Climatic corrections to Australian heat-flow data

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Surface heating subsequent to Pleistocene glaciation in Australia has resulted in a decrease in near-surface thermal gradients. Heat flow in shallow holes therefore appears to increase with the depths of determination. Some data obtained at depths less than 300 m may require positive corrections up to 25 percent, depending on the rate of glacier retreat and the amount of warming. Climatic models formulated for periglacial regions have been generalised for regional use. Surface temperatures are assumed to have increased by 5°C at 15 000 BP. The primary features of this model have been confirmed, using data previously published for deep holes remote from regions of glaciation near Kalgoorlie and Broken Hill.

Introduction

In regions of recent glaciation it is observed that surface heat-flow values increase with the depths of determination (Crain, 1968). This trend results from perturbations in the geothermal gradient, caused by surface warming subsequent to the retreat of the Pleistocene sheet ice.

Complex climatic models have been proposed for the northern hemisphere—including Holocene temperature fluctuations, but the magnitude of the perturbation remains contentious. Beck (1977) has reviewed the principal facts of climatic history, and concludes that corrections in excess of 20 percent may be required for some heat-flow data in Europe and North America.

However, the significance of climatic history earlier than the Pleistocene is yet to be demonstrated. For a single borehole in Canada no convincing trends were detected in data obtained at depths approaching 3000 m (Sass, Lachenbruch, & Jessop, 1971). It can be concluded that sequential climatic events in the Pleistocene have been partly cancelled during sub-surface propagation, and only the most recent event remains to be considered.

In Australia glacial perturbations have always been considered negligible, and average values of thermal conductivity have been used together with linear temperature gradients for calculating heat flow. Systematic changes in thermal gradient have been noted in some areas (Howard & Sass, 1964), and a pronounced near-surface curvature in gradient has been attributed to rapid clearing of vegetation with increased insolation subsequent to settlement (Hyndman & Everett, 1968). However, similar perturbations have also been noted in undeveloped desert regions which have little significant ground cover (Cull & Denham, 1979). Furthermore, well-determined linear geothermal gradients appear to be accompanied by unexplained systematic increases in thermal conductivity (Hyndman & Everett, 1968). All of these observations suggest secular changes in climate consistent with the models of glacier retreat proposed for the northern hemisphere.

New data have now been obtained in two boreholes close to regions of recent glaciation (Fig. 1). The first, designated CANBERRA, is a stratigraphic borehole located near the Bureau of Mineral Resources in the ACT (BMR 145, 35.30S, 149.15E); it penetrates Silurian limestone to a depth of 260 m. The second hole, WOODLAWN, was drilled during mineral exploration 15 km NW of Tarago in NSW (Jododex CE 12, 34.98S, 149.52E); it penetrates Silurian rhyolite to a depth of 250 m. In both holes heat flow appears to increase with the depth of determination; conductivity sampling errors are small, and climatic models for the Australian continent must therefore be considered before corrections can be suggested.

Measurements of surface heat flow

Temperatures were measured at 10 m intervals, using a thermistor probe attached to a 300 m cable. Changes in resistance were monitored at the surface with a Wheatstone bridge giving a resolution better than 0.01°C. Thermal conductivities were measured on core samples from each hole, using divided bar techniques. Ratcliffe's (1959) values for quartz, were adopted for calibration, and core sample conductivities are considered accurate to 1.5% (Cull & Sparksman, 1977).

Data for each hole are plotted in Figure 2. Consistent with the observations of Howard & Sass (1964), surface temperatures in both holes exceed the mean annual air temperature by approximately 3°C. However, surface boundary conditions are not readily specified from meteorological data, because of local variations in ground albedo and air coupling. For CANBERRA there is pronounced curvature in the temperature profile, reflecting a systematic decrease in thermal conductivity. However, four linear segments can be defined for the intervals 70-120 m, 130-180 m, 190-220 m,

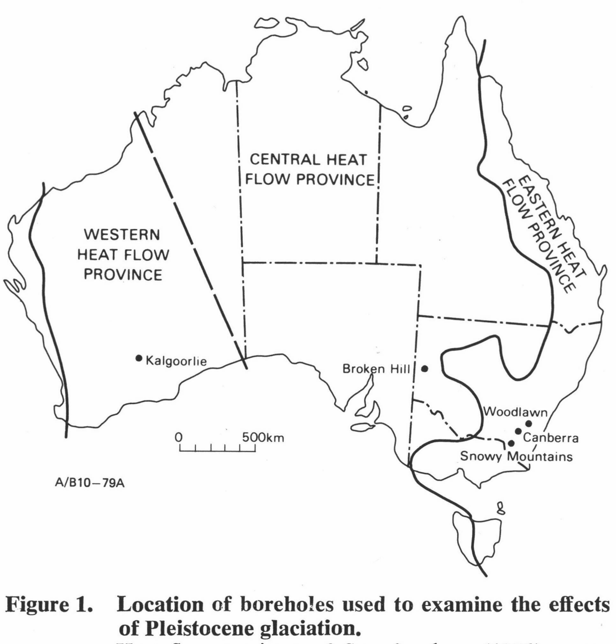

Figure 1. Location of boreholes used to examine the effects of Pleistocene glaciation.
Heat flow provinces of Sass & others (1976) superimposed.

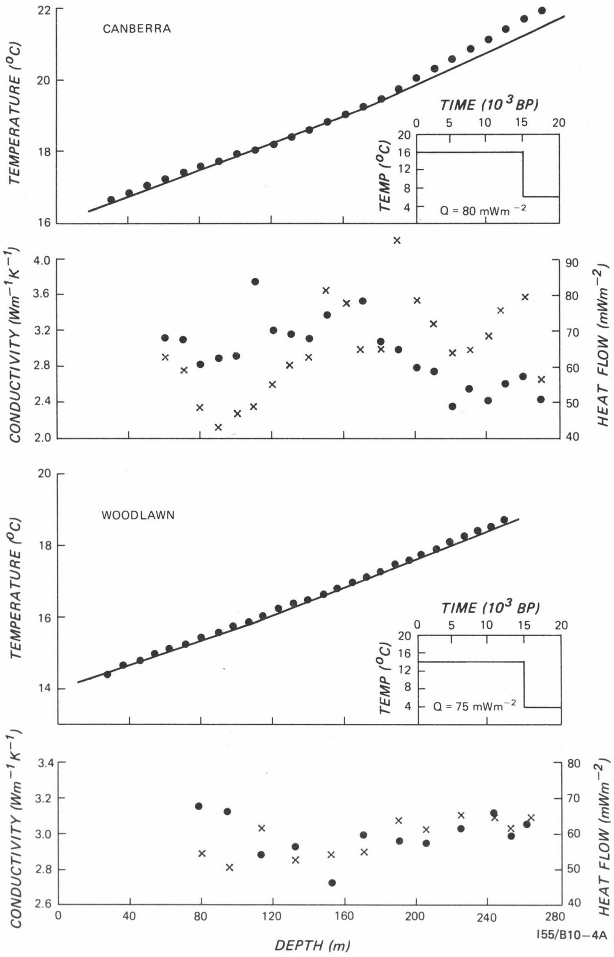

Figure 2. Borehole temperatures, conductivities, and heat flow as a function of depth at (a) Canberra, (b) Woodlawn.
Inset: climatic models used to generate solid line giving approximate fit to observed temperatures.

230-260 m. Separate determinations of heat flow were made for each interval, giving 48.6, 70.2, 73.8 and 74.2 mW m^{-2} respectively. A systematic variation of this type may be fortuitous in view of the possible sampling errors resulting from fluctuations in thermal conductivity. However, as shown below, the results are consistent with a secular change in surface temperature.

For WOODLAWN there is only slight curvature in the temperature profile; two linear segments can be used to approximate data in the intervals 40-160 m and 160-260 m. Thermal conductivity is reasonably uniform, and average values can be adopted, giving heat flows of 55.5 and 62.7 mW m^{-2}, respectively. If individual determinations of thermal conductivity are combined with apparent gradients in corresponding 10 m depth intervals, there is again some suggestion of an increase in heat flow with the depth of determination (Table 2). A similar trend can be observed with the CANBERRA data (Table 1).

Depth (*m*)	λ $Wm^{-1}K^{-1}$	β ($mK\ m^{-1}$)	Q ($mW\ m^{-2}$)
60	3.11	20.0	62.2
70	3.10	19.0	58.9
80	2.82	17.0	47.9
90	2.88	15.0	43.2
100	2.92	16.0	46.7
110	3.76	13.0	48.9
120	3.20	17.0	54.4
130	3.17	19.0	60.2
140	3.12	20.0	62.4
150	3.38	24.0	81.1
170	3.52	22.0	77.4
180	3.07	21.0	64.5
190	2.99	32.0	95.7
200	2.80	28.0	78.4
210	2.77	26.0	72.0
220	2.37	27.0	64.0
230	2.57	25.0	64.3
240	2.43	28.0	68.0
250	2.62	29.0	76.0
260	2.72	29.0	78.9
		average (13)	72.5
		standard deviation	9.6
		standard error	2.7

$Q = 72.5 \pm 2.7$ mW m^{-2}

Table 1. Determinations of heat flow as a function of depth at Canberra (BMR 145).

Depth (*m*)	λ $Wm^{-1}K^{-1}$	β ($mK\ m^{-1}$)	Q ($mW\ m^{-2}$)
78	3.16	17.24	54.48
94	3.13	16.28	50.96
113	2.89	21.43	61.93
132	2.93	18.29	53.59
152	2.73	20.00	54.60
170	2.99	18.51	55.32
190	2.96	21.79	64.50
205	2.94	20.51	60.30
225	3.03	21.79	66.02
243	3.11	21.05	65.47
253	2.99	21.05	62.94
262	3.07	(21.0)	(64.5)
		average (12)	59.55
		standard deviation	5.18
		standard error	1.49

$Q = 59.6 \pm 1.5$ mW m^{-2}

Table 2. Determinations of heat flow as a function of depth at Woodlawn (CE 12).

Secular changes in surface temperature

Climatic models for Australia during the Quaternary have been reviewed by Bowler & others (1976), and the principal facts summarised here are extracted from that work. Models for southern Australia are based primarily on changes in vegetation growth patterns, but there is good geological control with numerous glacial/periglacial features found in highland regions.

The evidence for glacier action in the Snowy Mountains is confined to an area of less than 50 km^2 near Mount Kosciusko, but periglacial features are more widespread, suggesting periods of low temperature for larger areas. Dating of organic moraine sediments indicates a glacier maximum at about 20 200 BP. Dates obtained from basal peats suggest a retreat prior to 14 500 BP, but the possibility is not discounted that small glaciers survived to 9000 BP.

Pollen analyses indicate that alpine herbfields were established at altitudes of 1800 m as early as 16 500 BP, with tall alpine herbfields and bog communities appearing at about 13 000 BP. A significant surge in growth is noted after 9000 BP, with a rise in treeline to present levels. Subsequent temperatures are considered similar to present values except for the period 3800-1700 BP, when a decrease of 3°C is indicated.

At Lake George near WOODLAWN pollen studies confirm the major trends noted for the Snowy Mountains. A cold period is provisionally dated between 22 000 and 14 000 BP. By 6000 BP, temperatures had increased to within 3°C of present values. Further evidence is derived from geomorphic studies of abandoned shorelines. High water levels, corresponding to reduced evaporation rates at low temperature, are indicated between 26 000 and 19 000 BP. Subsequent retreat may correspond to generally increasing temperatures, with temporary reversions to cooling at 15 000, 5000, and 3000 BP.

Ground temperatures in periglacial regions were at least 6°C and possibly 10°C less than the present summer mean (Bowler & others, 1976, p. 370). For CANBERRA and WOODLAWN, Pleistocene mean temperatures of about 4°C can be inferred, similar to present-day values of about 6°C at Kiandra and Kosciusko, where isolated snow banks occasionally persist through summer, causing near-periglacial conditions.

The above data suggest that glacier retreat, commencing about 15 000 BP, was substantially complete by 10 000 BP. A rapid increase in surface temperatures is indicated together with a subsequent period of general stability, which persists to the present.

Variations in geothermal gradient

Climatic models derived from the above data can be tested by matching observed and predicted temperature profiles at WOODLAWN and CANBERRA. Exact numerical solutions can be obtained for heat flow in uniform media, but highly complex integral equations are generated for more complex models. Consequently, finite difference techniques were adopted with summations by digital computer. A Schmidt slab was assumed for this purpose (Ingersoll & others, 1948, p. 209), so that thermal parameters could be varied with depth. Intervals having constant thermal characteristics were chosen to correspond with the location of core samples extracted at successively greater depths for measurements of thermal conductivity. Heat capacity was assumed to be constant with depth (880 J kg^{-1} K^{-1}), and thermal diffusivities were calculated for each interval from measurements of density and thermal conductivity (Beck, 1977, p. 25). Heat flow remains the only physical parameter to be specified. For both WOODLAWN and CANBERRA, the observed values of heat

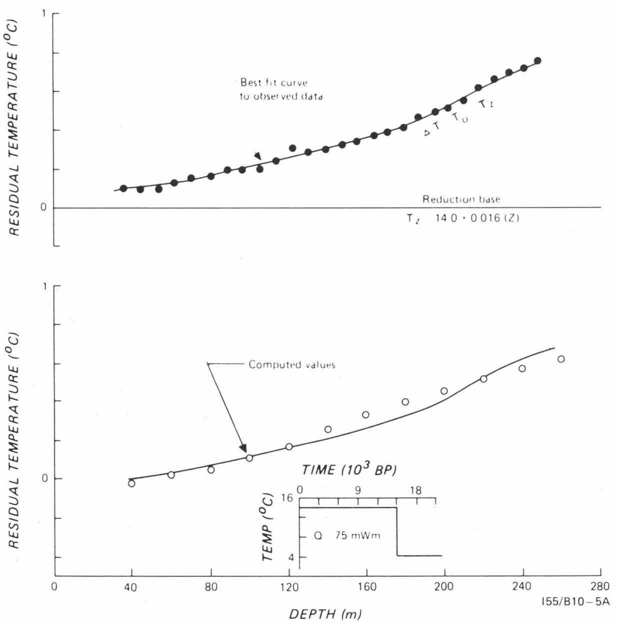

Figure 3. (a) Borehole temperature at Woodlawn related to arbitrary linear gradient; (b) Temperature excursions calculated from inset climatic model. Heat flow adjusted to obtain approximate fit to observed gradient (solid line).

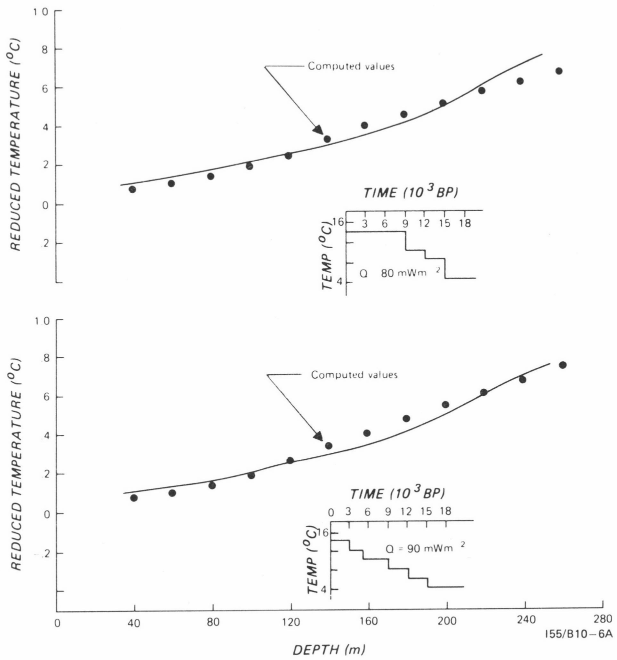

Figure 4. Increasing heat flow at Woodlawn to maintain approximate fit between calculated and observed temperatures for (a) intermediate and (b) slow rates of glacier retreat, corresponding to inset climatic models.

flow increase with depth. Consequently, temperature profiles have been computed for several values of heat flow with surface temperatures constrained according to the above data.

Calculated and observed profiles are compared in Figure 2 for a single step function increase in surface temperature of 10°C at 15 000 BP. To emphasise discrepancies the data in Figure 3 and Figure 4 are reduced in terms of departures from an arbitrary temperature gradient:

$$T_z = 14.0 + 0.016\ (z) \qquad \ldots\ldots 1$$

For WOODLAWN best agreement is obtained with heat flow of 75 mW m^{-2}, but a range from 70 to 80 mW m^{-2} is possible if the time of glacier retreat is varied by ± 3000 years. For CANBERRA, heat flow must be increased to give a range from 80 to 90 mW m^{-2}. In view of the large distance between sites, differences of this magnitude can be expected. In both cases corrections greater than 20 percent need to be made to the values previously obtained by fitting linear segments to the temperature gradient.

Rate of glacier retreat

With the single step model of glacier retreat, it has not been possible to remove all discrepancies between computed and observed temperature profiles. Departures are most noticeable for CANBERRA, but thermal parameters are more variable and sampling errors are expected to be greater than for WOODLAWN. Further attempts to match curvature are therefore related primarily to WOODLAWN data.

An obvious modification to the initial model is the insertion of a ramp function to approximate a more gradual glacier retreat. This is achieved with a series of smaller steps in surface temperature. Results are given in Figure 4 together with a description of the models for two rates of retreat. To maintain close fits

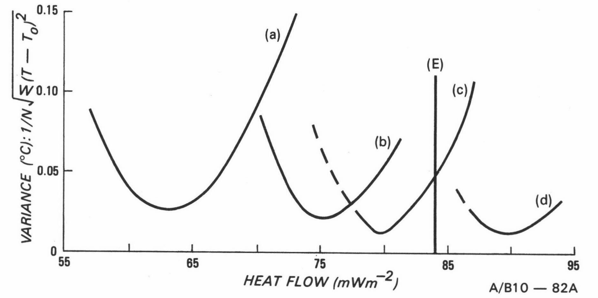

Figure 5. Variances resulting from differences between observed and calculated temperatures at Woodlawn for variable heat flow.

Curves correspond to climatic models with (a) no change in surface temperature, (b) 10°C step at 15 000 BP, (c) ramp from 15 000-9000 BP, (d) ramp from 15 000 BP to present. Heat flow observed in Snowy Mountains is indicated by (E), favouring models (c) and (d).

to the data it is necessary to increase heat flow in the computer models according to rate of glacier retreat. An extreme of 90 mW m^{-2} is possible for a slow continuous increase of surface temperature, but if temperatures are assumed constant from 9000 BP a value of 80 mW m^{-2} is more appropriate (Figure 5).

To select the most appropriate rate of retreat, it is necessary to obtain data at depths where thermal perturbations are negligible. However, there are no deep boreholes in the region of CANBERRA or WOODLAWN. The only heat flow data which may be suitable were obtained using tunnels in the Snowy Mountains (Sass & others, 1967), where a value of 84 mW m^{-2} was obtained at depths near 850 m, consistent with the range of values calculated above. Because of the suggested glacial perturbation, this result may be interpreted as a minimum value requiring a small positive correction (<5% at depths of 850 m). This would then give a value close to the maximum in the above models, indicating a slow increase in surface temperature (Figure 5). However, if there are significant lateral variations in regional heat flow, the preceding argument is not valid. Furthermore, the magnitude of the climatic perturbation in the Snowy Mountains may be difficult to establish. Some of that region was subject to full glaciation, whereas WOODLAWN and CANBERRA were situated in strictly periglacial regions.

If ground temperatures in the Snowy Mountains were generally near 0°C during glaciation, the subsequent warming must be less than 5°C (present mean annual air temperature) compared to 10°C possible at lower altitudes. With this smaller surface perturbation, the measured value of 84 mW m^{-2} at 850 m may need little correction (<5%). However, it can be argued that at the base of the glacier, surface temperatures may have been substantially less than 0°C (or the pressure melting point of ice, Beck 1977), causing a regional heat sink, affecting sub-surface temperatures over an area much greater than indicated by glacier cover. In these circumstances the amount of warming near the glaciated region may be almost the same as for WOODLAWN and CANBERRA; consequently, similar large corrections (>20%) may need to be made to heat-flow data.

An unambiguous result must await the drilling of a 1000 m hole in periglacial regions, but present variance data (Figure 5) indicate slow continuous warming.

Lateral modifications

Although glaciation was confined to southeast Australia, it is probable that contemporary surface temperatures were lowered throughout the continent. Any deep hole with uniform lithology (giving constant thermal conductivity) may therefore be used to confirm major aspects of glacial history. Suitable data have been obtained in the Precambrian shield near Kalgoorlie, where a 2770 m diamond-drill hole was logged to a depth of 1250 m (Hyndman & Everett, 1968). The measured portion was near vertical, penetrating dolomite to a depth of 340 m and basalt thereafter. A linear gradient of 9.26 mK m^{-1} was reported, but systematic increases in thermal conductivity were noted (Figure 6). Using the harmonic mean, a value of 34.3 ± 1.3 mW m^{-2} was calculated for heat flow. However, because thermal conductivities increase with depth, actual heat flow appears to exceed 40 mW m^{-2} in deep sections of the hole, which are assumed to be unaffected by climatic perturbations.

Climatic models for this area were formulated only for the postulated primary climatic event corresponding to glacier retreat in the Snowy Mountains. The deep section value of 40 mW m^{-2} was adopted for actual heat flow at Kalgoorlie, allowing more rigid modelling constraints than was possible with the Snowy Mountains data. A step function increase in the surface temperature was postulated at 15 000 BP, and thermal parameters were again assumed constant in the interval between core samples. The observed temperatures are most closely matched for models having an initial surface temperature of 18.5°C with a subsequent increase to 22.3°C at the present time. This result is consistent with the suggestion of general cooling of the continent during glaciation in the southeast. However, there was no ice in the area of Western Australia, and there appears to be a corresponding decrease in the amplitude of the step function.

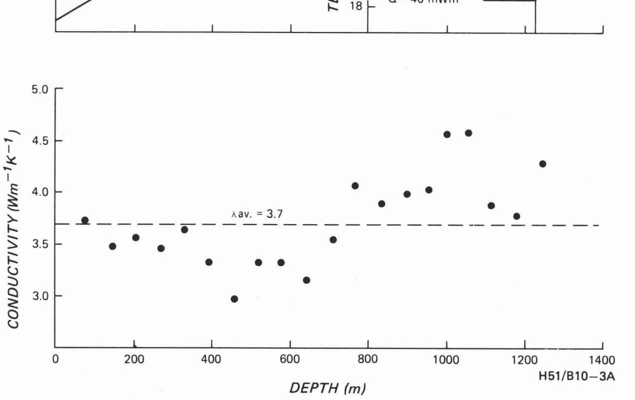

Figure 6. Borehole temperatures and conductivities at Kalgoorlie, WA.

Inset: climatic model used to compute temperatures giving approximate fit to linear gradient observed by Hyndman & Everett (1968).

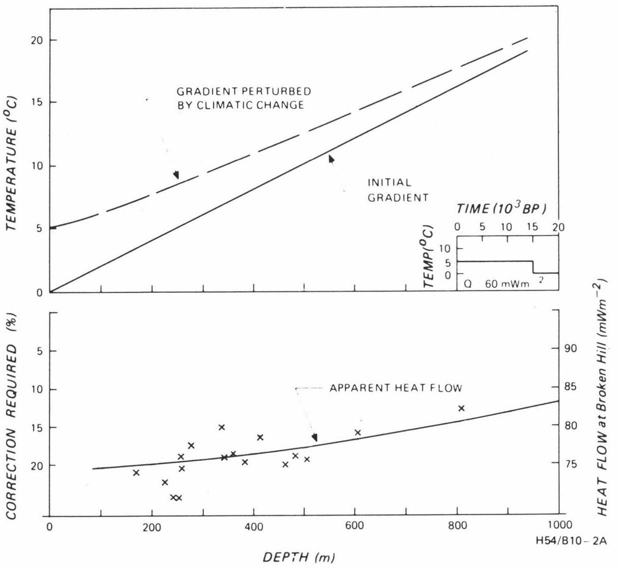

Figure 7. Temperature perturbations associated with representative climatic model causing increases in heat flow consistent with data from Broken Hill.

Corrections to regional data

In Australia most values of heat flow have been determined using temperature gradients obtained at depths less than 300 m (Hyndman & Everett, 1968, Howard & Sass, 1964, Sass & others, 1976). Most of these data will therefore require corrections for climatic perturbation similar to those indicated in the models presented above. However, the magnitude of the correction is variable; it depends on gradient reduction techniques, the depth of determination, and the site location with respect to the region of glaciation. Consequently, a representative model is suggested, to allow bulk correction of existing data.

Rates of warming are not well determined from present data; consequently, a step function increase in surface temperature is adopted, representing the primary climatic event. Furthermore, since regional variations occur in the magnitude of the temperature change, it is necessary to adopt a mid-range value of 5°C. Perturbations resulting from this model are shown as a function of depth in Figure 7, assuming average heat flow values of 60 mW m^{-2} in rock of uniform thermal conductivity (3 W m^{-1} K^{-1}) and diffusivity (10^{-6} m^2 s^{-1}). Corrections to apparent heat flow were calculated using the nominal thermal gradient at each depth, $\delta T/\delta z$. Consequently, where actual interval gradients ($\Delta T/\Delta z$) have been calculated from borehole data using least squares techniques, mid-point depths should be adopted to determine the relevant corrections to heat flow.

Data obtained at Broken Hill (31.95S, 141.47E) can be used to demonstrate that this model gives an adequate result. This region has been extensively surveyed and heat flow values have been obtained for 18 closely spaced holes (Sass & Le Marne, 1963). Unlike WOODLAWN and KALGOORLIE, the lithology is complex, and, as a result, thermal conductivities are highly variable; sampling errors are expected to be large and, consequently, climatic models can not be formulated for individual holes. However, when the results are plotted as a function of the depth of determination (assumed to be the mid-point of linear gradient) a trend emerges consistent with the general model of climatic change (Figure 7).

Since most of the published heat-flow data in Australia have been obtained at depths less than 300 m, corrections will generally be in the range 10-25 percent. For the West Australian Shield these corrections are similar in magnitude to those proposed by Beck (1977) for the Canadian Shield; consequently, there remains a near equivalence in mean values of heat flow, and similar tectonic histories can therefore be inferred. In other parts of Australia, climatic corrections may result in major changes within the heat-flow provinces suggested by Sass & others (1976) with the result that previous estimates of lateral temperature variations in the mantle may need revision.

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