Heat Flow in the Arctic[1]

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INTRODUCTION

Heat is continually escaping across the earth's surface because the interior is relatively warm, and heat flows by conduction from warm regions to cooler ones. This flux at the earth's solid surface of heat conducted from the interior is referred to in geophysics as "heat flow." Other things being equal, the more rapidly the temperature increases with depth (i.e., the greater the thermal gradient), the more rapid the heat flow. On the other hand, if the gradient is constant, the heat flow is more rapid, the greater the thermal conductivity. Generally, the amount of heat flow is equal to the product of these two quantities, thermal conductivity and thermal gradient. In order to measure the heat flow, it is necessary to measure them both.

How great is heat flow? Generally, on the order of one-millionth of a calorie escapes through each square centimetre of the earth's surface every second. (The unit will be called hfu for "heat-flow unit.") This is about enough to melt a 4-mm. layer of ice over the earth's surface each year. It is less by almost four orders of magnitude than the flux received by the earth from the sun. Hence, it has no detectable effect on the earth's surface temperature and, contrary to a widely held view, cannot generally be detected by airborne or satellite infrared measurements. Although this energy seems small, the amount leaving the earth in one month is approximately equal to the energy equivalent of the world's annual coal or oil production, and it exceeds by perhaps two orders of magnitude the rate of energy dissipation by the earth through volcanic or seismic processes.

Where does this earth heat originate? Certainly much of it must come from the decay of radioactive uranium, thorium, and potassium which occur in minute amounts in virtually all earth materials. It is likely that roughly half of the flux from the continents is contributed by these materials concentrated in the thick crust. The remainder must come from the underlying mantle. The thin crust of the ocean basins contains relatively small amounts of radioactive elements, and it could contribute no more than 5 or 10 per cent of the surface flux. It is known, however, that the heat flow from the ocean basins is not significantly different from that from the continents; therefore, much more heat must be flowing from the mantle beneath the oceans than from the mantle beneath the continents. Within the ocean basins and within the continents, both the surface flux and the distribution of crustal heat sources vary significantly. It is important to understand these variations, because they represent differences in temperature, physical state, and composition of underlying materials, and variations in the distribution of energy available for the work done by the earth in building its mountains and possibly drifting its continents.

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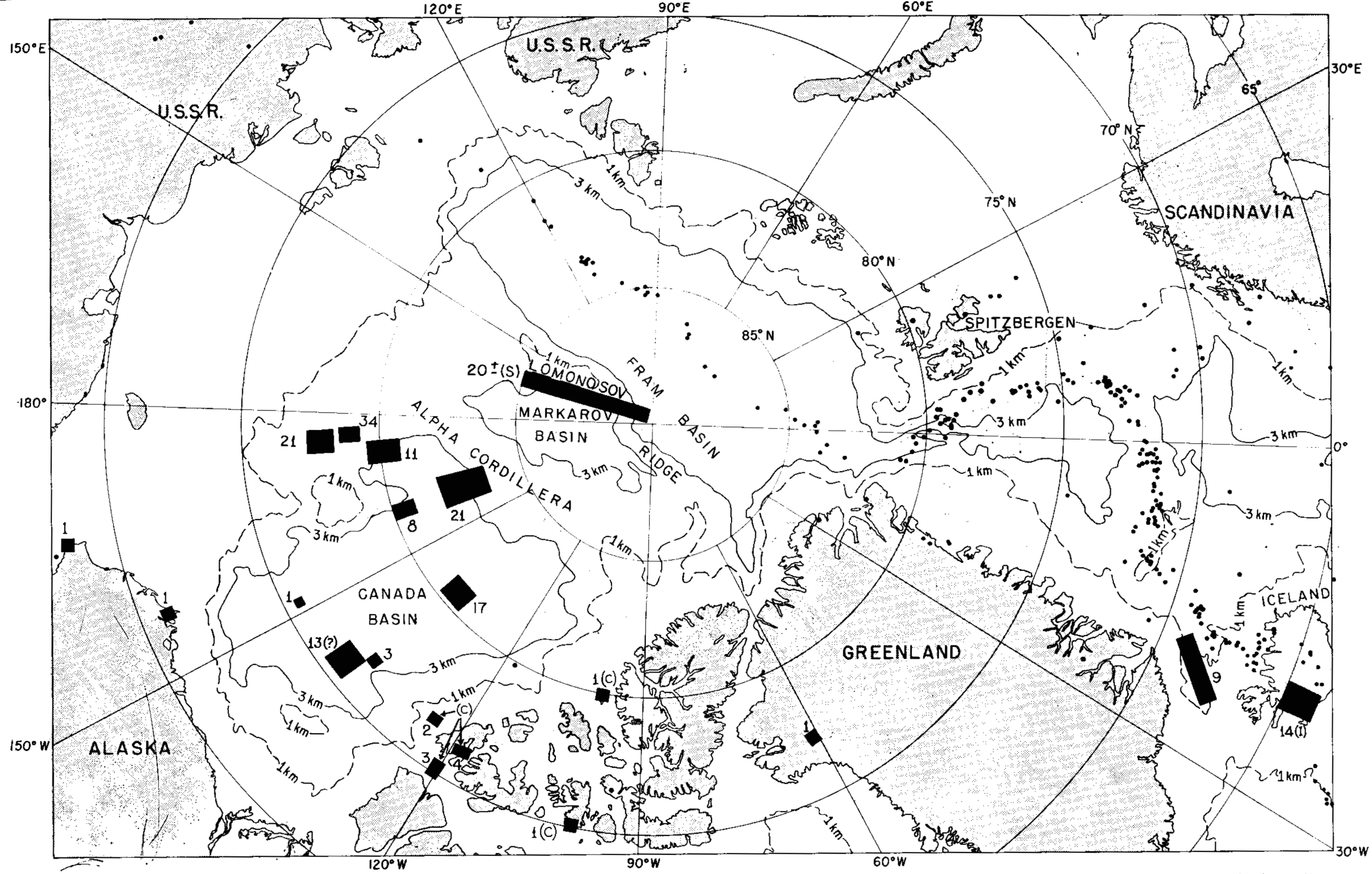

FIG. 1. Approximate location of heat-flow observations in the Arctic. Numbers indicate approximate number of measurements made in adjacent black quadrilaterals. Measurements by Soviet, Canadian and Icelandic scientists are denoted respectively by (S), (C) and (I). Dots denote seismic epicenters (Sykes 1965).

HEAT FLOW ON LAND

Fig. 1 illustrates the present distribution of heat-flow measurements in the arctic regions. Within this area there are only two published values of heat flow measured on land. One is at Cape Thompson, Alaska (Lachenbruch *et al.* 1966) and the other is at Resolute, Cornwallis Island, Northwest Territories (Misener 1955). The value at Cape Thompson is close to the world-wide average of 1.5 hfu, and the correct value at Cornwallis Island is probably somewhat less (Lachenbruch 1957). Shown also in Fig. 1 are two measurements determined from gradients in ice caps; one by Paterson (1968) on Meighen Island and the other by Hansen and Langway (1966) on Greenland. Although such measurements are uncertain because of the effects of ice accumulation and mass movement, both give reasonable values in the neighbourhood of 1 hfu. Several measurements on Iceland by Pálmason (1967) were made in shallow boreholes and are uncertain because of the effects of water movements. However, they generally suggest a high heat flow, well above 2 hfu, which is not surprising for this volcanic island situated athwart the mid-ocean rift system. The value shown for Barrow (Lachenbruch and Brewer 1959) is uncertain but probably close to the world-wide average. With these sparse and uncertain measurements, it is clear that no regional interpretation of land heat-flow patterns is yet possible in the Arctic. However, careful study of some of these geothermal results yields insight into problems peculiar to arctic heat-flow measurements and provides supplementary information of considerable interest concerning permafrost, climatic change and shoreline movements.

Fig. 2 shows measured temperature profiles from three boreholes at separate localities along the Alaskan arctic coast. Although the gradients vary by a factor

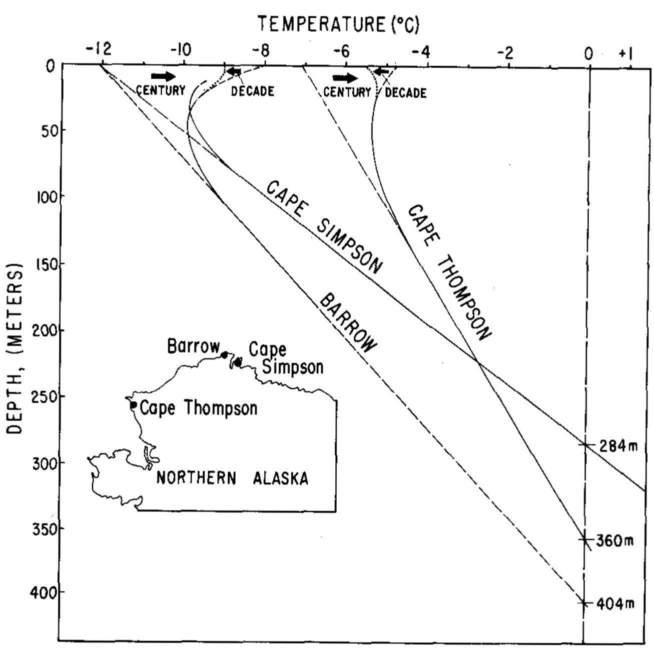

FIG. 2. Temperatures measured at three locations in arctic Alaska (solid lines). Extrapolations are shown as broken lines.

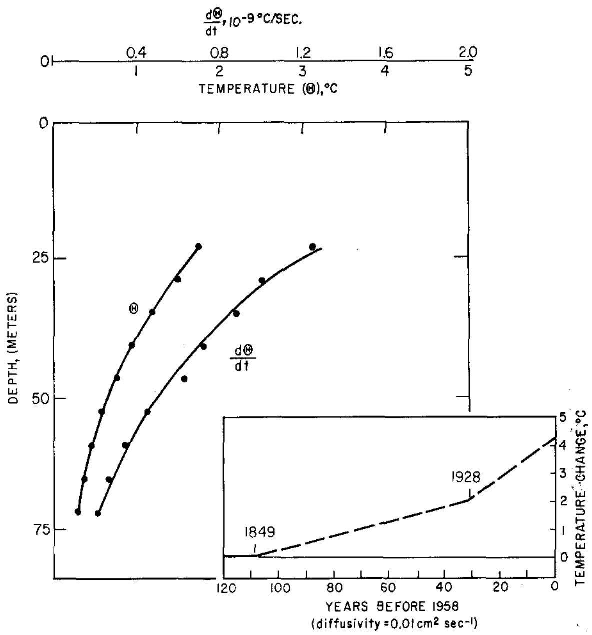

FIG. 3. Reconstruction of history of mean ground surface temperature from measurements in a well near Barrow, Alaska (dashed curve). Corresponding theoretically determined temperature anomaly, Θ, and its rate of change dΘ/dt (solid-line curves) are compared with measured values (dots) in upper graph.

of two, the heat flow at all three sites is probably within 10 per cent of the world-wide average. In other words, the gradient variations are evidently due to compensating variations in thermal conductivity. The danger of estimating permafrost depth from surface temperature alone is evident from this illustration. At Cape Thompson the surface temperature is 4°C. warmer than it is at Cape Simpson, but permafrost there is 76 m. deeper.

In areas of continuous permafrost, ground water is generally immobile and heat conduction theory can be applied to the analysis of earth temperatures up to within a few feet of the surface. The curvature in the upper 100 m. or so of the three curves in Fig. 2 clearly represents a climatic warming. The linear portions of these profiles represent thermal equilibrium established with a surface temperature determined by upward extrapolation to zero depth. Evidently Cape Simpson and Barrow formerly had a mean surface temperature of about −12.1°C. and this must have obtained, on the average, for many thousands of years. At Cape Thompson the long-term mean surface temperature was about −7.1°C. The change in surface temperature responsible for the warming of the upper 100 m. can be reconstructed approximately by heat-conduction theory (see e.g. Birch 1948). Such a reconstruction for the Barrow well is shown in Fig. 3. Because temperature observations were made in this well over a period of 8 years, it was actually possible to observe the rate of temperature change as a function of depth in addition to the total temperature anomaly (inset, Fig. 3). The broken line represents a theoretical reconstruction of the temperature change, and the solid curves show the anomaly it would produce. Hence the mean annual surface temperature at Barrow must have increased more than 4°C. since the middle of the nineteenth century. As the initial temperature was −12°C., the final temperature must have been about −8°C. However, the present mean surface

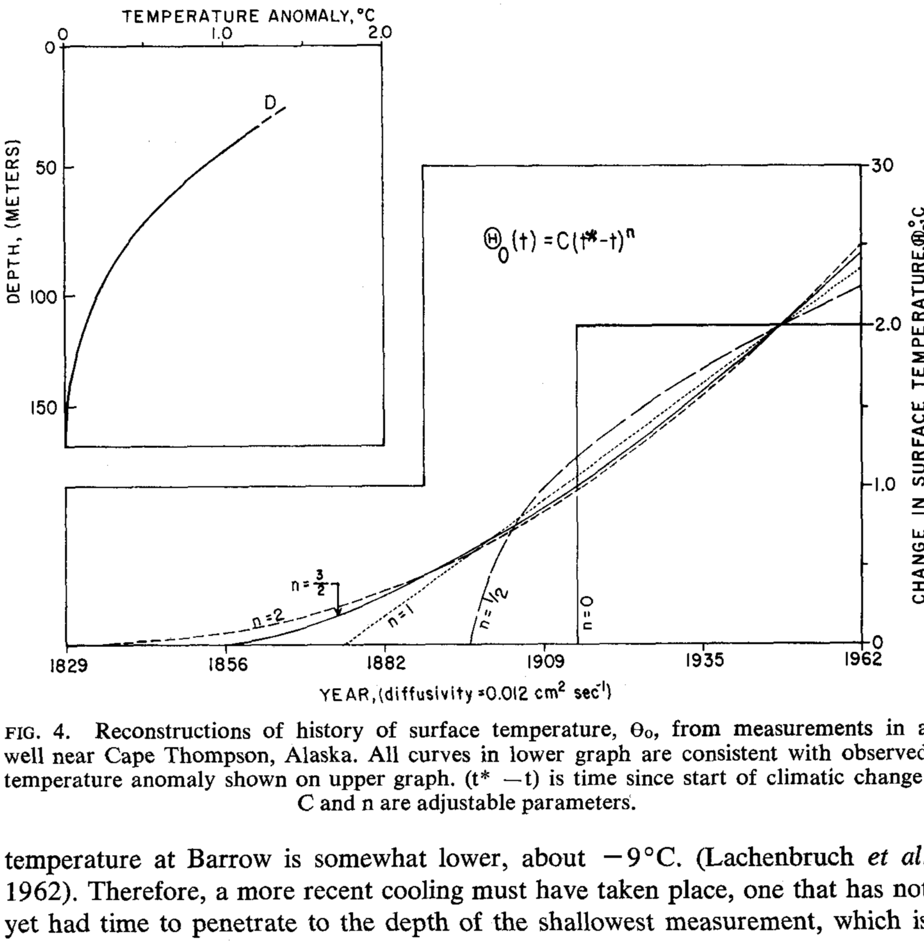

FIG. 4. Reconstructions of history of surface temperature, Θ_0, from measurements in a well near Cape Thompson, Alaska. All curves in lower graph are consistent with observed temperature anomaly shown on upper graph. (t^* —t) is time since start of climatic change; C and n are adjustable parameters.

temperature at Barrow is somewhat lower, about $-9\,°C$. (Lachenbruch *et al.* 1962). Therefore, a more recent cooling must have taken place, one that has not yet had time to penetrate to the depth of the shallowest measurement, which is on the order of 30 m. Such a cooling could hardly have been in progress more than a decade or so. A similar analysis at Cape Thompson (without information regarding the rate of cooling) is shown in Fig. 4. It is seen that the change is synchronous with the one in Barrow, although somewhat smaller. The mean surface temperature at Cape Thompson is again lower than the temperature predicted by the analysis, and a much more recent cooling is also indicated there.

It is clear that any attempt to make heat-flow measurements in this region from gradients determined in the upper 100 m. would fail, as these gradients would not represent steady flux from the earth's interior. Nevertheless these climatic perturbations give information that is interesting in itself.

More important than the climatic change to arctic heat-flow measurements is the effect of bodies of water in regions of continuous permafrost. There the mean temperature of the emergent surface may be -5 to $-15\,°C.$, in striking contrast to the bottoms of bodies of water that do not freeze to the bottom where the mean temperature is close to $0\,°C$. The result is that near such shorelines large amounts of heat enter the solid earth from beneath the water body and emerge again nearby. Such heat is easily mistaken for heat originating in the earth's interior. The

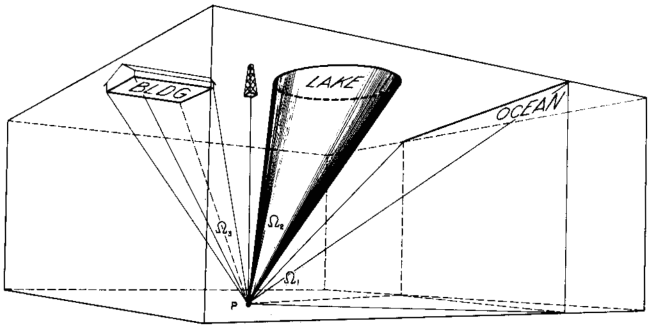

FIG. 5. Subsurface temperature effect of regions of anomalous surface temperature. Steady-state disturbance at any point, P, is the sum of solid angles (Ω) subtended by anomalous regions weighted by the anomalous temperature in each.

subsurface temperature effects of the warm spots beneath bodies of water are illustrated by the solid angle relations of Fig. 5. Their effects on permafrost distribution are shown in Fig. 6. The upper right-hand curve of Fig. 7 shows the measured temperatures at Resolute, Northwest Territories, at a point 365 m. from the ocean, and 460 m. from a large lake. The lower left-hand curve shows the profile corrected for these bodies of water. Evidently more than half of the heat flowing to the surface at the Resolute borehole entered the earth beneath the adjacent bodies of water. The heat flow there, which was originally interpreted as being almost twice the world average, is evidently somewhat lower than the world average.

Although thermal effects of water bodies can cause problems in arctic heat-flow measurements, they can supply information about the history of such bodies of water, as derived from measurements of the depth of permafrost. In two holes near Cape Thompson, one 120 m. from the shore and the other 1,200 m. from the shore, it was possible to estimate that the shoreline moved in to its present position about 4,000 years ago, Fig. 8 (Lachenbruch *et al.* 1966). A correction for latent heat effects increases the estimate to 6,000 years; a value consistent with archeological evidence (Giddings 1960).

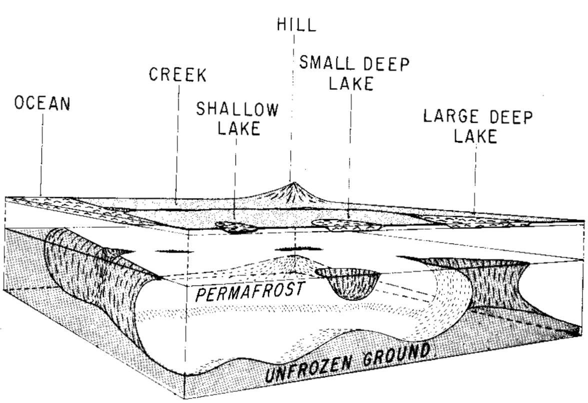

FIG. 6. Schematic representation of relation between surface features and permafrost distribution. "Deep lakes" do not freeze to bottom, "shallow lakes" do. Shown for mean ocean temperature greater than 0°C. (e.g., Cape Thompson, Alaska). For mean ocean temperature less than 0°C. (e.g., Barrow, Alaska), see Lachenbruch 1957, Fig. 4.

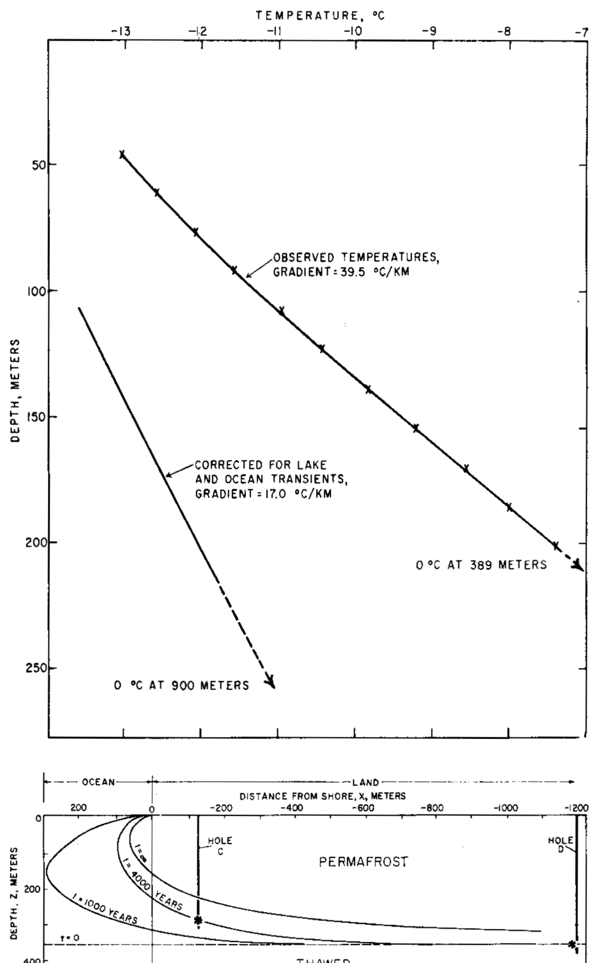

FIG. 7. Correction of observed temperatures for thermal effects of near-by bodies of water and shoreline regression in well at Resolute, N.W.T.

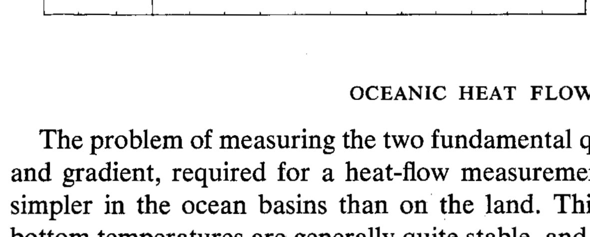

FIG. 8. Permafrost distribution near Cape Thompson, Alaska, computed for a rapid shoreline transgression t years ago; effects of latent heat neglected. Curve t = 4,000 yrs. bp close to present condition although time since transgression probably greater (see text). Asterisks denote measured depth of permafrost.

OCEANIC HEAT FLOW

The problem of measuring the two fundamental quantities, thermal conductivity and gradient, required for a heat-flow measurement is, strangely enough, much simpler in the ocean basins than on the land. This is primarily because ocean-bottom temperatures are generally quite stable, and it is only necessary to measure gradients to depths of a few metres in the bottom sediment to obtain steady-state values. Typical data are shown in Fig. 9 for one station on the Canada Abyssal Plain and a nearby one on the Alpha Rise. The conductivities determined from cores at the rise station are substantially higher than those from the station on the plain, but this effect is more than offset by the high gradient on the plain where the heat-flow value is much greater. The agreement of component heat flows over 1-metre intervals attests to the stability of the thermal conditions at depths of only a few metres. Although such conditions are typical of deep ocean,

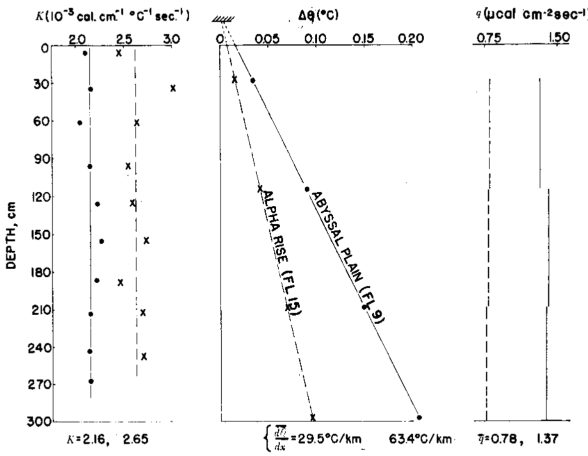

FIG. 9. Typical thermal results from the floor of the Canada Basin (solid lines and dots) and the Alpha Rise (broken lines and x's). K is thermal conductivity, $\Delta\Theta$ is sediment temperature less sea-bottom temperature, and q is heat flow.

they are not universal, particularly where the water depth does not exceed 2 km. This is illustrated by the nonlinear profiles from Denmark Strait (Fig. 10). These curvatures, like those shown previously for northern Alaska (Fig. 2) are the result of fluctuating surface temperatures; in this case, temperature changes at the ocean bottom on a time scale varying from a few hours to several weeks. Like the effects of climatic change on land, these perturbations provide information of considerable significance. In this case they reveal a previously undetected pattern of bottom-water oscillations with a period of a few weeks and a wave length of a few hundred kilometres (Lachenbruch and Marshall 1968). Analysis of the linear portions of these profiles yields a simple picture of decreasing heat flow along the traverse. As before, study of the complications in the thermal picture yields information with independent value.

The approximate locations of heat-flow measurements made in the Arctic Ocean as of this time are shown in Fig. 1. The region denoted with an (S) is the approximate position of the measurements obtained from a Soviet drifting station. The values obtained there have not been reported in detail, but they evidently tend to be above the world average (E. Lubimova, written communication and oral presentation at IUGG Heat-Flow Symposium, Zurich, Switzerland, 1967). The values denoted with a (C) were obtained through the ice in shallow water by scientists from the Dominion Observatory, Ottawa (Law *et al.* 1965; Paterson

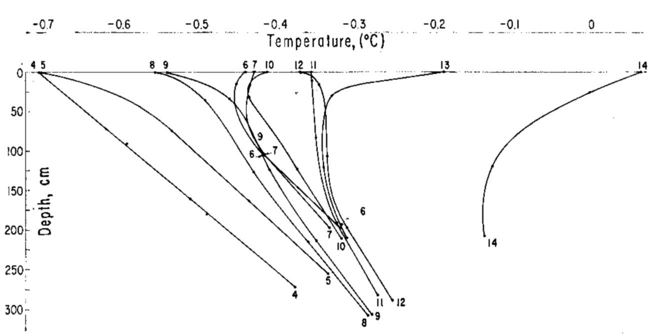

FIG. 10. Sediment temperatures beneath about 1 km. of water in Denmark Strait. Numbers on curves designate stations.

and Law, 1966). Values between the islands are close to the world average, and those farther off shore are much lower. The other oceanic values were obtained from drifting ice stations by the U.S. Geological Survey in cooperation with the Office of Naval Research. The measurements north of Iceland (from ARLIS II) confirm high heat flow near the mid-ocean rift system and suggest that the heat flow falls to normal values over a distance on the order of 100 km. (Lachenbruch and Marshall 1968). It is seen that the remainder of the measurements are in the Alaskan quadrant of the Arctic Ocean. No information is available from the large region of east longitude which is bisected by the mid-ocean rift system. This system is delineated by the dots on Fig. 1 which denote seismic epicenters (Sykes 1965).

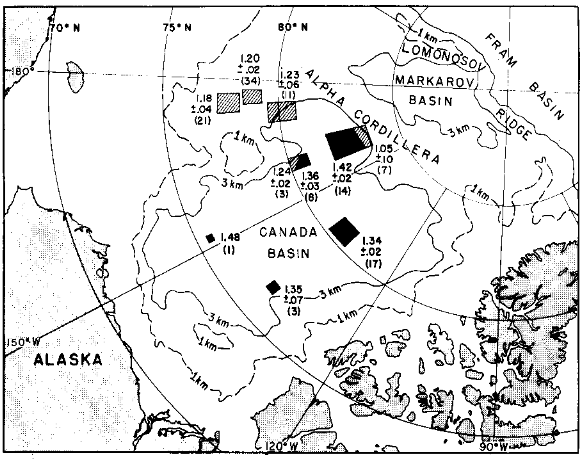

FIG. 11. U.S. Geological Survey heat-flow results from Alaska quadrant, Arctic Ocean. Three-digit number is average heat flow, number preceded by ± is standard error and number in parentheses is number of observations represented. Water depth is greater than 3500 m. in blackened regions, less than 3500 m. in crosshatched regions.

In Fig. 11 the results from the Alaskan quadrant are shown in greater detail. Measurements in the blackened regions were made beneath water more than 3,500 m. deep; in crosshatched regions water depths were less than 3,500 m. A cursory inspection shows that the shallower water stations generally yield a somewhat lower heat flow. The contrast in heat flow across the edge of the basin has been analysed in detail in the quadrangle at 83°N. (Fig. 11). The sharp change in heat flow observed at the edge of the Alpha Rise seems to require a lateral discontinuity in thermal conductivity across the entire crust. One interpretation suggests that the low-conductivity upland crust projects out tens of kilometres under the adjacent basin (Fig. 12). The model is inconsistent with previous views of the Alpha Rise, namely that it is mantle material or a lagging remnant of a foundering continent. It is consistent with the view that the rise is a great accumulation of basalt such as might be expected in an extinct mid-ocean ridge (Lachenbruch and Marshall 1966); this view is now supported by magnetic observations (King *et al.* 1966; Ostenso and Wold 1967). An alternative interpretation of the heat-flow anomaly, namely that it is caused by a deep dike parallel to the rise axis, is also consistent with this view (Lachenbruch and Marshall 1966).

Returning to the systematic difference between heat flow in the basin and on the adjacent uplands, we note the bimodel distribution in the histogram of Fig. 13.

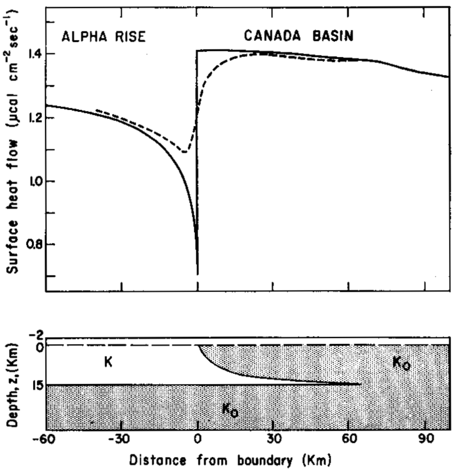

FIG. 12. Geothermal model of the Canada Basin-Alpha Rise boundary. Thermal conductivity in unshaded portion (K) is one-half that in shaded portion (K_0). Solid and dashed curves in upper graph represent theoretical heat flow for ocean bottom at z = 0 and z = −2 km. respectively. These two models bracket heat-flow observations.

The lower part of Fig. 13 shows that the heat flow from the deep basin is roughly 15 per cent greater, and considerably more uniform, than that in the surrounding regions. As these mean values have standard errors of only about 1 per cent the difference, about 0.2 hfu, is quite significant. It is substantially greater than the amount of heat that could be generated in the thin oceanic crust beneath the deep basins. Hence, these data suggest that the average heat flow from the mantle beneath the basin exceeds the average heat flow from the surface in the surround-

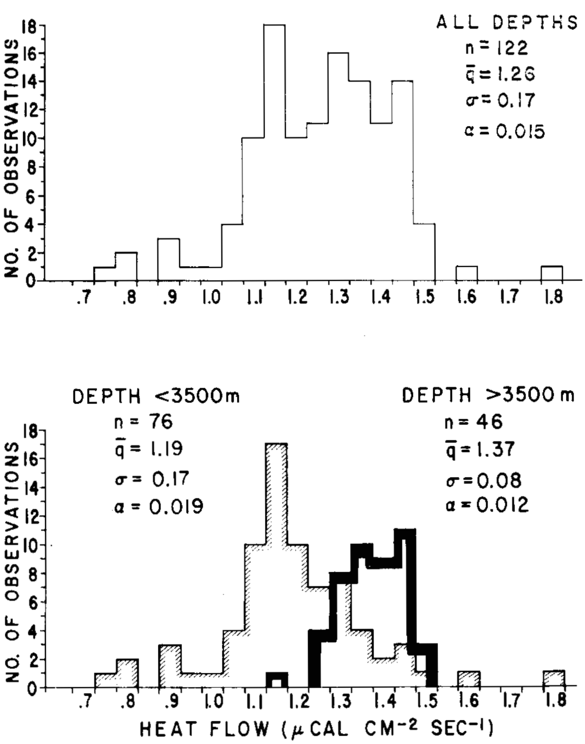

FIG. 13. Histogram of heat-flow observation shown in Fig. 11. Shading represents depths less than 3,500 m.; cross-hatching represents depths greater than 3,500 m.; n is number of samples, $\bar{q}$ is mean heat flow, σ is standard deviation, and α is standard error.

ing highlands. The mantles must be significantly different beneath these contrasting tectonic units.

FUTURE HEAT-FLOW STUDIES IN THE ARCTIC

Because of substantial logistic problems associated with field studies in arctic regions, it is obvious that arctic research should focus on those problem areas in which the Arctic offers a unique advantage. On the land, it is necessary in the future to increase greatly the number of heat-flow measurements so that we may delineate patterns and the relationship of heat flow to major tectonic provinces. Judging from experience in better-known areas, we might expect such information to lead to a more basic understanding of the geologically-observed tectonic contrasts.

It has been pointed out that regions of continuous permafrost offer a unique opportunity to apply simple conduction models to within a few feet of the surface. A fruitful area for future research will be to apply such models to geothermal data from permafrost to obtain accurate reconstructions of climatic fluctuations occurring over the past few centuries. The relation of such fluctuations to various environmental factors such as ice conditions in the Arctic Ocean are of particular interest, as they may yield insight into the mechanisms responsible for ice ages.

The remarkably large temperature difference between bodies of water and emergent surfaces at high latitudes provides opportunities to investigate shoreline fluctuations over the past 10,000 years by geothermal techniques. It might be rewarding to exploit this opportunity as the amount of near-shore drilling increases with economic development of the Arctic.

From the point of view of geothermal studies, the Arctic Ocean region is exceptional in two respects: 1) Much of it is accessible for very closely-spaced equilibrium observations at reasonable cost from stations on the ice, and 2) it contains a miniature ocean, smaller by an order of magnitude than the major oceans of the world. Over a relatively small area this ocean contains a great variety of sharply delineated features including what appear to be typical oceanic abyssal plains, a seismically-active mid-ocean ridge, two aseismic oceanic ridges of different types, and an assortment of continental slopes and shelves. These two unusual features make the Arctic Ocean an excellent place for detailed studies of the geothermal field within and at the boundaries of major crust — upper mantle units. Specifically it is particularly desirable to extend the heat-flow coverage to regions of east longitude and the vicinity of the arctic rift system.

Because the ice drifts more slowly by an order of magnitude than a vessel on the open sea, it provides a unique opportunity for very careful measurements of the temperature structure of the water and sediment very close to the ocean bottom. Further studies of this important interface are needed for an understanding of problems related to solid-earth heat flow and to physical oceanography.

Wherever geothermal studies are carried out, their value will be greatly enhanced by simultaneous observation of other geophysical quantities and by precise navigation and bathymetry in ocean areas as well as by regional geologic studies on the land.

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