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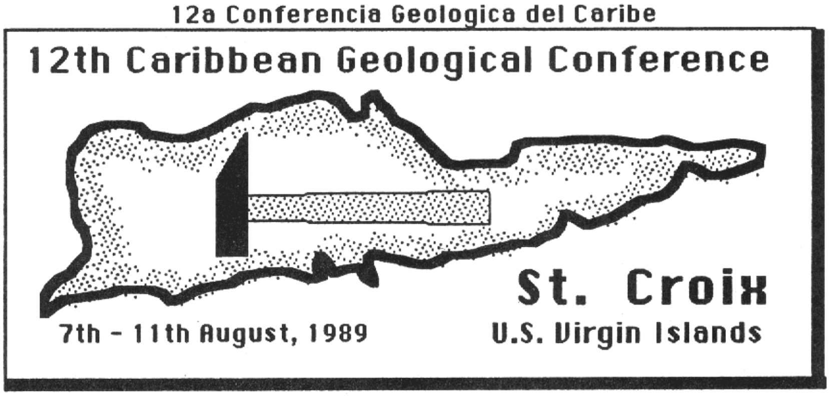

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SIGNIFICANCE OF GEOTHERMAL GRADIENTS IN PETROLEUM EXPLORATION IN TRINIDAD

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ABSTRACT

The correlation between positive geothermal anomalies and the occurrence of hydrocarbons is based on the premise that water is the major agent of both hydrocarbon migration and heat transfer in sedimentary basins, and suggests a genetic link between geothermal gradients, hydrodynamics and hydrocarbon occurrences. This association has generated growing interest in geothermal studies in relation to the occurrence of petroleum deposits and the importance of the temperature history experienced by the source rock in the maturation process.

Geothermal gradients were derived from bottom hole temperatures recorded on electric logs from 300 exploratory and development wells drilled over Trinidad, including the Gulf of Paria and the North Coast and East Coast marine areas. A study was undertaken to determine the temperature regimes and an iso-geothermal gradient map of Trinidad, showing local and regional variations in heat flow, is presented.

Geothermal gradients over Trinidad vary between 0.8°F and 1.8°F per 100' (15°C and 32°C per km), rarely exceeding 1.5°F/100' (28°C/km), and are comparable to the worldwide average of 1.4°F/100' (25°C/km). These variations are related primarily to: (i) position of basement (heat source) with respect to overlying sediments and (ii) difference in vertical and lateral thermal conductivity of the rocks due to lithologic variation.

INTRODUCTION

For more than 50 years individual geologists (e.g. Van Orstrand, 1934) have observed an association between hydrocarbon occurrences and positive temperature anomalies or 'hot spots' as reflected in higher local geothermal gradients relative to the regional gradient. Geothermal anomalies have been mapped over oilfields in several basins of the world and reported by Ball (1981), Gatenby (1981), Handique and Bharali (1981), Meyer and Mc Gee (1985), Majorowicz et al. (1988), Mc Gee et al. (1989). Structurally as well as stratigraphically controlled fields, and both oil and gas accumulations, show positive geothermal anomalies at producing levels.

Roberts (1981) has reviewed much of the relevant literature and Klemme (1972) has presented evidence to show that high geothermal gradients in clastic rock sequences enhance the processes of oil and gas formation, migration and entrapment.

The correlation between positive geothermal anomalies and the occurrence of hydrocarbons is based on the premise that water is the major agent of both hydrocarbon migration and heat transfer in sedimentary basins, and suggests a genetic association between geothermal gradients, hydrodynamics and hydrocarbon occurrences. This association has generated growing interest in geothermal studies in relation to petroleum deposits. Indeed according to Ovnatanov and Tamrazyan (1970), "Although many methods are used to explore for petroleum, the geothermal method definitely deserves to take its rightful place among the standard exploration tools".

Previous work on geothermal gradients over Trinidad is limited to 2 geothermal gradient maps done by Dominion Oil in 1958 and Shell in 1966. Both these maps were compiled largely from onshore data and are compatible in the recognition of relative hot spots in the northern Gulf of Paria and Balata oilfield areas, although they differ somewhat in the actual magnitude of these anomalies.

Since the last map was compiled in 1966 the North Coast and East Coast Marine Areas have been opened up to exploration and much new temperature data have been generated. Also, more than 400 wells have since been drilled in Trinmar's Soldado area, in addition to other wells drilled onshore, particularly in the Southern Basin. The present study is aimed at updating the 2 earlier geothermal gradient maps using new temperature data available subsequent to 1966, as well as including data from wells which were not available to either Dominion Oil or Shell previously.

The major objectives of this study are as follows:

(1) To determine whether any positive geothermal anomalies or 'hot spots' identified correlate with the presence of oilfields as reported in the literature in other parts of the world.

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(ii) To test the hypothesis that these 'hot spots' over oilfields originate in the upward and lateral movement of subsurface formation fluids, including oil, into traps bringing higher temperatures from depth.

(iii) To explain local and regional variations in the geothermal gradients over Trinidad in relation to lithological variations, basement configurations, structure and fluid dynamics.

METHODOLOGY

The temperature underground normally increases with depth below the surface, and the geothermal gradient is a measure of this rate of temperature increase with depth. The geothermal gradient is obtained by dividing the difference between the temperature of the formation and the mean annual surface temperature (ambient) by the depth of the formation, and is usually reported as °F/100' or °C/km.

Ambient temperatures for onshore and offshore wells have been considered uniform in this study and a value of 75°F (24°C) was used. This compares favourably with the 74°F (23°C) used by Talukdar et al. (1988) in Eastern Venezuela.

Most temperatures obtained from oil and gas wells are measured when the hole is under less than stable thermal conditions. Formation temperature is disturbed by the circulation of drilling fluid, which often results in the lower part of the hole being cooled and the upper part heated.

The primary sources of temperatures from wells are:

(i) Electrical logging runs.

(ii) Static bottom hole pressure (BHP) tests or temperature surveys.

(iii) Drill stem tests (DSTs).

Static BHPs and DSTs are the most reliable and provide the most accurate temperature data but are generally not available in large quantities locally. Although being the least reliable, due to the relatively brief time required to run logs, not allowing for subsurface temperatures to stabilize, maximum mud temperature readings recorded on the headings of electric well logs are the most abundant and are the only practical source of enough temperature data in Trinidad.

Due to the non-availability of such data as circulation time, time logger on bottom and time since cessation of circulation, and insufficient logging runs in most wells it was not possible to correct measured bottom hole temperatures (BHTs) for true formation temperature using the Horner technique of Fertl and Wichmann (1977). Since geothermal anomalies are what is being mapped in this study, and therefore the relative differences in geothermal gradients are more important than the absolute values, it is better to use uncorrected BHTs altogether (Handique and Bharali, 1981; Khan and Raza, 1986) rather than BHTs 'corrected' by applying some arbitrary correction factor (eg. 10-15%).

When temperatures were measured at different times the last value was chosen, and the data in each well were checked for consistency at different bottom hole depths (logging depths).

A disadvantage of using BHTs to determine geothermal gradients and temeprature anomalies is that some individual BHT data may be spurious due to careless measurements or recording mistakes. The effects of these are minimised by 'editing' the BHT data for obvious errors (e.g. low temperatures recorded after longer times since circulation stopped, sudden temperature reversals). Also, contouring techniques applied to map geothermal gradients produce a smoothing effect on the data, thus reducing the effects of individual unreasonable data.

Wells were selected on the basis of depth of penetration, both in terms of stratigraphy and footage, and location so as to provide adequate stratigraphic and geographic coverage. More than 1000 wells were examined in the first instance for reliability and consistency of temperature data, and eventually data from 300 wells were used to compile the geothermal gradient map (Figure 1).

Although every effort was made to select wells so as to provide a good geographic spread, this was not possible in some areas simply because of the absence of well data in undrilled areas. Thus only 8 wells are available in the North Coast Marine Area and data from only a few of the more than 200 wells drilled by Amoco off the east coast are accessible. The offshore Soldado area and the onshore Southern Basin, where several thousands of wells have been drilled, naturally have the greatest spread and concentration of data (Figure 1).

RESULTS AND DISCUSSION

The regional present day geothermal gradient map (Figure 1) shows that gradients over Trinidad vary from 0.8°F/100 (15°C/km) to 1.8°F/100 (32°C/km), and rarely exceed 1.5°F/100' (28°C/km). They are comparable to the worldwide average of 1.4°F/100' (25°C/km) and to the 1.3 - 1.4°F/100' reported by Talukdar et al. (1988) for the Maturin Subbasin of Eastern Venezuela.

The lowest gradients (08. - 1.0°F/100') are recorded in the Southeast Coast and North Coast Marine Areas, whereas everywhere onshore and in the Gulf of Paria gradients are >1.1°F/100'. The highest geothermal gradients (>1.5°F/100') are recorded as 10 anomalies or 'hot spots' and are listed as follows (Figure 1):

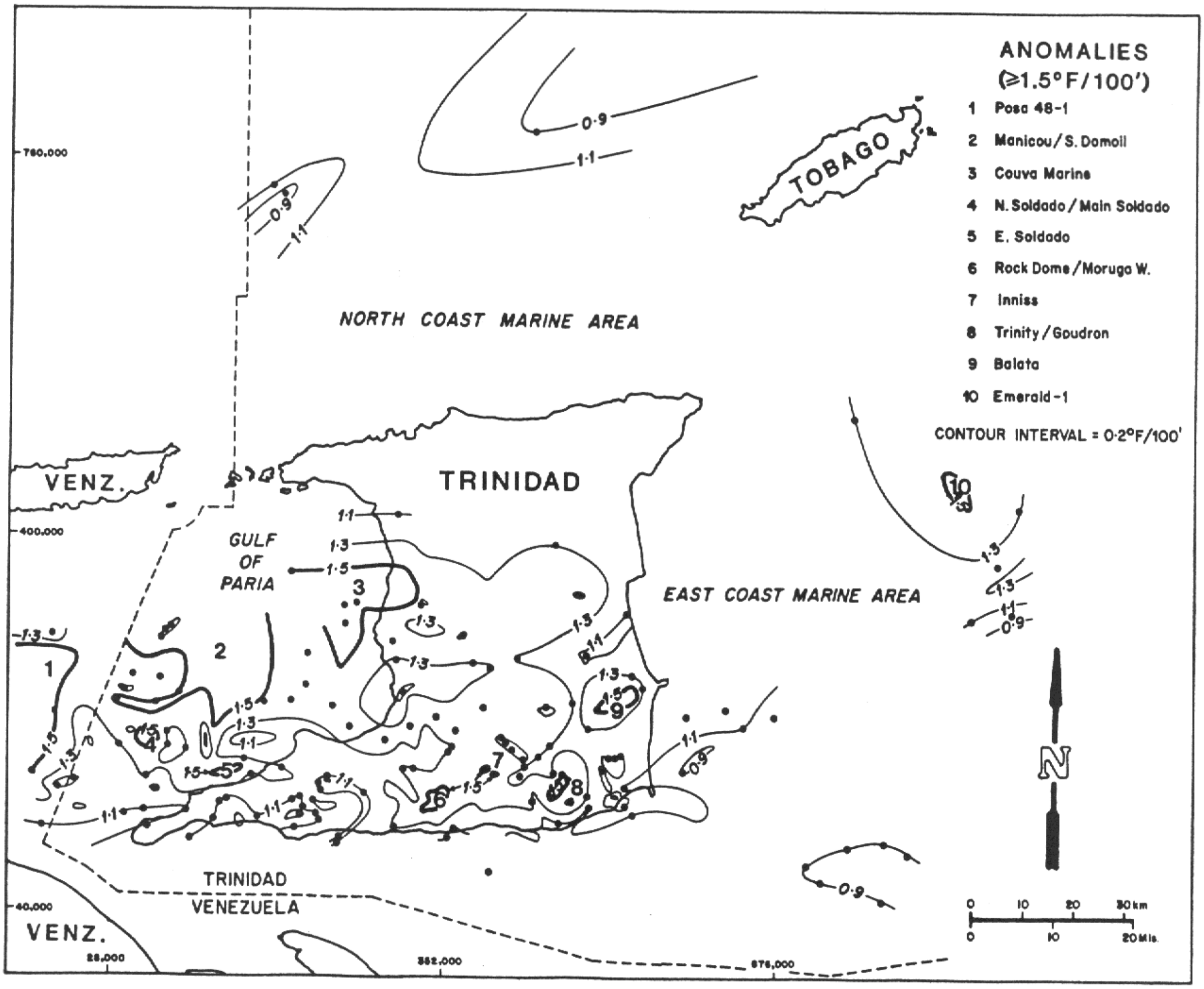

Figure 1. Geothermal gradient map of Trinidad, based on uncorrected bottom hole temperatures.

GULF OF PARIA - (1) Posa-48; (2) Manicou/South Domoil; (3) Couva Marine; (4) Main Soldado; (5) East Soldado;

SOUTHERN BASIN - (6) Rock Dome/Moruga West; (7) Inniss; (8) Trinity/ Goudron (9) Balata

EAST COAST MARINE AREA - (10) Emerald - 1

The principal sources of heat to the upper few miles of the earth's crust are in the outward flow of heat from the central core of the earth, in the presence of igneous magmas that are cooling, in the disintegration of radioactive elements and in the heat of subcrustal thermal convection currents (Levorsen, 1967).

Several factors produce lateral variations or anomalies in the earth's temperature field, resulting in regional variations in geothermal gradients in sedimentary basins. These are discussed by Hitchon (1984) and Meyer and Mc Gee (1985) and some of the more relevant factors are:

(i) Differences in heat flow rate from the source in the basement beneath the basin.

(ii) Lateral and vertical variations in thermal conductivity of the rocks due to a variety of causes (e.g. structural configuration, lithology (Figure 2), cementation, degree of compaction, permeability, fluid content).

(iii) Sources of heat within the rocks as a result of exothermic chemical reactions, mineralogical transformations and radioactive decay.

(iv) Recent intrusive or volcanic activity.

(v) Effects of moving water and other fluids (e.g. petroleum), including connate and meteoric water moving up and down through fractures

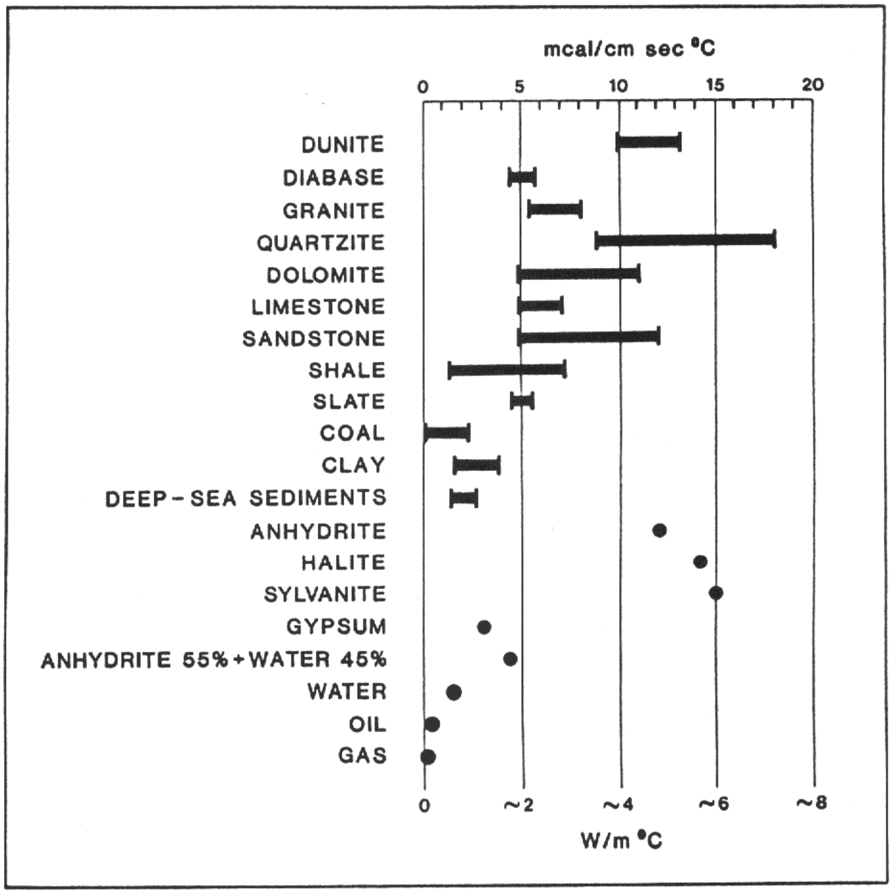

Figure 2. Thermal conductivity of various rocks and pore fluids under near surface conditions modified after Gretener (1981).

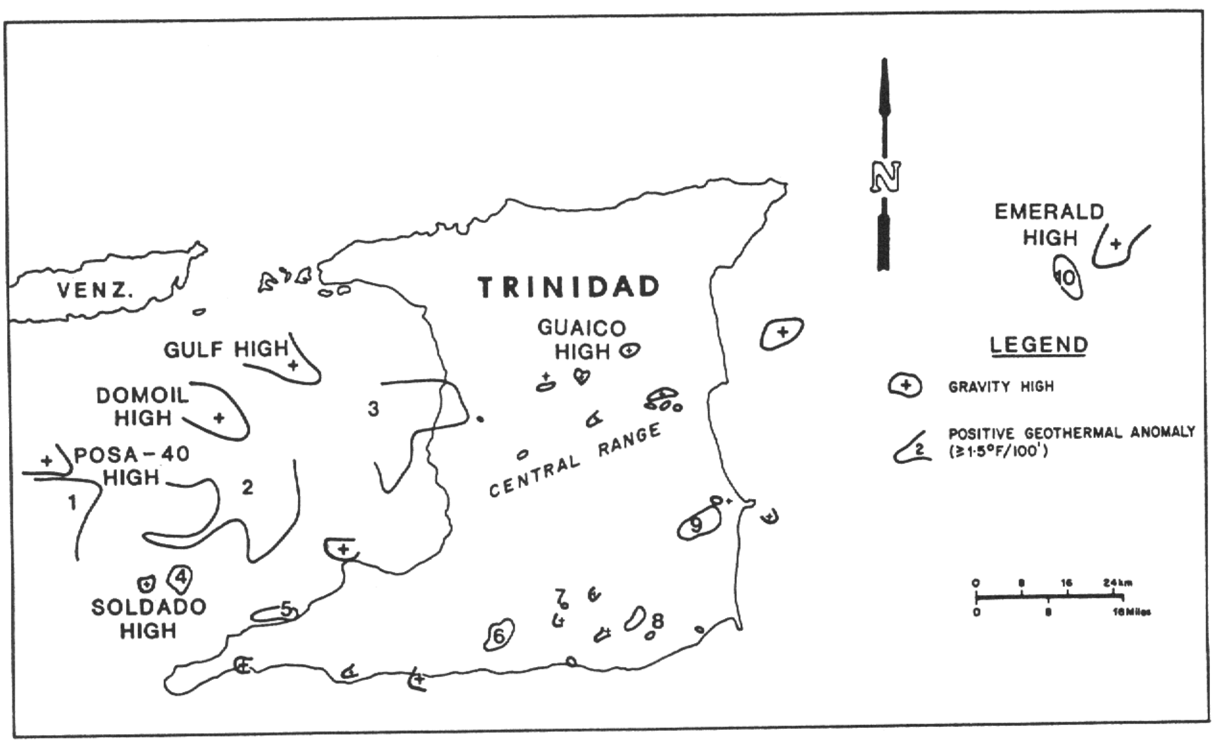

Figure 3. Principal gravity highs over Trinidad, from Bouguer anomaly gravity data. Anomalies numbered 1 to 10 are shown on Figure 1 and are discussed in the text

and pore spaces producing a warming and cooling effect respectively.

(vi) Tectonic friction causing heating.

Not all of these factors are equally important in any sedimentary basin and in some areas most of them can be dismissed as negligible or irrelevant. Factor (ii) is considered one of the primary causes of anomalous geotemperatures in most sedimentary basins. However, factor (v) has recently received considerable attention in the literature as a possible cause for positive geothermal anomalies recognised over oilfields (Meyer and Mc Gee, 1985; Zielinski et al., 1985; Mc Gee et al., 1989).

The geothermal gradient patterns mapped over Trinidad are now discussed in detail and possible explanations offered. The North Coast Marine Area (north of Trinidad and west of Tobago, Figure 1) displays low geothermal gradients (⩽1.2°F/100'). Basement in this area is mapped at approximately 10,000' and is similar in composition (low grade metamorphics) to what outcrops in the Northern Range to the south. Low heat flow in this area is confirmed by low vitrinite reflectance values (Ro⩽0.6% at 10,000'). In addition the gas discovered off the north coast is immature biogenic methane typical of low temperature diagenesis.

Basement drilled in the northern Gulf of Paria (Figure 1) is similar in composition and seismic character to that drilled in the northern North Coast Marine Area. The much higher geothermal gradients (1.2 - 1.8°F/100') recorded in the northern Gulf of Paria probably reflect different heat flow regimes related to the presence of at least 10 WNW-trending wrench faults north of the western extension of the Warm Springs Fault and parallel to the Los Bajos Fault, which are not present in the North Coast Marine Area. These faults would have acted as conduits for heat transfer from the heat source in the mantle to the sedimentary section of the earth's crust, possibly by thermal convection.

In the East Coast Marine Area south of Emerald - 1 (anomaly 10, Figure 1) data are limited since most of the wells have been drilled by Amoco. Available data indicate low geothermal gradients (generally ⩽1.0°F/100') and are in very good agreement with the values of 0.85 - 1.15°F/100' reported by Leonard (1983) for the Columbus Basin. Very high sand/shale ratios have been recorded for the Pliocene/Pleistocene section in this area of the east coast, which formed the depocentre of the proto-Orinoco delta (Michelson, 1976). The low geothermal gradients are probably due to a combination of high thermal conductivity of the sand-rich section (Figure 2) and rapid sedimentation rate, not allowing sufficient time for thermal equilibrium to be attained. Indeed Leonard (1983) observed a close correlation between areas with the lowest geothermal gradients and areas with thicker sections of Pleistocene sediments.

Geothermal gradients over onshore Trinidad and the Gulf of Paria vary from 1.1°F/100' to 1.8°F/100' but are mostly ⩽1.4°F/100'. Areas with geothermal gradients >1.5°F/100' are considered positive geothermal anomalies or hot spots and 9 such anomalies are mapped in the Gulf of Paria or onshore Trinidad, with a tenth in the northern East Coast Marine Area (Emerald - 1).

Anomaly 1 in the western Gulf of Paria is centred around Posa-48 (1.8°F/100'). This well encountered Lower Cretaceous limestones at 8800', overlain by Miocene/Pliocene clastics.

The Manicou/South Domoil geothermal anomaly 2 is located east of the Posa-48 anomaly and includes the small South Domoil oilfield (442,000 barrels) and the Manicou gas field. South Domoil - 5 drilled Lower Cretaceous at 7000' overlain by Pliocene/Pleistocene clastics.

Further east, anomaly 3 is centred around the Couva Marine wells (1.6 - 1.8°F/100') and is associated with a small oilfield (227,000 barrels). Miocene and younger shales, sandstones and conglomerates overlie Lower Cretaceous shales at 6500' and a 3000' - 7000' thick evaporite section at 9000' in Couva Marine - 2 and 8000' in Couva Offshore - 1. High heat flow in this area, as evidenced by higher than average geothermal gradients, is supported by high vitrinite reflectance values (Ro>2.0%) measured on Lower Cretaceous shales (Rodrigues, 1988).

As elsewhere (e.g. Shelton et al., 1974; Handique and Bharali, 1981) the geothermal patterns correlate with regional structural and gravity trends. High temperatures recorded as geothermal anomalies mapped in Posa-48, Manicou/South Domoil, Couva Marine and Emerald - 1 correspond to local structural highs which are the expression of basement highs associated with numerous deep-seated faults. Temperatures are highest on the crest of these local structures, decreasing toward the flanks. In addition to the known stratigraphy drilled in these wells, where Lower Cretaceous strata occur at depths of 6000' - 9000', Bouguer anomaly gravity data over Trinidad show gravity highs termed the Posa -40, Domoil, Gulf and Emerald Highs corresponding to anomalies 1,2, 3 and 10 respectively (Figure 3). Gravity highs are in many areas associated with anticlines or with horst blocks, both being structures which bring older denser rocks nearer the surface (Griffiths and King, 1974).

Eight of the 10 positive geothermal anomalies mapped are associated with oilfields (Figure 4): Manicou/South Domoil, Couva Marine, North and Main Soldado, East Soldado, Rock Dome/Moruga West, Inniss, Trinity/Goudron and Balata.

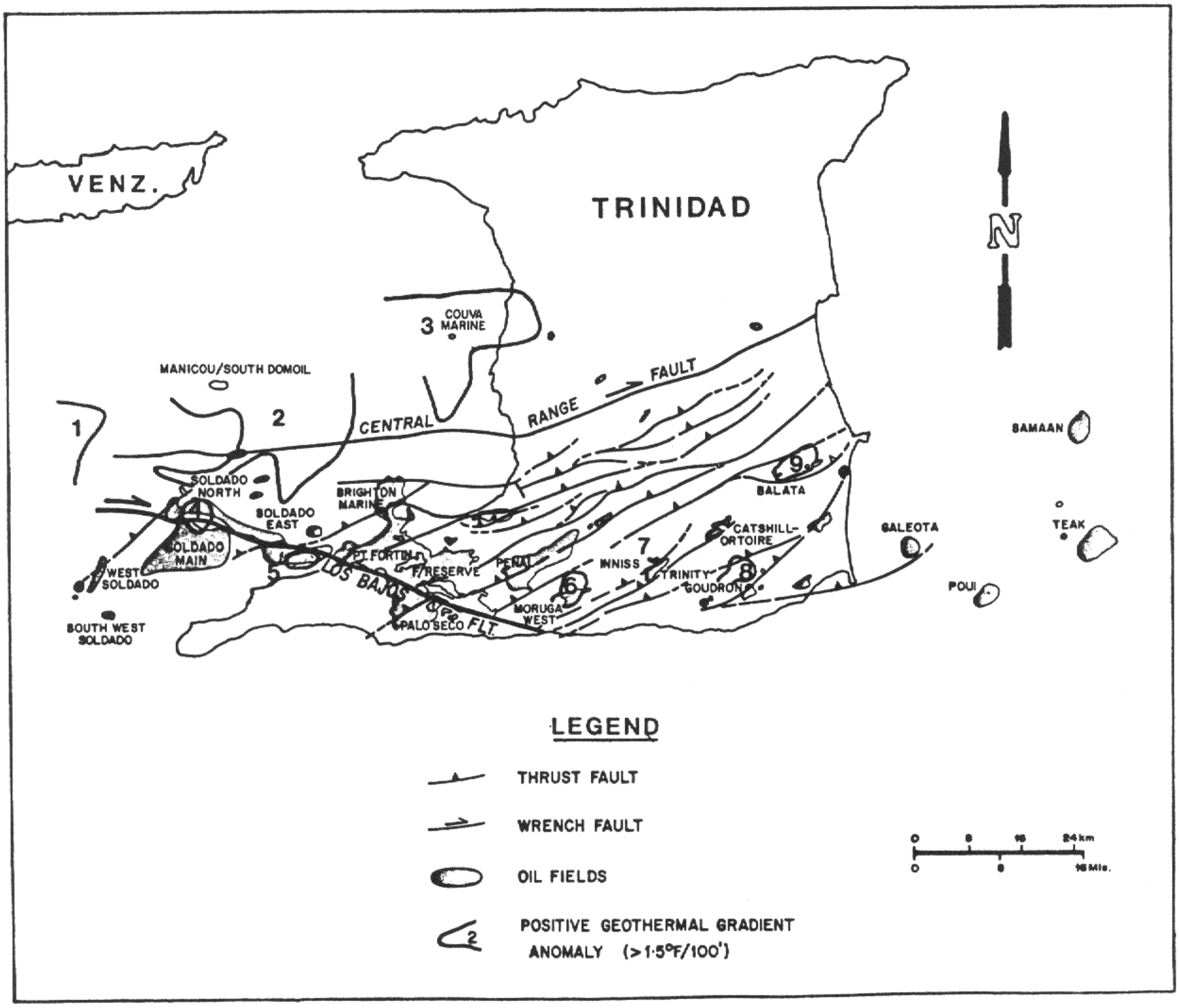

Figure 4. Major lineaments and distribution of producing oilfields, southern Trinidad.

The fact that positive anomalies were not recorded in many other oilfields (e.g. Forest Reserve, Palo Seco, Penal, Brighton Marine etc.) and that 2 positive anomalies (Posa - 48 and Emerald - 1) are not related geographically to producing fields suggest that the association between productive oilfields and positive geothermal anomalies may not be related simply to the presence of hydrocarbons, *per se*.

Gravity highs mapped from Bouguer anomaly gravity data show that 7 of the positive geothermal gradient anomalies are associated with gravity highs (Figure 1 and 3): Posa - 48 (1) Manicou/South Domoil (2), Couva Marine (3), North/Main Soldado (4), Inniss (7), Balata (9), and Emerald (10). On the other hand some gravity highs show no temperature anomalies (e.g. Brighton Marine and those aligned W-E along the Southern Range).

Anomalies 6 (Rock Dome/Moruga West) and 8 (Trinity/Goudron) show no correlation with gravity highs as mapped from Bouguer anomaly gravity data (Figure 3) and in both these areas original gravity data are rather sparse. However, wells drilled in these areas penetrated the Cretaceous at depths of 5000' - 12000' and the temperature anomalies recorded are probably related to the rise of basement configuration, resulting in higher temperatures on the crests of these local structures.

Anomaly 5 (East Soldado) which is also supported by the presence of overpressured shales, is more difficult to explain as this structure is not simple. Mc Dougall (1985) reported Pliocene/Pleistocene uplift along the south side of the Los Bajos fault and steep dips (40°) in the eastern portion of the field as due to mud tectonism producing an anticline or mud-cored uplift. The temperature anomaly may be related to heat influx associated with the upward intrusion of hot overpressured shales and accompanying water (mud tectonism) in the vicinity of the Los Bajos fault.

Both the gravity and oilfield distribution data (Figures 3 and 4) interpreted with respect to the occurrence of temperature anomalies (Figure 1) indicate that the observed temperature highs over some oil-fields may reflect the complex relationship between:

(i) lower thermal conductivity of hydrocarbon bearing reservoir rocks, which result from hydrocarbons (lower thermal conductivity, Figure 2) replacing water in these rocks;

(ii) lateral variations in rock conductivity due to lateral changes in structure or lithology (Figure 2);

(iii) the heat carried along with upward and lateral fluid movement, which becomes trapped when the fluids are trapped.

This study does not support the contention that positive geothermal anomalies are uniquely associated with oil or gas accumulations and hence could be used as an exploration tool.

In the first place, temperatures used in compiling the geothermal gradient map (Fig.1) are not producing level temperatures taken from measurements made during drill stem testing but are bottom hole temperatures. Geothermal gradients computed by taking the difference between the measured temperature at a given depth and the surface temperature at the same location and reporting this difference with respect to the depth of the measurement point actually represent the weighted average gradient of the entire stratigraphic sequence above the recording point. Therefore the value of the geothermal gradient calculated from this method depends largely on the depth of the recording point and the thermal properties of the overlying lithologies. Temperature deviations from the geothermal gradient (i.e. warmer and colder than average areas) may reflect several stratigraphic and lithologic features or the inhomogeneity of the solid matrix and of the fluids that locally affect the heat transfer process, as discussed above.

Secondly, non-hydrocarbon bearing water strata could conceivably produce temperature anomalies by themselves as long as a trap is present.

APPLICATIONS

Accurate temperature measurements are vital to meaningful interpretations of subsurface geothermics. Heat transfer mechanisms affect diagenetic processes, petroleum maturation and migration and the evolution of both the sedimentary basin and its hydrogeologic system.

Geothermal gradient or isothermal surface maps, when constructed from suitable temperature data, offer good reliability and may have several relevant applications:

(1) The geothermal gradient map can be used to determine depths of the oil window over Trinidad, below which liquid hydrocarbons are unlikely to be found. A regional correlation of the depth of oil window (150-300°F) combined with the stratigraphy could be a useful exploration tool.

(2) Low geothermal gradients recorded over southern Trinidad have implications for the timing and duration of oil generation and migration. Low geothermal gradients would mean that Upper Cretaceous source rocks would have attained oil generating maturity only relatively recently (e.g. over the last 5-10 million years).

Similarly, expulsion and migration of petroleum from source rocks are recent phenomena in Trinidad. In the case of the East Coast Marine Area very thick Neogene sediments (possibly >25,000') would mean that Upper Cretaceous source rocks entered and exited the oil window over a very short period of time, because of very high temperatures due to great depths of burial. This time period may be considered almost instantaneous in a geologic sense and would place severe time constraints on source rock maturity and migration avenue and trap availability.

(3) Knowledge of present day temperatures is useful in the delineation of areas with altered oils, especially in Tertiary reservoirs not subject to significant variations in gradients in the past.

(4) Increasing temperatures affect diagenetic reactions in the reservoir, oil to gas cracking, oil and gas volumes, viscosity and fluid pressure.

(5) Since overpressured shales, being an insulator, are often associated with abnormally high temperature gradients (Ovnatanov and Tamrazyan, 1970; Lewis and Rose, 1970) it may be possible to predict the presence of a high pressure zone before drilling into it by observing sudden increases in temperature with depth.

(6) The temperature profile for a new well can be predicted from the geothermal gradient map.

The temperatures recorded and used in this study, even if they were corrected for true formation temperature, are unlikely to be maximum paleotemperatures for the onshore wells due to recent uplift and erosion (which may be as much as 4000' in some areas). Thus present day temperatures may be as much as 35-55°F lower than those attained in the past, and whatever depths are calculated for the oil window or occurrence of biodegraded oils etc. should be considered absolute maxima.

SUMMARY AND CONCLUSIONS

The major objectives of this study were to determine whether positive geothermal anomalies or hot spots identified over Trinidad correlate with the presence of oilfields and can be used as an exploration tool and to explain local and regional variations in heat flow.

In the absence of more reliable temperature data geothermal gradients were calculated for more than 300 wells over Trinidad based on uncorrected bottom hole temperatures and an isogeothermal gradient map compiled.

The map represents the geothermal regime which reflects the summation of a number of geological/geophysical parameters expressed as thermal conductivity, thermal convection and hydrodynamics. Geothermal trends correlate with regional structural and gravity trends and stratigraphic features such as gross lithofacies.

Present day geothermal gradients over Trinidad vary from 0.8°F/100' to 1.8°F/100' but are mostly <1.5°F/100'. Lowest gradients are recorded in the North Coast and East Coast Marine Areas whereas highest gradients (>1.5°F/100') are mapped as 10 hot spots, viz. Posa-48, Manicou/South Domoil, Couva Marine, Main Soldado/North Soldado, East Soldado, Rock Dome/Moruga West, Inniss, Trinity/Goudron, Balata and Emerald - 1.

Some temperature highs are associated geographically with oilfields but this is not an unique association. The positive anomalies correspond to local structural highs which are the expression of basement highs. Lateral and vertical variations in thermal conductivity of the rocks due to a variety of causes (e.g. structural configuration, lithology) seem to be the main factor in producing thermal anomalies over Trinidad.

The geothermal gradient map has several relevant applications, e.g. in defining the depths of the oil window over Trinidad, in delineating areas with bacterially altered oils, in predicting the presence of overpressured shales and the temperature profile of a new well.

Greater effort should be made to ensure that accurate temperatures are measured and recorded at the well site during the drilling, logging and testing of wells.

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