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POSTGLACIAL TIME CALCULATIONS FROM RECENT GEOTHERMAL MEASUREMENTS IN THE CALUMET COPPER MINES

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ABSTRACT

The retreat of the glacial sheet a number of thousand years ago and the subsequent long-period surface temperature variations must almost certainly have left their impress on the geothermal curve. An attempt has been made to find such an effect and to interpret it in terms of past surface temperatures by subjecting to mathematical analysis a series of geothermal measurements recently made in the Calumet and Hecla conglomerate mine. The results indicate that the glacial epoch ended for this region 20,000–30,000 years ago, and that it was followed by a period with ground temperatures distinctly warmer than the present, succeeded in turn by one cooler, and lasting until comparatively recent times.

During the past three years a series of carefully made temperature measurements has been under way in the conglomerate mine of the Calumet and Hecla Company at Calumet, Michigan. These measurements have all been planned with careful attention to the laws of heat conduction, to the end that they may give, as accurately as possible, virgin rock temperatures unaffected by mining operations. Though there were more compelling reasons for initiating this study, the phase of the matter to be discussed here is the possibility of making certain geological time calculations from the geothermal, or temperature-depth curve, obtained in this investigation. It seems hardly necessary to explain that the results are by no means to be regarded at this time as either final or conclusive. It is our intention merely to show the experimental evidence and explain the method

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of calculation and the premises on which it is founded, as well as where it seems to lead. This is done with the hope that if this new method of attack on a certain phase of the problem of geological time seems worth while, it will be exploited as further opportunity offers until its value is finally either proved or disproved.

Everyone is familiar with the fact that changes in temperature of the surface of the ground make themselves felt, after an interval, at various depths. An ordinary cold wave or hot wave is propagated into the ground—slowly and with considerable attenuation—and a series of temperature measurements made at different depths a few feet below the surface, perhaps a week after its onslaught, would show clearly the effect on underground temperatures. This same thing is also happening on a much larger scale of time and involving greater depths. The retreat of the glacial sheet some thousands of years ago has resulted in a warming of the surface temperature in the regions concerned and a consequent small distortion of the geothermal curve. For the period of time contemplated in this discussion, which is of the order of 25,000 years, the major effect of this distortion will be felt within the first mile below the surface and this places the problem within the range of the Lake Superior copper mines, as regards possibilities of temperature measurement deep in the earth. There are other reasons, however, aside from their great depth, why these mines are peculiarly fitted for such study, for the region of the Keweenaw peninsula fulfils unusually well the special requirements of this problem. These will now be stated specifically.

REQUIREMENTS OF THE PROBLEM

1. The region to be studied in this connection must be free from heat sources, positive or negative: there must be no exothermic or endothermic reactions or processes taking place in the rocks for a mile below the surface; geological folding, radioactivity, and penetration of surface water should all be at a minimum.

2. The region should be reasonably flat and have a uniform geological structure for a mile or more in depth. Thin mineralized veins are of no consequence.

3. The thermal diffusivity (conductivity divided by specific heat and density) must be known for the rock, and the geothermal curve must be determined for about a mile in depth.

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4. It must be assumed that the glacial sheet had overlaid the region long enough—50,000 years or more—*so that the geothermal curve at the end of the Ice Age can be taken as a straight line*, starting with a surface temperature of 0° C. or 32° F.

The region under discussion fulfils these requirements remarkably well. The rock is a hard, close-grained trap which allows very little penetration of surface water to disturb the geothermal gradient due to heat conduction. The region is one of relative geological stability, with little evidence of exothermic or endothermic processes. Urry[1] has measured the radioactive content of the rocks of this region and the conclusion reached from his results is that the disturbing effect of the heat generated in this way is negligible.

Though the region is by no means flat, the relief is quite negligible in comparison with the depths involved, and is readily taken into account. The structure of the inclined Keweenawan lava flows is uniform—leaving out of consideration the conglomerate lode which is negligible in this connection—and the region has not undergone deformation since the Cambrian period. The possibility of variation of the thermal constants of the rock with pressure will be considered later, as will also requirements 3 and 4. That the last glacial sheet was present for a period amply long for our purpose will undoubtedly be allowed. It is possible, however, that its thickness was sufficient to produce a lowering of the melting point of ice under it and the effect of this as a possible error must be considered.

It would seem, then, that if a connection between the geologically recent thermal history of a region and deep-rock temperatures is to be discovered anywhere, it should be here. Lane[2], to whom we owe the conception of the problem, initiated this study in several papers of some years ago, using in his calculations the rock-temperature data available at that time. It shall be our purpose to attempt to enlarge on these calculations in the light of our recent geothermal measurements.

Two preliminary reports[3] on this work already have been published

[1] Wm. D. Urry, *Proc. Amer. Acad. of Arts and Sci.*, Vol. LXVIII (1933), p. 125.

[2] A. C. Lane, *Bull Geol. Soc. of Amer.*, Vol. XXXIV (1923), p. 703.

[3] L. R. Ingersoll, *Physics*, Vol. II (1932), p. 154; James Fisher, L. R. Ingersoll, and Harry Vivian, *Amer. Inst. Min. and Met. Engineers, Tech. Pub. No. 481.*

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and as the methods of temperature measurement have been described in detail it will be necessary only to outline them here. With a few exceptions to be mentioned later, all temperature measurements were made in drill holes from 7 to 14 feet deep run into the sides of drifts or other mine workings which were progressing rapidly forward, so that the rock in which the hole was drilled had been exposed for only a few days. Readings in the deeper holes gave temperatures constant to a few hundredths of a degree for a month or two, showing that any transient effect due to drilling, blasting, etc., was entirely lacking. Measurements on the foot and hanging sides of the lode gave results which differed by less than the error of measurement.

The thermometers were of the mercury type and of special construction, mounted in 1-inch bakelite tubes (Fig. 1) and with the bulb so insulated that there was a delay of about a minute after withdrawing from a hole before the mercury column moved, thus giving plenty of time for accurate reading. Calibration and occasional zero checks on these thermometers indicated that they were accurate over their range of 0–40° C. to a few hundredths of a degree. They were divided to 0.1° C. and all readings were expressed to 0.01°.

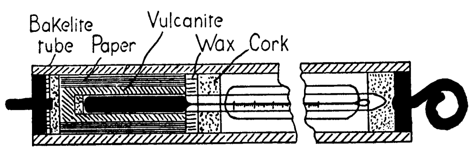

FIG. 1.—Section of mounted thermometer (Overall length, 35 cm).

The solid line curve of Figure 2 is the result of these determinations, giving such weight as we think allowable to the old Agassiz measurements. There are also three points which have recently been added to the curve, marked *O*, *C*, and *H*, made, not in special fresh drill holes as described above, but at the dead ends of old workings abandoned thirty or more years ago and not ventilated since that time. While these points are not so satisfactory as many of the others, they represent practically the only chance to get results near the surface. Gradient determinations along the drift in each case indicate that these points can probably be depended on to about half a degree.

The curve is made to cut the surface at 6.83° C. or 44.3° F. This is the average Calumet temperature for the last 45 years, assuming

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32° for the winter months, as would be the case on the ground under the snow, and accordingly this is taken as the average ground temperature. It will be noted that the curve falls slightly below the

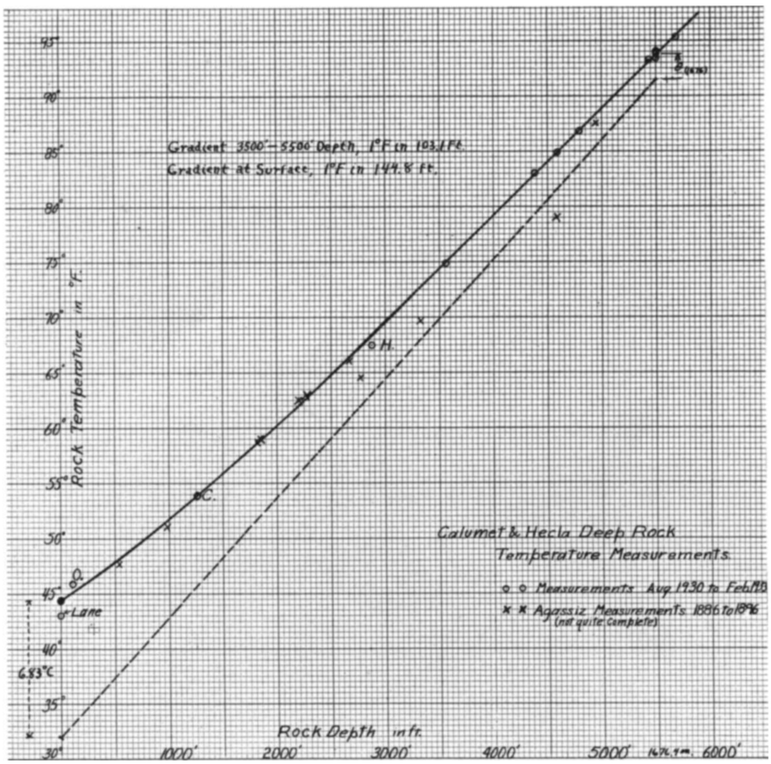

FIG. 2.—(Solid line), present geothermal curve; (broken line), assumed initial curve.

lowest temperature (i.e., highest mine level) point, one recently made in an old Osceola first-level drift, and slightly above the point taken by Lane as the average surface temperature. These considerations will be discussed later in connection with other sources of error.

THERMAL HISTORY CALCULATIONS

The solution of the Fourier heat conduction equation

$$\partial\theta/\partial t = h^2 \partial^2\theta/\partial x^2 \tag{1}$$

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subject to the boundary conditions

$$\theta = F(t) \text{ when } x = 0 \tag{2}$$

$$\theta = \quad 0 \text{ when } t = 0 \tag{3}$$

is[4], as first worked out by Riemann for this case where the surface temperature is a given function of the time,

$$\theta = \frac{2}{\sqrt{\pi}} \int_{\frac{x}{2h\sqrt{t}}}^{\infty} e^{-\beta} \cdot F\left(t - \frac{x^2}{4h^2\beta^2}\right) d\beta \,. \tag{4}$$

For the boundary conditions

$$\theta = F(t) \text{ when } x = 0 \tag{5}$$

$$\theta = Cx \quad \text{when } t = 0 \tag{6}$$

it can be very simply shown that the solution is

$$\theta = Cx + \frac{2}{\sqrt{\pi}} \int_{\frac{x}{2h\sqrt{t}}}^{\infty} e^{-\beta^2} \cdot F\left(t - \frac{x^2}{4h^2\beta^2}\right) d\beta \,. \tag{7}$$

This is the equation we have used. Here x is the depth below the average ground level in centimeters and t the time in seconds since the end of the ice age. The diffusivity h^2 has been determined[5] for this rock as 0.0075 c.g.s. units. θ is temperature in degrees C.

In using this equation it is much simpler if we can put

$$F\left(t - \frac{x^2}{4h^2\beta^2}\right) = \theta_1, \text{ a constant.}$$

We can also let it have different values at different times. For example, if we assume that the glacial age ended 24,000 years ago and

[4] W. E. Byerly, *Fourier's Series and Spherical Harmonics* (Boston: Ginn & Co. 1893), p. 88.

[5] Ingersoll, *op. cit.*

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that the temperature was 8° C. for 18,000 years, followed by 6.83° for the remaining 6,000 to the present time, equation 7 would read

$$\theta = Cx + \frac{2}{\sqrt{\pi}} \left\{ 8 \int_{\frac{x}{2h\sqrt{24000 \cdot s}}}^{\frac{x}{2h\sqrt{6000 \cdot s}}} e^{-\beta^2} d\beta + 6.83 \int_{\frac{x}{2h\sqrt{6000 \cdot s}}}^{\infty} e^{-\beta^2} d\beta \right\},$$

where S is the number of seconds in a year.

This reduces all the calculations to simple and straight-forward computation, using a table of probability integrals. The constant C or slope of the assumed initial geothermal curve is determined from equation 7 by substituting the observed value of θ for the 5,500-foot depth, i.e., using $x = 167640$ cm. (This value is indicated in the curve of Figure 2 as $\theta_{1676.}$) This automatically makes the computed and observed values of θ from equation 7 agree for the 5,500-foot point. These values will also evidently agree at the surface point because we naturally use 6.83° C., the present observed surface value, in our computation.

The values of θ have been computed from equation 7 in this way for each 500 feet in depth for nearly fifty assumed thermal histories. Five of these are shown in Figure 3, in which the plotted circles represent the differences between the observed and computed values, i.e., the deviations of the computed geothermal curve from the actual observed one. Of the simpler assumptions, A, B, and C, it is evident that C—that the Wisconsin ice sheet melted away from the region 20,000 years ago and that the present average ground temperature of 6.83° C. has existed since that time—is the best of the three. The discrepancy between this and the earlier figure[6] of about 30,000 years results from a change in the surface temperature and the surface end of our observed curve due to recent measurements.

Now a little experience with this computation brings out the fact that to make a better fit *we should assume that immediately following the Glacial age the temperature was somewhat higher than the present, succeeded in turn by one somewhat lower than today's average.* Assumption D of 10,000 years at 10° C., followed by 8,000 at 5°, rising 2,000 years ago to the present value, is about the best of any tried so far.

[6] *Ibid.*, p. 159.

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Equally good is E, which is of a type suggested to us by Dr. Lane. The departures in the last two cases are well within the probable

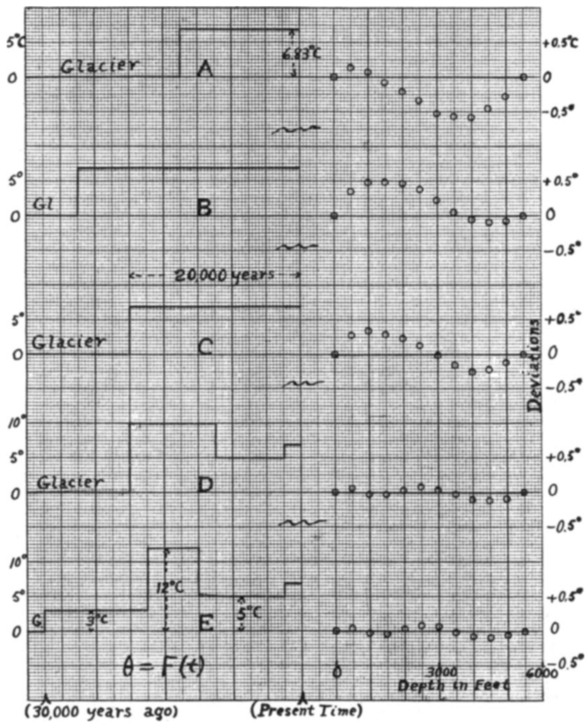

FIG. 3.—Five assumed "thermal histories" and resultant deviations from observed geothermal curve.

error of our observed curve, so more accurate analysis would be meaningless. In any case, it will, of course, be understood that these are merely block representations of essentially smooth curves.

DISCUSSION OF RESULTS. ERRORS

Undoubtedly the most severe criticism which can be urged against these results is the dependence we have to place on the exact form of a single geothermal curve. This should really be determined if possible for a number of locations in the same general region, but unfortunately this has not proved feasible as yet. We had hoped to be able to use some of Van Orstrand's valuable drill-hole data, but they

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do not offer a sufficient depth range at any one spot. Since the extension of our measurements to any other mines in the district seems out of the question just now, we have to be content accordingly with a single curve. It may be said, however, that many of our temperature holes are a mile or two apart laterally, so that the curve represents an average for a region of at least several square miles in area.

The next objection to this type of calculation might be based on the assumption of a uniform *initial* temperature gradient, starting at 0° C. at the surface. Now granted a glacier of reasonably long duration, say at least 50,000 years, as will probably be generally admitted, the only factor which would be likely to disturb the uniformity of the gradient would be a change in thermal conductivity with depth, i.e., pressure. This point has been considered with much care and is believed not to enter as a factor. For the pressures involved at the depth of a mile the density of the rock is increased only about 0.1 per cent. The increase in conductivity and consequent change in the geothermal gradient therefore would be expected to be of only this order of magnitude. If it were even five times as great, the effect on the curve would still be less than the probable error of measurement.

It is possible to reason that the glacier might be so thick that its pressure would cause a lowering of the melting point of ice. This would be of the order of 1° C. per mile of thickness of the ice, but would require that the water be under this pressure and this might not be the case. Assuming it to be so, however, the results would be left qualitatively about the same as at present, save that the *thicker* the glacier, the *less* the calculated time since its disappearance.

We are by no means satisfied with the probable accuracy of the points on our curve near the ground level. As no drifts or other cuttings have been run in the upper levels of the mine for some time, it has not been possible to determine temperature points with the same certainty as in the lower levels. The largest error, however, which we would be willing to admit as possible for the surface point would be about 1° F., and this would only shift the time scale a few thousand years one way or the other.

Our conclusions on the basis of these results may then be stated briefly as follows: The last glacial epoch ended for this region 20,000

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to 30,000 years ago. This was followed, perhaps after several thousand years, by a period distinctly warmer than the present, which was succeeded in turn by one slightly cooler and lasting until rather recent times. Of course this statement applies entirely to *average ground temperatures* and it is obvious that vegetation, snowfall, etc., may affect these independently of the average air temperatures. It is only right to point out, however, that these conclusions at least do not run counter to current geological and climatological opinion.[7]

NOTE: The authors wish to express thanks to Mr. James McNaughton, President of the Calumet and Hecla Company, for placing at the service of this investigation the facilities of the mines. They also want to acknowledge special indebtedness to Mr. Harry Vivian, Chief Engineer, and to Messrs. H. E. Jefferson, H. S. Donald, and R. F. Wilson, members of his staff, for their services in connection with the temperature measurements.

[7] Kirk Bryan, *Zs. f. Gletscherkunde*, Vol. XX (1932), p. 76; C. E. P. Brooks, *The Evolution of Climate* (London: Benn Bros., Ltd., 1925).

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