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Heat flow in the Ozark Plateau, Arkansas and Missouri: relationship to groundwater flow

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ABSTRACT

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Heat flow values were calculated from direct measurements of temperature and thermal conductivity at thirteen sites in the Arkansas–Missouri Ozark Plateau region. These thirteen values are augmented by 101 estimates of heat flow, based on thermal conductivity measurements and temperature gradients extrapolated from bottom-hole temperatures. The regional heat flow profile ranges from 9 mW m^{-2} to over 80 mW m^{-2}, but at least two distinct thermal regimes have been identified. Seven new heat flow determinations are combined with three previously published values for the St. Francois Mountains (SFM), a Precambrian exposure of granitic and rhyolitic basement rocks, average 47 mW m^{-2}. Radioactive heat production of 76 samples of the exposed rocks in the SFM averages 2.4 μW m^{-3} and a typical continental basement contribution of 14 mW m^{-2} is implied. Conversely, the sedimentary rock sequence of the plateau is characterized by an anomalously low heat flow, averaging approximately 27 mW m^{-2}. Groundwater transmissivity values that are based on data from 153 wells in deep regional aquifers demonstrate an inverse relationship to the observed heat flow patterns. The areas of high transmissivity that correspond to areas of low total heat flux suggest that the non-conservative vertical heat flow within the Ozark sedimentary sequence can be attributed to the effects of groundwater flow.

Introduction

The Ozark Plateau extends throughout north-central Arkansas and south-central Missouri. It is a tectonically stable sequence of Paleozoic sedimentary rocks that overlies a Proterozoic granite-rhyolite terrain and a sequence of layered Proterozoic rocks of unknown character (Bickford et al., 1981; Pratt et al., 1988). This portion of the North American craton is immediately adjacent to both the Ouachita orogen and the northernmost segment of the Mississippi Embayment (Fig. 1). Recognizing the proximity of this area to probable lithospheric contrasts to the south (Arvidson et al., 1982), heterogeneities proposed for the Ozark Plateau (Guinness et al., 1982; Bickford et al., 1981) and debates surrounding the thermal history of this region (Beales, 1976; Thacker and Anderson, 1977), a detailed investigation was conducted to acquire new estimates of heat flow. Combining these data with the limited heat production data, we sought to determine a geothermal character for the Ozarks. Field expeditions were conducted in late 1986 and mid-1987 and laboratory efforts were completed in early 1989.

Combs and Simmons (1973) reported heat flow values for the central states and demonstrated a typical heat flow of 59 mW m^{-2} characterizing the Interior Lowlands and a value of 42 mW m^{-2} characterizing the southern Great Plains. Lachenbruch and Sass (1977) later in-

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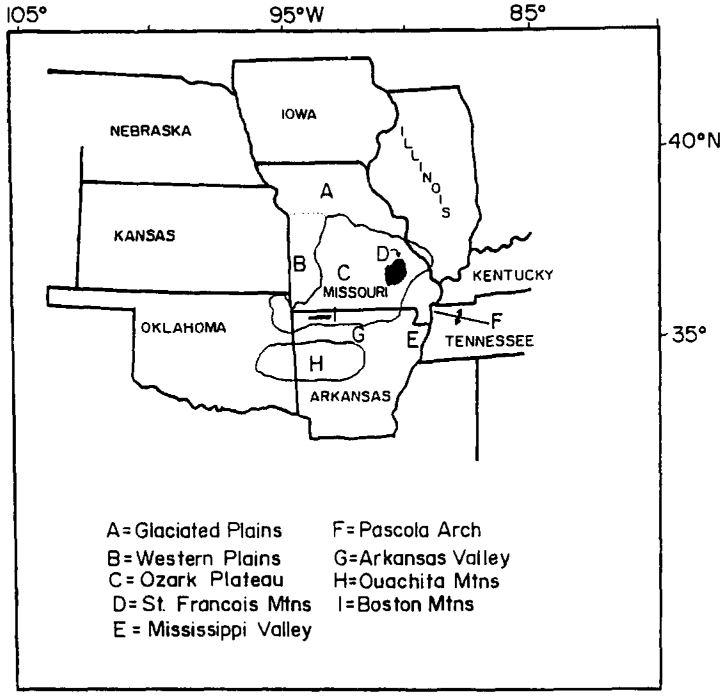

Fig. 1. Map of the study area showing major geologic and physiographic features.

cluded the Ozark Dome in the eastern United States heat flow province that was characterized as having a reduced heat flux of 31 mW m^{-2}. These and other assignments of the Ozark Plateau to specific thermal provinces relied on five early heat flow determinations in Missouri and Oklahoma by Roy et al. (1968a,b). Three of these values were in the exposed granite-rhyolite terrain of the St. Francois Mountains of Missouri (Fig. 2). These five values ranged from 52 to 59 mW m^{-2}.

Heat flow values for the upper Mississippi Valley area were reported by Jarrett (1982) and Jarrett et al. (1984). Eighteen values in the Mississippi Valley in Arkansas, Tennessee, and northern Mississippi averaged 52 mW m^{-2}. Values flanking the Mississippi Embayment in northern Mississippi and southern Arkansas are lower (12 values average 29 mW m^{-2}), but higher heat flow values in central Arkansas and northern Louisiana suggest a south-southwestwardly extension of the intrusive activity associated with the Reelfoot Rift (Jarrett et al., 1984; Meert et al., in prep.). Roy et al. (1980) reported measurements at six sites in northern Arkansas, but later discussions (R.F. Roy, pers. commun., 1984) resulted in the retraction, as unreliable, of all but two values. Values of 44 mW m^{-2} and 46 mW m^{-2}, both in the Ouachita Mountains, were considered valid.

Bottom-hole temperatures acquired prior to pump tests in water well logging were used by Fuller (1981) to estimate geothermal gradients for approximately 100 boreholes throughout Missouri. These values ranged from 3 K km^{-1} to over 40 K km^{-1} (Fig. 3). Including those values reported by Roy et al. (1968a,b), ten boreholes in the exposed igneous complex of the St. Francois Mountains yielded an average geothermal gradient of 15 K km^{-1}.

A comprehensive geothermal gradient reconnaissance of the Tennessee River Valley area by Von Frese et al. (1980) combined with data from a later study by Jarrett (1982), identified average geothermal gradients of 17

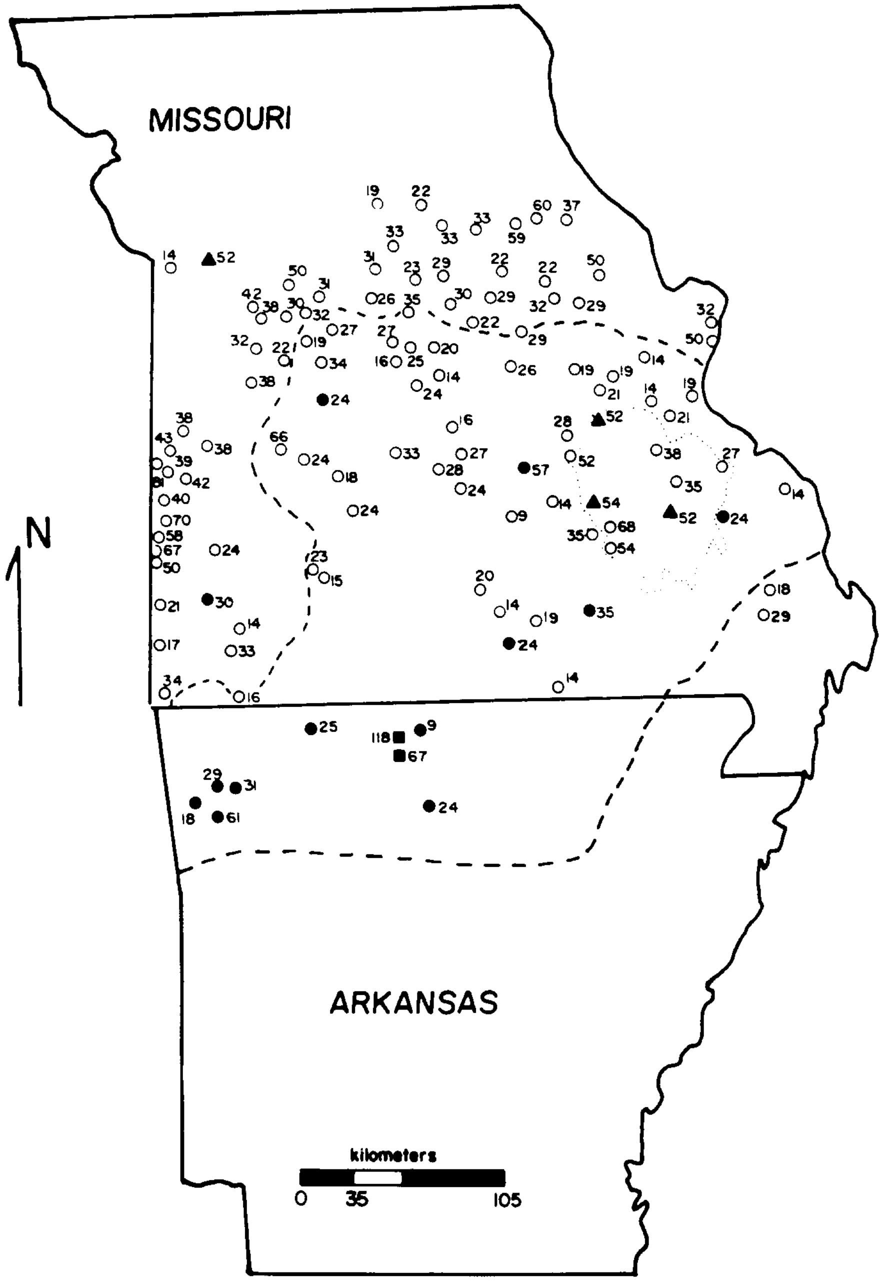

Fig. 2. Map of the Ozark Plateau in Arkansas and Missouri showing the locations of previously determined heat flow values along with those measured in this study (▲ = Roy et al., 1968a,b; ○ = Fuller, 1981; ■ = Roy et al., 1980; ● = this study).

K km^{-1} for the Mississippi Valley area. These values and eight thermal gradient estimates for the Mississippi Embayment region of south-eastern Missouri (average > 28 K km^{-1}) suggest regional values that are markedly different than the gradients reported for the Ozark Plateau.

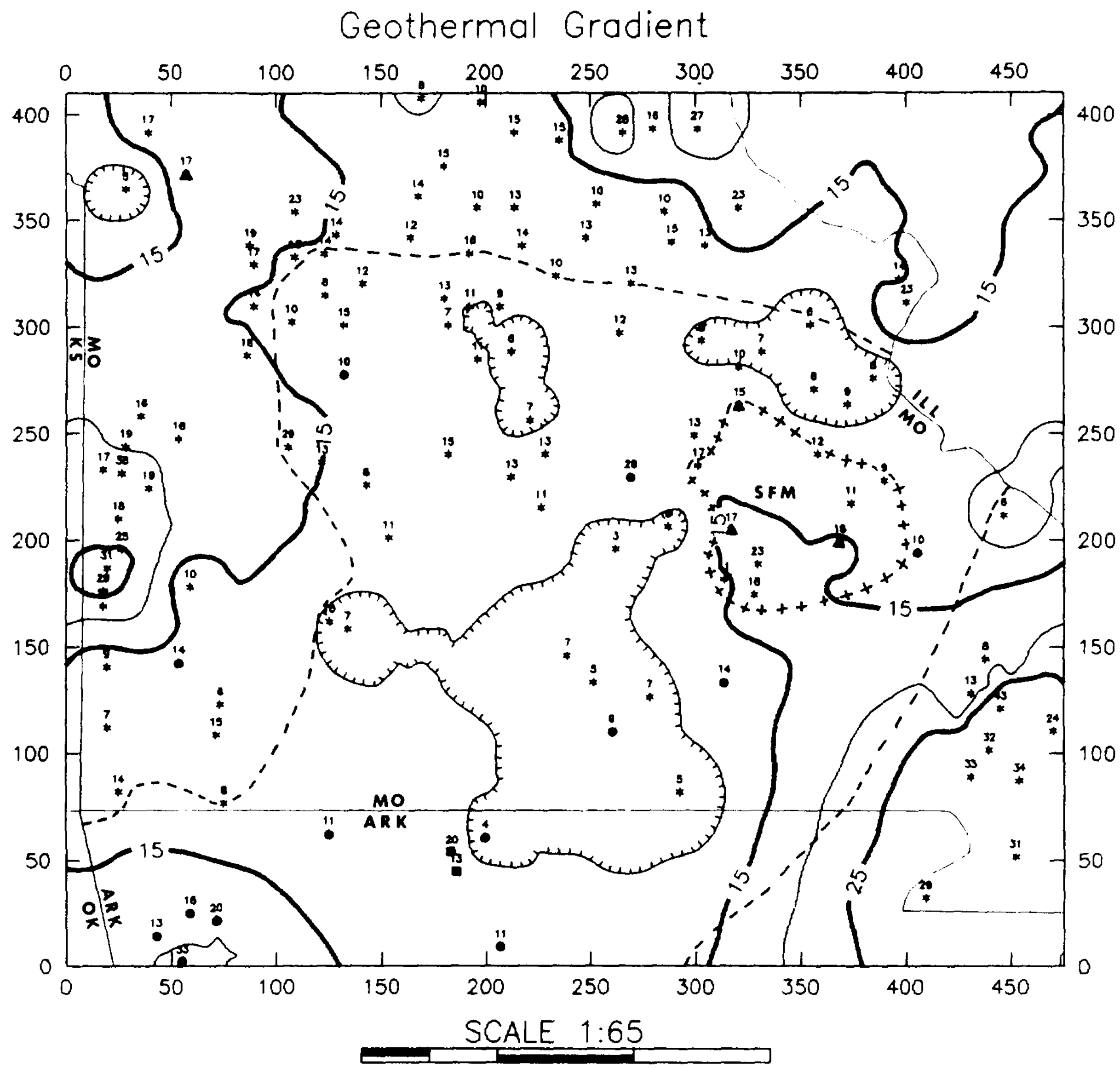

Fig. 3. Contoured geothermal gradient map of the Ozark Plateau showing gradient values obtained in this, and previous studies (symbols are the same as Fig. 2).

Geologic background

The Ozark Plateau is better described as the Ozark Dome (Bretz, 1965) because the sedimentary rocks exhibit a prevailing, mild outward dip away from the St. Francois Mountains (Fig. 4). The sedimentary sequence consists primarily of Ordovician-age limestones and dolomites with interbedded sandstones, shales, and chert (Bretz, 1965). The basal Cambrian Lamotte sandstone overlies the Precambrian igneous basement. Most outcrops in the Plateau region are of Ordovician age.

The St. Francois Mountains are in southeastern Missouri at the structural apex of the Ozark Dome (Fig. 4). Precambrian exposures here are the largest in the central portion of North America and thus they provide a window to the subsurface of the mid-continent

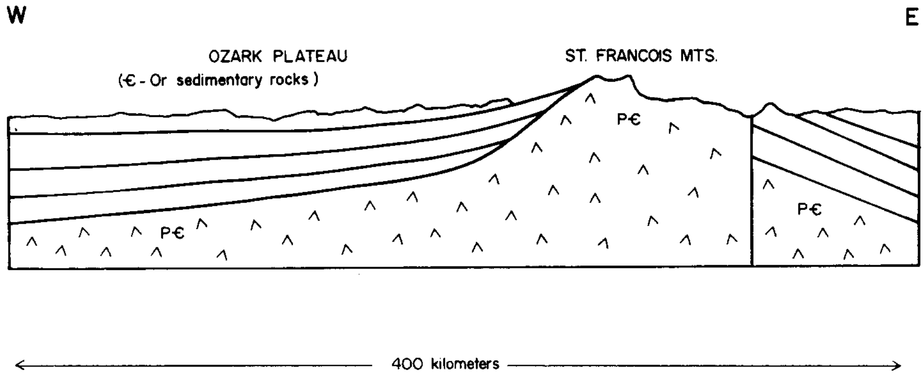

Fig. 4. Generalized east–west cross section through the Ozark Dome. Sedimentary rocks above the Precambrian basement are primarily limestones and dolomites.

(Sides et al., 1981). The mountains are composed of silicic volcanic rocks, ash-flow tuffs, and epizonal granitic plutons (Kisvarsanyi, 1980). The emplacement of the igneous rocks was described by Sides et al. (1981) and Kisvarsanyi (1980) as a caldera collapse-rejuvenation sequence. The oldest extruded rhyolites (1485 Ma, Bickford and Mose, 1975) are intruded by younger granites and minor amounts of mafic material (Amos and Desborough, 1970; Sides et al., 1981).

The Boston Mountains in northern Arkansas and Oklahoma represent the southern terminus of the Ozark Plateau (Bretz, 1965). These mountains, formed by erosion, lie north of the Ouachita Mountains and are separated from them by the Arkansas Valley. They are composed of Pennsylvanian-age shales and intercalated sandstones that represent the remnants of a once-complete Pennsylvanian sequence that covered the entire Ozark Dome.

Thacker and Anderson (1977) presented a scenario for the development of the Ozark Dome. They concluded that the Precambrian rocks were uplifted and eroded prior to a Late Cambrian transgression that deposited the Lamotte sandstone over the irregular bedrock surface. Patch-reef formation of the carbonate units developed during the Ordovician, and numerous depositional-erosional sequences occurred through the late Pennsylvanian. By their view, domal reactivation that resulted in the current configuration took place in the latest Pennsylvanian after deformational events occurred in the Ouachita Mountains to the south. Alternatively, Kisvarsanyi (1980) has suggested that the doming in the Ozarks may be due to recurrent hotspot activity during the Phanerozoic.

Heat flow determinations

Thirteen new heat flow values were computed using data for boreholes in the Ozark Mountains province and border regions. Another 101 values of heat flow were estimated by applying measured thermal conductivity values for representative borehole cuttings to sites for which thermal gradients were reported by Fuller (1981). These 114 new heat flow determinations and estimates were used to characterize the Ozark Plateau and surrounding provinces. A total of 56 values are in the Ozark Plateau province, 10 values are in the exposed igneous complex of the St. Francois Mountains, and 48 values are used to characterize the surrounding regions.

Borehole temperature values were measured with a thermistor probe coupled to a Mueller-type Wheatstone bridge with a 1000-m, four-conductor cable. The thermistor probe was calibrated in constant temperature baths using a platinum resistance thermometer and the temperature measurements in the boreholes are considered accurate to within ±0.2 K. The temperature values for the measurement at Leslie, Arkansas were recorded by the USGS.

Deep drill holes were sought on an opportunistic basis, and temperature measurements were made at discrete intervals in the wells. Wells undisturbed by pumping or recent drilling and at least 150 m deep were preferred, but the paucity of suitable wells in some areas necessarily introduced a bias into the spatial distribution of the data. The local relief at each of the measurement sites was to small to justify topographic corrections.

Only cutting samples were available for each of the boreholes logged. Thus, the thermal conductivity values were determined in the laboratory using a standard divided-bar apparatus following the procedures described by Sass et al. (1971). Porosity logs were not available for the chip samples so values of porosity were estimated at 15% for limestones, dolomites, and shales while a value of 25% porosity was used for sandstones. These values represent the median values for the porosity range of similar rocks described by Davis (1969). Deviations of 20–30% from these values have a negligible effect on the measured conductivities.

Thermal conductivity values for all cutting samples were averaged to a harmonic mean over the interval for which geothermal gradients were determined. Cutting samples were unavailable for several of the logged boreholes. Conductivity measurements for those sites were determined from the harmonic mean conductivity of representative samples from nearby boreholes which penetrated the same lithologies. Heat flow was computed by interval or least-squares methods for those boreholes where discrete temperature and thermal conductivity measurements were available. Otherwise, the heat flow estimates were computed from the product of mean harmonic conductivities and geothermal gradients computed from bottom-hole temperatures. We assign an accuracy of ±15% to the heat flow values from boreholes where temperature and thermal conductivity measurements were made at discrete intervals. The remaining heat flow values are assigned an accuracy ±20% (based on standard error of the mean for each heat flow province discussed below).

Discussion

Figure 2 depicts the distribution of all heat flow values for the Ozark Dome and surrounding regions. The values range from a low of 9 mW m^{-2} determined in a shallow (137 m) borehole in north-central Arkansas to over 80 mW m^{-2} in west-central Missouri. The average of all 56 borehole measurements and estimates from within the Ozark Dome sedimentary sequence is 27 mW m^{-2} (±4 SEM). The average heat flow for the ten measurements and estimates within the St. Francois Mountains igneous complex is 47 mW m^{-2} (±4 SEM). The average heat flow for the surrounding regions (excluding the Mississippi Embayment area) is 40 mW m^{-2} (±7 SEM). Two relatively anomalous values (Winslow, Arkansas and Rolla, Missouri) may not be representative due to drilling effects (Winslow, Arkansas) and an inability to duplicate measured values (Rolla, Missouri). The overall average of 27 mW m^{-2}, however, is significantly less than the 10-value average of 47 mW m^{-2} determined in the exposed igneous rocks of the St. Francois Mountains. The heat flow from the St. Francois Mountains is comparable to the average heat flow of 44 mW m^{-2} for Proterozoic terrains worldwide (Sclater et al., 1980).

Anomalously low heat flow also occurs in other regions in the Central and Southeastern United States. The Black Warrior Basin of northern Mississippi and the southern part of the Valley and Ridge province in Tennessee (Smith et al., 1981; Smith and Dees, 1982) both are characterized by heat flow values averaging less than 30 mW m^{-2}. While these values have been attributed to the blanketing effects of great thicknesses of sedimentary rocks, or to tectonically-related crustal variations, the

TABLE 1

Locations, gradients, conductivities, heat flow for all directly measured boreholes

Location	Lat/Long	Depth range (m)	Gradient ($K\ km^{-1}$)	Conductivity ($W\ m^{-1}\ K^{-1}$)	Heat flow ($mW\ m^{-2}$)
Fayetville Arkansas	36.117 N 94.007 W	120–195	17.9	1.64 (n=7)	29
Elkins Arkansas	36.014 N 93.952 W	100–215	20.4	1.52 (n=8)	31
Prairie Grove Arkansas	35.983 N 93.300 W	40–573	12.5	1.42 (n=14)	18
Bull Shoals Arkansas	36.383 N 92.600 W	20–137	4.0	2.20 (n=5)	9
Leslie Arkansas	35.817 N 92.567 W	30–1061	11.4	2.12 (n=27)	24
Green Forest Arkansas	36.318 N 93.433 W	40–175	11.3	2.18 (n=20)	25
Winslow Arkansas	35.820 N 94.172 W	30–300	33.2	1.85 (n=13)	61
Fredericktown Missouri	37.541 N 90.302 W	40–160	10.2	2.38 (n=9)	24
Joplin Missouri	37.118 N 94.367 W	60–380	13.6	2.22 (n=21)	30
Winona Missouri	37.030 N 91.333 W	60–260	14.2	2.45 (n=12)	34
West Plains Missouri	36.758 N 91.850 W	220–380	9.0	2.69 (n=17)	24
Rolla Missouri	37.933 N 91.756 W	40–160	25.7	2.21 (n=9)	57

(Note n is number of samples used to calculate harmonic mean).

relatively low heat flow in the Ozark Dome requires an alternative explanation. The thickness of the sedimentary rock sequence does not exceed 500 m and although the underlying crust has been the subject of proposed epeirogenic activity (Kisvarsanyi, 1980), no significant deformation or intrusive activity has occurred during the Phanerozoic.

Measurements at ten sites in the St. Francois Mountains yield an average geothermal gradient of 15 K km^{-1} ($\pm$1.3 SEM) and a corresponding average heat flux of 47 mW m^{-2}. These values are characteristic of thermal conditions for terrains with similar ages. Malan (1972) reported the results of gamma-ray analyses for uranium, thorium, and radioactive potassium in 76 igneous rock samples from the St. Francois Mountains. Table 2 summarizes those data and the calculated heat production values (average 2.4 μW m^{-3}) using the heat generation relationship given in Rybach (1973). Although the heat flow/heat production relationship has been called into question (Furlong and Chapman, 1987), these average values of heat flow and heat production plot near the relationship proposed by Roy et al.

TABLE 2

Heat production values

Sample name	#	U (ppm)	Th (ppm)	K (%)	$\mu W\ m^{-3}$
Plutonic rocks					
Slabtown Gr.	3	3.60	8.10	3.40	1.84
Graniteville Gr.	4	13.70	41.70	4.30	6.95
Carver Creek Gr.	4	4.20	15.40	4.70	2.64
Munger Gr.	4	5.10	10.10	4.80	2.51
Breadtray Gr.	3	6.40	22.50	5.00	3.75
Butler Hill Gr.	3	7.40	24.00	4.40	4.06
Silvermine Gr.	3	2.50	6.80	3.80	1.50
Knoblick Gr.	3	2.50	7.10	3.00	1.45
Weighted average	27	5.90	17.60	4.20	3.19
Average	8	5.70	16.90	4.30	3.12
Volcanic rocks					
Sample #680	3	3.10	7.60	6.30	1.95
Sample #720	3	2.70	6.80	3.50	1.54
Sample #740	2	1.20	10.10	4.40	1.45
Sample #760	6	3.10	10.80	3.90	1.95
Sample #770	6	3.20	10.50	4.00	1.96
Sample #790	2	5.30	16.60	6.10	3.14
Sample #810	2	3.00	13.20	5.60	2.25
Sample #810a	7	3.60	13.80	6.50	2.54
Sample #815	3	2.70	6.20	3.00	1.44
Sample #845	3	1.80	6.20	2.50	1.15
Sample #850	3	1.80	6.20	2.50	1.15
Stouts Creek	3	4.60	10.50	6.20	2.54
Keterside Tuff	1	1.10	4.40	2.50	0.84
Undifferentiated	1	4.90	14.90	4.10	2.73
Weighted average	49	3.10	10.10	4.50	1.96
Average	14	3.00	9.80	4.40	1.90
Combined average	76	4.09	12.76	4.39	2.40

Abundances taken from Malan (1971)

(1968a,b) for the Eastern United States heat flow province. Following the concept that the St. Francois Mountains represent the igneous basement under the Ozark Dome, it becomes reasonable to expect similar geothermal conditions for the basement throughout the Ozarks. Therefore, the heat flow observed in the St. Francois Mountains also is ascribed as that entering the base of the overlying sedimentary cover forming the Ozark Dome.

The anomalously low heat flow value (40% lower) which characterizes the Ozark Dome is related to anomalously low geothermal gradients (averaging 11 K km^{-1} $\pm$1.0 SEM). The average thermal conductivity of the sedimentary rocks is also lower than the average thermal conductivity of the igneous rocks in the St. Francois Mountains (2.4 W m^{-1} K^{-1} to 3.25 W m^{-1} K^{-1}) such that one would expect gradients within the sedimentary sequence to average 20 K km^{-1} if thermal conditions have reached steady-state. Figure 5a is a three-dimensional surface plot of thermal gradient values showing the low trough associated with the central Ozarks (OGL=Ozark Geothermal Low). Normal gradient values flank the central Ozarks to the southwest and north while higher gradients characterize the northern Mississippi Valley to the southeast. The St. Francois Mountains appear as an isolated positive projection in both the gradient and heat flow 3-D images (Fig. 5a,b). The obvious implication of these data is that heat loss occurs within the sedimentary sequence of the Ozark Dome, and the most logical mechanism is heat absorption and conveyance by hydrologic activity.

High groundwater flow rates (as fast as 1500 m d^{-1}) in the primarily carbonate units comprising the Ozark Dome are well documented (Robertson, 1963; Feder, 1983). Chemical analyses of the groundwaters in the Ozark Dome indicate a low concentration of total dissolved solids (TDS) typical of groundwater recharge areas and/or zones of rapid water movement (Fetter, 1980). Although local variations in secondary porosities and flow rates are high (Feder, 1983), the transmissivities of the aquifers within the Ozarks are a reasonable indicator of hydrologic activity. Figure 5c shows a three-dimensional surface representation of aquifer transmissivities within the Ozark region of Missouri (data were not available from Arkansas).

Within the Ozark Dome areas of high transmissivity, low total dissolved solids and cool spring temperatures correlate with those regions where geothermal gradients are low. Local flow systems, which are independent of the

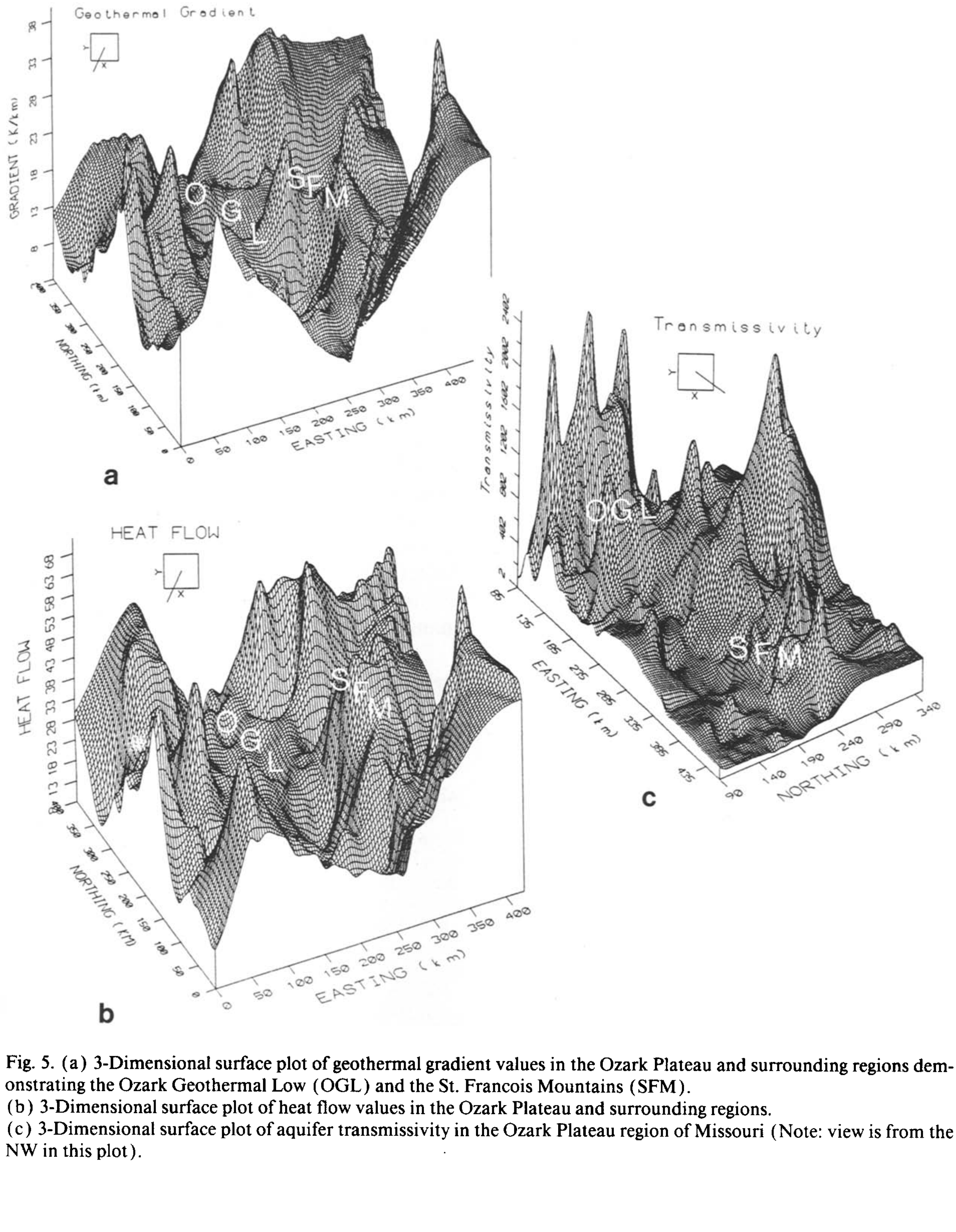

Fig. 5. (a) 3-Dimensional surface plot of geothermal gradient values in the Ozark Plateau and surrounding regions demonstrating the Ozark Geothermal Low (OGL) and the St. Francois Mountains (SFM).
(b) 3-Dimensional surface plot of heat flow values in the Ozark Plateau and surrounding regions.
(c) 3-Dimensional surface plot of aquifer transmissivity in the Ozark Plateau region of Missouri (Note: view is from the NW in this plot).

regional flow may account for those areas where no correlation exists. Areas of higher geothermal gradients (e.g. St Francois Mountains and Ozark border provinces) are characterized by either lower transmissivity and less prolific flow rates, or groundwater discharge and high TDS, or both. Thus, a heat loss in the central part of the Ozark Plateau can be attributed to the effects of regional groundwater flow within the sedimentary cover.

Mathematical models of groundwater advective disturbances in continental heat flow determinations have been developed on different scales for a variety of tectonic settings (for examples see Kilty and Chapman, 1982; Majorowicz et al., 1985; Gosnold and Fischer, 1986; Forster and Smith, 1989; Smith et al., 1989). These models have effectively demonstrated the role of groundwater flow in regions of non-conservative vertical heat flow. However, it is not always necessary to model the effects of these disturbances when hydrogeologic conditions provide the evidence for advective disturbances along clear boundaries (here the sedimentary–igneous interface) in a recharge area. These models may place quantitative constraints on the total amount of advective disturbance but are not required, in all cases, to explain the observed heat flow anomalies. We are currently attempting to model the Ozark Plateau thermal and hydrologic regimes to demonstrate these effects (Meert et al., in prep.); however, the qualitative evidence in favor of groundwater advective disturbances within the sedimentary sequence of the Ozark Plateau is equally compelling.

Conclusions

Heat flow in the Ozark Plateau region of Arkansas and Missouri can be broadly classified into two regions. The average flux in the St. Francois Mountains is 47 mW m^{-2} and is consistent with heat flow values for terrains with similar ages. The thermal regime in the St. Francois Mountains is ascribed to the base of the Ozark Plateau sedimentary sequence. The heat flow in the sedimentary sequence therefore is anomalously low and averages 27 mW m^{-2}. This non-conservative vertical heat flow regime can be explained by groundwater advective disturbances above the igneous–sedimentary rock interface in the Ozark Dome.

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