Terrestrial Heat Flow through Salt-Marsh Peat

Abstract. *Two measurements of the temperature gradient in salt-marsh peat made at an interval of ½ year permit the upward flow of heat to be estimated as 1.37 × 10^{-6} cal cm^{-2} sec^{-1}. This value corresponds closely to the average terrestrial heat flow, obtained in mines and wells.*

This report is concerned with measurements of terrestrial heat flow through the peat of a salt marsh. Lee and MacDonald reported in 1963 that useful measurements of heat flow were available from 665 oceanic and 92 continental positions (*1*). The oceanic positions are restricted to deep water where the temperature variation is negligible, while the positions on land have depended on the availability of deep wells or mines. Since a thermistor can be inserted into undisturbed peat by hand to depths where the seasonal variation in temperature is small, measurements of heat flow can be made inexpensively wherever sufficient depths of marsh peat are available. Such measurements could serve to supplement the present information on local variations in terrestrial heat flow.

A detailed study of the thermal regime in the peat of the salt marsh at Barnstable, Massachusetts, based on measurements at 21-day intervals over 2 years, has confirmed the theoretical expectation that thermal changes originating at the surface penetrated to depths as highly damped progressive waves (*2*). The mean temperature increased regularly with depth at a rate of 10.8 × 10^{-4} °C cm^{-1}. Fourier analysis showed that the annual component of the thermal wave accounted for most of the temperature variation when allowance was made for the increase in mean temperature with depth. The analysis yielded attenuation and phase-lag coefficients which were in agreement in fixing the thermal diffusivity of the peat at 1.57 × 10^{-3} cm^2 sec^{-1}.

Measurements of the density and specific heat of the peat gave an average volumetric heat capacity of 0.93 cal cm^{-3}. The thermal conductivity is therefore 1.46 × 10^{-3} cal cm^{-1} sec^{-1} $°C^{-1}$. The formula of Bullard and Day (*3*) which relates thermal conductivity to water content of oceanic sediments gives the same value for the peat when its average water content (77.9 percent wet weight) is applied and correction made for the mean temperature. When this value is multiplied by the gradient in mean temperature, the mean rate of upward diffusion of heat is 1.57 × 10^{-6} cal cm^{-2} sec^{-1}. This value is close to the average of the data for the earth as a whole which is 1.61 × 10^{-6} cal cm^{-2} sec^{-1} (*1*).

The layer of peat where these measurements were made was about 4.5 m in depth. The gradient in mean temperature above this depth was obtained by averaging out the seasonal variations in temperature. The attenuation of the thermal wave is such that at this depth the amplitude of the annual component is reduced to about 3 percent of its surface value. If measurements were made at greater depths the influence of the annual component would be small, while that of short-term fluctuations in temperature would be negligible. Moreover, if measurements were made on two dates ½ year apart there should be nodes, separated by half a wavelength, where the temperature on both dates is the same and equal to the mean temperature at their respective depths (see Fig. 1). From such observations the gradient in mean temperature could be obtained directly with very small errors arising from short-term fluctuations in surface temperature.

The distribution in temperature with depth has been measured on two dates 182 days apart at a place 1.1 km from the position where the earlier measurements were made and where the depth of peat was 9 m (*4*). The results are shown in Fig. 1. The straight line passing through the three nodes where the curves intersect gives the gradient in temperature with depth as 9.2 × 10^{-4} °C cm^{-1}. The average water content of the peat at this position is 80 percent of the wet weight. This value when applied to the equation of Bullard and Day (*3*), corrected to a temperature of 10°C, gives a thermal conductivity of 1.49 × 10^{-3} cal cm^{-1} sec^{-1} $°C^{-1}$. The upward heat flow is consequently 1.37 ×10^{-6} cal cm^{-2} sec^{-1}. This determination differs from that obtained from the earlier measurements by 15 percent.

The difference between the two estimates is small compared to the variation in heat flow sometimes observed over large geographical areas. Lee (*5*) gives the mean value of heat flow and the standard deviation of an individual datum for 73 continental positions as 1.43 ± 0.57 × 10^{-6} cal cm^{-2}

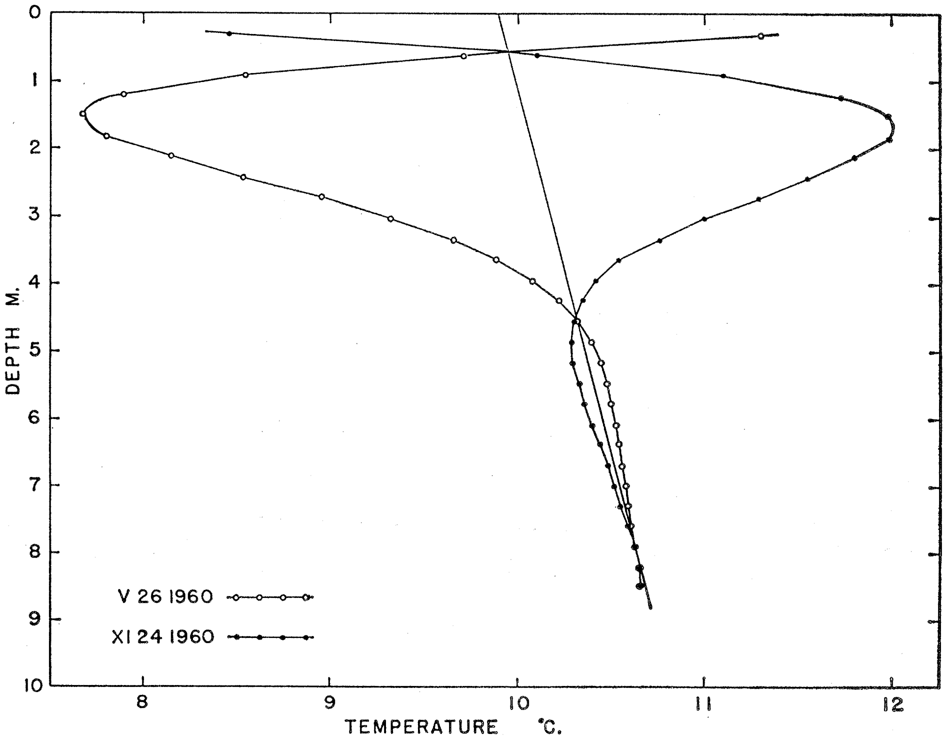

Fig. 1. Temperature gradient in salt-marsh peat measured on two dates 182 days apart. The straight line represents the geothermal gradient.

sec^{-1} and states that the error in analyzed heat flow is, generally speaking, about ± 10 percent (*2*). It is unlikely that the difference between the two determinations at Barnstable is due to a difference in the actual heat flow at the two positions separated by as small a distance as 1.1 km. It may be attributed rather to errors inherent in the method, namely the effects of long-term trends in the climate, such as an unusually cool year followed by an unusually warm one, to possible disturbances due to the movement of ground water in the depths of the peat and to actual errors in the temperature measurement. The measurement of terrestrial heat flow through marsh peat appears to be sufficiently precise to give useful information on its regional value. The procedures might also be usefully employed in freshwater peat bogs, but in such situations the movement of ground water may be found to invalidate the results.

ALFRED C. REDFIELD
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

References and Notes

1. W. H. K. Lee and G. J. F. MacDonald, *J. Geophys. Res.* **68**, 6481 (1963).
2. A. C. Redfield, *Tellus*, in press.
3. E. C. Bullard and A. Day, *Geophys. J.* **4**, 282 (1961).
4. The position is 0.3 km northeast of the crossing of Route 6A and the railroad track east of West Barnstable railroad station (41°42′18″N, 70°21′44″W). The character of the peat and the procedures of measurement were similar to those described previously (*2*).
5. W. H. K. Lee, *Rev. Geophys.* **1**, 449 (1963).
6. Contribution No. 1447 of the Woods Hole Oceanographic Institution.

22 March 1965

■

Sulfur: A New High-Pressure Form

Abstract. *Under high pressures and elevated temperatures, rhombic sulfur is converted to a new cubic form; this form was quenched at room temperature and pressure and studied by x-ray diffraction. Phase boundaries for this new form have been established.*

Elementary sulfur exists in many reasonably well defined forms (*1*). The temperature-pressure relation of sulfur up to 280°C and 20 kb has been established (*2*), and shows only the solid form of sulfur, rhombic sulfur. Bridgman (*3*) applied pressures up to 100 kb at and below room temperature without indications of a new phase of sulfur; he had anticipated the possibility of a metallic form analogous to black phosphorus. David and Hamann (*4*) subjected sulfur to shock pressures of about 250 kb, at which pressure the electric resistivity decreased to 0.03 ohm cm; this drastic reduction was attributed to a possibly metallic form of sulfur. Another interpretation (*5*) attributes this increase in conductivity to impurities as the sulfur is melting along the shock front.

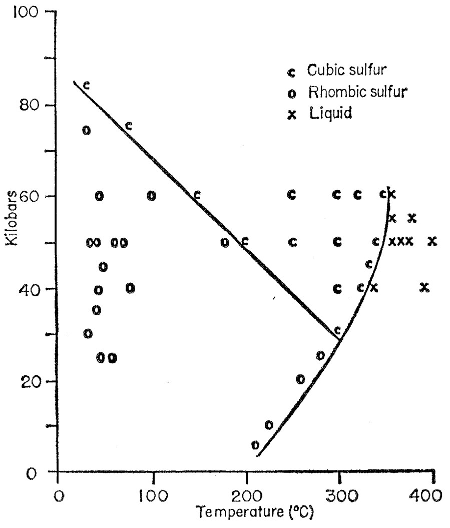

Fig. 1. High-pressure region of the phase diagram of sulfur.

The region above room temperature and at pressures greater than 20 kb is virtually unexplored for sulfur. Therefore, 20- to 30-mg samples of rhombic sulfur in powder form were subjected to pressures between 25 and 83 kb at temperatures at intervals between 25° and 400°C. An opposed-anvil, high-pressure apparatus (Tem-Pres model SJ-100) was used in the experiments. The samples were contained between 0.005-inch (0.13-mm) platinum sheets separated by a ring of the same material; under the conditions of the experiments, there was no indication of reaction between platinum and sulfur. An electric furnace surrounded the anvils and the sample. Occasionally in his experiments Bridgman experienced violent explosions, which he explained by the presence of oxygen adsorbed onto the sulfur. Zubova and Korotaeva (*6*) reached the same conclusion. In my investigation, explosions occurred only when the pressure seal between the platinum sheets and the ring became contaminated by sulfur and thus developed a leak; at elevated temperatures the sulfur burned when it contacted the atmosphere.

In the first of two types of experiment, after heating under pressure to a given temperature, the sample was slowly cooled to 50°C under the same pressure. In the other type of experiment, instead of cooling slowly, the sample was quenched in air. The quenching occurred the moment the pressure was released; the sample was withdrawn, at a given temperature, with a platinum wire that was welded to one of the platinum sheets. In both instances, x-ray diffraction patterns of the samples were obtained immediately.

The results were surprising. In the first series of experiments, when the sample was cooled under pressure, two different types of samples were obtained. One was a thin, solid wafer of rhombic sulfur, as shown by the x-ray pattern. Higher pressure and temperature caused a slight shift toward a more compressed lattice. The behavior of the other type of sample resembled that of plastic sulfur, indicating that it had been melted. The x-ray pattern showed only one single, very strong peak at about 4.04 Å. On exposure to the atmosphere, the plastic sulfur soon hardened and began to convert into rhombic sulfur. The time of conversion varied, depending on the applied pressure: samples prepared at the higher pressures converted at a lower rate. It is felt that the 4.04-Å peak corresponds to the 220 reflection (4.06 Å) of rhombic sulfur and that the crystal-

Table 1. Spacing and indexing of a new cubic form of sulfur.

*d*Å	Intensities	*hkl*
8.93	vw	110
6.55	w	200
6.07	vw	210
5.37	vw	211
4.89	w	220
4.50	m	300
4.31	m	310
4.16	vvw	311
3.91	vw	222
3.79	w-m	320
3.66	s	321
3.42	m	400
3.31	w-m	410
3.22	w	411
3.14	w	331
3.04	w	420
2.98	vw	421
2.93	w	332
2.83	w	422
2.73	w	500
2.68	m	510
2.66	vw	511
2.55	w	520
2.49	w	521
2.42	vw	440