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SALINE FLUID FLOW AND HYDROCARBON MIGRATION AND MATURATION AS RELATED TO GEOPRESSURE, FRIO FORMATION, BRAZORIA COUNTY, TEXAS[1]

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ABSTRACT

The Pleasant Bayou geopressured-geothermal test wells in Brazoria County, Texas, display a prominent thermal-maturity anomaly in the Oligocene Anahuac and Frio Formations. Highly geopressured, more-mature shales are interbedded with hydropressured to moderately geopressured sandstones in the upper Frio and Anahuac. In contrast, shales and sandstones in the lower Frio, including the Andrau geopressured-geothermal production zone, are highly geopressured but exhibit lower thermal maturities.

Vitrinite-reflectance data, supported by hydrocarbon-maturation data and anomalous concentrations of C_5 to C_7 hydrocarbons at Pleasant Bayou, indicate that the upper Frio was subjected to an extended period of hot, extremely saline, basinal fluid flow which caused the above thermal anomaly. Regional salinity studies (Morton and others, 1983) suggest that regional growth faults were the conduits for vertical basinal brine movement at depth. At shallower levels the upwelling waters migrated laterally through permeable sandstone-rich sections such as the upper Frio. Anomalously mature gasoline-range (C_5-C_7) hydrocarbons were introduced into the upper Frio by this process. Fluid influx in the lower Frio was probably limited by high geopressure, consequently maturity in the deep Frio section (greater than 14,000 ft) remained consistent with the regional geothermal gradient.

INTRODUCTION

During the past decade, a tremendous volume of information has been compiled on the geological setting of the Pleasant Bayou geopressured-geothermal test well site under the auspices of the U.S. Department of Energy Geothermal program. Synthesis of these data allows conclusions to be drawn regarding the age of geopressure and the influence of geopressure on fluid migration paths in the basin. Integration of formation-water chemistry, hydrocarbon-age and thermal-maturity

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data, and isotopic composition of hydrocarbons indicates that the upper Frio (shallower than present depths of 14,000 ft) experienced a dramatically different fluid-flow history than the lower Frio.

THERMAL-MATURITY PROFILES IN THE PLEASANT BAYOU WELLS

The Pleasant Bayou test wells display a prominent thermal-maturity anomaly in the deep geopressured Frio. Thermal maturity is estimated from vitrinite reflectance (R_o) and thermal alteration indices (TAI). These values were determined for the Pleasant Bayou wells and reported by Schwab (1980). However, Schwab's (1980) original thermal maturity values were consistently and anomalously lower than the results obtained by other laboratories (e.g., Dow, 1978) and thus have been corrected (Light and others, in prep.). Thermal maturity values in the Frio Formation increase with depth to the T5 marker at approximately 14,000 ft (Fig. 1). At this depth, thermal-maturity values display a departure from the trend exhibited by the overlying sediments and are characterized by markedly lower maturities. Like the shallower sediments, the overall trend within the deeper section is one of increasing maturity with depth (Fig. 1); however, the estimated maturity values plot near the normal maturity profile and are consistent with models using the extant geothermal gradient superimposed on the Pleasant Bayou subsidence curve. By contrast, the shallower sediments display considerably higher maturity values than those observed elsewhere on the Gulf Coast for similar depths (Fig. 1).

To more precisely define the anomalous maturity profile, vitrinite-reflectance measurements were made for seven core samples from the Phillips Houston GG No. 1 and JJ No. 1 wells on Chocolate Bayou dome and the Humble Skrabanek No. 1 and Vieman No. 1 wells on the south flank of the Danbury dome. Most of the samples are classed as mature; two from 17,000 ft and deeper are very mature. The vitrinite-reflectance values obtained do not form a clear linear trend when plotted against depth but rather form two discrete populations: a shallower group (10,500 to 12,000 ft) displaying comparatively higher maturities, and a deeper group (greater than 14,000 ft) displaying comparatively lower maturities (Light and others, in prep.) confirming the trends observed in analysis of cuttings. This is inconsistent with vitrinite-reflectance profiles for basins that have experienced continuous sedimentation, such as the Gulf Coast Basin, that normally define linear maturation profiles (Katz and others, 1984).

Thus, thermal-maturity data clearly indicate a thermal event that affected the upper Frio in the Pleasant Bayou area. Anomalously low maturities have been documented from the geopressured interval elsewhere on the Gulf Coast, for example at the L. R. Sweezy No. 1 well, Vermilion Parish, Louisiana (Hamilton and Stanley, 1984).

FURTHER EVIDENCE FOR BASINAL FLUID FLOW

Relative Age of Hydrocarbons and Thermal Maturity of Source Rocks

Because hydrocarbons in oils change as they mature, compositional variations may be used to estimate the age of the oil (Young and others, 1977). These computations require a knowledge of the burial history, geothermal gradient, and detailed chemical analyses of oils for the section with which the oil samples are associated.

The calculation of ages for gasoline-range hydrocarbons is based on the apparent disproportion of naphthenes to give paraffins and aromatics. Ten naphthenes (cyclopentane to ethylcyclopentane), seventeen paraffins (isopentane to N. heptane), and two aromatics (benzene and toluene) are used in the hydrocarbon-age calculation (Young and others, 1977). Detailed chromatographic analyses of only the C_5-C_7 (light-gasoline range) hydrocarbons were available for the Pleasant Bayou test wells through the interval 2,072-16,500 ft (Brown, 1980). These analyses of cuttings and core samples include 9 naphthenes, 16 paraffins, and 2 aromatics. Though the relative ages are therefore not directly compatible with Young and others' (1977) data, the error is probably small, as almost the complete suite of light-gasoline-range hydrocarbons is considered.

The time and temperature integrals (TTI) for various marker horizons have been estimated for the Pleasant Bayou wells using a burial history plot (Ewing and others, 1984a, 1984b). The marker horizons within the Oligocene Frio (T2 to Andrau sandstone interval) plot within the zone of Oligocene unmigrated hydrocarbons defined by Young and others (1977). However, the analyzed light hydrocarbon (naphthene) concentrations for the entire succession at Pleasant Bayou suggest that they are derived from much older rocks (Light and others, in prep.). This is consistent with Young and others' (1977) findings that hydrocarbons in the upper Tertiary reservoirs in the offshore Louisiana shelf were derived from Oligocene or older sediments buried from 12,000 to 24,000 ft. There has been a general upward migration of hydrocarbons in sediments both in the Pleasant Bayou area and in the Gulf Coast region (Burst, 1969; Young and others, 1977).

It is clear that the hydrocarbons have a deep source when the naphthene fraction of the Pleasant Bayou data is expressed as TTI and is plotted against depth (Fig. 2, plot F). The high thermal maturities (TTI) shown by hydrocarbons above the T5 marker horizon (Miocene, upper and lower Frio) compared with the estimated thermal maturity of the sediments derived from burial history indicate that they have migrated up from more deeply buried, more-mature source rocks. High geopressure below T5 probably arrested fluid invasion, and the hydrocarbons present are more locally derived.

The anomalously mature gasoline-range hydrocarbons in the upper Frio (T2 to T5 interval) occur over the same interval as the equivalent vitrinite-reflectance anomaly described in the previous section. This vitrinite reflectance, when corrected and expressed as TTI, is consistent with the burial history thermal-maturity profile for the lower Frio (below T5; Fig. 2, plots D and E). The vitrinite reflectance shows higher thermal maturities in the upper Frio (T2 to T5 interval) than the estimated (burial history) maturities (Fig. 2). This is similar to the behavior of the hydrocarbon-maturation data (based on composition) suggesting that the upper Frio has been invaded and heated by hot, hydrocarbon-bearing fluids. The presence of an anomalous concentration of C_5-C_7 hydrocarbons in the upper Frio (T3 to T5 succession; Fig. 2, plot B) in a zone of relatively low wetness is consistent with the idea that they have been introduced (Brown, 1980, and Fig. 2, plot A). The thermal maturity (vitrinite reflectance) above T5 is far lower than the compositional maturity of the contained hydrocarbons. This indicates that the hydrocarbon-bearing fluids had lost much of their heat by the time they reached these shallower levels. However, the hydrocarbon composition still records the high maturity of the source rocks in which it was generated. High thermal maturities above T2 (Miocene and Anahuac) are highly suspect as they are based on vitrinite-reflectance values less than 0.45% R_o (K. W. Schwab, personal communication, 1984).

Isotope Ratios

The isotopic composition of carbon (ΔC^{13} expressed as o/oo) in hydrocarbons depends on the thermal history and type of source material (Chung and Sackett, 1979; Stahl, 1977). For example, bacterially derived methane has a carbon isotope composition more negative than -55 o/oo; oil-associated methane ranges from -30 to -55 o/oo; coal and magmatic methane from -20 to -30 o/oo (Stahl and others, 1981; Schoell, 1983). The carbon isotopic ratio of methane from natural gas reservoirs increases in response to the increasing maturity of its source (Stahl, 1977). Indigenous gas (still trapped in its source rock) has the same carbon isotopic maturity as the thermal maturity of the rock in which it formed (Schoell, 1983). However, the isotopic compositions of gases do not alter appreciably if they migrate (Fuex, 1980; James, 1983; Schoell, 1983; Stahl and Carey, 1975); hence, hydrocarbons within the surface sediments from the Gulf of Mexico have carbon isotopic values which record the isotopic composition of their source (Stahl and others, 1981). Methane sampled directly from offshore Brazoria County has a carbon isotopic composition close to -37 o/oo. This converts to an isotopic maturity of about 2% R_0 (Stahl, 1977) and was probably derived from Oligocene or older sediments at depths below 20,000 ft (Dow, 1978).

For coexisting methane and carbon dioxide there is an approximate correspondence between the temperature at which they form and the temperature deduced from carbon isotopic composition (Bottinga, 1969). The average carbon isotope composition for methane for the coastal zone of Brazoria County has been shown to be about -37 o/oo (Stahl and others, 1981). The average carbon isotopic composition of carbon dioxide gas produced from Frio reservoirs is 5.3 o/oo (Lundegard and others, 1982). The temperature of formation of these gases is estimated at 220°C (428°F). This converts to a depth of about 20,000 ft using the present geothermal gradient of the Pleasant Bayou wells (Ewing and others, 1984a). These gases appear to have formed in the slope facies of the Vicksburg or lower Frio in Brazoria County.

CONCLUSION

Thermal-maturity profiles, supported by hydrocarbon maturation data and anomalous concentrations of C_5 to C_7 hydrocarbons in the T3 to T5 section in the Pleasant Bayou area, strongly suggest that the upper Frio (between present depths of 10,000 and 14,000 ft) was subjected to an extended period of hot basinal fluid flow. Thermal-maturity values in the lower Frio are consistent with the extant geothermal gradient, subsidence history, and maturity values observed elsewhere on the Gulf Coast, indicating that the geopressured lower Frio was insulated, and isolated, from this thermal event.

Methane and gasoline-range hydrocarbons contained in upper Frio sediments display isotope, relative-age, and thermal-maturity characteristics of a deep source, probably Vicksburg and lower Frio marine slope shales at depths of 20,000 ft and greater. Dewatering of these geopressured shales provided the hot water that transported heat and mature hydrocarbons to shallower levels (Fig. 3). As the thermal fluids migrated upward interaction with salt domes and mounds produced high salinities, elevated chlorine-to-bromine ratios and modified-marine connate water compositions (Kharaka and others, 1980). Evidence of the high salinity of the brines is present in formation waters in the geopressured interval (Morton and others, 1981, 1983) where salinities of 129,000 mg/L have been recorded. At higher levels the brines were diluted during intrusion into sediments containing water produced by clay mineral diagenesis and possibly, to a lesser extent, meteoric water. Resultant salinities are considerably lower (12,000 mg/L in the T3 sandstone); however, Cl/Br ratios are comparable with those in the geopressured interval confirming that saline brines passed through the upper Frio.

Migration pathways of the upwelling fluids are indicated by regional and local salinity studies (Morton and others, 1981, 1983) to be major faults at deeper levels. At shallower levels lateral migration takes place along sandstone-rich intervals; vertical movement continues along faults. Anomalous maturity values and aberrant C_5 to C_7 contents in the T3 to T5 interval, when compared with the remaining Frio stratigraphic column, suggest that the T3 to T5 sandstones composed a major migration pathway for hot saline brines and the contained hydrocarbons up and out of the basin (Fig. 3). The T3 and T4 sandstones are thick and display good lateral continuity throughout the Pleasant Bayou area. The T3 sandstone corresponds approximately to the boundary between normally pressured and geopressured sandstones (Morton and others, 1983). Based on a burial history model that incorporated isotopic dating of diagenetic minerals, Light and others (in prep.) suggest that the extensive flushing of the upper Frio sandstones began 14 mya. The temperatures recorded in the Pleasant Bayou No. 1 well over this interval are significantly higher than would have been predicted from the geothermal gradient deduced from the second well, suggesting that basinal fluid upwelling and lateral migration is currently active.

By contrast, the lower Frio (T5 and deeper) displays no evidence for extensive hot water invasion. The vast bulk of the upwelling geothermal brines clearly bypassed this sandstone-rich geopressured section, migrating vertically along major faults. High salinities indicate that small amounts of brine penetrated the geopressured interval but probably did so at much slower rates. The inferred limited water invasion of lower Frio sediments suggests that they were geopressured as early as 14 mya.

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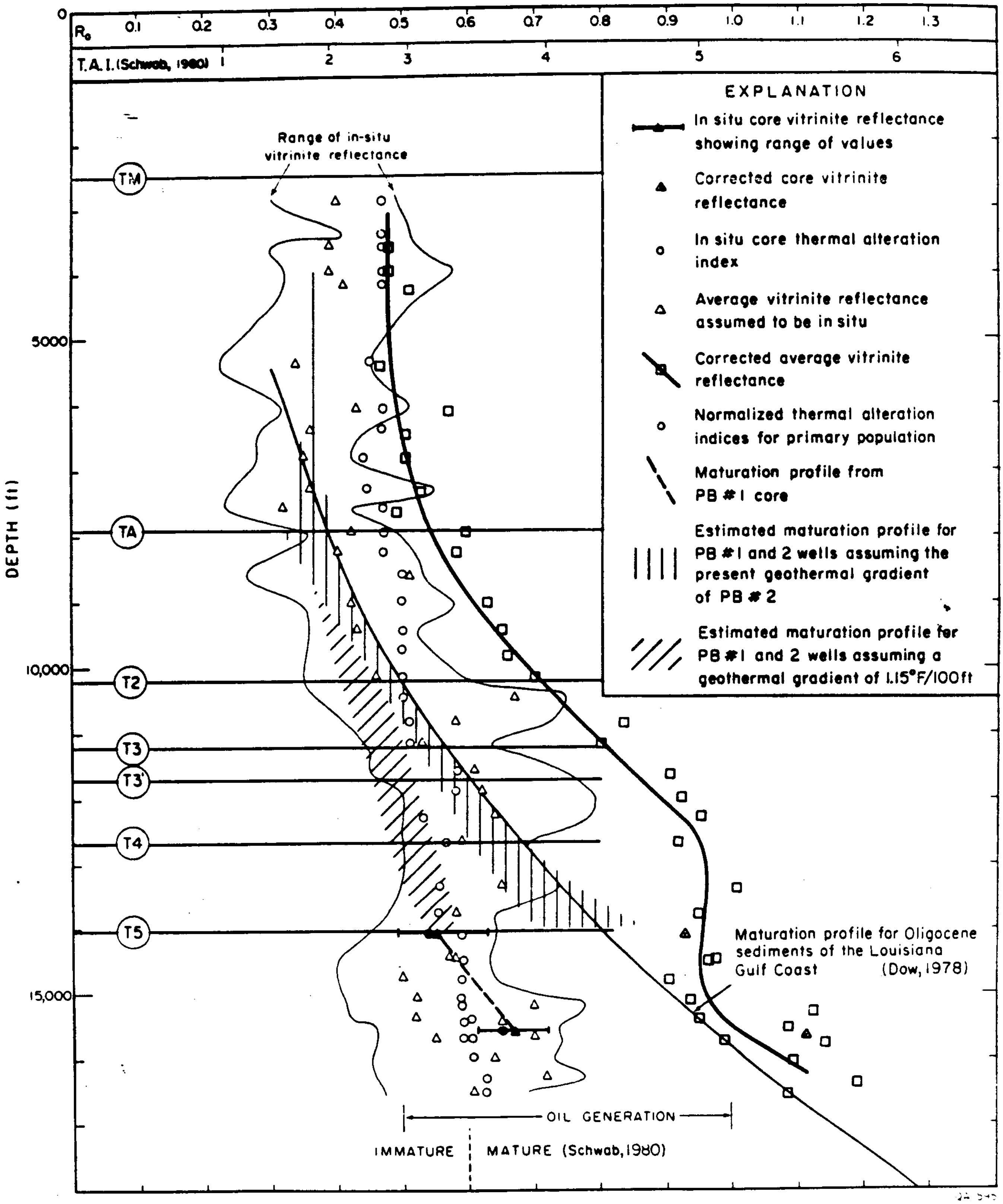
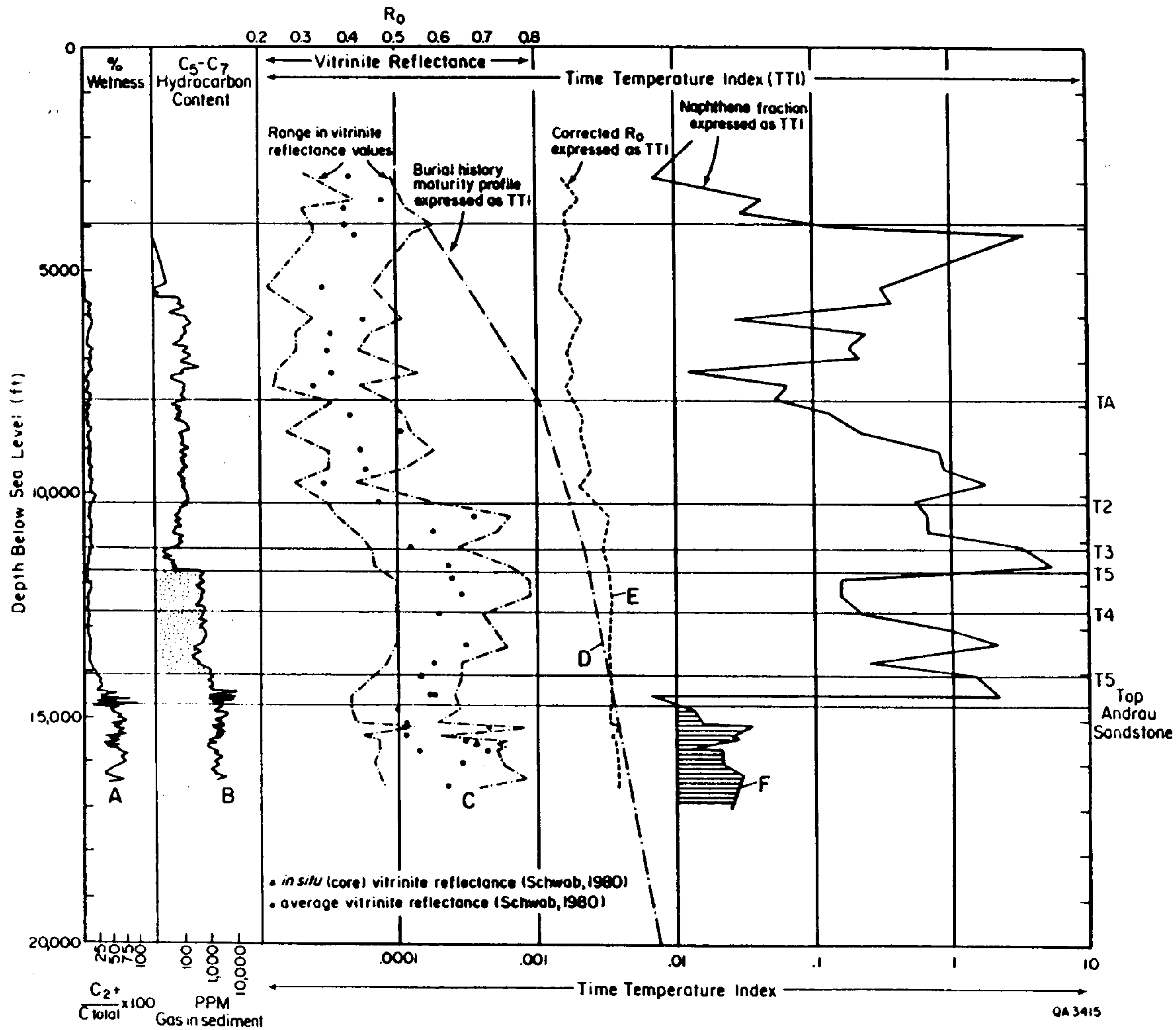
Fig. 1. Vitrinite reflectance and thermal alteration index profiles for the Pleasant Bayou No. 1 well (Brown, 1980; Schwab, 1980). The reflectance profile is compared to the regional reflectance (Dow, 1978) and to calculated profiles using the present-day geothermal gradient at the test well and a low gradient of 1.15°F/100 ft. Vitrinite-reflectance data was corrected to be comparable with Dow's and with Robertson Research data. Modified from Light and others (in prep.).

Fig. 2. Naphthene fraction expressed as time-temperature indices (TTI) vs. depth for the Pleasant Bayou No. 1 well compared with the burial history maturity profile and the corrected vitrinite reflectance both expressed as time-temperature indices (TTI). The uncorrected vitrinite reflectance, percent wetness, and C_5-C_7 hydrocarbon content in 1 million volumes of sediment vs. depth is shown for comparison. Stipple pattern represents a zone containing anomalous concentrations of C_5 to C_7 hydrocarbons; lined pattern indicates zone of containing hydrocarbons consistent with depth and thermal gradient.

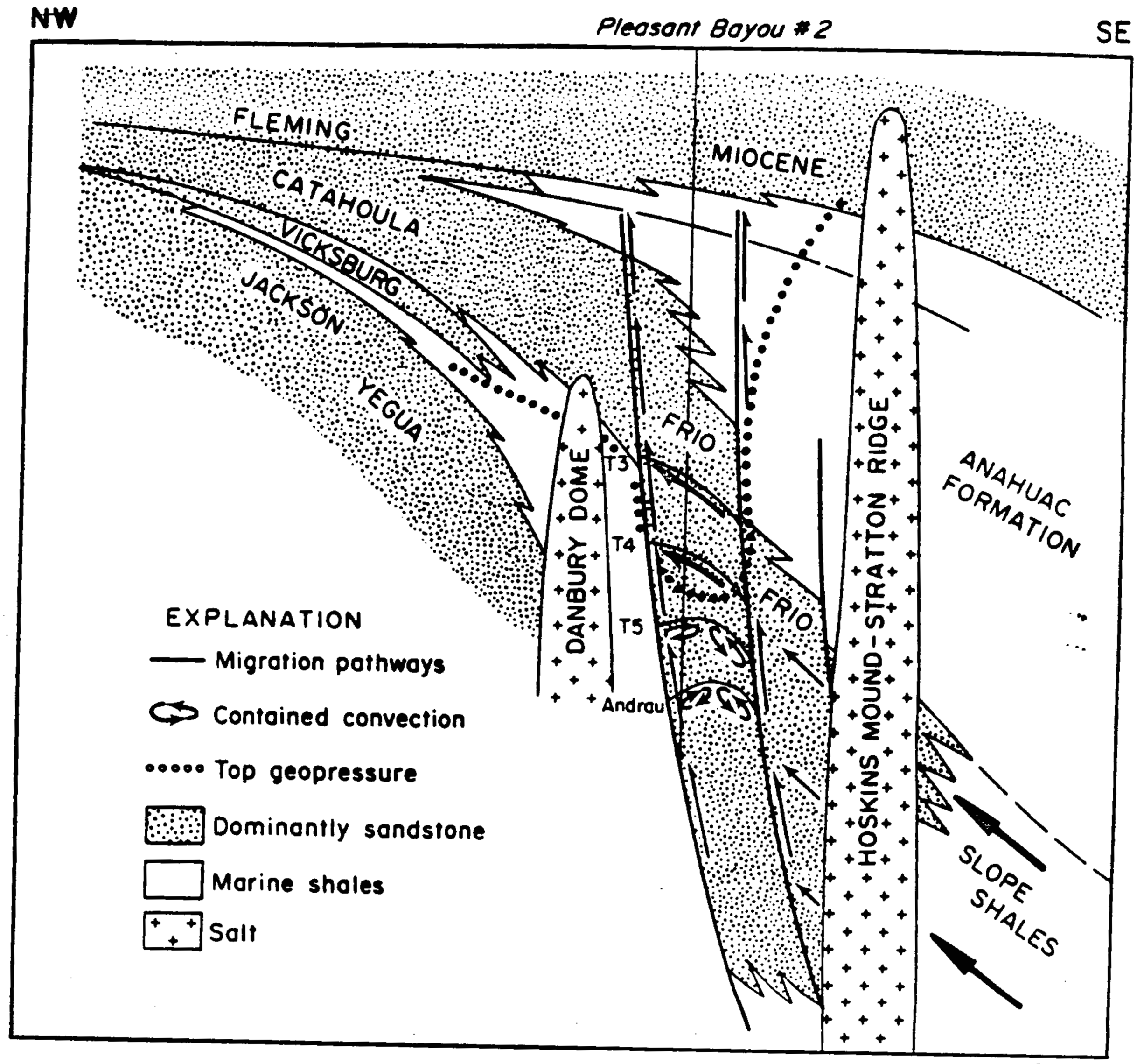
Fig. 3. Schematic cross section illustrating fluid migration pathways in the deep Frio Formation.



R_o 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3
T.A.I. (Schwab, 1980) 1 2 3 4 5 6
DEPTH (ft)
0
5000
10,000
15,000
TM
TA
T2
T3
T3'
T4
T5
Range of in-situ vitrinite reflectance
EXPLANATION
In situ core vitrinite reflectance showing range of values
Corrected core vitrinite reflectance
In situ core thermal alteration index
Average vitrinite reflectance assumed to be in situ
Corrected average vitrinite reflectance
Normalized thermal alteration indices for primary population
Maturation profile from PB #1 core
Estimated maturation profile for PB #1 and 2 wells assuming the present geothermal gradient of PB #2
Estimated maturation profile for PB #1 and 2 wells assuming a geothermal gradient of 1.15°F/100ft
Maturation profile for Oligocene sediments of the Louisiana Gulf Coast (Dow, 1978)
OIL GENERATION
IMMATURE
MATURE (Schwab, 1980)



Ro
0.2 0.3 0.4 0.5 0.6 0.7 0.8
% Wetness
C5-C7 Hydrocarbon Content
Vitrinite Reflectance
Time Temperature Index (TTI)
Range in vitrinite reflectance values
Burial history maturity profile expressed as TTI
Corrected Ro expressed as TTI
Naphthene fraction expressed as TTI
Depth Below Sea Level (ft)
0
5000
10,000
15,000
20,000
TA
T2
T3
T5
T4
T5
Top Andrau Sandstone
A
B
C
D
E
F
in situ (core) vitrinite reflectance (Schwab, 1980)
average vitrinite reflectance (Schwab, 1980)
25 50 75 100
100 1,000 10,000
.0001 .001 .01 .1 1 10
C2+ / C total x100
PPM Gas in sediment
Time Temperature Index
QA 3415


NW
Pleasant Bayou #2
SE
FLEMING
MIOCENE
CATAHOULA
VICKSBURG
JACKSON
YEGUA
FRIO
DANBURY DOME
T3
T4
T5
Andrau
FRIO
HOSKINS MOUND-STRATTON RIDGE
ANAHUAC FORMATION
SLOPE SHALES
EXPLANATION
Migration pathways
Contained convection
Top geopressure
Dominantly sandstone
Marine shales
Salt

QA 3414

Fi...