UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Heat Flow And Near-Surface Radioactivity In The Australian Continental Crust

OPEN-FILE REPORT 76-250

Menlo Park, California
1976

United States Department of the Interior

Geological Survey

HEAT FLOW AND NEAR-SURFACE RADIOACTIVITY IN THE AUSTRALIAN CONTINENTAL CRUST

by

J. H. Sass[1], J. C. Jaeger[2], and Robert J. Munroe[1]

[1]U.S. Geological Survey, Menlo Park, California 94025
[2]Research School of Earth Sciences, Australian National University, Canberra, A.C.T., Australia
Present address: Private Bag 5, P. O. Sorell, Tasmania 7172, Australia

Open-File Report 76-250

1976

This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards and nomenclature.

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Abstract

Heat-flow data have been obtained at 44 sites in various parts of Australia. These include seven sites from the old (∿ 2500 m.y.) Precambrian shield of Western Australia, seventeen from the younger (∿ 600 - 2000 m.y.) Precambrian rocks of South Australia, the Northern Territory, and Queensland, and twenty within the eastern Paleozoic and younger rocks. Thirty of the sites are located where no previous heat-flow data existed, and the remainder provide significant extensions or refinements of areas previously studied. Where the holes studied penetrated the crystalline basement rocks, or where the latter rocks were exposed within a few kilometers of the holes, the upper crustal radiogenic heat production has been estimated based on gamma-ray spectrometric determinations of U, Th, and K abundances. Three heat-flow provinces are recognized in Australia based on the linear relation ($q = q^* + DA_0$) between heat flow q and surface radioactivity A_0. New data from the Western Australian shield support earlier studies showing that heat flow is low to normal with values ranging from 0.7 to 1.2 hfu and with the majority of values less than 1.0 hfu, and the parameters $q^* = 0.63$ hfu and $D = 4.5$ km determined previously were confirmed. Heat flow in the Proterozoic shield of central Australia is quite variable, with values ranging between about 1 and 3 hfu. This variability is attributed mainly to variations in near-surface crustal radioactivity. The parameters of the heat-flow line are $q^* = 0.64$ hfu and $D = 11.1$ km and moderately high

temperatures are predicted for the lower crust and upper mantle.

Previous suggestions of a band of low-to-normal heat flow near the coast in eastern Australia were confirmed in some areas, but the zone is interrupted in at least one region (the Sydney Basin), where heat flow is about 2.0 hfu over a large area. The reduced heat flow, q*, in the Paleozoic intrusive rocks of eastern Australia varies from about 0.8 to 2.0 hfu. This variability might be related to thermal transients associated with Late Tertiary and younger volcanic and tectonic activity, even though the relation between heat-flow values and the age of volcanism is not a simple one. Parts of the high heat-flow area in the southeast might be exploitable for geothermal energy.

INTRODUCTION

In 1950, reliable measurements of terrestrial heat flow on continents numbered only a few with scattered measurements in South Africa, Britain and North America, mainly attributable to E. C. Bullard, A. E. Benfield, Francis Birch, A. D. Misener, and their associates. No Australian measurements were available, and one of us (J. C. Jaeger) initiated a geothermal studies program beginning with measurements at hydroelectric developments in Tasmania and tunnel excavations by the Snowy Mountains Hydroelectric Authority in Southern New South Wales. The first published results [Newstead and Beck, 1953; Beck, 1956] suggested heat flows that were unacceptably high in the context of world heat flow at that time [see Bullard, 1954; Birch, 1954]. Subsequent studies by L. E. Howard [Howard, 1965; Jaeger and Thyer, 1960; Howard and Sass, 1964] corroborated earlier indications of high heat flow in eastern Australia and established that low-to-normal values were characteristic of the Archaean (ages > 2500 m.y.) Shield of Western Australia. The latter observation and that of Kraskovski [1961] were the first published statements regarding systematic differences between heat flow on Precambrian shields and younger rocks. Between 1960 and 1970, further publications by J. H. Sass, J. C. Jaeger, R. D. Hyndman, L. E. Howard, A. E. LeMarne, and S. P. Clark, Jr., in various combinations (cited below in discussions of the appropriate localities) confirmed the earlier observations and raised the possibility of a band of low heat flow near the coast in eastern Australia. Hyndman et al. [1968] related measured heat flows to near-surface radioactivity in Western Australia, and Jaeger [1970] suggested a linear heat flow - heat production relation for the Australian Archaean Shield [cf. Roy et al., 1968].

The present work was undertaken to complete the Australian picture as far as possible on a geographical basis, to attempt to define heat flow - heat production provinces within the Australian continent, and to relate these results to what is presently known about the gross tectonic and geological state of Australia.

The Australian continent is the most conspicuous physiographic feature within the Indian Plate [see e.g., Vine, 1971; LePichon et al., 1973]. Unlike most other continents, the Australian continental margin does not include any parts of the plate boundary; the nearest one being the Indonesian Arc to the north. The continent is essentially a craton with Holocene tectonic activity limited to some basaltic volcanism in the southeast and three zones of moderately high seismicity [Cleary and Simpson, 1971; Doyle, 1971]. Most of the continent has been inactive throughout the Cenozoic era with the notable exception of an uplift in the eastern Paleozoic highlands accompanied by widespread volcanism throughout the Tertiary period [see Wellman, 1971, 1974; Wellman and McDougall, 1974a, 1974b]. One of the paradoxes resulting from juxtaposition of the tectonic setting and distribution of heat flow is the apparently high heat flux throughout most of the Precambrian and Paleozoic craton of central Australia (Figures 1 and 2). This paradox is addressed below in our discussion of heat flow versus surface radioactivity.

Most measurements were obtained by 'scrounging' boreholes drilled for mineral exploration or hydrologic studies. Three holes were drilled, however, in critical localities by the Australian National University, and numerous other holes (drilled by private industry and government agencies) were preserved by the installation of casing for later temperature measurements.

All temperature measurements were made using equipment identical in all important respects to the 'portable mode' or 'well-logging mode' described by Sass et al. [1971b], and the accuracy of measurements is of the same order (± 0.001°C for relative temperatures; better than 0.1°C for actual temperatures). Individual temperature measurements in all holes are listed by Munroe et al. [1975].

Laboratory work included determinations of thermal conductivity and concentrations of uranium, thorium, and potassium for estimates of crustal radiogenic heat. Most of these measurements were made in laboratories of the USGS; conductivity, by R. J. Munroe [Munroe et al., 1975], and radiometric measurements by C. M. Bunker [Bunker et al., 1975]. The remainder of laboratory studies were performed by G. T. Milburn, J. H. Sass, James Gill and H. Y. Tammemagi at the Australian National University.

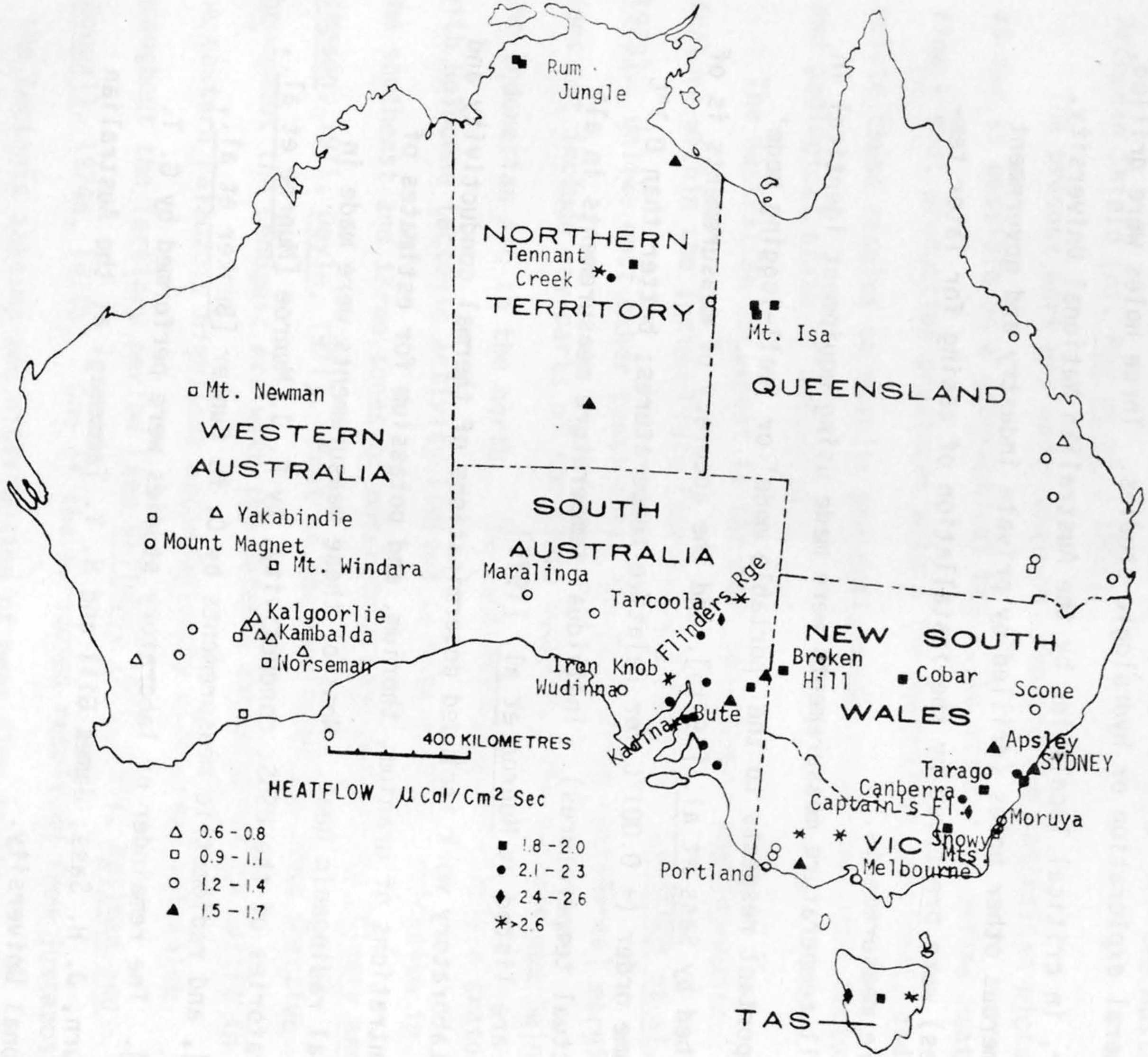

Figure 1a. Sketch map of Australia showing the locations of all heat-flow data.

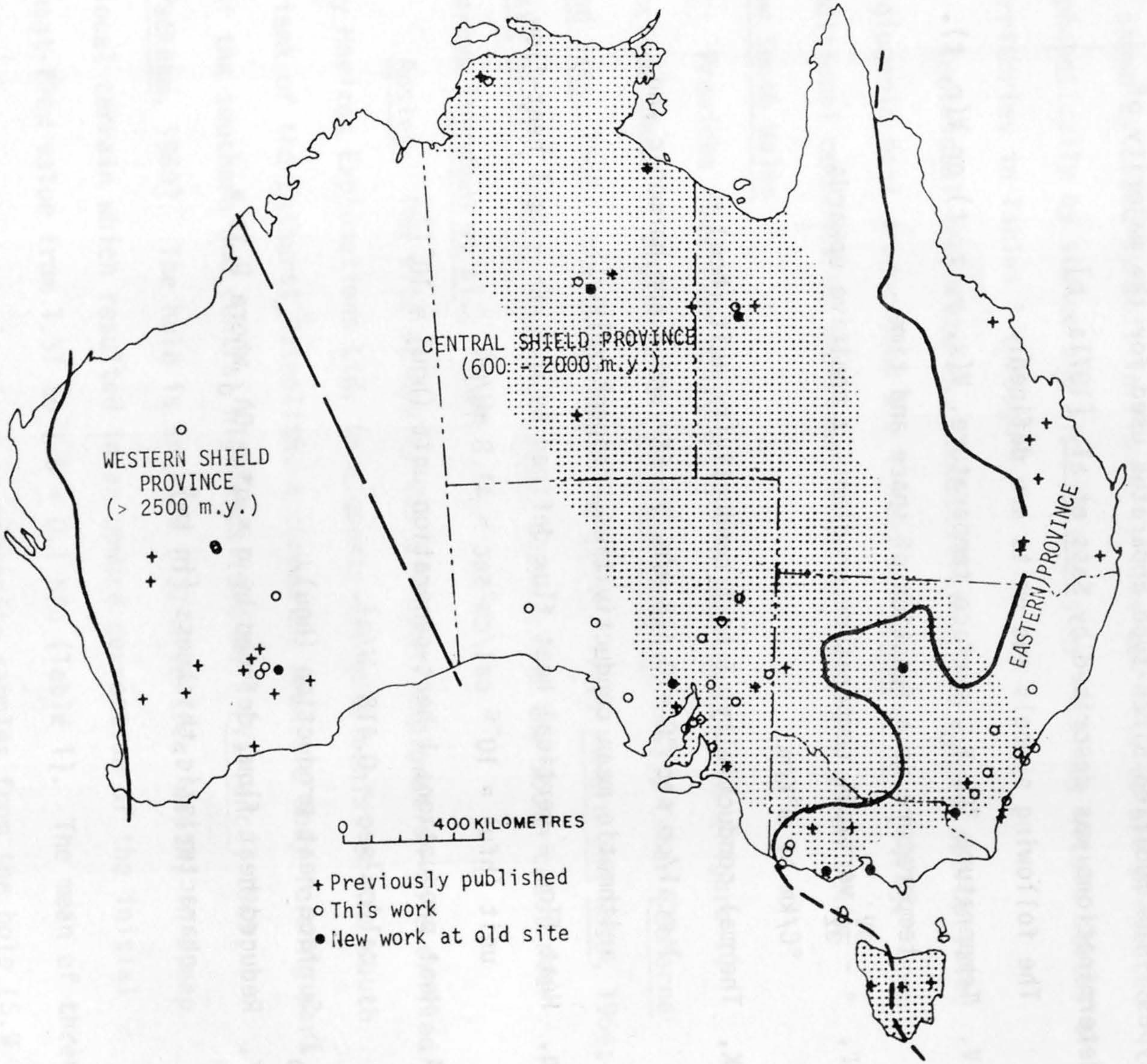

Figure 1b. Sketch map of Australia showing geographical relation between this work and previously published heat-flow values. Heavy lines designate approximate boundaries of the three heat-flow provinces. Pattern defines region characterized by high heat flow (> 1.5 hfu).

Thermal conductivity measurements in both cooperating laboratories were made on divided-bar apparatuses of the Birch [1950] or Beck [1957] types. The modified Birch-type apparatus used for the majority of determinations was described by Sass et al. [1971a, b].

The following symbols and units are defined:

V, Temperature °C; V_o, surface temperature, V(x, y, z, t) or V(r, t), temperature as a function of space and time.

Γ, $= -\frac{\partial V}{\partial z}$ vertical temperature gradient, z positive upwards, °C/km or m°K/m.

K, Thermal conductivity; 1 heat conductivity unit (hcu) = 1 mcal/cm sec °C = 0.418 w/m °K; $\langle K \rangle$ and $\overline{K}$ are harmonic and arithmetic mean conductivities, respectively.

q, Heat flow ≡ vertical heat flux defined by $q = \langle K \rangle \cdot \Gamma$; 1 heat-flow unit (hfu) = 10^{-6} cal/cm^{2}sec = 41.8 mW/m^2.

A, Heat production; 1 heat-generation unit (hgu) = 10^{-13} cal/cm^{3}sec = 0.418 μW/m^3.

A_o, Surface heat production (hgu).

q*, Reduced heat flow, defined by $q = q^* + DA_o$ where D is a characteristic thickness (in km).

HEAT-FLOW DATA

The geographic distribution of heat flow for the Australian continent is shown by coded symbols in Figure 1. The new results are presented alphabetically by states and alphabetically by locality within states or territories in Tables 1 through 7.

Individual temperatures, conductivities, and (where appropriate) radiogenic heat productions are listed by Munroe et al. [1975]. Some additional comments on individual sites or areas are given below.

New South Wales

Previous heat-flow measurements in New South Wales (Figure 1) include those at Broken Hill [Sass and LeMarne, 1963], Cobar [LeMarne and Sass, 1962], the Snowy Mountains [Beck, 1956; Howard and Sass, 1964; Sass et al., 1967], Canberra [Sass, 1964a], and the south coast near Moruya [Hyndman et al., 1969].

Apsley. The site at Apsley was a mineral exploration hole drilled by Horizon Explorations Ltd. in a quartz-sericite schist on the south flank of the Bathurst Batholith, a composite granitic body forming part of the southern and central highlands fold belt [Vallance, 1969; Packham, 1969]. The hole is shallow (137 m vertical depth) in steep local terrain which resulted in an upward correction of the initial heat-flow value from 1.31 to 1.5 ± 0.1 hfu (Table 1). The mean of three heat-production determinations on composite samples from the hole (5.9 ± 0.2 hgu) is within the range of heat-production measurements from the granitic rocks of the Bathurst Batholith [Table 2-2, Bunker et al., 1975].

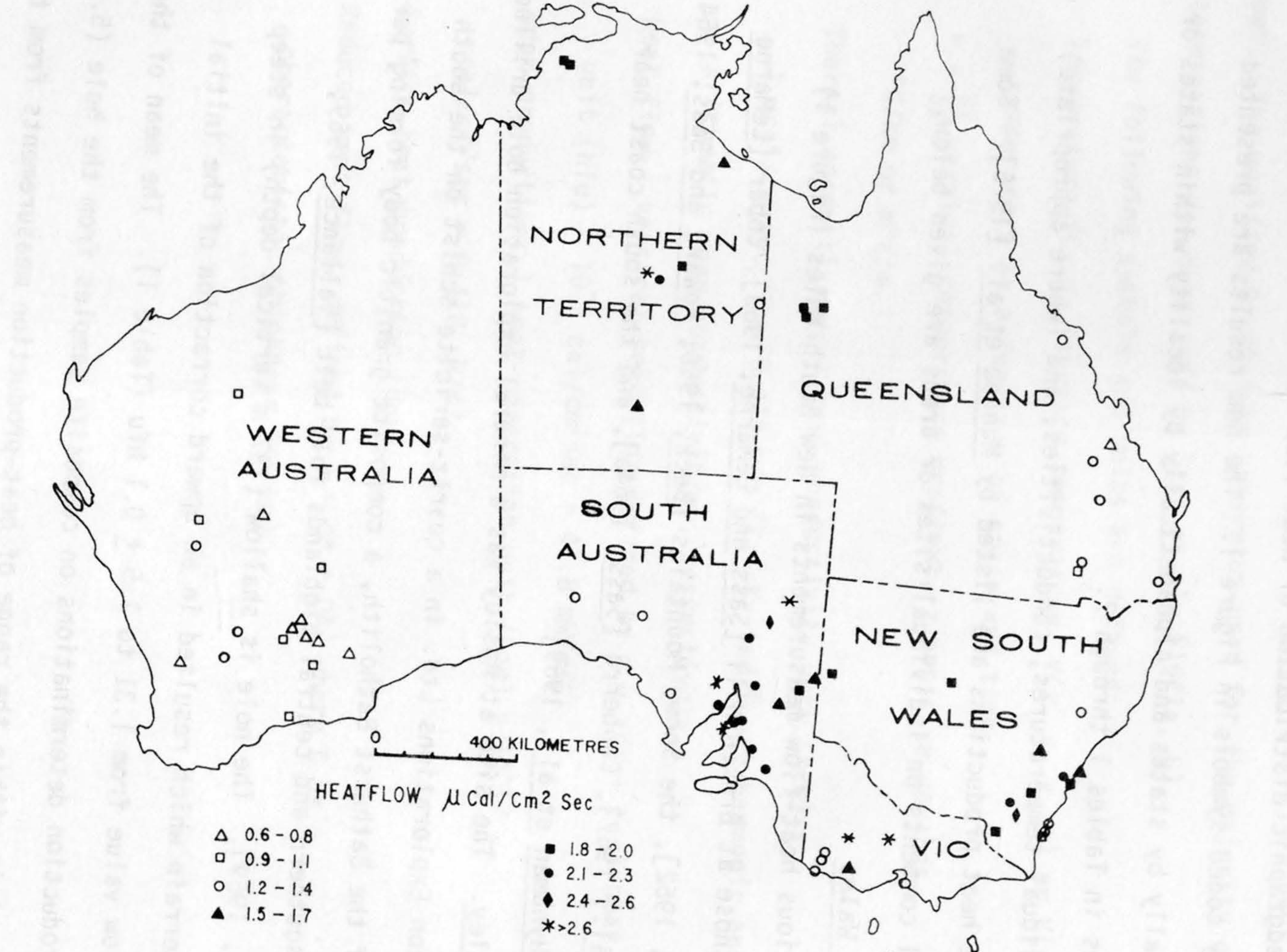

Figure 1c. Sketch map of Australia showing the locations of all heat-flow data.

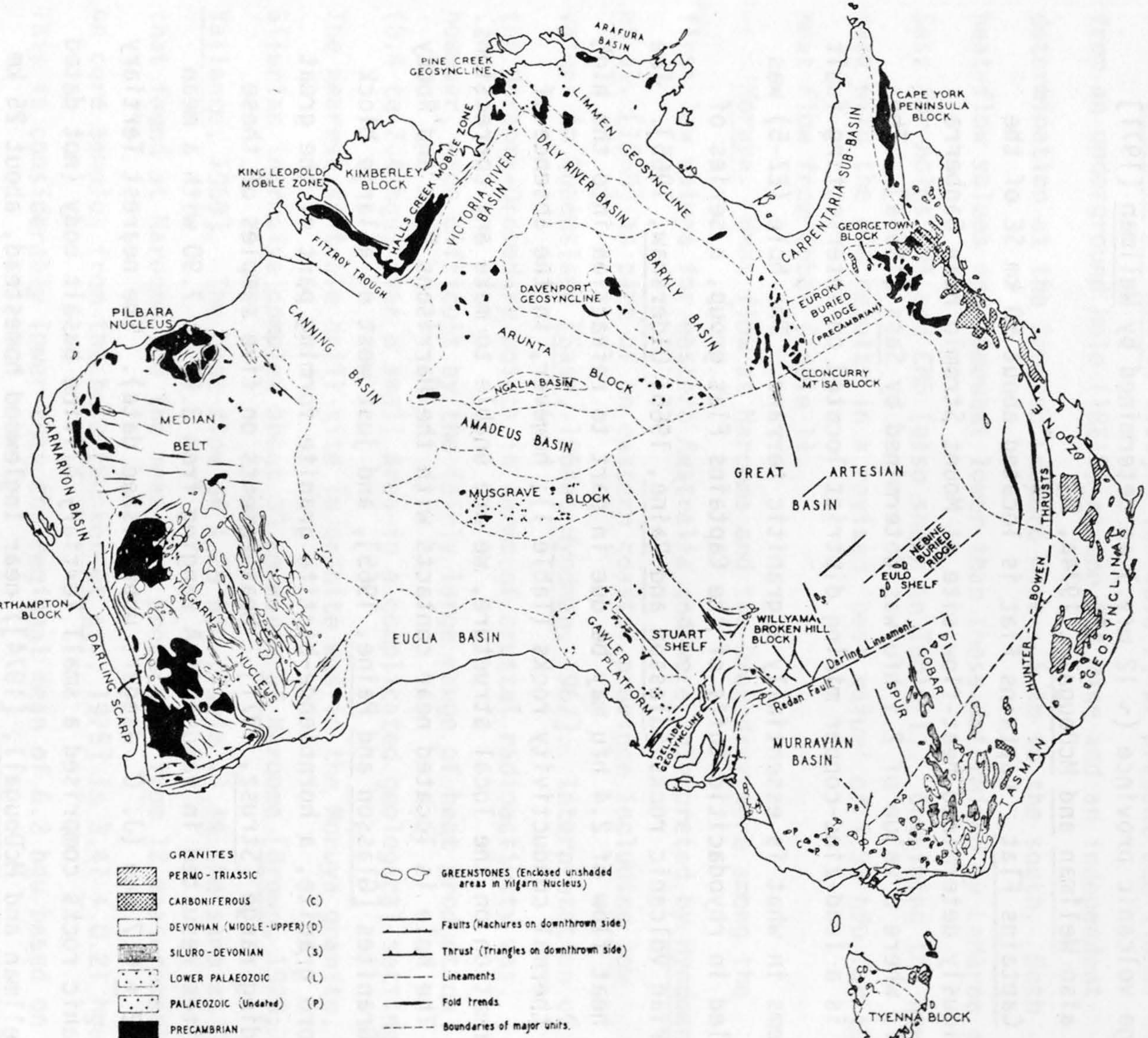

Figure 2. Major tectonic elements of Australia (reproduced from Hills [1965]).

Apsley is at the northwestern end of the Abercrombie volcanic province (∿ 18 m.y.) and some 20 km east of the eastern margin of the Orange volcanic province (∿ 12 m.y.) as determined by Wellman [1971] [see also Wellman and McDougall, 1974a, b].

Captains Flat. Captains Flat is located about 50 km SE of the previously determined heat-flow site at Mount Stromlo near Canberra A.C.T. where a value of 2.1 hfu was determined by Sass [1964a]. The area is a lead-zinc-copper mining district located on intersecting fault systems in what is essentially a granitic terrane. The hole (EZ-5) was drilled in rhyodacitic tuffs of the Captains Flat group, a series of Silurian volcanic rocks [Glasson and Paine, 1965; Oldershaw, 1965]. The high heat flow of 2.4 hfu may be due in part to refraction into the high mean thermal conductivity rocks (Table 1); however, in the absence of information on the local structure, we are unable to make any corrections.

The hole is located near contacts with the Harrisons Peak and Rocky Pic Granites [Glasson and Paine, 1965], and just west of a large block of Boro granite, a hornblende-biotite granite forming part of the great dividing range [Strusz, 1971]. Measurements on five samples of these granites resulted in values of A ranging from 3.95 to 7.90 with a mean of 5.2 ± 0.7 hgu (J. C. Jaeger, unpublished data). The nearest Tertiary volcanic rocks comprised a small Tertiary olivine basalt body (not dated by Wellman and McDougall, [1974]) near Inglewood homestead, about 25 km south of the heat-flow site [Strusz, 1971].

Cobar. LeMarne and Sass [1962] measured heat flows averaging about 2.2 hfu in two holes near the CSA Mine about 10 km north of the town of Cobar [Russell and Lewis, 1965]. In Table 1, we present additional data from an underground hole (18E16) at the CSA Mine and an independent determination at the Spotted Leopard Mine ~ 5 km to the south. Both heat-flow values are somewhat lower than those determined by LeMarne and Sass for holes CM4 and CM5 (also shown in Table 1). Combining the new data with the old results in a revised 'best value' of 1.98 hfu for the heat flow from Cobar (Table 1).

Moruya. Heat flow at Narooma and the Dromedary were among the first low values for eastern Australia and were interpreted by Hyndman et al. [1969] as part of an eastern coastal province including low values in Queensland [Sass, 1964a; Hyndman, 1967]. Interpretation of the Narooma-Dromedary points in terms of crustal radioactivity was, however, made difficult by the fairly large range of heat production (0.4 to 7.4 hgu) over a small area in a complicated geological setting. The nearest suitable drill site in granite was in the Moruya granite, a Silurian intrusive complex about 30 km north of Narooma [Brown, 1928; Vallance, 1969]. The heat flow of 1.28 hfu (Table 1) is the same as that found at Narooma and the mean heat production from 12 measurements on core samples from the hole [Bunker et al., 1975] is 3.47 ± 0.21 hgu. This is considerably lower than the regional mean of 6.2 hgu based on 23 samples of the Moruya granite measured by K. S. Heier and I. B. Lambert (unpublished data), but it does agree with measurements made on two surface samples collected within a radius of 10 km of the hole (J. C. Jaeger, unpublished data).

The Moruya site is within the 30± m.y. old Moruya volcanic province as defined by Wellman and McDougall [1974a].

Scone. The Scone borehole was drilled by Broken Hill Proprietary Ltd. at the extreme northern end of the Sydney Basin in the northern Hunter Valley, a part of the 'Northern Coalfields' subprovince of the main NSW coal province [Hanlon, 1953]. The hole was drilled in the Permian 'Singleton Coal Measures' [Mayne et al., 1974] which consist of sedimentary rocks interbedded with numerous seams of high quality bituminous coal. Because of the large differences in thermal gradients among depth intervals of a few tens of meters (caused by corresponding differences between thermal conductivities of noncarbonaceous sedimentary rocks and coaly layers), the heat flow of 1.17 ± 0.01 hfu (Table 1) was determined by the resistance integral method of Bullard [1939] [see Table 2-1 of Munroe et al., 1975]. Scone is located between two of the older Tertiary volcanic provinces of Wellman and McDougall [1974a], the east Liverpool volcano (∿ 40 m.y.) and the Barrington volcano (∿ 50 m.y.).

The Southern Sydney Basin. Extensive core drilling has been carried out by Australian Iron and Steel Proprietary Ltd. in the Illawara coalfields of the southern Sydney Basin. To prevent contamination of ground water, the holes were routinely filled with cement to a point above the Permian Illawara Coal measures, but they were accessible to depths of a few hundred meters within the impermeable Triassic Sandstones of the Hawkesbury Sandstone and Narrabeen Group [Mayne et al., 1974]. We were able to measure heat flow in three of these holes (Loddon, Nebo, and Wallandoola) and in another hole drilled by the NSW Geological Survey at Cape Banks in Sydney (Table 1). The heat flows range from 1.7 to 2.1 hfu, the highest heat flows yet measured along the east coast of Australia. The high heat flows are north of the Mittagong volcanic province of Wellman and McDougall [1974a] within which ages vary from 30 to more than 50 m.y.

Tarago. Two holes drilled in upper Devonian felsic volcanic and sedimentary rocks near Tarago [Strusz, 1971] yielded heat flows of 1.85 and 1.96 for a mean of 1.9 ± 0.1 hfu. Tarago is about 40 km west of the southern end of the Nerriga volcanic province ($\sim$ 40 m.y.) of Wellman and McDougall [1974a].

TABLE 1

New Heat-Flow Data*
New South Wales

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Apsley	33° 34'	149° 34'	884	65-137	15	9.69 ±0.20	13.5 ±0.06	1.31 ±0.02	1.5
Captain's Flat	35° 36'	149° 27'	914	66-263	12	10.50	23.0	2.42	2.4
EZ-5						±0.35	±0.06	±0.08	
Cobar									
CSA Mine									
18E16	31° 25'	145° 48'	280	549-779	10	10.23 ±0.75	18.8 ±0.2	1.92 ±0.14	
CM4			284	205-576	10	10.76 ±0.4	20.2 ±0.11	2.17 ±0.08	
CM5			284	147-354	6	10.05 ±0.2	20.5 ±0.10	2.06 ±0.04	
Spotted Leopard	31° 27'	145° 49'	268	161-367	15	8.42 ±0.04	20.97 ±0.09	1.77 ±0.09	
				Mean					1.98
Moruya	35° 54'	190° 7'	7	85-168	10	7.30 ±0.08	17.5 ±0.1	1.28 ±0.02	1.28
Scone	32° 05'	150° 49'	208	30-366	35	2.99 ±0.37	(39)	1.17 ±0.01	1.2

TABLE 1

New Heat-Flow Data*
New South Wales (continued)

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Southern Sydney Basin									
Cape Banks	34° 00'	151° 15'	5	152-213	6	7.61 ±0.33	22.5 ±0.1	1.71 ±0.07	
				213-320	7	5.34 ±0.07	30.6 ±0.1	1.63 ±0.02	
				320-427	6	6.50 ±0.09	26.8 ±0.1	1.74 ±0.02	
				Mean				1.69 ±0.03	1.7
Loddon	34° 14'	150° 46'	707	198-365	11	9.89 ±0.26	22.86 ±0.13	2.26 ±0.06	2.1
Nebo	34° 25'	150° 45'	52	104-202	5	9.2 ±0.9	19.25 ±0.12	1.77 ±0.17	
				202-287	7	7.5 ±0.3	27.1 ±0.4	2.03 ±0.09	
				Mean				1.90	1.9
Wallandoola	34° 19'	150° 44'	309	200-374	11	9.4 ±0.5	23.0 ±0.2	2.16 ±0.12	2.1
Tarago									
DH-40	35° 04'	149° 34'	800	45-285	25	8.05 ±0.50	22.93 ±0.04	1.85 ±0.11	
DH-47			793	47-265	25	8.18 ±0.43	23.97 ±0.09	1.96 ±0.10	
				Mean (2 holes)					1.90

*Definitions: N, number of thermal conductivity specimens; <K>, harmonic mean thermal conductivity; Γ, least squares temperature gradient over designated depth range; q(unc), uncorrected heat flow (hfu) = <K> · Γ; q(corr) corrected heat flow; ± refers to standard error.

Northern Territory

Previously published results include those at Rum Jungle and Tennant Creek [Howard and Sass, 1964], and Alice Springs and three sites in the eastern-central part of the territory by Hyndman [1967]. The present work (Figure 1) presents new data near the two sites discussed by Howard and Sass [1964].

Rum Jungle. Howard and Sass [1964] presented results from three holes near the Precambrian (Lower Proterozoic) Rum Jungle complex south of Darwin, N. T. [Walpole et al., 1968]. Component heat flows in formations of different conductivity varied between 1.0 and 2.3 hfu. A value of 2.0 hfu was adopted as the most likely value for the area and low values in steeply dipping amphibolite dikes were attributed to refraction. Roy et al. [1968] combined this heat-flow value with the mean heat production of 15 hgu found from measurements on 33 granitic rocks from the complex by Heir and Rhodes [1966] and noted that the heat flow - heat production relation for this site was comparable to that observed for the craton of eastern North America.

The Batchelor site (Table 2) was drilled in siliceous sedimentary rocks of the Crater formation [Walpole et al., 1968] about 10 km SE of the sites of previous measurements and 2 km south of the granitic complex discussed by Heier and Rhodes [1966]. The heat flow of 1.9 hfu confirms the earlier value adopted by Howard and Sass [1964].

Tennant Creek. Howard and Sass [1964] measured a heat flow of 2.3 hfu at the Peko Mine, about 10 km east of the town. The mineral region contains a number of working mines over an area of some 2000 km^2 within mineralized sedimentary rocks of the Warramunga group [see Crohn, 1965] comprising greywackes interbedded with shales, cherts, mudflow conglomerates, and slump breccias. The ore bodies are pipe-like structures usually of chalcopyrite and pyrrhotite enclosed in magnetite lenses. The Warramunga group is intruded by the granitic rocks of the Quartz Hill - White Hill and Cabbage Gum igneous complexes [Crohn, 1965]. The results of the new measurements near Tennant Creek and at Warrego, about 40 km NW of the town, are summarized in Table 2. In common with Rum Jungle (and indeed with many other mineralized regions) the main difficulty in interpreting the results arises from inadequate information about thermal conductivity and related lithology. The structure is very complicated, and the measured conductivity of the Warramunga sedimentary rocks ranged from 5 to 18 hcu. Despite the fact that the highest conductivities were measured on highly mineralized specimens, the correlation between conductivity and density is poor [see Munroe et al., 1975].

In the older mining area east of Tennant Creek, new (and deeper) measurements at the Peko Mine and neighboring prospects result in heat-flow values ranging from 1.8 to 2.3 and averaging 2.0 ± 0.1 hfu (Table 2). Temperature gradients are very much higher, however, in rocks of comparable thermal conductivity at Warrego and heat flows for individual depth intervals are in the range 2.6 to 3.4 with a mean of about 3 hfu (Table 2). Two clear-cut groups of data are involved in the latter estimate:

1) Data from holes 20, 21 and the upper 400 m of the other holes are in a relatively non-mineralized section of the mine area;

2) Between 400 and 670 meters, the last group of holes penetrated the ore body, a steeply dipping pipe-like structure. The ore body may be very crudely approximated by a vertical prolate spheroid of semi-axes a and b and eccentricity $e = (1 - b^2/a^2)^{1/2}$ [see section 10.1, Jaeger, 1965]. Then if q_i and K_i are the heat flux and conductivity in the spheroid and q_o and K_o the corresponding quantities at a distance,

$$\frac{q_i}{q_o} = \frac{K_i}{K_o + B_o(K_i - K_o)}$$

where

$$B_o = \frac{1 - e^2}{e^3} \left\{ \frac{1}{2} \ln \frac{1 + e}{1 - e} - e \right\}$$

Taking $a/b = 4$ so that $B_o = 0.0752$, $K_o = 8.8$ from Warrego 20 and 21 and $K_i = 12.0$ from Warrego 27, 29, 30, 31 gives $q_i/q_o = 1.33$. This may be compared with the ratio 1.27 between the heat-flow values from the mineralized and nonmineralized sections of the holes (Table 2).

The corrected mean value of 2.7 hfu for the heat flow from Warrego is significantly higher than that of 2.0 at Tennant Creek. Inasmuch as the higher heat flows reflect high gradients in rocks of comparable conductivity, regional refractive effects would seem to be ruled out as the cause of the higher values.

Abundances of radioelements from eight granitic outcrops in the area have been measured by Bunker et al. [1975]. One high value of A_0 (18.4 hgu) was measured about 20 km SE of Tennant Creek, but the remaining seven sites (including one from Black Angel near Warrego) have heat-production values ranging from 8.3 to 10.3 with an average of 9.3 ± 0.4 hgu. This compares favorably with a mean value of 9.7 hgu measured by Jaeger [1970] on 12 composite samples of the sedimentary rocks from the mines.

TABLE 2

New Heat-Flow Data*
Northern Territory

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Batchelor (70-R-54)	13° 02'	131° 05'	150	107-242	14	12.08 ±0.59	15.78 ±0.10	1.91 ±0.09	1.9
Tennant Creek Region									
Explorer 46	19° 40'	134° 13'	350	75-250	6	9.03 ±0.41	24.86 ±0.33	2.24 ±0.11	
				250-320	5	5.19 ±0.48	27.71 ±0.32	1.44 ±0.13	
				Mean				1.84 ±0.4	1.8
Juno	19° 43'	134° 15'	340						
900-73				320-542	9	10.3 ±0.5	23.03 ±0.12	2.37 ±0.12	2.3
900-75				346-518	16	9.5 ±0.5	22.88 ±0.24	2.17 ±0.12	2.1
				Mean (Juno)					2.2
Peko	19° 41'	134° 17'	330	374-558	16	9.52 ±0.69	22.00 ±0.50	2.09 ±0.16	2.0
				Mean (Tennant Creek)					2.0

TABLE 2

New Heat-Flow Data*
Northern Territory (continued)

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Tennant Creek Region (continued)									
Warrego	19° 27'	133° 49'	330						
20				48-240	8	9.0 ±0.4	28.9 ±0.3	2.60 ±0.12	
21				47-651	16	8.6 ±0.3	33.5 ±0.3	2.88 ±0.10	
27, 29, 30, 31				50-400	0	(8.6)	31.0 ±1.0	2.67	
				400-670	31	12.0 ±0.7	28.4 ±0.2	3.4 ±0.2	
				Mean (Warrego)				3.0	2.7†

*See footnote, Table 1, for definitions and explanations of abbreviations in table headings.
†Corrected for refraction (see text).

Queensland

The eastern part of Queensland (Figure 1) is characterized by low-to-normal heat flow [Sass, 1964a; Hyndman, 1967; Beck, 1976]. High heat flows were, however, measured in the Mount Isa region in the western part of the state, where all of the data presented here were obtained.

Mount Isa Region. Previous results include an estimate by Howard and Sass [1964] based on two holes in the main mine area, and a detailed profile by Hyndman and Sass [1966] involving 25 holes. All but two of the latter holes were along a 5 km north-south profile centered approximately on 20° 43' S, 139° 29' E. The two additional holes 8 km south and 5 km north of the main profile, respectively, provided confirmation of the mean heat flow of 1.96 hfu. The present results include three holes in the main mine area that extend the maximum measured depths to nearly 1.5 km below the ground surface, and a group of seven holes in the 'Northern Leases' about 20 km north of the original group.

Three new holes in the Mount Isa Mine area were measured (Table 3a); one on the 13 level (∿ 600 meters below ground surface) and two on the 15 level (∿ 720 meters below ground level). Cores were available from the actual holes or nearby ones, so that independent estimates of heat flow could be made.

FW-78-E decline number 1 and FW-82-E decline number 4 are collared about 120 meters apart and both are in silica dolomite, but the lower part of FW-82 penetrates a highly mineralized section. Differing gradients in the two sections are compensated by variations in thermal conductivity and the heat flows in both sections are essentially identical at 2.2. FW-82 is parallel to and about 100 meters from a steep contact with a greenstone of conductivity about 25% lower than the upper silica dolomites. The refractive effects would thus make our determination an overestimate and a reduction on the order of 10% seems reasonable resulting in a 'corrected' heat flow of around 2.0 hfu. FW-78 is collared only 70 meters from a steep greenstone contact but moves rapidly away to over 200 meters from the contact near the bottom of the hole. The mean gradient (18.4 $\pm$ 0.2) and mean conductivity (10.5 $\pm$ 0.5) result in a heat flow of 1.93 $\pm$ 0.09 hfu.

The average uncorrected heat flow from the three holes is about 2.1 hfu. When refractive effects are considered, this value is in excellent agreement with the earlier results of Hyndman and Sass [1966].

The holes in the northern leases (Table 3b) penetrate much the same rock types as those to the south and the contacts are also very steep. Here, no attempt was made to collect a complete suite of samples from each hole, and representative samples of each type were collected. The arithmetic means are shown in Table 4 [cf. Table 1, Hyndman and Sass, 1966]. As might be expected because of the complicated structure and variability of conductivity, the heat flows vary over a considerable range within this small area. Detailed knowledge of structure is useful in understanding the variations in heat flow, but the variability of conductivity within individual formations precludes meaningful refraction

TABLE 3

New Heat-Flow Data*
Queensland

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Mt. Isa	20° 45'	139° 29'	400						
a) Mt. Isa Mine									
FW/78	20° 41'	139° 29'	393	763- 821	7	10.5 ±0.5	18.4 ±0.2	1.93 ±0.09	
FW/82	20° 41'	139° 29'	393	764-1289	32	11.18 ±0.33	19.79 ±0.06	2.21 ±0.06	2.0
				1289-1451	10	13.2 ±0.7	16.6 ±0.2	2.19 ±0.03	
13/R5S	20° 42.2'	139° 29'	411	689- 819	5	9.4 ±1.0	22.6 ±0.3	2.1 ±0.2	
				819- 942	10	16.7 ±1.1	13.9 ±0.2	2.3 ±0.2	
b) Northern Leases									
J-184	20° 31.9'	139° 29'	414	99- 213	0†	11.5	16.4 ±0.1	1.89	
				213- 419	0	8.5	18.51 ±0.04	1.57	
				Mean				1.73	
S-172	20° 32.1'	139° 29.2'	393	68- 164	0	11.95 ±0.93	17.0 ±0.3	2.03	
I-210	20° 31.5'	139° 28.8'	405	106- 424	0	?	21.05 ±0.05		
				424- 831	0	12.0 ±1.0	19.14 ±0.04	2.30 ±0.19	

TABLE 3

New Heat-Flow Data*
Queensland (continued)

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
H-177	20° 32.1'	139° 29'	454	91- 381	0	11.6 ±2.6	19.09 ±0.05	2.21 ±0.5	
E-148	20° 32.5'	139° 29'	405	167- 282	0	8.98 ±0.61	18.22 ±0.06	1.64 ±0.11	
0-177	20° 32.0'	139° 29'	398	129- 244		9.15	20.22 ±0.03	1.85	

*See footnote, Table 1, for definitions and explanations of abbreviations in table headings.
†Thermal conductivities calculated from regional average conductivities, Table 4, and driller's logs.

TABLE 4

Mean Thermal Conductivities, Mount Isa Area

Rock*	N	K (arithmetic mean)	σ†
Judenan beds	6	14.18	0.58
Native Bee Siltstone	7	8.56	0.42
Magazine Shale	3	7.76	0.22
Spear Kennedy Siltstone	16	9.15	0.33
Western Greenstone	4	8.98	0.61
Dolerite Dikes	6	7.07	0.56
Urquhart Shale	16	11.95	0.93
Silica Dolomite	49	11.87	0.35
'Ore'	12	16.75	0.95

*Terminology is that of Mount Isa Mines geologists; see also Carter and Brooks [1965].

†Standard error.

calculations in the absence of many more determinations of conductivity. The mean q (weighted as to the depth interval used in the heat-flow calculation) for the northern leases is 1.98 ± 0.10 hfu. This is in excellent agreement with the determinations (both the present work and that of Hyndman and Sass [1966]) 20 km to the south, and 50 km east at the Blockade.

Two large elongate granitic bodies (the Sybella and Kalkadoon granites) are found in the region, one on each side of the Mount Isa fault zone [Carter and Brooks [1965]. Four samples of each granite were measured, and no systematic variation in heat generation was observed with a mean A_o of 9.3 ± 0.4 hgu from the eight samples. At the Blockade, two samples of Kalkadoon Granite had heat productions of 5.7 and 9.3 for a mean of 7.5 hgu.

South Australia

Previously published results from South Australia include a value at Radium Hill [Howard and Sass, 1964] and heat flows near Kanmantoo southeast of Adelaide and near Whyalla in the Middleback Range of the Eyre Peninsula [Sass, 1964a]. South Australia was a major target of this study in view of the high seismicity of the area [Cleary and Simpson, 1971; Doyle, 1971] and the preliminary results from the first large-scale magnetometer array study made in Australia [Gough et al., 1974]. The heat-flow data are listed in Table 5.

Bendigo Station. Considerable exploration was carried out by the South Australian Mines Department in Paleozoic granodiorites near Terowie on the eastern flank of the Adelaide Geosyncline (Figure 2) [see Thomson, 1965, 1970, 1973]. Heat flows from the two boreholes (drilled within ∿ 1 km of each other) agree very well averaging 1.5 hfu (Table 5), and the mean heat production from measurements on 12 composite samples [Table 4-1, Bunker et al., 1975] is 9.09 ± 0.29 hgu.

Bute. This hole (Table 5) was drilled by the South Australian Mines Department in Proterozoic metamorphosed volcanic and sedimentary rocks (B. P. Thomson, unpublished core logs). A high heat flow (2.1 hfu) was found at this site which is located in the northern Yorke Peninsula in a region characterized by high surface radioactivity [see Table 4-7 of Bunker et al., 1975].

Carrieton. Utah Development Corporation has been prospecting extensively near Carrieton in the southern Flinders Ranges. The drill hole (EDO-6, Table 5) penetrated sedimentary rocks (carbonates, siltstones and quartzites) of the Proterozoic Adelaide system (Utah Development Company, unpublished report, 1972). There are no outcrops of intrusive rocks in the area, so no determinations of heat production could be made.

Ediacara. A rotary hole was drilled by Carpentaria Explorations in poorly consolidated sediments interbedded with Cambrian limestones near the Black Eagle Mine in the Ediacara Field, central Flinders Ranges [see Broadhurst, 1953; Johnson, 1965]. Two intervals of differing gradients were used to obtain independent estimates of heat flow. Thermal conductivities are somewhat uncertain in that no core was available and conductivities were obtained from measurements on chips [Sass et al., 1971a] using estimated porosities; however, the agreement between the component heat fluxes is sufficiently good that we are confident of the high value of 2.3 hfu.

Iron Knob. Howard [1965] measured temperatures to a depth of 305 meters in DH-48, Iron Knob, located north of the Middleback Ranges [Owen and Whitehead, 1965]. Howard did not calculate a heat flow because of a lack of 'suitable' samples for thermal conductivity determinations. The hole penetrated about 200 meters of schists and amphibolite and then encountered a high grade iron ore zone. The angle of contact between amphibolite and ore is steep, averaging about 56° to the horizontal. No samples of amphibolite were available, but seven samples of the ore (mean density 4.7) had thermal conductivity ranging from 13 to 36 with a mean of about 22 hcu. Combining this with the least squares gradient in the lower part of the hole results in a heat flow of 6 hfu.

In the upper 200 meters, if we assume a conductivity value for amphibolite of 7 hcu (similar to that found by Sass [1964a] at the Iron Chieftan to the south) the heat flow in this section is 'only' 2.6 hfu. We can resolve the difference between the component heat flows by estimating the effect of geometrical refraction along the steeply dipping contact. From equation 55 of Jaeger [1965], if q_2 is the heat flow in the ore, and q_1 that in the amphibolite, K_2 and K_1 are the respective conductivities and α the dip of the contact, then

$$\frac{q_2}{q_1} = 1 + \frac{(K_2 - K_1)}{K_1} \sin^2\alpha$$

for $K_1 = 7$, $K_2 = 22$, and $\alpha = 56°$ then $q_2/q_1 \approxeq 2.5$ as compared with the actual ratio of 2.3 (Table 5). We adopt the value of 2.6 hfu as the most reasonable estimate for this hole.

The nearest granitic body, the Burkitt granite [Figure 7, Parkin, 1969] is about 10 km west of the site. Six samples of this rock yielded heat-production values ranging from 3 to 36 with a mean of 18 ± 5 hgu [see Table 4-6, Bunker et al., 1975].

Kadina Area. North Broken Hill Ltd. recently has drilled a number of core holes in the Wallaroo-Moonta Mining area [see Dickinson, 1953; Crawford, 1965]. Two of these holes (Kadina M-111 and M-118, Table 5) were accessible and provided heat-flow data. Hole M-111 was drilled in Precambrian metavolcanic and metasedimentary rocks; and M-118, in schists interbedded with porphyritic rocks. The heat flows (Table 5) indicate considerable variation over a short distance ($\sim$ 10 km). This variation might be explained in terms of the variation of radioactive heat generation in the local crystalline rocks. Heat production from eight samples is high and variable, ranging from 16 to over 120 hgu [Table 4-7, Bunker et al., 1975].

Maralinga. In an effort to obtain heat-flow data from the south-central part of the continent, temperatures were measured in several deep water bores in the (presently abandoned) nuclear test site reserve at Maralinga. Even though no water had been pumped from these wells for several years, hydrologic disturbances were evident in all profiles. The temperature gradient over a relatively undisturbed section of one of these was combined with conductivity determinations on chips to yield a very tentative value of 1.3 hfu for this site (shown in parentheses, Table 5).

Mootooroo. Mootooroo is near the western edge of the Precambrian Willyama block (Figure 2) [see also Thomson, 1970; King and Thomson, 1953; Parkin, 1969] which also includes the Broken Hill District in New South Wales. Sass and LeMarne [1963] have published a mean heat flow of 1.93 from Broken Hill and Howard and Sass [1964] a value of 1.8 from Radium Hill to the west. Hole MM-16 (Table 5) drilled by Mines Exploration Pty. Ltd. penetrated granitic gneisses and schists typical of other localities within the Willyama series. The heat flow of 1.6 hfu (Table 5) is somewhat lower than those on either side. Heat productions from

11 composite samples of the rocks from the hole average 7.4 ± 0.4 hgu [Table 4-2, Bunker et al., 1975].

Mt. McTaggart. Hole C2A was drilled in a copper prospect of North Flinders Mines N.L. It penetrated a steeply dipping microdolerite sill within Proterozoic sedimentary rocks of the northern Flinders Ranges. Because of the shallowness of the hole, the complicated structure, and the uncertainty of the topographic correction [Munroe et al., 1975] we consider this value of lower reliability than most others, and the heat flow of 2.4 hfu is shown within parentheses in Table 5.

Parabarana. North Flinders Mines N. L. also has carried out copper exploration in the Mount Painter province [Thomson, 1966; Coats et al., 1969] at the extreme northern tip of the Flinders Ranges. The hole penetrated extensively weathered and altered porphyritic granites and a very reliable heat-flow value of 3.0 hfu (Table 5), the highest yet measured in Australia was determined at the site. Radiometric measurements were not attempted on rocks from the hole because of the weathering and extreme alteration. Instead, measurements were made on fresh samples of Terrapinna granite [see Coats et al., 1969] provided by John A. Cooper of University of Adelaide. The mean of four heat-production determinations [Table 4-3, Bunker et al., 1975] was 18.8 ± 0.1 hgu. (Note: The heat-production values listed on page 61 of Munroe et al. [1975] are too low by 10 hgu).

Stockyard Gully. A hole was drilled by Auric Mineral Exploration N.L. in altered Precambrian gneisses of the Mount Lofty Ranges [see Thomson, 1965; Parkin, 1969]. The heat flow of 2.1 hfu (Table 5) agrees with measurements at Kanmantoo and Dawsley by Sass [1964a]. Measurements on four composite samples of this altered and mineralized material gave a mean heat production of 3.5 hgu (C. M. Bunker, unpublished data).

Tarcoola. This hole was drilled specifically to obtain a heat flow - heat production pair in the western part of the younger Precambrian rocks. The site is in the center of a group of granitic outcrops (Cooladdin granite) dated at about 1500 m.y. (B. P. Thomson, written communication). Below 150 meters, a very uniform gradient of 15.80 °C/km was found resulting in the first reliable low-to-normal heat-flow determination (1.18 hfu) in granitic rocks of the Gawler Platform (Figure 2). The mean A_0 of 6.35 ± 0.13 hgu from 20 specimens agrees with measurements on surrounding outcrops [Tables 4-4 and 4-6, Bunker et al., 1975].

Wudinna. Little Wuddina hill is situated among a number of 'inselbergs' of Buckleboo Granite in the south-western part of the Eyre Peninsula (Figure 1). This site is also in the Gawler Block of the larger Proterozoic Gawler Platform (Figure 2). The hole was sited on the basis of some preliminary high heat production ($\sim$ 10 hgu or greater) in the region. The drilling was designed to determine whether the high heat flows to the east extended westward and to investigate possible thermal effects

TABLE 5

New Heat-Flow Data*
South Australia

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Bendigo Station	33° 12'	139° 28'	229						
BD-3				100- 310	22	8.34 ±0.11	18.3 ±0.2	1.53 ±0.03	
BD-7				90- 295	12	8.04 ±0.10	18.5 ±0.2	1.49 ±0.02	
				Mean					1.52
Bute	33° 52'	138° 01'	116	52- 218	27	8.58 ±0.18	24.3 ±0.1	2.08 ±0.04	2.1
Carrieton (EDO-6)	32° 33'	138° 29'	520	150- 376	15	12.9 ±0.5	17.2 ±0.2	2.22 ±0.09	2.2
Ediacara (T-1)	30° 48'	138° 07'	290	50- 152	7	4.2 ±0.7	50 ±1	2.10 ±0.35	
				152- 213	5	3.85 0.21	66 1	2.54 0.14	
				Mean					2.3
Iron Knob (DH-48)	32° 43'	137° 08'	180	30- 213	0	7	36.9 ±0.3	2.6	
				213- 305	7	21.9 ±3.4	27.2 ±0.4	6.0 ±1.0	2.6
				Best value					2.6

TABLE 5

New Heat-Flow Data*
South Australia (continued)

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Kadina area M-111	33° 58'	137° 45'	46	286- 476	27	7.27 ±0.17	28.91 ±0.06	2.10 ±0.05	2.10
M-118	33° 59'	137° 40'	45	30- 259	16	8.79 ±0.44	31.2 ±0.5	2.74 ±0.14	2.7
				Mean (Kadina area)					2.4
Maralinga	30° 10'	131° 36'	180	183- 252	8	5.53 ±0.31	24.1 ±1.7	1.3 ±0.1	(1.3)
Mootooroo MM-16	32° 15'	140° 56'	220	30- 589	37	6.37 ±0.18	25.23 ±0.06	1.61 ±0.05	1.61
Mt. McTaggart (C2A)	30° 27'	139° 18'	147	97- 175	6	8.6 ±0.7	28.9 ±0.5	2.49 ±0.21	(2.4)
Parabarana	29° 59'	139° 43'	275	76- 320	17	7.62 ±0.48	40.0 ±0.5	3.05 ±0.2	3.0
Stockyard Gully	34° 46'	138° 48'	300	125- 185	15	9.28 ±0.37	22.9 ±0.3	2.13 ±0.19	2.1
Tarcoola	30° 37'	134° 30'	150	100- 304	20	7.58 ±0.06	15.60 ±0.03	1.18 ±0.01	1.18
Wudinna	32° 59'	135° 33'	240	198- 303	49	9.04 ±0.12	15.21 ±0.06	1.38 ±0.02	1.38

*See footnote, Table 1, for definitions and explanations of abbreviations in table headings.
†Corrected for refraction (see text).

associated with observed compressive stress features (A-tents) along the Cleve lineament [Jennings and Twidale, 1971], a major fault zone several hundred km long that passes close to the drill site. A disturbance to the temperature gradient, most probably caused by the conversion of the area to agriculture in the early 1900's [Twidale, 1971] is apparent in the upper 200 meters, but the lower 100 meters of the temperature profile is quite linear [Munroe et al., 1975] and a heat flow of 1.38 hfu was calculated (Table 5). The mean of 17 measurements of heat production, 11.8 ± 0.6 hgu confirmed the earlier reconnaissance on surface samples [Tables 4-5 and 4-6, Bunker et al., 1975].

Victoria

The only previously published heat flows from Victoria were values of 2.8 and 2.9 at Stawell and Castlemaine [Sass, 1964a] north of the youngest extensive area of igneous rocks in Australia, The Newer Volcanic province [Wellman, 1974]. Because of the existence of these young volcanic rocks and also because of the discovery of an electrical conductivity anomaly (The Otway conductor) by Bennett and Lilley [1974] [see also Lilley, 1975] a strong effort was made to obtain additional heat-flow data in southwestern Victoria. This effort was only moderately successful with three new values near the southwestern edge of the Newer Volcanic province and a single estimate near Sorrento on the Nepean Peninsula south of Port Phillip Bay (Figure 1). A rough estimate (based on earlier temperature measurements by Howard [1965]) was also made near Timboon. Unfortunately we were unable to investigate the Artesian Basin of Gippsland where some moderately high temperatures ($\sim$ 65°C) have been reported in fairly shallow (300 to 500 meters) oil and gas tests by Jenkin [1962].

Branxholme. Branxholme No. 1 was a water bore drilled by the Victorian Mines Department near the westernmost edge of the Newer Volcanic province. The well penetrated the basalt within $\sim$ 10 meters and penetrated the underlying Tertiary sedimentary rocks (Department of Mines, Victoria, unpublished logs). Despite a rather severe hydrologic disturbance to the gradient, we are fairly confident of the gradient and the resulting heat flow of 1.3 hfu (Table 6).

Heywood. Victorian Mines Department Well #13 at Heywood is located about 35 km SSW of the Branxholme well. It penetrated the Newer Volcanic rocks for about 30 meters and a shaley limestone (Mines Department Victoria unpublished logs) for the remainder of the logged interval.

Portland. Two water wells, #8 and #10, were logged and the results combined in Table 6. These wells penetrated some decomposed basalt and clay in the upper 60 meters, and thereafter were in marl and limestone (Mines Department, Victoria, unpublished well logs). The heat flow of 1.2 is rather surprising in view of the young ages ($\sim$ 3 m.y.) measured in the Newer Volcanics here [Aziz-Ur-Rahman and McDougall, 1972].

Sorrento. Howard [1965] measured temperatures in Nepean water bore #29 (Drilling Reports, Mines Department, Victoria) near Sorrento on the Nepean Peninsula south of Melbourne. The site is a few kilometers west of the Selwyn fault which has had vertical movement of at least 600 meters during the Cenozoic Era [Gostin, 1973]. It is also less than 1 km from the coast. The temperature profile in the upper 336 meters is curved, probably owing to its complicated Cenozoic history. Between 336 and 427 meters, however, the gradient is linear and a heat flow of 1.3 hfu (possibly still affected by thermal transients) was estimated (Table 6).

Timboon. Howard [1965] measured temperatures to 305 meters in Timboon #1 or #2, a water bore drilled by the Victorian Mines Department near Timboon in alternating layers of sandstone, limestone, and clay of

TABLE 6

New Heat-Flow Data*
Victoria

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Branxholme	37° 52'	141° 48'	160	25- 158	22	3.06 ±0.08	41.5	1.3	
Heywood	38° 08'	141° 32'	49	80- 540	16	3.74 ±0.19	31.0 ±1.0	1.2	
Portland (Holes 8 & 10)	38° 23'	141° 35'	46	50-1050	3	3.33 ±0.02	35.0 ±0.5	1.2	
Sorrento (NEP 29)	38° 21'	144° 44'	25	335- 427	15	3.45 ±0.21	42	1.3	
Timboon	38° 28'	142° 59'	115	90- 243	14	4.0 ±0.3	42.2 ±0.6	1.69 ±0.13	(1.7)

*See footnote, Table 1, for definitions and explanations of abbreviations in table headings.

the Tertiary sedimentary rocks of the region. There is some structure in the temperature profile and considerable variability in conductivity. The thermal conductivity of seven specimens measured by Howard [1965] ranged from 3.5 to 8.9 with a harmonic mean of 5.2 ± 0.7 hcu. We have measured an additional 14 specimens from a nearby well (#5A) giving a range of 2.6 to 6.2 with mean of 4.0 ± 0.3 hcu. Using this latter average and the gradient between 100 and 250 meters results in an uncertain estimate (shown in parentheses in Table 6) of 1.7 hfu.

Western Australia

Previous measurements of heat flow in Western Australia were confined to the Yilgarn Block [see e.g., Prider, 1965] of the Archaean Precambrian Shield [Howard and Sass, 1964; Sass, 1964b; Hyndman and Everett, 1968; Hyndman et al., 1968; Jaeger, 1970]. Jaeger [1970] reviewed the available data from Western Australia and tentatively defined a heat flow - heat production relation based on three specially drilled heat-flow holes. (Data from a fourth hole in gneisses fell considerably below the q-A_0 line established by the other three.) This preliminary relation was unique in that the slope, D, of the q-A_0 line defined by $q = q^* + DA_0$ was only 4.5 km as compared with values of 8-10 km in other regions [cf. Roy et al., 1968; Lachenbruch, 1968, 1970; Swanberg et al., 1974; Rao and Jessop, 1974]. The present work (Figure 1, Table 7) presents data from seven additional sites, 6 in the Yilgarn Block (Figure 2) and one at Mount Newman in the Pilbara Block of the old (∿ 2500 m.y.) Precambrian Shield [Prider, 1965].

Kambalda. Hyndman and Everett [1968] presented heat flows ranging from 0.65 to 0.71 and averaging 0.69 hfu from 7 holes drilled by Western Mining Ltd. in the mineralized mafic and ultramafic rocks of the Kalgoorlie Greenstone Belt [see Prider, 1965; Woodall, 1965].

In the present work, we obtained results from another greenstone hole (KD 262, Table 7) that agree with the previous values; however, in a much deeper hole in granite (KD 6003, Table 7) a significantly higher value of 0.82 hfu was obtained. Measurements on 13 core samples of fresh granite between depths of 340 and 1146 meters indicated no systematic variation of heat production with depth [Table 5-1, Bunker et al., 1975] and resulted in a mean A_0 of 3.09 $\pm$ 0.05 hgu.

Mount Goode-Yakabindie. Heat flow was measured at two nearby sites on Anaconda prospects near the northern end of the Kalgoorlie Greenstone Belt (Figure 1, Table 7). In this area, a heat flow of 0.81 hfu measured in granitic rocks (Mount Goode) agrees well with the value of 0.83 measured in interbedded metamorphosed ultramafic and sedimentary rocks at Yakabindie (Table 7). Measurements on six samples of the granite from Mount Goode results in a mean A_0 of 4.6 $\pm$ 0.2 hgu [Table 5-2, Bunker et al., 1975].

Mount Newman. Data are presented from two holes drilled in iron formation rocks at Mount Whaleback by Mount Newman Mining Company Pty. The sites are located in the Hammersley Iron Province of the Pilbara Block (Figure 2) of the Archaean Shield [Prider, 1965]. Because of the steep local topography, two-dimensional Lees type topographic corrections [Jaeger and Sass, 1963] were applied to the temperature gradients. The large scatter in thermal conductivities may be noted from the standard errors in Table 7 [see also pages 81 and 82 of Munroe et al., 1975]. The average of the two values is 1.1 hfu (Table 7).

Mount Windara. Thermal data were obtained from two holes drilled in ultramafic rocks by Poseidon Ltd. (Figure 1). Values from the two holes are in reasonable agreement with an average of 0.96 hfu (Table 7).

Heat-production measurements on five samples of gneissic rocks from the area average 2.8 $\pm$ 0.2 hgu [see Table 5-3, Bunker et al., 1975].

Wanaway-Widgiemooltha. South of Kambalda, two heat-flow values in the ultramafic rocks of the Kalgoorlie Greenstone Belt yield heat flows of 0.82 and 0.76 hfu (Table 7). Four measurements of heat production on samples from nearby granitic outcrops average 2.75 $\pm$ 0.09 hgu [Table 5-4, Bunker et al., 1975].

TABLE 7

New Heat-Flow Data*
Western Australia

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Kambalda									
KD 6003	31° 12'	121° 41'	342	46-1059	23	7.75 ±0.09	10.64 ±0.01	0.82 ±0.01	
KD 262	31° 14'	121° 41'	290	100- 350	12	11.76 ±0.61	6.21 ±0.02	0.73 ±0.04	
				350- 412	6	8.62 ±0.31	7.36 ±0.03	0.63 ±0.02	
				Mean (KD 262)					0.68
				Best value					0.75
Mt. Goode									
MGD 22B	27° 37'	120° 34'	488	24- 79	12	7.74 ±0.09	10.5 ±0.2	0.81 ±0.2	
Mt. Newman									
DH-48	23° 22'	119° 39'	657	146- 216	7	10.65 ±1.16	10.09 ±0.08	1.07 ±0.12	1.1
DH-73	23° 22'	119° 40'	707	259- 332	17	12.83 ±1.29	8.87 ±0.14	1.14 ±0.12	1.2
				Best value					1.1

TABLE 7

New Heat-Flow Data*
Western Australia (continued)

Locality	S. Lat.	E. Long.	Elev. (m)	Depth Range (m)	N	<K>	Γ	q(unc)	q(corr)
Mt. Windarra									
M-298	28° 29'	122° 14'	447	112- 213	18	10.54 ±0.64	9.90 ±0.05	1.04 ±0.06	
W-328	28° 30'	122° 14'	443	42- 175	11	9.93 ±0.72	8.98 ±0.05	0.89 ±0.06	
				175- 318	12	9.23 ±0.85	10.50 ±0.04	0.97 ±0.09	
				Mean (2 holes)					0.96
Wanaway									
W-10E	31° 38'	121° 32'	371	45- 513	33	6.89 ±0.20	11.83 ±0.05	0.82 ±0.02	
Widgiemooltha									
W 474A	31° 31'	121° 35'	317	39- 110	12	9.21 ±0.79	8.26 ±0.07	0.76 ±0.07	
Yakabindie									
SMD 356A	27° 25'	120° 34'	536	89- 235	8	8.12 ±0.22	10.20 ±0.09	0.83 ±0.02	

*See footnote, Table 1, for definitions and explanations of abbreviations in table headings.

HEAT FLOW AND MAJOR TECTONIC UNITS

The distribution of heat-flow measurements can be related to the major geologic features of the Australian continent by comparing Figure 1 to Figure 2, a reproduction of the map by Hills [1965]. The most obvious feature of the distribution is the paucity of data from the major sedimentary basins. The main reasons for this are:

1) the difficulty in arranging access to suitable boreholes,

2) the disequilibrium in most of the thermal data from oil and gas wells and the proprietary status of much of even this information,

and

3) the difficulty of obtaining representative values of thermal conductivity.

The relatively small number of measurements in the basins does, however, provide confirmation and extension of the gross heat-flow patterns measured in crystalline rocks. For example, low-to-normal heat flows of two oil wells in southern Queensland [Sass, 1964a] agree with measurements by Hyndman [1967] in the Paleozoic highlands to the north. Temperature gradients of 30 to 40 °C/km from water wells in the southern Great Artesian Basin [Hind and Helby, 1969] indicate that this zone of low-to-normal heat flow extends as far south as Scone (Figure 1). Northwest of Scone, gradients in the Great Artesian Basin gradually increase to values of 60 to 70 °C/km [Hind and Helby, 1969].

This indicates that the increase in heat flow between Scone and Cobar (Figure 1) extends northward at least as far as the Queensland border. Howard [1965] also estimated a high heat flux (∿ 2 hfu) from an oil test at Innamincka, South Australia, north of the Flinders Ranges (Figure 1) in the southwestern Great Artesian Basin (Figure 2). There are also some very large areas of basement rocks from which no heat-flow data have yet been obtained because of either a lack of drilling for minerals or logistic difficulties. These include (Figure 1 and 2): Southwestern Australia west of the Darling Scarp, a region of high seismicity [Cleary and Simpson, 1971; Doyle, 1971; Fitch et al., 1973]; the Kimberly, Musgrave, and Georgetown Blocks in the younger Precambrian rocks of central Australia; and the Cape York Peninsula Block of the eastern Paleozoic Highlands.

From the information now available (Figure 1), Howard's [1965] original suggestion that heat flow from the Archaean Shield of Western Australia was systematically lower than that for the remainder of the continent has been confirmed and strengthened. Eastern and central Australia cannot, however, be considered a province of uniformly high heat flow as it appeared from the earlier distribution [Howard and Sass, 1964; Sass, 1964a]. The major Proterozoic tectonic provinces of northern central Australia are characterized by high heat flow. The Adelaide Geosyncline and Willyama Block are also high heat-flow provinces, and there is a transition from low to high heat flow between the western and eastern sections of the Gawler platform (Figure 1, Figure 2). The Paleozoic Tasman Geosynclinal Zone (Figure 2) is not a simple heat-flow province. The section north and east of the Hunter-Bowen thrusts is characterized by low heat flow, and the southern part mainly by high heat flow, although there is a well-determined area of normal heat flow near Moruya and a suggestion of low-to-normal heat flow south of Melbourne and in extreme southwestern Victoria (Figure 1). Heat-flow variations within the Tasman Geosynclinal Zone are discussed below in the context of the Tertiary tectonic history of Australia.

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HEAT FLOW AND HEAT PRODUCTION

The discovery by Birch et al. [1968] of a linear relation between heat flow and heat production for the granitic rocks of the northeastern United States, its independent confirmation for the Sierra Nevada [Lachenbruch, 1968] and its extension to other heat-flow provinces in the United States [Roy et al., 1968] has added an important vertical dimension to the interpretation of heat-flow data obtained from plutonic and certain metamorphic terranes. Subject to the assumption that the abundance of radioactive material in the crust decreases exponentially (in a gross way) with depth, the crustal temperature profile beneath any point on the surface of a given heat-flow province can be estimated within useful limits if the surface radioactivity or the surface heat flow is known [see Lachenbruch, 1968, 1970].

For Australia, Howard and Sass [1964], Hyndman and Everett [1968], Hyndman et al., [1968, 1969], and Lambert and Heier [1967, 1968] all sought to explain variations in heat flow or to estimate crustal temperature profiles in terms of the vertical distribution of radioactivity, but the first heat flow - heat production line was proposed by Jaeger [1970] for the Archaean shield of Western Australia. K. S. Heier and I. B. Lambert (unpublished) measured and compiled heat-production data on over 2,000 specimens of granitic and metamorphic rocks collected for various purposes (age dating, physical properties measurements, etc.) by scientists of the Bureau of Mineral Resources and the Australian National University.

Very few precise locations were available to us so that only in rare cases could we use these heat-production data in conjunction with our heat-flow results. It is of interest, however, to examine the gross distribution of radioactivity over the continent based on these determinations. Figure 3 shows the average heat production, A_0, of intermediate and felsic plutonic and metamorphic rocks for 4° x 6° areas of the continent corresponding to individual sheets of the standard 1:1,000,000 International Map of the World. Examination of Figure 3 indicates that Australian rocks may be more radioactive than those on other continents, even on the Archaean shield which has low heat flow. The mean of all determinations is ∿ 7.5 hgu, a higher figure than that (∿ 5 hgu) found by Diment et al. [1975] for a comparable sample from the United States [see also Table 3 of Rao and Jessop, 1975]. As noted by Lambert and Heier [1967], there is not much difference between the mean radioelement abundances for rocks from Western Australia and those from the rest of the continent, certainly not enough to account for the difference in mean heat flows. If we compare the radioactivity distribution in the eastern and southeastern coastal regions (Figure 3) with the distribution of heat flow over the same area (Figure 1) it appears that the regional variations in heat flux are not matched by corresponding regional variations in the radioelement concentrations of the near-surface crystalline basement rocks.

Heat-flow Provinces

Heat flows presented in this paper and some previously published values have been compared with measurements of heat production on material

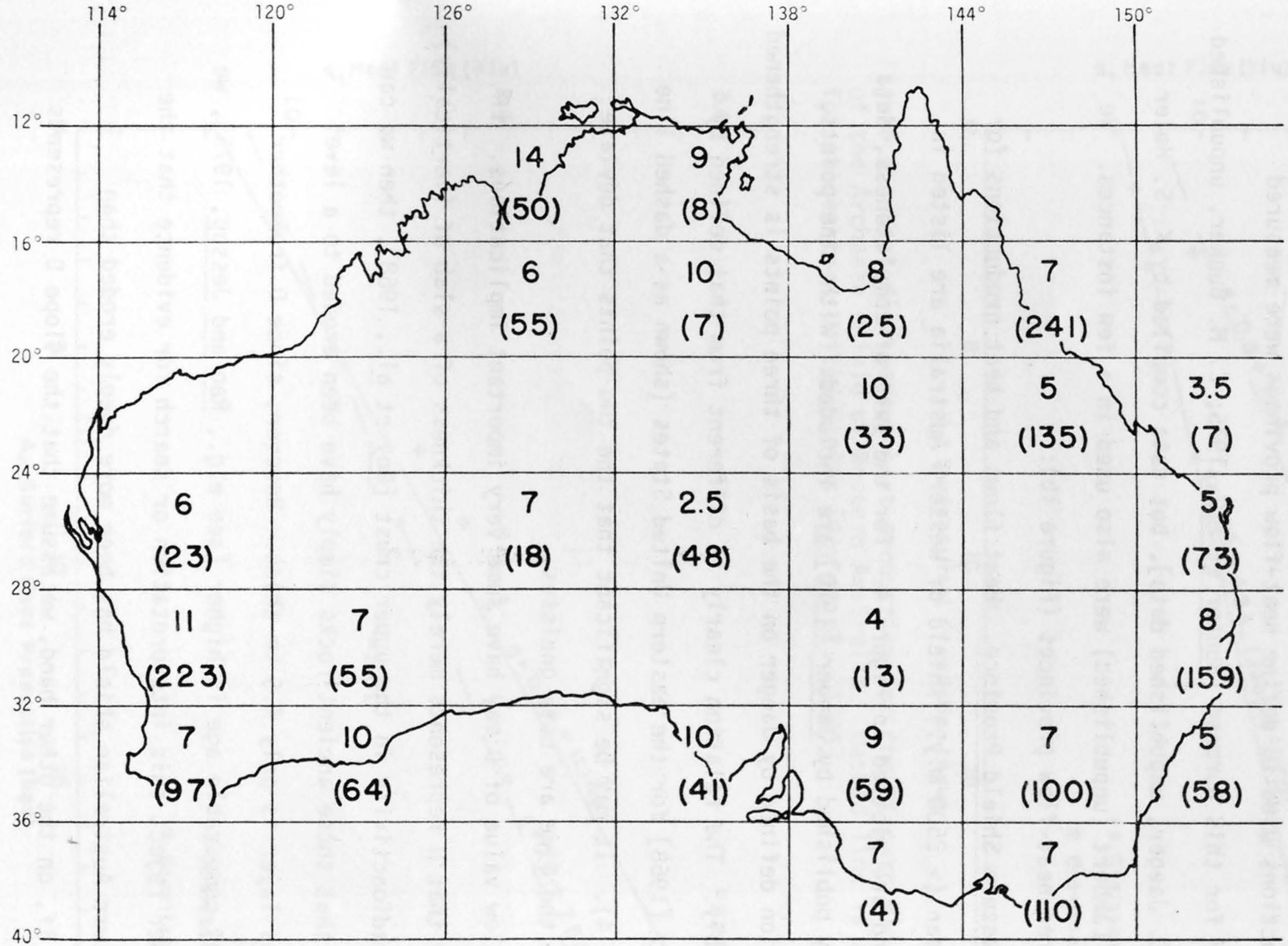

Figure 3. Mean heat production A_o of Felsic intrusive and metamorphic rocks for 4° x 6° areas of the Australian mainland (number of samples measured is shown in parentheses for each square). Data from K. S. Heier and I. B. Lambert, unpublished compilation.

that we could fairly identify with individual heat-flow sites. Most heat productions used to define heat-flow provinces were measured especially for this purpose [Bunker et al., 1975; C. M. Bunker, unpublished data; J. C. Jaeger, unpublished data], but data compiled by K. S. Heier and I. B. Lambert (unpublished) were also used in a few instances. We define three heat-flow provinces (Figure 1b):

1) Western Shield Province. Heat flows and heat productions for the Archaean (> 2500 m.y.) shield of Western Australia are listed in Table 8 and are plotted in Figure 4. For the sake of completeness, data previously published by Jaeger [1970] are included. With nine points, the relation defined by Jaeger on the basis of three points is strengthened considerably. The relation clearly is different from that defined by Roy et al. [1968] for the eastern United States (shown as a dashed line in Figure 4). It may be significant that the two points that deviate most from the line are both gneisses.

The low value of D may have some very important implications. If we assume that D represents merely the thickness of a slab of (vertically) uniform radioactivity in the upper crust [Roy et al., 1968], then we can conclude that these ancient rocks simply have been eroded to a level where this layer is only 4.5 km thick. However, since D from other shields of comparable age is higher [see e.g., Rao and Jessop, 1975], we must either reject this interpretation or search for evidence that the southwestern Australian shield has been more deeply eroded than others. If, on the other hand, we assume that the slope D represents

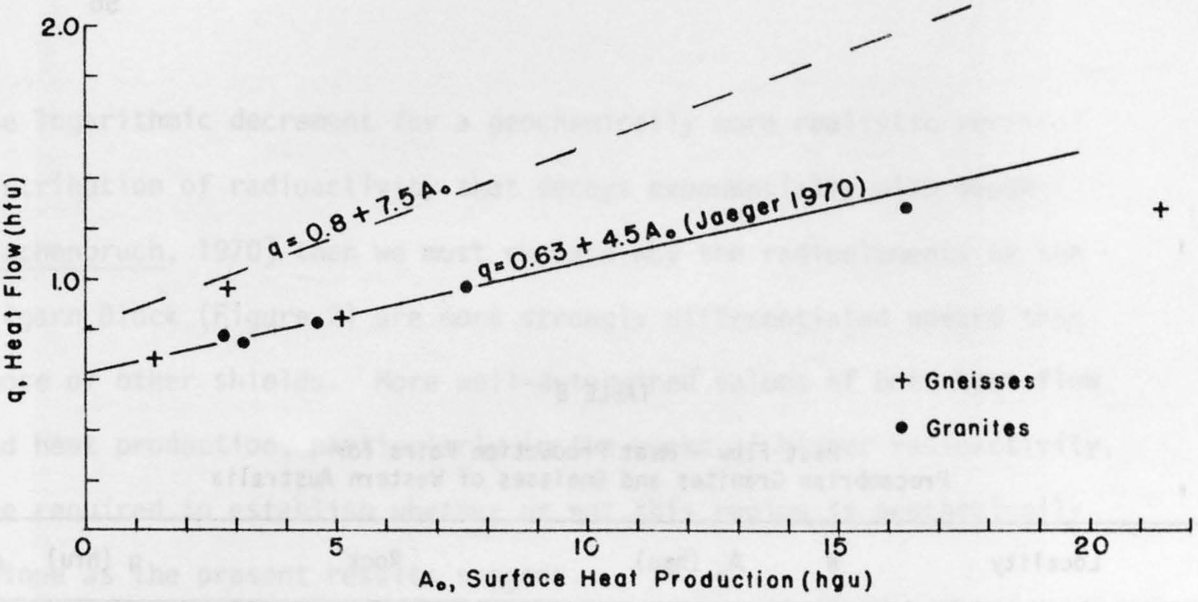

Figure 4. Heat flow versus heat production for the Yilgarn Block (Figure 2) of the Archaean shield of Western Australia. Dashed line is q-A_0 relation for the eastern United States [Roy et al., 1968].

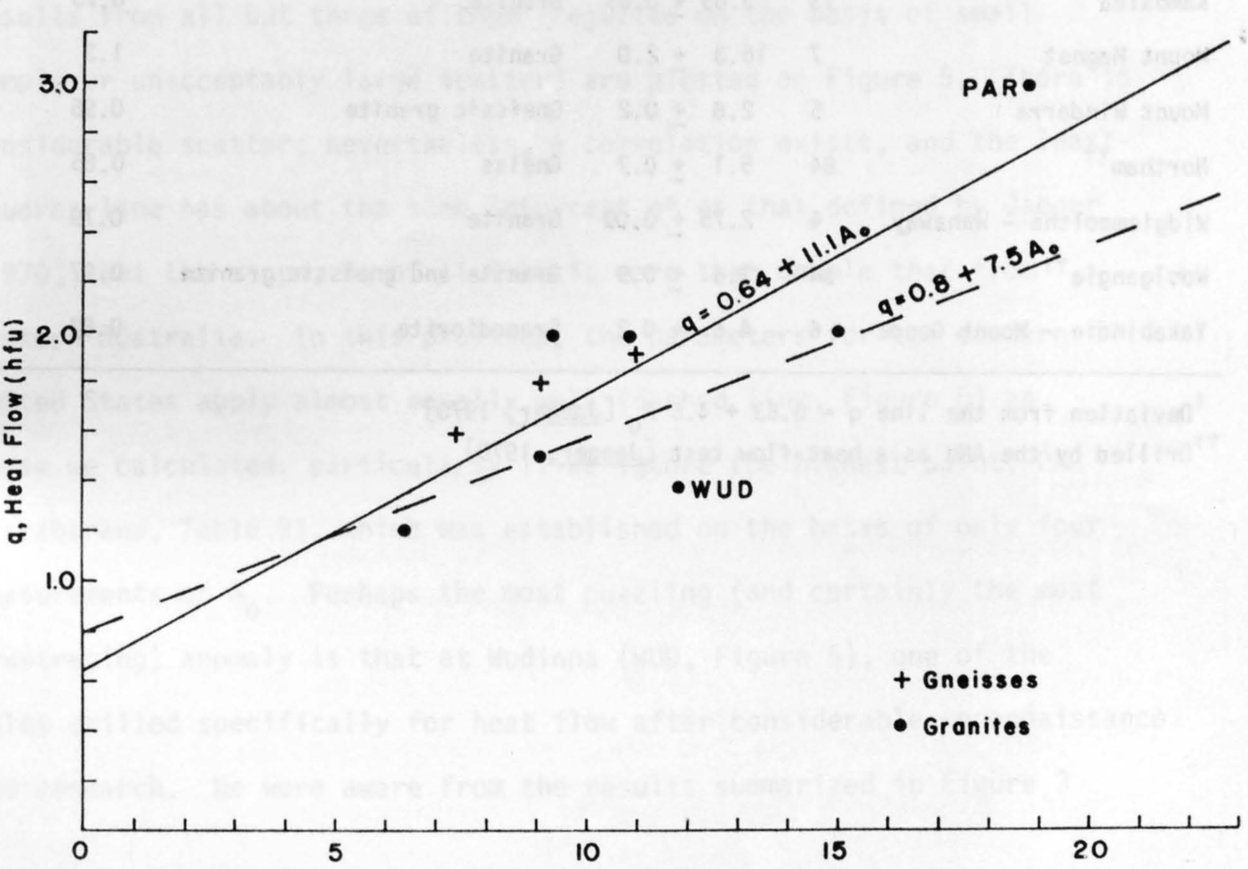

Figure 5. Heat flow versus heat production for the younger Precambrian rocks of central Australia. Dashed line is q-A_0 relation for the eastern United States [Roy et al., 1968].

TABLE 8

Heat Flow - Heat Production Pairs for
Precambrian Granites and Gneisses of Western Australia

Locality	N	A_o (hgu)	Rock	q (hfu)	Δq[†]
Doodlakine[††]	36	21.3 ± 1.1	Granitic gneiss	1.28	-.31
Fraser Range[††]	60	1.3 ± 0.1	Pyroxene granulite	0.69	0
Kambalda	13	3.09 ± 0.05	Granite	0.75	-.02
Mount Magnet	7	16.3 ± 2.0	Granite	1.3	-.06
Mount Windarra	5	2.8 ± 0.2	Gneissic granite	0.96	+.20
Northam[††]	84	5.1 ± 0.7	Gneiss	0.85	-.01
Widgiemooltha - Wanaway	4	2.75 ± 0.09	Granite	0.79	+.03
Woolgangie[††]	54	7.6 ± 0.9	Granite and gneissic granite	0.97	0
Yakabindie - Mount Goode	6	4.6 ± 0.2	Granodiorite	0.82	-.02

[†]Deviation from the line $q = 0.63 + 4.5\,A_o$ [Jaeger, 1970]
[††]Drilled by the ANU as a heat-flow test [Jaeger, 1970]

the logarithmic decrement for a geochemically more realistic vertical distribution of radioactivity that decays exponentially with depth [Lachenbruch, 1970] then we must explain why the radioelements of the Yilgarn Block (Figure 2) are more strongly differentiated upward than those of other shields. More well-determined values of both heat flow and heat production, particularly in the rocks of higher radioactivity, are required to establish whether or not this region is geochemically unique as the present results suggest.

2) Central Shield Province. Table 9 shows heat flow - heat production pairs for the younger Precambrian rocks of central Australia and the results from all but three of them (rejected on the basis of small sample or unacceptably large scatter) are plotted on Figure 5. There is considerable scatter; nevertheless, a correlation exists, and the least-squares line has about the same intercept q* as that defined by Jaeger [1970], but the slope, D, of 11.1 km is more than double that from Western Australia. In this province, the parameters for the eastern United States apply almost equally well (dashed line, Figure 5) as those we calculated, particularly if we ignore the highest point, PAR (Parabarana, Table 9), which was established on the basis of only four measurements of A_o. Perhaps the most puzzling (and certainly the most frustrating) anomaly is that at Wudinna (WUD, Figure 5), one of the holes drilled specifically for heat flow after considerable reconnaissance and research. We were aware from the results summarized in Figure 3

TABLE 9

Heat Flow - Heat Production Pairs for Precambrian Granites and Gneisses of Central Australia

Locality	N	A_o (hgu)	Rock	q (hgu)	$\Delta q^{\dagger}$
Bendigo Sta., SA	12	9.09 ± 0.29	Granite	1.52	-0.13
Blockade, Q†††	2	7.5 ± 2	Granite	1.8	+0.33
Broken Hill, NSW	56	11.0	Gneiss	1.93	+0.07
Iron Knob, SA†††	6	18 ± 5	Granite	2.6	+0.04
Mootooroo, SA	11	7.4 ± 0.4	Gneiss	1.61	+0.15
Mount Isa, Q	8	9.3 ± 0.4	Granite	2.0	+0.15
Parabarana, SA	4	18.8 ± 0.1	Granite	3.0	+0.28
Radium Hill, SA	4	9.1 ± 1.4	Paragneiss	1.8	+0.15
Rum Jungle, NT	33	15.0	Granite	2.0	-0.30
Tarcoola, SA††	20	6.35 ± 0.11	Granite	1.20	-0.14
Tennant Creek, NT	7	9.3 ± 0.4	Granite	2.0	+0.15
Whyalla, SA†††	2	20 ± 5	Granite	2.2	+0.66
Wuddina, SA††	17	11.8 ± 0.6	Granite	1.38	-0.57

† Deviation from the least-squares line $q = 0.64 + 11.1\,A_o$.
†† Drilled by the ANU as a heat-flow test.
††† Excluded from least-squares calculation because of small sample and/or large scatter.

that the region was one of high radioactivity, and we confirmed this at the Wudinna site before drilling. Figure 6 shows the distribution of heat production from all outcrops of crystalline rocks in the area. Samples include our own reconnaissance specimens and a suite of fresh specimens obtained by the South Australian Mines Department [Parker, 1971] using explosives. Individual radioelement concentrations and site names are given in Table 4-6 of Bunker et al. [1975]. Within a radius of 5 km of WUD (Figure 6), heat production varies from 3.3 to 19.5 hgu. A comparable variability is seen over the larger area of Figure 6. Most specimens have high heat production and the averages, both local and regional, are consistent with that found in the hole. It is possible, however, to explain the apparently low heat flow in terms of a sampling problem in characterizing the effective local radiogenic heat production. An extreme example of this problem is Iron Knob (Table 9) where the mean A_0 of 18 ± 5 hgu and the q of 2.6 hfu fortuitously fall precisely on the least-squares line from which they were excluded. An even more extreme example is the Bute-Kadina area of the Yorke Peninsula (Table 5) where q ranges from 2.1 to 2.7 hfu and A_0, from 16 to 120 hgu [Bunker et al., 1975, Table 4-7].

Considering the sampling problems illustrated above, the scatter in Figure 5 is not surprising, and some caution should be exercised in using the parameters of the q-A_0 line. We are satisfied that the q-A_0 relationship in central Australia is consistent with that from other cratons, but the exact agreement of q* between this province and the Archaean shield (Figure 4) is certainly fortuitous.

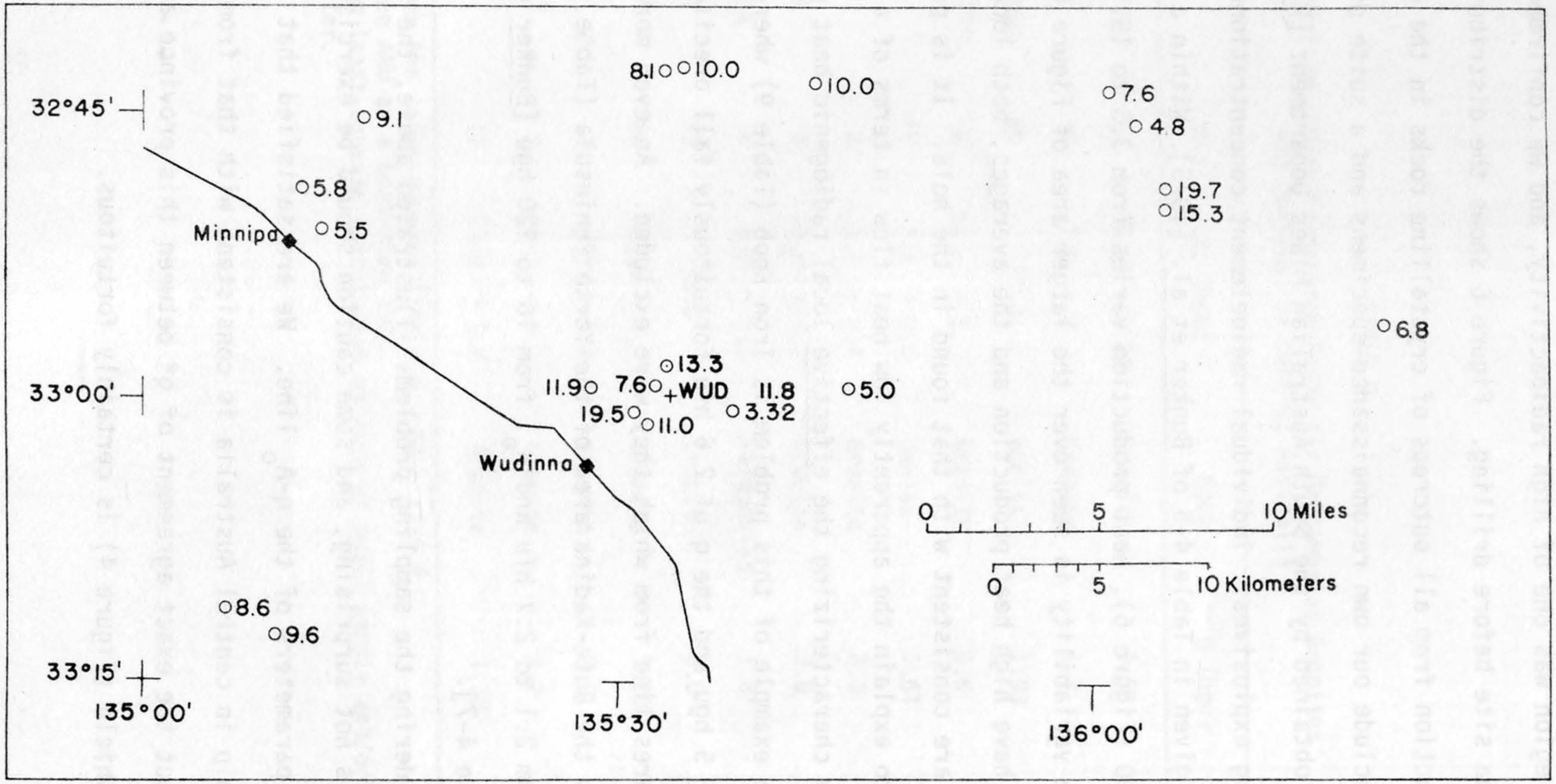

Figure 6. Heat production from granitic and metamorphic rocks in the Wudinna area, South Australia.

3) Eastern Province. The Tasman Geosynclinal Zone (Figure 2) is a Paleozoic structure [Brown et al., 1968; Oversby, 1971], but it has been subjected to Cenozoic uplift and volcanism that accompanied the drift of Australia away from Antarctica and New Zealand [Weissel and Hayes, 1971; Jones, 1971; Wellman and McDougall, 1974b]. The region contains subprovinces of both high and low heat flow (Figures 1 and 2, see also the discussion of heat flow and major tectonic units, above). The relation of heat flow to the Cenozoic tectonic history within the region is discussed below [see also Jaeger and Sass, 1976]. There is no simple relation between heat flow and radioactivity in this province, so we have somewhat arbitrarily calculated a 'reduced' or 'intercept' heat flow q* based on an assumed characteristic thickness D of 10 km (Table 10). Estimates of q* range from a near-cratonic value of 0.8 hfu near Moruya to over 2 hfu at Castlemaine, north of the Pliocene and Quaternary Newer Volcanic province in southwestern Victoria.

An area of interest is the Snowy Mountains subprovince in southeastern New South Wales (Figure 1). Sass et al. [1967] confirmed earlier estimates of heat flow by Beck [1956] and Howard [1965] but they observed differences within the $\sim$ 600 km^2 area that were too large to be ascribed to the normal sources of error. They pointed out that on the basis of preliminary measurements by K. S. Heier given by Kolbe and Taylor [1966] 'The observed variation in radioactivity at the surface is therefore nearly sufficient to account for the variation in heat flow.' In an attempt to substantiate this hypothesis, we measured heat productions

TABLE 10

Observed Heat Flow, q, Radioactivity, A_o, and Reduced Heat Flow, q*, (assuming D = 10 km) for Eastern Australian Paleozoic Intrusive Rocks

Locality	q (hfu)	N	A_o	q*
Bathurst (Apsley)	1.5	3	5.9 $\pm$ 0.2	0.91
Canberra	2.1	14	6.5 $\pm$ 0.6	1.45
Captain's Flat	2.4	5	5.2 $\pm$ 0.7	1.88
Dromedary	1.07	3	2.7 $\pm$ 0.3	0.80
Moruya	1.28	12	3.47 $\pm$ 0.2	0.93
Snowy Mountains	2.0	163	6.25 $\pm$ 0.15	1.38
Castlemaine	2.9	1†	8.2	2.1
Stawell	2.8	1†	7.5	2.0

†Single fresh specimens of granite obtained by blasting for K-AR dating.

on 163 samples from the tunnels [Bunker et al., 1975]. The average of all measurements is shown in Table 10 and the heat flow - heat production pairs, in Table 11. From Table 11 we conclude that there is very little variation in mean heat production among the tunnels and that furthermore, there is no correlation between heat flow and heat production on the scale of this region.

For the northern part of the eastern province (Figure 1) we were unable to obtain specimens for heat production, and we could not pinpoint the locations of samples measured by K. S. Heier and I. B. Lambert (unpublished compilation) with sufficient accuracy to identify them with any of the heat-flow determinations made by Hyndman [1967] near granitic rocks. A comparison of the heat flows in Figure 1 with the regional average (granitic) heat productions shown in Figure 3 indicates that values of q* between 0.6 and 0.8 hfu are most likely in the Queensland part of the Paleozoic highlands.

Crustal Temperature Profiles

Having defined three heat-flow provinces we can now examine the kinds of crustal temperature profiles we could expect for each. We follow Lachenbruch [1970] in assuming an exponential decrease of heat production with depth and thus define the temperature V as a function of depth (z) by [Lachenbruch, 1970, equation 20]

$$V(z) = \frac{q^*}{K}\, z + \frac{D^2}{K}\, A_0[1 - \exp(-z/D)]$$

TABLE 11

Heat flow* and radioactivity† for the Snowy Mountains Hydroelectric Tunnels

Tunnel	q (hfu)	N††	A_o (hgu)
Eucumbene-Snowy	2.3±0.2	44	6.17±0.18
Snowy-Geehi	2.0±0.2	9	5.71±0.25
Murray 1	2.0±0.2	14	6.87±0.61
Tooma-Tumut	1.7±0.2	73	6.21±0.15
Eucumbene-Tumut	1.8±0.4	11	6.90±0.56

* See Table 8 of Sass et al. [1967]

† See Tables 2-4 through 2-9 of Bunker et al. [1975]

†† Number of radioactivity determinations

We assume a value of 6 hcu for the thermal conductivity (K). Steady-state temperature profiles are shown for the three provinces in Figure 7. For the Precambrian provinces (Figure 7a, b) we use the values of q* and D determined empirically (Figures 4 and 5) and calculate temperature profiles beneath surface rocks with A_0 between 0 and 20 hgu. For the eastern province, we assume a constant mean surface heat production of 6 hgu (see Tables 10 and 11 and Figure 3) and calculate profiles for the range of q* estimated in Table 10.

The effect of D is seen by comparing Figures 7(a) and 7(b) where D is the only parameter changed. For the western shield province (Figure 7a) the model predicts a very narrow range of temperatures, with temperatures at the base of the crust in the range 400 to 500°C [cf. Hyndman et al., 1968]. In the younger central shield province, temperatures are higher; in the lower crust, they range from 400 to 800°C (Figure 7b). For the upper part of this range ($q > 2.6$, the points shown as asterisks in Figure 1), we might even expect some partial melting of crustal material under certain conditions [Stern and Wyllie, 1973]. In Figure 7c the dramatic effect of increasing the deep crustal and mantle contribution to the heat flow is clearly seen. For a heat flow of 2.0 (e.g., in the Snowy Mountains), the temperature predicted for the base of the crust is about 1000°C. For heat flows like those observed at Stawell and Castlemaine in Victoria (Figure 1, Table 10) the 'dry' basalt solidus [see e.g., Harris et al., 1970] or even the pyrolite solidus [see e.g., Ringwood and Green, 1969] would be exceeded under steady-state conditions between

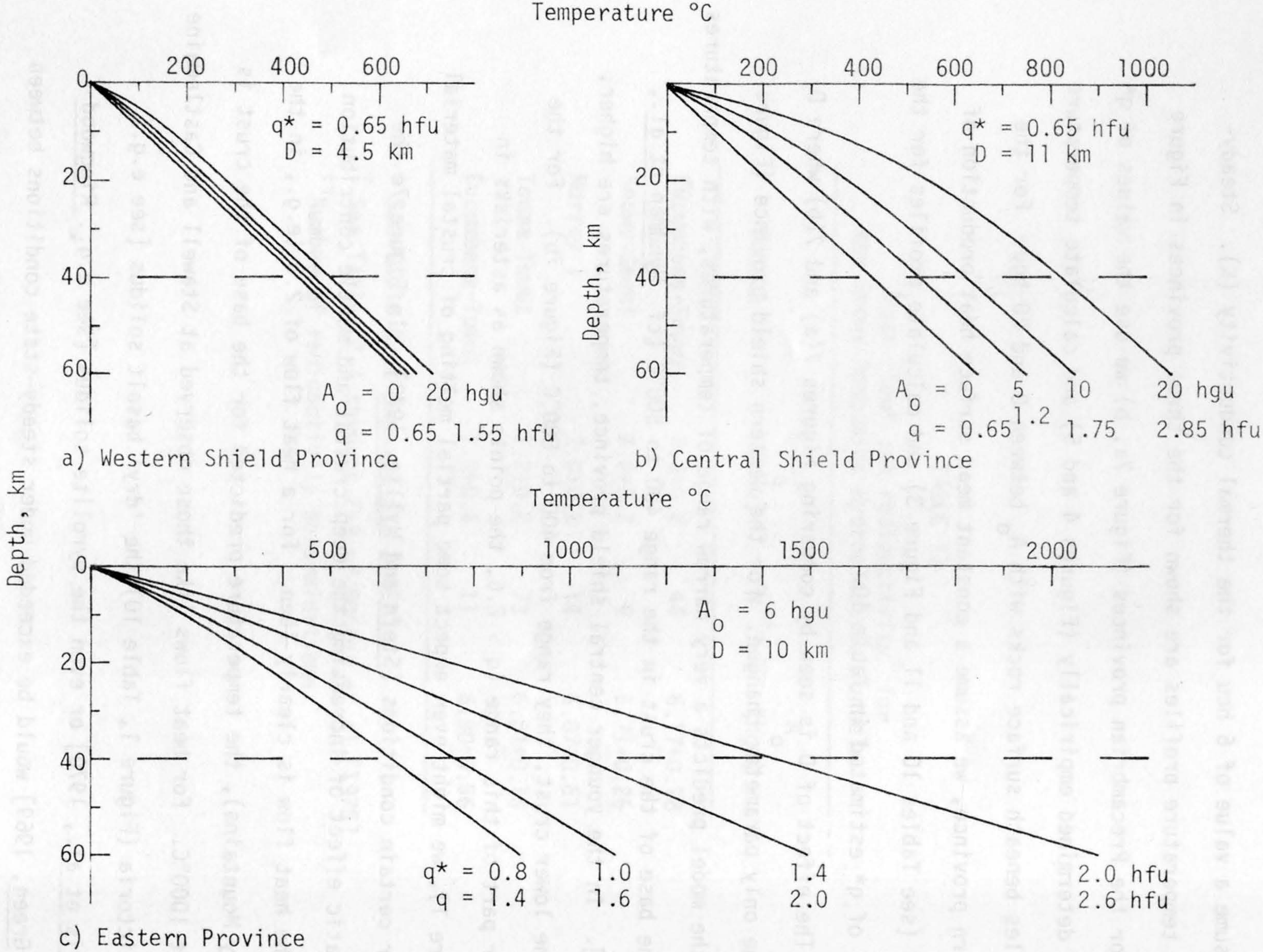

Figure 7. Theoretical steady-state temperature profiles for the three Australian heat-flow provinces (thermal conductivity is assumed constant = 6 hcu). Dashed horizontal line represents base of crust.

30 and 40 km. This is obviously unrealistic, and we must invoke a transient thermal state (melting or hydrothermal convection within the crust) to support heat flows of 2.6 or more (asterisks, Figure 1) in regions of moderate crustal radioactivity.

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HEAT FLOW AND CENOZOIC VOLCANISM

Igneous activity in eastern Australia evidently began about 70 m.y. ago with the rifting that preceded the separation of the Antarctic and Indian plates [Weissel and Hayes, 1971]. Between about 60 m.y. and the present, volcanic activity has occurred at a constant rate of about 300 km^3/m.y. [Wellman and McDougall, 1974b]. Two distinct types of volcanism are observed:

1) Lava fields consisting exclusively of basalt predominated between ∿60 and 34 m.y. b.p. and were distributed more or less randomly in time throughout the eastern Paleozoic highlands [Wellman and McDougall, 1974b].

2) Between 33 m.y. ago and the present, most volcanic rocks occurred as central volcanoes [Wellman and McDougall, 1974b]. These are well defined basaltic bodies with some associated felsic flows and felsic and mafic intrusions. They are arranged in a regular geometric pattern indicating a S 8°W migration of volcanism at a rate of 66 mm/y, which compares favorably with the rate of separation of Australia and Antarctica. Wellman and McDougall [1974b] interpret this observation in terms of northward migration of the continent over a stationary source of magma in the asthenosphere.

Figure 8 shows the remarkable southward progression of the central volcanoes together with the variation of heat flow with latitude in the Paleozoic rocks of the eastern coastal region. The gross variation

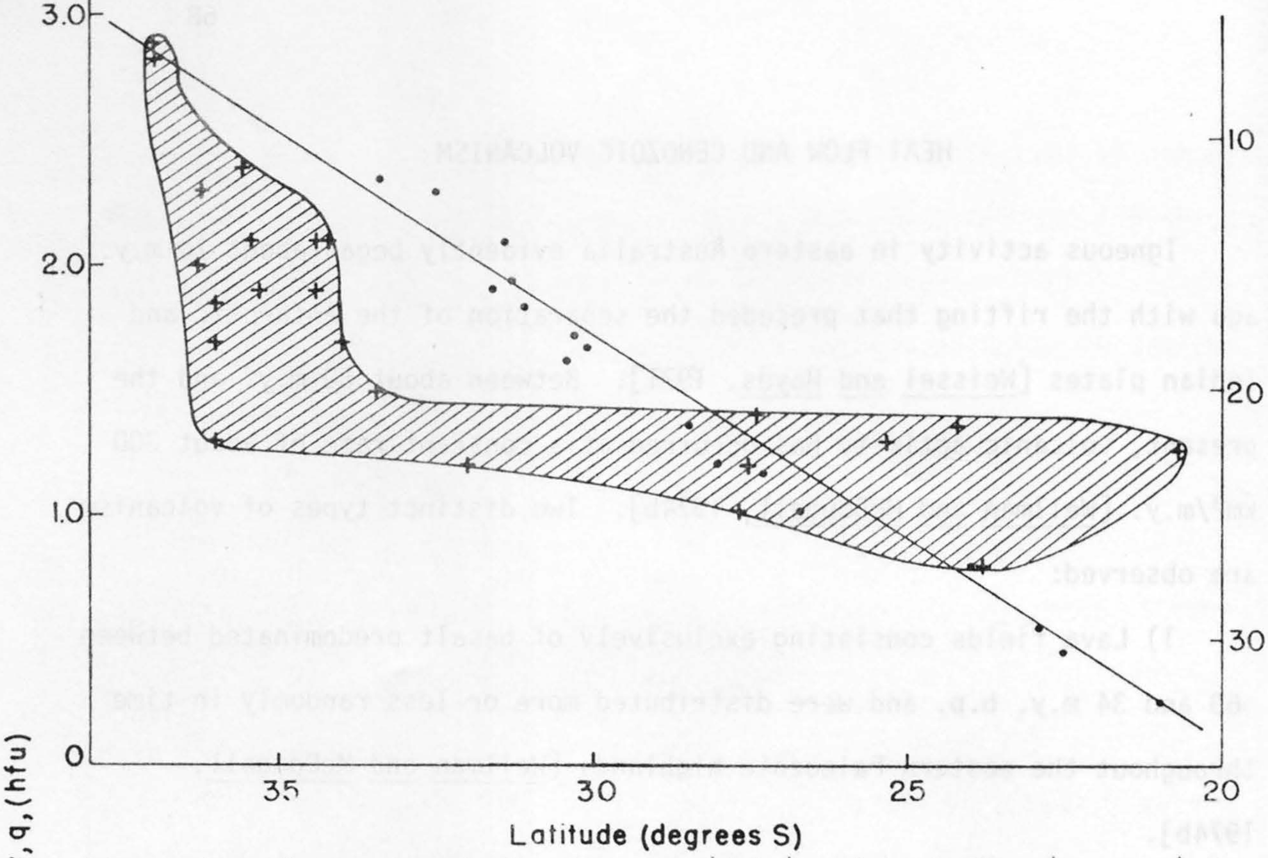

Figure 8a. Ages of central volcanoes (dots) and heat flow (crosses) from the Paleozoic rocks of eastern Australia as a function of latitude.

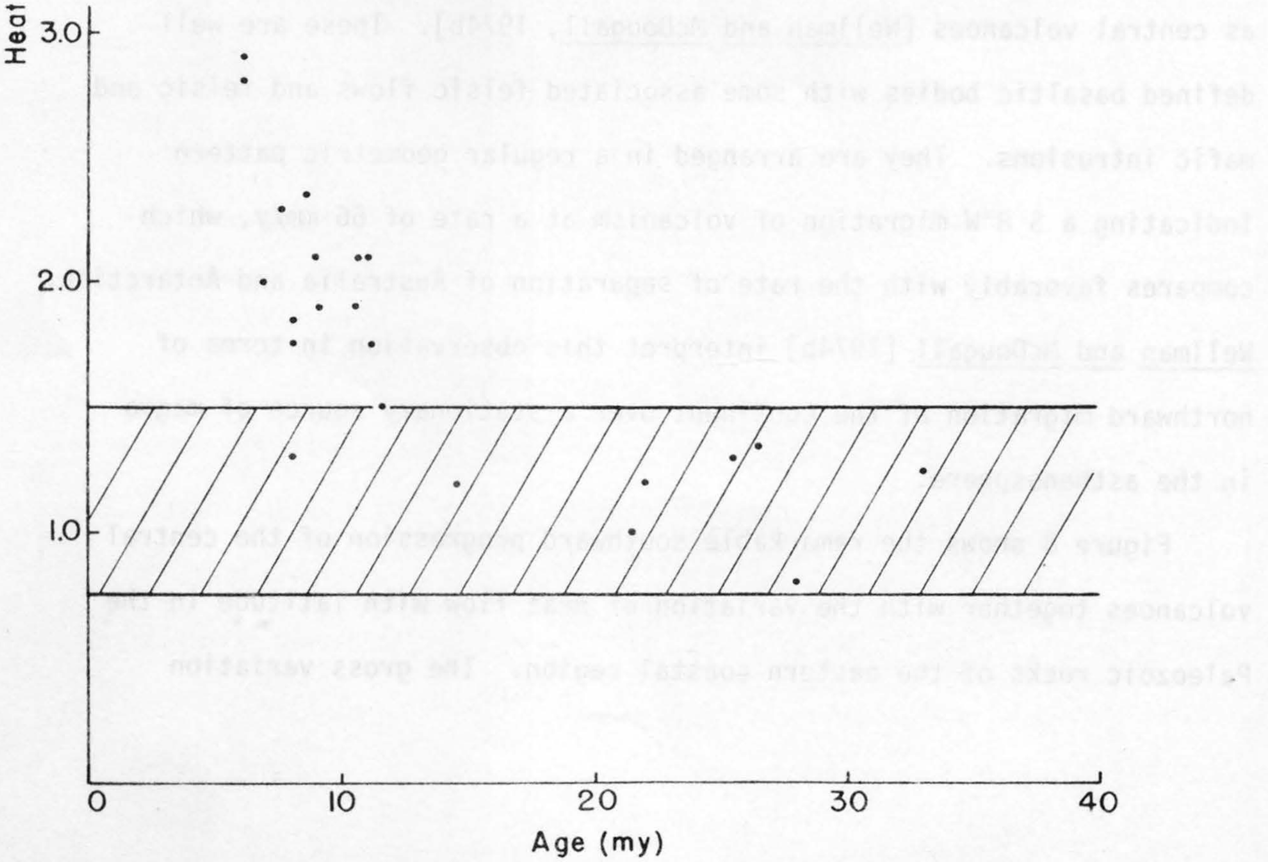

Figure 8b. Heat flow in eastern Australian Paleozoic rocks as a function of age of central-volcano type volcanism [Wellman and McDougall, 1974b] as inferred from the age-latitude relation. Shaded area indicates range of 'normal' heat flow from cratons.

of heat flow outlined in the shaded area of Figure 8a (replotted as heat flow at a given latitude versus age of central volcanism at that latitude in Figure 8b) is consistent with simple conduction models involving transient heat sources in the lower crust and upper mantle [Jaeger and Sass, 1976] particularly if we allow for lateral variations in crustal radioactivity.

There are at present no heat-flow determinations within or near any of the central volcanoes; however, several heat flows have been measured in or near lava fields where ages are not correlated with latitude [Wellman and McDougall, 1974b].

The detailed geochronologic results from ten of the lava fields [Wellman, 1971, 1974; Wellman and McDougall, 1974a; Aziz-Ur-Rahman and McDougall, 1972; McDougall et al., 1966] are compared with heat-flow determinations [Hyndman, 1967; Sass, 1964a; Sass et al., 1967; Jaeger, 1970 and present work] either inside or within 10 km of the edge of the field in Table 12. Heat flow is plotted against age of volcanism in Figure 9. For the lava fields, there appears to be no simple relation between age of volcanism and surface heat flow, q, or reduced heat flow, q*. This is not really surprising in view of the observation that these provinces are exclusively basaltic and thus are derived from the mantle along narrow conduits [Wellman and McDougall, 1974b] as compared with the central volcano provinces with their felsic flows and intrusive rocks. These might be expected to have involved larger volumes of molten material closer to the surface for a longer period than lava field provinces of comparable size.

TABLE 12

Heat Flow and Age of Cenozoic Volcanism for Eastern Australian Lava Fields

Lava field	Age range m.y.	Age nearest heat flow m.y.	Heat-flow locality	q (hfu)	q* (hfu)
Rockhampton, Q	66 - 70		Mt. Morgan	0.8	
Ipswich, Q	62 - 63		Ipswich	1.4	
East Liverpool, NSW	33 - 42	38	Scone	1.2	
Abercrombie, NSW	15 - 39	16	Bathurst	1.5	0.9
Mittagong, NSW	30 - 54	~35	S. Sydney Basin	~2.0	
Moruya, NSW	26 - 31	~30	Moruya	1.3	0.9
Snowy, NSW	17 - 22	~20	Eucumbene-Tumut	1.8	1.1
			Tooma-Tumut	1.7	1.1
Monaro, NSW	36 - 53	36	Eucumbene-Snowy	2.3	1.7
Flinders, VIC	39 - 47	42	Sorrento	1.3	
Newer Volcanics, VIC	<0.01 - 4.5	~2	Castlemaine	2.9	2.1
		0.6	Timboon	1.7	
		~3	Portland	1.2	

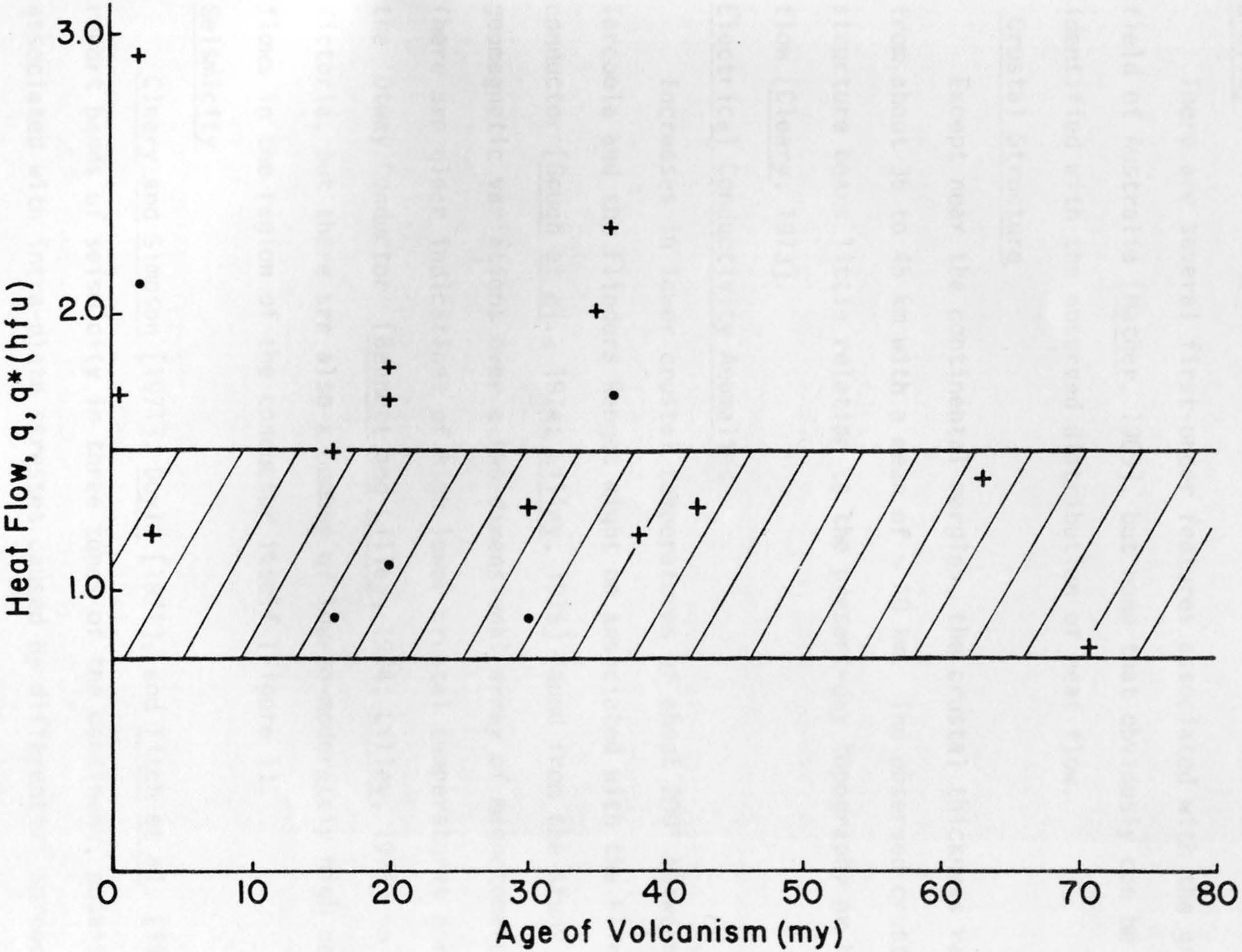

Figure 9. Heat flow (crosses) and reduced heat flow (dots) versus age of lava field type volcanism (Table 12). Shaded area shows the range of heat flow normally observed in stable continental areas.

HEAT FLOW AND OTHER GEOPHYSICAL PARAMETERS

Gravity

There are several first-order features associated with the gravity field of Australia [Mather, 1969], but none that obviously can be identified with the observed distribution of heat flow.

Crustal Structure

Except near the continental margins, the crustal thickness ranges from about 35 to 45 km with a mean of ~ 40 km. The observed crustal structure bears little relation to the present-day topography or heat flow [Cleary, 1973].

Electrical Conductivity Anomalies

Increases in lower crustal temperatures of about 200° between Tarcoola and the Flinders Ranges might be associated with the Flinders conductor [Gough et al., 1974; Lilley, 1975] found from the study of geomagnetic variations over a two-dimensional array of magnetometers. There are clear indications of high lower crustal temperatures north of the 'Otway Conductor' [Bennett and Lilley, 1974; Lilley, 1975] in southern Victoria, but there are also a number of low-to-moderately high heat flows in the region of the conductor itself (Figure 1).

Seismicity

Cleary and Simpson [1971], Doyle [1971], and Fitch et al. [1973] report bands of seismicity in three zones of the continent, possibly associated with intra-plate stresses caused by differential spreading rates along the Antarctic Ridge. For the westernmost band near the Darling

Scarp (Figure 2) we have no heat-flow data. The band of seismicity in the Adelaide geosynclinal region (Figure 2) is associated with high heat flow and surface radioactivity from which we deduce that temperatures in the lower crust and upper mantle are moderately high (Figure 7b). Generally high heat flow is also observed in the seismically active zone of eastern Australia.

P-Delays

In a study of compressional wave travel-times from nuclear explosions to various Australian stations, Cleary [1967] found that early arrivals predominate in Precambrian rocks and late ones in the Paleozoic eastern highlands. This is one geophysical observation that distinguishes the central Australian high heat-flow province from the apparently hotter southern part of the eastern province (compare theoretical temperature profiles for Figures 7b and c).

Q

Mereu et al. [1974] postulated a region of low Q and consequently of high temperature in the upper mantle beneath northern Australia from observations at the Warramunga seismic array near Tennant Creek (Figure 1) of earthquakes originating in the subduction zone to the northeast. P-arrivals at Warramunga are early [Cleary, 1967], and there is no evidence for low P_n velocities [Cleary, 1973]. These observations are consistent with the moderately high upper mantle temperatures predicted for this province using the empirical relations between heat flow and heat production (Figure 7b).

GEOTHERMAL ENERGY POTENTIAL

Until quite recently, the thrust of geothermal energy exploration and development has been concentrated on the high enthalpy systems most commonly encountered near active continental margins and zones of rifting within the continents [see e.g., Figure 1 of White, 1973]. However, with the escalating costs of energy and the accelerating development of the technology of energy extraction from lower temperature systems, there is an increasing interest in regions of moderately high heat flow as economically feasible energy sources [see White and Williams, 1975].

Even though the possibility of large capacity electrical power-generating plants like those in New Zealand and The Geysers area of California seems remote, moderately large binary-fluid generating systems might prove practicable in Tasmania, Victoria, and southeastern New South Wales. Elsewhere in eastern Australia, temperatures within a kilometer or so of the surface, particularly in many areas of low (thermal) conductivity basin sediments, should be sufficiently high that the energy can be extracted for space-heating, air conditioning, and agriculture.

GEOTHERMAL ENERGY POTENTIAL

Until quite recently, the thrust of geothermal energy exploration and development has been concentrated on the high enthalpy systems most commonly encountered near active continental margins and zones of rifting within the continents (see e.g., Figure 4 of White, 1973). However, with the escalating costs of energy and the accelerating development of the technology of energy extraction from lower temperature systems, there is an increasing interest in regions of moderately high heat flow as economically feasible energy sources (see White and Williams, 1975).

Even though the possibility of large capacity electrical power generating plants like those in New Zealand and the Geysers area of California seems remote, moderately large binary-fluid generating systems might prove practicable in Tasmania, Victoria, and southeastern New South Wales. Elsewhere in eastern Australia, temperatures within a kilometer or so of the surface, particularly in many areas of low (thermal) conductivity basin sediments, should be sufficiently high that the energy can be extracted for space-heating, air conditioning, and agriculture.

SUMMARY AND CONCLUSIONS

The new heat-flow data presented here confirm the patterns previously established and they provide significant extensions to the knowledge of the thermal state of Australia as summarized by Jaeger [1970]. In Western Australia (Figure 1) we have confirmed the earlier picture in the Kalgoorlie-Norseman region, extended the zone of low heat flow northward and eastward within the Yilgarn Block (Figure 2) and extended it northward to the Pilbara Block of the Archaean shield. Jaeger's [1970] heat flow - heat production relation for this region has been more firmly established and a narrow range of crustal temperatures is predicted from it.

The younger Precambrian shield of central Australia is a province characterized by high heat flow that can be explained in terms of the generally high radioactivity of the surface rocks of the region. The heat flow - heat production relationship is consistent with that from the North American craton. The moderately high steady-state crustal and upper mantle temperatures predicted from the q-A_0 relation seem reasonable in view of the relatively high seismicity, low Q, and normal P_n velocities under the province. There is a transition within the province from low-to-normal heat flows in the Gawler platform to high values in the Adelaide geosyncline and Willyama Blocks (Figure 2). The temperature differences of $\sim$ 200°C for the lower crust and upper mantle predicted for this transition (see Figure 7b) might be connected with the electrical conductivity anomaly (the Flinders conductor) discovered by Gough et al. [1974] [see also Lilley, 1975].

In the eastern province (Figure 1), the remarkably consistent southward migration with time of Cenozoic central volcanoes (or northward migration of the continent) is reflected in increasing heat flow from north to south (Figure 8) but no correlation is evident between the ages of lava fields and individual heat flows (Figure 9). The province is one of moderate crustal radioactivity (Figure 3) so that we have interpreted variations in surface flux (q) primarily in terms of the heat flow from the lower crust and upper mantle (q*). The high steady-state crustal and upper mantle temperatures predicted on this basis for regions with heat flows of 2 hfu or greater (Figure 7c) are consistent with the observed seismicity, volcanism, P-delays and electrical conductivity anomalies. The extraction of useful amounts of geothermal energy might well be feasible in the southern parts of this province.

Acknowledgments. We thank numerous individuals from the mining companies and state mines departments mentioned above. Professor A. R. Crawford was very helpful in the selection of drill sites and the collection of relatively fresh granite samples. The two heat-flow holes in South Australia were drilled by the Department of Mines, South Australia. We thank Brendan P. Thomson for facilitating the drilling and for his assistance in organizing other phases of our work in South Australia. Maureen Sass was extremely helpful in obtaining the data and in the various stages of processing of both rocks and data.

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