Texas Heat Flow Patterns*

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Abstract

New heat flow data are combined with BHT data in Texas and surrounding areas to more accurately define the thermal field. The results are interpreted in terms of local and regional geology and tectonics. The variation in heat flow across Texas can be explained by a combination of three factors: changes in basement radiogenic heat production, heat generation within sedimentary rocks, and the local effect of possible groundwater flow. In south and east Texas, in spite of the moderate heat flow values, temperatures are quite high in the sedimentary section, and thus there is significant geothermal potential.

The thermal pattern in north-central Texas defines the Ouachita tectonic front as an important thermal boundary. Heat flow values increase eastward from 48 mW/m^2 in the Fort Worth Basin to 61 mW/m^2 in the Ouachita tectonic front. It drops to 55 mW/m^2 in the interior zone to the east before increasing again to the interior of the Ouachita belt in Louisiana, probably due to a high radioactivity in the accreted basement rocks. In addition, a zone of heat flow values below 44 mW/m^2 extends from approximately 30 km north of Dallas towards Oklahoma and is linked to the low heat flow values recorded in the deep Anadarko Basin and in the frontal part of the Wichita Uplift.

Heat flow data derived from high-resolution temperature logs are compared to the values obtained from conventional BHT. The BHT-derived heat flow values suggest that the low heat flow in the Fort Worth basin and north of Dallas are isolated features and that they are not linked to the similarly low heat flow in Midland and Delaware basins. We interpret the 51 mW/m^2 values for the Palo Duro basin as a transition zone between low heat flow in the Midland Basin and higher heat flow immediately north of the Amarillo uplift north into Kansas.

Introduction

The study area described here extends from Palo Duro Basin in the west to the East Texas Basin, and a few kilometers into Louisiana. The area is interesting for several reasons. First it crosses the importantly economic Fort Worth Basin, where gas exploitation takes place from the Barnett Shale. In spite of the extensive drilling, thermal maturity, based only on bottom hole temperature data, is not entirely understood. Secondly it includes the

Ouachita Thrust Belt, and interpretation of the heat flow data determines thermal signatures for the types of basement on either sides of the tectonic belt. Also important for this area is the capability of extracting geothermal energy from a variety of sources (high grade, geothermal/geopressured fluids, abandoned or shut-in oil and gas fields; McKenna et al. 2005).

Data

Figure 1 shows the position of the new heat flow points on a structural map of southwestern U.S., while Table 1 shows the actual heat flow values. The techniques used to determine the heat flow values are described in detail in Negraru et al. (2008). Two wells are located in the Palo Duro Basin; two wells are located in the Fort Worth Basin; two are located in East Texas Basin close to Louisiana/Texas border: and 17 are wells of opportunity around the Ouachita Thrust Belt.

With a few exceptions, most of the wells show values between 50 and 60 mW/m^2. However, to determine basement heat flow, the radiogenic heat of the sediments must be removed from the surface heat flow values. Sediment heat generation tends to be ignored, but it may be significant. McKenna and Sharp (1998) published heat generation values for several Cenozoic units within the Gulf of Mexico and pointed out the importance of heat generation effects in basin modeling. Heat generation values for the sedimentary section were calculated from natural gamma radiation logs.

The natural gamma radiation log records the total gamma radiation of the formations, and in spite of the fact that it does not provide the individual contributions of the radioactive isotopes, it is related to the total heat generation. Rybach (1986) developed a simple relationship between heat generation and gamma ray log intensity, which was later refined (Bucker and Rybach, 1996) to:

$$A=0.0158(GR-0.8)$$

where A is the heat generation value in $\mu W/m^3$ and GR is the API value read on the natural gamma radiation log.

Among sedimentary rocks shales have the higher heat generation values than sandstone and limestone, and black marine shales in East Texas have higher heat generation values than the Permian shales in West Texas. For instance the highest heat generation value for any of the wells is obtained for the Eagle Ford shale (2.2 $\mu W/m^3$), whereas in Palo Duro Basin the Cisco shale has a heat generation value about half of this value (1.2 $\mu W/m^3$). However, to have a significant contribution to the total heat flow the shale thickness need to be relatively large.

The two wells in the Palo Duro Basin have surface heat flow values of 50 and 52 mW/m^2. Apart from the Cisco shale, only the upper part of the wells, with a thin Cenozoic and Mesozoic section can have a significant contribution to the surface heat flow. The total contribution for those wells is around 2 mW/m^2, which gives basement heat flow values of 48 and 50 mW/m^2. In a previous paper (Herrin and Clark, 1956), heat flow values were published for the Midland and Delaware basins. The value of 44 mW/m^2 is today the accepted heat flow value for this area. Up to now these were the only heat flow points west of the Ouachita fold belt. While the basement heat flow values for the Palo Duro Basin are within the error range of the Midland

Basin values, the difference appears to be real. Farther to the north the heat flow increases gradually north of the Amarillo Uplift to 55 mW/m^2 (Carter, 1993) in the Anadarko Basin.

The two wells in the Fort Worth basin have heat flow values of 48 mW/m^2, but the sedimentary columns have an unusual high percentage of shales. Because of the unusual high shale content, the total contribution of the radiogenic heat to the surface heat flow is 4 mW/m^2. If we remove this contribution from the surface heat flow, we obtain basement heat flow values of 44 mW/m^2, similar to the value published for the Midland Basin (Herrin and Clark, 1956). This implies that the basement in Fort Worth basin is similar (at least from the thermal point of view) to the basement in the Midland and Delaware basins.

The basement structure in north-central Texas is much more inhomogeneous. Surface heat flow values range from 41 mW/m^2 to over 60 mW/m^2. In spite of the presence of Eagle Ford Shale with very high heat generation, the overall heat generation for the whole sedimentary section can be neglected, as it is below 1 mW/m^2. All the variation therefore appears to be related to structural changes in the basement.

Figure 2 shows a geologic section with corresponding heat flow values. The heat flow in the Fort Worth Basin is 48 mW/m^2, whereas around the front of the Ouachita Belt there is an area with heat flow values that could be in excess of 60 mW/m^2. Farther to the east (the interior zone of the Ouachita Belt), the heat flow drops to values generally below 60 mW/m^2 but then increases significantly to the east. It appears, therefore, that the Ouachita belt is a major thermal boundary between the low heat flow in Permian-age West Texas Basin basement and high heat flow in the Mesozoic East Texas Basin basement. The anomalously low 41 mW/m^2 recorded in the Sherman well could be due to a continuation of mafic rocks outcropping in the Wichita Mountains immediately north of the study area. The southern continuation of the mafic rocks is inferred from gravity anomalies.

The easternmost heat flow points for this data set are located in Louisiana, a few kilometers from the border with Texas. They show high heat flow, in excess of 70 mW/m^2. This implies the presence of very high heat flow from below the sediments. This area of high heat flow, which extends to the east as far as Mississippi, is one of the most attractive geothermal resource in the eastern U.S. (Blackwell et. al. 2007; Negraru et. al. 2008). The oil and gas infrastructure there could significantly lower the cost of the whole geothermal investment.

Implication for the Thermal Maturity of the Barnett Shale

An interesting problem encountered in the Fort Worth Basin is understanding the thermal maturity of the Barnett shale. The presence of gas in the Upper Mississippian Barnett Shale implies past temperatures on the order of 150 to 200°C, high enough to allow the formation of methane. Initially the thermal maturation of the Barnett shale was attributed to high temperatures associated with the depths of burial of the formation. If the maximum paleotemperature was at least 150 °C and the current formation temperature is around 90°C, it is possible to make a first order determination of the amount of material eroded. Although the lithology of the wells drilled in the Fort Worth Basin consists mainly of shale (gradients around 40°C/km), the Cretaceous section which was eroded had less shale content. The gradients encountered in sandstone for this age would have been about 17°C/km (e.g., Paluxy Sandstone), while the gradients in the shales could have reached 44°C/km (e.g., Eagle Ford Shale); therefore, an average gradient of

33°C/km for the eroded Cretaceous section will be used. Assuming mean annual temperatures of 27°C (10°C higher in the Cretaceous) we obtain a temperature of 159°C at a depth of 4 km; therefore, the denudation history would indicate at least 1.5 km erosion (the maximum depth of the formation is up to 2500 m). This would be the minimum burial requirement for the thermal maturation of the Barnett Shale.

However, apatite fission track (AFT) studies on the Paleozoic Ouachita trend (Corrigan et al., 1998, and Winkler et al., 1999) give a different perspective. Fission tracks record the thermal history of the rock since the last cooling event (see Gallagher et al., 1998). Their main advantage is that they provide information about the times of the events. Unfortunately, the tracks that form are quickly destroyed at temperatures of 120 to 140°C, depending on the chemical composition of the apatite. These temperatures are too low for the requirements of the Barnett Shale to generate gas, but on the other hand their time history provides valuable information.

The AFT data from basement rocks suggest similar thermal history for the Llano and Tishomingo uplifts, both west of the Ouachita belt and both having maximum temperatures below 120°C in the last 370 my. The current thermal data suggest the basement beneath the Fort Worth Basin is Precambrian granite, similar to the Llano and Tishomingo Uplifts. As the maturation temperatures in the Fort Worth Basin must have been on the order of 150°C, and the AFT data suggest the basement rocks had temperatures below 120°C since the time of deposition of the Barnett Shale, it is clear that the thermochronology of the Precambrian Tishomingo and Llano Uplifts are not identical to the thermochronology of the basement beneath Fort Worth Basin. In the Llano Uplift the maximum temperature of 90°C was reached in Late Ordovician (450 Ma), prior to the deposition of the Barnett Shale, and this suggests that in contrast to the Fort Worth Basin basement, the Llano region has not been deeply buried since Early Paleozoic. However, the cooling history of the Marathon (in West Texas) and Benton Uplifts (in Arkansas), both in the frontal deformation zone of the Ouachitas, suggests that the maximum temperatures of 120°C were reached at 200 Ma (Triassic). But temperatures could have been higher before Triassic; therefore, the gas maturation appears to be related to the Ouachita tectonic event. Thus key to the maturation is the context of the Barnett Shale during the Ouachita orogeny.

The gas-producing zones in the Barnett formation are closely associated with local thermal anomalies (Zhao, 2004). This would rule out the depth of burial as the single cause of maturation. Therefore, models were proposed in which the maturation was driven by circulation of hot fluids, from east to west, associated with the Ouachita Thrust Fault (Bowker, 2003, Montgomery et. al. 2005). However, such convective models would require significant volumes of hot fluids in the permeable Ordovician Ellenburger Formation right beneath the Barnett Shale, and a major source of heat in the Ouachita belt. Analogies with the present-day geothermal systems suggest they are localized (Gosnold, 1999), on the order of a few km^2 and are probably not large enough to drive the maturation of Barnett Shale over the whole basin. In general the tectonic provinces where such hot fluids are encountered are either in the backarc of subduction zones, or in the rift regions (e.g., the high heat flow area in West Texas is associated with Rio Grande Rift), and the Fort Worth Basin does not appear to have been any of those.

In any case the Late Paleozoic collision event that took place during final assembly of Pangea appears to have been energetic enough to drive the gas maturation. The exact plate motions are not known, but the subduction zone must have followed the Ouachita trend, the only major remnant of this event, which is a thrust and fold belt with tectonic setting similar to the Mesozoic Northern Rocky Mountains. Therefore, the Fort Worth Basin was

probably a foreland over which the Ouachita rocks have been thrust and later eroded in the Cretaceous Gulfian cycle. This would support a burial maturation, as was proposed initially.

The gas occurrences in localized thermal anomalies could be also explained conductively. If the temperatures approach but do not quite reach regional maturation conditions, small heat flow anomalies could lead to local areas of maturation. Isolated positive 10 mW/m^2 heat flow anomalies could be high enough to lead to maturation, while in the rest of the basin the lower normal background heat flow could leave the organic material immature for gas and in the oil window. The present day heat flow patterns in Texas show that variations of 10 mW/m^2 or more are common for this area. These changes are interpreted to be related to different radiogenic heat production elements due to basement lithologic variations. The spatial variations of these anomalies are large enough to explain the differences in the gas maturation of the Barnett Shale; so heat flow could be the key to maturation. Thus the local basement structure might control the gas occurrences.

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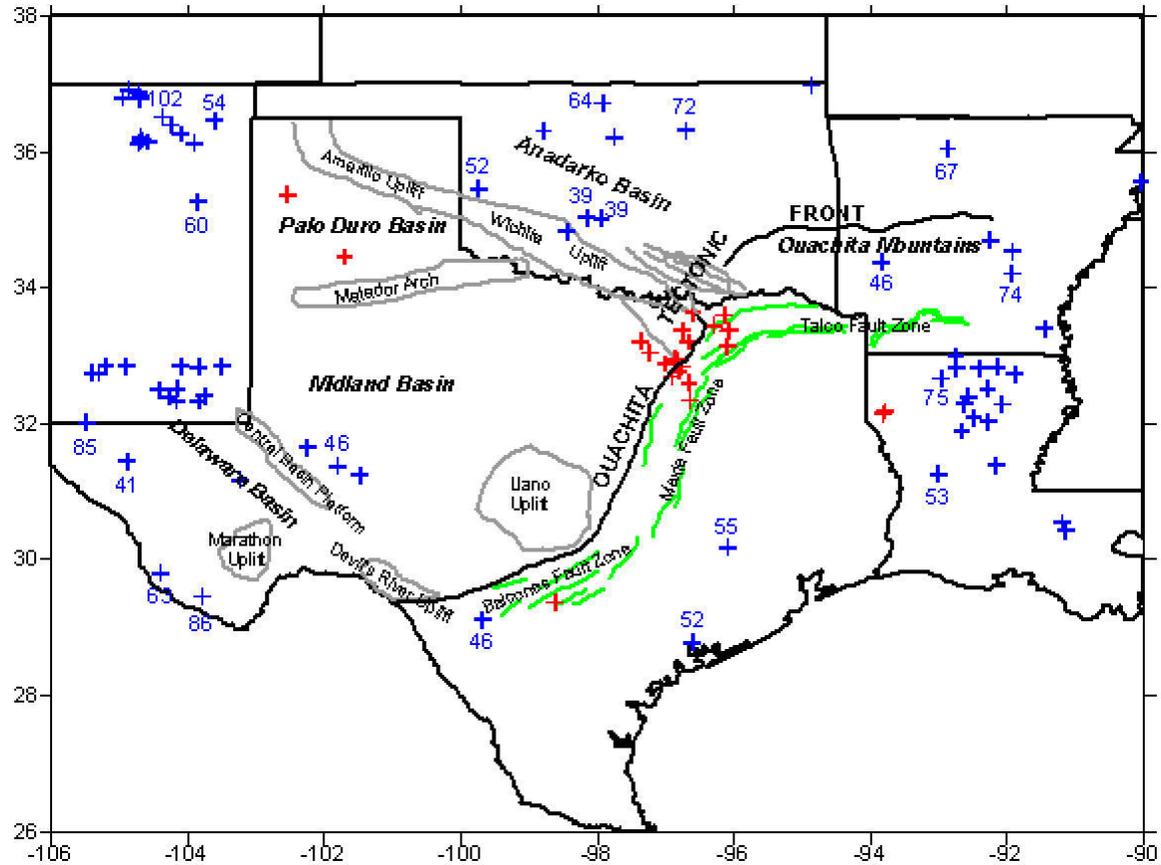
Figure 1. Location of published heat flow values (blue crosses) and of new values (red crosses) on schematic map of some major tectonic features of Texas, showing the position of basement uplifts and intervening basins, along with Balcones, Mexia and Talco fault zones.

Figure 2. Generalized geological section and corresponding heat flow values. The easternmost point represents an average heat flow value for Mexia fault zone.

Well name	Longitude	Latitude	Heat flow (mW/m2)
MNEV	-96.8386	32.9345	61 ± 2
Otis	-96.873	32.9553	52 ± 11
Cadiz	-96.8021	32.768	56 ± 9
SMU	-96.7681	32.8438	53 ± 4
Mobil Duncanville	-96.9038	32.6997	48 ± 2
Trigg	-96.9983	32.8852	61 ± 13
Bonham	-96.14	33.6	56 ± 6
Aswastika Co. Owens #1	-96.29	33.45	43 ± 6
Ferris Brick	-96.66	32.6	51 ± 6
Ennis	-96.64	32.35	52 ± 6
Wolfe City	-96.06	33.38	57 ± 6
Kimbell	-96.08	33.37	58 ± 6
Sherman	-96.6	33.64	41 ± 6
Greenville	-96.1	33.14	53 ± 6
Smith #1	-97.23511	33.04602	48 ± 5
Union Central #2	-97.36411	33.2095	48 ± 5
Mckinney	-96.6666	33.205	51 ± 5
Gunter	-96.75	33.374	44 ± 5
Mansfield #1	-101.7	34.46	52 ± 5
Zeeck #1	-102.54	35.37	50 ± 5
Mosley #1	-93.79	32.185	82 ± 6
Haynes #1	-93.8189	32.1483	82 ± 6
Lackland	-98.62	29.37	34

Table 1. Coordinates and heat flow for the new heat flow points.