Permafrost and the Geothermal Regimes

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Chapter 10

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Analysis of temperatures to a depth of 1200 ft beneath Ogotoruk Valley reveals that present earth temperatures at depth are strongly influenced by an extinct climate and by an ancient shoreline position. An active climatic change that has been in progress throughout the past century has increased the mean annual ground-surface temperature on the order of 2°C. If the present climate persists, the inland permafrost thickness eventually will be reduced from about 1170 to about 850 ft. Earth-temperature anomalies near the shoreline indicate a rapid encroachment of the Chukchi Sea several thousand years ago and imply that permafrost extends under the margin of the sea to a maximum distance of about 100 yards at a depth of 200 or 300 ft.

Preliminary results indicate that local heat flow from the interior of the earth is close to the world-wide average.

The purpose of this study was to collect sufficient data to provide an understanding of the major factors controlling the thermal regime in permafrost beneath the valley of Ogotoruk Creek in northwestern Alaska. Temperatures were measured in a few strategically located boreholes, and the thermal properties of selected specimens of frozen core obtained from these holes were determined. Where possible, the hole locations were selected to permit an analysis of the important role played by bodies of water. Although the thermal problems are simplified by the uniformity of the rock underlying the valley and by the absence of appreciable heat transfer by moving fluids in most of the permafrost, extensive information on thermal conductivity is needed before a detailed quantitative interpretation is attempted. We are just beginning to obtain laboratory measurements of thermal conductivity; therefore some of the results can be reported only in a general way at this time.

In Ogotoruk Valley the mean annual temperature of the air near the ground surface is well below 0°C (about −7°C to −8°C), and as a result the mean ground-surface temperature is also below 0°C (about −5°C to −6°C). Negative centigrade temperatures generally obtain to depths on the order of 1000 ft.

The earth materials that occupy the region of perennially negative temperature are defined as permafrost irrespective of the physical state of any moisture that might be present (Muller, 1945). Substantial amounts of unfrozen water can occur in permafrost as a result of freezing-point depression caused by dissolved solids, by hydrostatic pressure from the weight of overlying materials, or by capillarity and related interface phenomena.

Permafrost is bounded below by a 0°C isogeotherm, which, beneath a uniform, flat terrain, would be a flat surface. However, even in the absence of topographic relief, arctic terrain is rarely uniform in a thermal sense because ponds, streams, and other bodies of water cause large local thermal anomalies, which propagate downward and affect the temperature and hence the distribution of permafrost. Topographic relief generally results in a corresponding, though subdued, relief of the bottom of permafrost. Moreover, where topographic variation occurs, horizontal variations in the thermal properties of earth materials and sytematic variations in microclimate often occur. Each of these variations can cause additional irregularities on the 0°C isogeothermal surface.

Although the mean temperature of the ground surface is below 0°C, surface temperatures are above 0°C during most of a 4-month summer period. Thus a thin surficial layer, the "active layer," experiences positive centigrade temperatures annually. The base of the active layer, or the upper boundary of permafrost, is the depth at which the maximum annual temperature is 0°C. For practical purposes, it can be identified with the maximum depth of summer thawing in Ogotoruk Valley.

Changes in the temperature at the ground surface propagate slowly downward into the earth and produce lingering records of events, such as climatic change and shoreline movement. These changes can produce interesting surprises in thermal studies and under favorable circumstances can yield specific information on the unobserved events that produce them.

DETERMINATION OF NATURAL EARTH TEMPERATURES

The problem of determining natural earth temperatures has two parts, instrumentation for temperature measurement and determination of the temperature disturbance caused by drilling the hole in which temperatures are measured.

Temperature measurements were made with thermistors spliced into multiconductor cables at regularly spaced intervals. The cables were lowered into boreholes and left in place for at least 1 year. Periodic measurements of the resistance of each thermistor were made from the surface with a Wheatstone bridge; the resistances were converted to temperatures by using individual calibration data previously determined for each thermistor. With the particular thermistors and measuring equipment used in this study, the limit of accuracy is a few hundredths of a centigrade degree. Where possible, cables were returned to the laboratory for recalibration after a year or two of service as a check on the stability of the thermistors. For further details of instrumentation see Swartz (1954), Lachenbruch and Brewer (1959), and Lachenbruch *et al.* (1962).

Thermal cables were installed in four holes, designated A, B, C, and D (see Fig. 2), to depths of 584, 1015, 1000, and 1189 ft, respectively. Holes A and B were drilled during the summer of 1959 by conventional methods. The relatively warm drilling fluid caused thawing and sloughing of incompetent wall rock. This thawing and sloughing damaged the cables and rendered many of the thermistors, including all those below 500 ft, unreliable. Holes C and D were drilled in the summer of 1960 by the Cold Regions Research and Engineering Laboratory, U. S. Army Corps of Engineers. Their drilling with refrigerated fluid (see Chap. 6) required special techniques developed by Robert Lange, who directed the highly successful drilling. Drilling with refrigerated fluid had three great advantages over the conventional drilling of the previous year: (1) the wall was maintained in a frozen and competent condition, and thus there was no damage to the cables; (2) frozen natural-state permafrost cores were obtained for laboratory tests; and (3) relatively little thermal disturbance resulted; so natural earth temperatures were rapidly restored.

A theoretical analysis of the dissipation of heat introduced by drilling (Bullard, 1947; Lachenbruch and Brewer, 1959) shows that under fairly general conditions the return of the temperature $\Theta(z,t)$ to its natural predrilling value $\Theta_0(z)$, at any depth z, can be described by

$$\Theta(z,t) = A \ln\left(\frac{t-s}{t}\right) + \Theta_0(z) \qquad (t \gg s) \tag{1}$$

where t is the time since the drill bit reached the depth z, s is the value of t at the cessation of drilling, and A is a constant sensitive to the temperature of the drilling fluid. Thus, a semilogarithmic plot of observed temperature vs. $(t-s)/t$ should yield a straight line of slope A, which, when extrapolated to $(t-s)/t = 1.0$, i.e., infinite time, should yield the natural, or equilibrium, temperature Θ_0. The method is illustrated in Fig. 1 with data taken near the 300-ft depth in each of the four holes. Note the rapid approach to equilibrium, indicated by the small slopes, of the two holes, C and D, drilled with refrigerated fluid. The positive slope for hole C indicates that the permafrost at the 300-ft depth was actually cooled by the drilling process. The equilibrium temperature is determined by a short extrapolation. The natural earth temperatures determined by extrapolation are presented for all four holes in Fig. 2 and will be discussed later.

NEAR-SURFACE TEMPERATURES

The air temperature near the ground and the ground-surface temperature are subject to short-term fluctuations of large amplitude corresponding to diurnal changes, to random warm spells and cold snaps, and to periodic annual seasonal changes. Recording three-pen thermographs installed on the tundra near holes C

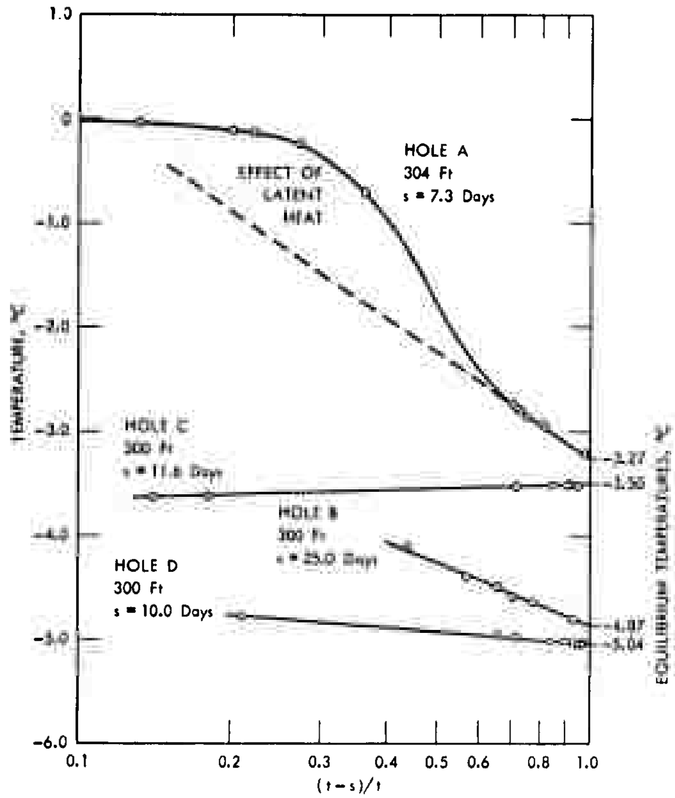

Fig. 1—Dissipation of the drilling disturbance near the 300-ft depth. Holes C and D were drilled with refrigerated fluid.

and D permitted a study of the downward propagation of such fluctuations. These instruments provided a continuous record of the temperature (1) in the air (4 ft above the ground surface in a standard U. S. Weather Bureau shelter), (2) 1 in. beneath the ground surface, and (3) 28 in. beneath the ground surface near the base of the active layer. Thermograph observations near hole D are summarized on the upper scale in Fig. 3. Several thermistors installed throughout the upper 50 ft of holes C and D showed the short-term temperature fluctuations in the underlying permafrost. The thermistors were read weekly or biweekly whenever possible. Data from hole D are presented on the lower temperature scale in Fig. 3.

The general form of the irregular curves obtained from air and from the active layer was obtained by smoothing the data as follows: (1) Mean daily temperatures were obtained by graphical integration of the thermograph records; (2) 5-day sliding averages were computed from the means; and (3) these were averaged in 5-day increments and plotted. October is the most interesting month

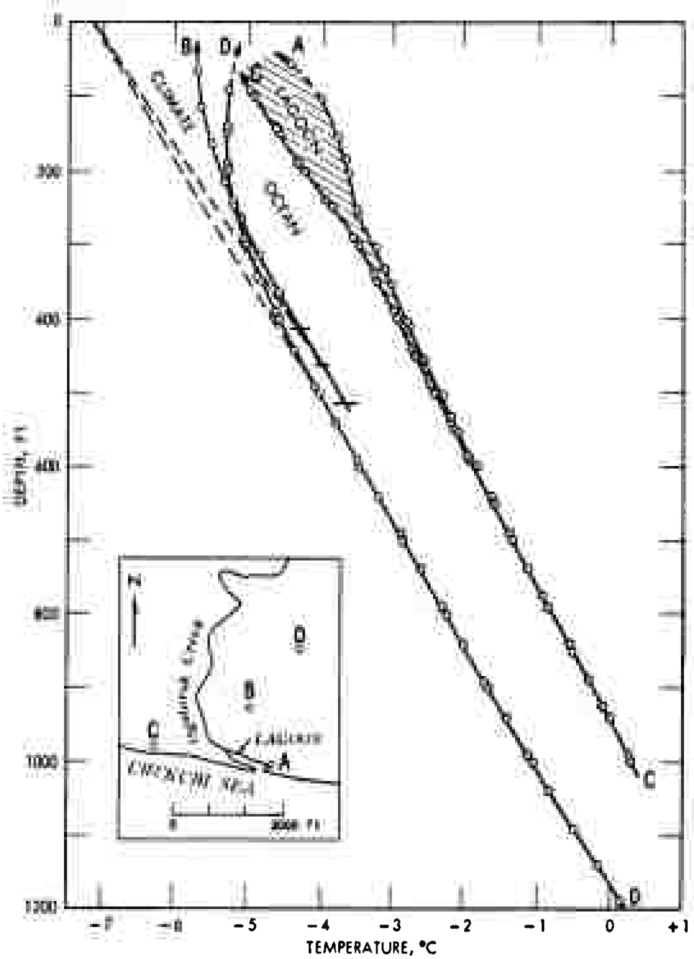

Fig. 2—Equilibrium temperatures in holes A, B, C, and D. Shading indicates temperature anomalies associated primarily with the ocean, the lagoon, or climatic change.

of the year since most of the freeze-up occurs then. Unfortunately it is the only month for which active-layer temperatures are not presently available. Since more near-surface temperature data are being accumulated, only a brief qualitative discussion will be given at this time.

Perhaps the most conspicuous aspect of Fig. 3 is the smoothing of the thermal fluctuations as they penetrate the earth. Even when they are artifically smoothed and plotted on a contracted temperature scale, the surficial temperatures appear most irregular compared with the unsmoothed data obtained from permafrost a few feet below. Most of this smoothing can be explained by the fact that conducted

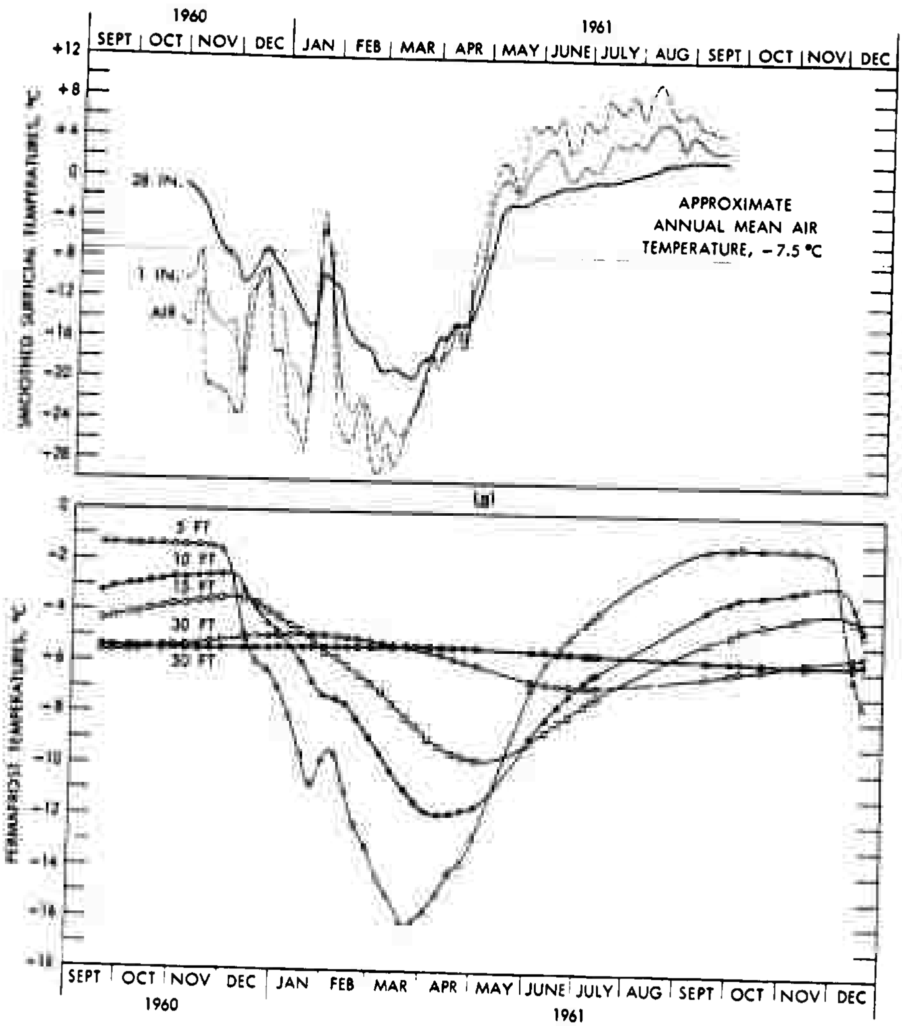

Fig. 3—Near-surface thermal regime at hole D in the air and active layer (a) and in permafrost (b).

temperature waves are attenuated exponentially with depth, the negative exponent being proportional to the square root of the frequency. Thus the high-frequency components (short-term fluctuations) of the surface temperature are attenuated rapidly; and only the fundamental frequency, that with a period of 1 year, is significant at depths greater than 15 or 20 ft. The annual wave also ultimately vanishes as its amplitude passes from about 15°C at the surface to a little over 3°C at −15 ft and 0.15°C at −50 ft. At depths greater than 70 ft, the annual wave is no longer detectable even with the most sensitive thermal elements. Systematic temperature changes that persist over many years, climatic changes, for example, can, of course, penetrate to much greater depths. Such a change is discussed in the next section.

Figure 3 shows that temperature fluctuations at the ground surface are considerably more subdued than those in the air and that very significant attenuation occurs in the active layer between the surface and the 28-in. depth. Much of this attenuation in the active layer is the result of seasonal liberation and absorption of latent heat from the freezing and thawing of interstitial water and is not related to the normal attenuation in conduction discussed above. A significant shift in the mean annual temperature probably occurs between the air and the ground surface, but this cannot be investigated until more data are available and precise calibration checks are made on the thermograph elements.

Since the thermograph element at −28 in. is within a few inches of the base of the active layer, it can be inferred from Fig. 3 that the freeze-up of the active layer at this site was completed by about November 1 in 1960. Very rapid cooling normally follows freeze-up of the active layer, but this cooling was offset somewhat at the 28-in. depth by the effects of the warm spell in the first half of November. Rapid cooling is conspicuous, however, at the 5- and 10-ft depths in early December. It represents a rapid adjustment of the thermal gradient after the retardation of winter cooling by the liberation of latent heat in the refreezing active layer (Lachenbruch *et al.*, 1962).

In addition to attenuation, the phase retardation, or time delay in the downward propagation of temperature fluctuations, is conspicuous in Fig. 3. Both effects are well illustrated by the warm spell that occurred about January 22 at the surface. The effects of the warm spell appear 10 days later at the 5-ft depth with a 20-fold reduction in amplitude. At the 15-ft depth the effects are scarcely detectable as a slight change in slope in mid-February. Note that, because of the phase retardation in the annual wave, maximum temperatures occur in midwinter and minimum temperatures in midsummer at the 30-ft depth.

RECENT CLIMATIC CHANGE

Temperatures below the depths of annual change will be discussed for hole D (Fig. 2) first because this hole is remote from bodies of water and their complicating thermal effects. The almost linear portion of the curve below −500 ft represents steady heat flow from the earth through relatively homogeneous materials. Extrapolation of this straight line to the surface ($z = 0$) yields a temperature of −7.1°C. The results of this extrapolation strongly suggest that the linear temperature profile at depth developed under thermal equilibrium with a mean ground-surface temperature of −7.1°C. Extrapolation of the measured profile suggests that the present mean surface temperature at hole D is about −5°C. The curvature in the upper 500 ft evidently represents a departure from thermal equilibrium caused by a recent trend toward higher mean ground-surface temperatures. The nature of this trend, which presumably represents a climatic change, can be investigated with the theory of heat conduction. The problem has been discussed by Birch (1948).

By assuming different models for the changing mean annual surface temperature, we can calculate the magnitude of the change and the time it would have to have started to produce the observed effect on permafrost temperatures. If the observed profile at hole D is subtracted from the linear extrapolation, the climatic anomaly can be determined (curve D, Fig. 4, part a). The mean annual surface temperature, Θ_s, was assumed to have varied as

$$\Theta_s = \Theta_s^* \left(\frac{l^* - \lambda}{l^*}\right)^n - \overline{\Theta}_s \qquad 0 \le \lambda \le l^* \tag{2}$$

where λ represents time before the present and $\overline{\Theta}_s$ is the mean surface temperature at the start of the change. The value of $\overline{\Theta}_s$ determined from curve D Fig. 2 is −7.1°C. The duration of the climatic change, l^*, and the magnitude of the change, Θ_s^*, are adjusted to give the best fit to the observed anomaly for different forms of the surface-temperature change. The forms are selected by adjusting the exponent n. Actually, a value for the thermal diffusivity, α, must be assumed before the time can be considered independently (see Fig. 4, part b).

Results for five models of the surface-temperature history are presented in Fig. 4, part b. Thus, if the change occurred abruptly as a simple step function, $n = 0$, it took place about 55 years ago and had a magnitude of 2°C. If the change is best represented by a linearly increasing surface temperature, $n = 1$, it started about 100 years ago and now has attained a magnitude of about $2\frac{1}{4}$°C. Accelerating changes of the form $n = \frac{3}{2}$ and $n = 2$ would have to have started about 125 and 150 years ago, respectively. The four models $n = 0$, $\frac{1}{2}$, 1, and $\frac{3}{2}$ fit the observations (curve D, Fig. 4, part a), with a standard error of about 0.01°C and a maximum error of 0.02°C. The model $n = 2$ yields a standard error of about 0.02°C and a maximum error of 0.04°C.

Since these differences are close to the limits of uncertainty of the measurements, there is no basis for selection between the models. Nevertheless, they all tell the same general story: the climatic change was essentially an event of the last hundred years,† and it increased the mean ground-surface temperature at hole D by 2° to $2\frac{1}{4}$°C. A similar and contemporaneous event has been detected at Point Barrow (Lachenbruch and Brewer, 1959) and at Cape Simpson. The effects of a recent increase in mean ground-surface temperature are conspicuous also in geothermal data taken at Resolute Bay, Northwest Territories, Canada (Misener, 1955).

If the ground surface were warmed by a constant rate of heat supply per unit area, then the surface temperature would increase as the square root of time.

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†*Note added in proof:* Further conductivity testing has revealed that the early samples tested were atypical and that the mean thermal conductivity for the formation is about 7×10^{-3} cal/°C/sec/cm. This yields a heat flow of about 1.4×10^{-6} cal/cm²/sec, which, by coincidence, is still "close to the worldwide average" since many determinations in the interim have resulted in an upward revision of the average. Because the mean conductivity is 7 instead of 5.5×10^{-3} cal/cm/°C/sec as originally assumed, the diffusivity values used in calculation of shoreline movements and climatic change were proportionally low; hence the time determined from these analyses should be revised downward by 25% or so. The general results are unchanged.

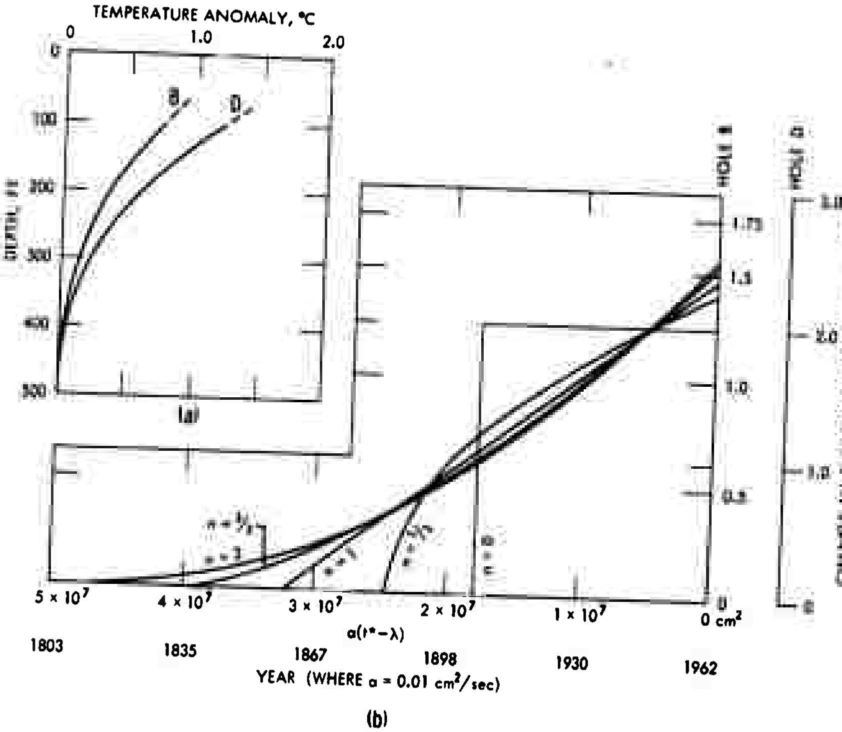

Fig. 4—Analysis of recent climatic change. (a) Climatic warming as a function of depth at holes B and D. (b) Theoretical models of ground-surface temperature history consistent with observed earth temperatures. (α = thermal diffusivity.)

Thus, an analysis of the case $n = \frac{1}{2}$ (Fig. 4, part b), reveals that the climatic warming is equivalent to the introduction of heat through the ground surface at the rate of about 20 cal/cm^2 per year for the past eight decades. This rate is about half as great as the steady flow of heat from the earth's warm interior but only a percent or so of the flow of heat that annually enters the ground surface at temperatures above the mean and leaves it at temperatures below the mean with the changing seasons.

The linearity of the thermal profile below −500 ft suggests that before the recent warming the mean ground-surface temperature had been relatively stable for several centuries. This is borne out by the fact that the recent warming trend cannot be accounted for as part of a simple periodic fluctuation about a long-term mean. The data imply further that large-scale systematic changes have not occurred in the last few thousand years.

If the present surface-temperature conditions were to persist for several thousand years, the temperature profile at hole D should assume an equilibrium configuration represented by a straight line parallel to the existing profile at depth and intersecting the surface at about −5°C. Under such conditions the 0°C isotherm (bottom of permafrost) would lie at a depth of only about −850 ft. In this sense about 25% of the permafrost beneath Ogotoruk Valley is the product of an extinct climate.

It is important to emphasize that the increase in mean annual ground-surface temperature does not necessarily imply that the mean annual air temperature has increased. Subtle changes in other climatic parameters could account for the trend. Although this change in mean ground-surface temperature might not, in itself, be important to local biological systems, it probably was accompanied by marked changes in other more biologically significant parameters, such as amplitude of seasonal temperature variation or quantity of winter snow or summer rain. The mean annual ground-surface temperature just happens to be the quantity accessible to a geothermal analysis.

HOLE B AND THE SURFACE MICROENVIRONMENT

The thermal profile at hole B has a similar but less pronounced curvature than that at hole D (Fig. 2). Since only three uncertain measurements are available below the 400-ft depth in hole B, it is not possible to determine the gradient accurately at depth. One reasonable interpretation is represented by the straight line drawn asymptotic to the profile for hole B in Fig. 2. This interpretation would imply that before the recent climatic change the mean surface temperatures at holes B and D were the same, or −7.1°C. The corresponding geothermal anomaly is plotted as curve B in Fig. 4, part a. Curve B can be obtained within instrumental error by multiplying the abscissa for curve D by a factor of 0.62. Thus the five models represented in Fig. 4, part b, account for curve B within instrumental error if the temperature scale is reduced by 0.62. Hence a total change of mean surface temperature at hole D of 2°C corresponds to one at hole B of about 1.25°C.

The difference in the present mean annual surface temperatures over the half mile or so between holes D and B seems to be real although the value of this difference, about ¾°C, can be adjusted somewhat, depending on the model used as a basis for interpretation. The evidence is inconclusive, but it does suggest that the mean annual ground-surface temperatures at the two sites were not significantly different before the climatic change. Thus it is likely that the microenvironmental difference causing the present disparity between the surface temperatures at holes B and D probably evolved during the last century and might well be in the process of change today. As an example, the surface in the vicinity of hole D has high microrelief with *Eriophorum* tussocks interspersed with bare mineral soil. At hole B the microrelief is less extreme, and the vegetal mat is more continuous. If the rough surface near hole D traps more drifting snow, this could account for the difference (Lachenbruch, 1959). The existing data could then be interpreted as an indication that the extreme microrelief developed recently near hole D, perhaps as a result of the climatic change. Several other possible causes could be mentioned, but the identification of the most likely factors is best left to the ecologists.

EFFECTS OF BODIES OF WATER

Holes A, B, C, and D were drilled at varying distances from the shoreline (insert, Fig. 2). It is suggested by the shading in Fig. 2 that the major difference between the temperature profiles is the result of the thermal effects of the ocean and lagoon. Such bodies of water can cause surprisingly large geothermal effects at high latitudes because the perennially unfrozen bottom sediments have a mean temperature above the freezing temperature of the water that contacts them, but the emergent land surface is generally many degrees colder. Thus, when a body of water forms or when a shoreline moves, the temperature of a portion of the earth's surface changes radically. The resulting geothermal disturbance propagates downward and laterally into the earth; it takes thousands of years before thermal equilibrium is approached in the permafrost zone. Measurements of these anomalies can yield information on the chronology of shoreline movements. Such information is fundamental to an understanding of the geothermal regime in coastal permafrost areas (Lachenbruch, 1957a, 1957b; Lachenbruch *et al.*, 1962).

The thermal disturbance caused at depth by a surface body of water can be calculated from a knowledge of the following: topographic configuration of the solid surface, present shoreline configuration, past history of the shoreline configuration, thermal diffusivity of earth materials (assumed uniform), mean annual temperature of the bottom sediments (assumed uniform), and mean annual temperature of the surrounding emergent surface (assumed uniform).

The interesting inverse problem in permafrost is to estimate the shoreline history from a knowledge of the other five factors and of the thermal disturbance, the latter being inferred from direct measurement of earth temperature. As in the inverse problem for climatic change, the results are ambiguous, but they can be useful.

Since the bottom of the Chukchi Sea slopes very gently (Scholl and Sainsbury, 1961) and the lagoon is less than 10 ft deep, topographic relief can be neglected in calculations for depths greater than 100 ft. The present shoreline configuration can be obtained from maps, and the thermal diffusivity can be estimated (about 0.01 cm^2/sec) from laboratory measurements on frozen core. The mean annual temperature of the ground surface is taken as $-7.1°C$ since effects of the recent climatic warming are unimportant in these calculations.

Brewer† has shown that the temperature of shallow coastal waters near Point Barrow is quite uniform both vertically and horizontally and that mean annual bottom-sediment temperatures can be estimated accurately from daily observations of water temperature near the beach. Off the mouth of Ogotoruk Creek such observations gave an average annual bottom-sediment temperature of about +0.65°C for 1960. Comparison of this value with data covering 5 years from Point Barrow† and 4 years from Wales, Alaska (G. L. Bloom, personal communication, 1960) suggests that 1960 mean water temperatures were slightly lower than average and that a reasonable long-term average off the mouth of Ogotoruk Creek is +0.75°C. The corresponding averages for Point Barrow and

†M. C. Brewer, Ice, Water, and Bottom Temperatures near Point Barrow, Alaska, unpublished.

Wales taken from the data of Brewer and Bloom are about −0.45°C and +0.90°C, respectively. It will be assumed that the mean bottom-sediment temperature has remained close to this value (+0.75°C) for the past several thousand years. This assumption is supported by evidence from Point Barrow that the recent climatic change had little effect on submerged surfaces (Lachenbruch *et al.*, 1962) and by evidence from hole D that indicates a uniform gradient at depth and hence precludes systematic mean surface-temperature changes within the last few thousand years.

On the basis of these assumptions, the thermal anomaly caused by the sea at hole C (385 ft inland) has been computed from heat-conduction theory (Lachenbruch, 1957a). In Fig. 5 the curve marked $t = \infty$ represents the effect the sea would have if the shoreline had been in its present position long enough for thermal equilibrium to obtain. The other two broken curves in Fig. 5 represent the thermal effect to be expected at hole C if the shoreline had moved suddenly to its present position 4000 or 1000 years ago.

Curve C-D (Fig. 5) represents the difference between the temperatures measured at holes C and D. It can be shown that hole D is so far inland (3900 ft) that temperatures there are unaffected by the ocean. Hence, if other conditions are equal at the two sites, curve C-D represents the thermal disturbance caused by the sea at hole C. Curve C-B represents the difference between measured temperatures at holes C and B (about 2000 ft inland). From the shapes of curves C-B and C-D, it is clear that the theoretical model (broken lines) is too simple to account for details of the ocean disturbance. Since C-D does not increase with depth, however, the present shoreline position evidently has not been occupied long enough for the ground to attain thermal equilibrium with the sea. The simple model of a rapid shoreline transgression 4000 years ago fits curve C-D very well below 700 ft and hence agrees with the measured depth of permafrost at hole C (945 ft). Near the surface, C-B and C-D bracket

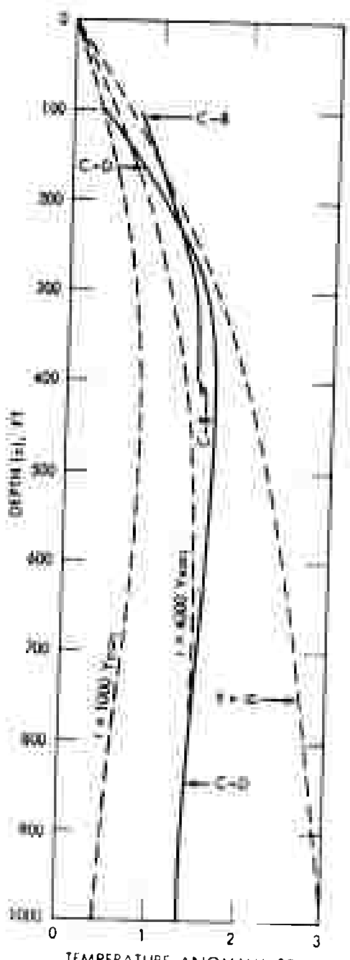

Fig. 5—Analysis of thermal effects of the ocean. Curve C-B represents temperature differences between holes C and B. Curve C-D represents temperature differences between holes C and D. Broken lines represent the computed effect at hole C of a rapid shoreline transgression to the present position t years ago.

the theoretical curves; thus their departure from the model can be explained if the mean surface temperature at hole C is intermediate between that at hole B and at hole D. The departure of C-B from C-D at depth is evidently the result of local topographic effects at hole B and possibly of a minor difference in thermal conductivity.

If the departure at intermediate depth between curve C-D and the curve t 4000 were to be explained in terms of shoreline history, we would be forced to infer that several thousand years ago the transgressing shoreline "overshot" by several hundred feet and then retreated to its present position in the last century. However, such an explanation is precluded by the present beach morphology. Although alternative explanations are possible, the most likely explanation is that the disparity represents the combined effect of a low-conductivity layer in hole C between-200 and -300 ft, as indicated by the change in gradient (Fig. 2), and the neglected effects of the latent heat of melting interstitial ice at the rising base of permafrost. A preliminary calculation accounting for these effects suggests that the thermal data are consistent with a rapid shoreline transgression occurring about 6000 years ago.† Although this date is consistent with that inferred by Giddings (1960) from archeological studies and by Moore (1960) from study of the beaches, it could be revised upward or downward by as much as 50% when additional thermal conductivity values become available and make more refined calculations possible.

The distribution of permafrost corresponding to the theoretical models represented in Fig. 5 is shown in Fig. 6. The theoretical curve corresponding to a rapid transgression 4000 years ago gives the depth of permafrost correctly at the two places where it was measured (holes C and D) and probably provides a reasonable approximation to the actual permafrost distribution even though the actual date of transgression is underestimated because of the neglected effects

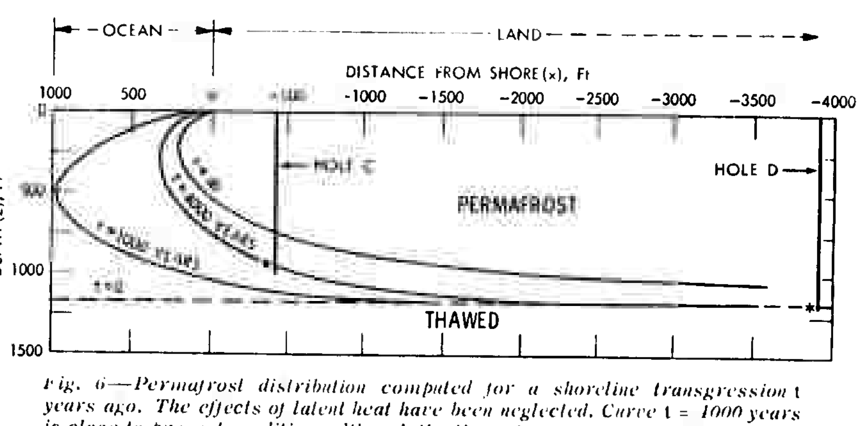

Fig. 6—Permafrost distribution computed for a shoreline transgression t years ago. The effects of latent heat have been neglected. Curve t = 1000 years is close to present conditions although the time since transgression is probably greater. Asterisks denote the measured depth of permafrost.

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†See footnote on p. 156.

of latent heat. The amount by which the time of movement is underestimated by this model can be thought of as the time required to melt the interstitial ice between the curves $t = 0$ and $t = 4000$ (Fig. 6). The average ice content is believed to be about 1% or less.

As implied in Fig. 2, the major cause of the difference between the temperatures at holes A and C is the thermal effect of the lagoon. If the linear shoreline trend is projected across the mouth of the lagoon, holes A and C are about the same distance from it; hence the thermal effects of the sea are expected to be about the same in each hole, and the convergence at depth of the temperature profiles for holes A and C (Fig. 2) is not surprising. Since the size, shape, and depth of the lagoon vary appreciably from year to year, it is not possible to study its thermal effect in detail by theoretical methods. Nevertheless, application of the three-dimensional heat-conduction model (Lachenbruch, 1957b) shows that the difference between the temperature profiles at holes A and C is of the expected general form and magnitude if the lagoon is assumed to have occupied its present position for the last few thousand years.

PRELIMINARY ESTIMATE OF EARTH HEAT FLOW

Since the temperatures in hole D are not influenced by the thermal effects of bodies of water, the increase in temperature with depth below −500 ft can be identified with the outward flow of heat from the earth's interior. The linearity of the profile suggests that the rocks have a relatively uniform thermal conductivity when viewed on the scale of the thermistor spacing. Although detailed information is not yet available on the conductivity, we ran about 24 tests on frozen core selected at random while we were developing and refining the conductivity apparatus. The core samples yielded an average value of 5.5×10^{-3} cal/cm/°C/sec. Multiplying this average value by the mean thermal gradient below −500 ft in hole D (19.8×10^{-4}°C/cm) yields a heat flow of about 1.1×10^{-6} cal/cm²/sec, which is close to the worldwide average as we know it today.† The greatest uncertainty in this calculation lies in the selection of the mean value of the thermal conductivity, which might be adjusted by as much as 10 or 15% after more extensive measurements are made. The neglected thermal effects of topographic relief would affect the results by only about 2%, and the effects of a hypothetical change in mean ground-surface temperature at the end of Wisconsin glaciation, by possibly 10%. Since the area was not glaciated in Wisconsin time, however, there is no evidence that any such change occurred; nor is there any rational basis for speculating if such a hypothetical change might have been a warming or a cooling.

Heat-flow studies at Resolute Bay, Northwest Territories, Canada (Misener, 1955), and at Norman Wells (Garland and Lennox, 1962) have led some authors to suggest that arctic North America is a region of greater than normal heat flow. The results from Ogotoruk Valley are not consistent with such a generalization.

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†See footnote on p. 156.

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