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Terrestrial Heat Flow in the Brazilian Highlands

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We report heat flow measurements from 84 boreholes and one underground mine at 19 widely spaced sites in eastern and central parts of Brazil. Three sites in the stable São Francisco Craton comprising rocks with Transamazonic ages (2600–1800 Ma) or older present an average heat flow of 42 ± 5 (sem (standard error of the mean)) mW m^{-2}, eight sites located in the Late Precambrian Braziliane metamorphic belt have an average heat flow of 55 ± 4 (sem) mW m^{-2}, and three sites in the Paraná basin, locus of Late Jurassic–Early Cretaceous basaltic volcanicity, have a mean heat flow of 68 ± 6 (sem) mW m^{-2}. Heat flow results from the Late Cretaceous–Early Tertiary alkalic intrusion of Poços de Caldas have yielded a site mean of 55 mW m^{-2}, comparable to results obtained from the Braziliane belt into which the alkalic plug has intruded. Four other sites yielded results of lesser quality and are not included in the above means. The age-grouped means show a systematic decrease of heat flow with increasing time since the last tectonothermal event, in agreement with global data for terrains of similar age elsewhere. Heat production measurements of aggregate samples reflect the variability of the rock types, ranging from the ultramafics with characteristic low heat generation (<0.1 μW m^{-3}) to the alkalic rocks with very high heat generation (>20 μW m^{-3}). Radio isotope concentrations of the surface rocks at several sites are thought not to be representative of the crustal distribution. A best fitting line to four acceptable heat flow–heat production pairs from metamorphic terrains of the Brazilian Coastal Shield tentatively defines a heat flow province with a reduced heat flow of 28 ± 7 mW m^{-2} and a slope (depth distribution parameter) of 13 ± 2 km, both within the range found in other shield areas, although the slope of 13 km is among the largest reported for heat flow provinces. Thus the Brazilian shield is characterized by surface and reduced heat flow not unlike other shields, but its heat production appears to be less concentrated near the surface and distributed over a greater depth.

INTRODUCTION

We report 19 new heat flow and heat production measurements in the Precambrian shields and the Phanerozoic Paraná sedimentary basin of Brazil. The area under investigation, comprising the eastern and central parts of Brazil, is situated approximately in the middle of the South American Plate, well removed from the present-day plate boundaries, the Mid-Atlantic Ridge to the east and the Andean subduction zone to the west.

Most of the South American continent east of the Andean orogenic belt appears to be an extensive platform whose folded basement was stabilized during the Precambrian, after a succession of remobilization events [*Almeida et al.*, 1973; *Cordani et al.*, 1973]. The field measurements were carried out in 1975 and 1976, in 'holes of opportunity,' i.e., boreholes drilled for mineral exploration purposes and not sited specifically as geothermal investigation holes. However, the widespread drilling activity in Brazil has permitted measurements in several different tectonic elements of the South American continent.

HEAT FLOW MEASUREMENTS

Temperature Gradients

Temperature survey attempts in several hundred surface and underground boreholes yielded more than 80 geothermal gradients. The boreholes have been grouped into 19 sites according to geologic and geographic setting, each site having from 1 to 20 boreholes. A list of the heat flow sites along with tectonic or stratigraphic age and characteristic rock type ordered by latitude is found in Table 1, and the locations are indicated in Figure 1. Some sites have several boreholes separated by as much as 30 km, whereas a few consist of only a single borehole. Consequently, Table 1 shows only approximate coordinates, average elevation, and the most representative rock type for sites comprising more than one borehole. Detailed summaries of individual boreholes can be found in the work of *Vitorello* [1978]. The given ages correspond to the tectonic age range obtained from the *Tectonic Map of Brazil* [1971]. Paraná basin sites show ages of the outcropping formations.

The subsurface temperature field can be visualized best from temperature versus depth profiles (geotherms). Figure 2 shows a representative geotherm of every site listed in Table 1, with the exceptions of Nova Lima (site 10), where the profile extends below 2000 m, and of Vazante (site 9), whose geotherms were virtually coincident with those from Morro Agudo (site 8). The geotherms from the Paraná basin plot over the geotherms from the Precambrian shield, and therefore a comprehensible display of the data dictated their separation into two groups: representative geotherms principally from the Precambrian shield are plotted on the right of Figure 2, whereas those from the Paraná basin are plotted on the left.

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TABLE 1. List of the Heat Flow Sites in Brazil

Site Number	Location (State)	South Latitude	West Longitude	Tectonic Age, Ma	Rock Type	Mean Elevation, m	N
1	Currais Novos (RN)	6°20′	36°35′	900–550	paragneisses	315	5
2	Caraíba-Poço de Fora (BA)	9°50′	39°51′	2600–1800	granulites and ultramafics	455	20
3	Jacobina (BA)	11°15′	40°30′	2600–1800	quartzites	800–900	11
4	Arraial (BA)	12°30′	42°50′	2600–1800	biotite schists	600	2
5	Cana Brava (GO)	13°32′	48°14′	900–550	serpentinites	405	3
6	Niquelândia (GO)	14°13′	48°18′	900–550	mafic and ultramafics	570	2
7	Americano do Brasil (GO)	16°14′	50°05′	900–550	mafic and ultramafics	230	2
8	Morro Agudo (MG)	17°30′	46°50′	900–550	dolomites	580	5
9	Vazante (MG)	18°00′	46°45′	900–550	dolomites	650	1
10	Nova Lima (MG)	19°59′	43°51′	900–550	schists	750–800	UM
11	Bico de Pedra (MG)	20°26′	43°36′	900–550	paragneisses, quartzites	1410	1
12	Cachoeira do Itapemerim (ES)	20°51′	41°06′	900–550	dolomites	326	1
13	Poços de Caldas (MG)	21°48′	46°35′	80–63	alkaline intrusion	1200–1300	9
14	São Paulo (SP)	23°40′	46°40′	900–550	mica schist	800	2
15	State of São Paulo	22°00′	48°30′	Cretaceous	basalt	400–600	4
16	Figueira-Curiúva (PR)	24°00′	50°25′	Permian	shales and siltstones	500–800	5
17	Papanduva-Taió (SC)	26°40′	50°05′	Permian	shales and sandstones	600–800	3
18	Araranguá-Lauro Müller (SC)	28°40′	49°20′	Permian	shales and siltstones	0–250	2
19	Butiá-Rio Pardo (RS)	30°00′	52°30′	Permian	shales and siltstones	20–60	6

N, number of boreholes that yielded reasonable geothermal gradients; UM, underground mine; RN, Rio Grande do Norte; BA, Bahia; GO, Goiás; MG, Minas Gerais; ES, Espírito Santo; SP, São Paulo; PR, Paraná; SC, Santa Catarina; RS, Rio Grande do Sul.

Average geothermal gradients from Precambrian sites (14.5 K km^{-1}) and from Paraná basin sites (28.0 K km^{-1}) have been inserted in the lower portion of the figure to facilitate visual comparisons. The younger Poços de Caldas intrusion into the shield area (site 13) has notably higher gradients, comparable to the ones from the Paraná basin.

The hydrologically disturbed near-surface portions of the geotherms are not shown. The small departures from a straight line observed in several of the geotherms are usually caused by a combination of natural and artificial effects that must be evaluated to enable a proper interpretation of the profile. The major effects include variation in lithology, and hence of conductivity with depth, surface temperature fluctuations, subsurface heat sources and sinks, and structural and topographic perturbations. The effects of lithological variation are easily assessed from the thermal conductivity values; however, the effects of perturbations arising from other causes are more difficult to evaluate. Lack of necessary information on the paleoclimatic and erosional history of areas under investigation precluded the calculation of meaningful corrections for these effects, if any are indeed needed. Most of the sites in Brazil are located in areas of subdued relief, where the disturbance due to the topography is probably constrained to the upper 100-m depth. Topographic corrections in areas of significant relief, such as Jacobina (site 3) and Poços de Caldas (site 13), require an accurate representation of the topographic surface of an area extending to several kilometers around the site and also of the temperatures on such surfaces, neither of which were available to the writers.

The drilling operation also disturbs the borehole temperature profile to the extent that a time lapse of several days is required for the rock temperature to return to its undisturbed value. However, in cases in which the borehole was still thermally disturbed, a series of consecutive measurements were made at several time intervals so that the decaying temperature disturbance could be extrapolated to its equilibrium position, in the manner suggested by *Lachenbruch and Brewer* [1959]. Corrections were also applied to temperature measurements in horizontal boreholes within the underground gold

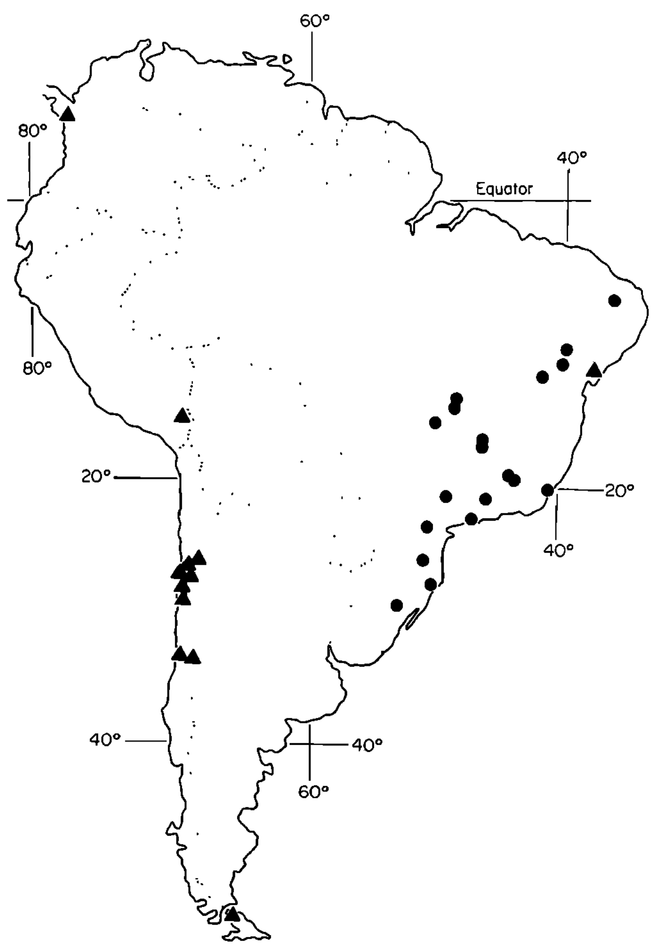

Fig. 1. Heat flow sites in South America. Circles indicate sites of 19 new measurements in eastern and central Brazil reported herein. Triangles indicate sites of other previously published heat flow measurements.

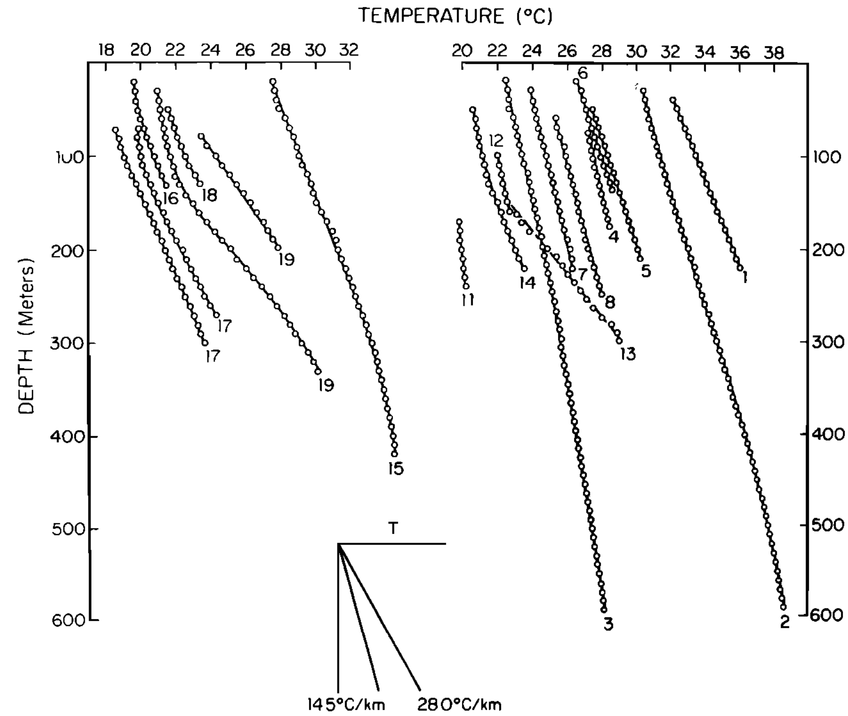

Fig. 2. Representative temperature versus depth (below local surface) profiles of sites located in Precambrian terrains (right side), Paraná basin (left side) and Poços de Caldas (13). The profiles are identified by numbers corresponding to the sites listed in Table 1. Average geothermal gradients of Precambrian sites (14.5 K/km) and of Paraná basin (28.0 K/km) are shown at bottom.

mine of Nova Lima, because of disturbances caused by artificial cooling of the main galleries.

Routinely, the measurements from shallow boreholes within the Paraná basin were carefully examined for possible hydrological disturbances because the several intercalated aquifers, basinal structure, and high annual rainfall provide an ideal setting for large-scale water movements.

Meister [1973] has also assembled geothermal gradient data from over 500 petroleum boreholes in 15 sedimentary basins of Brazil. These results offer a first look at the thermal state of the Brazilian sedimentary basins, but their usefulness is also limited because no thermal conductivity measurements accompany the gradient estimates and because the bottom hole temperatures used in the study apparently were not corrected for the drilling disturbances (i.e., no explicit mention of such corrections was made by the author). According to his com-

TABLE 2. Summary of the Heat Flow Data From Brazil

Site	N	Depth Range, m	n	k, W/mK	dT/dz, K/km	$q \pm$ sem, mW/m^2
1, Currais Novos	5	10–289	35	2.87	23.9	69 ± 7
2, Caraíba-Poço de Fora	20	30–590	70	2.79	13.6	37 ± 4
3, Jacobina	11	7–591	32	6.95	7.2	51 ± 12
4, Arraial	2	80–179	20	3.45	10.8	38 ± 4
5, Cana Brava	3	30–224	23	2.62	18.1	48 ± 3
6, Niquelândia	2	30–138	10	3.55	17.6	63 ± 3
7, Americano	2	30–230	32	2.55	15.0	38 ± 5
8, Morro Agudo	5	10–248	29	4.46	11.7	52 ± 7
9, Vazante	1	20–278	13	3.09	14.8	46 ± 6
10, Nova Lima	UM	0–2180	28	3.84	14.6	56 ± 4
11, Bico de Pedra	1	190–240	8	3.40	(6.8)	(23 ± 16)
12, Cachoeira	1	110–160	7	2.28	(11.5)	(26 ± 4)
13, Poços de Caldas	9	40–308	126	2.11	27.7	55 ± 7
14, São Paulo	2	130–230	18*	3.02	22.0	66 ± 3
15, State of São Paulo	4	60–320	8	1.70	(21.0)	(36 ± 5)
16, Figueira	5	20–160	10	2.38	22.0	52 ± 11
17, Papanduva-Taió	3	50–300	40	3.09	24.1	75 ± 7
18, Araranguá	2	80–166		(2.85)	26.7	(76 ± 8)
19, Butiá-Rio Pardo	6	20–330	19†	2.75	28.1	77 ± 15

N, number of boreholes; n, total number of thermal conductivity specimens; k, harmonic mean conductivity of all site specimens; dT/dz, weighted mean least squares temperature gradient; q, weighted mean heat flow; sem, standard error of the weighted mean; UM, underground mine. Estimated conductivity, or poor quality gradient, is shown in parentheses.

* Conductivity measurements on rock fragments.

† Conductivity measurements on discs and rock fragments.

pilation, average gradients in Mesozoic coastal grabens associated with the breakup of the Gondwana supercontinent are the highest in Brazil, ranging from 19 to 25 K km^{-1}. The older Paleozoic intracratonic basins reveal an average range of 17–21 K km^{-1}. These reported mean geothermal gradients for the Paraná basin, 17 K km^{-1} for 39 petroleum boreholes by *Meister* [1973] and 16 K km^{-1} for three petroleum sites by *Uyeda and Watanabe* [1970], are lower than the gradients reported here (see Table 2 and Figure 3). The earlier measurements were drawn from a wider area and from deeper levels than those that we report; the average depth is 2200 m, and many of them reach the basement rocks below the basin. However, bottom hole temperatures taken in deep boreholes during or shortly after drilling tend to be lower than the virgin rock temperature owing to the cooling effect of large amounts of drilling fluid used in rotary drilling [*Dowdle and Cobb,* 1975]. The effect of the fluid heat exchange in holes of this depth is to warm the top of the hole while cooling the bottom. Investigations elsewhere have shown the bottom hole temperatures to be reduced 10–100 K from the virgin rock temperature [*Raymond,* 1969; *Holmes and Swift,* 1970]. The drilling disturbance is a likely source for the apparent discrepancy between the estimates of gradients by Meister and those reported here. A second explanation may be that the mean thermal conductivity of the deeper sediments is greater than that of the shallow sedimentary rock samples of this study.

Thermal Conductivity

Most of the measurements of thermal conductivity for this project were made on rock discs in a divided-bar apparatus of the type described by *Birch* [1950] but with several modifications described by *Sass et al.* [1971]. The rock discs were presaturated with water, and the conductivity measurement was obtained at the in situ temperature of the sample. For boreholes where only drill cuttings were available, thermal conductivity determinations were obtained from a divided-bar measurement of a cylindrical cell containing water-saturated rock fragments, following the method outlined by *Sass et al.* [1971]. The harmonic mean conductivity of all specimens from each site is given in Table 2.

Heat Flow

The vertical component of heat flow q for each borehole has been calculated from the steady state, one-dimensional relation $q = k\, dT/dz$. The summarized heat flow data of Table 2 show the weighted least squares temperature gradient and weighted mean heat flow of each site, both calculated with the use of the reciprocal of the standard errors of the individual borehole values as weighting factors [*Beers,* 1962, p. 37]. The listed heat flow uncertainty corresponds to the standard errors of the weighted mean heat flow values. For each borehole the standard error of the mean combines the errors in the determinations of the temperature gradient and conductivity.

When the fluctuations in conductivity and temperature gradient are more frequent, or the depth interval of the fluctuation is ill defined, the heat flow can be estimated from the slope of the following linear relation [*Bullard,* 1939]: $T = T_0 + q\sum(1/k)\, dz$.

This method also provides an opportunity to detect disturbing effects, such as water circulation, undetected uplift or erosion, climatic changes, and others. Plots of temperature versus summed thermal resistance are shown in Figure 3 for several boreholes. Calculations were also performed routinely for sequential 20- or 30-m depth intervals throughout the borehole to check for serious temperature fluctuations not accounted for by the variations in the conductivities of the available samples. Differences in heat flow at a given site arising from the different methods of calculation described above were usually less than 5%.

The heat flow mean for each site is shown in Table 2 and in Figure 4. The values within parentheses should be treated as only fair estimates, because of too few gradients or insufficient conductivity measurements. The heat flow from Bico de Pedra (site 11) was calculated from a gradient obtained in a depth interval of only 50 m, above which the temperature profile suggests a strong thermal disturbance, possibly by water circulation. The value from Cachoeira (site 12) likewise was calculated from a depth interval of 50 m, with the upper section of the borehole being apparently disturbed by a possible surface warming due to the development of various open pit mines. The gradients utilized in the calculation of the heat flux for

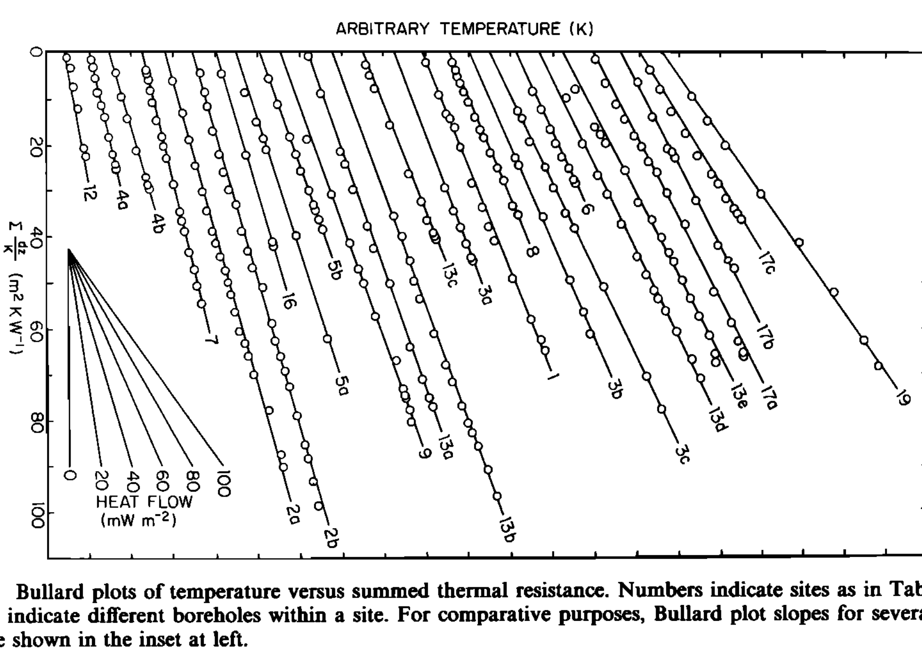

Fig. 3. Bullard plots of temperature versus summed thermal resistance. Numbers indicate sites as in Table 1, letters following indicate different boreholes within a site. For comparative purposes, Bullard plot slopes for several heat flow values are shown in the inset at left.

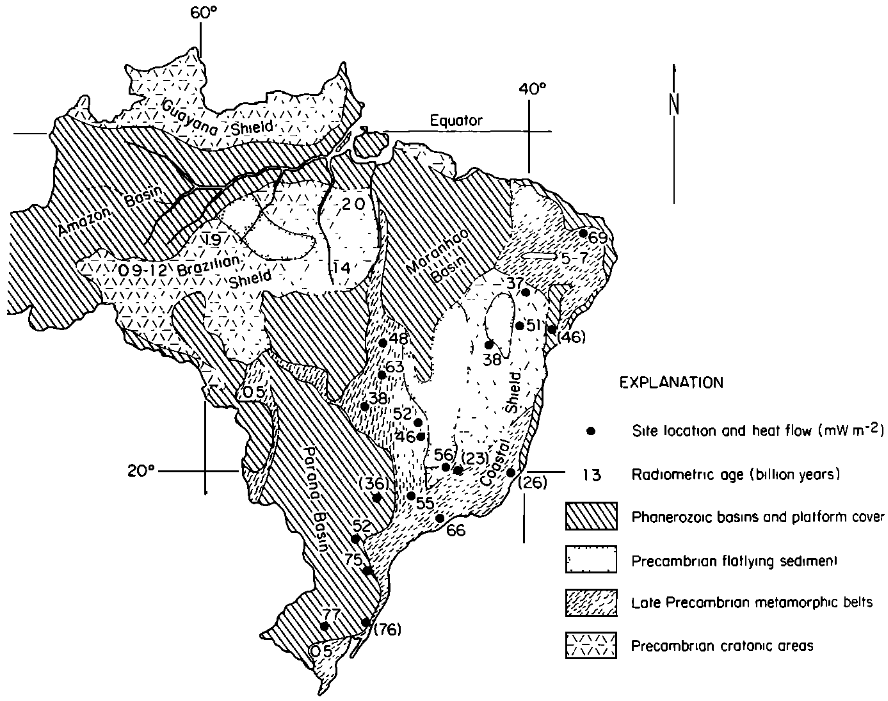

Fig. 4. Generalized tectonic map of Brazil showing geothermal measurement sites and corresponding heat flow results (in milliwatts per square meter). The heat flow of 46 mW m^{-2} by *Carvalho and Vacquier* [1977] in the Recôncavo basin of easternmost Brazil is also included. Heat flow values in parentheses represent determinations based on estimated thermal conductivities or low-quality temperature gradient.

the boreholes within the state of São Paulo (site 15) come from the basalts of the Serra Geral Formation. The basalts overlie the sandstones of the Botucatu Formation, a major aquifer within the Paraná basin, which is nearly isothermal in places, indicating a hydrological disturbance.

Radiogenic Heat Production

Measurements of the radiogenic heat production of near-surface rocks within the area where heat flow measurements have been made are essential for an estimate of the amount that near-surface sources contribute to the regional variation of surface heat flow. After the separation of the radiogenic contribution of the enriched crustal layers, one is able to estimate the heat flux originating from other sources deeper in the earth, an important parameter for thermal models of the earth's interior.

Therefore the interpretation of the heat flow data gathered in Brazil requires the knowledge of the crustal distribution of the radioactive elements ^{238}U, ^{235}U, ^{232}Th, and ^{40}K, since the natural decay of these isotopes is the predominant source of heat within the lithosphere.

In this study, abundances of the radioelements in the samples have been determined by the gamma ray method and were transformed into heat production according to the extensively used relation given by *Birch* [1954]: $A_0 = 10^{-5}\rho(9.69U + 2.65Th + 3.58K)$, where A_0 is heat production in microwatts per cubic meter, ρ is density in kilograms per cubic meter, U and Th are uranium and thorium concentrations in parts per million, and K is potassium content in percent. The samples analyzed were aggregates produced from several consecutive specimens collected at regular intervals along the drill core. Samples from outcroppings were not utilized. A uniform value of 2670 kg m^{-3} was assumed for the density, since the bulk of the samples consists of granitic gneisses and mica schists. Radioelement abundances from the higher-density mafic and ultramafic rocks (Cana Brava, Niquelândia, Americano do Brasil) were below the detection levels of the apparatus used. The results are summarized in Table 3.

Discussion of Heat Flow and Heat Production Results

The variation in heat production of the Brazilian samples is closely associated with rock type, ranging from the low heat generation (<0.1 μW m^{-3}) of the ultramafic complexes of central Brazil (Niquelândia, Cana Brava, Americano) to the very high heat generation (>28 μW m^{-3}) of the alkalic intrusion of Poços de Caldas. Most of the remaining sites, excluding results from sedimentary rocks of the Paraná basin, are represented by metamorphic rocks of relatively low radiogenic content. This observation reflects the fact that the Brazilian Coastal Shield is characterized by the predominance of metamorphosed rocks such as gneisses and granulites and some basic rocks such as amphibolites and gabbros. Several investigators have presented evidence of low radiogenic values in high-grade metamorphic terrains [*Heier and Adams,* 1965; *Lambert and Heier,* 1968; *Smithson and Heier,* 1971]. Moreover, the relatively low radioelement content is often attributed to partial loss of a melt phase during metamorphism or dehydration processes. The Caraíba–Poco de Fora site, in particular, is extremely depleted in uranium. The additional fact that Th/U ratios for samples from this site are very high suggests a loss of U relative to Th.

The analyzed sedimentary rocks of the Paraná basin, mostly Permian shales, show values that are comparable to values compiled by *Clark et al.* [1966] for common shales. The heat production of the sediments (sandstones, siltstones, dark

TABLE 3. Radioactive Element Abundance and Heat Production at Each Site

Site	n	Thorium, ppm ± s.d.	Uranium, ppm ± s.d.	Potassium, % ± s.d.	A_0, μW m^{-3} ± s.d.
1, Currais Novos	22	21.1 ± 13	5.9 ± 5.5	2.4 ± 1.6	3.3 ± 2.1
2, Caraíba-Poço de Fora	10	7.5 ± 5	0.2 ± 0.4	1.8 ± 0.5	0.8 ± 0.4
3, Jacobina:					
metasediments	2	4.9	2.0	0.3	0.9
gneisses (basement)	2	15.0	0.4	4.6	1.6
4, Arraial	4	8.7 ± 1	3.9 ± 0.1	4.2 ± 0.1	2.0 ± 0.1
8, Morro Agudo	1	4.8	1.1	2.2	0.9
9, Vazante	2	8.6	1.1	2.5	1.1
10, Nova Lima	17	4.4 ± 2	1.0 ± 0.4	1.0 ± 0.6	0.7 ± 0.3
11, Bico de Pedra	2	4.0	0.9	2.4	0.7
12, Cachoeira do Itapemerim	1	BDL	1.0	0.9	0.3
13, Poços de Caldas	8	105.1 ± 65	79.1 ± 103	8.1 ± 2.0	28.8 ± 31
14, São Paulo	18	18.1 ± 5	4.5 ± 2.1	2.9 ± 0.4	2.7 ± 0.8
16, Figueira-Curiúva	3	16.3 ± 1	14.7 ± 0.2	1.7 ± 0.1	3.8 ± 1.8
17, Papanduva-Taió	3	9.7 ± 2	1.9 ± 0.6	1.9 ± 0.2	1.3 ± 0.3
19, Butiá-Rio Pardo	4	14.5 ± 2	3.1 ± 1.2	2.1 ± 0.7	2.0 ± 0.5

n, number of specimens; s.d., standard deviation; A_0, radiogenic heat production; BDL; below detection level. Specimens from Niquelândia, Cana Brava, and Americano do Brasil (sites 5, 6, and 7) indicated radioelement content BDL.

shales) from Figueira-Curiúva (site 16) is, however, similar to enriched granites and about twice as large as the other two sites (17 and 19) in the Paraná basin.

Figure 5 shows a heat flow–heat generation graph exclusive of the sites located in the Paraná basin and Poços de Caldas, since the heat production of the sediments of the Paraná basin or the enriched alkalic pipe cannot be considered representative of the basement rock below or surrounding the sites. A linear relationship of the form $q_0 = q_r + bA_0$ is not clear cut. Here q_0 is the surface heat flow, A_0 is the heat production of the surface rocks, q_r is the 'reduced' heat flow (the heat flow intercept for zero heat production), and the slope b is a quantity with dimension of depth that characterizes the vertical heat source distribution [*Roy et al.*, 1968]. However, upon closer examination of the individual site values, a case for a

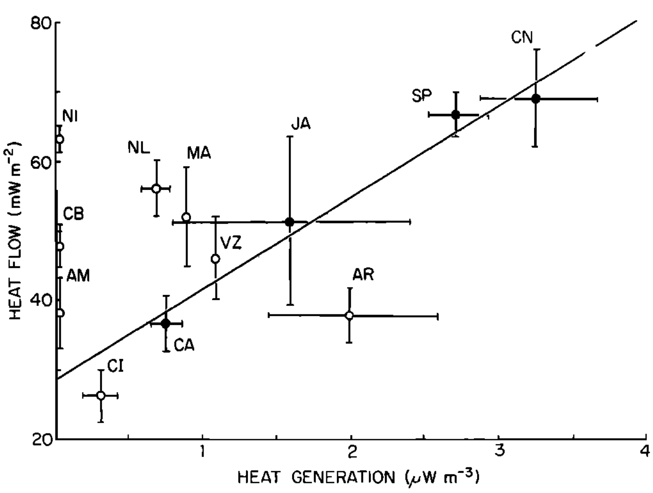

Fig. 5. Heat flow and heat generation results at individual sites. (Vertical and horizontal bars correspond to the standard error of the means.) Open circles correspond to heat production values that cannot be considered representative of the basement rocks below or surrounding the sites. The linear relationship obtained from four sites (solid circles: CN, Currais Novos; SP, São Paulo; JA, Jacobina; CA, Caraíba) has a slope of 13.1 ± 1.5 km and an intercept (reduced heat flow) of 28.3 ± 7.0 mW m^{-2}. The other sites are AR, Arraial; CI, Cachoeira do Itapemerim; VZ, Vazante; MA, Morro Agudo; NL, Nova Lima; NI, Niquelândia; CB, Cana Brava; and AM, Americano do Brasil.

linear relationship can be made. At this point a short digression will be useful to explore some details of the heat flow–heat production relationship.

Occasionally, a thin surface layer of anomalously low or high radiogenic content will yield values of q_0 and A_0 that do not conform to the heat flow–heat production relationship, since the surface heat flow will probably be characterized by the radiogenic content of the material beneath [*Hyndman et al.*, 1968]. A good illustration comes from studies by *Sass et al.* [1972] in the Ilímaussaq alkali intrusion in the Greenland shield, where the low heat flow values obtained at the surface are inconsistent with the high heat generation values obtained from the surface rocks. In Brazil the extremely high radioelement content in rocks of Poços de Caldas, comparable with similar alkalic intrusions elsewhere, is also inconsistent with the measured heat flow, much like the Ilímaussaq intrusion of Greenland. Sedimentary basins composed of clastics and carbonates poor in radioelement content, basaltic flows, and obducted ophiolite complexes are good examples of shallow structures overlying deeper rocks that have the characteristic radiogenic heat production of the area. An example is provided by heat flow measurements in boreholes of a greenstone belt in the Kalgoorlie region of western Australia. The low heat generation obtained in mafic rocks was found to be inconsistent with the relatively high heat flow measured at the surface, providing support to an interpretation of gravity data that suggested a shallow structure for the greenstones of that area [*Jaeger*, 1970]. Thus the heat flow results from the sites located in the serpentinite-ultramafic bodies of central Brazil (Niquelandia, Cana Brava, Americano do Brasil) can be explained by a richer radioactive crust underlying the ultramafic bodies, at least beneath the area of measurements. At present there is no firm geological or geophysical evidence to demonstrate that these ultramafics are obducted ophiolites, but if they are, the surface heat flow could be explained by a radiogenic contribution from an underlying gneissic basement.

Likewise, the heat production of calcareous Precambrian sediments from the Morro Agudo, Vazante, and Cachoeira do Itapemerim sites should not be considered representative of the basement below. Heat generation in quartz-biotite-schists and dolomites from boreholes of Arraial, a narrow mineralized metasedimentary zone within cratonic basement, are possibly not representative of the granulites and gneisses of the basement either. At this site, deposition of the ore minerals, probably by hydrothermal solutions [*Johnson*, 1962], may well have been accompanied by deposition of radioelements.

Thus there remain four sites (Currais Novos, São Paulo, Jacobina, and Caraíba) that could conform to the heat flow–heat production relationship, if indeed one exists in the Brazilian highlands. A best fitting line through these four sites provides a reduced heat flow (intercept) of 28.3 ± 7 (s.d.) mW m^{-2} and a depth parameter (slope) of 13.1 ± 2 (s.d.) km. The number of boreholes and heat generation measurements for these sites are: Currais Novos, 5 boreholes and 22 samples; São Paulo, 2 boreholes and 18 samples, Caraíba, 20 boreholes and 10 samples; Jacobina, 11 boreholes and 2 aggregate samples of basement rocks rather than from the overlying quartzites. Thus these sites comprise almost half of the total determinations. Nevertheless, the linear relationship should be considered preliminary owing to the small number of sites.

A puzzling anomaly is that of Nova Lima, where temperature and heat generation measurements, made in several underground boreholes, place the site well above the postulated linear relationship of Figure 6. There is no geological evidence that indicates the existence of enriched underlying material. In fact, the existing evidence indicates that the Rio da Velhas Series that comprises the underground mine extends to several kilometers below the surface [*Door*, 1969]. A heat flow value of 23 mW m^{-2} from the nearby borehole of Bico de Pedra (site 11) is considered unreliable, for reasons discussed previously.

An enhanced heat flow can also be ascribed to deep-seated tectonic sources, rather than unusual radioelement concentration in the crust. This explanation has been utilized by *Chapman and Pollack* [1977] as a possible interpretation of the relatively high heat flow measured in the Precambrian rocks of central Africa. An enhancement of the heat flow of Nova Lima, Morro Agudo, Vazante, and Americano do Brasil, which are located within 200 km or less of Mesozoic-Cenozoic alkalic intrusions (see Figure 7), by deep-seated heat sources, perhaps associated with an aulacogen as suggested by *Herz* [1977], is thus a possible explanation.

The preliminary parameters of the heat flow–heat production relationship obtained in Brazil fall within the range of values that are typical of shield areas elsewhere [*Rao and Jessop*, 1975]. Reduced heat flow in Precambrian terrains ranges from 25 to 32 mW m^{-2}, and the depth of heat source distribution varies from 4.5 km in western Australia to 14.8 km in the Late Proterozoic regions of India. Younger tectonic regions are usually characterized by well above average reduced heat flow [*Pollack and Chapman*, 1977], the highest of which (50–60 mW m^{-2}) has been documented in areas that have been affected by Mesozoic-Cenozoic tectonism, such as the Basin and Range province of North America [*Lachenbruch and Sass*, 1977].

In summary, a provisional linear relationship, tentatively suggested on the basis of four apparently reliable sites, has yielded a reduced heat flow and heat source depth distribution parameter very similar to parameters proposed for shields elsewhere. The fact that the sites that define the linear rela-

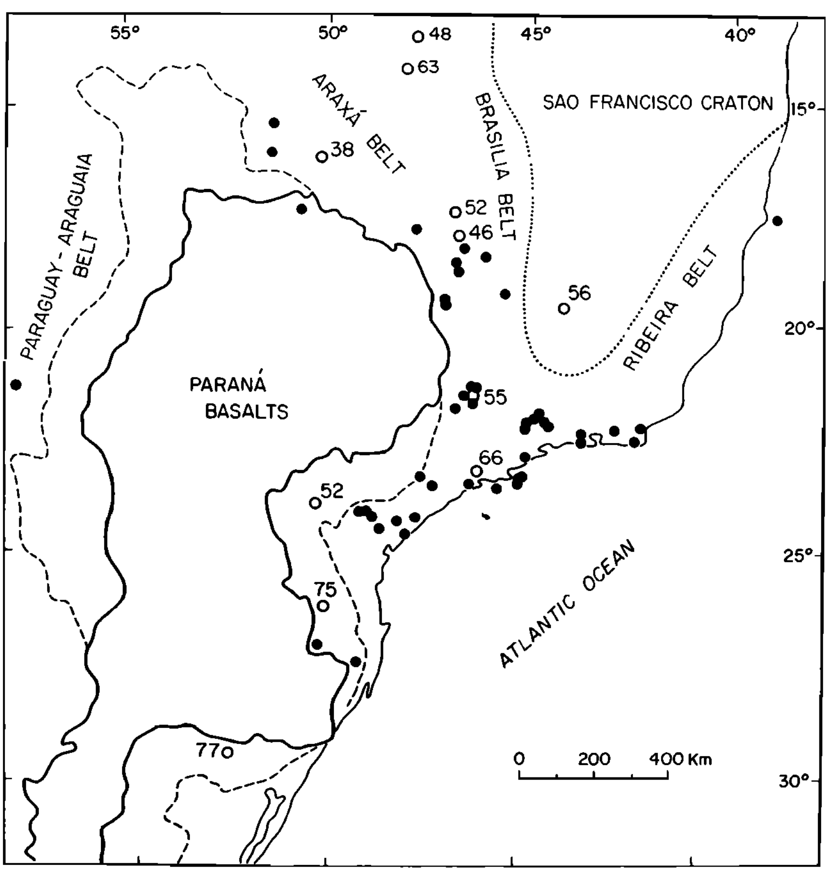

Fig. 6. Map of southern Brazil showing the geographic relationship between heat flow sites (open circles, heat flow in milliwatts per square meter), alkalic intrusions (solid circles), the basaltic plateau of the Serra Geral eruptives (solid line), the areal extent of the Paraná basin (dashed line), and approximate boundaries of the São Francisco Craton (dotted line).

tionship are found in tectonic units of different age (see Table 1) is not unique. The heat flow province of eastern North America [*Roy et al.*, 1968] also comprises both Precambrian and Phanerozoic sites.

VARIATION OF HEAT FLOW WITH TECTONIC SETTING AND AGE

Most of the South American continent east of the Andean orogenic belt appears to be an extensive platform whose folded basement was stabilized during the Precambrian, after a succession of remobilization events [*Almeida et al.*, 1973; *Cordani et al.*, 1973]. The basement comprises the Brazilian Coastal Shield, the Brazilian Shield, and the Guayana Shield, in eastern, central, and northern Brazil, respectively; the Brazilian Coastal Shield includes the São Francisco craton and an encircling belt of mid and late Precambrian mobile belts. Superimposed upon the extensive Precambrian basement are three large Phanerozoic intracratonic sedimentary basins, the Paraná, Maranhão (Parnaiba), and Amazonas. Along the Atlantic coast can be found several small fault-bounded basins that were formed at the time of the opening of the South Atlantic Ocean. The simplified tectonic map in Figure 4 (modified after *Cordani et al.* [1973]) shows the locations of these principal tectonic elements.

Extensive radiometric dating within the shields has revealed several metamorphic provinces of distinctly different age ranges [*Cordani et al.*, 1968]. Most of the age determinations are in the central and eastern parts of Brazil, approximately the same area covered by the geothermal measurements. There remain large areas that are poorly known and unclassified in the most recent *Tectonic Map of Brazil* [1971].

The majority of the radiometric dates belongs to two predominant tectonic events. First, ages corresponding to the Transamazonic folding (2600–1800 Ma) represent a time of widespread continental remobilization possibly involving the whole of Brazil. They are found in all metamorphic belts that have not been affected by later events and also in basement rocks or within 'relic blocks' in younger metamorphic belts. Second, the Braziliane folding (900–550 Ma) represents a time of extensive remobilization, along belts that usually surround the older cratonic areas.

In terms of overall geological characteristics, these belts can be roughly classified into two broad but distinct tectonic environments: the stable cratons, stabilized at the end of the Transamazonic deformation, and the mobile belts, repeatedly affected by younger deformations. Even after the end of the Braziliane event the mobile belts are distinguished as the sites of alkalic and anorogenic volcanism and mineralization, suggesting a persisting deep-seated difference between the mobile belts and stable cratons, perhaps related to residual heat from the previous tectonothermal event.

The intracratonic sedimentary basins appear to overlap the Precambrian belts. Radiometric dates indicate Braziliane age for the basement beneath the Maranhão and Lower Amazonas basins and a mid-Cambrian age beneath Upper and Middle Amazonas basins [*Kovach et al.*, 1976]. The existence of a Late Precambrian metamorphic belt underlying the Paleozoic sediments of the Paraná basin is a distinct possibility but remains a matter of conjecture.

As the South American and African continents were fractured by rifting at the end of the Mesozoic, large volumes of tholeiitic basalts were extruded along large tensional fractures or intruded as dikes and sills within the sedimentary strata of the Paraná basin. Radiometric dates indicate a period of maximum activity about 120–130 Ma ago [*Cordani and Vandoros*, 1967].

Another thermal disturbance at that time is the onset of alkalic volcanism, restricted to the Braziliane fold belts east and north of the Paraná basin. The alkalic occurrences are distributed throughout the Cretaceous and Cenozoic [*Herz*, 1977] but cluster around two major ages, 120–130 Ma and 50–80 Ma [*Amaral et al.*, 1967]. Both of these age peaks are associated with uplifting along the Brazilian Coastal Shield and in central east Brazil [*Asmus*, 1975; *Soares et al.*, 1978]. The well-known alkalic occurrence at Poços de Caldas was erupted during the second major period of activity, 64–77 Ma.

Several marginal basins were also formed in deep graben and semigraben along the present Atlantic coast, in a tectonic environment that is considered typical of divergent continental margins. The sedimentary history of these marginal basins suggests that tensional movements started as early as Late Jurassic along faults apparently controlled by Precambrian lineaments [*Ponte et al.*, 1977]. In most of these basins the sedimentary strata have been intruded by basic igneous rocks during two prominent periods of intense volcanic activity that have been radiometrically dated at 120–130 and 50–80 Ma ago [*Ponte et al.*, 1977].

The 15 heat flow sites that have yielded reliable heat flow results (Figure 4) are situated in three principal tectonic provinces: (1) three sites (2, 3, and 4) in the stable São Francisco Craton of the Brazilian Coastal Shield comprising rocks with Transamazonic ages or older [*Almeida et al.*, 1973]; (2) nine sites (1, 5, 6, 7, 8, 9, 10, 13, and 14) in the Braziliane mobile belts of northeast, central, and eastern Brazil; and (3) three sites (16, 17, and 19) in the Paraná basin.

These provinces represent three tectonothermal events that occurred in Mid Precambrian, Late Precambrian, and Late Jurassic–Early Cretaceous (basaltic volcanism). The alkaline magmatism of Poços de Caldas (site 13) is located within the Braziliane Mobile Belt of eastern Brazil but is of Late Cretaceous–Early Tertiary age. The site of Nova Lima is included in the Braziliane group, as the region of the 'Iron Quadrangle,' where Nova Lima is located, was last effected by a tectonothermal event ranging from 450 to 550 Ma [*Herz*, 1970].

The influence of past tectonothermal events on present-day heat flow values, manifest as a decrease of heat flow with increasing tectonic age of a terrain, was first noted by *Polyak and Smirnov* [1968] and *Hamza and Verma* [1969]. The variation of heat flow with age has recently been reevaluated, in light of many additional data, by *Chapman and Furlong* [1977] and *Sclater et al.* [1980]. In Brazil an inverse correlation between measured geothermal gradients and tectonic age was noted by *Vitorello et al.* [1978] in an earlier stage of the present investigation, and the pattern continues in the heat flow as well, as discussed below.

Heat flow at sites within the São Francisco Craton is low, with an average of 42 ± 5 (sem (standard error of the mean)) mW m^{-2}, typical of shield areas [*Rao and Jessop*, 1975]. The highest heat flow values come from Jacobina, northeastern portion of the São Francisco Craton, where significant topographic relief, complex surface temperature distribution, and east-dipping quartzite layers complicate the underground temperature distribution. We believe that the Jacobina site mean corresponds to an upper limit heat flow estimate.

The Late Precambrian Braziliane belt, geographically better represented than the Transamazonic belt, is characterized by a wider range of heat flow values, from 38 mW m^{-2} in Americano do Brazil, central Brazil, to 69 mW m^{-2} in Currais Novos, northeast Brazil. The average of eight sites within regions of Braziliane age is 55 ± 5 (sem) mW m^{-2}. The three sites in the Paraná basin have a mean heat flow of 68 ± 8 (sem) mW m^{-2}.

While the São Francisco Craton appears to have been left undisturbed since its mid-Precambrian cratonization, except for some small areas affected by the Braziliane folding [*Herz*, 1970], the Late Precambrian Braziliane metamorphic belt that surrounds the Paraná basin to the east and to the north has been the locus of sporadic alkalic magmatism in the Mesozoic and Cenozoic (Figure 6). *Neill* [1973] and *Herz* [1977] have suggested that the alkalic belt is the failed arm (aulacogen) of a triple junction, while *Marsh* [1973] believes the intrusions lie along extensions of transform faults. Nevertheless, both hypotheses imply the existence of thermal overprinting in the Braziliane metamorphic belt, at least locally. Consequently, the thermal disturbances from both the alkalic magmatism and the volcanism in the Paraná basin would possibly be observable today as residual heat.

The likelihood that the thermal disturbance associated with the alkalic intrusions would have visible regional effects in the metamorphic terrain depends on the depth, size, and intensity of the disturbance, none of which are well known. The heat flow values from sites within the alkalic belt are not anomalously high. The average heat flow of six sites situated in the proximity of the alkalic belt is 53 mW m^{-2}, slightly less than the average of eight sites in the Braziliane metamorphic belt. The Poços de Caldas site, located directly on a circular alkalic intrusion of approximately 35-km diameter and about 400–500 m higher than the adjacent area, has a site mean of 55 mW m^{-2}. However, this value probably represents a low estimate of the true heat flow because of the topographic relief. Lack of detailed topographic information has prevented calculations leading to meaningful corrections, yet even allowing for an increase of 20% for this correction, the values obtained would not exceed other values found within the Braziliane belt. Moreover, the radioactive elements contained in the alkalic plug probably make a substantial contribution to the surface heat flow. The radioelement abundance determinations from the borehole samples (Table 3) are biased, however, toward mineralized zones and should be used only with caution to estimate the total radiogenic contribution of the volcanic plug.

In contrast to the alkalic magmatism, the volcanism in the Paraná basin signifies a major thermal disturbance, yielding the second largest volume of flood basalt on earth, conservatively estimated at 350,000 km^3 by *Leinz* [1949]. Radiometric dating of the basaltic flows indicates a time span from 119 to 147 Ma [*Cordani and Vandoros*, 1967] for the extrusion of the basalts, which implies an unusually large concentration of thermal energy for almost 30 Ma over a wide region, as suggested by the numerous fissures geographically distributed throughout the plateau. This major thermal pulse, a significant thermal perturbation within the crust and upper mantle, is likely to be responsible for the elevated heat flow values obtained at the southeastern part of the Paraná basin.

Vitorello and Pollack [1980] have analyzed the decay of a tectonothermal perturbation as one component of the general variation of heat flow with tectonic age. Their models show a present-day residual heat flow of some 14 mW m^{-2} from a thermal event 135 Ma ago. Subtracting this estimate from the heat flow average of 68 mW m^{-2} within the Paraná basin, the value of 53 mW m^{-2} obtained agrees with the mean of the Braziliane metamorphic belt, which could be the basement underlying the basin.

The mean heat flow of these tectonic provinces is plotted versus tectonic age in Figure 7, along with a reference curve that represents the generalized decay of continental heat flow with tectonic age. The generalized curve [*Chapman and Furlong*, 1977] derives from some 1500 measurements on six continents. The variation of heat flow with tectonic age in Brazil appears to be not significantly different from the global pattern.

A limited number of heat flow measurements have been made elsewhere in South America. These include eight sites in northern Chile and one in Tierra del Fuego reported by *Uyeda et al.* [1978*a*], a cluster of marine-type measurements in Lake Titicaca by *Sclater et al.* [1970], and isolated determinations in northwest Colombia by *Sass et al.* [1974] and in northeast Brazil by *Carvalho and Vacquier* [1977]. These sites are shown in Figure 1. Additional heat flow estimates exist in northern Chile [*Diment et al.*, 1965] and in western Argentina [*Uyeda et al.*, 1978*b*] but cannot be used with confidence owing to inadequate control on the thermal conductivity. These sites are not shown in Figure 1.

In addition to continental data, there also exists a sizable body of oceanic measurements both to the east and west of the continent [*Jessop et al.*, 1976; *Anderson et al.*, 1976; *Lee and Von Herzen*, 1977]. We have plotted in Figure 8 a geothermal profile running from the East Pacific Rise, across South America, to the Mid-Atlantic Ridge. The oceanic profiles utilize data between 5°S and 30°S; all continental data are plotted according to their longitude. The schematic tectonic section shown below the data is very generalized; in particular, the Paraná basin, while it is shown correctly with respect to longitude, should not be viewed as a 'midcontinent' feature. It is actually truncated by the Atlantic Ocean.

The geothermal profile of Figure 8 shows the well-known decrease of oceanic heat flow with age and the 'apparent' heat

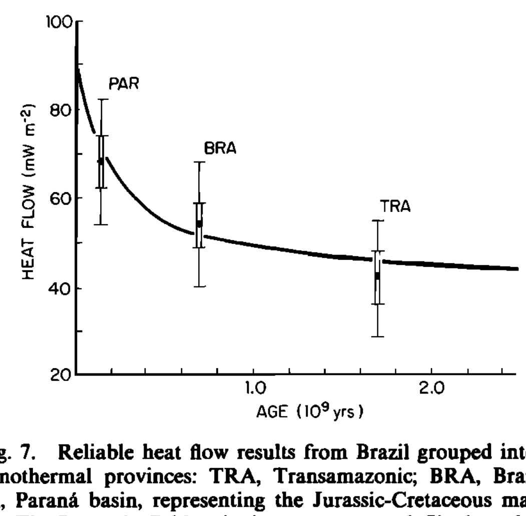

Fig. 7. Reliable heat flow results from Brazil grouped into three tectonothermal provinces: TRA, Transamazonic; BRA, Braziliane; PAR, Paraná basin, representing the Jurassic-Cretaceous magmatic event. The Poços de Caldas site is not represented. Single and double vertical bars represent standard deviation and standard error of the mean, respectively. The solid line is a curve of heat flow versus tectonic age obtained by *Chapman and Furlong* [1977] from some 1500 continental heat flow measurements in the global catalog of *Jessop et al.* [1976].

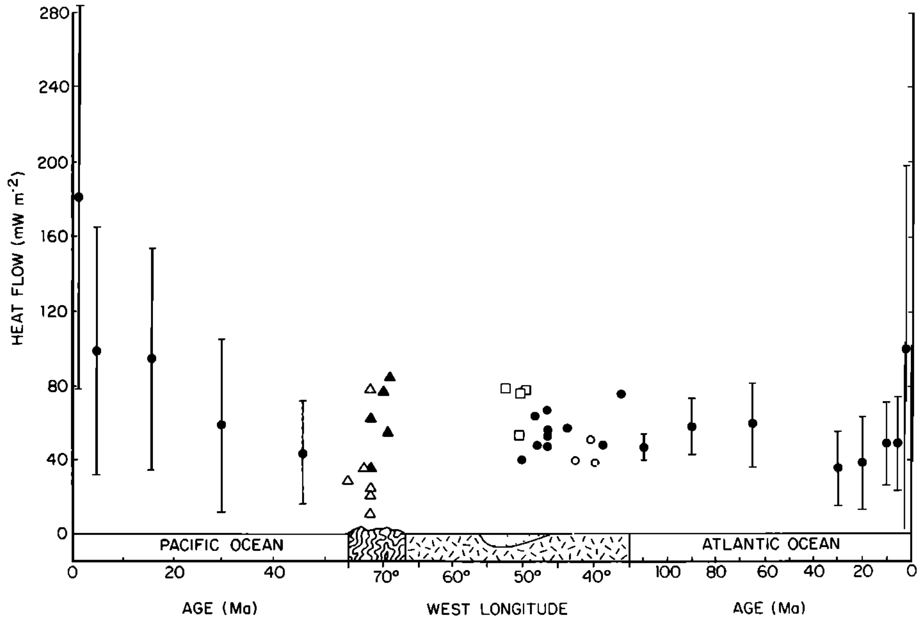

Fig. 8. Composite west-east transcontinental heat flow profile from the East Pacific Rise to the Mid-Atlantic Ridge. The oceanic profile is obtained from published measurements between latitudes 5°S and 39°S and shows the mean and standard deviation of reported heat flow values according to the age of the ocean floor. On the South American continent the individual site values are plotted according to their longitude and are not closely related to the schematic continental boundary of the diagram. Open circles, solid circles, and squares represent sites in the São Francisco Craton, Braziliane belts, and Paraná basin, respectively. Triangles represent other published heat flow values; in the Andean region, sites below 1000-m elevation (coastal region and western foothills) are shown as open triangles, and those above 1000 m are shown as solid triangles.

flow lows on the 0–40 Ma Atlantic Ocean and 0–10 Ma Pacific (probably caused by seawater circulating through the young oceanic crust which has not yet been sealed with a sediment blanket). In the Andean zone the observations range widely, but when the data are segregated into low-altitude (near trench) and high-altitude ('volcanic arc') groups, one can begin to see the characteristic low heat flow adjacent to the trench and the higher heat flow of the volcanic zone further inland. The data, of course, are yet too few to go beyond the suggestion of such a zonation. The Andean Cordillera and the gap in observations between about 55°W and 70°W are the target of geothermal measurement programs currently under way in our respective institutions.

The new heat flow data from eastern and central Brazil, also displayed in Figure 8, show rather clearly the variation in heat flow between the three tectonic elements studied: high heat flow in the Paraná basin, moderate heat flow in the Braziliane belts, and lower heat flow in the São Francisco Craton.

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