890'
<u>Cib. haz. sand</u>	263	7,261'	10,880'	3,619'

The map of the Cibicides hazzardi marker sand is the only structural map done of a surface defined by a lithologic unit. Both the unconformity and top of geopressure maps define surfaces that cut across lithologic boundaries. The criteria for picking the unconformity were discussed in the section on stratigraphy. The criteria for defining the "top" of

geopressured zone will now be discussed.

Fertl and Timko (1975) have outlined several methods for determining abnormally pressured environments in the well bore. One of the most useful methods involves the evaluation of logging tool responses to shales on well logs. Figure 4 is a diagram showing how various well logging parameters respond to normally pressured and overpressured shales. Since induction-electrical logs were available for all wells, the resistivity deviation method was used to pick the top of the geopressured zone. Normally pressured shales show an increase in resistivity with depth due to the loss of water with normal compaction. Below the top of the pressure seal (cap rock), the shales are undercompacted and show a marked decrease in resistivity as pressure builds within the transition zone. In the study area the shale section making up the transition zone is as thick as 600 to 800 feet. At the base of the transition zone the geopressure gradient reaches a maximum and the resistivity again increases with depth as this gradient is maintained. For the purpose of this study, the base of the transition zone was defined as the top of geopressure. It is important to note that this point does not correspond to a specific pressure. It merely shows the base of the effective seal where the pressure gradient has reached a maximum.

The development of structural features in the area has

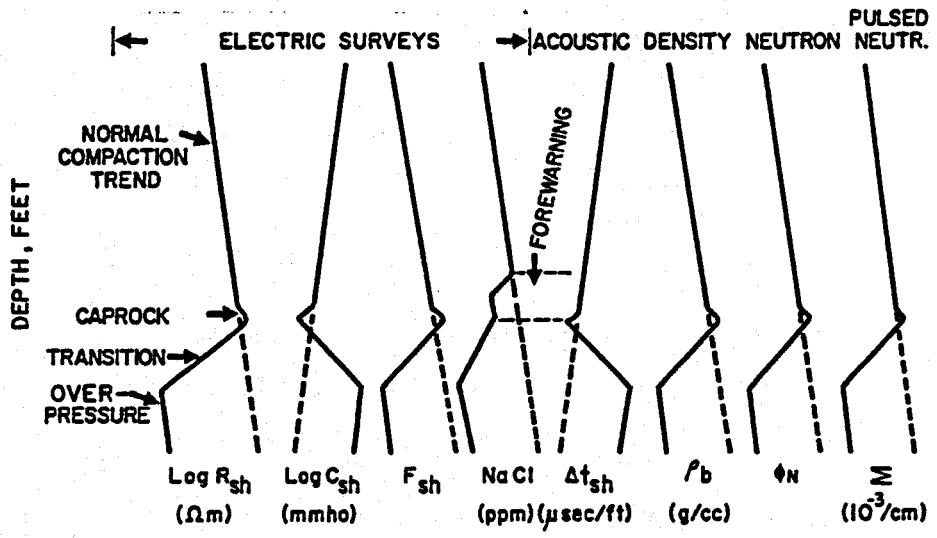


FIGURE 4. HOW WELL LOGGING PARAMETERS RESPOND TO NORMAL PRESSURE AND OVERPRESSURE (FERTL AND TIMKO, 1975).

been influenced primarily by salt dome growth and to a lesser extent by sediment distribution. Domal uplift in the northern half of the area was accompanied by salt withdrawal in the southern portion, establishing it as a depositional basin. Structural features in the northern part are a direct result of salt intrusion. In the southern part structural features are related to the large-scale movements of the thick sediment wedge over the underlying salt.

A comparison of the structural maps and cross sections shows that two types of positive topographic features are developed in the study area. These features are those which have not shown any growth since the formation of the Hackberry unconformity, and those which have developed since the unconformity.

The first type includes the Manchester-Holmwood, West Manchester, Southwest Manchester, and South Iowa anticlines. Bornhauser (1960) attributed the formation of these preunconformity anticlines to gravity folding. A comparison of the unconformity and geopressure maps shows that the relief on the stratal surfaces draped over the anticlines becomes less pronounced as the features are buried beneath the overlying sediments. The effects of the highs are no longer visible on the Cibicides hazzardi sand horizon; the unit was deposited over a relatively smooth surface. The anticlines controlled the structure of the pre-Cibicides hazzardi sediments in

that strata were differentially compacted over the highs.

Post-unconformity structural highs can be divided into those related to salt intrusion, and those related to depositional processes. The only highs related to deposition are the series of anticlines developed below growth fault "Q". These anticlines form a continuous belt from Bell City Field in the east to Coulee Hippolyte Field in the west. Deposition of the Cibicides hazzardi marker sand was contemporaneous with fault movement. This resulted in "roll-over" of the strata into the fault. Fault "J" is the only other fault in the study area showing significant growth. The symmetry of the structural contours across the fault shows that no significant roll-over occurred.

Salt intrusion is responsible for the development of structural highs in the northern portion of the study area. Domal uplift is most pronounced over Iowa Dome. Salt has been encountered by drilling to as shallow as 8,896 feet. Figures 5 and 6 show the structure of the top of salt and a north-south cross-section across the salt, respectively. A deep piercement feature, the salt core of Iowa Dome, has a northeast-southwest elongation. The salt core measures 3.5 miles on its long axis and approximately 2.5 miles on its short axis at a depth of 12,000 feet. Uplift and faulting of the dome are related to two stages of salt movement (Figure 6). The uplift at Gillis-English Bayou Dome is not as

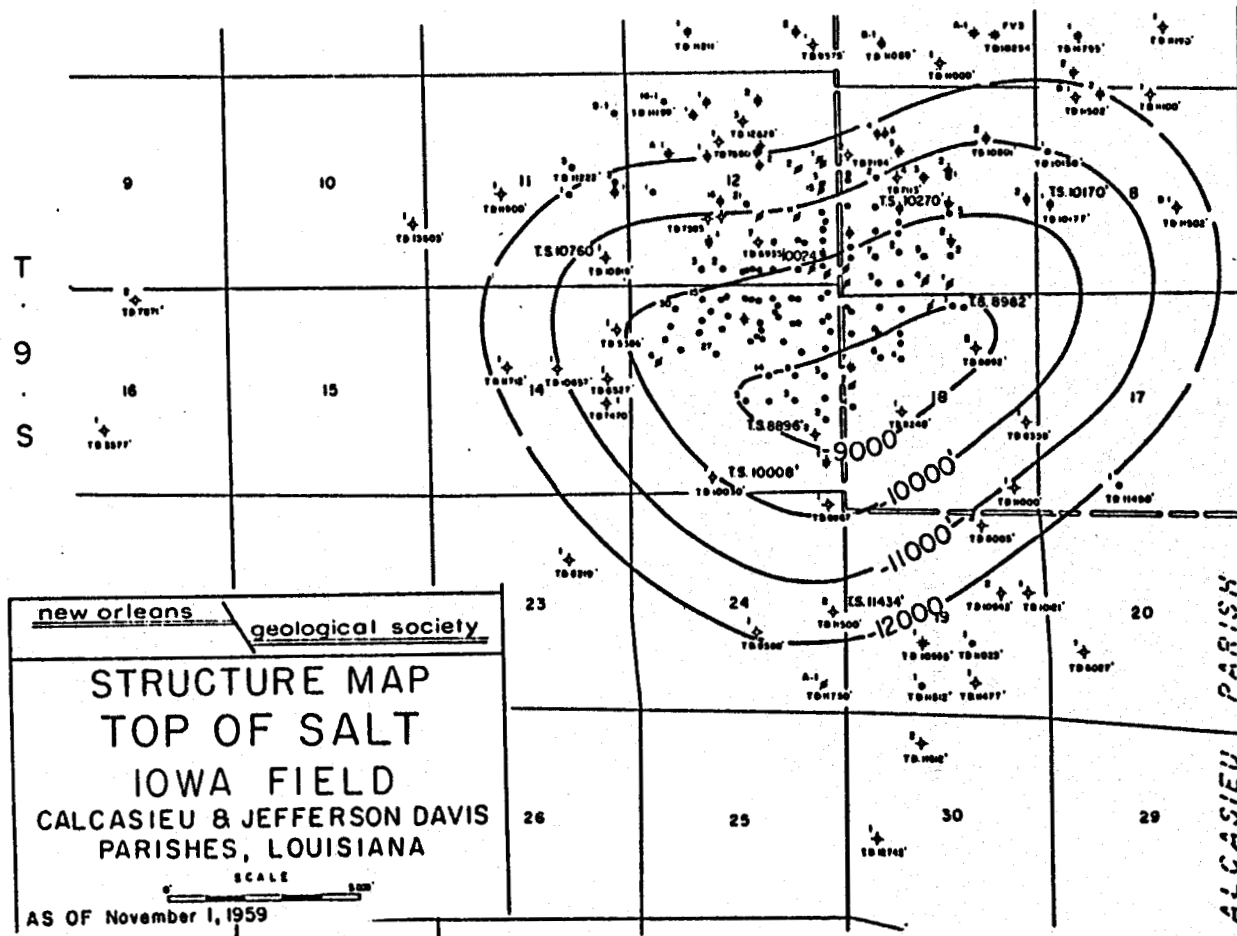


FIGURE 5. STRUCTURE TOP OF SALT, IOWA DOME (ATWATER AND FORMAN, 1959).

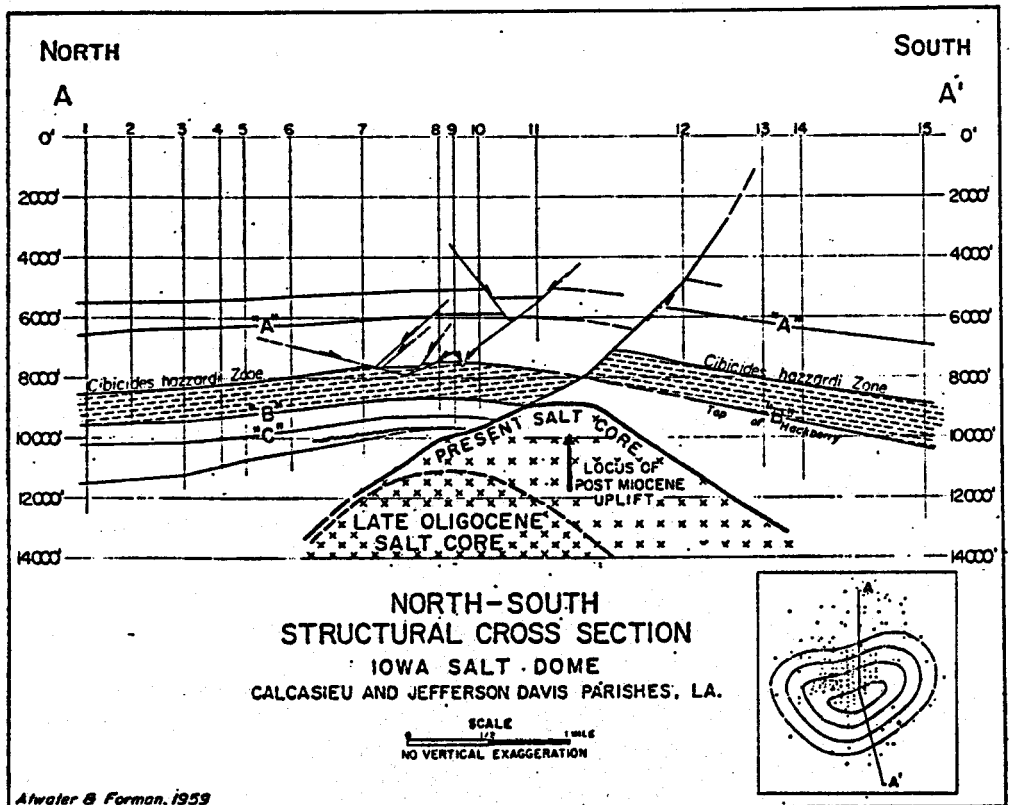


FIGURE 6. NORTH-SOUTH STRUCTURAL CROSS SECTION, IOWA DOME (ATWATER AND FORMAN, 1959).

pronounced as that at Iowa Dome. Uplift is presumably the result of deep-seated salt movement. To date there has been no salt penetrated by any of the field's wells.

Faults in the study area are of two classes: those related to salt tectonics and those related to sediment movement. A system of crestal graben faults and radial faults is associated with each salt dome. These faults are genetically related to salt intrusion. The faults form when strata fail under tensional stress developed during stretching over the intruding salt. The greater differential compaction of sediments over the flanks of the domes than their crests also contributes to the formation of radial faults. Crestal graben faulting generally results when a second later opposing fault forms in an effort to fill the potential void created by the first formed fault.

At Gillis-English Bayou Dome, crestal graben faulting has developed only in the shallower Anahuac deposits. These faults generally do not extend to the Cibicides hazzardi horizon. Radial faults "A", "B", and "C" are normal down-to-the-south faults which extend outward from the dome. Fault "W" is a down-to-the-north fault. It was a later fault that formed in response to the development of fault "B". The throw of the faults is greatest adjacent to the domes and decreases outward until the faults die out within a few miles of the dome.

The faulting at Iowa Dome is more extensive due to the greater uplift of the dome. Extensive crestal graben faulting is present in the shallower beds, but does not extend down to the Cibicides hazzardi horizon. Faults "D", "H", and "I" are radial faults which formed during the first stage of the growth of the dome. On the south flank of the dome a graben exists where faults "H" and "I" criss-cross in east and west directions. Fault "I" displaces fault "H", showing that fault "H" was formed first. Figure 6 shows the second major stage of salt movement which uplifted the southern flank of the dome. This uplift resulted in the formation of down-to-the-north fault "F". Faults "G" and "E" were later or contemporaneously formed down-to-the-south relief faults into fault "F".

Faults related to sediment movement and deposition are found in the southern half of the study area. Faults "J" and "Q" are the only faults in the area that show significant growth. In the interval between Cibicides hazzardi and the unconformity, the displacement along fault "J" increases from 40 to 100 feet, to 400 feet. Over this same interval fault "Q" increases from approximately 530 feet to 1,000 feet. The concordance of structural contours across fault "J" suggests that deposition on the downthrown side of the fault was gradual and widespread enough to maintain structural continuity across the fault. This is further confirmed by the Hackberry

Massive "A" net sand map. The map shows that deposition of the sand directly south of the fault was not appreciably greater than that north of the fault.

The well developed roll-over of sediments south of fault "Q" shows that deposition on the immediate downthrown side of the fault was greater than on the upthrown side. Minor down-to-the-south faults "R", "S", "T", "U", and "V" occur south of fault "Q". It is not known whether these minor faults show growth with depth. Most of the wells south of fault "Q" are relatively shallow, and adequate control was not available to map the top of geopressure.

The system of southwest-northeast trending down-to-the-southeast faults between faults "J" and "Q" are post-depositional. They probably formed in response to stresses caused by the large scale downdip movement of the sediment wedge over the underlying salt. These faults maintain approximately the same displacement on all three horizons mapped. Most of the displacement along the faults occurred during the initial break, with only minor movements thereafter as a response to deposition. These faults die out near the base of the Miocene massive sand section, which suggests that the faults formed between late Anahuac and early Miocene deposition.

RESERVOIR INVESTIGATIONS

The potential recoverable energy of interest in this study is contained within the hot, overpressured waters within the Hackberry massive "A" sand. This energy is in the forms of heat, pressure, and dissolved methane. Reservoir investigations were conducted to achieve the following goals:

1. Determine the values of the reservoir parameters pertinent to energy production;
2. Define a prospect and choose a drill site which would maximize the amount of recoverable energy;
3. Determine the energy reserves within the prospect.

The reservoir parameters of interest include the porosity and permeability of the formation, as well as the temperature, pressure, and salinity of the formation waters. Salinity determinations were included because the amount of methane dissolved in the water is a function of the water's temperature, pressure, and salinity. In the following sections, maps of the temperature and pressure variations in the reservoir will be used in conjunction with the net sand and unconformity maps to delineate a prospect area. Porosity data will be used to calculate the volume of water within the reservoir. Finally, the amount of methane within the reservoir waters will be determined.

TEMPERATURE

Sediments dissipate much of their heat by transferring it to circulating subsurface waters. Where geopressure seals form, water circulation is arrested and heat builds up below the seal. Geothermal gradients along the Gulf Coast are known to range from about 1.4° to 2.4°F per 100 feet (Bebout, 1975). Within the geopressured zone the temperature gradient increases rapidly compared to the overlying hydro pressured zone (Jones, 1975). This was found to be the case in the study area. Below the top of geopressure within the Hackberry shale section, temperatures begin to rise more rapidly with depth than in the overlying sediments. A study of the geopressured sediments in Manchester Field by Schmidt (1971) has shown that the geothermal gradient increases from 1.3°F per 100 feet in the hydro pressured zone to 2.1°F per 100 feet in the geopressured zone.

Within the study area, the temperatures at the top of the reservoir sand were estimated. No temperature logs or other direct measurements were available to determine the exact temperature of the reservoir sand. The only temperature data available were the bottom hole temperature measurements from well logs. The deep wells which penetrated the reservoir sand were drilled and cased in sections. Within the geopressured zone at least one bottom hole temperature was available both above and below the sand in these wells.

Given these two temperatures, a linear gradient was assumed and the temperature at the top of the sand was interpolated.

This calculated temperature is erroneously low for a number of reasons and had to be corrected. The first problem involves the time lag between the drilling of the formation and the time the temperature is recorded by the logging tool. A common practice in the Gulf Coast is to circulate mud through the hole at least several hours before running any logging tools. This is done to properly clean out the hole and to avoid lodging of the tool downhole. The mud is circulated from the surface to the bottom of the hole, then back to the surface. In the process, heat from the formation is transferred to the mud and dissipated at the surface. Since the thermal conductivity of rock is relatively low, it takes time for the formation adjacent to the well bore to heat back up to equilibrium temperature after circulation is stopped. Therefore, the bottom hole temperature recorded will be affected by the number of hours mud was circulated prior to logging. Secondly, it will be affected by the amount of time after circulation was stopped before the log was run. The net effect is that bottom hole electric log temperatures are generally lower than actual formation temperatures.

Temperature data are also recorded during bottom hole pressure tests. Bottom hole pressure tests are conducted several hours after mud circulation has been stopped in order

to allow the formation to more closely reach equilibrium temperature and pressure. Figure 7 is a graph of electric log and bottom hole pressure test temperatures versus depth for the Manchester Field area by Schmidt (1971). The graph shows that electric log temperatures are consistently lower than bottom hole pressure test temperatures. Although the latter are closer to the actual reservoir temperatures, they are still generally 30° to 50°F lower than true formation temperatures (Jam, 1969).

Another problem in using electric log temperatures is the inaccuracy of the thermometers used. Logs run before about 1960 used a single thermometer which was not very accurate. The amount of error has been reduced since this time by using better thermometers, and taking the average temperature from three thermometers run simultaneously.

Assuming a linear temperature gradient between two points also contributes to the error. In reality the gradient between the points may be erratic due to the complex interactions of physical and chemical processes within the formation.

Electric log bottom hole temperatures were corrected to approximate true equilibrium temperatures using the following relationship developed by Kehle (1971):

$$TE = TL - 8.819 \times 10^{-1} D^3 - 2.143 \times 10^{-8} D^2 + 4.375 \times 10^{-3} D - 1.018$$

where TE = equilibrium temperature (°F)

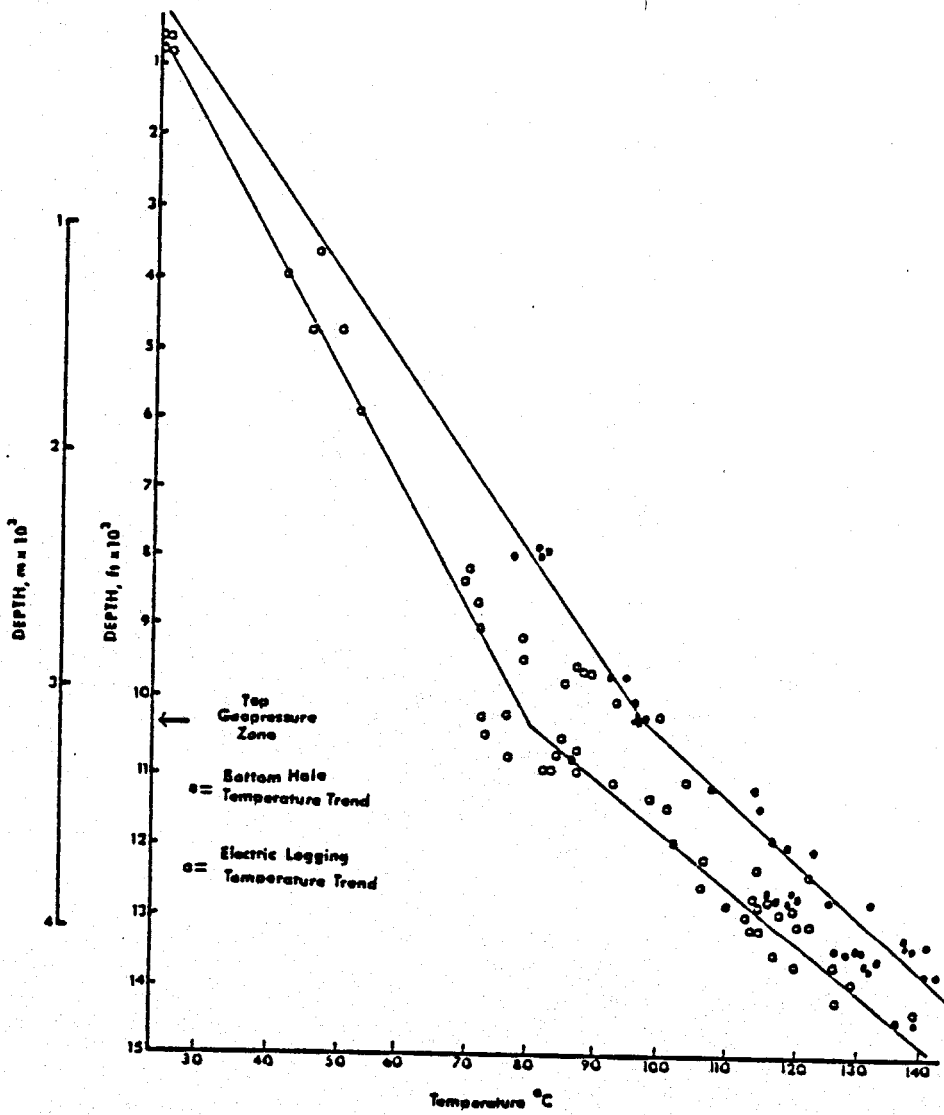


FIGURE 7. FORMATION TEMPERATURE VERSUS DEPTH, MANCHESTER FIELD (SCHMIDT, 1971).

TL = bottom hole temperature from well logs (°F)

D - depth in feet

This relationship is based on a statistical study of many wells over a wide area of the Gulf Coast. A plot of the temperature corrections derived from the Kehle relationship is shown in Figure 8.

After the electric log temperatures were corrected and plotted on a map, it became apparent that the temperature values just east of the Gillis-English Bayou Dome were inconsistent. In one instance, two wells less than a mile apart had a temperature difference of 72°F. Since these wells were drilled in the early 1950's it was assumed that some of the original bottom hole temperatures were anomalous due to inaccurate thermometers. In order to correct these temperatures, two plots of temperature versus depth were constructed. Figure 9 is a plot of the temperatures north of fault "B" and Figure 10 is for the wells south of fault "B". An average temperature line was fit through the data points for each area. Formation temperatures for the depth of the top of the reservoir sand were taken from the average temperature line. These temperatures were then corrected using the Kehle equation. On the temperature map (Plate 7) the corrected temperatures are designated with a "c" subscript. The anomalous uncorrected temperatures were included on the map and are circled. In the rest of the study area the corrected

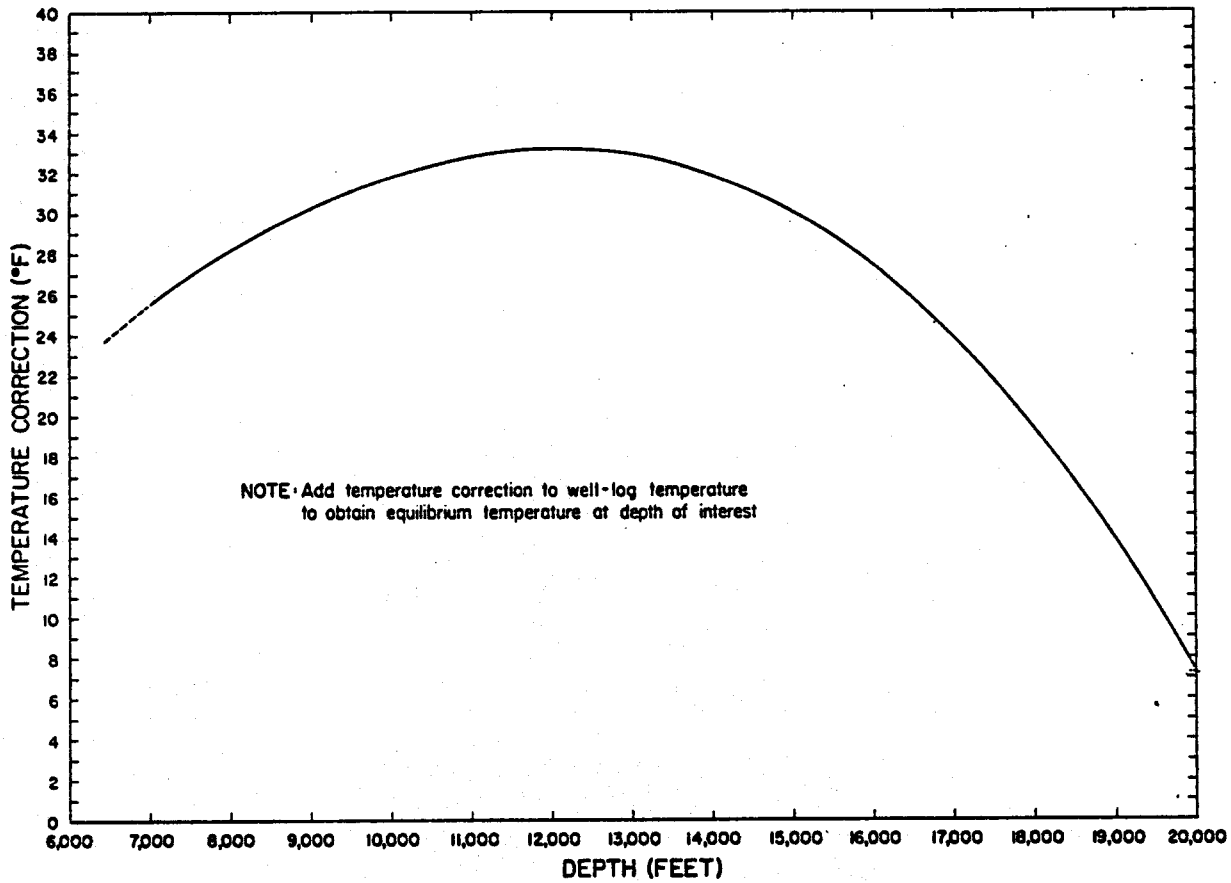


FIGURE 8. TEMPERATURE CORRECTIONS AS A FUNCTION OF DEPTH FOR ADJUSTING WELL-LOG TEMPERATURES TO APPROXIMATE EQUILIBRIUM TEMPERATURES (BEBOUT, 1978).

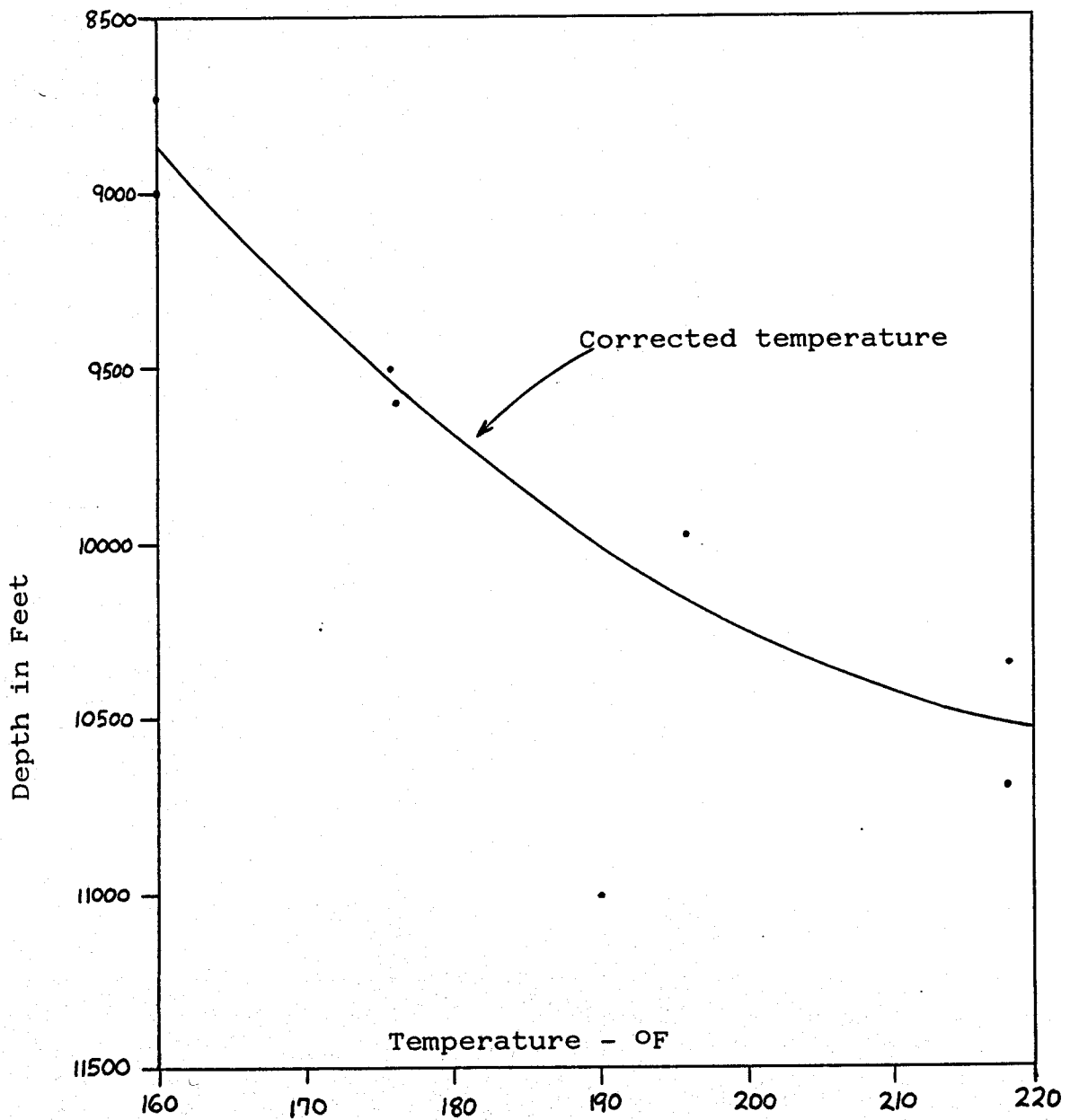


FIGURE 9. CORRECTED RESERVOIR TEMPERATURES BASED ON CASING POINT TEMPERATURES VERSUS DEPTH, GILLIS-ENGLISH BAYOU NORTH AREA.

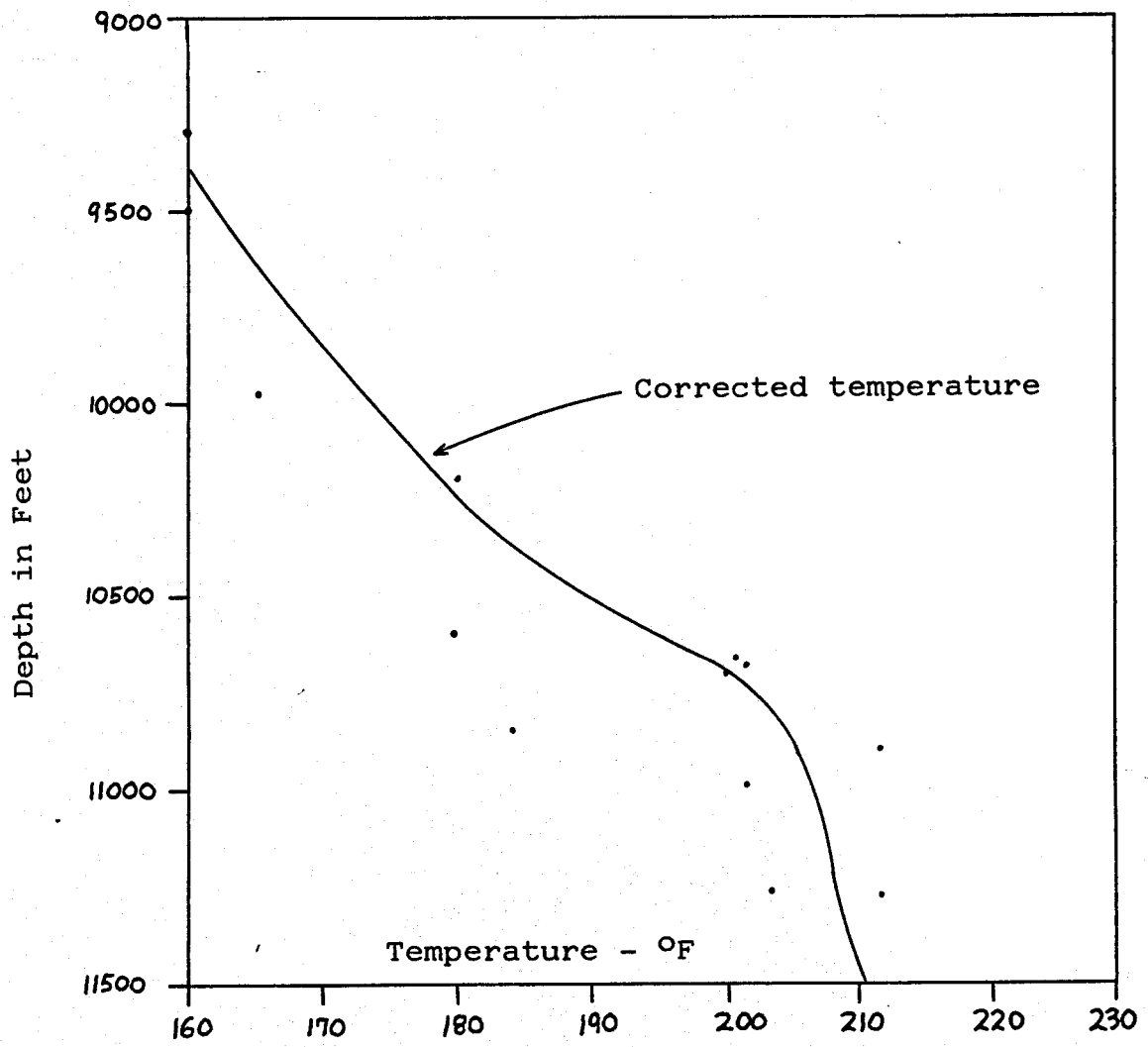


FIGURE 10. CORRECTED RESERVOIR TEMPERATURES BASED ON CASING POINT TEMPERATURES VERSUS DEPTH, GILLIS-ENGLISH BAYOU SOUTH AREA.

temperatures were more consistent. Only three other temperatures were considered anomalous. These are shown circled and were ignored when contouring.

A total of 73 wells penetrated the reservoir sand. Most of these wells are in the southern part of the study area. Because of the sparse well control, the location of faults was not incorporated in mapping. Since temperatures are related to depth, major faults should show up as areas with steeper temperature gradients.

A comparison of the reservoir temperature map (Plate 7) with the net sand and unconformity maps shows that structurally higher areas have lower temperatures, while higher temperatures are restricted to low depositional basins. This relationship shows up particularly well in the southern portion of the area. Lower temperatures are found over the anticlines. Two areas of high temperature associated with thick sand deposits occur in T.10 S., R.7 W. The first area is a low with 200 feet of net sand centered around section 14. The reservoir temperature is 280°F. A larger area with 400 feet of net sand is centered around section 20. This area lies within a 280°F isotherm.

The minimum temperature recorded was 209°F in the northern part of the area. The maximum temperature was 283°F from a Manchester Field well. Above the Manchester area, isothermal contours generally conform to the shape of the channel.

It should be realized that since well control is so sparse in this area, this configuration is highly interpretative. Between South Iowa Field and just east of Manchester Field, the temperature gradient becomes steeper. This trend corresponds with the trace of fault "J" and shows the temperature variation across the fault. The relationship between isothermal contours and the fault trace breaks down northwest of Manchester Field. The 270° line dips northward above the fault trace. The anomalously high temperature north of the fault trace may indicate that the upthrown block of fault "J" is not sealed. The higher northward temperature may be due to the escape of hot water northward along the fault plane.

In terms of maximum temperature and net sand, the area surrounding sections 19 and 20, T.10 S., R.7 W., appears the most attractive as a prospect.

RESERVOIR PRESSURES

Reservoir fluid pressures are an important aspect of the geopressured-geothermal aquifers because they control the primary driving forces that produce the geothermal waters. For this reason a map was constructed to show the pressure at the top of the reservoir sand. The pressures were calculated by converting the mud weight, MW, used for the bottom hole logging run, into a pressure gradient, G, using the following equation:

$$G(\text{psi/ft}) = \text{MW}(\text{lbs/gallon})/19.27 \text{ lbs/gallon/psi/ft}$$

This gradient was then multiplied by the depth of interest within a particular well to arrive at the formation pressure. The pounds per square inch pressure calculated is termed the "maximum expected pressure" and is higher than the actual formation pressure. In order to understand the relationship between these two pressures, it is first necessary to review the role drilling mud plays in controlling formation pressures.

When drilling, the weight of the mud is varied so that the pressure exerted against the formation by the column of mud is greater than the inward force exerted by the formation. The pressure exerted by the mud is always kept slightly greater than the formation pressure to keep formation fluids from invading the well bore. Invasion of formation fluids can result in a "kick" or blowout. The extra margin of pressure maintained above the formation pressure is referred to as the kick tolerance. At the same time, the weight of the mud must be kept low enough so that the pressure it exerts will not fracture the formation in any uncased portion of the hole. While drilling into an abnormally pressured section the mud weight is constantly increased as the average formation pressure gradient increases with depth. The mud weight can be increased until there is a danger of fracturing the formation in a shallower, uncased portion of the hole. At this point

drilling is stopped, well logs are run, and the open section of the hole is cased.

Although it is a close approximation, the maximum expected pressure calculated will always exceed the true formation pressure. The accuracy of this approximation is limited by several factors. The first problem involves the kick tolerance. The actual mud weight used exerts a pressure that is greater than the formation pressure. There is no general rule of thumb for the amount of kick tolerance used. In a wildcat area where little subsurface information on pressured zones is available, muds may be overbalanced. In proven areas the mud may be very close to balanced with only a .1 lbs/gallon kick tolerance. As will be seen later, some of the wells in the study area appear to have been drilled excessively overbalanced.

A second problem is the assumption that the pressure gradient calculated at the casing point does not change further up the hole from the depth of interest. On electric logs, mud weights are given only for the casing points. Any changes in the mud weight which were made between casing points are not shown. This was not a major problem in the study area. Most of the wells which penetrated the reservoir sand were not drilled much deeper. It seems safe to assume that the pressure gradient within a pressured section could not normally increase significantly over a short distance.

A third problem is the possibility that the mud weight used in drilling the hole is not necessarily the same as the mud weight present when the logging tool was run. Mud weights in the hole may be changed when the hole is being conditioned prior to running a logging tool. This is particularly true in wells with gas sands. Sonic logs are sensitive to any gas that is within the drilling mud. Often the heaviest possible mud will be used during logging to keep gas from seeping into the well bore. Since many of the producing wells in the study area are gas wells, this is a possible source of error.

The amount of error involved in using the maximum expected pressure is not known. Bottom hole pressure tests for specific wells were not available for comparison. The only information available was an average reservoir pressure calculated from bottom hole pressure tests from six Coastal States wells. The wells are located in sections 21, 22, 27, and 28 of T.10 S., R.7 W. The average pressure from the wells was 11,490 psi (Louisiana Conservation Office). The average pressure using the maximum expected pressure calculation for the same six wells was 11,735 psi, 245 psi higher than the Coastal States value.

Plate 8 is a map of the maximum expected pressures calculated for the top of the reservoir sand. While attempting to contour the data points it became apparent that the values south of fault "J" were more consistent than those north of

the fault. In order to investigate these differences two graphs were constructed illustrating casing point mud weights versus depth. Figure 11 is a graph of the wells between faults "B" and "C" southeast of Gillis-English Bayou Dome. Figure 12 is a graph of the wells in the Manchester Field area. The Manchester Field data show that the mud weights used at a specific depth did not vary significantly from one well to another. In contrast, wells in the Gillis-English Bayou area showed as much as a 2.0 lbs/gallon variance at the same depth. It is felt that many of these wells were drilled overbalanced. They were drilled early in the history of the development of the area before adequate information on subsurface pressures was available. In order to correct these values a minimum pressure trend line was established (Figure 11). Pressure values for the wells in this area were then read off the trend line for the depth of interest. The pressure values for the rest of the wells north of fault "J" were not corrected because of insufficient control.

Even after correcting a portion of the wells north of fault "J", the area could not be contoured satisfactorily. This was due in part to lack of well control. It may also indicate that the area is more structurally complex than this study shows. The maximum expected pressure in this area varies from 8,284 psi to 10,908 psi. The lower pressures just north of fault "J" support the idea that the upthrown

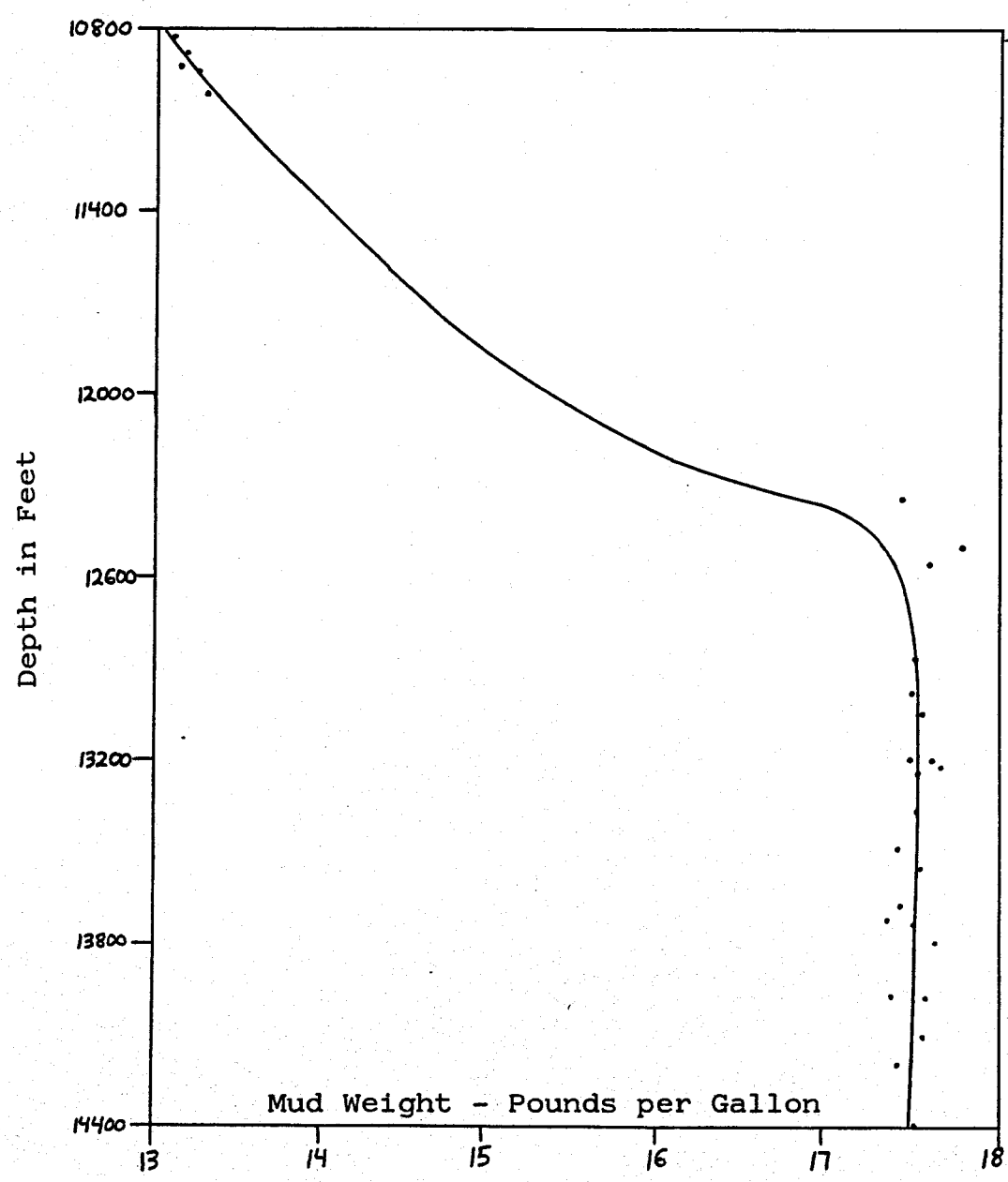


FIGURE 11. PLOT OF CASING POINT MUD WEIGHT VERSUS DEPTH SHOWING INCREASE FROM 13.1 TO 17.7 LBS./GAL. DATA FROM MANCHESTER FIELD, SECTIONS 7, 8, 9, 15, 16, 17.

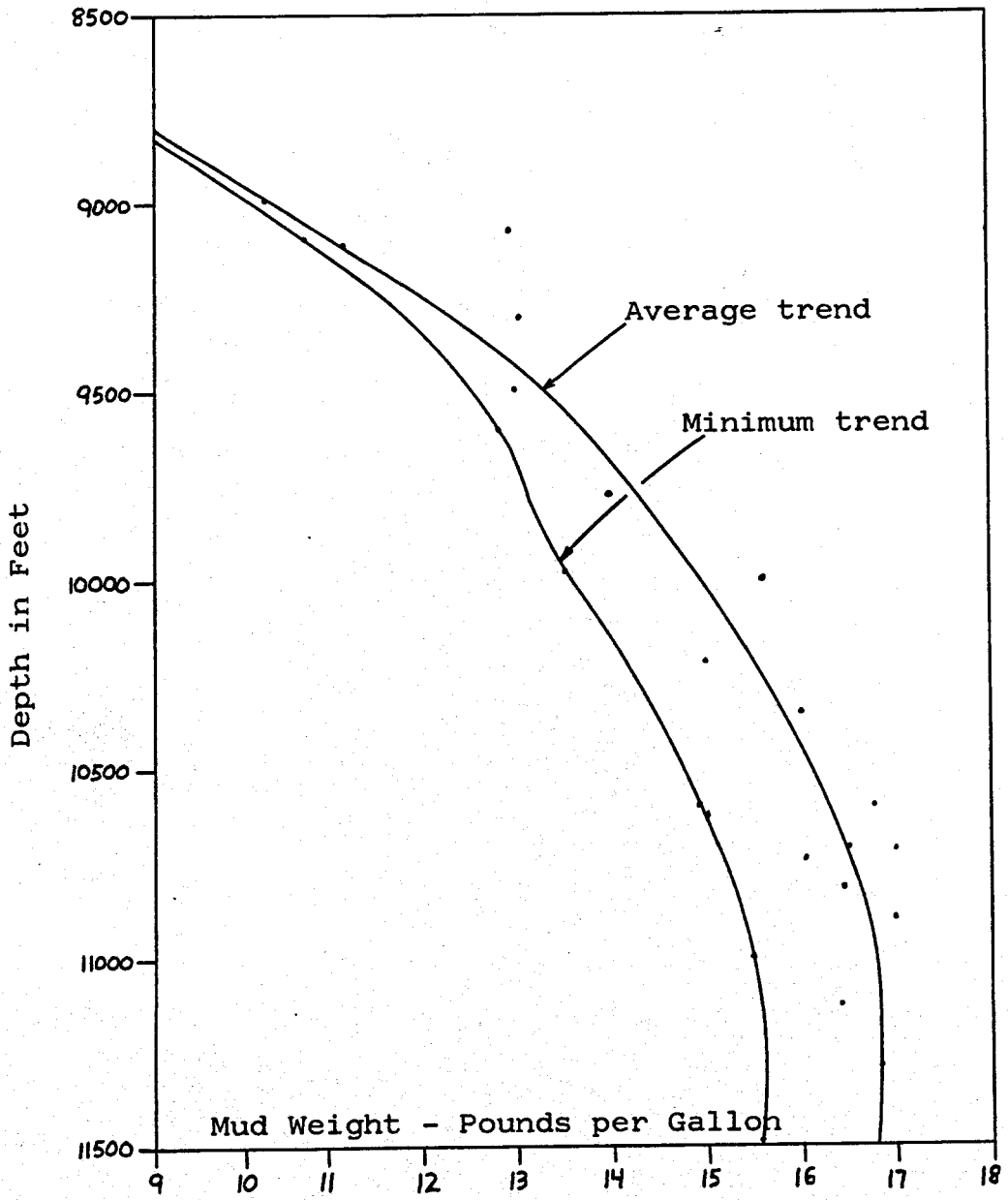


FIGURE 12. PLOT OF CASING POINT MUD WEIGHT VERSUS DEPTH FOR THE GILLIS-ENGLISH BAYOU SOUTH AREA.

block is not sealed with respect to the fault. For this reason the area north of fault "J" was not considered as a potential prospect.

South of fault "J" more control was present and pressure values are more consistent. Only four values were considered anomalous. These are shown circled and were ignored when contouring. A comparison of the unconformity and pressure maps shows a positive correlation between pressure and depth. Structurally high areas show lower pressures, while structural lows show higher pressure. Pressures in the area vary from 11,422 psi to 11,825 psi. A pressure of 12,000 psi is inferred around sections 19, 20, and 30. In terms of maximum pressure and net sand, the area centered around sections 19 and 20 appears to have the most potential for a geopressed-geothermal prospect.

SALINITY

The salinity of the reservoir waters is an important consideration in evaluating a geothermal prospect. The amount of methane in solution and the effective permeability in the reservoir are both in part controlled by the salinity of the waters. Salinity determinations are also important in anticipating surface equipment needed and solutions to waste disposal problems. Ideally, a prospect should have reservoir waters with low salinities in order to maximize recoverable

energy, extend equipment life, and reduce the handling problems of the disposed waters.

Waters in the aquifers of the Gulf Coast exhibit significant areal and vertical variations in the concentration of dissolved solids. Variations are a function of the aquifers pressure, temperature, geologic structure, lithology, and formation geometry (Wallace, 1977). The salinity of sediments near the surface is initially 35,000 ppm. As shales compact with depth they act as semipermeable membranes, releasing water and retaining dissolved solids (Fertl, 1970). They begin to osmotically concentrate these dissolved solids, and salinity increases with depth. In areas where geopressured zones are encountered, the salinity reaches a maximum just above the geopressure seal. Below the seal, the salinity of the formation waters decreases rapidly. This decrease is related to the higher temperatures below the seal. The higher temperature results in the conversion of montmorillonite to illite, releasing intercrystalline water which dilutes the formation waters (Burst, 1969).

Two methods are available to determine the salinity of formation waters. The first method is the chemical analysis of produced formation waters. The second method involves estimating the salinity from electric log resistivity curves using empirical formulae. At the time of this writing, there is a controversy over the accuracy of the log-derived values.

Dorfman (1980) made a comparison between produced water and log-derived salinities for the same formations. He found that for intervals with mud densities greater than 14 lb./gallon, the log-derived salinities were low by as much as 100 percent. Because of its inaccuracy, this method was not used.

Chemical analyses of produced formation waters were only available for five wells in the study area. These wells are all located in Manchester Field. Schmidt (1971) conducted a study of the chemical composition of waters obtained from the sands and shales in these wells. The change in the salinity of waters within the sands with depth is shown for each of the wells in Figure 13. The average salinity trend for all five wells is shown in Figure 14. The salinity increases from 120,000 ppm. at 3,000 feet to greater than 180,000 ppm. at the top of the geopressure zone. Below the geopressure seal the salinity drops abruptly to approximately 20,000 ppm. and remains low to 14,000 feet. In the nearby Hackberry Field, where there were no abnormally pressured zones encountered, salinities increased to 180,000 ppm. at 14,000 feet. This relationship supports the idea that the lower salinity in Manchester Field is a result of the geopressured environment. An average salinity of 20,000 ppm. will be assumed for waters within the reservoir sand south of fault "J" because of the limited data control.

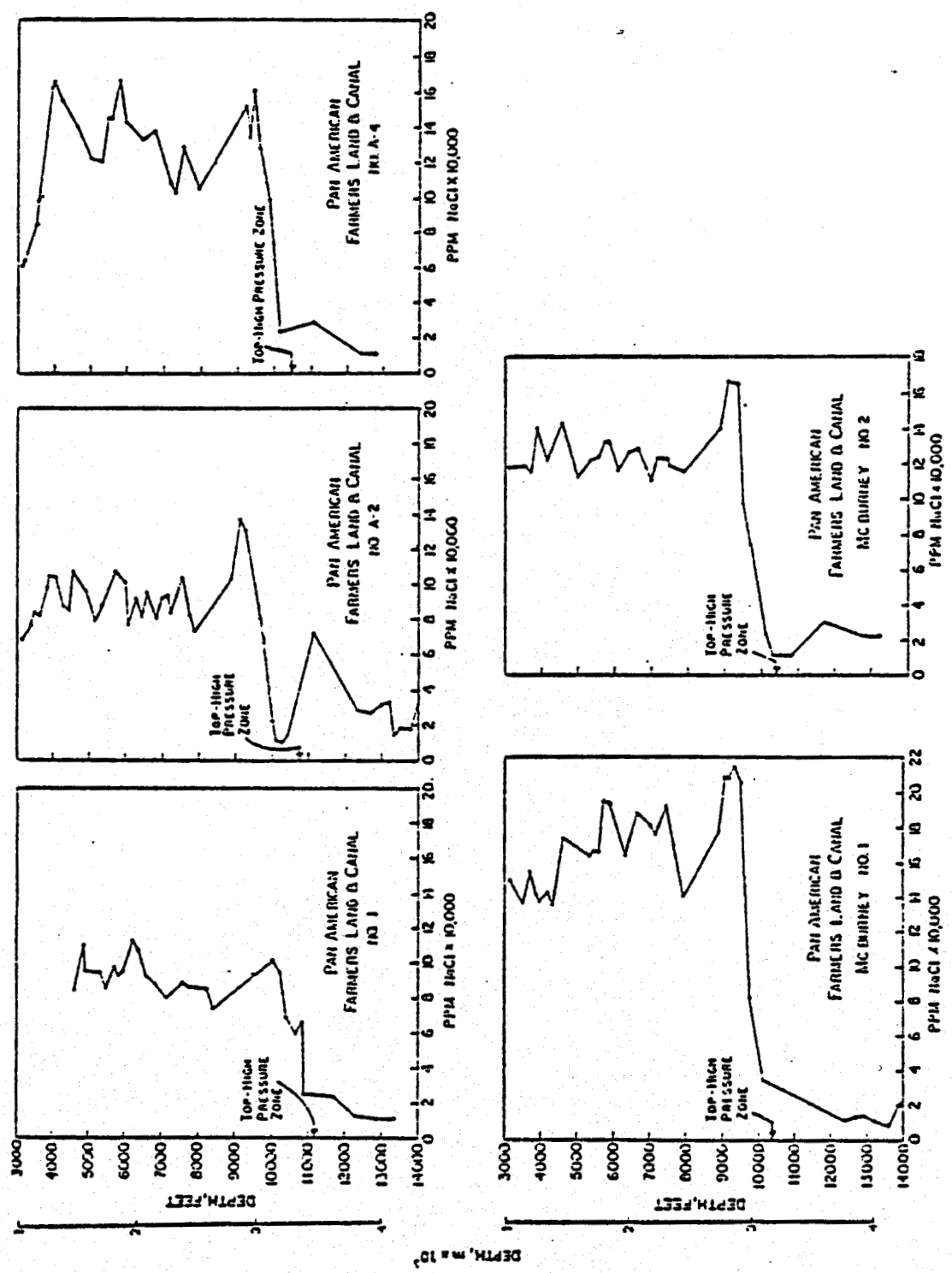


FIGURE 13. VARIATIONS IN THE SALINITIES OF SANDS PLOTTED AGAINST DEPTH FROM MANCHESTER FIELD, LOUISIANA (SCHMIDT, 1971).

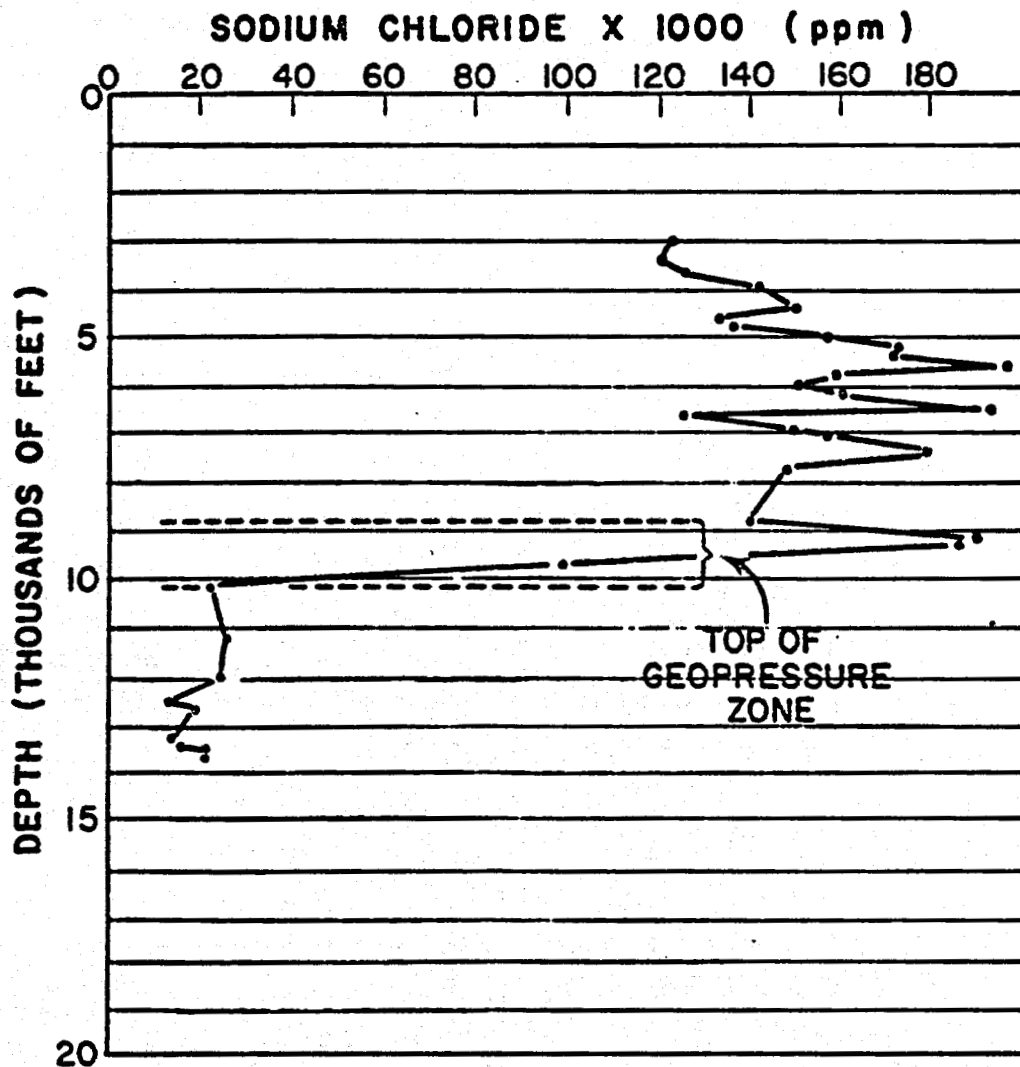


FIGURE 14. CHANGE IN FORMATION WATER SALINITY WITH DEPTH RELATED TO THE OCCURRENCE OF THE GEOPRESSURED ZONE, MANCHESTER FIELD, CALCASIEU PARISH, LOUISIANA (SCHMIDT, 1971).

POROSITY AND PERMEABILITY

The porosity and permeability of sands and shales vary widely in South Louisiana depending on burial depth and the pore pressure of the sediments. In normally pressured sediments the porosity of sand deposits decreases linearly with depth at a rate of about 1.28 percent per 100 feet between 1,600 feet and 10,800 feet (Jones, 1975). The porosity of shales also decreases with depth but is nonlinear. An abrupt reversal of these trends occurs at the top of the geopressed zone (Figure 15). Through the pressure seal, porosity increases in both sands and shales due to undercompaction. Porosities may be as much as 10 percent higher than at an equivalent depth in a normally pressured zone (Jones, 1975). Although there is no direct relationship between porosity and permeability, permeability generally increases with increased porosity. The environment of the geopressed zone also increases permeability. The effective permeability of the water is increased due to a decrease in its viscosity. The viscosity decrease results from the increased temperature and lower salinity encountered in the geopressed zone. The effective permeability may increase three to five fold as viscosity decreases (Figure 16).

Porosity data for the reservoir sand were obtained from sidewall cores, sonic logs, and formation density logs from eleven wells. Permeability data came from sidewall cores

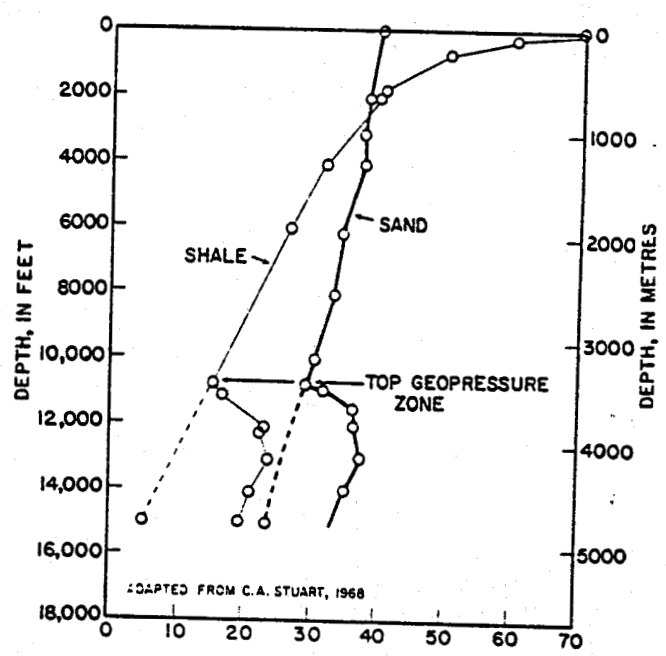


FIGURE 15. RELATION OF POROSITY TO DEPTH OF BURIAL IN SAND AND SHALE BEDS OF CENOZOIC AGE IN THE HYDROPRESSURE ZONE AND GEOPRESSURE ZONE, GULF COAST BASIN (JONES, 1975).

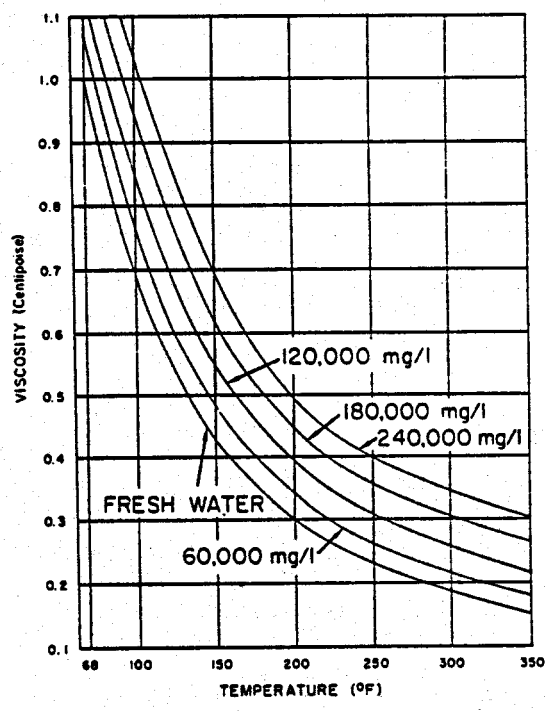


FIGURE 16. RELATION BETWEEN VISCOSITY, TEMPERATURE, AND DISSOLVED SOLIDS CONTENT OF WATER (PIRSON, 1963).

taken in seven of these wells. The data and location of these wells are shown on Plate 14.

The reliability of data obtained from sidewall cores has been questioned by many workers. The cores are taken by impacting a hollow cylinder into the formation. This impact may fracture the core and result in anomalously high porosity and permeability determinations. Additional error may result from the cores being tested outside their true environment. At higher temperatures and pressures within the reservoir, their porosity and permeability may be different. Sonic logs measure the travel time of an acoustic wave through the formation. Porosities calculated from sonic logs run in under-compacted sediments tend to be higher than the true formation porosities. In contrast, formation density log-derived porosities are considered fairly accurate. The permeability value of 1,480 millidarcys in the Humble St. Romain No. 1 well (Sec. 5, T.10 S., R.6 W.) was the only data point considered anomalously high. This value is almost twice as high as the next largest permeability value. For this reason it was disregarded.

Data were obtained for only two wells north of fault "J". No conclusions will be drawn for this area due to lack of control. South of fault "J" data are concentrated mainly in the Holmwood-South Manchester area. Within this area porosity and permeability probably vary both vertically and

laterally. Because of the limited number of control points, averages were assumed for the entire area. The average porosity and permeability for the area south of fault "J" are 23.0 percent and 392 millidarcys, respectively.

RESERVOIR VOLUME

In terms of the maximum pressure, temperature, and net sand, the area surrounding sections 19 and 20, R.10 S., R.7 W., is the most promising area for a geopressured-geothermal prospect. This area will be referred to as the Chloe Prospect. The boundaries of the prospect correspond to two faults and two structural ridges across which the flow of reservoir waters is restricted. The prospect is bounded to the north and south by faults "J" and "Q", respectively. To the east it is bounded by the crest of the Manchester anticline. The western boundary is the crest of the West Manchester anticline. The surface area and total thickness of the reservoir sand was found by grid integrating the corresponding data within the reservoir drainage perimeter outlined on Plate 14. A one square inch grid was used in the investigations. The reservoir volume was calculated by multiplying the surface area times the average thickness for each grid, and adding all the grids within the prospect.

The calculation yielded a total sand volume of .84 cubic miles. Assuming a porosity of 23 percent, the reservoir

would contain .19 cubic miles of fluid, or an equivalent of 5,100,000,000 barrels.

METHANE CONTENT

The hot, geopressured waters within the reservoir are assumed to be saturated with dissolved methane. Studies have shown that the amount of methane that can be dissolved in water is a function of its temperature, pressure, and salinity. Increasing the pressure and temperature both increase the solubility of methane in water. At the same time, increasing the NaCl concentration in water at constant temperature and pressure markedly decreases the solubility of methane. Presently there is no general agreement among researchers as to the extent these parameters affect methane solubility. For the purpose of this report, the calculation of methane solubility will be based on the experimental work of Blount, Price, Wenger, and Tarullo (1979).

Calculation of the total dissolved methane within the reservoir was based on the following averages:

Salinity	20,000 ppm.
Temperature	270°F
Pressure	11,500 psi
Water Volume	5,100,000,000 bbls.

Figures 17 and 18 show that at constant pressure and NaCl concentration, increasing the temperature increases the aqueous solubility of methane. It can be seen that the solubility of methane is essentially linear with respect to temperature within the range of interest. Figures 19 and 20 show that at constant temperature and pressure, plots of increasing NaCl concentration versus methane concentration are linear. Because the amount of methane in solution is nonlinear with respect to pressure, the average reservoir salinity and pressure were used in Figures 19 and 20 to calculate the solubilities at 212°F and 338°F. The methane solubility at 270°F was then interpolated between these temperatures. The amount of methane in solution was calculated to be 50.5 standard cubic feet per barrel. Assuming 100 percent methane saturation and a reservoir volume of 5,100,000,000 barrels, the total methane within the reservoir is 258,000,000,000 standard cubic feet.

METHANE SOLUBILITY IN SCF/Bbl

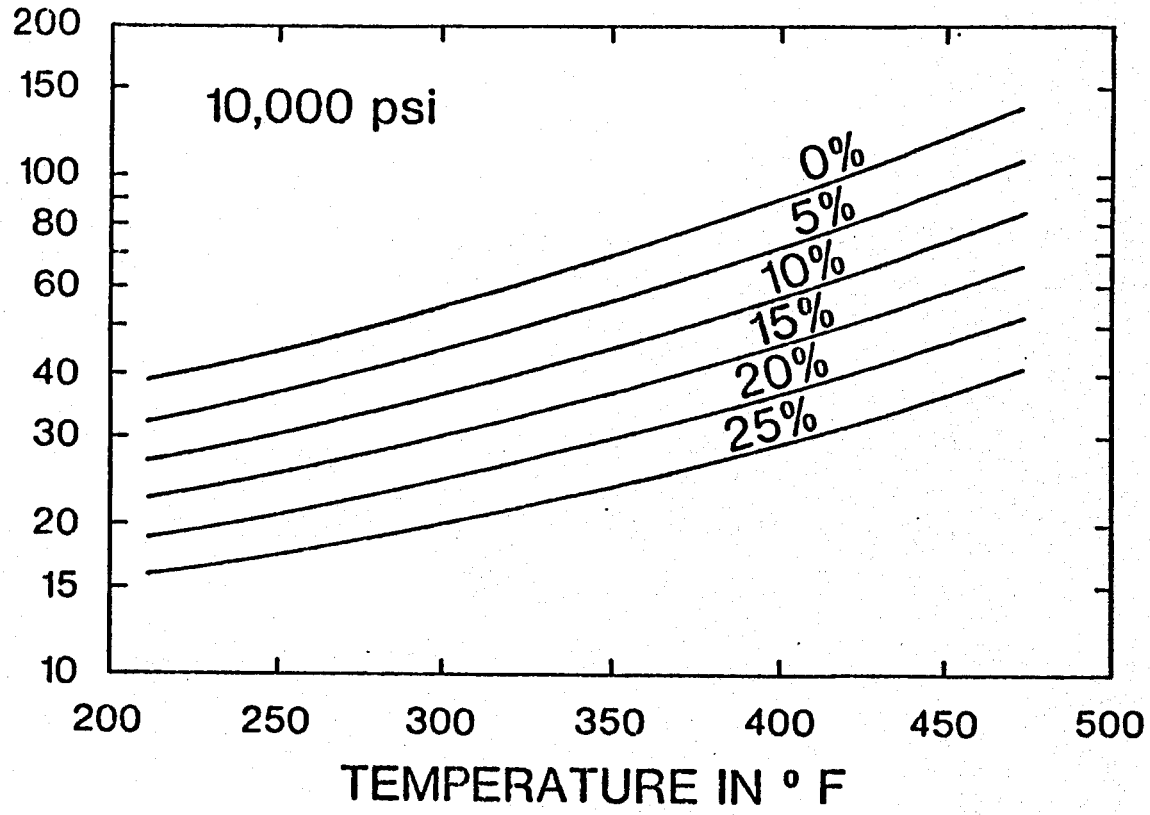


FIGURE 17. CALCULATED VALUES FOR SOLUBILITY OF METHANE (IN STANDARD CUBIC FEET PER BARREL OF BRINE) IN AQUEOUS NaCl SOLUTIONS AT 10,000 psi AT SIX DIFFERENT SALINITIES AS A FUNCTION OF TEMPERATURE (BLOUNT, ET. AL., 1979).

METHANE SOLUBILITY IN SCF/Bbl

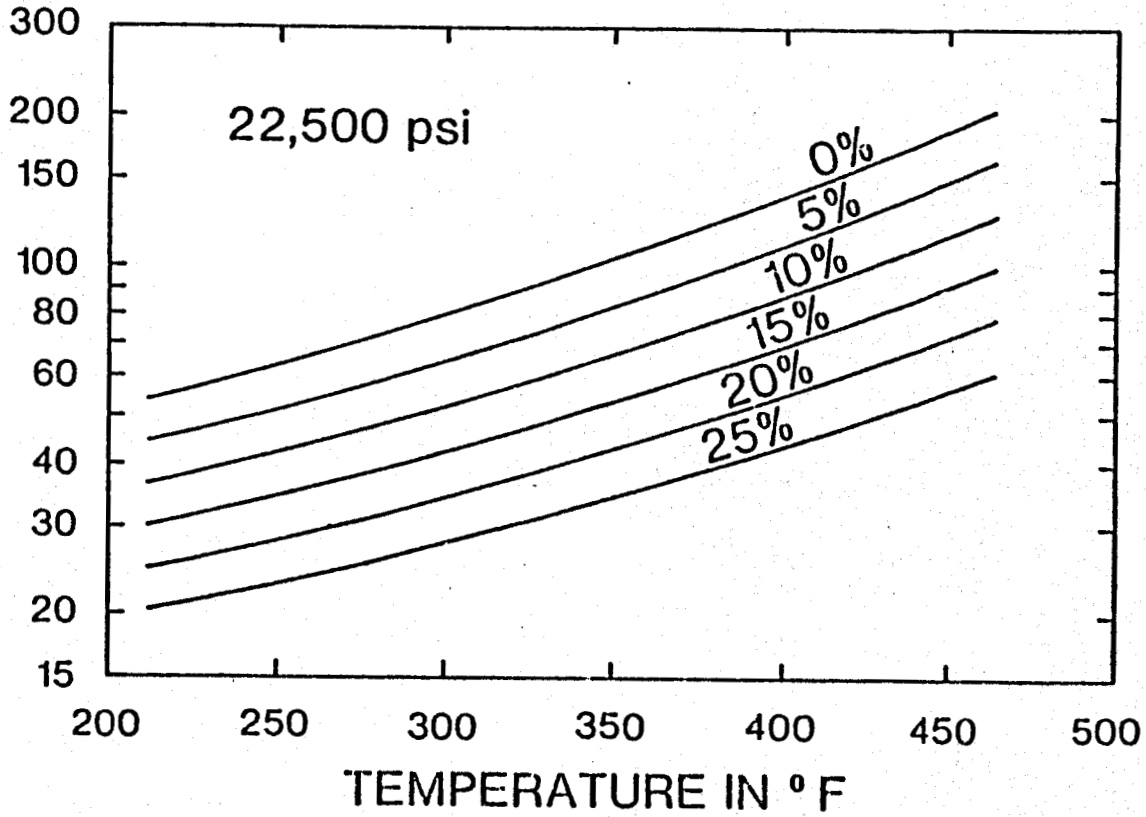


FIGURE 18. CALCULATED VALUES FOR SOLUBILITY OF METHANE (IN STANDARD CUBIC FEET PER BARREL OF BRINE) IN AQUEOUS NaCl SOLUTIONS AT 22,500 psi AT SIX DIFFERENT SALINITIES AS A FUNCTION OF TEMPERATURE (BLOUNT, ET. AL., 1979).

METHANE SOLUBILITY
IN SCF/Bbl

B 74

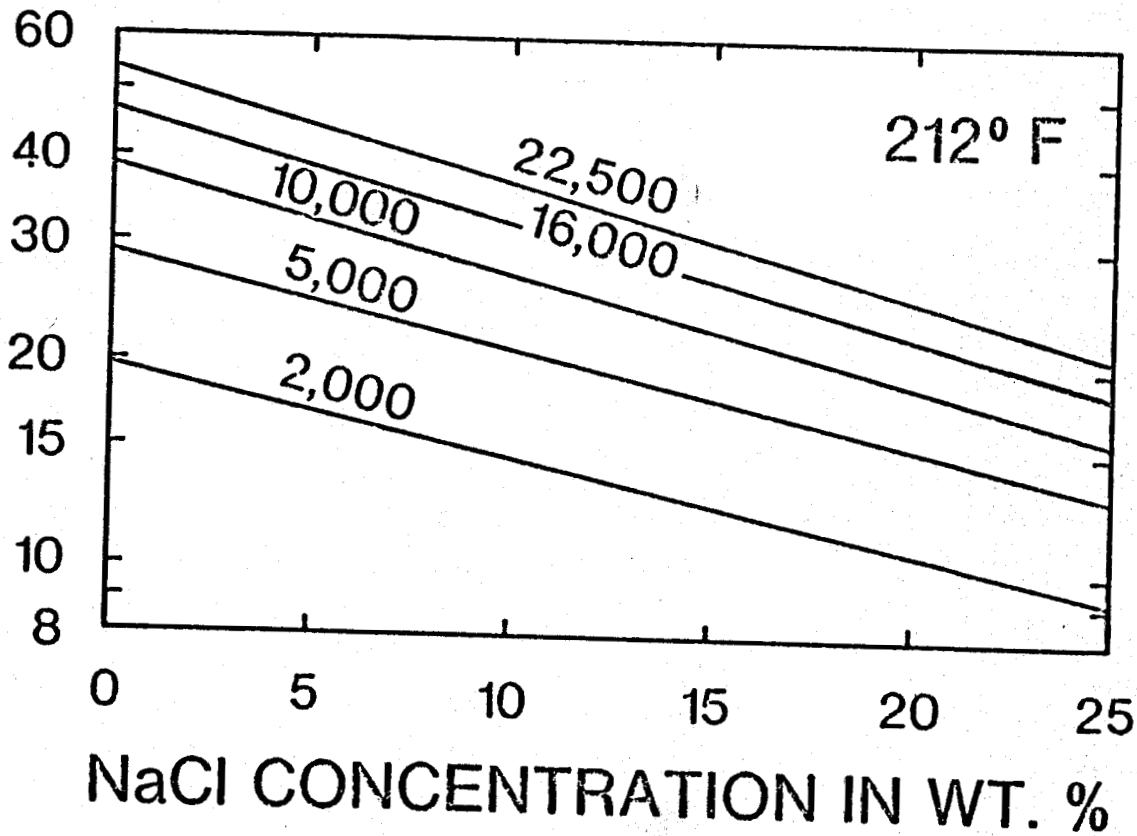


FIGURE 19. CALCULATED VALUES FOR SOLUBILITY OF METHANE (IN STANDARD CUBIC FEET PER BARREL OF BRINE) IN AQUEOUS SOLUTIONS AT 212°F AT CONSTANT PRESSURES AS A FUNCTION OF NaCl CONCENTRATION (BLOUNT, ET. AL., 1979).

METHANE SOLUBILITY IN SCF/Bbl

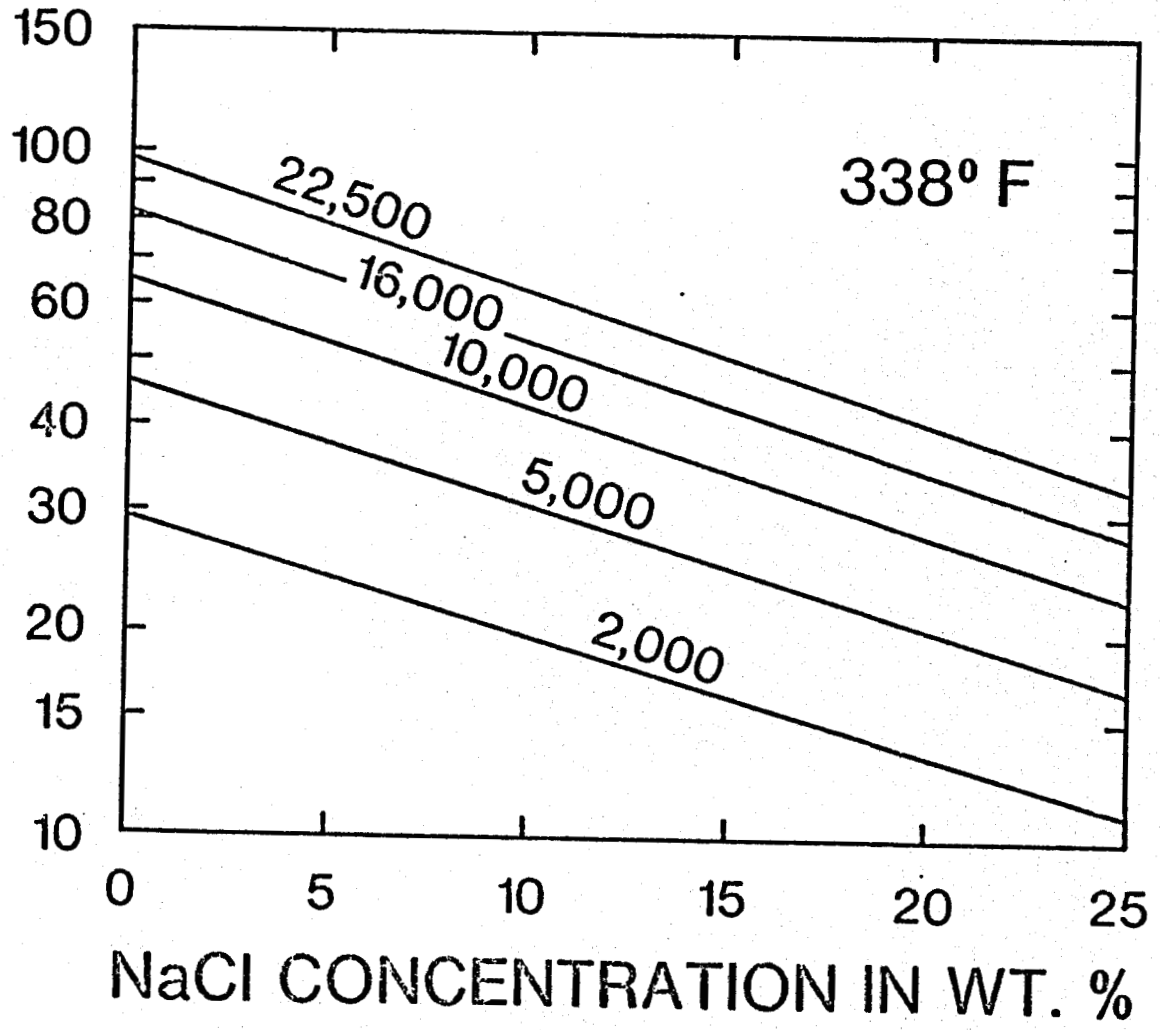


FIGURE 20. CALCULATED VALUES FOR SOLUBILITY OF METHANE (IN STANDARD CUBIC FEET PER BARREL OF BRINE) IN AQUEOUS SOLUTIONS AT 338°F AT CONSTANT PRESSURES AS A FUNCTION OF NaCl CONCENTRATION (BLOUNT, ET. AL., 1979).

EVALUATION OF THE CHLOE PROSPECT

There are many technological and economic factors involved in predicting the reservoir performance and the recoverable energy of a geopressured-geothermal prospect. Because the technology of geopressured-geothermal utilization is in its early stages of development, many of these factors are still unknown. Preliminary studies have suggested that water temperatures in Gulf Coast aquifers are not high enough for large scale electrical applications. Current programs are emphasizing the recovery of methane and use of hot water for industrial processes. Determination of the minimum acceptable fluid pressure, temperature, salinity, and reservoir volume would depend upon the specific application. The evaluation of the Chloe prospect in terms of recoverable energy and possible utilization is beyond the scope of this report. Instead this evaluation will focus on the assessment of the resource in place within the reservoir and the general optimum conditions which would maximize its recovery.

Jones (1975) has defined the general conditions for a geopressured-geothermal prospect as follows:

1. A relatively shallow geopressured zone;
2. High aquifer temperatures;
3. Low water salinity;

4. Thick reservoir sands with adequate hydraulic continuity;
5. Adequate porosity and permeability;
6. Areas with little or no hydrocarbon production.

The depth necessary to drill in order to encounter the geopressed aquifer is an important consideration in choosing a prospect area. The expense generally increases with increasing depth. Figure 14 shows the optimum location for the drilling of the geopressed-geothermal test well. The well would have to be drilled to a depth of approximately 13,500 feet to encounter the base of the reservoir sand. By present day drilling standards this is a moderate depth. The 73 wells which penetrated the reservoir sand attest to the feasibility of drilling and completing a well at this depth.

It has been shown that the temperatures and pressures within the reservoir sand are considerably higher than within sediments at an equivalent depth in a hydro pressured zone. The average reservoir temperature and pressure were found to be 270°F and 11,500 psi, respectively. These data were calculated for the top of the sand only. Temperatures and pressures are undoubtedly higher with increasing depth in the reservoir. Should a well be drilled at the proposed test site, the temperature and pressure encountered should reach a maximum of approximately 285°F and 12,300 psi, respectively.

The average salinity of the reservoir water was

estimated to be 20,000 ppm. At the same depth in the nearby Hackberry field the average salinity is about 180,000 ppm. The relatively low salinity in the prospect area results in a higher volume of dissolved methane in the reservoir waters. The lower salinity would also minimize the corrosion of surface equipment and disposal problems of the waste water.

A relatively large reservoir with hydraulic continuity is an important criteria for a prospect. This is essential for the long-term production of water at large rates from the aquifer system. It has been shown that within the prospect area the reservoir is a thick, laterally continuous sand with adequate porosity and permeability. It is free of faults or major flexures, which would impair the flow of fluids to the well bore.

The final criterion is that the prospect be within an area of little or no hydrocarbon production. The reason for this is that, by law, petroleum production has preference over water production from aquifers in Louisiana. This may be a limiting factor in the development of the Chloe prospect. Hydrocarbons are being produced from updip pinchouts of the reservoir sand. Production of large amounts of water downdip from these accumulations might disrupt the water drive necessary for the extraction of these hydrocarbons. This appears to be the only limiting factor in the development of the prospect.

In summary the averaged reservoir parameters for the evaluation of the Chloe prospect are shown in Table 2.

Table 2

Average Reservoir Parameters

Pressure	11,500 psi
Temperature	270°F
Salinity	20,000 ppm.
Porosity	23%
Permeability	392 md.
Reservoir Volume	.84 miles ³
Fluid Volume	5.1x10 ⁹ bbls. (.19 miles ³)
Methane Content	50.5 scf./bbl.
Total Methane	2.58x10 ¹¹ scf.

CONCLUSIONS

A combination of structural and reservoir analysis has led to the following conclusions.

1. The development of structural features in the study area has been dominated primarily by salt tectonics, and to a lesser extent by sediment distribution.

2. A major period of deformation following the deposition of the Middle Frio sediments resulted in the formation of a north-south trending submarine channel system.

3. The thick, massive Hackberry sands were deposited by turbidity currents which flowed through the channels.

4. Rapid deposition of the Hackberry shales and overlying Upper Frio sediments led to the creation of the geopressured zone. The primary pressure seals are the limey sands and shales of the Upper Hackberry and Upper Frio.

5. The abnormally high pressures, temperatures, porosities and permeabilities, and low salinities found in the Hackberry sands are a direct result of the formation of the geopressured zone.

6. The thick, laterally continuous Hackberry sands within the Chloe prospect were considered to meet the general requirements for a geopressured-geothermal prospect.

7. Should a well be drilled for testing purposes, the

optimum location would be in the northwest corner of
section 20, T.10 S., R.7 W.

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ABSTRACT

SUBSURFACE EVALUATION OF THE GEOPRESSURED-
GEOTHERMAL CHLOE PROSPECT
CALCASIEU PARISH,
LOUISIANA

RANDALL J. KURTH

A 123 square mile area approximately 10 miles east of Lake Charles, Louisiana, has been studied to assess its potential geopressured-geothermal resources. Subsurface information was used to study the structure and stratigraphy of the area as they related to the development of geopressured aquifers. The Middle Frio Hackberry wedge was found to contain the geopressured-geothermal reservoir sand, as well as the shales responsible for the origin and sealing of the geopressured strata. The major reservoir within the wedge is the Hackberry massive "A" sand.

Salt tectonics during post-Nonion struma time caused local subsidence which formed an oversteepened slope environment in the study area. Slumping of the slope initiated turbidity currents which eroded a system of north-south trending submarine channels. Later episodic turbidity currents deposited the Hackberry massive "A" sand; first in the axes of channels and later away from the channels on

the unconformable surface. As flows became less frequent, the massive Hackberry shale sequence was deposited over the sands in deep water. Subsequently, a shallow shelf environment was established as the Upper Frio and Anahuac deposits prograded across the study area.

The rapid deposition of the upper Hackberry shale provided the necessary conditions for the development of the geopressured zone. Low resistivity shale seals, osmotic seals, and limey sand and shale seals formed in the thick shale sequence. The origin of pressures within the geopressured zone is related to undercompaction, diagenetic conversion of montmorillonite to illite, and aquathermal pressuring.

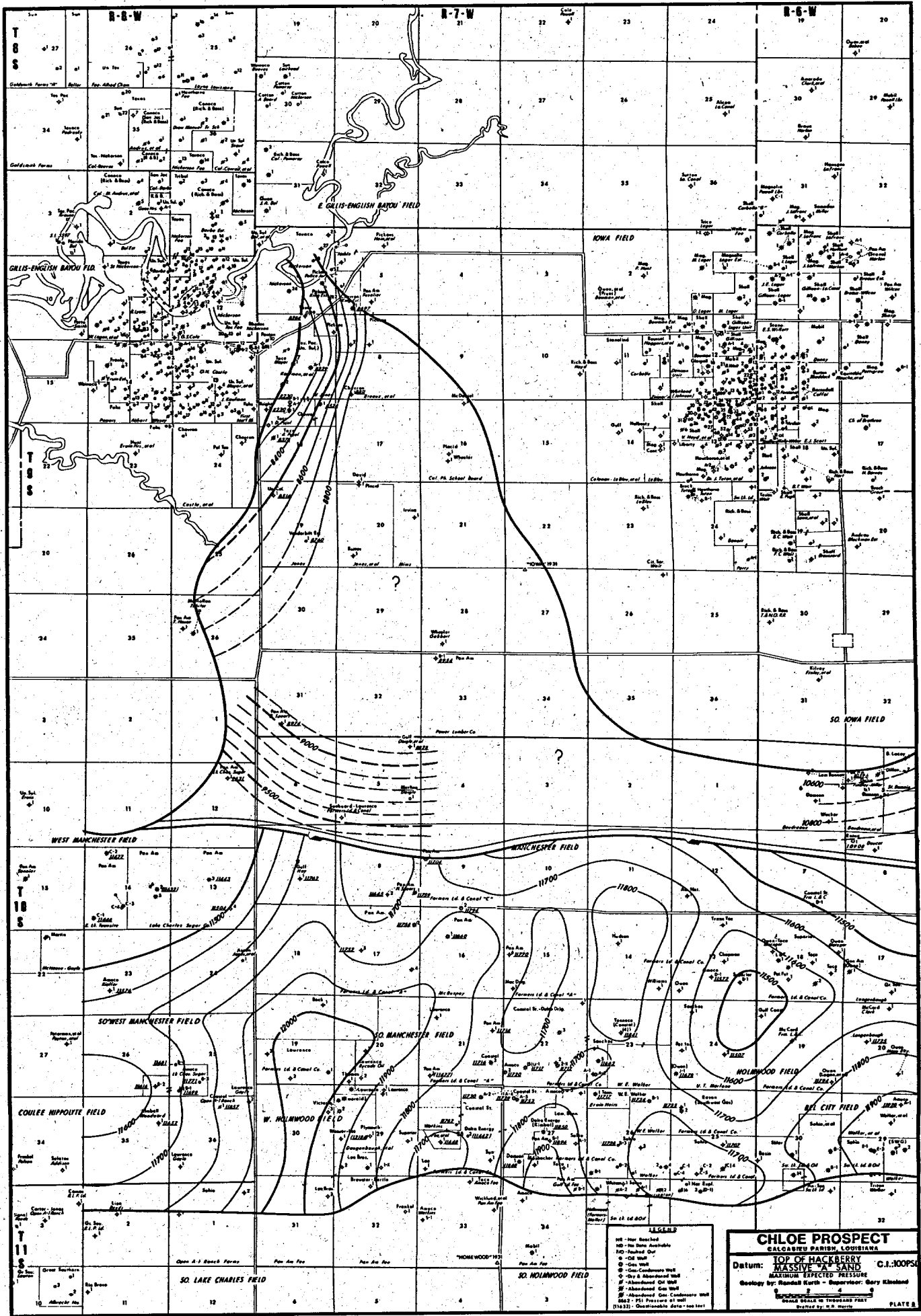
Maps of reservoir parameters were used in conjunction with net sand and structural maps to define the Chloe prospect. Within the prospect area, the reservoir was found to be a thick, laterally continuous sand which met the general requirements for a geopressured-geothermal prospect. The averaged reservoir parameters pertinent to the evaluation of the prospect are as follows:

Pressure	11,500 psi
Temperature	270°F
Salinity	20,000 ppm.
Porosity	23%

Permeability	392 md.
Reservoir Volume	.84 miles ³
Fluid Volume	5.1x10 ⁹ bbls. (.19 miles ³)
Methane Content	50.5 scf/bbl.
Total Methane	2.58x10 ¹¹ scf.

BIOGRAPHY

Randall J. Kurth was born in Silver Springs, Maryland on April 2, 1955. Upon graduation from Springbrook High in 1973, he attended the University of Maryland and received a Bachelor of Science degree in Geology in May of 1978. In August, 1979 the author entered Graduate School at the University of Southwestern Louisiana, and will complete the requirements for a Master of Science degree in Geology in December of 1981.



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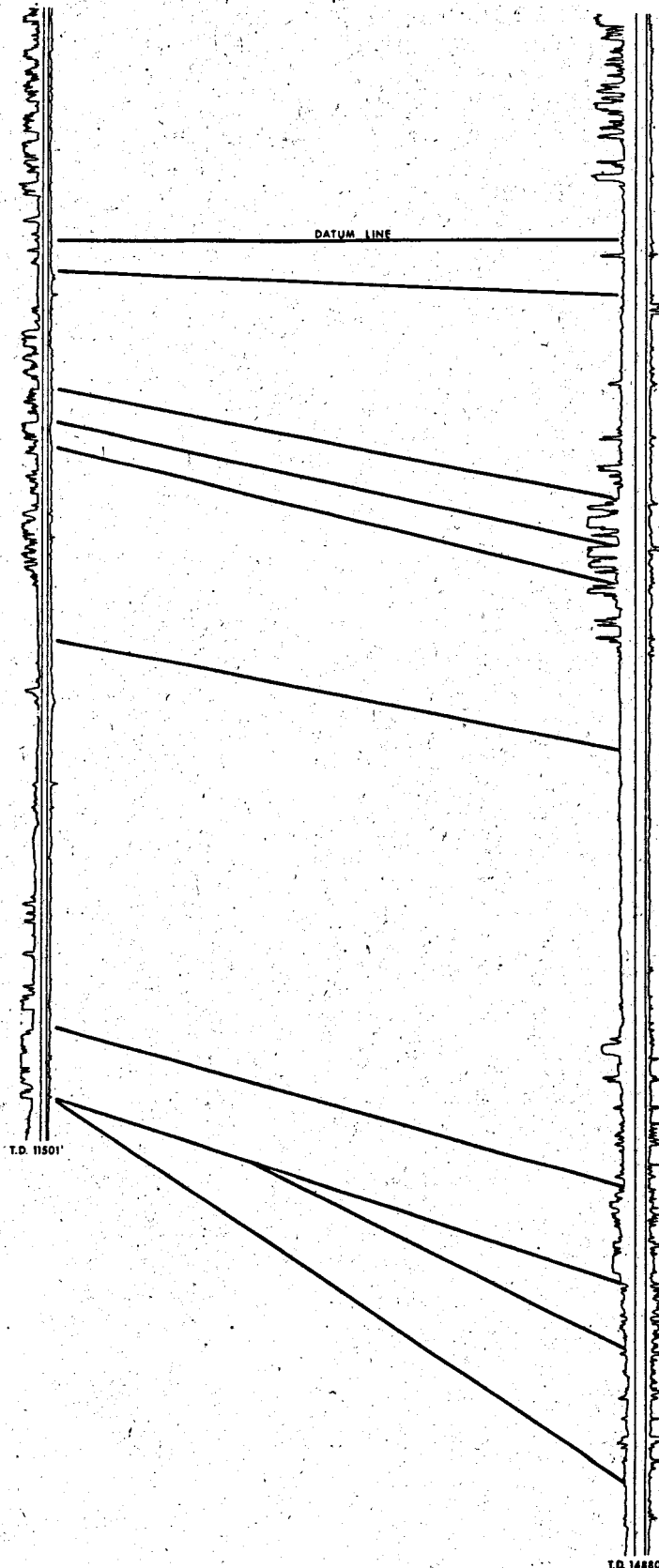
DOWNDIP TYPE LOG COMPOSITE

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J. BREAUX NO. 1

PLYMOUTH OIL
DAUGHENBAUGH NO. 1
PAN AM
W. MC BURNEY NO. 1



- HET. LIME
- BOLIVINA PERCA
- 1ST. CAMERINA SD.
- 2ND. CAMERINA SD.
- CIB. HAZ. MARKER SD.
- HAYS SD.
- TOP HACKBERRY SHALE
- HACKBERRY "A" SD.
- HACKBERRY UNCONFORMITY
- NODOSARIA BLANPEDI
- TEXULARIA SELIGI
- VICKSBURG UNCONFORMITY
- ANOMALINA BILATERALIS



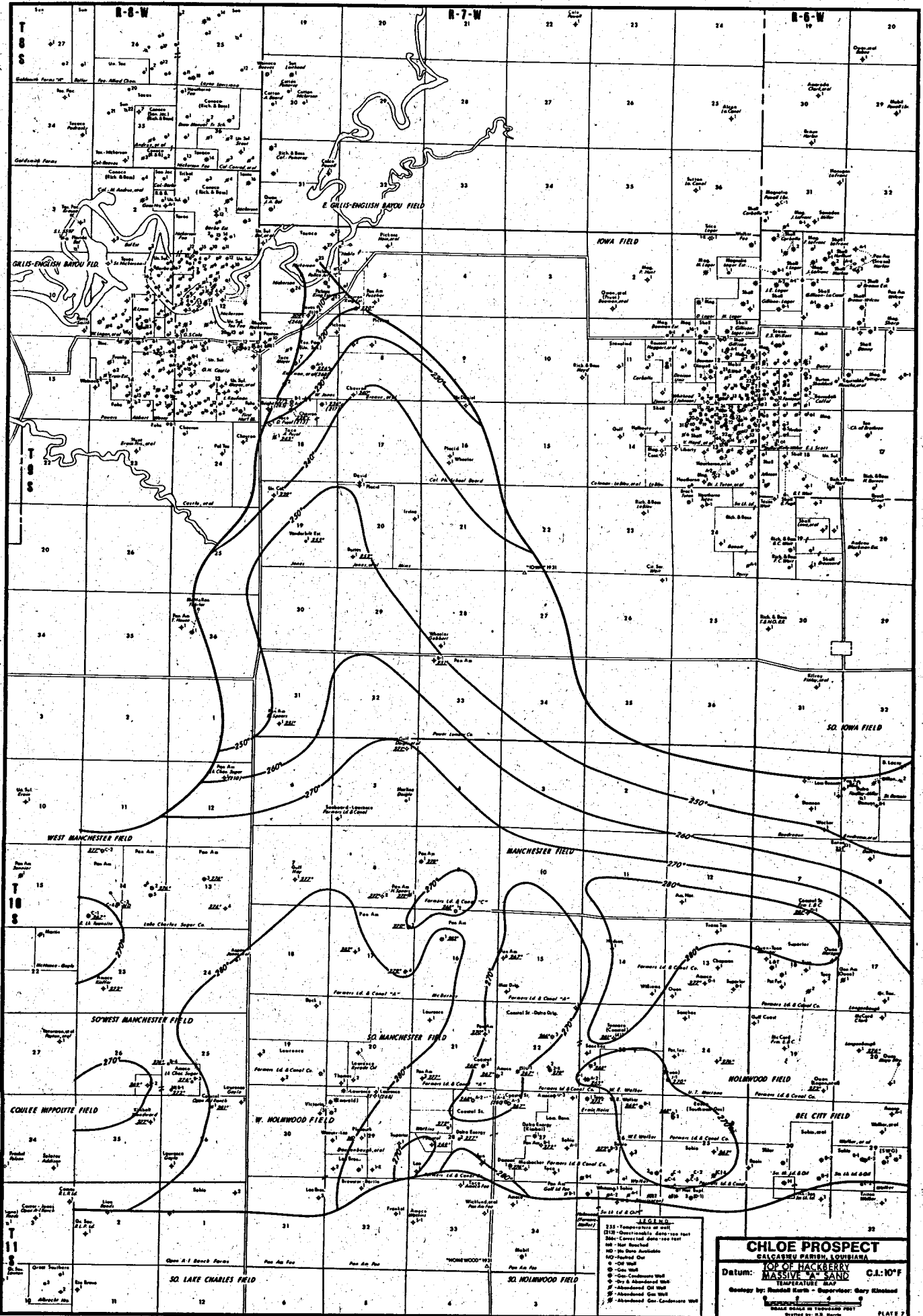
- HET. LIME
- BOLIVINA PERCA
- 1ST. CAMERINA SD.
- 2ND. CAMERINA SD.
- CIB. HAZ. MARKER SD.
- HAYS SD.
- TOP HACKBERRY SHALE
- HACKBERRY "A" SD.
- HACKBERRY UNCONFORMITY
- NONION STRUMA
- NODOSARIA BLANPEDI



CHLOE PROSPECT
CALCASIEU PARISH, LOUISIANA

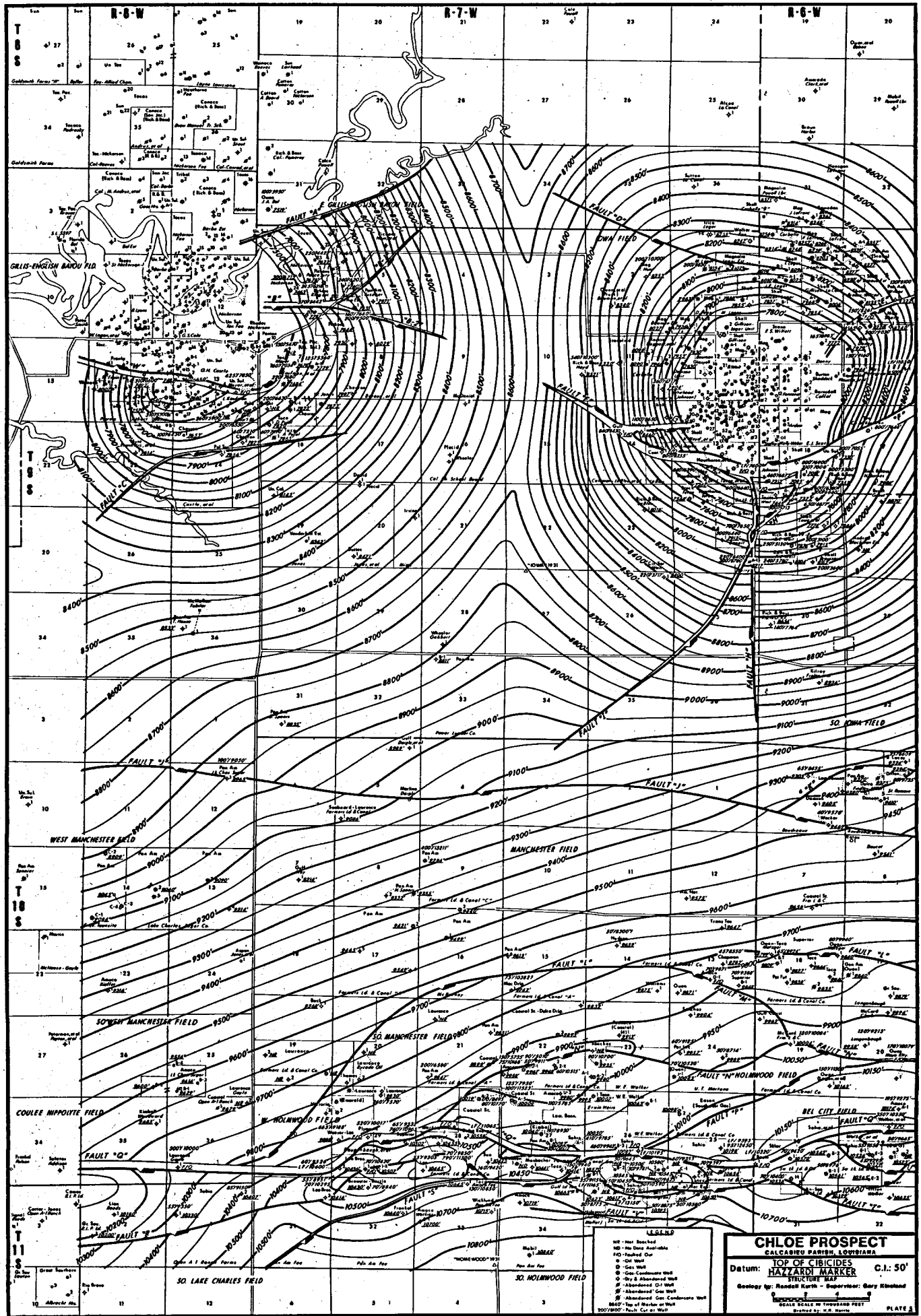
TYPE SECTION
GENERALIZED NORTH - SOUTH SECTION
ILLUSTRATING STRATIGRAPHIC AND
STRUCTURAL RELATIONSHIPS BETWEEN THE
UPDIP AND DOWNDIP TYPE LOGS.

GEOLOGY: RANDALL, KURTH JULY 1, 1981
SUPERVISOR: GARY KINSLAND DRAFTSMAN: M.E.H.

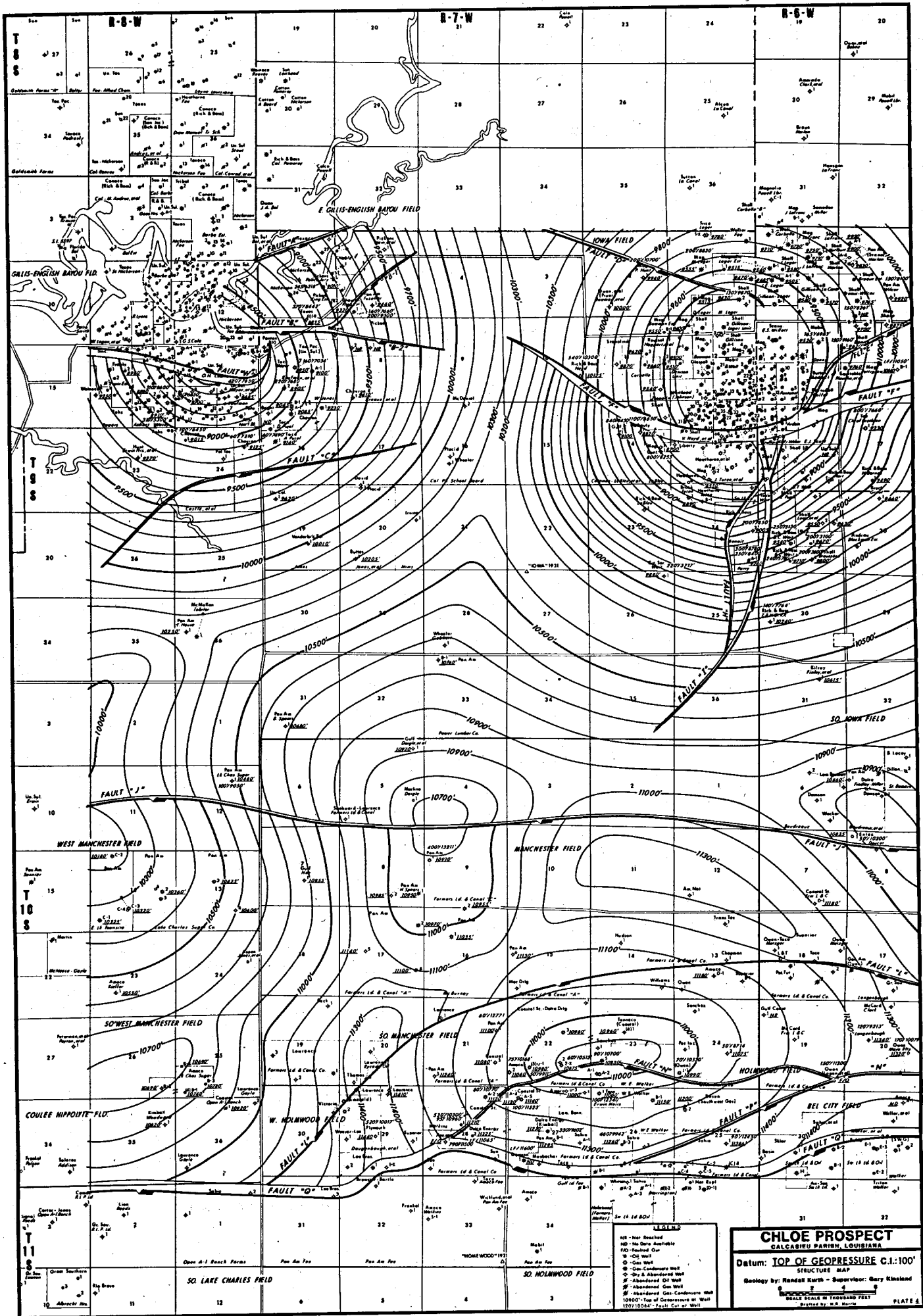


CHLOE PROSPECT
 CALCASIEU PARISH, LOUISIANA
 Datum: TOP OF HACKBERRY MASSIVE "A" SAND C.I.: 10°F
 Temperature Map
 Geology by: Russell Smith - Geologist; Gary Elwood
 Geophysical by: Schlumberger
 Made in the U.S.A. 1958
 PLATE 2

LEGEND
 255 - Temperature at well
 210 - Questionable data - see text
 180 - Not reached
 150 - No Data Available
 140 - Observed Oil
 130 - Oil Well
 120 - Gas Condensate Well
 110 - Oil & Gas Condensate Well
 100 - Abandoned Oil Well
 90 - Abandoned Gas Well
 80 - Abandoned Gas Condensate Well

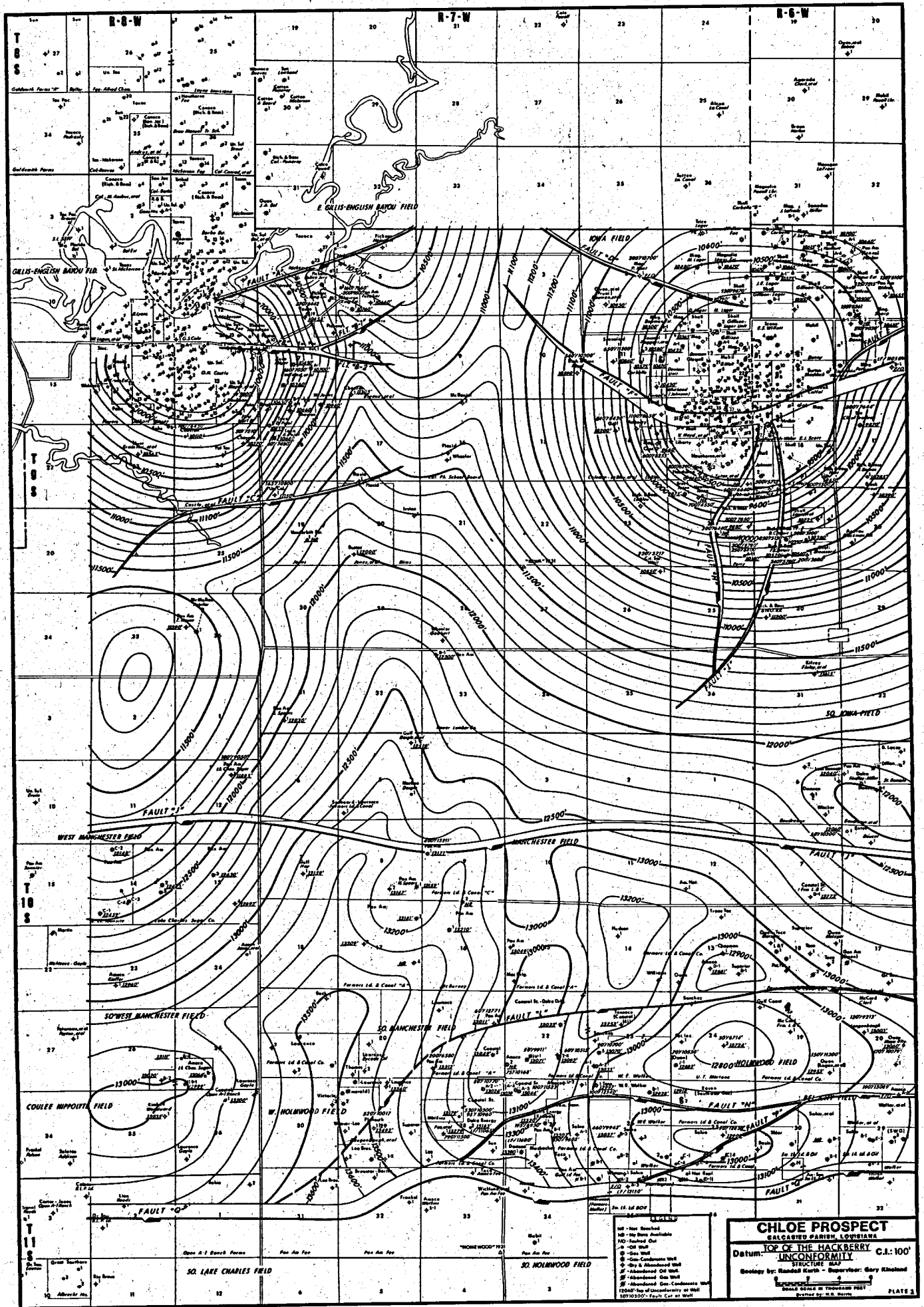


CHLOE PROSPECT
 CALCASIEU PARISH, LOUISIANA
 Datum: TOP OF CIBICIDES
 HAZARDI MARKER
 STRUTURE MAP
 Geology by: Ransom North - Supervisor: Gary H. Hinesland
 1950
 Scale: 1" = 1000 FEET
 Plate 1

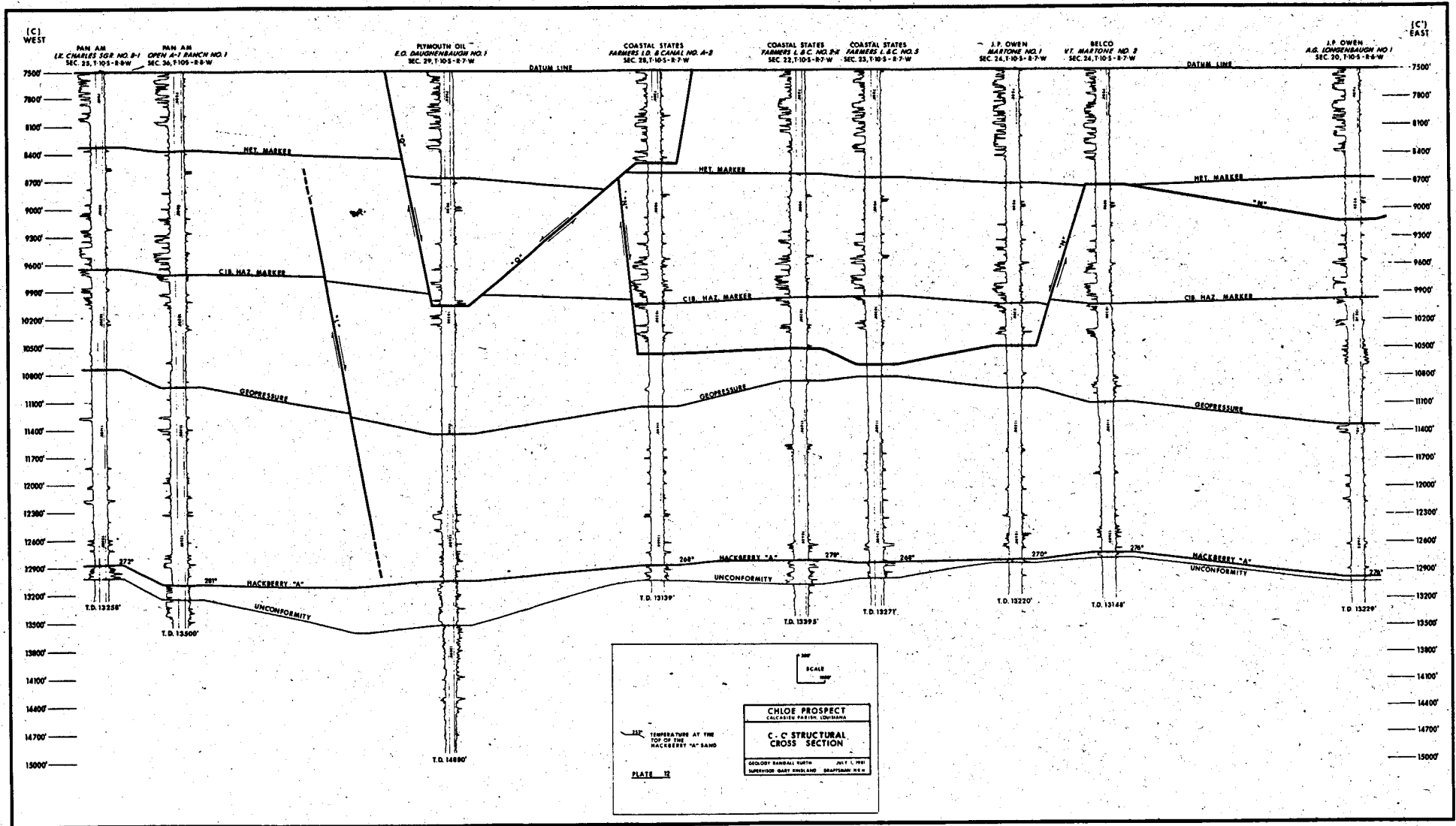


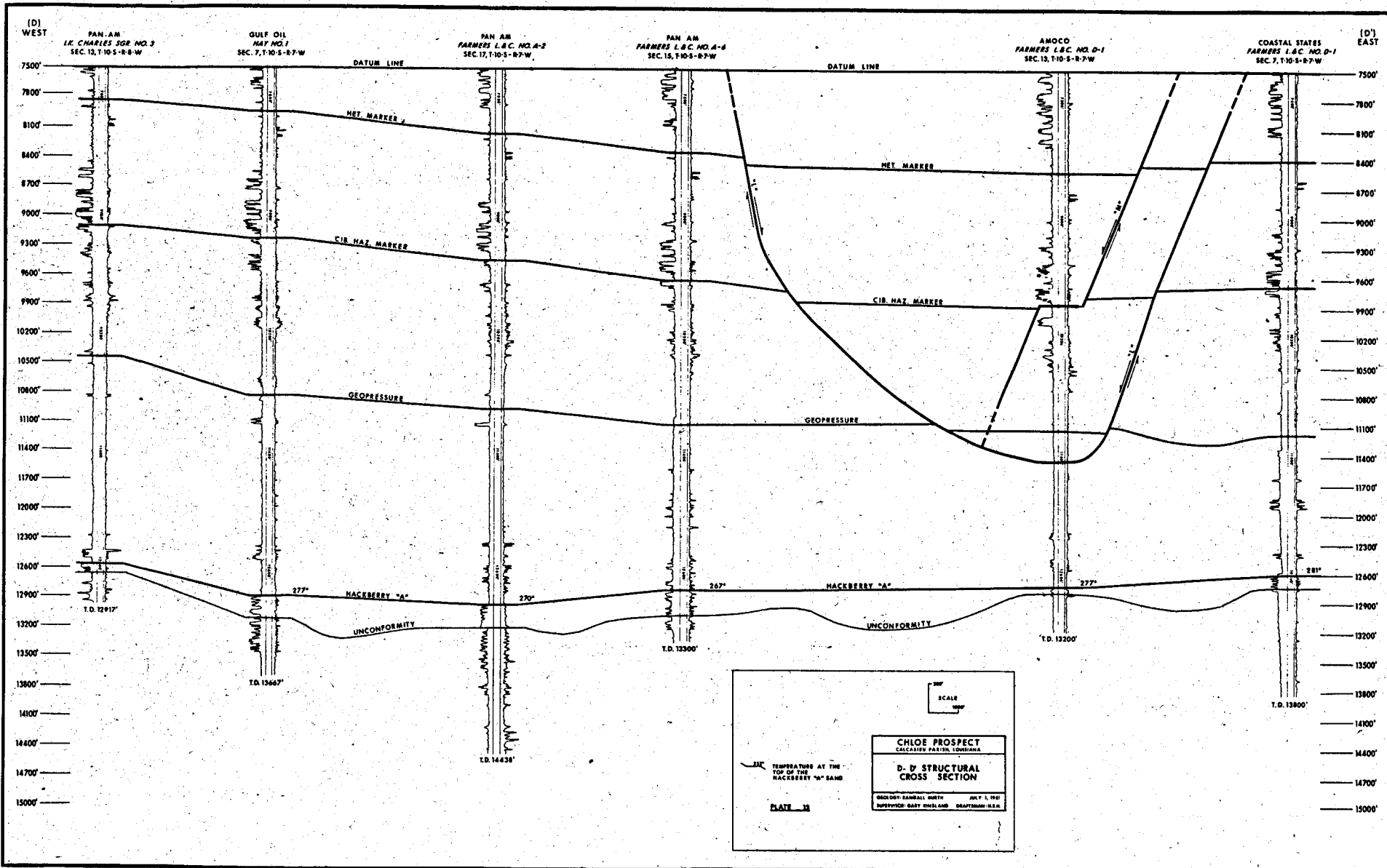
CHLOË PROSPECT
 CALCASIEU PARISH, LOUISIANA
 Datum: TOP OF GEOPRESSURE C.I. 100'
 STRUCTURE MAP
 Geology by: Randal Kurth - Supervisor: Gary Kineland
 SCALE: SCALE IN THOUSAND FEET
 PLATE A

LEGEND
 10 - Not Reached
 100 - No Data Available
 100 - Contained Oil
 100 - Oil Well
 100 - Gas Well
 100 - Gas Condensate Well
 100 - Dry & Abandoned Well
 100 - Abandoned Oil Well
 100 - Abandoned Gas Condensate Well
 100 - Top of Geopressure at Well
 100 - 1000' - Fault Cut at Well



CHLOE PROSPECT
 CALCASIEU PARISH, LOUISIANA
 Datum: TOP OF THE HACKBERRY C.A.: 100'
 STRUCTURE MAP
 UNCONFORMITY
 Geology by: Ronald Keith - Supervisor: Gary Rhoads
 SCALE 5000' BY TRANSVERSE DISTANCE
 PLATE 3





(E)
WEST

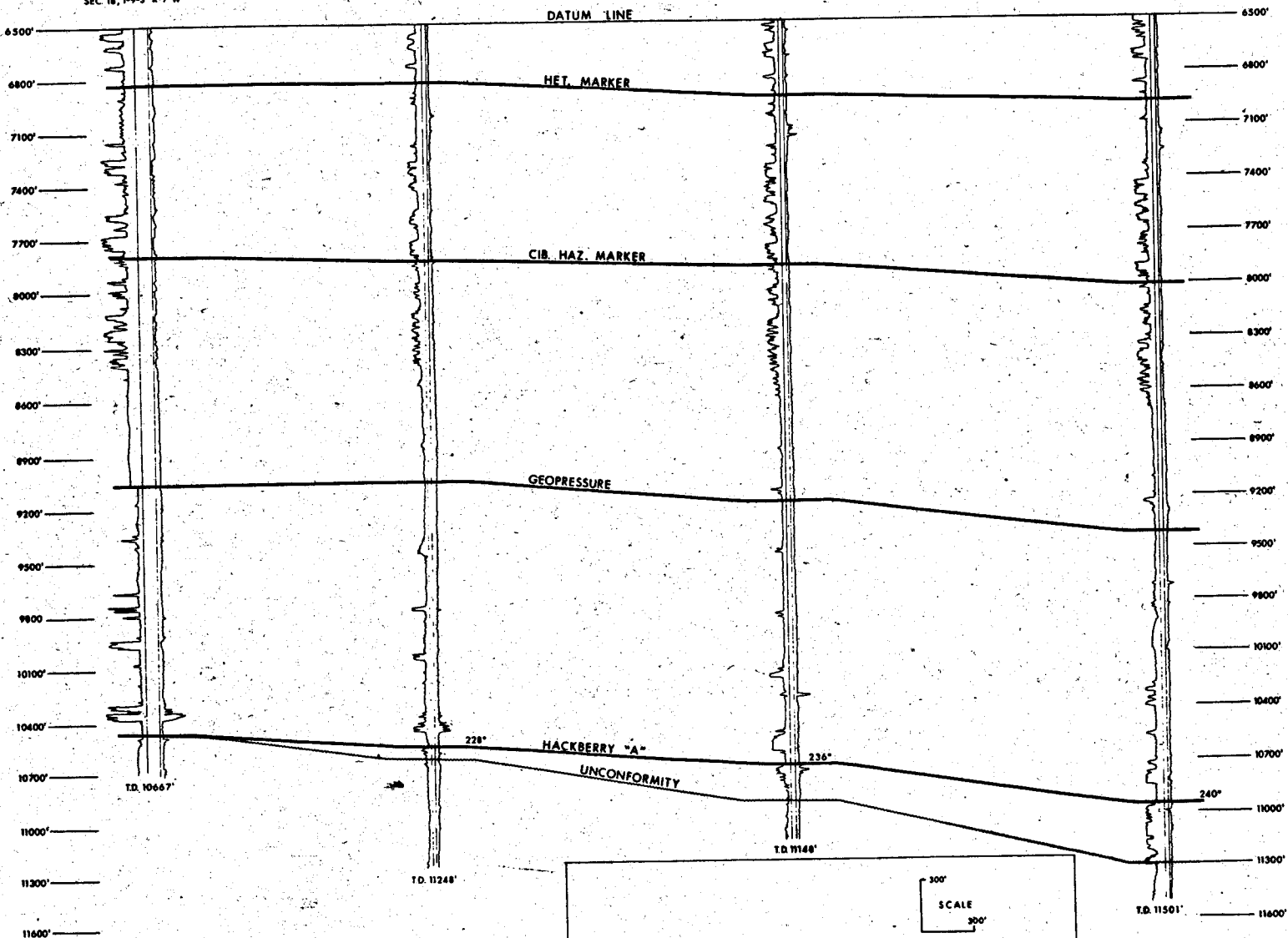
TOCE OIL
A. PUJOL NO. 1
SEC. 18, T-9-S R-7-W

CALIFORNIA CO.
D. PUJOL NO. 1
SEC. 18, T-9-S R-7-W

CALIFORNIA CO.
W.D. JONES NO. 1
SEC. 18, T-9-S R-7-W

CALIFORNIA CO.
J. BREAUX NO. 1
SEC. 8, T-9-S R-7-W

(E)
EAST

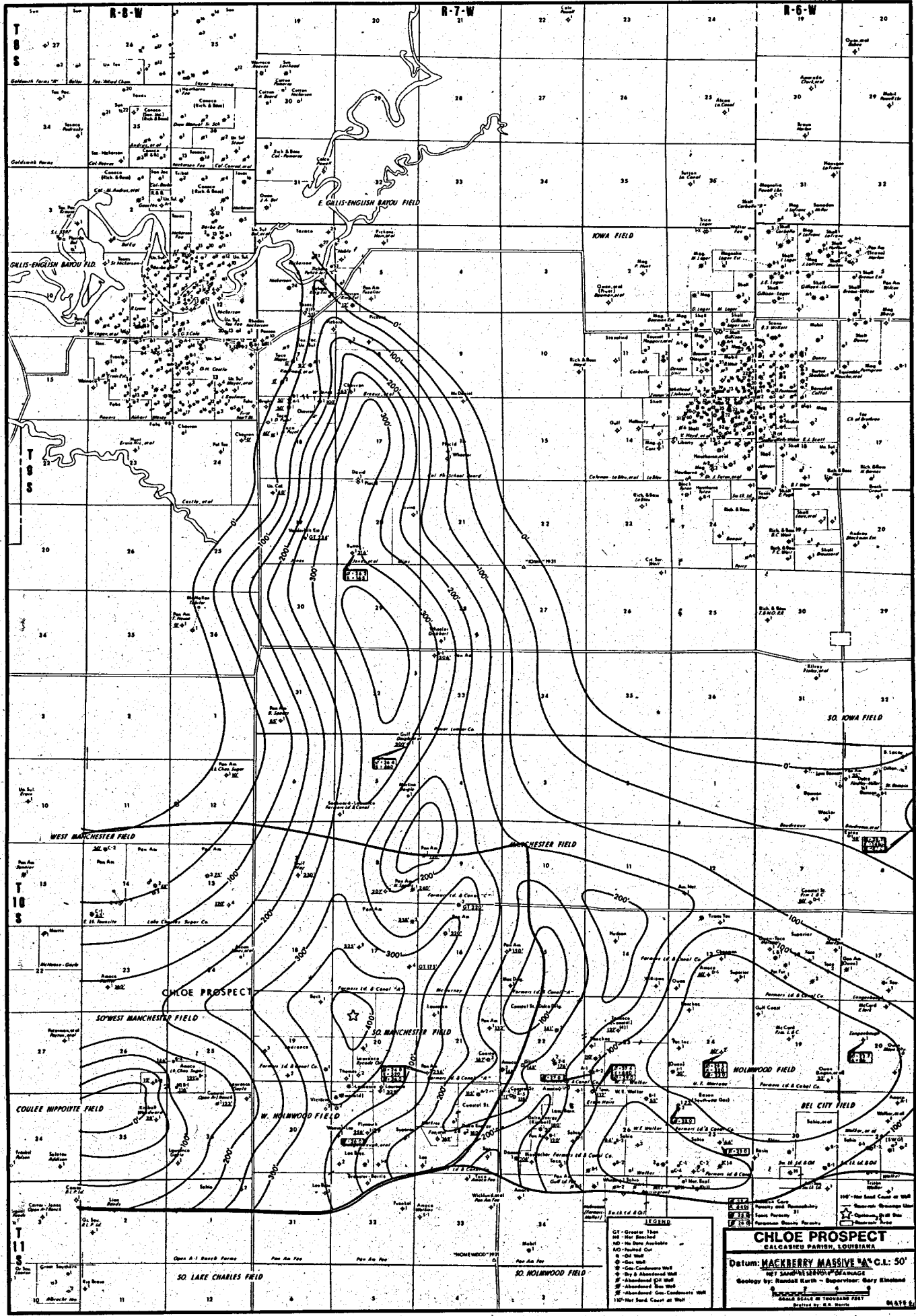


252° TEMPERATURE AT THE TOP OF THE HACKBERRY "A" SAND

PLATE 15

CHLOE PROSPECT CALCASIEU PARISH, LOUISIANA	
E - E' STRUCTURAL CROSS SECTION	
GEOLOGY: RANDALL KURTH	JULY 1, 1981
SUPERVISOR: GARY KINSLAND	DRAFTSMAN: H.R.M.

B102



CHLOE PROSPECT
 CALCASIEU PARISH, LOUISIANA

Datum: **HACKBERRY MASSIVE N.C. 50'**
 Geology by: **Ronald Keith** - Supervisor: **Gary Kinkead**

SCALE: 1" = 1000' FEET
 DRAWN BY: G.S. DUNN

- LEGEND**
- GT - Greater than 100' thick
 - ND - No Data Available
 - OW - Oil Well
 - GW - Gas Well
 - CC - Conductor Well
 - AB - Abandoned Well
 - AW - Abandoned Oil Well
 - AW - Abandoned Gas Well
 - CC - Conductor Well
 - 100' - 100' Sand, Cont. at Well