# The Thermal Conductivities of Ocean Sediments

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*Abstract.* As a part of the measurement of heat flow through the ocean floor, the thermal conductivities of samples of sediment from the Pacific, Atlantic, and Mediterranean areas have been determined in the laboratory by a steady-state method. Average values over a wide range of water content are found to depend more on water content than on solid phase constituents, and conductivities can be read from a diagram if the amount of contained sea water or the wet density of the sediment is known. A graph is included, showing the conductivities of wet, granular materials other than ocean sediment.

## INTRODUCTION

Heat flow from the interior of the earth outward through the ocean floor can be estimated if the conductivities and the temperature gradients of the sediments are known. The first estimation of oceanic heat flow by measurements of this kind was made possible by the work of the 1947 Swedish expedition in the *Albatross* [*Pettersson,* 1949]. The present paper is concerned with thermal conductivity measurements on sediment cores supplied in airtight containers by various expeditions.

Initial steady-state conductivity measurements at this laboratory were carried out by Mr. D. W. Butler on red clays collected in 1950 by the mid-Pacific expedition of the Scripps Institution of Oceanography [*Revelle and Maxwell,* 1952]. Subsequently the writer made further measurements, on Atlantic sediment cores from a 1952 *R. R. S. Discovery II* expedition [*Bullard,* 1954], on Mediterranean sediments in 1955, and on a few samples of sediments taken in the southeast Pacific (stations 10, 29, and 32 of the Scripps Institution *Downwind* expedition) [*Natl. Phys. Lab. Report,* 1958; *Von Herzen,* 1959]. The latter measurements were made so that the steady-state results might be compared with those obtained from the transient method employed by Von Herzen.

The result of the above work was to show that the major factor in fixing the conductivities was the amount of contained sea water, and that variations in solid phase constituents were relatively unimportant. It therefore seemed possible to treat ocean sediments collectively, whether of organic or inorganic origin, and from the following graphs and a diagram conductivity assessments can rapidly be made. Measurements on other wet granular materials were also made, and a few results are given for comparison.

## APPARATUS AND MEASUREMENT

The apparatus used consisted fundamentally of a flat, circular, metal hot plate, containing an electrical heater, and a pair of water-cooled cold plates (Fig. 1). The plate faces were lapped flat. Thin ebonite rings, externally of the same diameter as the plates, containing ocean sediment or other wet granular material, were positioned as shown. Plate temperatures were measured by fine thermocouples inserted into small holes drilled parallel and near to the plate surfaces. A 120-volt battery was used as energy source; current and voltage were measured potentiometrically. Glass-wool insulation reduced edge losses to a small amount. A vertical load was applied to the top cold-plate assembly. The conductivity values were derived from the usual, steady-state equation, after allowing for heat flow through the ebonite rings. The apparatus was constructed in several sizes: plate diameters approximately 3, 5, and 7½ cm (Fig. 2). The smaller sizes were used for ocean sediment, and, since the plate diameter did not exceed the core diameter from which the samples were sliced, unnecessary manipulation of the sediment was avoided. The apparatus with 7½-cm plates was used for other wet granular materials, such as

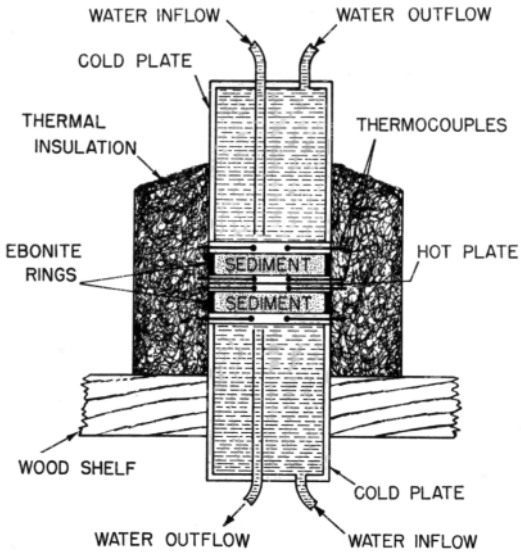


Fig. 1. Disk apparatus (schematic). Thermocouple and heater leads not shown.

copper powder, quartz sand, and diatomaceous earth with added water. Evaporation was prevented by greasing the joints between rings and plates. The accuracy of measurement was assessed at about ±3 per cent.

The bulk densities of the specimens were determined after test. The specimens were then oven dried at about 100°C and the water content evaluated. In the case of many of the ocean sediments, the chlorine content of dried samples was determined, and the original percentage of sea water in the sample when it was collected was calculated from chlorinity data (assuming that all the chlorine in the sediment was derived from sea water present at the time of collection); thus losses by evaporation could be assessed. Comparison with water-content values obtained by oven drying showed that the chlorine test gave calculated water contents within 1 per cent of those obtained by the direct drying method. The formula used for the calculation was

$$\%\ \text{water (wet wt.)} = 50.8C/(1 + 0.508C)$$

where $C$ is the percentage of chlorine by weight on the dry weight of the sample, and the determination is based on the assumption of 3.45 per cent by weight of total salts in sea water and 1.9 per cent chlorine.

## Corrections and Results

*Water loss and temperature coefficient.* Most conductivities were determined at mean specimen temperatures between 20°C and 25°C, and these, plotted against water content in Figure 3, lie near a smooth curve, even when the specimen has obviously lost water (often apparently due to migration under gravity during laboratory storage, as in the case of the Atlantic specimen shown, with 20 per cent water content). Hence the conductivity of the sediment before it lost water can always be deduced from the graph if its original water content is known. The shape of the curve for water contents less than 30 per cent, representing mainly an artificial condition for ocean sediment, is not accurately known, but other data for wet, granular material lead one to assume an inflexion in the curve commencing at about this water content.

A correction is needed to reduce the conductivities to deep ocean-bottom temperatures of a few degrees centigrade, and the corrected curve is shown dotted in Figure 3. The temperature coefficient has been calculated from unpublished data by Butler, who measured specimens of Pacific sediments of differing water contents at about 4°C, in a disk apparatus shielded from heat gain by a low-temperature surround, and found approximately a 6 per cent reduction in conductivity from 25°C to 4°C in each case. A

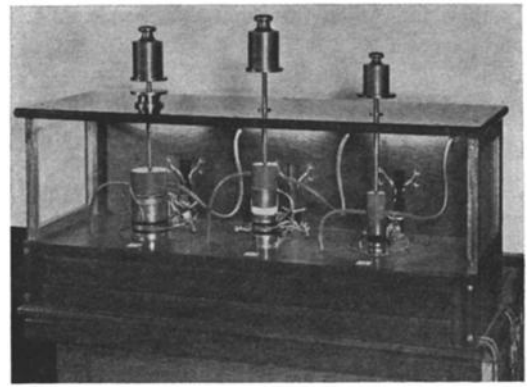

Fig. 2. Cabinet containing three disk thermal conductivity apparatus of similar type but of different sizes.

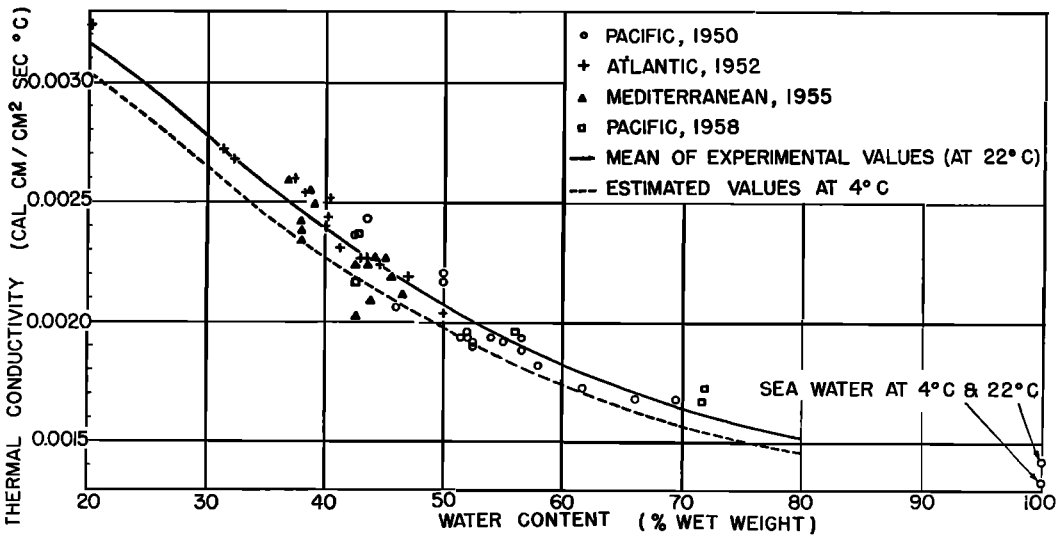


Fig. 3. Ocean sediment. Thermal conductivity (at 1 atm) versus water content by weight.

similar order of decrease is evident for sea water and pure water [*Nukiyama and Yoshizawa,* 1934; *Challoner and Powell,* 1956].

The foregoing values are shown in Table 1. The sea-water points in Figure 3 have been mainly adopted from the Japanese [who gave $K = 0.4747(1 + 0.00224t)$ over the range 10°C to 71°C, where $K$ is the thermal conductivity in kcal m/m² hour °C, and $t$ the temperature in °C] but the 22°C point has been raised slightly because their results on pure water at this temperature are lower than the more recent (1956) determinations at this laboratory.

*Salinity and pressure.* Since the difference in the conductivities of pure water and sea water is only a few per cent, a conductivity correction for salinity variations from sediment to sediment is unnecessary. Variations of less than 1

TABLE 1. Ocean Sediment, Water, Sea Water: Change of Thermal Conductivity with Temperature

| Substance | Temperature, °C | Thermal Conductivity, $\frac{\text{cal cm}}{\text{cm}^2 \text{ sec °C}} \times 10^4$ | Decrease in Thermal Conductivity over Temperature Range, % | Observer |
|---|---|---|---|---|
| Pacific sediment (moisture content 52% of wet weight, wet density 1.40 g/cm³) | 25<br>4 | 19.0<br>17.9 | 5.8 | Butler, 1950* |
| Pacific sediment (moisture content 66.5% of wet weight, wet density 1.23 g/cm³) | 25<br>4 | 17.0<br>16.0 | 5.9 | Butler, 1950* |
| Pure water | 25<br>5 | 14.3<br>13.7 | 4.2 | *Nukiyama and Yoshizawa* [1934] |
| Pure water | 25<br>4 | 14.6<br>13.7 | 6.2 | *Challoner and Powell* [1956] |
| Sea water | 30<br>10 | 14.1<br>13.5 | 4.3 | *Nukiyama and Yoshizawa* [1934] |

* Unpublished data.

per cent in the thermal conductivity of sea water for salinity changes of the order of 10 g/kg have been noted [*Krümmel*, 1907; *Barratt and Nettleton*, 1929].

The thermal conductivities of the sediment grains are only likely to change by small amounts due to ocean-bottom pressures, and it should be sufficient to consider the change in the conductivity of water alone in estimating the conductivity of the sediment. Approximations to the relative effects of pressure on the conductivities of solid and liquid phases can be obtained from the average values of *Birch and Clark* [1945] for several water-saturated sedimentary rocks, and from the values of *Lawson, Lowell, and Jain* [1959] for pure water. These values show, for solid and liquid, respective increases in conductivity of about ½ and 1 per cent for pressure increases of the order of that found at a depth of 1000 fathoms of sea water. A correction of 1 per cent per 1000 fathoms to the measured sediment conductivities at atmospheric pressure appears reasonable.

*Bulk density.* Figure 4 shows variations in the bulk density of the sediments with their water content. If there is no gas in the sediment, this curve should be of the form

$$\rho = \frac{\rho_s}{1 + (w/100)(\rho_s/\rho_L - 1)} \qquad (1)$$

where $\rho$ is the bulk density, $\rho_s$ and $\rho_L$ are the densities of the solid and liquid phases, and $w$ is the water content (per cent wet weight). Taking $\rho_L = 1.03$ g/cm³ and $\rho_s = 2.35$ g/cm³ yields a curve close to the experimental points between water contents of 40 and 70 per cent. In the case of sediments whose water contents are below about 38 per cent, the experimental bulk densities are higher than the ones calculated from the formula. Possibly the few specimens which were so low in water content may have contained sediment of a higher density than average. From a number of tests on grain densities by a displacement method, $\rho_s$ was found to vary between about 2.0 and 2.6 g/cm³. *Bullard* [1954] gave $\rho = 2.32 - 0.0181w$, based on experimental values found by the writer, over a limited range of water content, for Atlantic sediment.

*Conductivity diagram.* When measurements are not available or speed is essential, working values for thermal conductivity can be obtained from Figure 5 if we know either bulk densities or water contents related to the dry or wet state of the sediment. The diagram was constructed by assuming average values for $\rho_s$ and $\rho_L$ and then substituting these in simple theoretical equations similar to (1).

## Other Materials

It is useful to compare changes of conductivity in ocean sediment over a limited range of water content with similar variations in other granular material over a much wider range of water content. Figure 6 shows some provisional

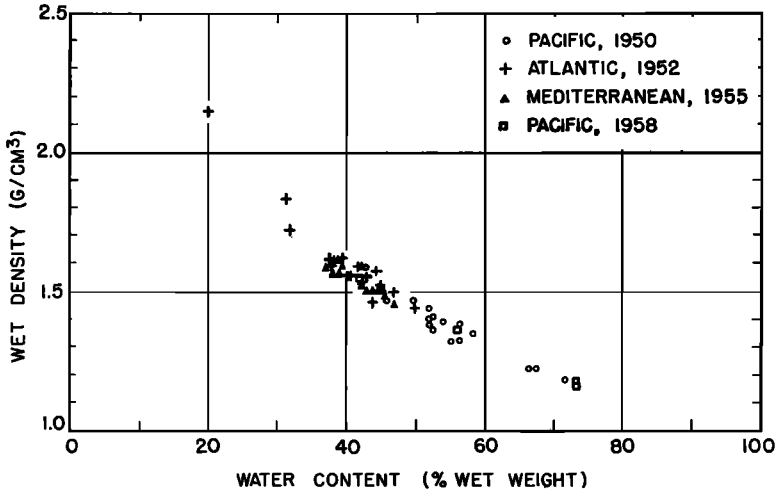


Fig. 4. Ocean sediment. Bulk density versus water content by weight.

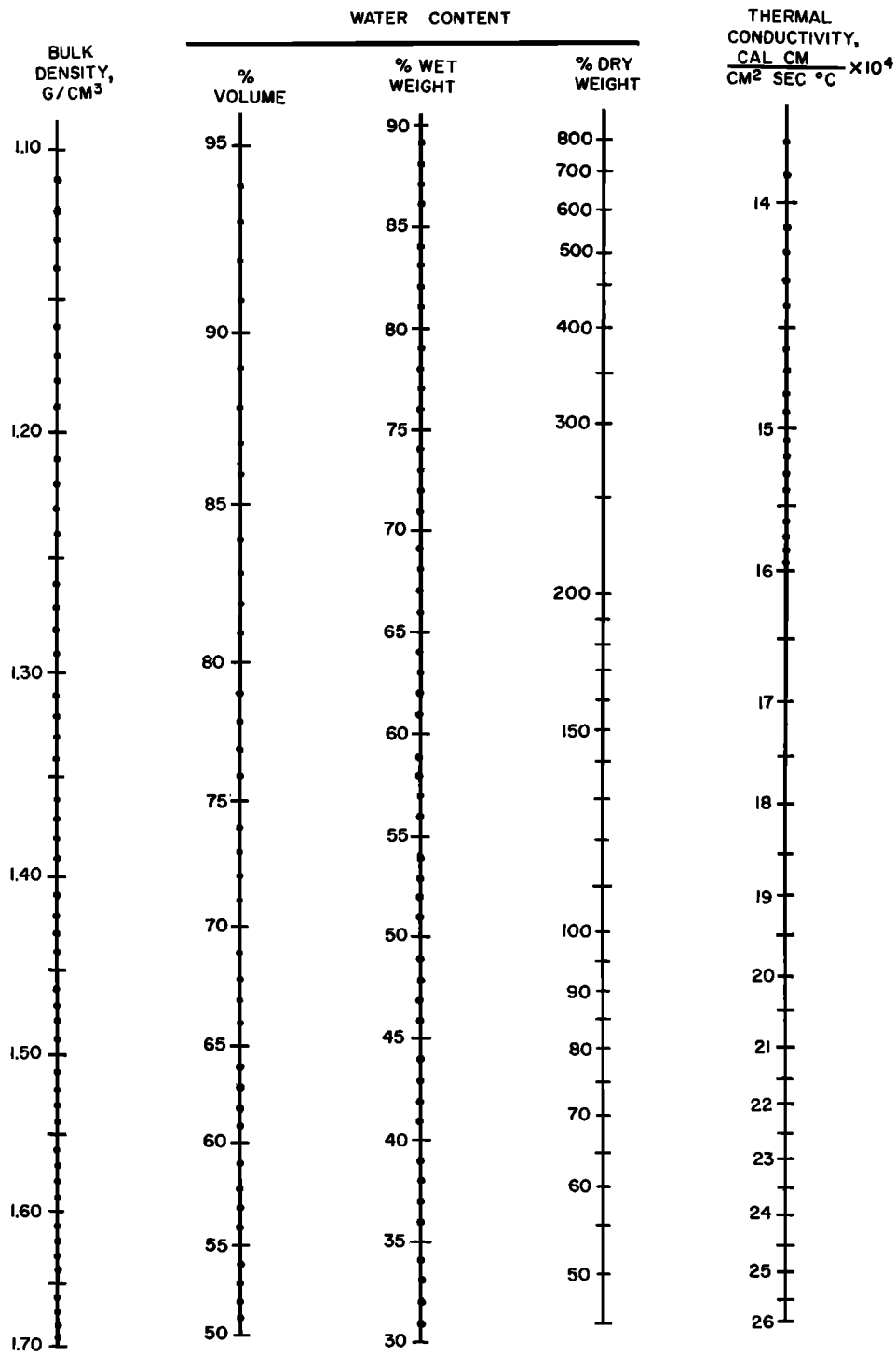


Fig. 5. Ocean sediment. Diagram for assessment of thermal conductivity at 4°C and 1 atmosphere. Add 1 per cent per 1000 fathoms and 1 per cent per 4°C temperature increase.

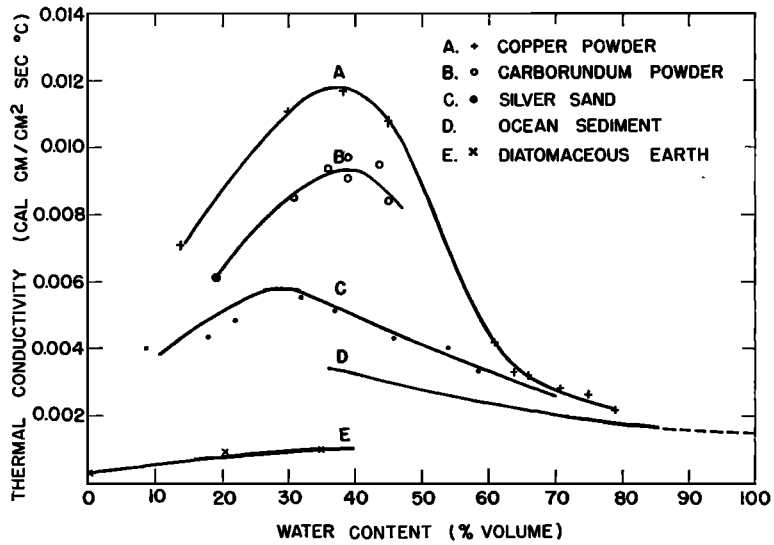


Fig. 6. Wet granular material. Thermal conductivity (at 1 atm) versus water content by volume.

results for the materials studied at the National Physical Laboratory. Experimental points for the ocean sediment curve *D* are not shown, since these are equivalent to those of the curve (at 22°C) given in Figure 3; they are plotted against water content by volume for an average value of density for sediment grains. As the water content is increased from zero, the air between the powder grains is gradually replaced by the higher-conductivity liquid, and the conductivity of the wet powder increases, at first rapidly and then more slowly. Saturation occurs at 30 to 37 per cent content by volume, when all voids are filled. Further additions of water will lead to diminution in solid material per unit volume as this is replaced by liquid, and, if the conductivity of the water is less than that of the grain material, the conductivity of the mix will decrease after saturation point has been reached, to a lower limit, which is the thermal conductivity of water. Loss of contact between the grains may also aid this decrease. The suspension of grains within a continuous phase for high water contents was achieved by mixing the powders with agar and water and testing the specimen in the form of a jelly, the continuous phase having a conductivity close to water. This method is described by *Orr and Dallavalle* [1954].

It will be seen from Figure 6 that the ratio of the conductivity of a water/copper powder mix to that of a water/sand mix for a water content of 50 per cent by volume is about 2:1 whereas the ratio of the conductivities of the solid grains is probably of the order 50:1. It is clear that the relatively small differences in the conductivities of ocean sediment grains can be neglected and that the diagram of Figure 5 may be confidently used to obtain conductivity values for diverse sediments.

Details of further work on the conductivities of other wet granular materials, including some in nonaqueous media, are outside the scope of this paper. There is a need for more practical data, for most theories for computing the conductivities of solid/liquid mixes are based on, or are suitable for, only a limited range of materials and conditions.

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