Natural Gas Production and Anomalous Geothermal Gradients of the Deep Tuscaloosa Formation

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1. Abstract

For the largest producing natural gas fields in the onshore Gulf of Mexico Basin, the relation between temperature versus depth was investigated. Prolific natural gas reservoirs with the highest temperatures were found in the Upper Cretaceous downdip Tuscaloosa trend in Louisiana. Temperature and production trends from the deepest field, Judge Digby field, in Pointe Coupe Parish, Louisiana, were investigated to characterize the environment of natural gas in the downdip Tuscaloosa trend. The average production depth in the Judge Digby field is approximately 22,000 ft. Temperatures as high as 400°F are typically found at depth in Judge Digby field and are anomalously low when compared to temperature trends extrapolated to similar depths regionally.

At 22,000 ft, the minimum and maximum temperatures for all reservoirs in Gulf Coast producing gas fields are 330 and 550°F, respectively; the average temperature is 430°F. The relatively depressed geothermal gradients in the Judge Digby field may be due to high rates of sediment preservation, which may have delayed the thermal equilibration of the sediment package with respect to the surrounding rock.

Analyzing burial history and thermal maturation indicates that the deep Tuscaloosa trend in the Judge Digby field is currently in the gas generation window. Using temperature trends as an exploration tool may have important implications for undiscovered hydrocarbons at greater depths in currently producing reservoirs, and for settings that are geologically analogous to the Judge Digby field.

2. Introduction

The relations among temperature, pressure, and hydrocarbon accumulation have been investigated by researchers at Statoil for 120,000 producing reservoirs worldwide, excluding the onshore United States (Bjorkum and others, 2005; Ehrenberg and others, 2008; Nadeau, 2008). These studies, which are graphically summarized in figure 1, found that approximately 90 percent of hydrocarbon accumulations worldwide are situated in the 140 to 250°F temperature range referred to as the Golden Zone. Ehrenberg and others (2008) and Bjorkum and others (2005) also concluded that in the majority of clastic basins worldwide, the top of overpressure roughly corresponds to the 140°F isotherm; and the zone of hard overpressure, the zone in which near lithostatic pressures occur, begins at approximately the 250°F isotherm. They also concluded that the 140 to 250°F thermal zone corresponds to the overpressured region of the subsurface in which the majority of producing hydrocarbon reservoirs are located.

Furthermore, they maintain that temperature can be used as a complement to the characterization of a petroleum system to refine the analysis of reservoir quality and hydrocarbon accumulation preservation. In general, biodegradation of hydrocarbon accumulations occurs in reservoirs with temperatures cooler than 140°F. Reservoir quality typically decreases with depth in reservoirs warmer than 140°F as porosity is reduced due to quartz cementation and the illite to smectite transition. At approximately 250°F and above, thermal cracking and subsequent dissipation of hydrocarbons may lead to a decrease in the volume of the accumulation.

Figure 2. Temperature distribution by depth for all producing natural gas fields in the onshore Gulf of Mexico Basin.

Figure 3. Pressure in pounds per gallon (ppg) versus temperature for 107 wellbores in the Judge Digby field, Pointe Coupe Parish, Louisiana.

Figure 1. Pressure increases at various depths in different basins worldwide. Pressure increases at a similar temperature zone in different basins worldwide. This temperature is called the Golden Zone and corresponds to the greatest cumulative production (after Bjorkum and others, 2005; Ehrenberg and others, 2008; Nadeau, 2008).

3. Gulf of Mexico Basin and the Tuscaloosa Trend

For the largest producing natural gas fields in the onshore Gulf of Mexico Basin, the relations among temperature, pressure, and depth were investigated (fig. 2). The maximum and minimum temperature envelopes for these gas fields were interpreted along with an average geothermal gradient for the region. Gradients are assumed to be linear with depth. Based on these data (NRG Associates, 2008), shown with permission (Richard Nehring, written commun., 2010), the maximum temperature gradient is 2.18°F/100 ft, and the minimum temperature gradient is 1.20°F/100 ft. The average temperature gradient is approximately 1.58°F/100 ft.

Prolific natural gas reservoirs with the highest temperatures were found in the downdip Tuscaloosa trend in Louisiana. One such gas field is the Judge Digby field. The production depths in the Judge Digby field range from approximately 18,000 to 24,000 ft, with an average of 22,000 ft. The Judge Digby field is characterized by an extreme drilling environment, with well penetrations down to 24,000 ft, initial reservoir pressures up to 18 pounds per gallon (ppg), and bottomhole temperatures above 400°F. The first well was drilled by Chevron in 1977 (Christina and Martin, 1979), and the field has experienced active re-development since 1996 due to increased natural gas demand and improved drilling technologies. The downdip Tuscaloosa trend is approximately 1,200-ft thick in this location. The average reservoir porosity in the Judge Digby field is above 20 percent with permeabilities as high as 1,000 millidarcy (mD). This is due to the preservation of primary porosity by chlorite cement, which inhibited quartz cementation, and secondary porosity development from carbonate dissolution (Thomson, 1979, 1982).

4. The Judge Digby Field

For the Judge Digby field, 184 bottomhole temperatures were obtained from purchased header files from multiple wireline logging tool runs conducted in 107 separate wellbores during the multi-stage drilling of each well. Table 1 provides the minimums, maximums, and arithmetic averages of these temperatures by depth.

A geothermal gradient using all temperature and depth data was calculated for the production zone of interest from 18,000 to 24,000 ft. This gradient is 1.74°F/100 ft over the productive interval; and the gradient is 1.54°F/100 ft calculated from the surface. This indicates that the temperature gradients over the production depths in the Judge Digby are near the minimum temperature gradients for the onshore Gulf Coast.

The relation between pressure and temperature for the Judge Digby field (fig. 3) shows that temperatures ranging from 320 to 410°F correspond to pressures from 14 ppg to 18 ppg. The natural gas production was further subdivided into 1,000-ft depth increments for a higher resolution analysis. As such, cumulative production for the field was summed over 1,000 ft increments to give a measure of production at distinct depths within the producing zone.

Depth (ft)	Minimum Temp (°F)	Maximum Temp (°F)	Average Temp (°F)	Data Points
4,000	98	102	101	3
8,000	150	190	170	4
10,000	158	225	180	3
13,000	200	200	200	1
14,000	210	210	210	2
15,000	230	276	243	7
16,000	240	270	255	28
17,000	--	--	--	0
18,000	310	340	325	4
19,000	328	358	346	9
20,000	332	378	355	53
21,000	276	387	364	58
22,000	366	396	386	9
23,000	398	402	399	3

Table 1. Temperature data for 184 bottomhole temperature readings were obtained during the drilling stages for 107 wellbores in the Judge Digby field. A high-resolution temperature gradient specific to the production zone for this field was calculated. The temperature gradient is 1.74°F/100 ft over the productive interval; and 1.54°F/100 ft calculated from the surface. Burke (2010a) provides this database.