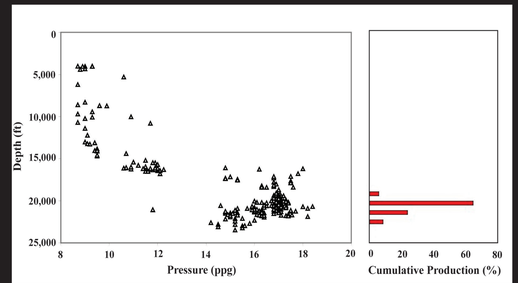

Figure 4. Pressure in pounds per gallon (ppg) versus depth in feet (ft) for wells in the Judge Digby field. Cumulative production (IHS Energy Group, 2008a, 2008b) was subdivided by depth increments of 1,000 ft.

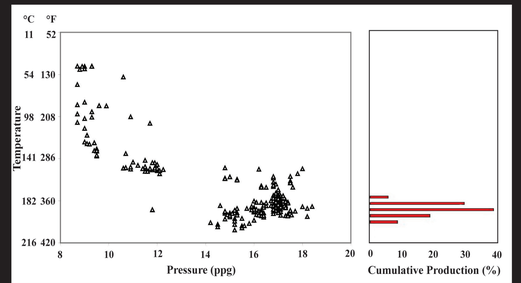

Figure 5. Pressure in pounds per gallon (ppg) versus temperature for wells in the Judge Digby field. Cumulative production (IHS Energy Group, 2008a, 2008b) was subdivided by temperature increments of 10°F.

4. Pressure, Temperature, and Production Relations

The relation of pressure and production as a function of depth (fig. 4) reveals that in the Judge Digby field, the greatest natural gas production is extracted from a depth range of 20,000 to 21,000 ft and at pressures from 16 to 18 ppg (Burke, 2010b).

A second order polynomial, empirical relation based on the well data (with an R2 = 0.99) was derived for converting depths to temperatures over the production interval. The relation between pressure and cumulative production as a function of this converted temperature (fig. 5) is shown as cumulative production summed for 10°F temperature increments. Accordingly, the greatest natural gas production corresponds to temperatures ranging between 350 to 390°F, and a Golden Zone around 365°F. These temperatures are much higher than the thermal zonations typically found in producing reservoirs worldwide (Bjørkum and others, 2005; Ehrenberg and others, 2008; Nadeau, 2008), but are lower than the regional trend for the onshore Gulf Coast.

Formation Name	Top Depth	Base Depth	Interval Thickness	Age at Top	Age at Base	Interval Duration	Preserv. Rate
	TVDSS	TVDSS	ft	Ma	Ma	Ma	ft/Ma
Overburden	0	6,040	6,040	0	23.7	23.7	255
HET Lime	6,040	8,475	2,435	23.7	28.4	4.7	518
Vicksburg Fm.	8,475	9,555	1,080	28.4	33.9	5.5	196
Sparta Fm.	9,555	10,635	1,080	33.9	48.6	14.7	73
Wilcox Gp.	10,635	14,340	3,705	48.6	57.2	8.6	431
Midway Gp.	14,340	16,370	2,030	57.2	65.5	8.3	245
Selma Chalk	16,370	17,995	1,625	65.5	85.8	20.3	80
Eutaw Shale	17,995	19,045	1,050	85.8	89.3	3.5	300
Pilot Lime	19,045	19,200	155	89.3	93.5	4.2	37
TUSC A sand	19,200	20,415	1,215	93.5	95.5	2.0	608
TUSC B sand	20,415	21,680	1,265	95.5	97.5	2.0	633
TUSC C sand	21,680	22,430	750	97.5	99.5	2.0	375

Table 2. Preservation rates were calculated based on the present day thicknesses of stratigraphic units divided by the duration of the depositional episode. This calculation reflects the combined effects of sedimentation rates and compaction rates for a quantitative comparison of preservation rates for various geologic formations. These values do not take into account any erosion that might have occurred at the top of the B and C sands. Note the high rates of preservation for the Tuscaloosa Formation (TUSC) A and B sands. The *Heterostegina texana* lime, or HET lime, is a biostratigraphic marker in the undifferentiated overburden. Note that TVDSS indicates true vertical depth subsea.

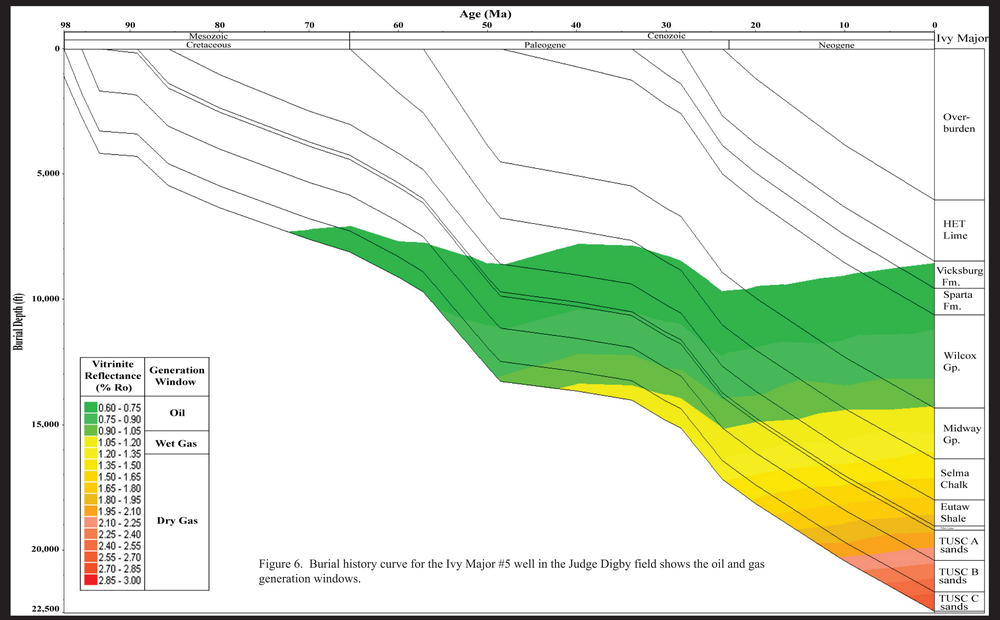

Figure 6. Burial history curve for the Ivy Major #5 well in the Judge Digby field shows the oil and gas generation windows.

5. Production and Petrophysical Analyses

Production and petrophysical analyses were conducted for the Ivy Major #5 well in the Judge Digby field in order to study sediment preservation rates and possible linkages to temperature anomalies within the downdip Tuscaloosa trend in Louisiana. The Ivy Major #5 well was drilled by Schlumberger for BP in 2007 (Cox and others, 2007). This well fully penetrates the Tuscaloosa A and B sands, but not the C sand, which is located at 21,700 ft in this well. Data from the nearby Parlange #5 well (Sheppard and others, 1997) in the Judge Digby field, which fully penetrates the Tuscaloosa C sand and penetrates the top of the D sand, were used to delineate the boundary between the B and C sands in this study. Table 2 provides a synopsis of the results.

This result may support the hypothesis that the rapidly deposited Tuscaloosa sediment package has not yet had adequate time to reach thermal equilibrium with the surrounding sediments. Although the producing reservoir is extremely deep, the temperature anomaly allows this formation to contain hydrocarbons. Future work in thermal maturity modeling will attempt to determine the hydrocarbon cracking kinetics down to 35,000 ft in order to quantify a maximum depth for a generating petroleum system in the downdip Tuscaloosa trend.

6. Burial history and Thermal Maturation Analyses

A burial history and thermal maturity study was conducted for BP's Ivy Major #5 well using PetroMod basin modeling software. The mean random reflectance (% Ro) for vitrinite maturation is calculated from time, *t*, temperature, *T*, and a series of first order Arrhenius equations for multiple hydrocarbon activation energies, *E*, (Sweeney and Burnham, 1990) as:

$$\frac{dk}{dt} = -\sum_i w_i A \exp\left[-E_i / RT(t)\right]$$

in which the summation index represents hydrocarbon catagenesis reactions, *k* is the amount of unaltered vitrinite, *R* is the universal gas constant, and *A* is an appropriate frequency factor constant. Thermal maturation for a Type II kerogen was calibrated using the logging temperatures recorded in the wellbore during drilling. This study indicates that the base of the Tuscaloosa A sands entered the oil generation window approximately 56 m.y. ago (fig. 6), and entered the wet gas generation window at approximately 24 Ma. This represents an oil generation duration of about 32 m.y. The Tuscaloosa A sands entered the dry gas generation window at 17 Ma and currently reside in the gas generation window. The present day vitrinite reflectance of the Tuscaloosa A sands ranges from 1.92 to 2.21 percent. The base of the Tuscaloosa B sands entered the oil generation window approximately 67 m.y. ago, and entered the wet gas generation window at approximately 35 Ma. Approximately 21 m.y. ago the Tuscaloosa B sands entered the dry gas generation window, and the present day vitrinite reflectance of the Tuscaloosa B sands ranges from 2.21 to 2.53 percent. From approximately 72 to 43 Ma, the Tuscaloosa C sands were in the oil generation window. The Tuscaloosa C sands entered the dry gas generation window 23 m.y. ago and currently reside in the gas generation window. The present day vitrinite reflectance of the Tuscaloosa C sands ranges from 2.53 to 2.72 percent.

Based on the vitrinite reflectance percentages from the thermal maturity study, the deep Tuscaloosa trend in southern Louisiana currently resides within the gas generation window. The marine shales that are interbedded within the formation could represent a potential source of the natural gas charging the deep Tuscaloosa trend in this location. If this is the case, then the deep Tuscaloosa in this location could be considered a self-sourcing system.

7. Summary

Geothermal gradients were derived from average field temperatures from all major producing natural gas fields located in the onshore Gulf of Mexico Basin. The relations among temperature, pressure, and production were studied in detail for the Judge Digby field. The Judge Digby field exhibits higher reservoir temperatures than the temperatures found in the majority of basins worldwide. However, the Judge Digby field has lower temperatures than the average extrapolated temperature trend for the regional onshore Gulf of Mexico Basin. Additionally, the temperature in the onshore Gulf of Mexico Basin is much higher than temperatures generally found in basins worldwide.

Analysis of production and petrophysical data indicates that the decreased temperatures in the Judge Digby field may be related to high sedimentation rates in addition to high preservation rates. This may have delayed the sediment package from reaching thermal equilibrium with the surrounding formation. Based on these temperatures, a burial history and thermal maturation analysis of vitrinite reflectance indicates that the deep Tuscaloosa trend in Louisiana is currently in the natural gas generation window, which may have implications for hydrocarbon generation sourced from interbedded shales. The results from this work are applicable to decreasing the exploration risk for undiscovered hydrocarbon accumulations in frontier regions. Rock units exhibiting high preservation rates and low temperatures at depth could represent significant exploration targets.

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