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3

Geothermal and Geopressure Patterns of Bayou Carlin–Lake Sand Area, South Louisiana: Implications[1]

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Abstract The Bayou Carlin–Lake Sand area is part of a well-known "hot belt" and geopressured region of south Louisiana. The area is characterized by a rim syncline (with Cote Blanche salt dome) on the northwest, a gulfward-dipping growth fault on the south, and productive structures of Lake Sand, East Lake Sand, and Bayou Carlin fields. Lake Sand field produces mostly gas from the anticline on the downthrown side of a growth fault. In East Lake Sand field gas accumulations are on the upthrown side of the eastward extension of the growth fault. Bayou Carlin field consists essentially of stratigraphic traps north and northeast of the two fields. The mapping of the geopressured zone shows that its roof shallows over the structural highs and the downthrown side of the growth fault, and that the geopressure roof has thermal halos over the structural highs. The geothermal mapping of structural horizons in the hydropressured and geopressured zones indicates that the isothermal contours approximate the subsurface structures. The geoisotherms (depth contours) of the 250°F (121°C) datum and isotherms (temperature contours) at four depth levels (10,000; 12,000; 14,000; and 16,000 ft or 3,048; 3,658; 4,267; 4,877 m) suggest that the structural highs are associated with thermal highs, and that the rim synclinal zone of the Cote Blanche salt dome is hot because of a greater heat flow from the salt diapir. These features also are reflected by the computerized residuals of the isotherms from the first-order polynomial surfaces at those depth levels. The geothermal highs on the productive structures, particularly those associated with growth faults, easily are explainable in terms of the mechanism of primary migration of hot fluids from the deeper levels up the fault planes into the permeable sand bodies in the vicinity of the faults. The geothermal mapping technique, possibly with appropriate computer applications, has great potential as an effective adjunct to the conventional tools used for petroleum exploration. The geothermal approach is recommended for selecting areas of possible petroleum prospects prior to detailed appraisal, for delineating untested rollover anticlines against growth faults, and for locating deeper hydrocarbon accumulations of commercial significance.

INTRODUCTION

In recent published literature the relation between hydrocarbon locations and the thermal histories of sedimentary basins has been emphasized. Among the noteworthy papers, Jones (1975) has recognized a distinct genetic association between hydrocarbon and hydrothermal regimes in the northern Gulf of Mexico basin; Klemme (1975) has emphasized that high geothermal gradients in clastic sequences enhance the maturation, migration, and accumulation of petroleum; Reel and Griffin (1971) depicted potentially petroliferous trends of Florida by mapping geothermal gradients; Ovnatanov and Tamrazyan (1970) reported the discovery, resulting from the geothermal studies of Apsheron Peninsula of Azerbaijan, USSR, of an offshore deep-seated gas-bearing structure. These works pertain, on a regional basis, either to entire basins or their major units. A closer look at subunits of petroliferous provinces is also in order. To this end, the present paper focuses on a relatively small region, the Bayou Carlin–Lake Sand area of south Louisiana (Fig. 1). This falls in the "hot belt" of south Louisiana recognized by Jam et al (1969). The area also is characterized by abnormal subsurface pressures as documented initially by Jones (1969). This study examines the patterns of subsurface pressures and temperatures in light of the known geologic history of the area and recommends geothermal-geopressure mapping as an important and regular adjunct to the conventional approaches to petroleum exploration where well control exists.

GEOLOGIC FRAMEWORK

The study area is located between two domes in the well-known "Five Islands trend" of south Louisiana (Fig. 1). The subsurface has a Miocene residual high (Kumar, 1972) between the older rim syncline of the Bayou Sale dome on the southeast, and a younger rim syncline associated with the Cote Blanche salt dome on the northwest. It (Fig. 2) is traversed by two principal systems of faults: the Bayou Carlin faults dipping northwesterly toward Cote Blanche, and the Lake

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The basic data for this study were compiled from the open files of the Department of Conservation of the State of Louisiana during the writer's doctoral work at Louisiana State University, Baton Rouge, during 1970-72. Subsequently, additional wells were drilled, but the newly available data warrant no significant changes in the illustrations of this paper.

During the early phase of the work the writer benefitted from his professional association with C. O. Durham and W. A. Romans of Gulf Geothermal Corporation, Baton Rouge, and expresses his grateful appreciation to them. He also thanks D. H. Kupfer and P. H. Jones of Louisiana State University, Baton Rouge, for discussing some aspects of this study.

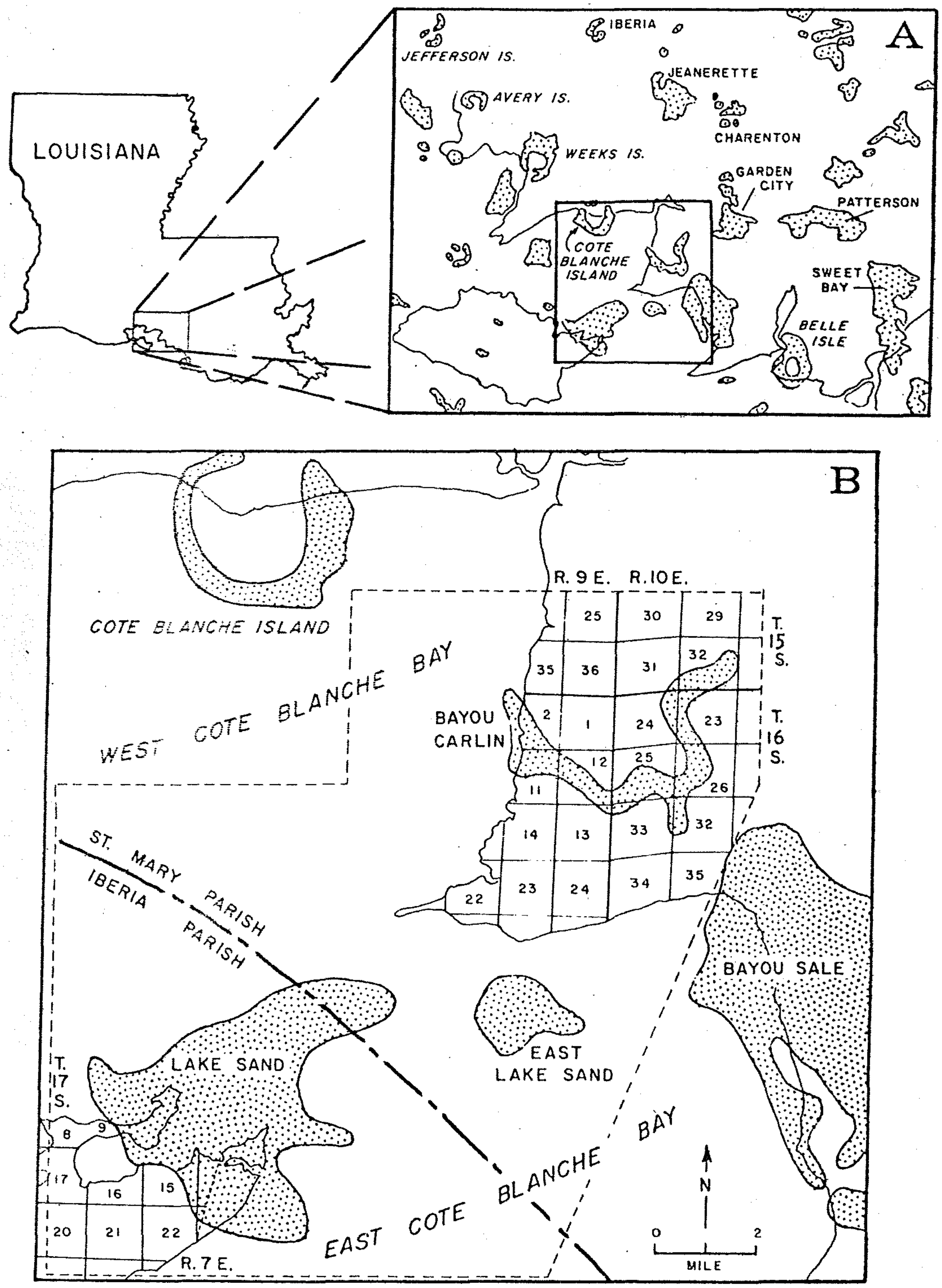

FIG. 1—A, Bayou Carlin–Lake Sand area and adjacent petroleum fields (Louisiana Geological Survey, 1973a). B, Enlargement of square in A; Bayou Carlin–Lake Sand study area is within dashed lines. Details from Louisiana Geological Survey (1973b).

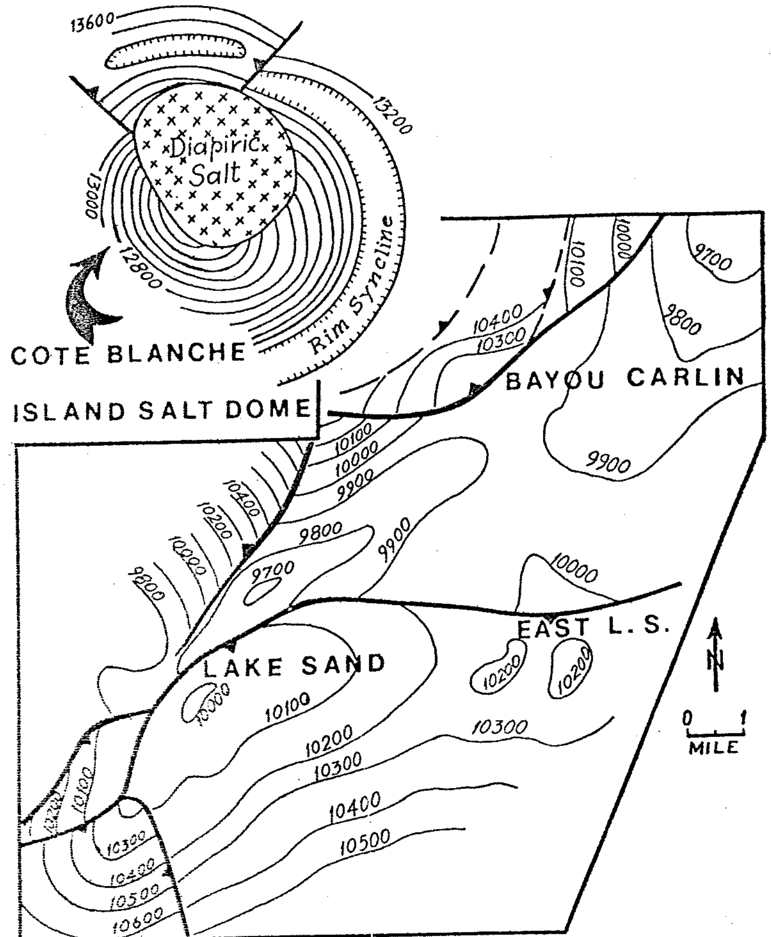

FIG. 2—Structural map on datum near top of *Bigenerina humblei* zone. Structure of Cote Blanche Island after Atwater and Forman (1959). Contour interval is 100 ft (30 m).

Sand fault dipping south. The latter, developed with pronounced growth (syndepositional) features, predates the Bayou Carlin faults, which lack growth features. The subsurface lithologic succession consists essentially of repeated sequences of sandstone, siltstone, and shale.

The main petroleum field, Lake Sand (Fig. 1), produces mostly gas from the anticline on the downthrown side of the growth fault. East Lake Sand field is productive of gas from deeper levels on the upthrown side of the fault. Bayou Carlin field, north and northeast of these fields, has primarily stratigraphic traps with gas.

NATURE OF DATA

The present study is based on the electric-log data from about 150 wells most of which are deeper than 10,000 ft (3,048 m). To construct graphs and maps of geopressures and geotemperatures, the mud density and bottom-hole temperatures from the headings of the electric logs were used. The bottom-hole temperatures, which normally are lower than the equilibrium subsurface temperatures, were converted to approximate equilibrium temperatures according to the empirical correction curve of Kehle (1971). For formation pressures, although their estimates based on mud weights exceed, often substantially, their actual values, the mud data are readily available and are used with varied degrees of reservation, depending on the objective of the investigation. For the present work, the mud density (pounds per gallon) is taken to reflect numerically the geostatic ratio or formation pressure (subsurface pressure) as follows:

Pressure gradient (pounds per square inch/foot) due to a mud column of density, n pounds/gallon equals,

$$\frac{n}{231} \times 12 \quad (1 \text{ gal} = 231 \text{ cu in.})$$

or

$$= 0.05n.$$

Geostatic Ratio (at a depth of d ft)

$$= \frac{\text{Formation pressure at d ft}}{\text{Overburden pressure at d ft}}$$

$$= \frac{\text{Formation pressure gradient} \times \text{depth}}{\text{Overburden pressure gradient} \times \text{depth}}$$

$$= \frac{(0.05 \times \text{psi/ft}) \times d_1}{(1.00 \text{ psi/ft}) \times d} = 0.05n$$

$$= 0.05 \times \text{mud density (lb/gal)}.$$

For the Gulf of Mexico basin, the geostatic ratio ranges between 0.465 (corresponding to 9.3 lb/gal of mud) in the hydropressured zone, and 1.00 (corresponding to 20 lb/gal of mud) or slightly more (Parker, 1973) in the perfect geopressured zone.

VERTICAL PATTERNS OF GEOPRESSURES AND GEOTEMPERATURES

For each of the wells of the study area a graph of mud density and temperature compared to depth was plotted. These well graphs displayed marked variations in their pattern relative to the Lake Sand growth fault, as illustrated in Figure 3. The graphs were used to determine temperatures at stipulated depths for geothermal mapping described in the succeeding section.

For the subareas north and south of the Lake Sand fault, composite plots of mud density and temperature were prepared by synthesizing the individual well graphs. The composite plots shown as Figure 4 indicate distinctly the hydropressured (Stuart, 1970) and geopressured (Jones, 1969) zones. From a comparison of the composite plots it is evident that the top of the geopressured zone (characterized by a mud density exceeding 14 lb/gal) lies much shallower south of the growth fault (Lake Sand) than on the north. The top of the geopressured zone (corresponding to a mud density of 18 lb/gal) on the downthrown side of the fault lies at a depth of about 14,200 ft (4,328 m) and that on the north (upthrown side) is about 1,800 ft (549 m) deeper. The top of the geopressured zone is marked by the increase of the geothermal gradient to about 5°F/100 ft (2.78°C/30 m) from the normal value of 1°F/100 ft (0.56°C/30 m) in the hydropressured zone. This is as expected, in keeping with the trend described by Jones (1969) and Wallace (1970). The sharp change in the geothermal gradient is more distinct in the Lake Sand area than in Bayou Carlin area. The variations in the geothermal gradient are considered to be a reflection of reservoir geometry and hydrodynamics, both of which are influenced by structural deformations (Jones and Wallace, 1974).

AREAL PATTERNS OF GEOPRESSURES AND GEOTEMPERATURES

The individual well graphs of temperature show pronounced changes in the thermal gradient, particularly within the transition between the hydropressured and geopressured zones. Hence, for investigating small areas such as the present one, the maps of geothermal gradients are not so serviceable as the isothermal maps for selected depth levels and the geoisothermal maps (isothermal surfaces) for selected temperature datums. Moreover, the maps of the structure and temperature of the roof of the geopressured zone could aid in explaining the distribution of hydrocarbon accumulations particularly in the transitional zone or near the floor of the hydropressured zone. So far as the study area is concerned, one has to take cognizance of the influence that the growth faults, salt domes, and facies changes could have on the spatial distribution of geotemperature. To isolate the effect of structure on the geotemperature distribution it also is imperative to construct isothermal maps of structural horizons.

Methodology

On the basis of the individual well graphs similar to Figure 3 the following mapping was attempted: (a) maps of the structure and temperature at the top of the geopressured zone; (b) isothermal contour maps of two structural horizons—one (upper horizon) within the hydropressured zone, close to its base, and the other (lower horizon) within the geopressure zone; (c) geoisothermal contour maps of three temperature datums: 200°F, 250°F, and 300°F (90, 121, 149°C); (d) isothermal contour maps at four depth levels: 10,000, 12,000, 14,000, and 16,000 ft (3,048; 3,658; 4,267; 4,877 m).

The subsurface values (temperatures and depths) for these maps were determined from the individual well graphs of mud density and temperature, mostly by interpolation with close control points on the graphs. The interpolation or extrapolation of the data in the transitional

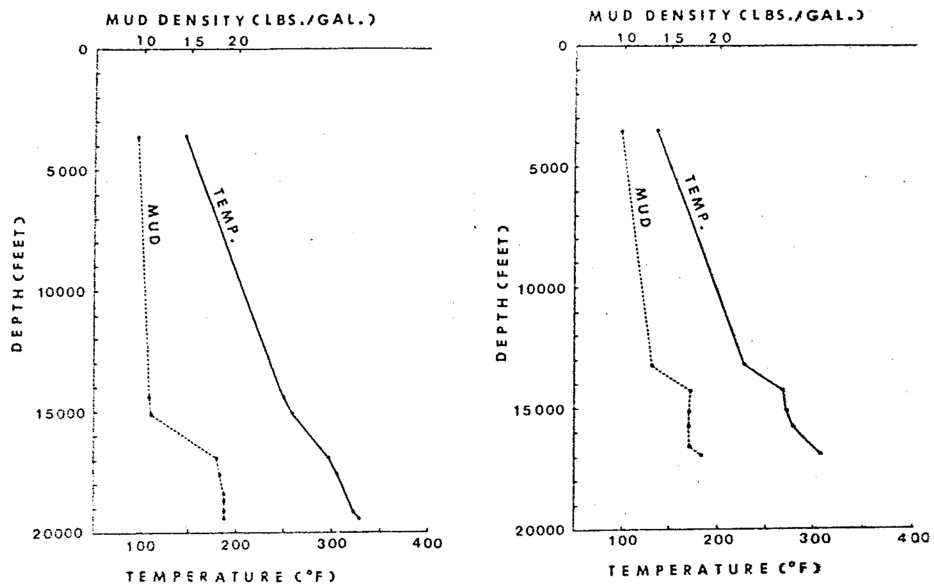

FIG. 3—Typical individual well graphs of mud density (formation pressure) and temperature versus depth.

At left, north of Lake Sand fault, Sunray DX Oil Co. S/L 4267, no. 1, West Bayou Carlin, St. Mary, Louisiana, TD 19,600 ft (5,974 m).

At right, south of Lake Sand fault, Humble Oil and Refining Co. S/L 1706, no. 4, Lake Sand, Iberia, Louisiana, TD 17,051 ft (5,197 m).

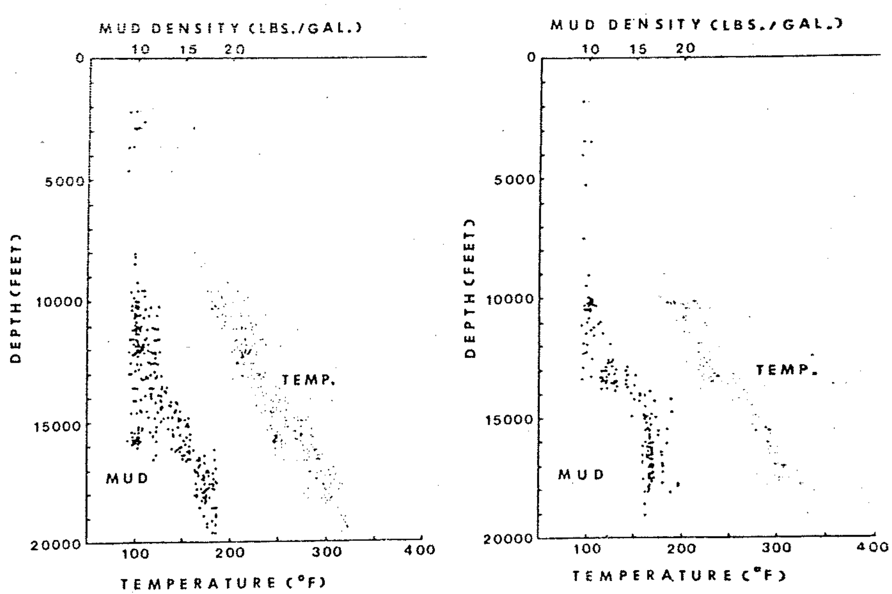

FIG. 4—Composite graphs of mud density (formation pressure) and temperature versus depth. constructed by combining individual graphs of about 150 wells (similar to Fig. 3). Top of geopressured zone is much shallower south (left diagram) of Lake Sand fault than on north (right diagram).

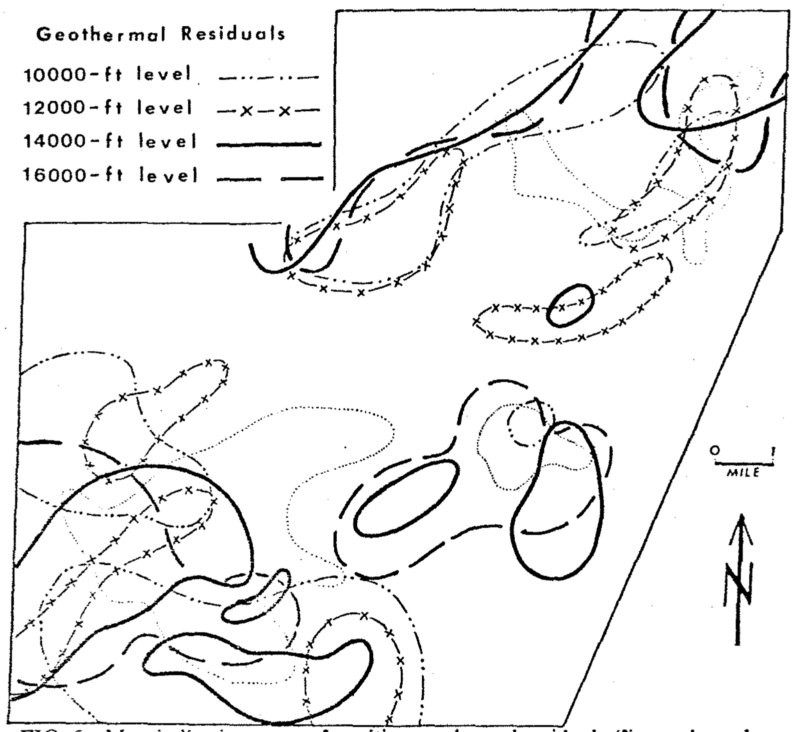

FIG. 5—Map indicating areas of positive geothermal residuals (first-order polynomial, computer derived) at depth levels of 10,000; 12,000; 14,000; and 16,000 ft (3,048; 3,658, 4,267; 4,877 m). Outlines of petroleum fields are shown with dotted lines. Areas of positive residuals are outlined by closed contours as explained at top-left corner.

geopressured zone is unreliable and was avoided. This, coupled with the fact that all wells are not deep enough and that normally only a few temperature measurements per well exist, limits the availability of useful data for the construction of maps. In several wells the temperature measurements are not available for shallow depths, or they are available only at depth intervals too wide to be suitable for reliable interpolations or extrapolations. The resulting data are inadequate for the construction of geoisothermal maps for 200°F and 300°F (90 and 149°C) that are not included here for the obvious reason.

On each of the preceding maps, outlines of petroleum fields and faults are indicated to facilitate the evaluation of the relation between the geopressure-geothermal patterns and the structure of the area.

Prior to the construction of these maps, it was ascertained whether or not the area had geothermal anomalies of mappable significance. This was accomplished by mapping computer-derived well residuals (from the first-order polynomial surface) of the isotherms for the four depth levels: 10,000; 12,000; 14,000; and 16,000 ft (3,048; 3,658; 4,267; 4,877 m). The positive residuals are depicted in Figure 5 which provides a quick-glance map of the geothermally interesting parts of the area to be discussed.

Appraisal of Maps

As explained earlier, the various maps constructed are appraised in light of the available information on the tectonics and productive structures of the area. From the contours and the distribution of control wells in Figures 6 through 14 it is evident that some of the contouring is based on rather sparse well control and is more interpretive in nature.

Maps of geopressure top—The contour map of the geopressure top (Fig. 6) shows that the roof of the geopressured zone is shallowest on the downthrown side of, and adjacent to, the Lake Sand growth fault. The highs of the roof surface considerably overlap the structural highs of Bayou Carlin and Lake Sand fields. The structure (minor) of East Lake Sand field is not reflected well by the configuration of the geopressure roof.

The isothermal map of the geopressure top (Fig. 7) shows that the downthrown side of the

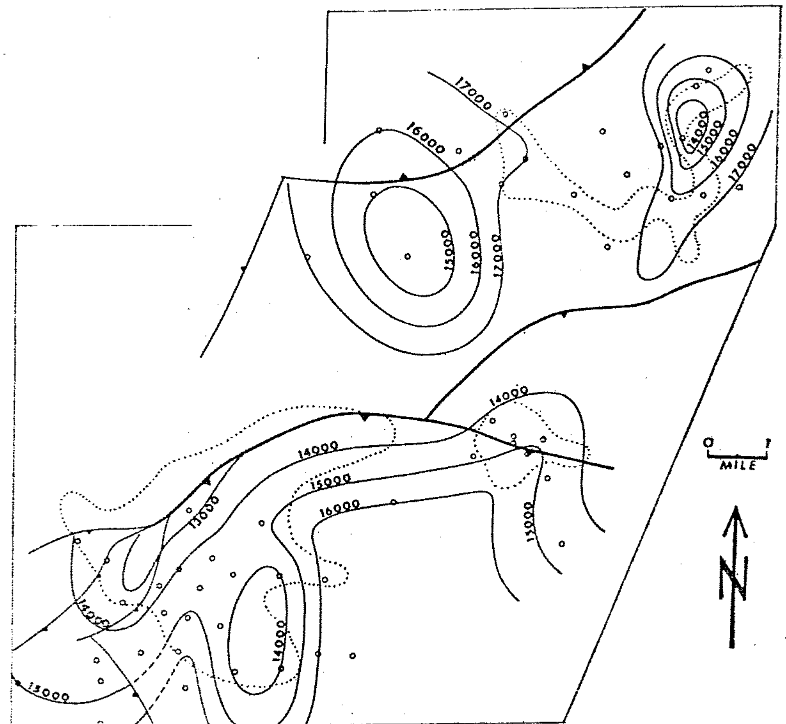

FIG. 6—Subsurface contours on top of geopressured zone. Small circles indicate control wells; fault lines are normal faults with barbs on downthrown side. Contour interval is 100 ft (30 m).

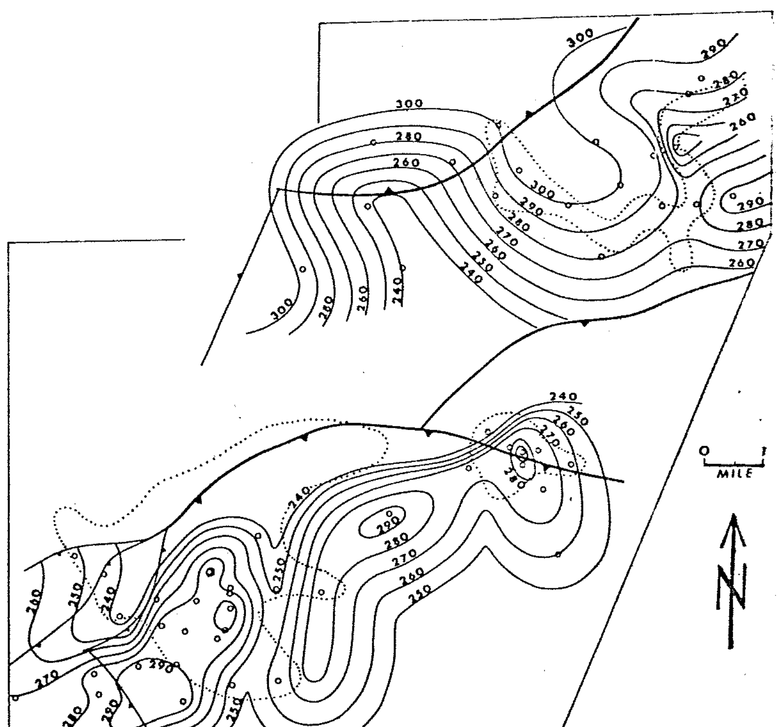

FIG. 7—Isotherms of top of geopressured zone. Contour interval is 10°F (5.6°C).

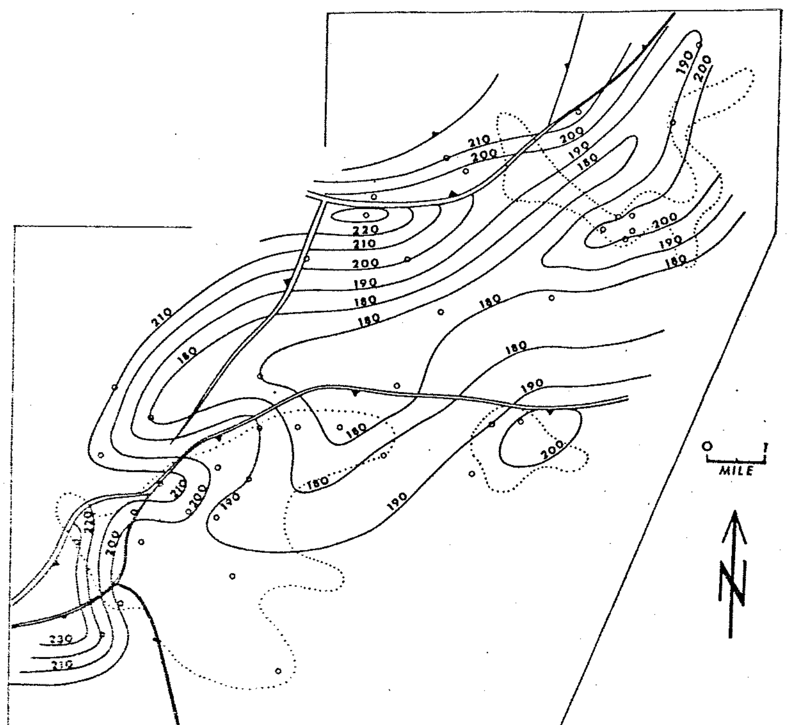

FIG. 8—Isotherms of structural horizon (at about 10,000 ft or 3,048 m) in hydropressured zone. Contour interval is 10°F (5.6°C).

Lake Sand growth fault is characterized by geothermal highs somewhat displaced away from the fault zone. Directly in the vicinity of the fault appear the lowest isotherms where the zone of dip reversal of the anticline lies. In the East Lake Sand area, a hot spot is present across the fault reflecting a thermal communication between the two sides of the fault, unlike the area (Lake Sand field) just on the west. On the north, the geothermal highs are across the Bayou Carlin fault (post-depositional type) with hot spots near the rim syncline of the Cote Blanche dome in the northwest.

Isothermal maps of structural horizons—The isotherms (Fig. 8) on the upper structural horizon (in the hydropressured zone, close to its floor) show that the Lake Sand area has geothermal highs east and west of a thermal saddle against the main growth fault. This saddle merges with the low just on the upthrown side of the fault. In the Bayou Carlin area geothermal highs appear over the structural high on the northeast, and also near the rim syncline of the Cote Blanche dome in the northwest.

The isotherms (Fig. 9) of the lower horizon (in the geopressured zone, close to its roof) depict geothermal highs (separated by a saddle) south of the growth fault in the Lake Sand area. In the Bayou Carlin area, the geothermal highs approximate the structural highs. On the northwest, temperatures indicate an abrupt rise over the rim syncline.

From these two maps it is evident that the geothermal highs mark the productive structural highs and also the structural lows like the rim syncline. The configuration and location of the geothermal highs do not conform strictly to the geometry of the structure. This is attributed to factors other than the structural control for geothermal distribution, for instance, lithologic variations, hydrodynamic aspects of the faults and strata involved, and limitations in data distribution.

Isothermal surface map (250°F or 121°C geoisotherms)—The highs in the geoisothermal map (Fig. 10) appear over the structural highs of Bayou Carlin, East Lake Sand, Lake Sand, and also on the west.

Isothermal maps—The isotherms at the 10,000-ft (3,046 m) level (Fig. 11) show that in the Lake Sand area the downthrown side of the growth fault is marked by geothermal highs separated by saddles. On the north, the structural highs of the Bayou Carlin area have thermal halos (geother-

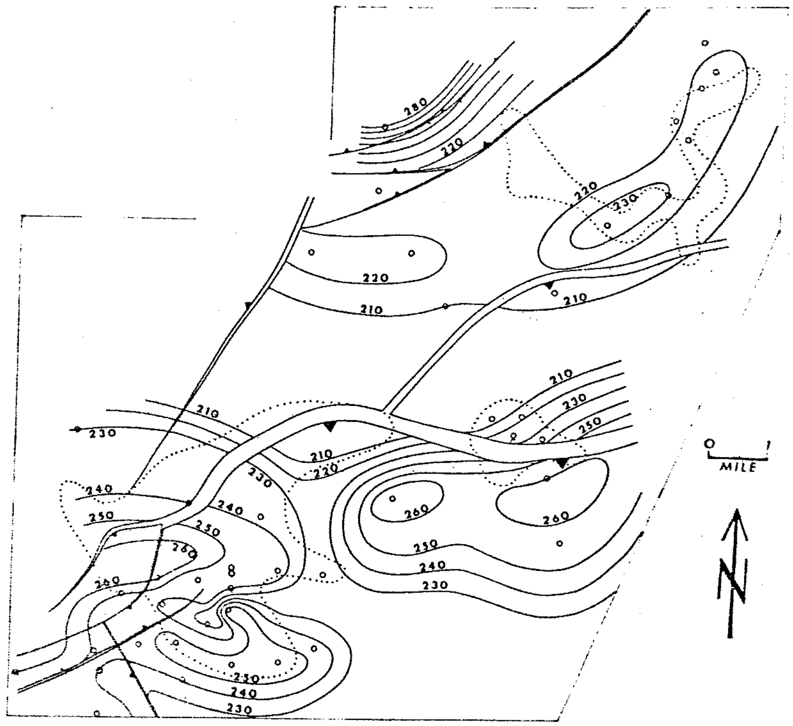

FIG. 9—Isotherms of structural horizon (at about 13,000 ft or 3,962 m) in geopressured zone. Contour interval is 10°F (5.6°C).

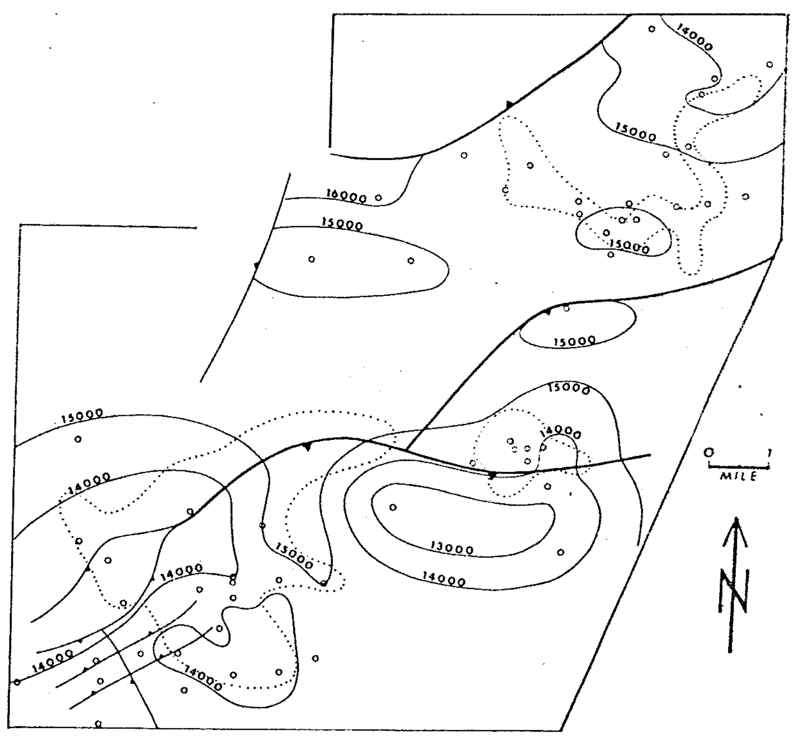

FIG. 10—Geoisotherms (depth contours) of 250°F (121°C) datum. Contour interval is 1,000 ft.

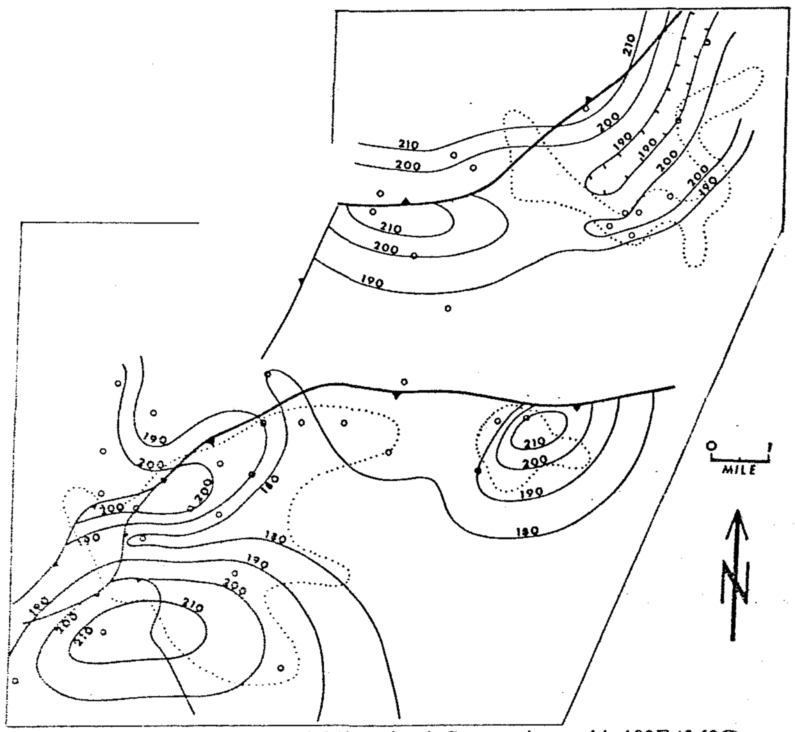

FIG. 11—Isotherms at 10,000-ft (3,048 m) level. Contour interval is 10°F (5.6°C).

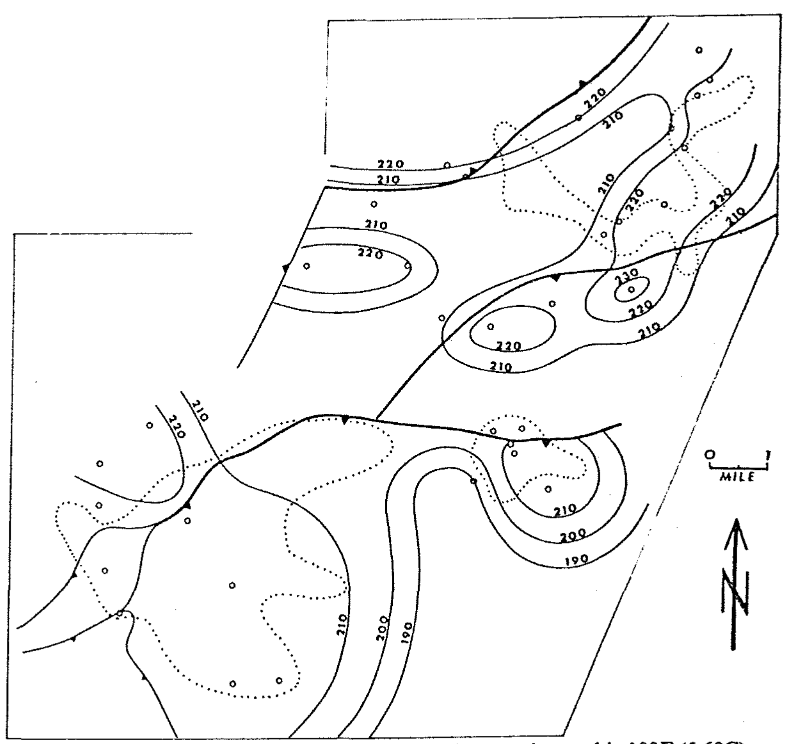

FIG. 12—Isotherms at 12,000-ft (3,658 m) level. Contour interval is 10°F (5.6°C).

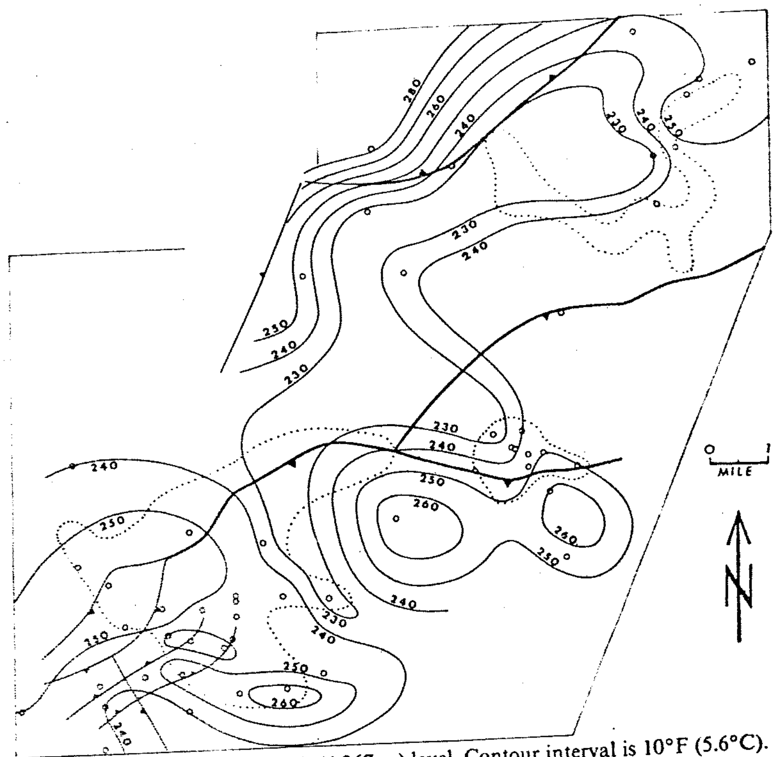

FIG. 13—Isotherms at 14,000-ft (4,267 m) level. Contour interval is 10°F (5.6°C).

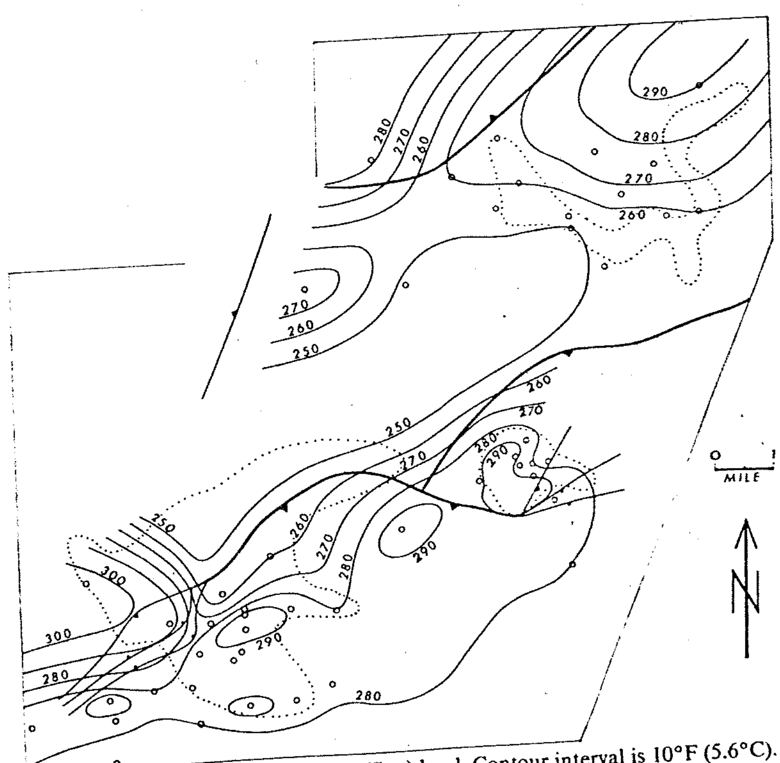

FIG. 14—Isotherms at 16,000-ft (4,877 m) level. Contour interval is 10°F (5.6°C).

mal highs). Toward the rim syncline in the northwest an abrupt rise in geotemperature is reflected.

The isotherms at the 12,000-ft (4,267 m) level (Fig. 12) show a geothermal high on the downthrown side of the growth fault in the East Lake Sand area. Over Lake Sand field, though the temperature data are scanty, a geothermal high is suggested. In the Bayou Carlin area the structural highs are associated with thermal halos, which extend southerly across a fault that branches off the Lake Sand fault southward. Toward the northwest, the isotherms reflect a pronounced rise.

The isotherms at the 14,000-ft (4,276 m) level (Fig. 13) show that the downthrown side of the Lake Sand fault has geothermal highs separated by a saddle. On the northeast, the structural high of Bayou Carlin is marked by a thermal halo. Northwestward, a high geothermal rise is reflected.

The isotherms at the 16,000-ft (4,877 m) level (Fig. 14) show thermal halos on the structural high on the downthrown side of the fault in Lake Sand field. In the west another clear thermal high also is present. In the East Lake Sand area the geothermal high extends across the upthrown side of the fault (productive of gas). To the northwest, the isotherms rise in magnitude as on the previous maps.

These maps indicate that at the deeper levels the variation range of geotemperature values increases.

A comparison of these maps (Figs. 11-14) with the geothermal residuals map (Fig. 5) reveals that the latter approximates the other maps in essential features.

DISCUSSION

From the preceding appraisal of the maps the following points are of interest.

1. By computerized-residuals mapping of geotemperatures it is possible to locate quickly geothermal features of interest and economize on time and effort for such mapping programs. When computer maps are available only some critical maps need to be constructed manually.

2. In the Bayou Carlin area the structural highs are marked by geothermal halos and the highs of the roof of the geopressured zone.

3. Toward the rim syncline of the Cote Blanche salt dome, and also the West Cote Blanche dome, the geotemperature registers a rising trend.

4. Lake Sand field anticline has a geothermal high on its structural crest. Toward the growth fault and down structure the geotemperature declines.

5. The downthrown side of the growth fault is characterized by the shallow roof of the geopressured zone, which is highest in the immediate vicinity of the fault.

6. In the East Lake Sand area the geothermal highs appear across the growth fault, embracing particularly the productive field on the upthrown side of the fault.

7. Like the structural relief, the isothermal relief increases with depth, being greatest in the geopressured zone.

An important aspect of this study is to answer the question—what causes the observed geothermal anomalies? The obvious situation is represented by the rim syncline toward which the geotemperature has been elevated by the heat flow from the salt intrusion (Miocene) in the Cote Blanche area. Similarly the West Cote Blanche dome seems to be responsible for high geotemperatures in the southwest (or west of Lake Sand field). Of special significance is the association of the geothermal halos with the structural highs in Bayou Carlin and Lake Sand fields. In the latter, the geothermal high is over the structural closure with a cooler zone in the dip reversal into the fault. Similar geothermal anomalies have been observed by the writer over some other productive anticlines elsewhere in Louisiana. Such geothermal anomalies can be explained as follows: as the geopressured zone develops, the upward heat transmission is impeded in the undercompacted sediment because of the relatively high specific heat and low conductivity of water (the mineral grains have about ⅓ less specific heat and about 5 times higher conductivity); the heat received from below is locked up within the geopressured zone, thereby elevating the geotemperature. In the geopressured zone water has a greater phase continuum than do the discrete grains of undercompacted sediments, thus encouraging thermal convection. The hotter water moves to the higher part of the structure, giving rise to a thermal high coincident with the structural high. Such a thermal high is normal on the downthrown side of the fault, as in Lake Sand field. But a similar thermal high also could be present on the upthrown side of or across the fault as in the case of East Lake Sand field. This is explained easily by invoking the mechanism of primary migration of petroleum envisaged by Jones (1975) and Price (1976). They recognized faults as fluid barriers (seals) in the hydropressured zone and as hydraulic carriers (conduits) for the upward migration of fluids in the geopressured zone. Thus, the hot fluids from the deeper levels (essentially, water with dissolved hydrocarbons) migrate up the fault plane and enter the permeable sand bodies against the fault to create thermal highs in the Lake Sand area on the downthrown side and also on the upthrown side as in East Lake Sand field.

Particularly noteworthy is that the geothermal mapping of horizons above and below the roof of the geopressured zone reflects the overall geologic structures of the area. Hence, even in a region with only shallow wells (bottomed close to the floor of the hydropressured zone), geothermal mapping could turn out to be rewarding in terms of revealing structures of interest. This is indeed significant in the context of petroleum-exploration efforts. Geothermal mapping has a great potential as an effective adjunct to the conventional geologic tools for petroleum exploration. As mentioned by Hobson and Tiratsoo (1975), mapping of surface-rock temperatures occasionally has been successful in locating and identifying underlying structure and faults. The mapping of subsurface temperatures should prove much more effective.

The geothermal mapping technique could be utilized for: (1) selecting areas of promise for detailed mapping or seismic traversing, (2) determining the presence of anticlines or rollovers (unknown, untested) against growth faults, and (3) working out prospects for deep-seated pools.

For geothermal mapping, depth contouring of isothermal surfaces or temperature contouring of depth horizons is recommended. The choice between the two approaches of mapping, however, depends on the availability of adequate data permitting a minimum of interpolation or extrapolation. In a field or small region where the depth intervals at which wells are logged are approximately similar or the same, the isotherms of certain depth horizons can be constructed with a greater confidence than with geoisotherms of temperature datums. Nevertheless, the maps could be supplemented by other types of maps if needed.

CONCLUSIONS

1. The geothermal gradient has a more distinctive change in the Lake Sand area than in Bayou Carlin. The top of the geopressured zone is considerably shallower over the downthrown side (south) of the Lake Sand fault than on the north.

2. The roof of the geopressured zone is shallowest over the structural highs of Bayou Carlin and Lake Sand fields and the growth fault. The geopressure roof has thermal halos over the structural highs as well as the rim syncline (structural low) of the Cote Blanche dome.

3. The isothermal contours of structural horizons above and below the geopressure roof indicate that the productive structural highs as well as the structural lows like the rim syncline are characterized by geothermal highs.

4. The geoisothermal (250°F or 121°C) highs embrace the structural highs of the area.

5. The isotherms of depth levels (10,000; 12,000; 14,000; and 16,000 ft or 3,048; 3,658; 4,267; 4,877 m) indicate highs over the productive structures of Bayou Carlin, East Lake Sand, and Lake Sand fields. In the vicinity of the salt domes on the northwest and west, geothermal highs are reflected even over the structural lows (rim synclines).

6. In areas like the Gulf Coast region, geothermal mapping incorporating even shallow-well data has a significant potential for further petroleum exploration.

7. Geothermal mapping is recommended for selecting areas of possible petroleum prospects, for delineating the untested rollover structures against growth faults, and for locating deeper petroleum prospects, using available shallow-well data. This could be accomplished quickly by appropriate computer applications.

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