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CLIMATICALLY PERTURBED TEMPERATURE GRADIENTS AND THEIR EFFECT ON REGIONAL AND CONTINENTAL HEAT-FLOW MEANS

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ABSTRACT

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It is well known that significant corrections to measured heat-flow values are required in limited areas that have been subjected to the advance and retreat of ice sheets. However, important activities such as the Wisconsin glacial cycle must have been accompanied by temperature changes of global extent. Therefore, even those continental areas that were not subject to glaciation may have suffered important mean surface temperature changes, thus leading to the need to correct heat-flow measurements made in such areas. Furthermore, there have been significant widespread changes in climate during the Holocene, leading to a need to correct for short-term temperature changes as well.

Applying corrections to existing data for a surface thermal history of the Holocene and Pleistocene, it is found that correlation between heat-flow values and borehole depths are significantly reduced, that both positive and negative correlations of heat flow with conductivity may be due to neglect of climatic corrections, and that many heat-flow values, particularly from shallow holes (less than 400 meters deep), may need corrections of several tenths of a heat-flow unit (several mW m^{-2}).

It is concluded that mean heat-flow values for heat-flow provinces, and continents as a whole, may be too low by as much as 20 or 30% and that the mean oceanic and continental heat-flow values may not be equal.

INTRODUCTION

The apparent equivalence of continental and oceanic heat flows has been commented on since the first oceanic measurements were reported (Revelle and Maxwell, 1952) and must be explained by one or more of the following.

(1) The abundance of radiogenic heat sources in the upper mantle beneath the oceans is greater than that of the upper mantle beneath the continents.

(2) The abundance figures for radiogenic heat sources in the mantle beneath the oceans are the same as in the mantle beneath the continents but are distributed to a much greater depth.

(3) There are significant heat sources, tectonic or geochemical, in the

oceanic crust which are not present in the continental crust.

(4) There are systematic errors in one or both groups of equilibrium heat-flow measurements.

(5) There is some unknown process.

The principle purpose of this paper is to elaborate on some earlier work (Beck, 1970) in which it was pointed out that there may be systematic errors in the continental heat-flow values. However, we first briefly review some of the other possible solutions.

Since considerable use is made of data in earlier papers the CGS system of units is the principal one used with SI units given in brackets where practical.

REVIEW

Table I lists some typical heat-production values for common rock types in the crust and mantle. It can be seen that the oceanic crust is too thin by an order of magnitude for it to produce one heat-flow unit (1 HFU = 1 μcal cm^{-2} sec^{-1} = 41.87 mW m^{-2}) although it could be argued that the effect of eclogite integrated to a depth of 500 km could produce 1 HFU. The two principal problems here are first, that the time constant for the conductive process is such that heat from a depth of 500 km has not had time to reach the surface, and second, if the upper mantles beneath the continents and oceans are the same then the mean equilibrium heat-flow values over continents and oceans should be significantly different.

If the radiogenic heat sources in the upper mantle are concentrated by an order of magnitude more than is currently thought to be true, enough heat could be supplied to satisfy the oceanic requirements but again the oceanic and continental mean equilibrium heat-flow values should be different. This difficulty could be overcome if the ultrabasic heat sources are preferentially concentrated beneath the oceanic crust; in such a case the implication is that there is a fundamental difference between the upper mantles under continents and oceans which would lead to enormous difficulties in plate-tectonic theory.

TABLE I

Typical heat-production values

Rock type	Heat production (fcal cm^{-3} sec^{-1})	Heat production (nWm^{-3})	Length of a column required to give surface flow of 1 μcal cm^{-2} sec^{-1} (km)
Granite	700	2840	14
Basalt	90	370	100
Eclogite	20	90	500
Dunite	0.2	1	46000

Heat sources in the oceanic crust and upper mantle that are not present in the continental crust and upper mantle have also been proposed and indeed have been identified locally. Transfer of heat by convection in the upper mantle, first proposed by Bullard (1954) before plate theory was developed, must now be considered most unlikely as a general explanatory mechanism although the process occurs in the vicinity of mid-ocean ridges. There is no problem with postulating geochemical and hydrothermal activity for specific anomalous areas (Anderson and Halunen, 1974; Muecke et al., 1974; Scott et al., 1974) but they are not satisfactory as a thermal source to satisfy the heat-flow requirements in the oceanic basins. A more useful set of geochemical reactions between sea water and basalt, capable of producing as much as 1 HFU, has been proposed by Hart (1973a,b), but the thermodynamics of the reactions are not well known. Migration of sea water into the basaltic crust and back again to the sea floor has been proposed by Spooner and Fyfe (1973), with the thermal energy being supplied principally by the latent heat of crystallization of hot molten basalt at shallow depths. If this latter process has been going on for a few thousand million years, it can be inferred that there must be a continuous energy source operating in conjunction with plate motions; this in turn implies that heat loss may occur near the downgoing edge of the plate for which there is little evidence. Alternatively, if the energy is gained from deep in the mantle, by convection cells, the implication is that the upper mantle is significantly non-homogeneous in the transverse direction. Nevertheless, both of these latter mechanisms are attractive but require much more work before they can be considered as a universal mode of supplying the necessary thermal energy.

Whether or not such general heat-generating mechanisms exist in the oceanic crust, there is a possibility that the continental heat-flow values are systematically in error because of neglect of corrections which should be applied to allow for climatic changes on a global scale.

CLIMATIC CORRECTIONS

Pleistocene variations

Anderson (1934) was the first to recognize that the retreat of the ice sheet at the end of the Pleistocene, would have a significant effect on subsurface temperatures; Benfield (1939) was the first to apply a correction to heat-flow data to allow for these effects. Since that time similar corrections have not been applied systematically even in regions known to have been subjected to the advance and retreat of ice sheets, principally because of the difficulties in establishing the times of advance and retreat and, more particularly, the temperature difference occurring between various stages of a glacial epoch; the terminology of Fairbridge (1973) is used throughout.

Goguel (1957) pointed out that neglect of the glacial corrections might mean that continental heat-flow values were systematically in error by as much as 25%. The first attempt to determine if there was a systematic effect was made by Crain (1967, 1968) who found that a correlation between borehole depth and heat-flow values disappeared when corrections were applied for the retreat of the Wisconsin ice sheet; the correction also increased the mean heat-flow value for a group of boreholes in the Appalachian system by 30% relative to the uncorrected value. Horai (1969), using a Pleistocene temperature pattern given by Emiliani (1955), but assuming the temperature at base of an ice sheet was at its pressure melting point near 0° C, gave curves for the corrections to allow for the Wisconsin, Illinoian, Kansan and Nebraskan glacial cycles dating back to 300,000 YBP (years before present); he concluded that it would not be possible to detect a systematic error in the mean continental heat-flow values unless the error was greater than 0.2 HFU.

Beck (1970) pointed out that in spite of the data from the Antarctic ice sheet (Gow et al., 1968) the measured temperature of −13° C at the base of the Greenland ice sheet (Hansen and Langway, 1966) indicated that the ice-sheet corrections might be seriously underestimated if it was universally assumed that the temperature at the base of an ice sheet was at the pressure melting point of a confined ice—water system; he also concluded that even in areas which had not been covered by ice sheets, neglect of corrections for global climatic variations associated with the glacial cycles could contribute significantly to a systemic underestimate of continental heat-flow values. Jessop (1971) allowed for interstadial periods and produced a generalized contour map of corrections to be applied to deglaciated regions of Canada; amongst other things he concluded that, if the temperature at the base of the Pleistocene ice sheet was at the pressure melting point of a confined ice—water system, some regions would require a negative correction because the exposed surfaces are now at sub-zero temperatures. Ciaranfi et al. (1973) applied power spectral analysis to the curves of Emiliani (1955, 1966) and concluded that the maximum disturbance to the temperature gradient was −6° C/km for material of diffusivity 0.010 cm^2 sec^{-1} (1 mm^2 s^{-1}).

All these authors were concerned primarily with the thermal effects associated with the advance and retreat of ice sheets, principally in areas which had been subjected to the glacial cycle.

Holocene variations

It is now becoming clear that in certain circumstances, for some heat-flow values obtained in relatively shallow holes, climatic changes in the Holocene may also have important effects; the effects may decrease or increase the magnitude of the Pleistocene corrections depending on the details of the climatic history and depth range of measurements.

The principal difficulty is that the more recent the change the more it is affected by local conditions yet the more accurately we need to know the magnitude and temporal function of the surface temperature change.

Some attempts have been made to deduce surface temperature variations from the geothermal data. At one site, Beck and Judge (1969) deduced information on surface temperature variations for the last century. This was followed up by Cermak (1971) who deduced information on thermal events at two other sites in Canada over the last millenium, one conclusion being that the surface temperature had risen by 2.3° C over the last century. More recently, Fanelli et al. (1974) have used Lamb's (1969) curves of temperature for the last 10,000 years to correct some of their heat-flow values for climatic variations during the Holocene.

Review of recent work on climatic changes

For the last five years a large body of data has been accumulating concerning Holocene, as well as Pleistocene, temperature changes. The inferences from biological, lithological, geochemical, as well as geological studies are now more reliable than they used to be. Veek and Chappell (1970) correlated sea-level changes with ice-sheet formation from a study of coral reef terraces. Burckle (1972) used evidence from diatoms to conclude that there had been three distinct cool periods at approximately 4600, 2800 and 1000 YPB. LaMarche (1974), from a study of long tree-ring records of Californian bristle-cone pines, concluded that there had been periods of high temperatures centred about 800 YBP and established a pattern of earlier temperature changes going back to 5500 YBP with a one-thousand year cold period centred around 2500 YBP. Simpson (1975) inferred from changes in carbonate composition and distribution of foraminifera that there had been a cooling of the ocean waters off Peru of 5–6° C during glacial times.

Farrand (1971) summarizes much work on deep-sea cores, palynology, pluvial lakes, snow lines, frost action and fauna in the Mediterranean area and finds that the climate was 3–10° C cooler in glacial times than at present. Kraus (1973) argues that during ice ages the cloud cover was greater, but precipitation was less, than now and that any change in tropical sea surface temperature would be amplified threefold in the upper troposphere. This increases the albedo, which in turn increases the cloud cover and reduces the planetary temperature; in particular he argues for a difference between present and ice-age temperatures of 30° C for the summers of the deglaciated continental regions, more than 10° C for sea surface temperatures in the Atlantic region north of the 50th parallel, and a 3 or 4° C change for the Caribbean and tropical Atlantic. Emiliani (1971) gives Pleistocene–Holocene ranges of temperatures as 5–10° C for the continents, 7–8° C for the Caribbean, 5–6° C for the equatorial Atlantic and 3–4° C for the equatorial Pacific.

Probably some of the most important information on patterns of temperature variations in the past has come from a study of the $^{18}O/^{16}O$ oxygen isotope abundance ratio changes in various materials. The early work of Emiliani (1955, 1966) on deep-sea cores is well known. More recently a considerable amount of information has been obtained from detailed analyses on ice cores drilled from the Greenland and Antarctic ice sheets. Dansgaard et al. (1970) have shown a remarkable correlation in the oxygen isotope ratio variation of the ice core from the deep hole at Camp Century, Greenland, the variations obtained by Emiliani (1955, 1966), and the events found by Van der Hammen et al. (1967) from detailed pollen studies. Later work on ice cores from the Antarctic (Johnsen et al., 1972) is in reasonable agreement in general, but differs in detail, with the Greenland data. The differences are attributed to the basic differences between the ice sheets, the Antarctic sheet being largely at its pressure melting point and therefore subject to considerable movement, leading to difficulties in correlating the core data. However, it may also mean that the global thermal regime in the southern hemisphere, at least at high latitudes, may differ somewhat from that of the northern hemisphere.

Although the $^{18}O/^{16}O$ values in snow are well correlated (correlation coefficient = 0.84) with the mean daily air temperature (Schriber et al., 1975) at the time of precipitation, the details of the variations tend to become "smeared" as the snow becomes buried and turns into ice such that a typical sample of core may give only an average value for a time span of the order of decades. Nevertheless, on the long time scale of the Holocene and Pleistocene, the $^{18}O/^{16}O$ variations are believed to reflect accurately the pattern of variations in the global temperatures. The main difficulty is in calibrating the $^{18}O/^{16}O$ ratios in ice cores to give the magnitude of the surface temperature changes on a global scale (Dansgaard et al., 1971); there is also a minor problem in determining the correct chronological scale (Shackleton and Opdyke, 1973). At the present time, these scales must of necessity be obtained from geological–biological inferences, but once established, and making the reasonable assumption that the $^{18}O/^{16}O$ variations are linearly related to temperatures, a past surface temperature history can be established. Some of the recently proposed newer methods of obtaining temperature variations (Bada et al., 1973; Schiegl, 1974) may later lead to more accurate estimates of the amplitude of the variations.

Confirmation of the pattern of temperature changes is also beginning to appear from attempts being made to correlate climatic variations with variations in geophysical phenomena such as magnetic intensity changes (Wollin et al., 1973; Chiu, 1974; King, 1974), the sun spot cycle (Southward et al., 1975) and other astronomical phenomena (Emiliani and Shackleton, 1974; Kukla, 1975).

From the brief review above it might appear that there are considerable difficulties in deducing a comprehensive picture of past climatic variations. Although there are undoubtedly difficulties, a number of consistent aspects emerge from the large body of data available. First, for Pleistocene times the pattern of temperature variation appears to be well established with considerable detail being given from the oxygen isotope $^{18}O/^{16}O$ ratio variations. Second, for Holocene times the global pattern of temperature variations generally follows that given by Lamb (1966). Third, the time of occurrence of the temperature variation is latitude dependent, the change first starting at low latitudes. Fourth, the amplitudes of the temperature variations are latitude-dependent with the smallest amplitude occurring at low latitude; there is also some evidence from Chinese data (Anonymous, 1973) that at least some of the minor temperature variations in the Holocene are also longitude-dependent.

Using this information it is possible to construct a surface thermal history that is generally applicable to the globe and from this to obtain estimates of corrections that should be applied for the past climatic history. If application of these corrections leads to improvement in the consistency of the continental terrestrial heat-flow data then it may be concluded that at least some improvement in the reliability of continental heat-flow data has been made.

CALCULATION OF THE EFFECTS OF PAST CLIMATIC CHANGES

In calculating corrections to be applied, eight basic events have been employed up to 120,000 YBP, for three ranges of latitude and several values of thermal conductivity; the reason for choosing to vary conductivity rather than diffusivity will be discussed later. For events prior to 120,000 YBP the temperature variations are unimportant at depths to 3 km which covers all but a very few holes in which heat-flow measurements have been obtained.

For the latitude range 40—60° the pattern of temperature variations for the Pleistocene follows that given by the $^{18}O/^{16}O$ ratio variations in the ice cores from Camp Century, Greenland, with the temperature rise at the beginning of the Holocene taken as 12°C; this essentially assumes that the temperature at the base of the ice sheet was close to its pressure melting point. If ice-sheet base temperatures were closer to those observed for the Greenland ice cap, the corrections developed in this section would be much larger. The pattern of temperature variation for the Holocene is based upon information contained in the papers briefly reviewed above.

All but the two most recent thermal events have been approximated by step changes in temperature. The error introduced by using a step change to approximate a more complex function, for example a linear change, of temperature versus time, depends upon the time elapsed since the event. For events occurring prior to about 1000 YBP the errors are not significant; even for relatively recent events the difference in the disturbance to underground temperature gradients is not serious. For instance, replacing a linear change of 0.2°C/decade from 80 to 120 YBP by a step change of 1°C at 100 YBP, the error introduced is only 10% at a depth of 100 m. However, for the two most recent events, linear changes of temperature with time have been used. Details of the pattern of temperature changes used for latitudes 40°—60° are given in Table II.

For different ranges of latitude these values were multiplied by a factor of F for the T_n and F^{-2} for the V_n. These adjustments give about the right

TABLE II

Surface thermal history used in this work

n	V_n/F^2 (°C)	t_nF (YBP)
1	−9	65000
2	−3	35000
3	12	10000
4	1.5	7000
5	−1,5	2000
6	0.75	1000
7	−1.5°C/century	700−500
8	+0.5°C/decade	150−100

F = 1 for latitudes 40°−60°, F = 1.25 for latitudes 20°−40°, F = 1.5 for latitudes 0°−20°.

times for the climatic optimum shift (Fairbridge, 1972) and about the right magnitudes for the amplitudes of the temperature variation at climatic optimum as given by the numerous authors cited above.

For a series of step changes of temperature, V_n, occurring at times t_n at the surface of a homogeneous, isotropic, semi-infinite medium the disturbance to underground temperatures, ΔV_z at a depth of z is given by:

$$\Delta V_z = \Sigma V_n \operatorname{erfc}(z/\sqrt{4\kappa t_n}) \tag{1}$$

where $\kappa = k/\rho c$ and is the thermal diffusivity, k is the thermal conductivity and ρc the thermal capacity of the medium.

Differentiation with respect to z gives the disturbance to the temperature gradients, ΔG_z, as:

$$\Delta G_z = \Sigma(-V_n)\,(\pi\kappa t_n)^{-1/2}\,[\exp(z^2/4\kappa t_n)]^{-1} \tag{2}$$

V_n may be of either sign and, contrary to assumptions made by most authors, a change of temperature at one time does not have to be matched by an equal change of opposite sign at some other time.

In all the work to date concerning the effect of climatic variations on underground temperatures the diffusivity has been taken to be 0.01 cm^2 sec^{-1} (1 mm^2 s^{-1}) with some authors computing curves for 3 or 4 values of different diffusivity. However, the thermal capacity for a wide variety of solid materials covers quite a limited range centred around 0.5 cal g^{-1} °C^{-1} (2.1 kJ kg^{-1} K^{-1}). In particular, laboratory and in-situ experiments (Beck et al., 1971) with sedimentary rocks covering a wide range of thermal conductivities gave values of thermal capacity ranging from 0.45 to 0.65 (1.88 to 2.72 kJ kg^{-1} K^{-1}); a curve from Beck et al. is shown in Fig. 1. Therefore, for this work, in eqs. 1 and 2 the thermal diffusivity is varied by varying the thermal conductivity while keeping the thermal capacity constant at 0.55 (2.30 kJ kg^{-1} K^{-1}).

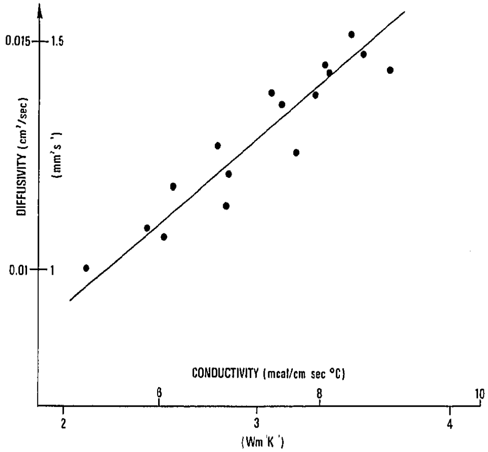

Fig. 1. Plot of thermal diffusivity versus conductivity demonstrating relative constancy of thermal capacity over a wide range of conductivities. Materials are water saturated porous limestones, sandstones and shales; slope of line gives thermal capacity of 0.6 cal g^{-1} $°C^{-1}$ (2.5 kJ kg^{-1} K^{-1}).

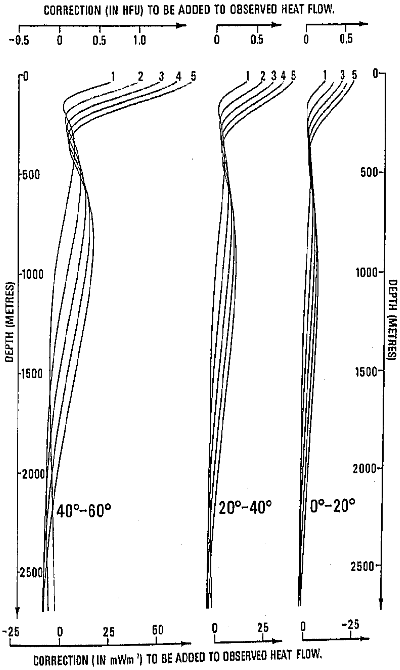

Fig. 2. Corrections required to be added to observed heat-flow values to allow for surface thermal history of past 120,000 years. Three families of curves are shown for latitude ranges of 0—20°, 20—40°, 40—60°. Numbers on curves are for different values of thermal conductivity: *1* = 3 mcal/cm sec °C (1.26 Wm^{-1} K^{-1}); *2* = 6 mcal/cm sec °C (2.51 Wm^{-1} K^{-1}); *3* = 9 mcal/cm sec °C (3.77 Wm^{-1} K^{-1}); *4* = 12 mcal/cm sec °C (5.02 Wm^{-1} K^{-1}); *5* = 15 mcal/cm sec °C (6.28 Wm^{-1} K^{-1}).

The linear increase of temperature centred around 120 YBP and 600 YBP has been approximated by a series of small steps in temperature; this was done simply for the convenience of programming and leads to no sensible error. Typical curves are shown in Fig. 2 for a range of conductivities, and are presented in the form of the amount by which the observed heat flow should be increased to obtain the equilibrium heat flow had the climatic variations not occurred.

It can be seen from the curves that for most conductivity values there is a major effect on the heat-flow measurements in the range of 100—500 meters, a range in which Holocene temperature variations may have an important effect and from which many of the heat-flow measurements used to compute the continental mean have been made.

APPLICATION OF THE RESULTS

The results indicate that the errors, and therefore the uncorrected heat-flow values, are latitude- and conductivity-dependent as well as depth-dependent. Therefore the ideal test of the validity of this approach would require three groups of several boreholes in regions of known constant heat flow. Two of the groups should also be in regions of identical conductivity; of these two groups one should consist of holes of depth ranges from about 200—3000 m and drilled over a narrow latitude band, while the second group should be of a constant depth but spread over a wide latitude range. The third group should consist of holes at one latitude and all of a given depth but drilled in regions of widely differing conductivity.

Since the ideal is not attainable the corrections have been tested in a number of cases; the first was to recalculate Crain's (1968) data for the Appalachian system.

The work of Crain (1968)

There are a number of problems associated with Crain's work.

First, he used the summarized data given by Lee and Uyeda (1965). In this work, only the maximum depth of the borehole was given; however, in many cases the heat-flow values quoted were derived from only a very limited section of the borehole. Therefore, in plotting the results it would be more logical to use the mean depth over which the heat-flow value was derived rather than the maximum depth of the hole. Second, only a one step function was used to allow for the retreat of the ice sheet at the beginning of the Holocene. Third, in one instance two heat-flow values were given for one borehole and the mean was taken; however, on consulting the original data the lower heat-flow value was derived using a thermal conductivity computed from a knowledge of the structure of the rocks, whereas the higher heat flow was obtained using measured thermal conductivities. It is felt that it would have been better to take the heat-flow value given for the measured thermal conductivities. Finally, I have been unable to reproduce the correlation coefficient given by Crain for his data after applying his correction for the effect of the retreat of the last ice sheet.

The approach used by Crain has therefore been re-used but all the original publications have been consulted before applying corrections of the type illustrated in Fig. 2. The results, in Table III, are compared with Crain's original results; the figures in brackets alongside his results are the recomputed values using a heat-flow value of 1.4 HFU (58.6 mW m^{-2}) for data point 1133. It can be seen that although there are differences in detail the basic conclusion of Crain is unchanged — namely, that the mean heat-flow value is significantly increased and that an original correlation between depth of measurement and heat flow is much reduced after applying corrections for climatic variations.

It is worth pointing out that Crain's approach using a one-step function would tend to over-correct for the Pleistocene effect and that a negative correlation coefficient should be expected if the original correlation is due to climatic effects. Thus the negative correlation coefficient strengthens rather then weakens the present argument.

Variation of heat flow with depth in single boreholes

Under ideal conditions it should be possible to detect variations of heat flow with depth caused by neglect of corrections for climatic variation. Unfortunately, unless measurements are made in a section of the hole where the curvature of the correction is large, usually the upper parts of the hole which are often avoided for other reasons, or over a reasonable depth range, the normal errors of measurements are likely to obscure the effect. This can be seen from Fig. 3 where for a region of constant conductivity, 6.67 TCU (2.79 Wm^{-1} K^{-1}), and heat flow, 1 HFU (41.9 mWm^{-2}), the true equilibrium temperatures are shown as a continuous line of 15°C/Km (15 mKm^{-1}) and the temperature disturbed by the thermal history for 40—60° N shown in Table II are plotted every 50 m. It can easily be seen that because of the Holocene climatic variations the points for the upper few hundred meters of the hole wander slightly about the smoothly changing curve which would be produced for the Pleistocene corrections above.

Except for the regions of obvious curvature, any straight line drawn through the points, even if measured at 10-m intervals, for a section a few hundred meters long would give a slope with a standard deviation well within generally accepted tolerances. If the conductivity is known to vary, a Bullard plot would be constructed with similar results.

The principal causes of error that place the signal below noise level come from the variability of thermal conductivity, particularly in sedimentary sections, the possibility of genuine heat-flow variations from other causes such as refraction effects (Roy, 1963) and the possibility of minor sources or sinks of heat (Hamza and Beck, 1975). Methods of measuring temperature

TABLE III

Comparison of work for the Appalachian system

Data No.	Crain's data			This work					References
	max depth (m)	Q_1 (HFU)	Q_2 (HFU)	mean depth (m)	lat. (°N)	K (TCU)	Q_1 (HFU)	Q_2 (HFU)	
55	250	0.82	1.29	180	46	3.0	0.82	0.87	Saull et al., 1962
44	300	1.03	1.71	200	44	6.4	1.03	1.14	Misener et al., 1951
46	300	1.05	1.49	265	46	6.7	1.05	1.16	Misener et al., 1951
									Misener and Thompson, 1950
1133	312	1.25	1.51	225	37	7.8	1.40	1.49	Diment et al., 1965b
53	340	0.74	1.19	300	45	12.0	0.74	0.86	Saull et al., 1962
54	450	0.81	1.24	300	45	5.1	0.81	0.97	Saull et al., 1962
1134 (7)	600	1.00	1.37	500	33	6.5	1.00	1.15	Diment et al., 1965a
32	880	0.73	1.00	545	36	6.2	0.73	0.89	Diment and Robertson, 1963
33 (3)	925	1.12	1.39	600	39	7.1	1.12	1.29	Diment and Werre, 1964
29	1500	1.20	1.29	900	41	4.1	1.20	1.25	Joyner, 1960
30 (2)	1500	1.40	1.49	1400	42	3.8	1.40	1.30	Joyner, 1960
31 (2)	2200	1.20	1.21	1850	39	3.7	1.20	1.10	Joyner, 1960
Means		1.21 (1.04)	1.46 (1.36)				1.04	1.12	
Std. error		0.18 (0.24)	0.21 (0.22)				0.24	0.19	
Correlation coeff.		0.58 (0.46)	—0.06 (—0.28)				0.51	0.20	

Data point numbers and Crain's data taken from Lee and Uyeda (1965).
Q_1 = uncorrected heat-flow value in μcal cm^{-2} sec^{-1}.
Q_2 = heat-flow value corrected for climatic effects.
Numbers in brackets are recomputed values — see text.

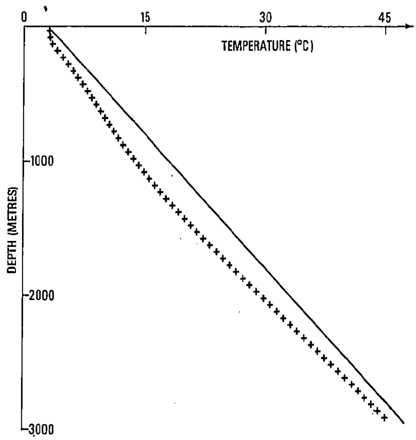

Fig. 3. Plot of 15°C/km (15 mKm^{-1}) equilibrium temperature gradient (straight line), and present underground temperature distribution (points) due to perturbing surface temperatures according to thermal history given in Table II. Conductivity assumed was 6.67 mcal/cm sec °C (2.79 Wm^{-1} K^{-1}).

and depth are now so accurate that it is unlikely that modern measurements would cause significant error in heat-flow values. It is only when holes are sufficiently deep that it becomes possible to separate the signal from noise with some confidence.

Gupta et al. (1970) report a number of measurements from India from boreholes drilled to depths greater then 1 km in a small region lying between 21 and 24°N latitude. For a number of the holes two values of heat flow were obtained using different depth ranges that were sufficiently deep that they would not be subject to serious error arising from relatively minor surface temperature variations controlled by local climatic variations. The authors do not specify mean conductivities for each hole but examining the more detailed data the mean value would lie between 4 and 6 TCU (1.67–2.51 Wm^{-1} K^{-1}). Their data and the results after applying corrections illustrated in Fig. 2 are given in Table IV. It can be seen that there is an improvement in agreement between the heat-flow values at various depths. The improvement appears to be better than it really is since if the second decimal place is used minor differences still persist.

More recently, Decker and Smithson (1975) reported a systematic variation of heat flow in a borehole in Texas, latitude 30° N, which they attributed to refraction effects due to a conductivity contrast. However, it is most unlikely that the 30% heat-flow variation observed is due to refraction effects since the conductivity contrast is only 10%. The depth ranges in the borehole are such that the thermal effects associated with the "little ice age", superimposed on the deglaciation effects, become important. Applying the

TABLE IV

Effect of climatic corrections applied to the data of Gupta et al. (1970)

Hole No.	Depth range (m)	Mean depth (m)	Q_1 (original)		Q_2 (corrected)	
			(HFU)	(mWm^{-2})	(HFU)	(mWm^{-2})
K58	550– 975	760	1.7	71	1.8	75
	975–1200	1090	1.8	75	1.85	77
K27	560–1000	780	1.8	75	1.9	80
	1000–1220	1110	1.9	80	1.95	82
Kat-9	525– 725	625	1.9	80	2.05	86
	725–1000	960	2.2	92	2.25	94
A-2	750–1200	970	1.7	71	1.85	77
A28	400– 500	450	1.5	63	1.65	69
	500–1175	840	1.65	69	1.75	73
A170	700–1200	950	1.5	63	1.55	65
C-10	850–1225	1040	2.4	100	2.45	103
C-36	850–1100	1000	2.3	96	2.35	99
C-33	850–1200	1030	2.0	84	2.05	86

Mean conductivity taken as 5.0 TCU (2.1 $Wm^{-1} K^{-1}$) for all holes. All holes are in latitude range 22°–24°N.

corrections illustrated in Fig. 2 the original results and the climatically corrected results are shown in Table V. Once again, an improvement in consistency can be observed.

Conductivity dependence

Decker and Roy (1974) have given details of measurements in twenty boreholes in the Canadian Shield. These holes can be divided into two groups. The first are within a few kilometers of each other at latitude 44°15′N; all are in regions of relatively high thermal conductivity ranging from 9.4 to 12.0 (3.94 to 5.02 $Wm^{-1} K^{-1}$) with a mean of 11.3 TCU (4.73 $Wm^{-1} K^{-1}$) with a mean depth of measurement for the group of 315 meters. The second

TABLE V

Effect of climatic corrections applied to the data from a Texas borehole (Decker and Smithson, 1975)

Depth range	Mean depth	Q_1 (original)		Q_2 (corrected)	
		(HFU)	(mWm^{-2})	(HFU)	(mWm^{-2})
180–560	370	2.06	86	2.15	90
560–620	590	1.93	81	2.12	89
620–880	750	1.51	63	1.70	71

TABLE VI

Results for twenty holes in the Canadian Shield (Decker and Roy, 1974)

Group	n	Mean K		Mean depth (meters)	Q_1 (original)		Q_2 (corrected)	
		(TCU)	($Wm^{-1} K^{-1}$)		(HFU)	(mWm^{-2})	(HFU)	(mWm^{-2})
1	13	11.3	4.37	315	1.15	48	1.26	53
2	7	5.6	2.34	330	0.96	40	1.16	49

TABLE VII

Typical climatic corrections (in HFU) to be added to the observed heat-flow value

Lat. (°)	K (TCU)	Depths in meters								K ($Wm^{-1} K^{-1}$)
		100	200	300	400	500	1000	1500	2000	
40—60	4.0	0.31	0.08	0.18	0.23	0.22	—0.01	—0.10	—0.10	1.67
	8.0	0.73	0.17	0.12	0.23	0.30	0.20	—0.02	—0.13	3.35
	12.0	1.07	0.38	0.12	0.18	0.29	0.34	0.12	—0.07	5.02
20—40	4.0	0.21	0.04	0.08	0.12	0.13	0.03	—0.05	—0.06	1.67
	8.0	0.47	0.14	0.06	0.10	0.15	0.14	0.03	—0.05	3.35
	12.0	0.65	0.28	0.09	0.08	0.13	0.21	0.11	0.00	5.02
0—20	4.0	0.16	0.03	0.04	0.07	0.08	0.03	—0.02	—0.04	1.67
	8.0	0.32	0.11	0.04	0.05	0.09	0.10	0.03	—0.02	3.35
	12.0	0.43	0.22	0.07	0.04	0.07	0.14	0.09	0.02	5.02

group is more widely spread with the latitude ranging 44–48° N but all are in regions of relatively low thermal conductivity ranging from 4.4 to 7.9 (1.84–3.31 $Wm^{-1} K^{-1}$) with a mean of 5.6 TCU (2.34 $Wm^{-1} K^{-1}$) with the mean depth of measurement for the group being 330 meters. The mean heat flows from the two groups differ by nearly 20% with the difference narrowing to less than 10% after corrections are applied. The results are shown in Table VI.

EFFECT ON THEORIES OF CORRELATION BETWEEN HEAT-FLOW VALUES AND THERMAL CONDUCTIVITY

For some time there has been disagreement in the literature as to whether there is a correlation between heat-flow values and thermal conductivity. Horai and Nur (1970) analyzed many data and concluded that there was a positive correlation. The results of Horai and Nur were criticized by Naidu (1971) who argued that the results of Horai and Nur could be explained just as well by a random heat-flow process. More recently Negi et al. (1974) have presented data from the sedimentary basins of India and have argued that they showed a negative correlation between heat flow and thermal conductivity; some of their conclusions have been criticized by Hamza (1974). It is possible that all three groups are correct.

Table VII gives some typical values of the correction to be added to the observed heat flow at various depths and in the three latitude ranges for the climatic scheme used in this paper. It can be seen that, for instance, at low latitudes if the mean depth over which the heat-flow measurements have been made is approximately 200 meters the correction required for low thermal conductivity regions is made much smaller than that required for high thermal conductivity regions; this means that the observed heat-flow values will be negatively correlated with thermal conductivity. It can also be seen that at intermediate latitudes at a mean depth of 1 km the same comments apply. On the other hand, using the illustrations from high latitudes, if the mean depth is 300–400 meters, the correction required for low-conductivity regions is higher than that required for high-conductivity regions; this means that the observed heat-flow value will be positively correlated with the thermal conductivity.

In general, for all three latitude ranges if heat-flow values have been derived from relatively shallow boreholes with a mean depth range up to about 250 meters the required corrections increase with increasing conductivity so that in all cases, for shallow boreholes, the thermal conductivity and heat-flow values will be negatively correlated. Between mean depths of about 250 meters and 700 meters the relationship between conductivity and corrections to be applied is complex, as can be seen from Fig. 2, and depends upon latitude but in some regions of the hole the correction can decrease with increasing conductivity. Below about 700 meters the corrections to be applied again become consistent with the correction required increasing with increase of conductivity at all latitudes.

In the work of Negi et al. (1974) much of the data used comes from the work of Rao et al. (1970) and Gupta et al. (1970). The values quoted by Gupta et al. come from the intermediate latitude range and, as a group, the measurements were made up to relatively large depths, greater than 1 km, and in regions of relatively low conductivity, around 5.0 TCU (2.09 Wm^{-1} K^{-1}). On the other hand, the work of Rao et al. was made at low latitudes, the heat-flow values generally being derived from relatively shallow holes, with mean depths around 200 meters, and in regions of relatively high conductivity, 8.0 TCU (3.35 Wm^{-1} K^{-1}). It can be seen from Table VII that in these circumstances the climatic corrections required are greater for the shallow, high-conductivity holes than for the deeper, low-conductivity holes. That is, a negative correlation between thermal conductivity and observed heat flow should be expected. If the holes used by Horai and Nur (1970) fall into the intermediate depth range, i.e. between about 250 and 700 m, positive correlations between heat flow and thermal conductivity might be expected as well as negative correlations.

EFFECT OF CLIMATIC CORRECTIONS ON THE MEAN CONTINENTAL HEAT-FLOW VALUE

Without a thorough analysis of all continental heat-flow values, taking into account latitude, depth range of measurements, and thermal conductivity as well as climatic variations, it is impossible to make explicit statements as to the actual magnitude of change that will result to the global mean heat-flow value after the application of climatic corrections to all values. However, it has been shown that the effect of climatic corrections can be very important particularly in holes of only a few hundred meters depth. Corrections of several tenths of a heat-flow unit may be needed in many instances, especially for those measurements made in high latitudes. Even at low latitudes the corrections may be important in regions of high conductivity and with boreholes less than 300 meters deep.

In shield areas the correction required probably amounts to 20% and may be considerably more in some regions. One of the best indications of the necessity of correcting for climatic effects in areas that have never been glaciated comes from a comparison of the Canadian and West Australian shields. Mean heat-flow values for these regions are approximately the same (Lee and Uyeda, 1965; Rao and Jessop, 1975). However, the values quoted for the Canadian shield are based upon values which have not been corrected for either Pleistocene or Holocene variations; if corrections are applied and increase the mean values by 20% or more, we are left with the problem that the mean value becomes significantly different from that of the West Australian shield. Therefore, either similar corrections should be applied to the data for the West Australian shield or we have to accept that the West

Australian shield is fundamentally different from the Canadian shield; to date there is no evidence for this latter hypothesis.

If the mean continental heat-flow value is significantly higher than the presently accepted value, the problem of explaining the heat flows over oceans and continents becomes somewhat easier. However, what may be of considerably more importance is whether or not climatic corrections would significantly after some of the regional mean values of heat flow on which some theories depend. For instance, for a typical heat-flow—heat-production plot (Roy et al.) for a heat-flow province, if the area of the province is small, implying uniform conductivity and climate, the corrections for each heat-flow value may be constant no matter what the heat-flow value. The net effect would be to increase the value of the intercept (the subcrustal contribution) by the magnitude of the correction but the slope of the line would be unchanged. On the other hand, the climatic corrections may not be constant, particularly if the heat-flow values have been derived from shallow holes, and both the slope and the intercept values may change.

DISCUSSION

Enough evidence has been presented to demonstrate that effects of climatic variations in the Holocene, as well as in the Pleistocene, may be far more important than has hitherto been realized. The principal difficulty is that even if generally applicable and well defined global corrections can be obtained, they are likely to be modified due to more recent short-period surface temperature variations that depend on local climate. The heat-flow value obtained from a borehole is probably reliable over a region with a radius that is only a few times the depth of the borehole. The variability of local climate is extremely complex to predict or deduce but depends on such things as elevation, local topography, type of surface cover, etc.; for example, recent extensive work by Smith (1975) shows that removal of only 10 cm of organic cover can lead to a 3°C decrease in the mean daily temperature measured at a detph of 10 cm. It can therefore be seen that to correct for local climate variations is not easy. In fact, it might be easier to deduce past temperature variations assuming a constant heat flow.

Some idea of climatic variations could be obtained by using the curvature often found in Bullard plots (Bullard, 1939). A section of constant thermal conductivity, given by the Bullard plot, is substituted for the variable conductivity section, a theoretical temperature—depth curve is found, and the curvature of the residuals is examined to see if reasonable estimates of past surface temperature variations can be obtained. Alternatively, a method might be developed whereby layers of differing thermal conductivity or diffusivity can be successively stripped to obtain better detail of temperature variations in the subsurface. In an area where several boreholes are available, a test for consistency would demonstrate the general applicability of the correction for local effects.

Although corrections for climatic effects will be increasingly affected by local, rather then global, conditions as t_n becomes smaller, there is some compensation in the fact that the smaller the value of t_n the less important the correction is at greater depths in the borehole. A simple criterion for estimating whether or not a surface effect can be ignored at any given depth can be derived.

It is well known that for sinusoidal variations of surface temperature the amplitude of the disturbance at a depth, z_λ, of one wavelength, λ, is 0.2% of the surface amplitude (Jaeger, 1965) where:

$$\lambda = 2(\pi \kappa P)^{1/2} \tag{3}$$

and P is the period of the variation. If P is 100 years, $\kappa = 0.01$ cm^2 sec^{-1} (1 mm^2 s^{-1}) then $z_\lambda = 200$ m. A similar criterion for a step function at time t_n requires that:

$$\mathrm{erf}(t_n) > 0.998 \tag{4}$$

For a step change in temperature applied 100 YBP the depth z_1 at which the amplitude of the step change is less than 0.2% of the surface change is about 250 meters; therefore the effects of a step change in temperature at the surface would be felt somewhat more deeply than a continuously applied sinusoidal oscillation. Similarly, for a change in temperature applied 300 YBP, $z_1 = 450$ meters. Even if we relax the requirements to 10% of the surface temperature variation, i.e. $\mathrm{erf}(t_n) > 0.9$, the depth at which this occurs is 240 meters for a change in temperature 300 YBP. Much more important is the depth, z_g, at which the disturbance to the temperature gradient, ΔG_z becomes insignificant. A value of 1°C/km (1 mKm^{-1}) is arbitrarily chosen as the limit below which the disturbance to the gradient can be ignored; this may represent as much as 10% error in shield areas (typical gradient of 10°C/km) and as little as 3% error in sedimentary areas. Substituting the appropriate numbers in eq. 2 we find that for $\Delta G_z < 1$°C/km, $z_g = 260$ m for a unit change in temperature 300 YBP; the equivalent depth for a change 100 YBP is $z_g = 170$ m.

If it is accepted that thermal capacity remains essentially constant and that the important thermal property is conductivity then the depth of penetration will be a function of thermal conductivity. If $c = 0.55$ (2.3 kJ kg^{-1} K^{-1}) a diffusivity of 0.01 cm^2 sec^{-1} (1 mm^2 s^{-1}) corresponds to a conductivity of 5.5 TCU (2.30 Wm^{-1} K^{-1}). If the conductivity is 8.25 TCU (3.45 Wm^{-1} K^{-1}) corresponding to a diffusivity of 0.015 cm^2 sec^{-1} (1.5 mm^2 s^{-1}) the corresponding values of z_g for unit changes 100 and 350 YBP are approximately 200 and 300 m.

CONCLUSIONS

Heat-flow values derived from continents, especially in relatively shallow holes, may be systematically too low and should be closely inspected for the effects of surface temperature changes during the Holocene as well as during the Pleistocene and corrections applied where feasible. The magnitude of the corrections will depend on latitude, thermal conductivity, depth range from which the measurements have been made as well as upon the form and magnitude of the surface temperature variations; a multivariate analysis of all the continental heat-flow values should be carried out to search for such correlations. If after applying climatic corrections upon the lines described in this paper the correlations, if any, are significantly reduced, then it can be inferred that climatic corrections should be applied to all future heat-flow data.

Since one of the problems in analyzing the global data is that insufficient data is given in the summary forms, important additional information may be required before a proper analysis is undertaken. One such item is the depth range over which a particular heat-flow value has been derived; another may be the apparent surface temperatures extrapolated from various depths.

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