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RESOLVING HEAT FLOW ANOMALIES IN SHALLOW BOREHOLES - FEASIBILITY STUDIES

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ABSTRACT

Secular changes in surface temperature cause perturbations to the geothermal gradient which are significant to depths of at least 1000 m. Few drillholes in Australia exceed this depth and consequently absolute determinations of heat flow are rare. In contrast, diurnal and seasonal fluctuations are negligible at depths greater than 30 m. Consequently heat flow anomalies may be most readily identified using relative values obtained at a standard depth in shallow bore holes subject to similar secular corrections. Two probes have been considered for this purpose.

Probes which are designed to approximate a laterally infinite layer of known thermal conductivity can be used in boreholes of diameter greater than 14 cm. However, the small temperature differences generated across the probe material could cause technical problems in resolving possible anomalies.

Gradient probes may be used in existing boreholes of small diameter, but sufficient core must then be available for measurements of thermal conductivity. Probes of this type may be calibrated in existing holes which have been previously used for absolute determinations of heat flow.

It is recommended that disposable gradient probes be constructed with thermistor sensors having a separation of 5 m. It is suggested that the standard burial depth should be 100 m.

INTRODUCTION

Perturbations in the geothermal field are detected by observations of surface heat flow, allowing extrapolation of near-surface temperature gradients according to the expression

$$Q = \beta\lambda \qquad (1)$$

where Q ($mW\ m^{-2}$) is defined as surface heat flow, β($mK\ m^{-1}$) is the geothermal gradient, and λ($W\ m^{-1}\ K^{-1}$) is the thermal conductivity of the rocks in which the gradient is established.

The techniques used in BMR for measuring β and λ have been described by Cull & Sparksman (1977). On land β is usually measured in boreholes at depths greater than 100 m. However, the normal temperature gradient is disturbed by drilling; consequently casing must be inserted to preserve the hole while equilibrium is regained over periods extending to several months. Field surveys must therefore be planned with long-range objectives, usually of a regional nature. Detailed surveys of local structure also require many measurements of λ. Sample preparation is complex and tedious and, with conventional divided bar apparatus, only 5-10 core samples can be measured each day.

In contrast, measurements of heat flow at sea are very simple; probes are inserted in sea floor sediments and, after minimal delay (station time ~1hr) for equilibration of β, transient heat pulses of short duration are used for in situ determinations of λ. Similar techniques have been used for measurements of λ on land but with little success (Beck, 1965).

A compromise is now suggested to reduce drilling requirements and limit the number of measurements of λ required to determine heat flow on land. The concept involves probe burial at a standard depth subject to uniform secular perturbations. Relative values of heat flow could then be obtained, suitable for studies of crustal structure.

2. SURFACE TEMPERATURES

Heat generated within the Earth escapes at rates of approximately 100 $mW\ m^{-2}$. In contrast, heat is received from the Sun at rates up to 1000 Wm^{-2}. Consequently temperatures measured near the surface of the Earth depend on diurnal, seasonal, and secular perturbations of insolation. Carslaw & Jaeger (1959, p. 65) have considered the problem of periodic surface heating, and derived the solution.

$$T = T_o \exp(-\xi z) \cos(\omega t - \xi z) \tag{2}$$

where $\xi = 2\pi/P$, P is the period, $\xi = (\omega/2\kappa)^{1/2}$, and κ is the thermal diffusivity. The time-dependent term results in an effective wavelength $(4\pi\kappa P)^{1/2}$ approximately equal to 1 metre for the diurnal wave and 20 metres for the annual wave (assuming a representative $\kappa = 10^{-6}\ m^2/s$). The maximum amplitude of the disturbance is governed by the exponential term in equation (2). At a depth of one wavelength the surface amplitude is reduced by a factor exp $(-2\pi) = 0.0019$ and consequently for most purposes the diurnal and annual waves can be neglected.

Secular perturbations are more difficult to resolve. However, large changes in surface temperature must result from the retreat of sheet ice associated with periods of glaciation (Beck, 1977), and recent cultural changes to the land surface may have caused increased local insolation (Hyndman & Everett, 1968). Changes of this type can be modelled as a step function in surface temperature for which Carslaw & Jaeger (1959, p. 59) have given the solution

$$T = T_o \operatorname{erf}\left(\frac{Z}{2\sqrt{\kappa t}}\right). \tag{3}$$

If surface temperatures increased by 10^oC after glaciation at 10 000 B.P., errors exceeding 20 percent may come about in geothermal gradients measured at depths less than 1000 m (Crain, 1968). Few temperature data have been obtained at depths greater than 1000 m because in general holes of this depth must be cased. Such casing is expensive and consequently absolute determinations of heat flow are rare. Existing data have been obtained at various shallower depths and are therefore subject to different levels of correction (Fig. 1). Furthermore, the amplitude of any secular change probably varies

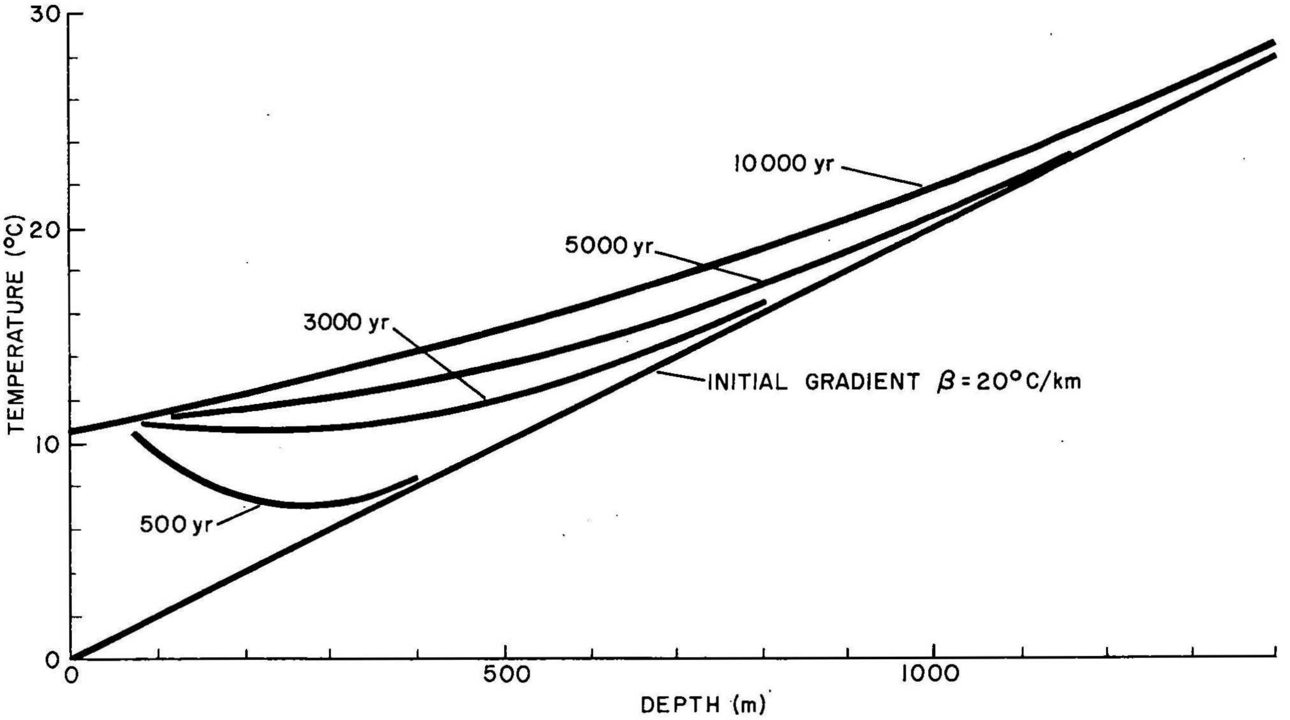

Fig I. Perturbations in the Geothermal Gradient as a result of a step function increase in surface temperature according to location; maximum amplitudes can be expected in regions of past glaciation, decreasing near the more temperate zones (Cull, 1979). Anomalous heat flow values may therefore result solely from procedural differences in measuring the thermal gradient.

Although exact values of heat flow may not be accurately determined even at depths of 1000 m, data requiring unspecified but identical corrections can be obtained for small survey regions in shallow holes at a standard depth. These relative values can be used in modelling local structure. A suitable standard depth can be calculated from the propagation characteristics of the annual temperature wave.

Perturbations to the geothermal gradient can be calculated by differentiating equation 2 to give the expression

$$\frac{\partial T}{\partial z} = T_o\, e^{-\xi z} (+ \xi)\, (\sin (\omega t - \xi z) - \cos (\omega t - \xi z)) \qquad (4)$$

At any depth the magnitude of this perturbation varies with time; the minimum (zero) disturbance occurs when

$$\sin (\omega t - \xi z) = \sin (\pi/2 - \omega t + \xi z)$$

$$\text{ie.} \qquad t_{min} = (\pi/4 + \xi z)\,/\omega \qquad (5)$$

In practice the thermal diffusivity of near-surface layers cannot be well determined and consequently t_{min} cannot be calculated with any great precision. Furthermore, gradients are measured in terms of $\Delta T/\Delta z$ and consequently t_{min} is different for the two observation points. For these reasons measurements are best made at depths where the maximum possible amplitude of the annual perturbation is negligible. In equation (4) maxima occur at times.

$$t_{max} = (3\pi/4 + \xi z)/\omega \qquad (6)$$

and the amplitudes of the maxima are expressed

$$\frac{\partial T}{\partial z}_{max} = T_o \, e^{-\xi z} \quad \xi\sqrt{2} \qquad (7)$$

These maxima are plotted as a function of depth in Figure 2. Observations must be made at depths greater than 30 m if gradients are required with a 1-percent accuracy independent of the time of measurement. Gradients obtained at depths less than 20 m will be subject to errors greater than 25 percent.

3. HEAT FLOW PROBES

(1) Slab probes

Measurements of thermal conductivity are both tedious and time consuming. Consequently a sensor of known thermal conductivity was designed to approximate a laterally infinite slab replacing the rocks in situ. A schematic assembly is shown in Figure 3. For an infinite slab, heat flow can be obtained immediately after in situ equilibration of temperatures. Gradients can be calculated directly from temperatures measured at each face of the slab and these are directly related to heat flow according to the thermal parameters of the chosen material (equation 1). However, in practice lateral dimensions are constrained by the diameter of the borehole. Auger holes can be drilled with diameters of approximately 1 m, but in hard rock the cost and time involved would be unrealistic. Consequently, there is a maximum practical probe diameter of approximately 14 cm corresponding to common drill stem sizes.

With probe diameters so restricted two opposing conditions must be satisfied. The slab must have sufficient thickness that temperature differences across the face can be resolved, but the ratio of thickness to diameter must

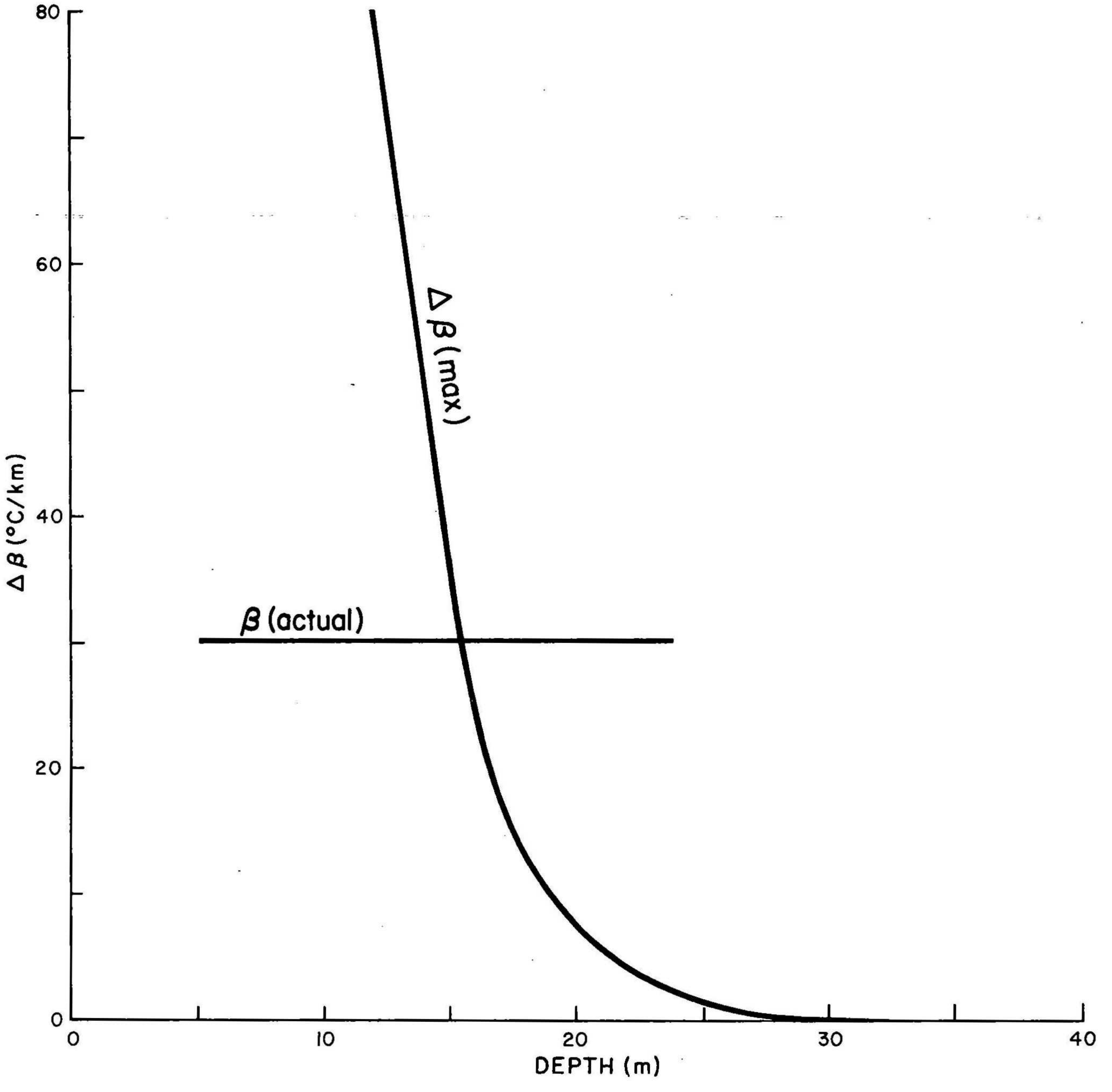

Fig. 2 Maximum amplitudes of Diurnal Perturbation ($\Delta\beta$) added to nominal Geothermal Gradient (β)

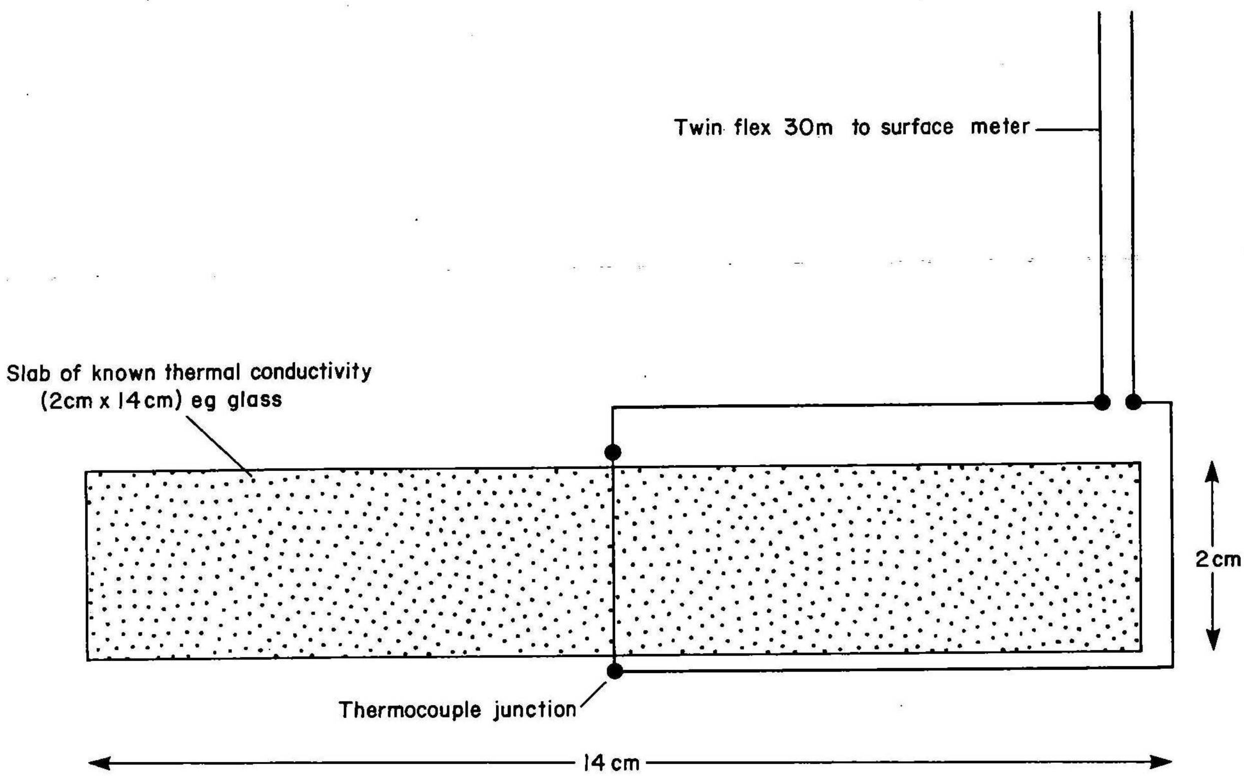

Fig.3 Schematic of slab probe designed to approximate an infinite layer of known thermal conducivity

be small in order to approximate a laterally infinite layer. If common thermocouples are used for measuring temperatures, together with meters having a sensitivity of 0.01 μV (not presently available for field work), a slab thickness greater than 2 cm is required to resolve changes in heat flow of 5 $mW\ m^{-2}$.

Finite difference computer modelling techniques were used to study the refraction of heat near practical probes of limited dimension. Perturbations depend not only on thermal conductivity contrasts between the slab and the surrounding country rock, but also on the absolute value of heat flow (Fig. 4). In most circumstances, errors in perceived heat flow are less than 5 percent and, in uniform lithologies (giving constant contrast in thermal conductivity) relative values may be resolved to within 2 percent. Slab probe results may therefore be compared favourably with existing regional heat flow data (where accuracy is limited by core sampling errors) but instrument quality must be of the highest laboratory standard; at present this may not be practical for field work.

(2) Gradient probes

Although slab probes could be used in special purpose holes of larger diameter they would not be suitable for use in the many existing bore-holes drilled for routine mineral exploration, stratigraphic sampling, or water-table observations. In general these holes must be logged with tools of diameter less than 5 cm; suitable temperature probes can be constructed housing a thermistor (or thermocouple) sensor. Normally, a single thermistor is lowered to successive depths and temperatures are recorded at discrete intervals after a period of equilibration. Thermal gradients are then computed from linear segments using a least-squares approximation method. For statistical analysis, several segments may be grouped to comprise intervals exceeding 100 m; as a result, thermal conductivity must be measured on numerous core samples characterising the interval prior to determination of heat flow.

For measurements of heat flow at shallow depth, only small intervals can be used to determine thermal gradients. With simple single sensor probes depth errors may then be significant. This difficulty can be avoided by recording differential temperatures using two thermistors with a fixed separation (Fig. 5). Least-squares approximation is not required with probes of this type, and thermal gradients can be determined with great precision over small intervals. If core is extracted from the complete interval, thermal conductivity (or resistivity) can be determined with negligible sampling error, allowing accurate calculations of heat flow.

A minimum sensor spacing must be specified for probes of this type. If sensor separation is made only about the same as the borehole diameter then conditions would be similar to those considered for the slab probe. The conductivity of the core sample would then be unrelated to the apparent gradient, and heat flow along the axis of the borehole would depend on conductivity contrasts caused by fluid fill, wall casing, and mud content. However, this situation also applies in conventional surveys of heat flow, where it can be demonstrated that apparent gradients are determined primarily by the rock conductivity for intervals about one order of magnitude greater than the borehole diameter. In contrast, if sensor separation is made very large the number of thermal conductivity measurements must also be increased and little advantage results compared to conventional methods. Separations of 1-5 m can therefore be specified, giving large output compared to the slab probe. With thermocouple sensors heat flow anomalies of 5 $mW\ m^{-2}$ should be detected using meters having resolution of 0.1 μV. If thermistor sensors are used ($\sim$3K Æ 25°C) an anomaly of this magnitude should result in changes in resistance of about 0.5 ohm/m. Differences as small as 0.1 ohm can be detected using a Wheatstone bridge, but calibration error and subsequent drift can not be discounted. Practical gradient probes may therefore require sensor separations of about 5 m.

4. RECOMMENDATIONS

Because sensor separations of less than 2 cm are required for practical slab probes, only very small temperature differences are generated. Consequently only the most sensitive meters can be used for recording. Some improvement may result if thermopiles are incorporated in the design, but construction then

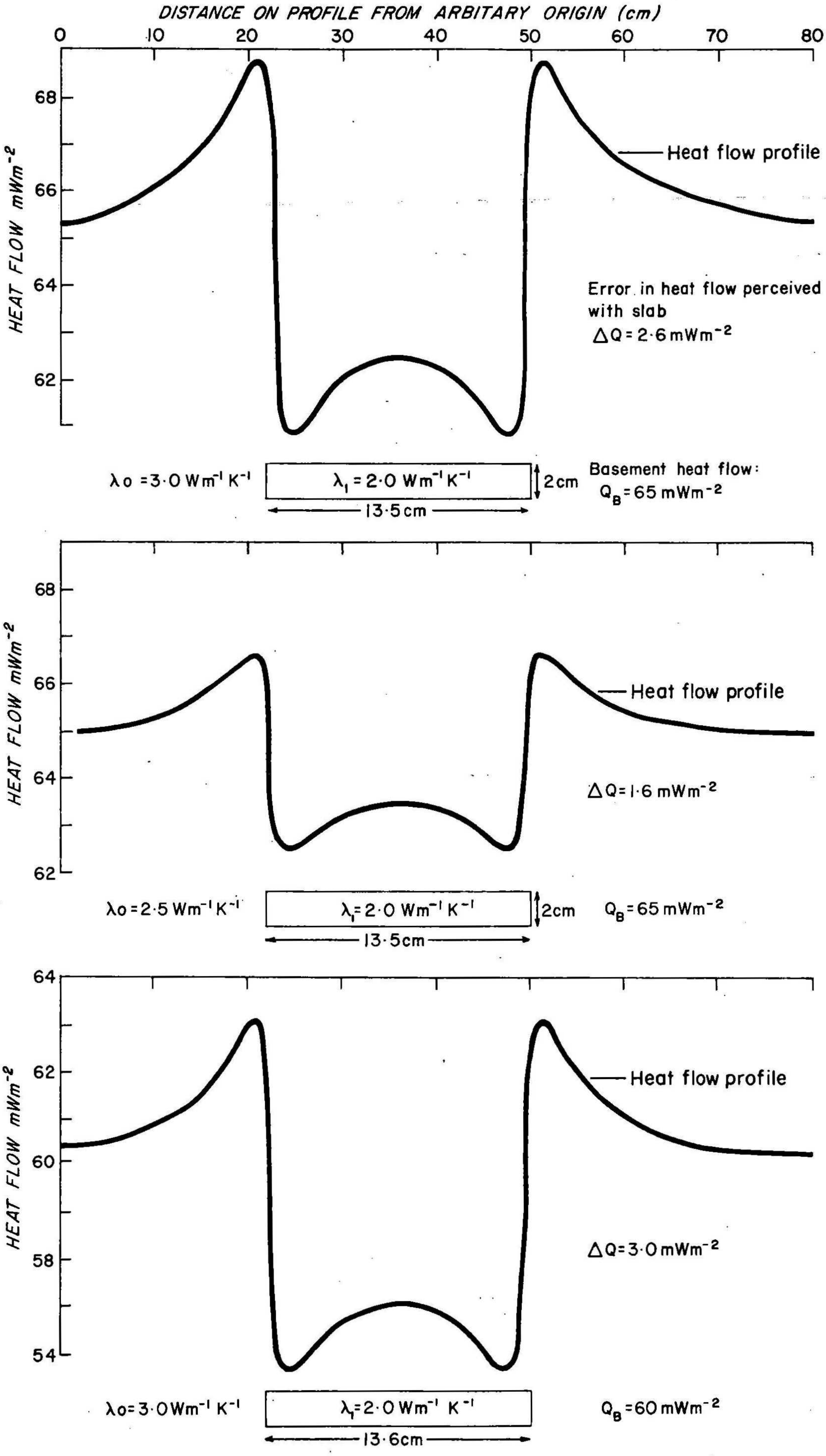

Fig. 4 Refraction of heat near slab probes

(a) Effect of maximum anticipated conductivity contrasts

(b) Effect of anticipated common contrasts in conductivity

(c) Effect of variable heat flow on magnitude of refraction

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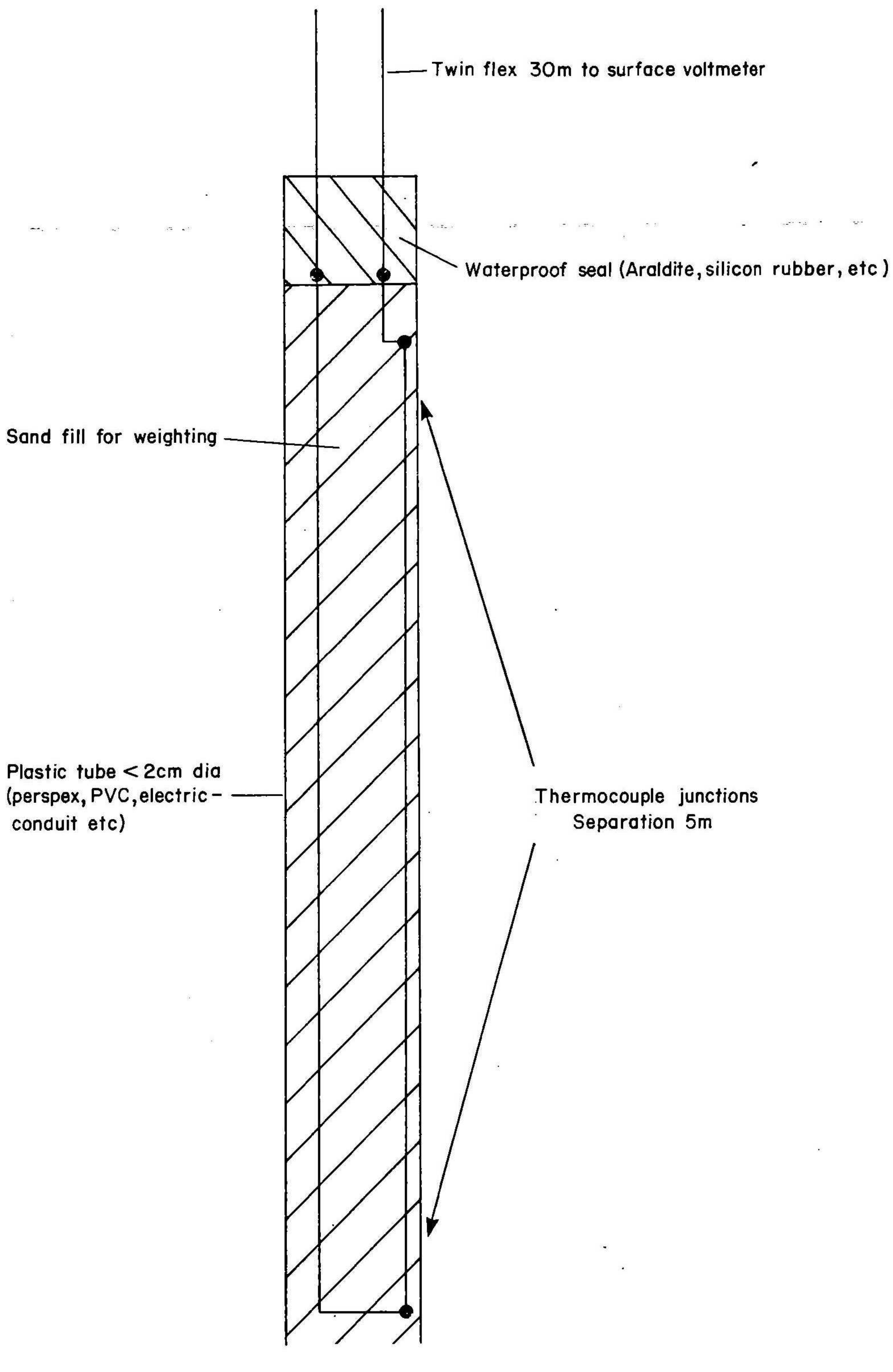

Fig. 5 Schematic of constant interval gradient probe

becomes complex and further conductivity contrasts are introduced. Furthermore, the slab probe can be used routinely only with special-purpose drilling, requiring fully devoted rig facilities. The slab technique appears most useful for small local surveys with high-density observation grids since no thermal conductivity measurements are required. However, in view of the technical difficulties associated with the slab probe, field trials may not be immediately justified.

The gradient probe appears more generally applicable, being suitable for regional surveys incorporating holes of opportunity. Relatively large temperature differences are observed and no technical difficulties are anticipated. However, provision must be made for measurements of thermal conductivity. In general a minimum of four or five samples of core should be used to characterise each interval, but for a homogeneous stratum one sample may be sufficient - in this case sampling errors are assumed to be zero. Any initial field trials should be conducted in existing deep boreholes previously used for absolute measurements of heat flow. Relative values may then be correlated with these data and resolution can be tested using known regional anomalies. For subsequent surveys special-purpose holes should be drilled to a standard depth exceeding 30 m; a depth of 100 m is suggested so that annual and secular perturbations (associated with changes in land use) are minimal.

Core must be extracted from the bottom 5 m of each borehole, coinciding with the interval in which the thermal gradient is to be measured. The probe should be inserted as soon as possible after coring so that thermal equilibrium can be regained. For this reason the hole should be filled with water or soil so that no further perturbations are possible prior to measurement. If soil must be used for fill, retrieval may be impossible and probes should be regarded as disposable. Drilling time may vary, but no more than ten hours would be required for average conditions; temperature measurements should therefore be possible within 48 hours (Jaeger, 1961). For maximum efficiency disposable probes could be buried during one field season and all measurements could be completed in a single traverse during the next season. Disposable sensors would cost $20-30/hole compared to casing costs of $200-300.

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