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THE THERMAL CONDUCTIVITY OF ROCKS AND ITS DEPENDENCE UPON TEMPERATURE AND COMPOSITION.*

FRANCIS BIRCH AND HARRY CLARK.

ABSTRACT. An apparatus for the measurement of absolute thermal conductivity between 0 and 500° C. is described. Results are given for 18 igneous rocks, seven sedimentary and metamorphic rocks, three single crystals and four glasses. At 0° C., the conductivities of all of the rocks lie between 0.014 and 0.004 cal/cm.sec.deg.; at 200° C., all lie between 0.009 and 0.004. The conductivities of the poorest conductors,—the glasses and the feldspar aggregates,—increase with the temperature; the conductivities of all of the other materials decrease as the temperature increases. The aggregates having the highest conductivities are the ultrabasic rocks. The results are discussed in the light of theories of heat conduction in crystals. A simple method of computation is shown to account for the conductivities of fresh igneous rocks in terms of their mineral compositions and the measured conductivities of approximately monomineral aggregates.

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PART I.

I. INTRODUCTION.

KNOWLEDGE of the thermal conductivity of the materials of the earth's crust is required for the quantitative treatment of numerous problems of geology and geophysics. Studies of the present and former rates of heat loss from the earth's

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surface, of the cooling of igneous intrusive bodies, of changes of level on heating and cooling, of the differentiation of ore deposits, depend upon numerical values of the conductivity at ordinary and at elevated temperatures. A large number of published papers bear witness at once to a sustained interest in this subject and to a failure to achieve a systematic understanding of the problem. The published values for many kinds of rocks present a chaotic appearance, with a relatively wide range for rocks of the same general type. Adequate descriptions of specimens have rarely been given. The experimental difficulties of obtaining good absolute values for the thermal conductivity of poor conductors have doubtless contributed to the confusion. The inherent complexity of the problem is such that little progress can be expected except by systematic studies with close attention to the various factors,—temperature, stress, permeating medium,—which characterize the conditions below the earth's surface. The present work is an attempt to initiate such a study, principally of the igneous rocks and of the correlation of conductivity with temperature and with composition.

The properties of rocks must ultimately be related to those of the constituent minerals, but the conductivities of most of the more abundant rock-forming minerals have never been determined, probably because these minerals so rarely occur as unflawed crystals of suitable size. Instead of devising a micro-technique for working with very small, single-crystal specimens, it seemed preferable to begin with the rocks themselves and with suitably chosen monomineral aggregates. In this way, while certain fundamental questions remain temporarily unanswered, values for many "typical" specimens become available for immediate use in other investigations, and a correlation of conductivity with composition has become possible in terms of the conductivities of the monomineral aggregates.

The results of the present work are in certain respects in contradiction to the preconceptions which might arise from a review of the older literature. One reason may be the preoccupation of former experimenters with granite and basalt (among the igneous rocks); the study of these materials can hardly reveal the systematic relations among the various types of rocks. No data have previously been obtained for the ultrabasic rocks, but these are of importance not only because of their rôle in geological theory but also because of the presence

of ultrabasic minerals in the intermediate rocks. Similarly, studies of the anorthosites show clearly the effect of the important plagioclase content in basaltic and intermediate types.

A large fraction of the first part of this paper is necessarily devoted to description of the apparatus and to the various tests by which the reliability of the measurements was established. Readers willing to take the details of the measurements for granted may pass at once to the description of the materials and to the numerical results. In the second part, an effort is made to interpret these results in terms of our knowledge of the mechanism of heat conduction in crystals, of the composition of the rocks, and of the properties of the components. The consequences of this discussion may be partially summarized in the statement that a good account of the conductivity of the igneous rocks and of its variation with temperature may be given by a simple theory in terms of the conductivities of monomineral aggregates of the predominant minerals of these rocks.

II. APPARATUS AND METHOD.

A. Choice of method.

The factors influencing the choice of a method for measuring the thermal conductivity of rocks up to moderately high temperatures will be briefly reviewed. Igneous rocks are not readily machined; complicated shapes, and especially long holes of small diameter, are to be avoided. The use of refractory cements introduces uncertainties, due to the cracking of such cements at high temperatures, and to the differential expansion of cement and rock. Flat circular discs are conveniently produced by coring, sawing, grinding, and finally lapping the surfaces to whatever degree of flatness is required. A limit to the useful degree of precision is evidently imposed by the warping of the surfaces of an aggregate of non-cubic crystals upon heating. Another advantage of the disc shape is that it permits the study of conductivity in different directions with respect to crystal axes, bedding planes, or other elements of symmetry of the material.

One of the chief difficulties encountered in measurements on non-metals is in effecting thermal contact between the temperature-measuring devices and the surfaces whose temperature must be measured. The thermal resistance of an air film 0.001

cm. thick is equal to that of a copper layer nearly 20 cm. thick, or of a layer of trap rock about 0.1 cm. thick. The importance of eliminating air films, or of correcting for them, is evident, and many experimenters have used such materials as pitch or glycerine to improve the contact. Aside from the possibility that such expedients may not be perfectly effective in displacing air films, no single liquid is satisfactory for the whole temperature range contemplated for the present work. The use of a gas such as helium or hydrogen thus suggested itself, the conductivity of these gases being of the same order as that of most liquids. By using successively two gases of known but different conductivities, the effect of thin gas layers can be substantially eliminated. It was subsequently remarked that a similar procedure had been employed for low-temperature measurements by Eucken,¹ who used three gases in order to eliminate heat losses as well. In the present work, helium and nitrogen were regularly used for each measurement. In order to avoid heat losses, it seemed advisable to adopt a guard-ring method, with a specimen in the form of a rather thin, flat plate.

The conductivity of a polycrystalline aggregate is not a quantity that can be defined in the usual way, in terms of the thermal gradient and heat flow at a point. In geological applications we are interested in the average flow of heat per unit area produced by some average difference of temperature affecting masses of large dimensions. It is essential that experimental specimens be of such a size that the average values found will be characteristic of large masses. The larger the specimen, however, the slower will be the process of making measurements. The compromise with respect to the dimensions of the specimen which has been adopted is not necessarily the optimum, but it appears to be satisfactory for nearly all of the materials. The usual thickness was 0.250 inch (6.35 mm.), with a diameter of 1.500 inch (38.1 mm.). For most of the rocks, such a specimen would comprise some thousands of individual crystals, and might properly be considered representative. The exceptional cases will be discussed below.

The pioneer work of Poole² showed that unless suitable precautions are taken, measurements of the conductivity of rocks at high temperatures are likely to be vitiated by permanent changes which probably have no counterpart in rocks slowly

¹ Eucken, A.: *Ann. Phys.* 34, 185, 1911.

² Poole, H. H.: *Phil. Mag.* 24, 45, 1912; 27, 58, 1914; 46, 408, 1923.

cooled or heated under hundreds or thousands of meters of overburden. In the present work, frequent checks at low temperature were made after exposure to progressively higher temperatures in order to find just where permanent changes began to appear. Usually the rocks could be carried to at least 300° C. before any significant irreversible changes were observed. Below this temperature, it may be supposed that the observed change is largely a reversible temperature effect, although the properties of even the freshest rock may depend upon its whole geological history.

B. Description of apparatus.

A vertical section of the apparatus, omitting the thermostat, all wires, and fine details, is shown in Fig. 1a; Fig. 1b is an enlargement of the lower part of Fig. 1a. The apparatus has circular symmetry about the vertical axis. S is the specimen, a flat, circular disc. It lies between the circular copper pieces P (the "plate") and H (the "heater"). H contains a heating element, 1.5 ohms of No. 26 nichrome wire wound on mica, by which it is kept a few degrees hotter than P. Lateral heat-loss from the specimen is prevented by the guard ring G, made of isolantite. The copper cylinder D (the "dome") which rests upon the guard ring, contains a heating element by which it is kept at the same temperature as H. Thermocouples are provided for measuring the temperature of P, the difference of temperature between H and P, and the difference of temperature between D and P. Aside from minor corrections, the mean apparent thermal conductivity of the specimen may be computed from its dimensions, the temperature drop from H to P, and the rate of heat production in H when H and D are at the same constant temperature.

The copper parts P, H, and D were first annealed, the contact surfaces lapped flat, plated with chromium or gold, and relapped, but not polished. The construction is such that each piece is free to seat itself, but is kept properly centered, in spite of differential expansion of the materials. The plate P is attached to D by three vertical screws which go up through P and through holes in the guard ring into tapped holes in D. The screws are insulated from P by pyrex bushings and mica washers. The specimen is centered by three pegs of silica glass about 0.120 inch in diameter and somewhat shorter than

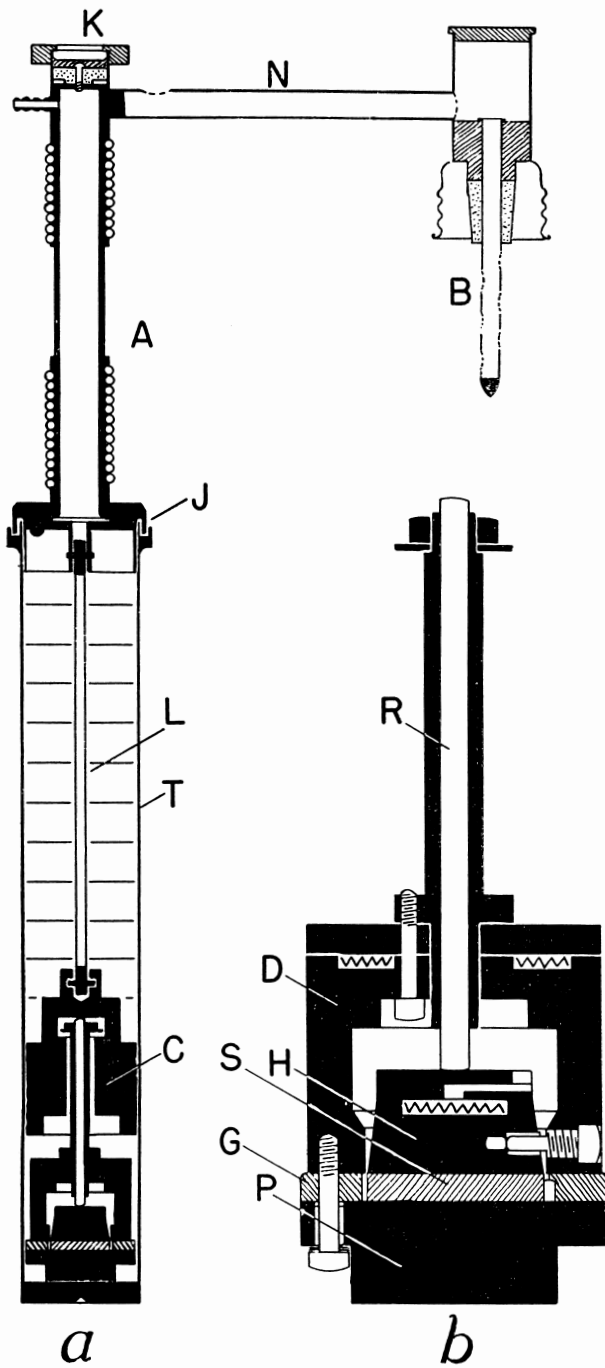


Fig. 1. Section through apparatus. (b) is an enlarged drawing of the lower part of (a).

the thickness of the specimen; they stand on end on P in semi-circular recesses in the inner curved surface of G. The heater is centered by three radial screws set in D from the outside, projecting into holes in H, from which they are insulated by pyrex tubes and rods. There is enough play to permit H to seat itself upon specimens of slightly different thicknesses. The dome is hung loosely from the steel cylinder C which in turn is linked to the upper tube A by the long, thin-walled steel tube L. A specimen having been inserted, the tube T is lifted into place and soft-soldered to A at J. The parts P, H, D, S, and G are self-seating, and C which weighs about three pounds rests on the pyrex rod R, which in turn presses H against S and P.

Ten fine wires, six of No. 26 copper from the heating elements and four thermoelement wires, are carried through glass tubes and beads from H, D, and P through a wax joint at K; the thermoelements pass through N to B where their junctions with copper are immersed in ice and water in a thermos bottle.

The outer steel tube T, 3 inches in diameter and 20 inches long, dips into a thermostatic bath to a depth of about 12 inches. A water circulation protects the soldered joint at J. Mica discs, separated by thin glass spacers, fill the upper part of the tube; they are intended to reduce convection in this region. The heavy block C remains at a steady temperature close to that of the bath, and facilitates regulation of the temperature of D. Two baths are required, one containing motor oil for temperatures up to 200° C., the other containing a mixture of sodium and potassium nitrates for higher temperatures. (An ice bath was employed for temperatures near 0° C.) These liquids are contained in steel cylinders of three gallons capacity, each wrapped in asbestos paper, wound with nichrome ribbon, set on bricks in large steel cans, and well insulated with rock wool. Each bath is stirred by removable stirrers; all apparatus must be removed from the salt bath before it is allowed to freeze. For most of the measurements, the temperature was controlled by hand adjustment of a rheostat; toward the end of the work, a thyatron regulator was used with some saving of time. The large mass of the bath is useful in insuring that temperature changes be slow.

Currents for heating H and D are furnished by separate storage batteries controlled by manganin resistances. The power input to H is found by measuring the current and the

potential drop across the heating element. To make sure that the power thus found is actually delivered to H, it is necessary to wind the copper current leads around inside the walls of H for 4 cm., separated from the wall by very thin mica, before they are silver-soldered to the nichrome. The potential leads are attached to the current leads outside H. Losses along these wires are reduced by the action of D, which is at the same temperature as H. Both current and potential drop are measured with a Leeds and Northrup Type K potentiometer, with standard resistances and Weston cell.

The thermoelements are of 0.008 inch platinum and platinum-10 per cent rhodium, from Baker and Company. Each of the junctions in H, D, and P is made by passing the wires through holes drilled axially in small copper plugs, silver-soldering to the farther end of the plugs, which are then driven into deep, close-fitting holes in the large copper pieces. Four wires are used: one of platinum to each of the pieces H, D, and P, and one common wire of platin-rhodium, which leads first to P, then to H and to D. The couple for measuring the temperature of P is led directly to the potentiometer through a specially constructed switch. The temperature difference between H and P is always small, usually about 5° C., and enters directly in the final result. The thermocouple voltage of this circuit is balanced against the voltage drop of an adjustable auxiliary current through a small fixed resistance; the drop across a large resistance due to the same current is measured with the potentiometer. The temperature difference between D and P is measured in the same way. The switches and auxiliary resistances are in an enclosed well-insulated box.

In operation, the currents in H and D are adjusted by hand until equilibrium is reached with the desired difference of temperature between H and P, and the same difference between D and P; a number of readjustments are usually necessary to accomplish this. Data are then taken every 15 minutes for about two hours, with continued fine adjustment of the currents. This process is carried out at each temperature, with the apparatus filled first with helium, then with nitrogen. Usually a day is required for the determination of the conductivity at a single temperature.

C. Method of calculation. Estimated precision.

The calculation of the mean thermal conductivity is based upon the following principal assumptions: (1) when the dome and the heater are at the same constant temperature, all of the heat produced in the heater flows through the specimen to the plate; (2) the transfer of heat from the heater to the specimen and from the specimen to the plate is by conduction through the thin gas-films between these surfaces. The validity of these assumptions, within the uncertainty acknowledged for the final result, was tested by suitable variations of the conditions; these tests are described below. If Q is the heat input per second to the heater, ΔT the difference of temperature between heater and plate at equilibrium, A the area and D the thickness of the specimen, an apparent conductivity K' may be computed for each gas filling, at each temperature, from the elementary relation, $K' = QD/A\Delta T$; the apparent conductivity in helium will be called K'_h , in nitrogen, K'_n . The reciprocals of these will be the apparent resistivities, R'_h and R'_n . Assuming gas films of uniform, not necessarily equal, thicknesses on the two sides of the specimen, which remain the same for the two gas fillings at a given temperature, we can compute the apparent resistivity by adding the resistivity of the specimen R and the resistivity of the gas films, obtaining the two equations,

$$R'_h = R + y/H, R'_n = R + y/N,$$

where y is the thickness of the double gas film, divided by D ; H and N are the thermal conductivities of helium and of nitrogen, respectively, at this temperature. Eliminating y , we find

$$R = (R'_h - R'_n N/H) / (1 - N/H)$$

for the resistivity of the specimen. Thus in addition to the measured quantities, we need to know the ratio of the conductivities of helium and nitrogen, as a function of temperature. According to the International Critical Tables, the conductivities may be expressed in terms of Sutherland's formula,

$$K_t = K_o (273 + C) (T/273)^{3/2} / (T + C)$$

where T is the absolute temperature, and K_o and C are constants, given in Table 1. These constants were determined for temperatures below 100° C.; more recent measurements,³ giving

³ Dickens, B. G.: Proc. Roy. Soc. A 143, 517, 1934; Kannuluik, W. G. and Martin, L. H.: idem, 144, 496, 1934.

slightly different values of the two conductivities at 0° C., show very nearly the same ratio, N/H being 1/6.1 at 0° C.; at 500° C., the formula gives for this ratio, 1/5.3. Recent measurement⁴ of the conductivity of nitrogen at 500° C. gives a value within a few per cent of the value found by extrapolation with the constants given below. Since the ratio N/H is always close to 1/6, R is nearly equal to R'_b, the greatest difference being about six per cent for the best conductor. It is consequently not essential that the ratio N/H be very accurately known.

TABLE 1.

Constants in Sutherland's Formula for Thermal Conductivity.

	K ₀ (joules/cm.sec.deg.)	C. degrees
Helium	13.9 · 10 ⁻⁴	33
Nitrogen	2.28 · 10 ⁻⁴	114

Actually, the distribution of the film thickness over the area of contact is not known, and indeed, changes from specimen to specimen and from one temperature to another. The assumption of a uniform film is a first approximation which can be justified by elementary computations when the film resistance is relatively small, as in nearly all of the present work. Since the computed correction to the apparent value in helium is at most six per cent, and usually not more than three, it is unlikely that any serious error is introduced by the use of a mean film thickness.

A consideration which might conceivably be of importance for the specimens of relatively high conductivity is the so-called "temperature-jump" or temperature discontinuity between the surfaces of the solid parts and the gas layers. The study of conduction in gases at low pressure⁵ has shown that at a solid-gas interface there is a discontinuity of temperature, proportional to the normal temperature gradient, to the mean free path in the gas, and to a factor which depends upon the roughness of the surface and the nature of the gas, the "accommodation coefficient." If we work through the theory to find the effect of this phenomenon upon the resistivity of our specimens, using the somewhat uncertain data which are to be found for accommodation coefficients, we find an additional resistance per

⁴ Wilner, T., and Borelius, G.: *Ann. Phys.* 4, 316, 1930.

⁵ Knudsen, M.: *Ann. Phys.* 34, 593, 1911; Loeb, L. B.: *Kinetic Theory of Gases*, New York, 1927.

cm.², at 0° C. and 760 mm. of mercury, equal to 1.2 cm.sec.-deg./cal., whereas the resistivity of the quartz single crystal parallel to the principal axis is about 37 cm.sec.deg./cal. at 0° C. This correction would thus amount to about 3.3 per cent, and it should be inversely proportional to the pressure of the gas. An experimental test showed that, in fact, the correction must be smaller than this at the pressures used in this work, regularly 96 cm. of mercury. A series of measurements of conductivity of the quartz single crystal parallel to the axis were made at a number of different pressures, at a single mean temperature, 58.3° C. The results are shown in Table 2, where the conductivity is computed in the usual way, ignoring temperature discontinuities. If the correction were as much as 3 per cent at 120 cm. pressure, it should be nearly 12 per cent at 35 cm.; in fact, the difference is about one per cent, that is, within the experimental error. There is an indication of the beginning of an effect at 10 cm. This is fairly satisfactory evidence that the theory of the temperature jump as it exists at present is inadequate for pressures of this order, and that no correction need be applied for this effect.

TABLE 2.

Test of the effect of gas pressure on measured conductivity.
 Quartz single crystal, heat flow parallel to axis, 58.3° C.

Pressure, cm. of Hg.	K. cal./cm.sec.deg.
120	0.0218 _s
76	.0219 _s
35	.0216 _s
10	.0194 _s

It is of the utmost importance to exclude convective transfer of heat from the heater to the plate, and the apparatus was designed to make this effect small. The heater and the dome, the hotter parts, are above the plate, which in turn is warmer than the bottom of the steel container. The principle of keeping the warmer parts above the cooler cannot of course be extended to the lateral surfaces of the tube, and the upper part of the tube is considerably cooler than the region around the dome. Circulation in the upper part of the tube is reduced by a series of baffles. Circulation in the vital region around the heater must be very nearly eliminated by the close fit of the heater, specimen and plate and the dome, guard ring and plate:

the openings through the dome for the various wires are small and nearly filled with glass tubes. Finally, the temperature differences are kept as small as possible. Direct tests of the importance of convection were made in several ways. A series of runs with different temperature drops between heater and plate, at the standard gas pressure, 96 cm., were made with the silica glass specimen, one of the poorest conductors. A similar series was carried out with all of the important spaces below the steel cylinder C well plugged with cotton. The mean temperature of the specimen was kept constant for these tests. The measured conductivity of the specimen was unaffected by these changes of the conditions, within the error expected from other sources; since this was the most favorable specimen for discovering convective effects, it is unlikely that convection plays a significant part.

Instead of solving for R , the "true" resistivity, we may be interested in finding y , which is proportional to the film thickness. The surfaces of all the specimens were intended to be plane, to begin with, with a precision of about 0.0001 inch; we expect to find effective film thicknesses of this order. Eliminating R , we find

$$y = (R'_h - R'_n) / (1/H - 1/N).$$

From this we find that the double film thicknesses all lie between 0.0002 and 0.0005 inch; thus the order of magnitude is about right. It is difficult to say more, since a variable amount of internal space may be included. To a large extent, the variation appears to be attributable to slight differences in the original perfection of the surfaces; the minimum values are found for the two quartz crystal specimens, the silica glass specimen, and the two quartzitic sandstone specimens, which are all suitable for precise lapping.

In estimating the precision with which the conductivities are determined, it is evident that the various measured quantities are known with an accuracy considerably greater than that of the final values. The current and potential drop in the heater circuit were measured to four significant figures, and at intervals during which neither changed by more than 0.1 per cent. The difference in temperature between the heater and the dome was kept at less than 0.1 per cent of the difference between the heater and plate; preliminary experiments using large differences between D and H showed that this regulation permitted an error not greater than 0.1 per cent in the heat

flow through the specimen. This figure includes all gains or losses of heat from the heater when the tube is filled with helium; with nitrogen, it is smaller.

The thermocouple wire was calibrated at the melting points of four Bureau of Standards' certified samples, and at the boiling point of water. The results differed from the table given in the International Critical Tables by 0.25 per cent in the same direction at all five temperatures. Tests for uniformity with steep thermal gradients in the wire showed that the wires were extremely uniform. The measurement of absolute temperature should be correct to within 0.05° C. The temperature difference between H and P, which enters directly in the computation of conductivity, is accurate to about 0.5 per cent. Although it is almost impossible to obtain a reliable direct calibration of a differential thermocouple, the good agreement obtained after rewiring, on several occasions, confirms the other evidence indicating the reliability of these wires.

The precision with which the specimens were shaped permitted an easy and accurate determination of the density from the weight and computed volume; the values are given in the next section. No correction has been applied to the values of conductivity for the thermal expansion of the specimens. The necessarily loose fit of the specimen among the glass centering pegs may allow as much as 0.5 per cent of the area of the face of the specimen to project laterally beyond the heater, at maximum eccentricity. Even though no heat enters the part not in contact with H, the lines of flow from the part in contact spread out and become nearly normal in a fraction of the thickness of the specimen. The greatest uncertainty from this source probably does not exceed 0.2 per cent.

A final consideration is that direct radiation may account for the transfer of a fraction of the heat from H to P. For small temperature differences, the black-body law gives a variation of heat exchange by radiation increasing as the third power of the absolute temperature. If the specimen were perfectly transparent to the radiant heat, and if the copper pieces H and P emitted and absorbed radiation according to black-body laws, then the fraction of the total heat exchange attributable to radiation could be very large at 500° C.,—about 30 per cent for such poor conductors as silica glass, about three per cent for good conductors such as quartz. These are maximum values which are certainly not reached;

the emissivity of the metal surfaces is considerably below that for a black body at such low temperatures, and even the glasses are probably not perfectly transparent for this radiation; existing data are too meager to permit a detailed calculation even for silica glass, a large part of the energy being in the region of very long wave lengths where little work has been done. It seems safe to assume that the error from this cause is negligible for the crystalline rocks and single crystals, and for the glasses at temperatures below about 300° C. In a vitreous shell deep in the earth, at high temperature, radiation might well play an important part in the transfer of heat; its effect seems to have been little studied for such a system.

Summing up, the apparent conductivities are determined with random errors of the order of one per cent; uncertainties of the same order enter in the extrapolation of these values to find the true conductivity at the highest temperatures, the total uncertainty should not exceed four per cent, except for possible radiation corrections for the glasses.

III. DESCRIPTION OF MATERIALS.

The rock specimens used in the present work were made from large, fresh blocks which were selected under the direction of the Committee for Research in Experimental Geology and Geophysics and which have already supplied samples for a number of other studies, principally of elasticity.⁶ The compositions and grain sizes have been determined from thin sections, with supplementary study of some of the particular samples used for the thermal measurements. The analyses as determined from examination of a few thin sections, even unusually large ones, may fail to represent accurately the composition of any particular specimen, especially if the rock is of coarse grain. Apparently the only way to overcome this difficulty would involve the destruction of the specimen; at present this procedure does not appear to be warranted. Table 3 gives the designations of the specimens, their places of origin, and their bulk densities; where several values are given for the density, these are the densities of different samples of the same material.

The descriptions and chemical analyses of many of these rocks have already been published in various communications⁶:

⁶ Zisman, W. A.: Proc. Nat. Acad. Sci. 19, 653 and 666, 1933; Ide, J. M.: idem, 22, 81, 1936; Birch, F. and Bancroft, D.: J. Geol. 46, 59 and 113, 1938.

descriptions of more recently acquired specimens are given below. The results of Rosiwal analyses of the "mixed" rocks are given in Table 4; this summarizes compactly descriptions many of which are published in detail elsewhere. The composition of the monomineral rocks is shown in Table 5.

TABLE 3.
Materials studied.

Designation	Place of origin	Density	Mean crystal diameter mm.
<i>Igneous rocks</i>			
Granite	Rockport, Mass.	2.609, 2.612	1.5-2
Granite	Barre, Vermont	2.648	1
Granite	Westerly, R. I.	2.643	.5
Quartz monzonite	Porterville, Cal.	2.637	1
Tonalite	Val Verde, Cal.	2.735	1
Augite syenite	Peninsula Station, Ont.	2.799	2
Albitite	Sylmar, Pa.	2.609	.6
Anorthosite	Farm Doornspruit 878, Transvaal	2.740	1.5
Anorthosite	New Glasgow, Quebec	2.704	.5
Anorthosite	Stillwater Complex, Mont.	2.737	2
Diabase	Frederick, Md.	3.013	.3
Diabase	Vinal Haven, Maine	2.962	.5
Diabase	Westfield, Mass.	2.962	.5
Gabbro ("norite")	French Creek, Pa.	3.033	.5
Gabbro	Mellen, Wis.	2.862, 2.879	3
Hypersthene	Stillwater Complex, Mont.	3.261	2.5
Bronzite	Pilansberg, Transvaal	3.289	2
Dunite	Balsam Gap, N. C.	3.269, 3.252	1
<i>Sedimentary and metamorphic rocks</i>			
Quartzitic sandstone	Allentown, Pa.	2.638, 2.647	.3
Marble	Proctor, Vermont	2.688, 2.687	.4
Gneiss	Pelham, Mass.	2.644, 2.641	.2
Slate	Pa.	2.763	
Limestone	Solenhofen, Bavaria	2.605	.001-.01
Limestone	Nazareth, Pa.	2.688	
Dolomite	Bethlehem, Pa.	2.826	.01
<i>Single Crystals</i>			
Quartz		2.652	
Calcite		2.713	
Halite		2.160	
<i>Glasses</i>			
Silica	Thermal Syndicate, Ltd.	2.199	
No. 774 Pyrex	Corning Glass Co.	2.229	
Obsidian	Modoc, Cal.	2.440	
Diabase	General Electric Co.	2.757	

TABLE 4.
Volume percentages of minerals.

	Quartz	Orthoclase	Albite	Plagioclase	Biotite	Amphibole	Pyroxene	Olivine	Rest
Granite, Rockport	28	64(a)				6			2
Granite, Barre	26	25	37		9				3(b)
Granite, Westerly	19	33(c)	40		6				2
Quartz monzonite	34	27		33 Ab ₇₂ An ₂₈	4.5	.2(d)	.4		1
Tonalite	28			50 Ab ₃₅ An ₄₅	15	7(d)			
Augite syenite		84.3			.4		12.9(j)	1.6	.8
Diabase, Maryland				48 Ab ₃₃ An ₆₇	1		49(e)	1	1
Diabase, Vinal Haven				61 Ab ₄₅ An ₅₅	4		19(f)	13	3
Diabase, Westfield				66 Ab ₄₆ An ₅₄			32(g)		2
Gabbro, French Creek				51 Ab ₃₅ An ₆₅	.5		47(h)		1.5
Gabbro, Mellen				72 Ab ₄₀ An ₆₀	1.2		14.1(i)	11.4	1.3

(a) micropertthite

(b) muscovite

(c) microcline

(d) hornblende

(e) 24 augite, 25 hypersthene

(f) hypersthene, Mg:Fe = 8:2

(g) augite

(h) augite 32, hypersthene 15

(i) diallage

(j) aegirite-augite

Descriptions of the new specimens follow:

Granite, from Barre, Vermont, is of medium grain, holocrystalline, anhedral. The average dimensions of the quartz crystals are about 1.2 by 0.8 mm.; of the feldspars, which are slightly kaolinized and sericitized, 1.5 by 1 mm. Accessory biotite and muscovite occurs in smaller grains.

Quartz monzonite, from Porterville, California, was collected and kindly forwarded by Prof. Ian Campbell. The average size of the quartz crystals is roughly 0.8 mm., of the plagioclase, about 1.0 mm., of the orthoclase, about 1.0 mm., in irregular patches. The plagioclase is zoned and slightly altered to sericite and kaolin.

Tonalite, from Val Verde, California, was also collected by Professor Campbell; it shows very slight kaolinization of the feldspars. The average grain sizes are: quartz, 1.0 by 0.8; plagioclase, 1.4 by 1.1 mm.; biotite, 1.2 by 0.9 mm.

Albitite, from near Sylmar, Pennsylvania, was kindly collected by Prof. E. H. Watson. The rock is almost completely anhedral grains of fresh plagioclase, of the composition Ab₈₈An₁₂; the average grain size is about 0.6 mm. Small amounts of iron-rich amphibole (actinolite) occur in irregular patches.

Anorthosite, from the Stillwater Igneous Complex, Montana, was collected by Professor Larsen. It is a fresh holocrystalline rock composed of labradorite, of average grain size of 2.8 by 1.0 mm., with minute amounts of an unidentified dark mineral.

Anorthosite, from Farm Doornspruit 878, Transvaal, is a coarse-grained rock composed of bytownite, of mean grain size of 1.5 mm. Throughout much of the rock the plagioclase is clear and fresh, but in places it has been considerably altered to sericite and kaolin. The pyroxene, amounting to 3.5 per cent, is so completely chloritized that it was not possible to determine its true composition. The masses of chlorite contain small grains of titanite; originally the pyroxene was interstitial or showed an ophitic texture with the feldspars. A few grains of pyrite and apatite are present.

Anorthosite, from New Glasgow, Quebec, is a granular rock with a maximum grain diameter of 1.7 mm. and an average of 0.5 mm. The labradorite is essentially all of the same composition; little zoning is shown. Many of the grains have been fractured and sericite has developed along these fractures as well as along the grain boundaries. About one per cent of quartz is found in small rounded grains, 0.1 to 0.05 mm. in diameter, completely enclosed in the labradorite. The small amounts of carbonate and serpentine are intimately associated, and are probably derived from alteration of olivine.

The quartz and calcite single crystals were obtained through the kindness of Prof. C. Palache from the Harvard Mineralogical Museum. The quartz specimens were cut from a single crystal originally nearly a foot long, with well-developed external form. Except for a few visible fractures, the whole crystal was perfectly transparent; a spectroscopic analysis showed that the greatest impurity was copper, of which less than 0.01 per cent was present. The orientation of the two discs was checked after the experiment by Professor Palache and by Dr. H. Berman; the deviations from the intended directions, perpendicular and parallel to the principal axis, were less than a degree. The corrections required for these deviations are negligible.

The calcite was slightly pinkish before heating; this color was lost from one of the specimens during the experiments. The spectroscopic analysis showed magnesium and manganese in small quantities, greater than 0.01 per cent, but less than one per cent. One of the specimens (heat flow perpendicular to the axis) was cracked during the series of measurements, but since the results continued to fall along a smooth curve, it is not known when the cracking occurred. Apparently no serious change in the conduction through the crystal took place. The other specimen had a small flaw, which did not, however, develop into a real fracture.

The halite was a clear two-inch cube, obtained from Ward's Natural Science Establishment. The analysis showed no impurity

greater than 0.01 per cent. The lapping was done with oil instead of with water, as in the other cases.

TABLE 5

Composition of monomineral rocks.	
Volume percentages.	
Albitite	98.6 Ab ₉₈ An ₁₂ 1.4 actinolite
Anorthosite	
Stillwater	99+ Ab ₉₅ An ₀₅
Anorthosite	
Transvaal	96.5 Ab ₂₀ An ₈₀ 3.5 pyroxene
Anorthosite	
Quebec	94.4 Ab ₄₀ An ₆₀ 1 quartz, 4.6 sericite, serpentine, carbonate
Hypersthénite	
Stillwater	93.5 hypersthène Mg:Fe::6:1 4 hornblende, 2.5 magnetite and olivine
Bronzite	
Transvaal	92.5 bronzite 3.8 plagioclase, 1.7 hornblende, 2 magnetite
Dunite	97 olivine (92 Mg ₂ SiO ₄ , 8 Fe ₂ SiO ₄) 2 serpentine, 1 hornblende, chromite, carbonate

IV. NUMERICAL RESULTS.

The mass of experimental data is very considerable; probably no real purpose would be served by publishing it in detail. What seems a practical compromise in the method of presentation has been selected. The measured values of conductivity have all been plotted against the temperature in the following figures; smooth curves, that fit these points with the precision of the measurements are shown, and the values read from these curves at 50°-intervals are tabulated. In many cases it would be possible to draw other curves with as good justification, but within the range of the experiments, the differences would not exceed one or two per cent. Any considerable extrapolation beyond this range would be open to serious uncertainty for many of the samples, where reversals of curvature are possible.

The conductivity is expressed in the figures and tables in units of 10⁻³ calories/cm.sec.deg.C. Conversion to units of 10⁻³ watts/cm.deg.C. follows on multiplication by 4.18. Fig. 2 shows the measured values for the two orientations in the quartz single crystal, and for the two specimens of the quartzitic sandstone. These curves are very nearly hyperbolic; the resistivity (the reciprocal of the conductivity) of quartz parallel to the axis, in particular, is closely linear over the whole

range from 0° to 350°; this is shown in Fig. 8. There appear to be no other measurements for quartz above 100°.

Fig. 3 shows the conductivity for the group of materials composed chiefly of calcite, as well as for samples of dolomite, slate, and halite. The curve for halite is hyperbolic from 0 to 400° C.; the resistivity is given by a linear relation, $R = 68.5$

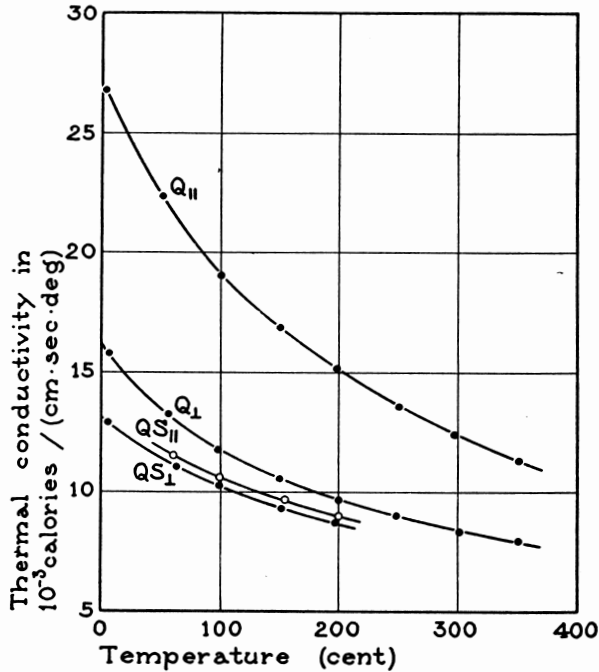


Fig. 2. Thermal conductivity of quartz and of a quartzitic sandstone.
 QS_{\perp} Quartzitic sandstone, Penn., \perp bed-plane.
 $QS_{||}$ Quartzitic sandstone, Penn., $||$ bed-plane.
 Q_{\perp} Quartz single crystal \perp optic axis.
 $Q_{||}$ Quartz single crystal $||$ optic axis.

$(1 + 0.00483 t) ^\circ C. \text{ cm. sec. / cal.}$, where t is the temperature centigrade. This has not been corrected for thermal expansion; the correction would increase the resistivity by about two per cent at 400° C., the thermal expansion of the halite being much greater than for any of the other materials. The conductivity of the slate was measured across the foliation; attempts to shape a specimen for measurements along the foliation failed as the thin disc always came apart. The calcite and limestones will be discussed at some length below. The

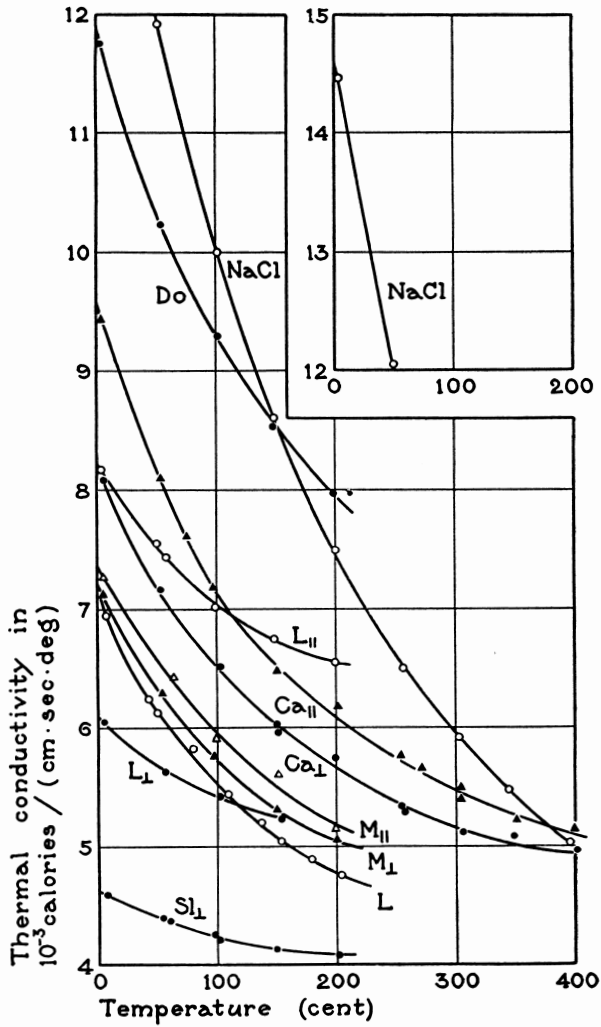


Fig. 3. Thermal conductivity of calcite, marble, limestone, dolomite, halite and slate.

- | | |
|------------------|---|
| Sl _⊥ | Slate, Penn., ⊥ bed-plane. |
| L _⊥ | Limestone, Penn., ⊥ bed-plane. |
| L | Limestone, Penn., bed-plane. |
| L | Limestone, Solenhofen. |
| M _⊥ | Marble, Vermont, ⊥ bed-plane. |
| M | Marble, Vermont, bed-plane. |
| Ca _⊥ | Calcite, single crystal, ⊥ optic-axis. |
| Ca | Calcite, single crystal, optic-axis. |
| Do | Dolomite, Penn. |
| NaCl | Halite. |

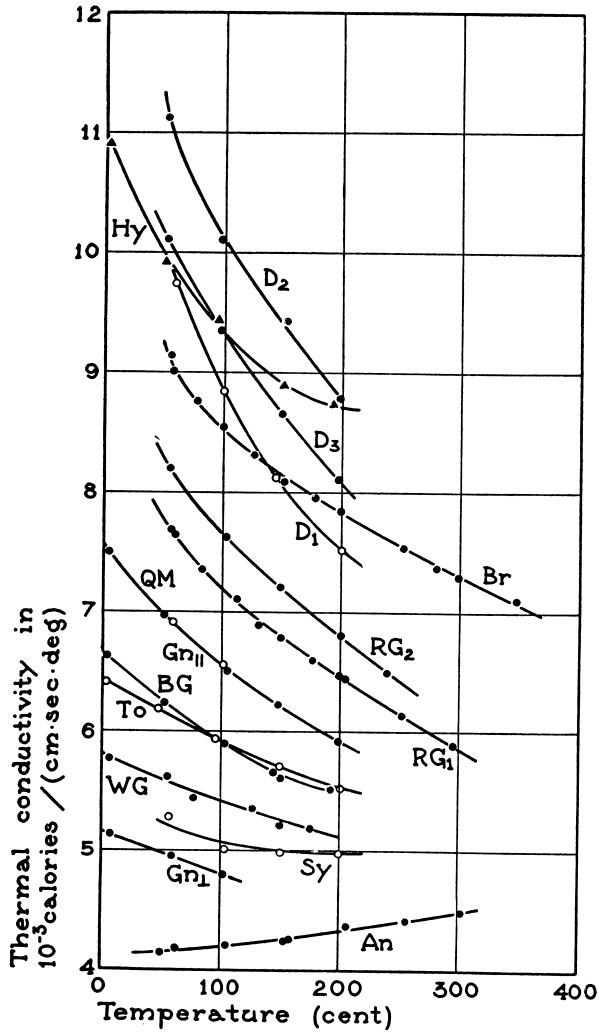


Fig. 4. Thermal conductivity of holocrystalline rocks.

An	Anorthosite, Quebec.	RG ₁	Rockport Granite 1.
Gn _⊥	Gneiss, Pelham, ⊥ bed-plane.	RG ₂	Rockport Granite 2.
Gn _∥	Gneiss, Pelham, ∥ bed-plane.	Br	Bronzite.
Sy	Syenite, Ontario.	Hy	Hypersthene.
WG	Westerly Granite.	D ₁	Dunite 1.
To	Tonalite, Calif.	D ₂	Dunite 2.
BG	Barre Granite.	D ₃	Dunite 3.
QM	Quartz monzonite, Calif.		

relatively high value for the dolomite is noteworthy, nearly twice as high as for the marble and limestones.

Fig. 4 displays the conductivities of a number of holocrystalline igneous rocks and two samples of a granitic gneiss. Strikingly high values are found for the ultrabasic rocks. The three curves for dunite are for three different samples of the same block; the structure of this material is very irregular, some crystals being very small, others very large, and it is not sur-

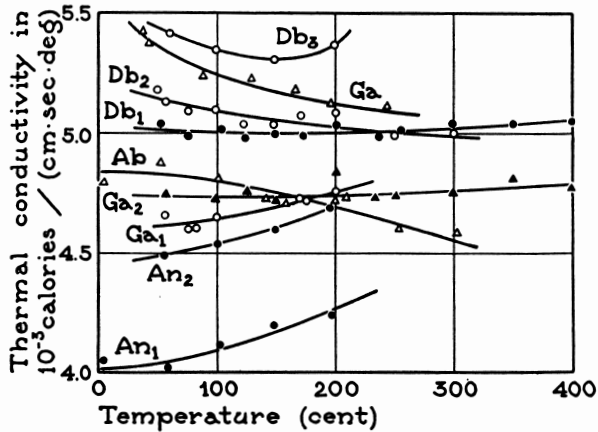


Fig. 5. Thermal conductivity of anorthosites and diabasic rocks.

An ₁	Anorthosite, Stillwater.
An ₂	Anorthosite, Transvaal.
Ga ₁	Gabbro, Wisconsin 1.
Ga ₂	Gabbro, Wisconsin 2.
Ab	Albitite.
Db ₁	Diabase, Mt. Holyoke.
Db ₂	Diabase, Vinal Haven.
Ga	Gabbro, French Creek.
Db ₃	Diabase, Maryland.

prising to find some variation among the samples. The change with temperature is also very large for these rocks. A fairly large spread is found among the granite specimens and the closely related quartz monzonite and tonalite. These relations will be discussed below. Of the two samples of Pelham gneiss, the one with the heat flow across the foliation has a low conductivity, the other, with heat flow parallel to the foliation, coincides with the curve for the quartz monzonite; the points are shown as open circles. The syenite is low, with a

tendency toward independence of temperature. The anorthosite shows a definite *increase* of conductivity with increasing temperature.

Two other anorthosites, showing this same kind of variation, together with a number of rocks of gabbroic composition, are grouped in Fig. 5. The albitite shows a small decrease of conductivity with rising temperature. The conductivity of the gabbros and diabases is very nearly independent of the temperature. The vertical scale of this figure is double that of the others. It is easy to see at once, qualitatively, the reflection of variation of composition in these rocks. They consist principally of plagioclase feldspar and pyroxene; the upward tendency (of the conductivity) of the plagioclase minerals roughly counterbalances the downward tendency of the pyroxenes and olivine. Two specimens of the Wisconsin gabbro were studied on account of the coarse grain of this rock; the results are in fairly close agreement.

We recall, finally, that all of the points plotted in these figures may be considered to represent reversible temperature effects; in many of the runs, measurements were made at higher temperatures but were discarded when subsequent measurements at lower temperatures failed to return to their previous values. In all cases, this irreversibility consisted in a permanent lowering of the conductivity, in agreement with the results of Poole.

The smoothed values, taken from these curves, are tabulated in Table 6, and their reciprocals, the resistivities, in Table 7. Measurements near 0° C. were made in a number of cases; in others, the values given for this temperature were found by extrapolating from about 50°; extrapolated values are enclosed in parentheses and are of lower precision. The designations "parallel" and "perpendicular" in the tables and figures refer to the direction of heat flow with respect to bedding planes in the case of the rocks in which such planes were detectable, or with respect to the principal axis of the quartz and calcite single crystals.

Although the thermal conductivity is the more familiar quantity, the curves of resistivity versus temperature are very much more nearly linear in general, and hence rather more convenient for interpolation. The resistivities are tabulated for anyone who would like to construct such curves; they are probably to be preferred for any extrapolation which one cares to risk.

TABLE 6.
Thermal Conductivity.

Temperature °C.	Smoothed values, in 10^{-3} cal./cm.sec.deg.C.								
	0	50	100	150	200	250	300	350	400
<i>Single crystals</i>									
Quartz,									
parallel	27.3	22.4	19.0	16.8	15.1	13.6	12.3	11.3	(10.3)
perpendicular	16.3	13.5	11.8	10.6	9.7	8.9 _s	8.4	7.9	(7.4)
Calcite,									
parallel	9.56	8.12	7.15	6.53	6.10	5.73	5.47	5.26	5.08
perpendicular	8.30	7.17	6.50	6.03	5.66	5.38	5.16	5.00	4.92
Halite	14.6	12.0	10.05	8.58	7.45	6.60	5.95	5.50	4.98
<i>Igneous rocks</i>									
Granite									
Rockport 1	(8.40)	7.80	7.20	6.80	6.46	6.15	5.86		
Rockport 2	(9.09)	8.30	7.66	7.20	6.80	6.42			
Barre	6.66	6.25	5.90	5.64	5.50				
Westerly	5.80	5.60	5.42	5.26	5.12				
Quartz monzonite	7.56	6.98	6.55	6.20	5.91				
Tonalite	6.42	6.15	5.90	5.70	5.52				
Syenite		5.25	5.08	5.00	4.99				
Albitite	4.85	4.84	4.80	4.76	4.70	4.63	4.55		
Anorthosite									
Transvaal	(4.43)	4.49	4.54	4.61	4.69				
Quebec	(4.13)	4.18	4.20	4.26	4.34	4.41	4.50		
Montana	4.02	4.05	4.10	4.17	4.27				
Diabase									
Maryland	(5.62)	5.44	5.35	5.32	5.37				
Vinal Haven	(5.23)	5.15	5.10	5.06	5.03	5.01	4.99		
Westfield	(5.04)	5.02	5.01	5.01	5.01	5.02	5.03	5.04	5.06
Gabbro									
French Creek	(5.55)	5.37	5.25	5.18	5.13	5.10			
Wisconsin 1		4.62	4.65	4.70	4.75				
Wisconsin 2	(4.75)	4.75	4.75	4.75	4.76	4.77	4.78	4.79	4.81
Pyroxenite									
Bronzitite,									
Transvaal	(11.1)	9.20	8.51	8.14	7.83	7.56	7.30	7.00	
Hypersthenite,									
Montana	11.0	10.0	9.32	8.90	8.70				
Dunite 1	(11.8)	10.0	8.82	8.03	7.52	7.20			
" 2	(14.3)	11.4	10.1	9.40	8.77				
" 3	(11.2)	10.1	9.30	8.62	8.08				
<i>Sedimentary and metamorphic rocks</i>									
Quartzitic sandstone									
parallel to bed	13.6	11.8	10.6	9.7	9.0				
perpendicular	13.1	11.4	10.3	9.35	8.65				
Gneiss, parallel	(7.42)	7.00	6.58						
Gneiss, perpendicular	(5.17)	4.98	4.82						
Marble, parallel	7.36	6.44	5.95	5.50	5.19				
perpendicular	7.20	6.32	5.72	5.30	5.05				
Limestone,									
Solenhofen	7.20	6.14	5.53	5.03	4.77				
Pennsylvania									
parallel to bed	8.24	7.55	7.04	6.72	6.54				
perpendicular	6.09	5.68	5.41	5.24					
Dolomite	11.9	10.3	9.3	8.55	7.95				
Slate, perpendicular	4.63	4.40	4.23	4.13	4.08				

The principal resistivities of quartz are plotted in Fig. 8 for comparison with the measurements of other observers.

Smoothed values for the glasses are tabulated in Table 8;

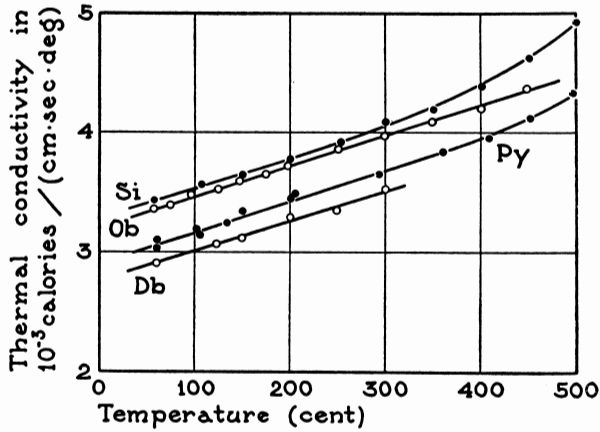


Fig. 6. Thermal conductivity of several glasses.

- Db Diabase glass, artificial.
- Py Pyrex glass.
- Ob Obsidian, modoc.
- Si Silica glass.

these values are taken from the curves of Fig. 6. The upward curvature of the conductivity of silica glass and pyrex glass may be a result of radiative transfer of heat, which, as we have seen, may become important for the glasses above 300°. The flatness of the curve for obsidian also suggests this explanation for the silica glass, although there need be no connection between opaqueness for visible radiation and opaqueness for the long waves in which the thermal energy of black-body radiation is concentrated at these temperatures.

TABLE 7.
Thermal Resistivity.
Sec.cm.deg./cal.

	Temperature °C.								
	0	50	100	150	200	250	300	350	400
<i>Single crystals</i>									
Quartz,									
parallel	36.6	44.6	52.6	59.5	66.2	73.5	81.3	88.5	(97.1)
perpendicular	61.3	74.1	84.7	94.3	103	112	119	127	(135)
Calcite,									
parallel	105	123	140	153	164	175	183	190	197
perpendicular	121	140	154	166	177	186	194	200	203
Halite	68.5	83.3	99.5	117	134	152	168	185	201
<i>Igneous rocks</i>									
Granite									
Rockport 1	(119)	128	139	147	155	163	171		
Rockport 2	(110)	121	131	139	147	156			
Barre	150	160	170	177	182				
Westerly	172	179	185	190	195				
Quartz monzonite	132	143	153	161	169				
Tonalite	156	163	170	175	181				
Syenite		191	197	200	200				
Albitite	206	207	208	210	213	216	220		
Anorthosite									
Transvaal	(226)	223	220	217	213				
Quebec	(242)	239	238	235	230	227	222		
Montana	249	247	244	240	234				
Diabase									
Maryland	(178)	184	187	188	186				
Vinal Haven	(191)	194	196	198	199	200	200		
Westfield	(198)	199	200	200	200	199	199	198	198
Gabbro									
French Creek	(180)	186	191	193	195	196			
Wisconsin 1		217	215	213	211				
Wisconsin 2	(211)	211	211	211	210	210	209	209	208
Pyroxenite									
Bronzite,	(90)	109	118	123	128	132	137	143	
Hypersthene,	91	100	107	112	115				
Dunite 1	(85)	100	113	125	133	139			
" 2	(70)	88	99	106	114				
" 3	(89)	99	108	116	124				
<i>Sedimentary and metamorphic rocks</i>									
Quartzitic sandstone									
parallel to bed	73.5	84.7	94.3	103	111				
perpendicular	76.3	87.7	97.1	107	116				
Gneiss, parallel	(135)	143	152						
Gneiss, perpendicular	(193)	201	208						
Marble, parallel	136	156	168	182	193				
perpendicular	139	158	175	189	198				
Limestone,									
Solenhofen	139	163	181	197	210				
Pennsylvania									
parallel to bed	121	133	142	149	153				
perpendicular	164	176	185	191					
Dolomite	84	97	108	117	126				
Slate, perpendicular	216	227	236	242	245				

TABLE 8.

Thermal Conductivity of Glasses.
Smoothed values, in 10^{-3} cal./cm.sec.deg.C.

	Temperature °C.										
	0	50	100	150	200	250	300	350	400	450	500
Silica	3.25	3.43	3.54	3.66	3.78	3.92	4.06	4.26	4.42	4.64	4.95
Pyrex 774	2.88	3.02	3.15	3.29	3.45	3.56	3.70	3.85	3.96	4.12	4.38
Obsidian	3.21	3.35	3.48	3.60	3.74	3.86	4.00	4.15	4.26	4.39	4.52
Diabase	2.74	2.87	3.00	3.14	3.27	3.40	3.53				

The best guarantee of the accuracy of the present work is to be found in the regularity of the observations, and in the careful design and testing of the apparatus. Measurements of thermal conductivity of apparently the same materials by different observers frequently display startling discrepancies of absolute value, even when the material is relatively well defined as in the case of a "pure" metal. These differences are not entirely the result of errors of measurement but are often the expression of real differences in the material, with respect to impurities, crystal size, crystal perfection and so on. The best agreement might be expected for such materials as silica glass and perhaps single crystals of high purity and perfection, such as quartz. For the purpose of showing that the present measurements exhibit no large systematic error, the measurements of other observers on a few materials will be examined in some detail.

Silica glass. This material as made at the present time is generally of a purity exceeding 99.8 per cent silica, and it seems unlikely that impurities amounting to 0.2 per cent can have a large effect upon its conductivity. In this respect, glasses differ greatly from crystals, for reasons which will be suggested below. The measurements for this glass nevertheless show wide discrepancies. In Fig. 7 are plotted the values of Kaye and Higgins,⁷ Eucken, Seemann, and Ito as well as the present ones. Barratt's values are too low to go on this plot. This comparison can hardly lead to any very definite conclusions, although certain values seem clearly erroneous, such as Barratt's, and Eucken's 100° point (marked ? in his paper). All of the other measurements fall in a rather broad band, with a breadth varying between 10 to 12 per cent of the mean value. Our values agree best with those of Kaye and Higgins. The values

⁷ Kaye, G. W. C., and Higgins, W. F.: Proc. Roy. Soc. A 113, 335, 1926; Eucken, A.: Ann. Phys. 34, 185, 1911; Seemann, H. E.: Phys. Rev. 31, 119, 1928; Ito, S.: Mazda Res. Rep. 4, 188, 1929; Barratt, T.: Proc. Phys. Soc. Lond. 27, 81, 1914.

ascribed to Ito were computed from the linear formula in which his results were summarized; the original paper, with the experimental points, was not available. There seems to be no evidence here that the present measurements are too high or too low.

Pyrex glass. The composition of this glass is doubtless more variable than that of silica glass, and correspondingly less weight

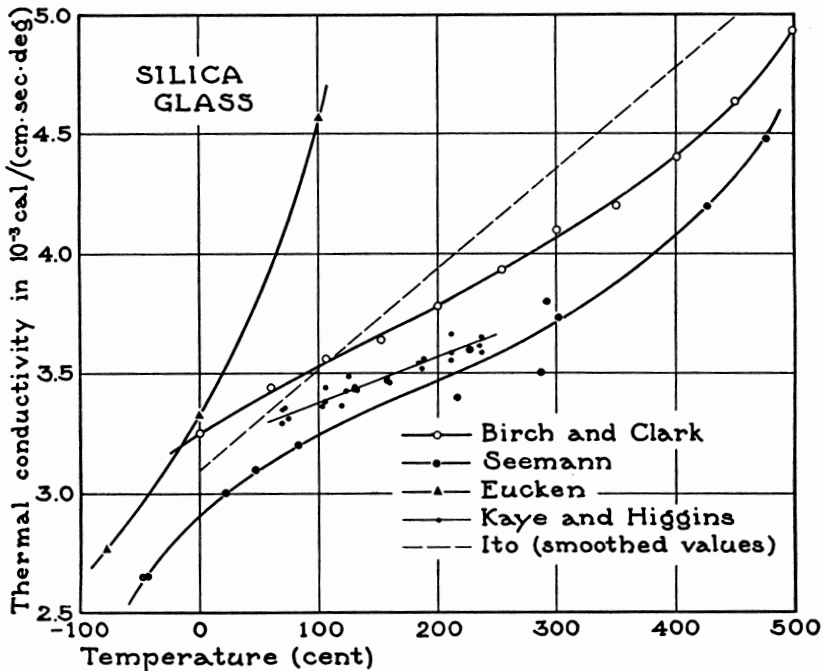


Fig. 7. Thermal conductivity of silica glass as given by different observers.

should be attached to a comparison of values. With respect to the values of Stephens⁸ and of Bridgman,⁹ the present ones are high. Bridgman's measurements show no change of conductivity between 30° and 75°, while Stephens' give an increase of over ten per cent in this interval. Bridgman's values are probably too low for some of the materials which he studied, and there seems to be no published account of Stephens' method of obtaining his absolute value. The reference deals with the relative change with temperature.

⁸ Stephens, R. W. B.: *Phil. Mag.* 14, 897, 1932.

⁹ Bridgman, P. W.: *This Journal* 7, 81, 1924.

Quartz. This material would seem well suited as a standard of comparison. The purity is exceptionally high, and "secondary" or "mosaic" structure almost if not entirely absent in crystals of optical quality. Measurements by Eucken,⁷ Griffiths and Kaye,¹⁰ Kaye and Higgins,⁷ Tuschmidt,¹¹ and Lees¹² are shown with the pres-

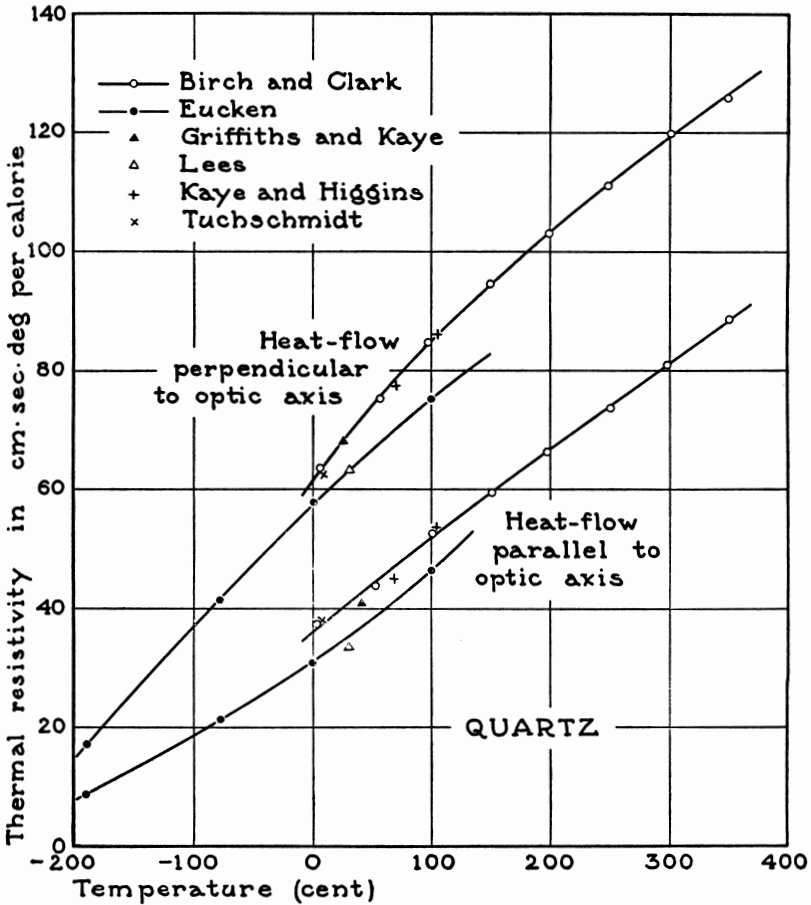


Fig. 8. Thermal resistivity of quartz as given by different observers.

ent values in Fig. 8, where the *resistivities* have been plotted instead of conductivities. The present values agree well with those of Griffiths and Kaye, Kaye and Higgins, and Tuschmidt; they differ by from 7 to 20 per cent from those of Lees and of Eucken. There

¹⁰ Griffiths, E., and Kaye, G. W. C.: Proc. Roy. Soc. 104, 71, 1923.

¹¹ Tuschmidt, A.: Diss. Zurich 1883.

¹² Lees, C. H.: Phil. Trans. Roy. Soc. Lond. 183A, 461, 1892; 191, 399, 1898.

seems to be no reliable, objective way of deciding between the two sets of values; the differences may be the result of real differences in the material.

Calcite. Our values agree fairly well with the old ones of Tuschmidt; Eucken and Lees give very much higher conductivities. Our crystal was of somewhat inferior quality, which may well account for some, if not all, of the difference.

Halite. The present specimen was made from a natural rocksalt crystal and the values are in fair accord with those of Lees and of Eucken for similar but of course not identical material. Tuschmidt and Bridgman give much lower values. Eucken and Kuhn¹³ have shown that very pure single crystals, artificially grown from solution or melt, may have conductivities nearly 50 per cent greater, at 0°C., than natural crystals. It is consequently not possible to judge the precision of any observations by comparison of results for the impure or doubtful materials. The analysis indicated, however, that the present crystal was of high purity; it is likely that other factors are important, such as "secondary" structure, which is known to exist in rocksalt. This will be discussed more fully in the next section.

Taking all of these comparisons into account, we conclude that there is no evidence of any serious error in the absolute values of the present conductivity measurements. The internal consistency of the work may be judged by the regularity of the experimental points plotted in Figs. 2 to 8.

¹³ Eucken, A., and Kuhn, G.: *Z. f. phys. Chem.* 134, 193, 1928.

(End of Part I)—To be continued.

GORDON MCKAY LABORATORY,
HARVARD UNIVERSITY,
CAMBRIDGE, MASS.