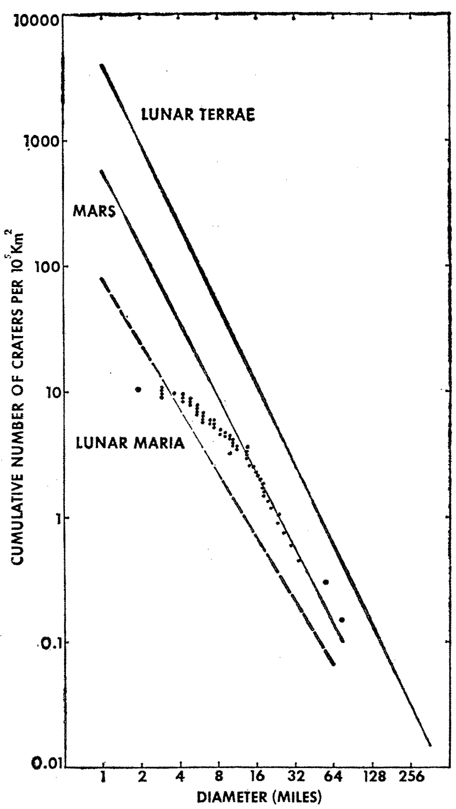

Fig. 1. Relation between the number of craters and their diameter on Moon and Mars.

about 2×10^9 years, as seems probable, then the age of the visible Martian surface is about 2.8×10^9 years. If we limit our comparison to the straight-line portion of the Martian crater-count chart, diameters greater than 20 km, then the Martian craters are less abundant than the craters of the lunar terrae by a factor of 3.7 instead of 7; then $A = 50$ and the calculated age is 3.4×10^9 years.

It might be expected that the proximity of Mars to the asteroid belt would lead to a greater number of impacts there than on the Moon. In this event, the surface of Mars will be younger than calculated above, and it is almost certainly younger than the lunar maria.

Only if the rate of infall on Mars is considerably less than it has been on the Moon and if the age of the lunar maria is very considerably greater than has been calculated could the age of the Martian surface approach the age of the solar system, 4.5×10^9 years. Neither alternative appears likely.

Öpik's very important papers (*6*) suggest that the rate at which asteroids and comets will strike a given area on Mars is considerably higher than their collision rate with Earth or Moon; the difference may approach a factor of 25.

Mariner IV showed (*7*, *8*) that the flux of micrometeorites increased by a factor of about 5 as the spacecraft moved from Earth to Mars. This value is somewhat smaller than the earlier data for larger masses.

Let us assume that the factor actually is 10 for those objects capable of producing larger craters and the age of the lunar maria is 2×10^9 years and the frequency of impacts has declined at the same rate for Mars as for the Moon, then the present Martian surface is $(3.4 \times 10^9)/10$ years old, or about 3.4×10^8 years.

Conversely, if the rates of infall of asteroids on Mars and the Moon differ by the factor of 10 but have been constant in the past at the present rates, then the age of the lunar maria would be calculated as an impossible 10^{10} years, and the Martian surface would be $10^{10} \times 50/(10 \times 10)$, or 5×10^9 years. Both figures are greater than the accepted ages of the planets.

Inasmuch as the rate of infall on the lunar maria, since their formation, has decreased by a factor of about 9 if their age is 2×10^9 years, and by a larger factor if they are somewhat younger, it seems reasonable to suggest that the rate of infall on Mars has similarly declined and that the age of the Martian surface is not very far from 3.4×10^8 years.

If the present frequency of large infalls on Mars is as low as the observed micrometeorite flux near the planet, the age of the Martian surface would only be doubled, to about 6.8×10^8 years. It appears highly probable that the surface of Mars which was photographed by Mariner IV is quite young, geologically speaking.

A substantial amount of erosion on Mars is indicated.

RALPH B. BALDWIN

Oliver Machinery Company,
Grand Rapids, Michigan 49502

References

1. R. B. Baldwin, *The Face of the Moon* (Univ. of Chicago Press, Chicago, 1949), chap. 12.
2. R. B. Leighton, B. C. Murray, R. P. Sharp, J. D. Allen, R. K. Sloan, *Science* **149**, 627 (1965).
3. R. B. Baldwin, *Astron. J.* **69**, 377 (1964).
4. G. S Hawkins, *Nature* **197**, 781 (1963).
5. R. B. Baldwin, *The Measure of the Moon* (Univ. of Chicago Press, Chicago, 1963).
6. E. J. Öpik, *Proc. Roy. Irish Acad.* **54**, 165 (1951); *Advan. Astron. Astrophys.* **2**, 219 (1963).
7. W. M. Alexander, "Interplanetary dust particle flux measurements between 1.0 and 1.5 AU from Mariner 4 cosmic dust experiment," preprint, fifth Western National Meeting program of American Geophysical Union (1965), p. 532.
8. W M. Alexander, C. W. McCracken, J. L. Bohn, *Science* **149**, 1240 (1965).

25 August 1965, revised 15 September 1965.

Terrestrial Heat Flow: Measurement in Lake Bottoms

Abstract. *The feasibility of measuring terrestrial heat flow in lakes has been investigated in Lake Superior. The temperature gradient and thermal conductivity of the sediment were measured at each of four stations in water depths exceeding 250 meters. Consideration of the effects of climatic variations suggests that they may not seriously affect the values for heat flow obtained by this method. The values measured are in reasonable agreement with other continental values in the shield areas.*

Theories of the dynamics of tectonic forces reshaping the face of the earth invariably call upon thermal sources and imbalances as the driving energy; measurement of heat flow thus becomes an important test of the validity of the theories. The radioactive decay of elements within the earth produces a flow of heat through the surface of about 1×10^{-6} cal cm^{-2} sec^{-1}. Measurement of this heat flow and its geographic variations may provide information on the distribution of radioactive elements in the earth and on the nature of the processes by which the heat reaches the surface.

Meaningful values for heat flow can be obtained only in areas where steady-state conditions prevail. On land this requires measurements in mines or boreholes at depths of some hundreds of meters where effects of variations in atmospheric temperature are negligible. In the oceans, because of the apparent long-term temperature stability of oceanic bottom waters, measurements may be made in the upper few meters of sediment (*1*). Continental measurements have lagged behind oceanic measurements because of the difficulty and expense entailed in bore-hole measurements. Because variations in atmospheric temperature are greatly reduced at the bottom of deep lakes, we thought it possible, by applying oceanic techniques to lakes, to greatly accelerate and broaden knowledge of continental areas regarding heat flow. Work was initiated in Lake Superior during July 1963 from the U.S. Coast Guard cutter *Woodrush*.

Temperature gradients in the bottom sediments of Lake Superior were determined at four stations (Table 1) by means of thermistor probes attached to outrigger fins on a 4-m piston corer; equipment and techniques resembled

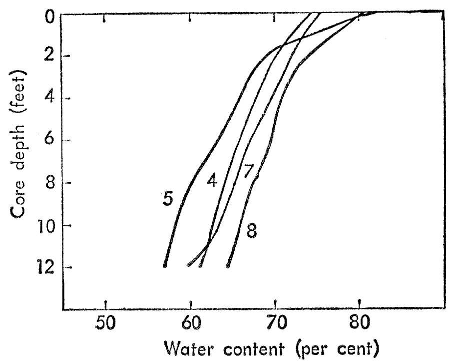

Fig. 1. Water content of bottom muds from Lake Superior cores. Numbers on curves refer to the stations listed in Table 1.

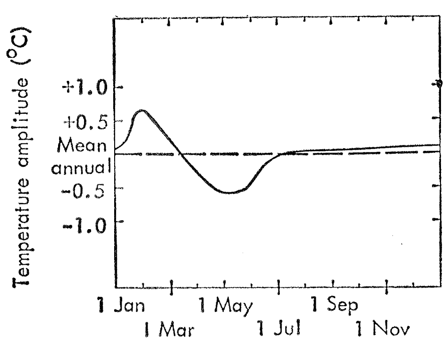

Fig. 2. Estimated annual temperature cycle of Lake Superior bottom water.

those developed for oceanic work (*2*). Resistance of the thermistors was measured with a bridge capable of 0.001°C resolution; because of calibration shifts during the corer drops, however, the relative temperatures are probably not better than 0.005°C. Thermal conductivities of the sediments were obtained from the water content by the method of Ratcliffe (*3*).

Figure 1 shows the very regular way in which the water content decreases with depth in these lake sediments. In contrast, Table 1 shows that the temperature gradients are not linear as would be expected under steady-state conditions. This nonlinearity is due largely to the small seasonal variations in temperature of bottom water that most temperate lakes undergo (*4*). The exact value of this seasonal variation in Lake Superior is not known, but data for Lake Superior, Lake Michigan, and Cayuga Lake (*5*) have been used to deduce an approximate curve for Lake Superior (Fig. 2). The main uncertainty in this curve is the amplitude of the variation, which depends in detail on water depth and circulation pattern; there are probably also shorter-period variations that have been smoothed out, as suggested by our complete year-round data from Seneca Lake (*6*). If the annual cycle of water temperature were precisely known, its effects on the sediment gradient could, in principle, be completely removed by correction. The approximate curve of Fig. 2 was Fourier analyzed and used to correct the gradient data of Table 1; the resultant gradients appear in Fig. 3. Some nonlinearity still persists and may be due either to the approximate nature of the corrections or to temperature variations over periods greater than 1 year. The deeper part of each gradient will most nearly approach steady-state conditions, since the annual cycle is sharply attenuated with depth. By use of conductivities determined from Fig. 1 and of the lowest segments of the gradients, heat-flow values of 0.75, 0.79, 0.87, and 0.30 μcal cm^{-2} sec^{-1} are calculated for stations 4, 5, 7, and 8, respectively. Three of these agree well with a value of 0.93 μcal cm^{-2} sec^{-1} reported from a deep mine on the Keweenaw Peninsula (*7*). The anomalously low value is probably not meaningful because a large shift in thermistor calibration occurred during coring No. 8.

Small uncertainties in these values may result from effects of topography and sedimentation rate. A much greater uncertainty, however, reflects the effect of any long-term variations in the water temperatures; the accuracy of heat-flow values obtained by this technique depends on proper evaluation of this effect. To test the magnitudes involved, we calculated (*8*) the minimum amplitude of a harmonic water-

Table 1. Temperatures in sediments below Lake Superior, 1963.

Depth (m) Water	Depth (m) Sediment	Temp. (°C)
Station 4, 47°49.3′N, 88°54.4′W; south of Isle Royale		
245	0	
	1.14	3.469
	2.92	3.665
	4.24	3.759
Station 5, 47°34.6′N, 88°13.2′W; north of Copper Harbor		
270	0	3.629
	1.14	3.514
	2.92	3.684
	4.24	3.779
Station 7, 48°1.5′N, 86°14.0′W; west of Otter Head		
290	0	3.458
	1.19	3.405
	2.94	3.608
	4.29	3.711
Station 8, 47°10.6′N, 91°14.6′W; south of Split Rock		
278	0	3.495
	1.19	3.485
	2.94	3.644
	4.29	3.702

temperature variation that would produce a 10-percent error in the sediment gradient at depths of 4 and 10 m; the results, as functions of period, appear in Fig. 4.

Clearly, accuracy of measurements within 10 percent imposes severe restrictions on amplitude of variations in the temperature of bottom water. The short-term variations can be easily circumvented by deeper probe penetrations or corrected by year-round recording of water temperatures. Disturbances in the 100-year-period range are maximally effective in altering the

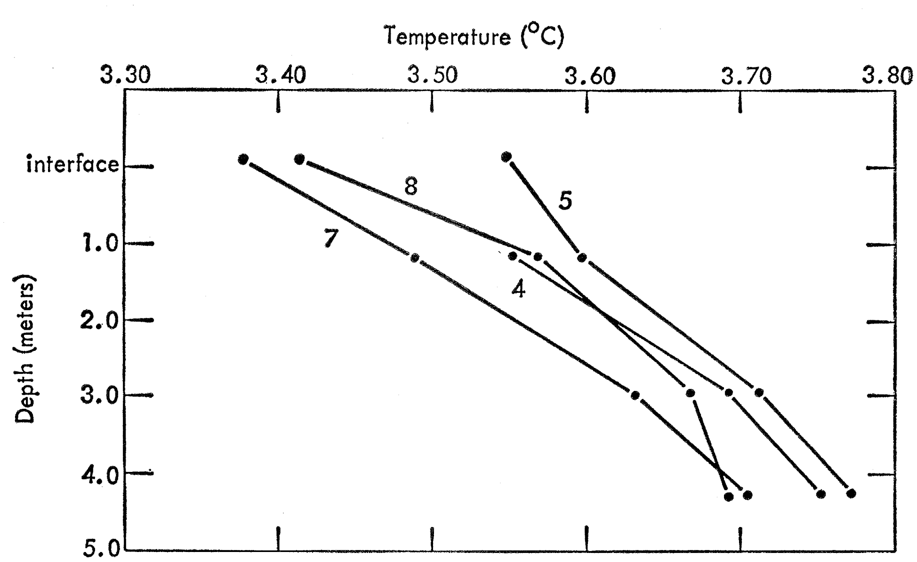

Fig. 3. Temperature gradients in the sediments of Lake Superior; the data of Table 1 are corrected for the annual cycle in Fig. 2.

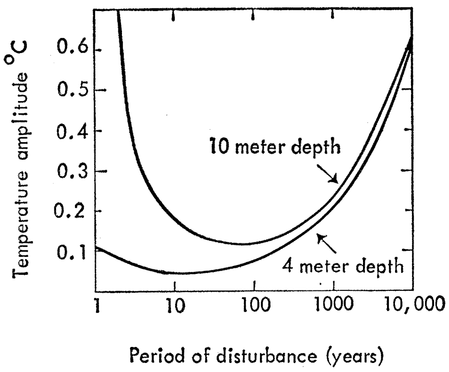

Fig. 4. Amplitude of a harmonic-temperature disturbance that will cause a 10-percent error in the measured temperature gradient in typical lake-bottom sediments. Curves are for measurements of depths of 4 and 10 m.

thermal gradient, but these periods can at least be recognized by the measurable nonlinearity of the gradient. The very long periods are less effective but, because of their long wavelength in the sediment, the effects will appear linear over distances of 5 to 10 m.

There is abundant evidence from climatic records of variation of 1° to 2°C in atmospheric temperature over periods of tens and hundreds of years. These variations are highly attenuated in the bottom water of temperate lakes by the relative stability of water at its 4°C maximum density point (*6*). This large attenuation factor (30 times or more) suggests that long-term climatic effects may not seriously affect the measurement of terrestrial heat flow in lakes.

S. R. HART
J. S. STEINHART
Department of Terrestrial Magnetism, Carnegie Institute of Washington, Washington, D.C.

References and Note

1. E. C. Bullard, A. E. Maxwell, R. Revelle, *Advan. Geophys.* **3**, 153 (1956).
2. R. Gerard, M. G. Langseth, M. Ewing, *J. Geophys. Res.* **67**, 785 (1962).
3. E. H. Ratcliffe, *ibid* **65**, 1535 (1960).
4. G. E. Hutchinson, *A Treatise on Limnology* (Wiley, New York, 1957).
5. A. M. Beeton, J. H. Johnson, S. H. Smith, "Special scientific report, fisheries No. 297," U.S. Fish and Wildlife Service, 1959; E. B. Henson, A. S. Bradshaw, D. C. Chandler, "Memoir 378," Cornell Univ. Agr. Exp. Sta., Ithaca, N.Y., 1961; P. E. Church, "Misc. reports No. 4" (1942), "Misc. reports No. 18" (1945), Inst. Meteorol., Univ. of Chicago.
6. J. S. Steinhart and S. R. Hart, "Annual report of the director of the department of terrestrial magnetism," *Carnegie Inst. of Washington Year Book '64* (1965).
7. F. Birch, *Amer. J. Sci.* **252**, 1 (1954).
8. By methods similar to those of L. R. Ingersoll, O. J. Zobell, A. C. Ingersoll, *Heat Conduction* (Univ. of Wisconsin, Madison, 1954), p. 49.
9. We thank the captain and crew of *Woodrush* for their assistance.

6 August 1965

Chert: Modern Inorganic Deposition in a Carbonate-Precipitating Locality

Abstract. *Chert is precipitating as gelatinous opal-cristobalite in lakes associated with the Coorong Lagoon of South Australia. Dolomite, magnesite, and magnesian calcite are also being deposited. High* pH *(9.5 to 10.2) causes dissolution of detrital silicates; lowering of* pH *(7.0 to 6.5) and drying of the lakes cause precipitation of chert.*

Chert is inorganically precipitating in ephemeral lakes associated with the Coorong Lagoon (*1*) of South Australia. The term *chert* generally applies to a variety of fine-grained silica that precipitates initially as an almost-amorphous gel composed of water and small crystallites of rudimentary cristobalite structure; this material gradually recrystallizes to chalcedony, a variety of microcrystalline low quartz that is the major constituent of ancient chert (*2*).

In many places, such as the Gulf of California and the zones of high productivity in the oceans, sediments are receiving large contributions of biologically precipitated opaline silica. We now report the first discovery, to our knowledge, of inorganic precipitation of silica gel in a modern sedimentary environment.

The dominant precipitates of the lakes are dolomite, magnesite, and magnesian calcite. The surface of the sediment, which completely dries during the dry summer, contains plates of desiccated sediment that are related to mud cracks. These plates are more resistant to softening when wet than is common for normal dried carbonate sediments of the area. Material in the outermost several millimeters of these plates has a porcelaneous texture. This somewhat hardened surface extends around the sides and edges of the plates but it is not apparent on the undersides. The plates, typically about 1 cm thick and about 10 cm across, are complex; some of them contain fragments indicating that the plates have been broken and reincorporated. The edges are rounded and the upper surface is pitted and irregular. In some places on the lake bed, where they remain in their original position with respect to desiccation cracks, the plates cover almost the entire surface of the nonindurated sediment and constitute a bed which extends for tens to hundreds of meters. Some of the plates are distorted.

The carbonate minerals from the plate material were dissolved with 1:1 hydrochloric acid, leaving a gelatinous substance. If the fragments were dissolved very slowly in cold hydrochloric acid, the remaining gelatinous material retained the original shapes of the fragments. Most of the sediment at the surface of the lakes becomes quite hard to a depth of 20 cm or more during seasonal drying, but softens again when saturated with water. This unconsolidated sediment contains a noncoherent insoluble gel.

X-ray diffraction patterns of the gel (Fig. 1) are very diffuse and show an extremely broad diffraction maximum centering at about 4.0 Å, which is characteristic of opal-cristobalite (*2*). Superimposed on this broad and diffuse pattern is a pattern of detrital quartz. Heating the opal-cristobalite to 940°C for 10 hours produces material that yields a sharp cristobalite reflection at about 4.04 Å (*3*). X-ray diffraction patterns of the unconsolidated gel and of the gel that tends to retain

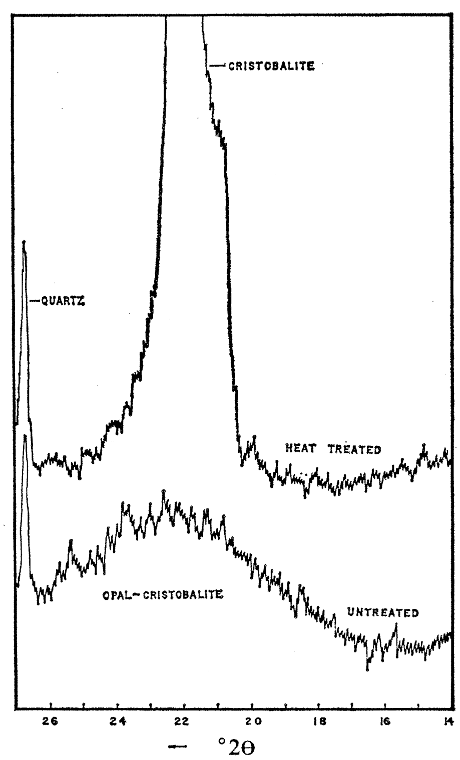

Fig. 1. X-ray-diffractometer traces of opal-cristobalite from dolomite-magnesite sediment: normal material (bottom), and similar material heated at 940°C for 10 hours (top).