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53. *Studies of the Thermal State of the Earth. The 17th Paper: Variation of Thermal Conductivity of Rocks. Part 2*

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Abstracts

Thermal conductivity of fused silica, crystalline quartz, hurz burgites, lherzolites and dunite is measured in a temperature range from the room temperature to about 1400°*C* by a modified Kingery method.

Thermal conductivity of the fused silica agreed with Birch's data in temperature range from the room temperature to 500°*C*. The conductivity of the crystalline quartz is found to be higher than Birch's values in α-quartz range. It is found that the conductivities in the *X* and *C* axis of the crystalline quartz are inverted at the transition point of the α- and β-quartz. The phonon part of the conductivities of rocks differs considerably for different specimens. It is confirmed that the conductivities of all the measured rocks increase with temperature at temperatures higher than 1200°*C*. This phenomenon indicates that radiative or excitonic effect becomes important at high temperatures.

I. Introduction

Knowledge of the thermal and pressure variation of the thermal conductivity of rocks is important in geothermics. But, so far, the measurement of this quantity has been made in a limited range of temperature, say below 600°*C*[1),2)]. Within the earth's mantle, much higher temperature seems to prevail.

The thermal conductivity of some ceramics has been measured in a temperature range from the room temperature to about 1800°*C* by Kingery et al.[3)] Among the materials investigated by Kingery et al., forsterite

1) F. Birch, and H. Clark, *Amer. J. Sci.*, **238** (1940), 529 and 613.

2) K. Kawada, *Bull. Earthq. Res. Inst.*, **42** (1964), 631.

3) W. D. Kingery, J. Francl, R. L. Coble, and T. Vasilos, *J. Amer. Cer. Soc.*, **37** (1954), 107. M. McQuarrie, *J. Amer. Cer. Soc.*, **37** (1954), 91.

and periclase are the important substances constituting the upper mantle. According to their measurements, the thermal conductivity of forsterite decreases with increasing temperature. But the rate of decrease in the temperature range above 1000°*C* is less than that which would be expected from the phonon theory. The conductivity of periclase decreases with temperature in a temperature range from the room temperature to about 1300°*C*, and increases from about 1300°*C* with increasing temperature. These observations seemed to indicate the importance of non-phonon transport of heat at higher temperatures.

Theoretical investigation of the thermal conductivity of rocks at elevated temperatures was carried out by S. P. Clark[4], H. A. Lubimoba[5] and A. W. Lawson and J. C. Jamieson[6]. It was shown that the radiative or the excitonic conduction can be expected to play an important role at high temperatures.

In order to investigate the thermal conductivity of rocks and minerals at elevated temperatures more closely, the present work has been carried out. The range of temperature covered in the present study is from the room temperature to about 1400°*C*. The work is still in a preliminary state, but some of the results appear to be of some significance as they show a marked increase of the thermal conductivity with temperature in high temperature range.

II. Apparatus and Method

The method of measurement of thermal conductivity of rocks employed in our preceding study[7], covering the temperatures up to 600°*C*, was a comparative method called the divided bar method. The divided bar method is not suitable for measurements at higher temperatures, because the silver paste for the thermal contact between the bars and sample cannot be used at temperatures above 700°*C* or so. The method of measurement employed in the present study is essentially the same as the one used by Kingery for measuring the thermal conductivity of ceramics at high temperature[8].

4) S. P. CLARK, Jr., *Trans. Amer. Geophys. Union*, **38** (1957), 931. *Bull. Geol. Soc. Amer.*, **17** (1956), 1123.

5) H. A. LUBIMOVA, *Akad. Nauk SSSR, Inst. Fiziki Zemli Trudy*, **178** (1960), 72.

6) A. W. LAWSON and J. C. JAMIESON, *J. Geol.*, **66** (1958), 540.

7) K. KAWADA, *ibid.*, 2).

8) W. D. KINGERY, *J. Amer. Cer. Soc.*, **37** (1954), 88., *Property Measurements at high Temperatures*, (John Wiley and Sons, New York, 1959), ch. 4.

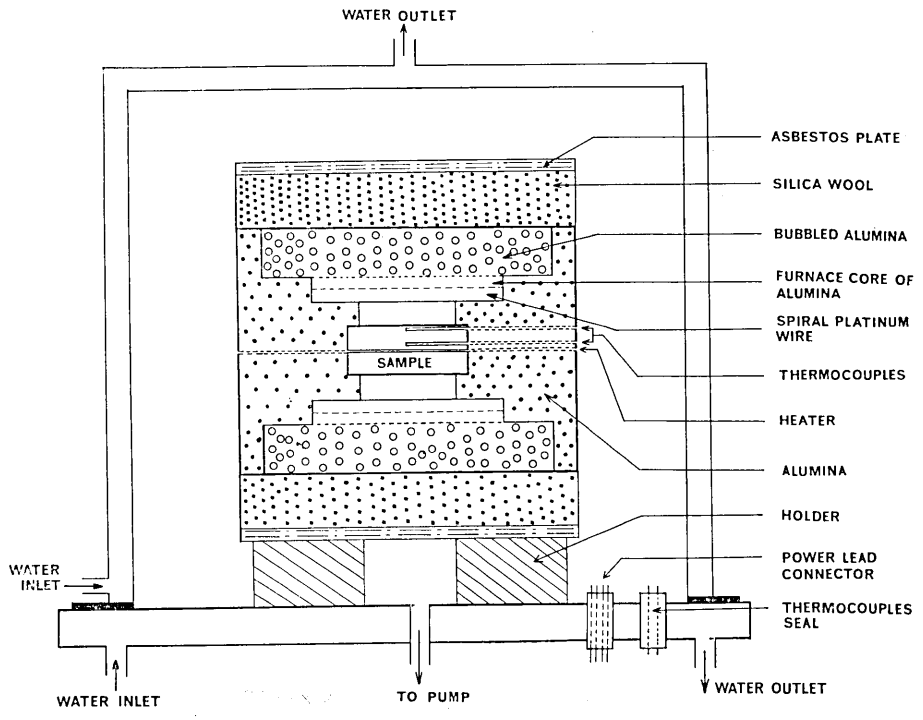

Fig. 1. Equipment for measurement of thermal conductivity of rocks.

Fig. 1 is a schematic diagram of the apparatus used in the present study. The specimen is made in a cylinder of 2.5 *cm* in diameter and 5 *cm* in length, and a hole of 0.25 *cm* in diameter is drilled through along the axis. Two other holes 0.18 *cm* in diameter with 2.5 *cm* in length were drilled at distances 0.3 *cm* and 1.2 *cm* from the axis of the specimen. A platinum wire containing 20% rhodium was inserted in the axial hole and the electric current made to flow in the wire. It is difficult to raise the temperature of the specimen by the platinum wire only. Therefore, a platinum electric furnace was employed. The heat flows in the radial direction of the specimen. The amount of heat passing through the sample is given by the product of the electric current and the voltage across the ends of the heater. Temperature of the specimen is measured with two platinum vs. platinum–13% rhodium thermocouples which are placed in the two 0.18 *cm* thick holes. In the measurement of the thermal conductivity of the

specimen, it is important that the temperature of the surface of the specimen be controlled at a lower level than that of the inner surface of the electric furnace. This control was effected by an automatic temperature controller. A potentiometer was used for the e.m.f. readings of the thermocouples. Readings were taken to 1 μv while approximately 6 μv corresponds to 1°C for all the thermocouples throughout the temperature range concerned (0°C—1450°C).

In a steady state, the thermal conductivity of the specimen is given by[9]

$$K=\frac{1}{2\pi LJ}\log\frac{r_2}{r_1}\cdot\frac{I\cdot V}{T_1-T_2}$$

where J is the mechanical equivalent of heat, L length of heater, r_1 and r_2 distances from the central axis to the inner and outer thermocouples, I electric current, V voltage between the ends of the electric heater, T_1 and T_2 temperatures at inner and outer thermocouple holes.

It is important to vary the temperature of the specimen very slowly in the experiments of this kind. Unless we make the temperature change sufficiently slowly, the porosity or the crack of the specimen seems to increase. Under very favourable conditions, one run of experiment took seven to ten days.

It is, moreover, necessary that we do not oxidize the specimen at high temperature. If the specimen is oxidized, the thermal variation of the conductivity shows irreversibility in the heating and cooling processes. Usually, the conductivity become smaller when oxidation takes place. To avoid the oxidization of the specimen, the whole system was once evacuated to $10^{-2}-10^{-3}$ *mmHg*, and then argon gas was allowed in. In actuality, this process was repeated twice.

To ascertain the reversibility in the thermal change of the thermal conductivity, the following cycles of heating and cooling were made: in the first cycle, the temperature of the specimen is raised very slowly from the room temperature to 900°C, and then lowered gradually from 900°C to the room temperature, and in the second cycle, the temperature is raised very slowly from the room temperature to 1450°C and then cooled to the room temperature. Such cyclic heating and cooling was found to be effective in realizing the reversibility. If we raise the temperature of the specimen from the room temperature to 1450°C in one step, the

9) H. S. CARSLAW and J. C. JAEGER, *Conduction of Heat in Solids*, (Oxford, 1959), Ch. 7., W. D. KINGERY, *ibid.*, 3).

reversibility of the conductivity was not realized. After such a treatment, the specimen becomes fairly porous, but not after the composite cycles described above.

III. Description of Materials

Samples used in the present study are crystalline quartz, fused silica, peridotites, olivine nodules and dunite.

Fused silica and crystalline quartz are often used as standard sample in measuring thermal conductivity. Therefore, these substances have been investigated in detail, so that it is possible to evaluate the quality of a new equipment of thermal conductivity from the measurement on fused silica and crystalline quartz.

Quartz is one of the most abundant minerals and occurs as an essential constituent of many igneous, sedimentary and metamorphic rocks. It has four polymorphs: α-quartz, β-quartz, tridymite and cristobalite. The three principal crystalline forms of SiO_2, quartz, triydmite and cristobalite, have quite distinct crystal structures. The transformations from one to another are, however, somewhat sluggish, so that the higher temperature forms, cristobalite and tridymite, can exist metastably below their inversion temperatures. α-quartz has trigonal symmetry and β-quartz has hexagonal symmetry. The phase change from α- to β-quartz occurs rapidly and reversibly at $573°C$[10]. However, the phase change from β-quartz to tridymite occurs gradually and its change is not reversible. This inversion temperature is $870°C$[11]. The phase change from tridymite to cristobalite occurs gradually and not reversibly at $1470°C$[12].

From various geophysical bases, it may be considered that peridotite, olivine nodule and dunite are the substances constituting the upper mantle. Three hurz burgites used in the present study are from the Twin Sisters Mountains, northern Washington, U. S. A. They were collected by G. Thompson of Stanford University. This sample has the following mineral composition: 60% olivine, 40% enstatite, and very little chromite.

Two lherzolites are from Horoman in Hokkaido and were collected by I. Yokoyama of Hokkaido University. This sample has the following mineral composition: 70% olivine, 25% enstatite, 5% augite+picotite, and

10) W. A. Deer, R. A. Howie and Z. Zussman, *Rock Forming Minerals*, Vol. 1 (Longmans, 1964), Ch. 1.

11) W. A. Deer, et al.., *ibid.*, 10).

12) W. A. Deer, et al., *ibid.*, 10).

very little tremorite. This sample is a deformed peridotite, that is, under the microscope, olivine crystals are granulated in margins along closely-spaced shear cracks and are optically anomalous having distinct wavy extinction.

Two lherzolites, collected by H. Kuno of the University of Tokyo, are from Ichinomegata in Akita Prefecture, Japan. This sample has the following mineral composition: 60% olivine, 20% enstatite, 15% augite, 5% spinel and 0.1% plagioclase.

One dunite is obtained from Karatsu in northern Kyushu. It was collected by S. Uyeda and K. Horai of the University of Tokyo. This sample has the following mineral composition: 90% olivine, 10% chromite, and 1% augite.

IV. Experimental Results

Thermal conductivity of fused silica up to 1300°C is shown in Fig. 2 and Table 1. The conductivity value of fused silica obtained in the present

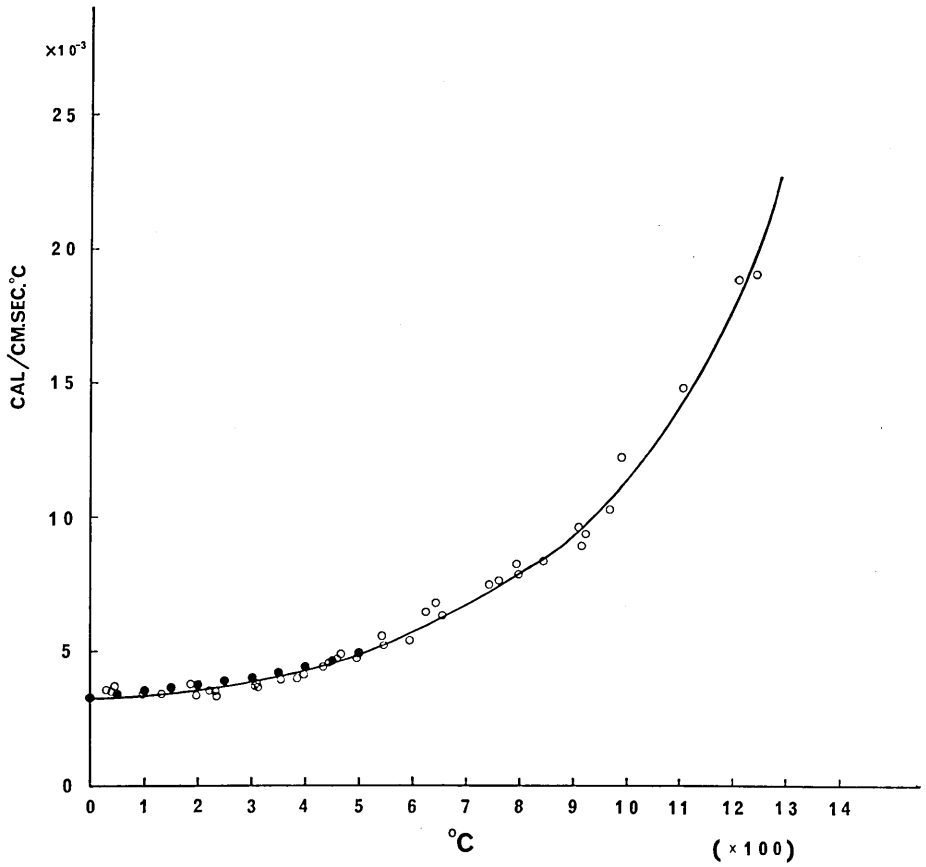

Fig. 2. Thermal conductivity of fused silica. Double circle is Birch's data. Hollow circle is cycle heating and cooling data. Solid circle is cooling data from 1240°C to the room temperature.

Table 1. Thermal conductivities of fused silica and crystalline quartz.

Fused silica			Crystalline quartz		
Temperature °C.	Conductivity *cal/sec. cm. °C*	Resistivity	Temperature. °C	Conductivity in the *X* direction *cal/sec. cm. °C*	Conductivity in the *C* direction *cal/sec. cm. °C*
27	3.60×10^{-3}	277.8	31	17.11×10^{-3}	27.93×10^{-3}
38	3.58	279.3	36	17.02	
43	3.72	268.8	37		27.77
98	3.45	289.9	39	17.21	26.28
132	3.47	288.2	108	15.34	
187	3.79	263.9	109		24.18
198	3.33	300.3	176	14.93	
222	3.57	280.1	180		22.27
233	3.55	281.7	202	13.30	
234	3.38	295.9	204		20.75
305	3.75	266.7	263	12.52	
309	3.77	265.3	266		16.74
311	3.69	271.0	280	11.01	
355	3.98	251.3	282		15.71
385	3.98	251.2	360	10.68	
397	4.10	243.9	363		14.46
433	4.41	226.8	366	10.64	
444	4.60	216.9	369		14.16
459	4.72	211.9	428	10.86	
467	4.92	203.3	432		13.66
498	4.75	210.5	471	10.45	
543	5.66	176.7	475		12.33
546	5.23	191.2	479	10.54	
595	5.38	185.9	484		12.09
626	6.51	153.6	545	10.78	
643	6.87	145.6	552		11.28
655	6.33	158.0	553	10.73	
742	7.55	132.5	560	8.86	
762	7.70	129.9	564		8.36
793	8.34	119.9	567	11.20	
794	7.98	125.3	570	11.13	
844	8.47	118.1	571		11.06
908	9.76	102.5	579	8.63	

(to be continued)

(continued)

Fused silica			Crystalline quartz		
Temperature °C.	Conductivity cal/sec. cm. °C	Resistivity	Temperature °C.	Conductivity in the X direction cal/sec. cm. °C	Conductivity in the C direction cal/sec. cm. °C
917	9.00×10^{-3}	111.1	580	8.35×10^{-3}	
922	9.42	106.2	582		8.75×10^{-3}
968	10.39	96.2	595		8.71
986	12.41	80.6	610	11.59	
1103	14.97	66.8	622		8.88
1206	19.09	52.4	656	12.81	
1241	19.25	51.9	670		9.74
			691	13.37	
			706		10.07
			744	15.29	
			758		11.09
			790	16.25	
			805		11.71
			830	17.01	
			837	17.07	
			846		12.47
			853		12.44
			860	18.79	
			878		12.57
			901	20.46	
			920		13.48
			977	26.84	
			997		16.68
			1060	28.80	
			1080		19.72

measurement agrees with Birch's data in the temperature range below 500°C. The thermal conductivity of fused silica, as seen in Fig. 2, *increases* with increasing temperature.

Thermal conductivity of crystalline quartz up to 1100°C is presented in Fig. 3 and Table 1. It is seen that thermal conductivity of crystalline quartz has higher value than that of Birch's value at lower temperature, say below 500°C, where the conductivity decreases with increasing temperature. In the transition point between α- and β-quartz, thermal conduc-

tivities make abrupt changes. Thermal conductivity in the direction of the C-axis is higher than that in the direction of the X-axis in α-quartz, but in β-quartz the conductivity in the direction of the C-axis is lower than that in the direction of the X-axis.

The difference of the crystal structure of α- and β-quartz is not conspicuous as indicated in the previous section. Therefore, the changes in the thermal conductivity near the transition point are remarkable. To the

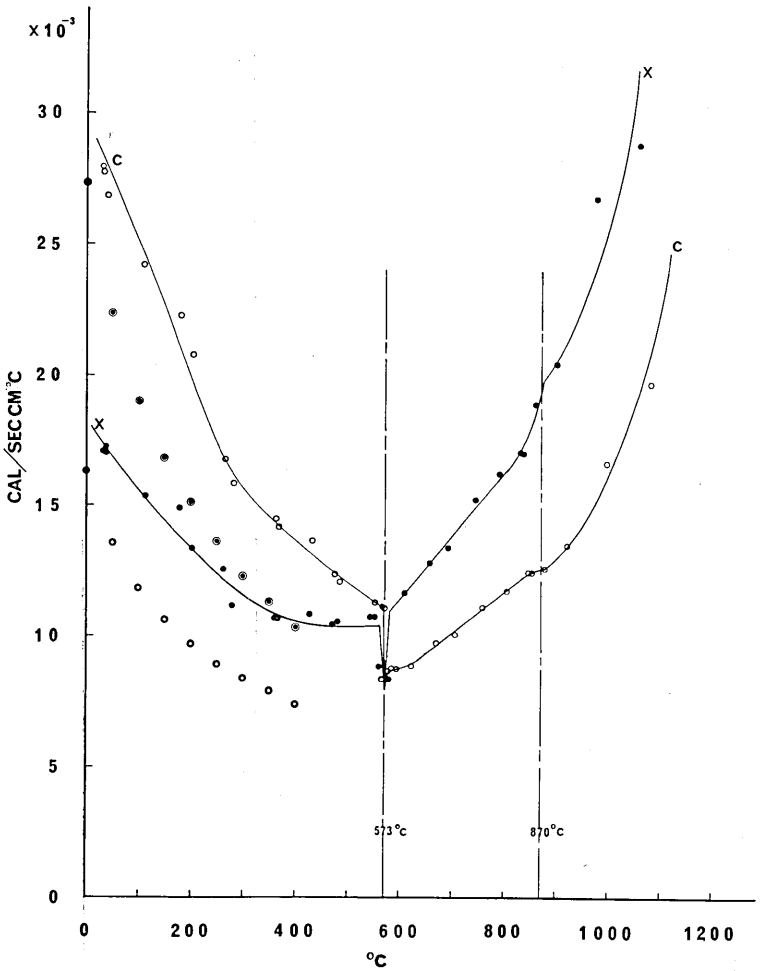

Fig. 3. Thermal conductivity of crystalline quartz. Double and double solid circles are Birch's data.

Table 2. Thermal conductivity of Twin Sisters hurz burgite.

Specimen T-1			Specimen T-1		
Temperature °C	Conductivity *cal/sec. cm. °C.*	Resistivity	Temperature °C	Conductivity *cal/sec. cm. °C.*	Resistivity
34	20.87×10^{-3}	47.9	816	9.75×10^{-3}	102.6
71	18.59	53.8	912	10.12	98.2
94	17.37	57.6	916	9.59	104.3
120	14.51	68.9	984	10.29	97.2
126	16.37	61.1	1111	10.04	99.6
149	15.04	66.5	1178	9.52	105.0
175	13.71	72.9	1185	9.46	105.7
224	14.56	68.7	1248	10.45	95.7
269	12.39	80.7	790	7.68	130.2
281	12.45	80.3	973	6.71	149.0
338	12.11	82.6	1134	6.62	151.1
381	11.54	86.7	1134	6.43	155.5
422	11.08	90.3	1223	6.96	143.7
508	11.04	90.6	1246	6.27	159.5
544	11.10	90.1	1319	7.97	125.5
601	10.42	96.0	1415	12.12	82.5
696	10.23	97.8			

Specimen T-2			Specimen T-2		
Temperature °C.	Conductivity *cal/sec. cm. °C.*	Resistivity	Temperature °C.	Conductivity *cal/sec. cm. °C.*	Resistivity
38	19.78×10^{-3}	50.6	755	9.52×10^{-3}	105.0
43	21.63	46.2	883	8.16	122.5
50	19.10	52.4	944	8.77	114.0
84	18.97	52.7	965	8.79	113.8
117	16.84	59.4	1061	8.55	117.0
174	13.22	75.6	1073	8.06	124.1
225	13.19	75.8	1130	7.96	125.6
275	11.73	85.3	1150	7.57	132.1
290	12.02	83.2	1197	7.24	138.1
360	11.27	88.7	1261	8.01	124.8
366	10.92	91.6	1283	8.49	117.8
495	10.42	96.0	1291	8.58	116.6
554	10.26	97.5	1341	9.29	107.6
629	9.40	106.4	1376	10.72	93.3
701	9.32	107.3	1380	11.41	87.6

(to be continued)

(continued)

Specimen T-3			Specimen T-3		
Temperature °C.	Conductivity *cal/sec. cm. °C.*	Resistivity	Temperature °C.	Conductivity *cal/sec. cm. °C.*	Resistivity
39	19.57×10^{-3}	51.1	680	8.95×10^{-3}	111.7
185	14.94	66.9	797	9.52	105.0
247	13.36	74.9	875	9.09	110.0
310	12.52	79.9	991	8.82	113.4
347	11.68	85.6	1067	8.15	122.7
395	10.71	93.4	1143	6.58	152.0
489	10.73	93.2	1180	6.67	149.0
610	9.73	102.8			

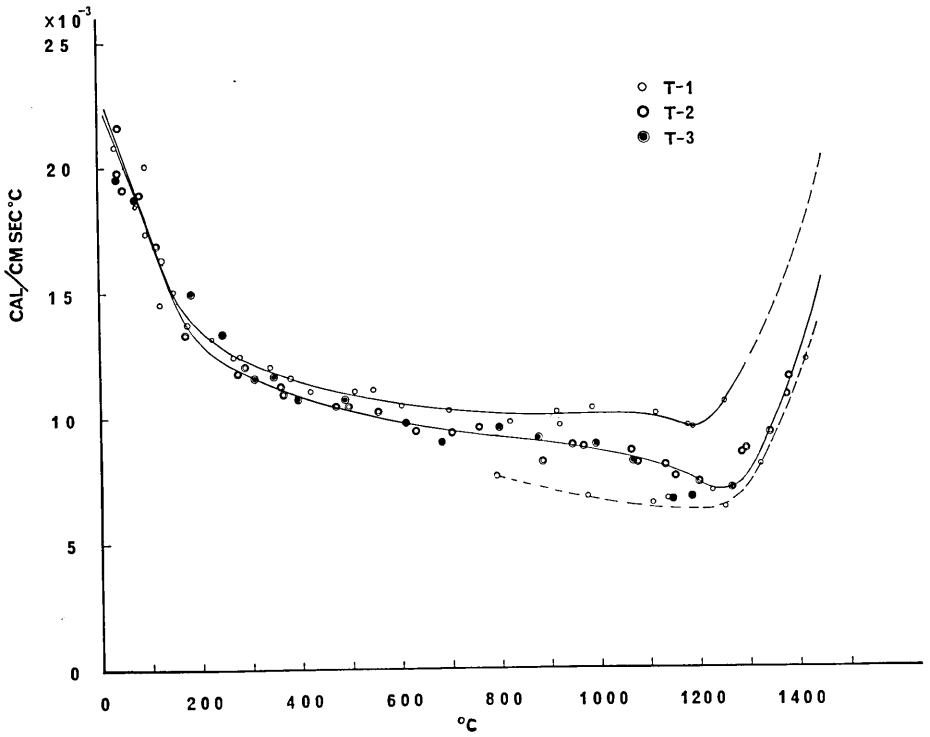

Fig. 4. Thermal conductivity of Twin Sisters Mountain hurz burgite.

author's knowledge, this phenomenon has not been found previously. The variations in the present experiment are completely reversible over the α- to β-quartz transition. As seen in the previous section, in the present work, the amount of heat flow in the radial direction is assumed to be axially symmetrical. Whether or not this assumption holds in the anisotropic substance such as crystalline quartz is not obvious. This problem will be discussed in a forthcoming paper.

Thermal conductivity of β-quartz makes an almost linear change. There is no abrupt change or inversion phenomenon at β-quartz—tridymite transition.

Thermal conductivities of three hurz burgites from Tiwn Sisters Mountains are shown in Fig. 4 and Table 2. Actual measurement was carried out very slowly from the room temperature to about 900°*C*, and then the temperature was gradually lowered from about 900°*C* to the room temperature. Then the temperature was again raised from the room temperature to about 1250°*C*. Reproducibility of the measurement is very good in the range from the room temperature to 900°*C*. When the temperature approached to 1180°*C*, the thermal conductivity of *T*-1 fell. After that, the conductivity seemed to give an indication to increase with the increasing temperature. Unfortunately, however, the heater in the specimen cut at 1350°*C* after the measurement at 1250°*C*. Then the temperature was lowered very slowly to the room temperature. With a new heater in, the same specimen *T*-1 was remeasured from the room temperature to about 1400°*C*. The conductivity was about 30% lower than in the first heating at about 100°*C*. This was perhaps due to the formation of cracks and pores, or some other alterations of the specimen. However, when we continued the measurement, the conductivity began to increase from 1250°*C* as shown by the dotted line in Fig. 4. The specimen *T*-2 had the same dimension as the specimen *T*-1. Method of measurement of the specimen *T*-2 was entirely the same as in the case of *T*-1, except that the process of evacuation and filling with argon gas was applied only once in the cace of *T*-2. The specimen after the experiment showed some indication of oxidation. In order to investigate the influence of the dimension on the thermal conductivity, specimen *T*-3 was made 1 cm shorter than specimen *T*-1, while the diameter was kept the same. Results of specimen *T*-3 are entirely similar to those of *T*-2 (see Fig. 4). It is seen that difference of this order in the dimension does not seriously influence the measured value of conductivity. It is almost certain that the thermal conductivity decreases always by a few to ten percent to approach a minimum value at about

1200—1250°*C*.

Thermal conductivities of two lherzolites from Ichinomegata are shown in Table 3 and Fig. 5. The dimension of the specimen and experimental conditions are the same as specimen *T*-1. Thermal conductivity of specimen *I*-1 was about 50% lower than that of specimen *T*-1, *T*-2 and *T*-3 at the room temperature. The anomaly of thermal conductivity was found at about 170°*C*; the conductivity of specimen *I*-1 decreases linearly

Table 3. Thermal conductivity of Ichinomegata lherzolite.

Specimen *I*-1			Specimen *I*-2		
Temperature °*C*.	Conductivity *cal/sec. cm. °C*.	Resistivity	Temperature °*C*.	Conductivity *cal/sec. cm. °C*.	Resistivity
34	9.03×10^{-3}	110.7	38	7.95×10^{-3}	125.8
69	8.35	119.8	72	7.18	139.3
105	7.51	133.2	104	6.76	147.9
148	6.84	146.2	105	6.72	148.8
155	6.89	145.1	118	6.84	146.2
164	7.10	140.0	145	6.21	161.0
176	9.03	110.7	149	5.66	176.7
181	9.06	110.4	169	5.49	182.1
184	8.94	111.9	179	7.86	127.2
185	8.76	114.2	180	6.36	157.2
193	9.06	110.4	182	8.08	123.8
242	8.25	121.2	194	7.55	132.5
294	7.65	130.7	201	8.09	123.6
356	7.47	133.9	207	7.79	128.4
407	7.34	136.2	235	7.38	135.5
454	7.43	134.6	238	7.44	134.4
547	7.36	135.9	272	7.78	128.5
638	7.14	140.1	349	7.54	132.6
734	6.63	150.8	388	7.32	136.6
825	6.49	154.1	466	7.46	134.0
912	6.55	152.7			
991	6.45	155.0			
1087	6.27	159.5			
1157	7.05	141.8			
1189	7.30	137.0			
1240	10.49	95.3			

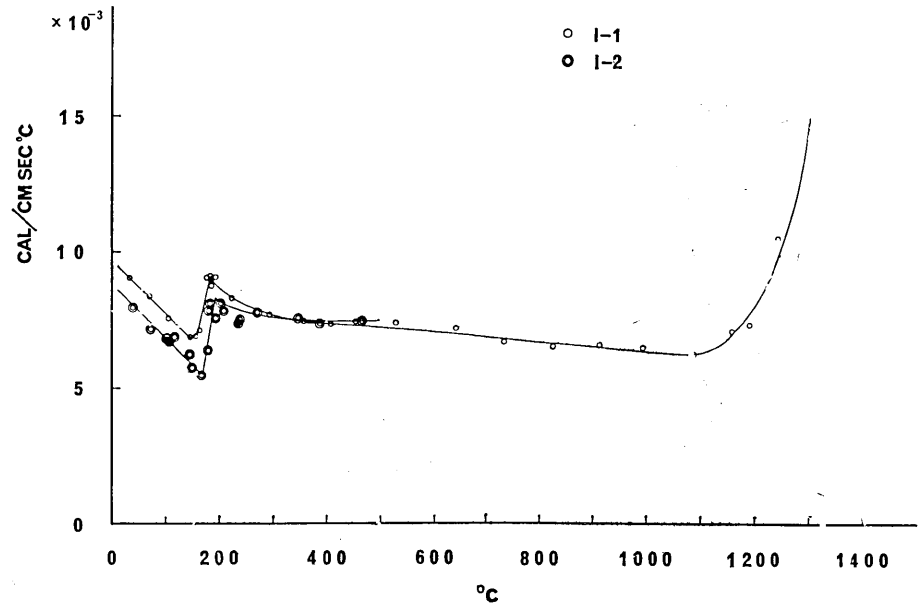

Fig. 5. Thermal conductivity of Ichinomegata lherzolite.

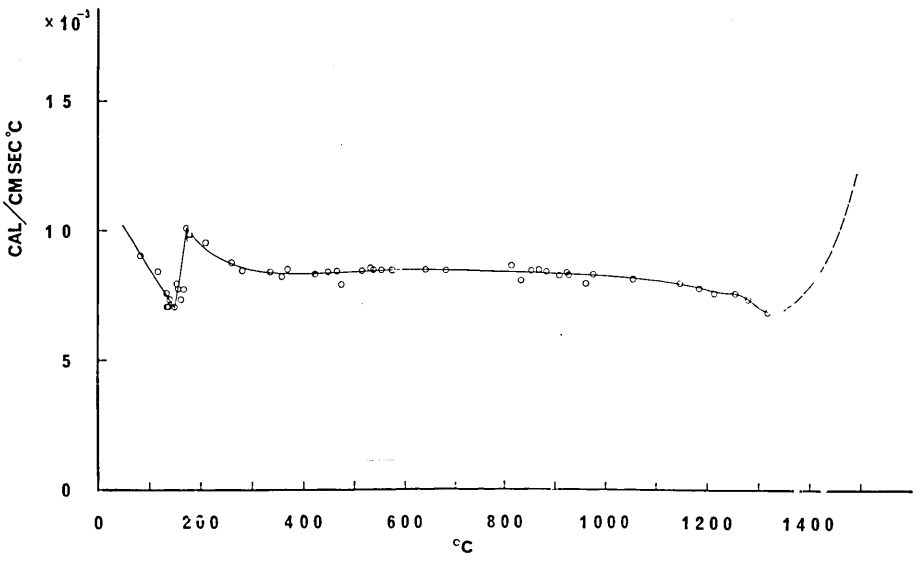

Fig. 6. Thermal conductivity of Karatsu dunite.

from the room temperature to 170°*C*, and increases abruptly at 170°*C*. After this abrupt change, thermal conductivity makes normal variation with the rise in temperature. A pronounced rise of the conductivity above 1200°*C* was observed for this specimen also. The specimen *I*-2 was used in order to confirm the anomalous change of thermal conductivity around 170°*C*. The results were found to be the same as specimen *I*-1. It is to be noted that this anomalous behaviour was observed in the cooling process from about 500°*C* also: this indicates that the phenomenon is not related to such processes as dehydration.

Thermal conductivity of one dunite sampled at Karatsu is shown in Fig. 6 and Table 4. This specimen *K*-1 showed the thermal variation of

Table 4. Thermal conductivity of Karatsu dunite.

Temperature °*C*.	Conductivity *cal/sec. cm. °C.*	Resistivity	Temperature °*C*.	Conductivity *cal/sec. cm. °C.*	Resistivity
82	9.01×10^{-3}	111.0	474	7.91×10^{-3}	126.4
115	8.90	119.0	514	8.50	117.6
133	7.59	131.8	530	8.61	116.1
136	7.06	141.6	536	8.52	117.5
138	7.38	135.5	552	8.54	117.1
149	7.06	141.6	573	8.54	117.1
154	7.95	125.8	679	8.54	117.1
156	7.74	129.2	810	8.76	114.2
163	7.34	136.2	829	8.18	122.2
164	7.06	141.6	850	8.57	116.7
167	7.71	129.7	864	8.60	116.3
173	10.08	99.2	880	8.51	117.5
177	9.88	101.2	906	8.35	119.8
179	9.66	103.5	919	8.49	117.8
188	9.88	101.2	924	8.42	118.8
209	9.55	104.7	957	8.09	123.6
259	8.77	114.7	971	8.42	118.8
281	8.48	117.9	1051	8.28	120.8
334	8.44	118.5	1141	8.14	122.9
356	8.22	121.7	1181	7.97	125,5
368	8.51	117.5	1208	7.76	128.9
421	8.34	119.9	1250	7.74	129.2
447	8.43	118.6	1276	7.57	132.1
465	8.44	118.5	1310	7.05	141.8

the thermal conductivity entirely equivalent to that of the specimen *I*-1 and *I*-2: *i.e.* the anomalous behaviour below 170°*C* being found for this specimen also. Specimen *K*-1 also showed a good reproducibility in the temperature range from the room temperature to about 900°*C*. The conductivity began to decrease at 1280°*C*, and it seemed as if it was to approach to a minimum. However, such a behavior could not be confirmed, because the specimen started to melt. If an analogy is allowed from *T*-1, *T*-2 and *I*-1, the thermal conductivity at temperatures higher than 1310°*C* would have changed as a dotted line, if no melting took place.

Thermal conductivities of two lherzolites sampled at Horoman are shown in Fig. 7 and Table 5. These specimens revealed completely different temperature variations of thermal conductivity in comparison with the specimen described so far. Thermal conductivity of specimen *H*-1 increased with increasing temperatures from 100°*C* to 840°*C*. The conductivity

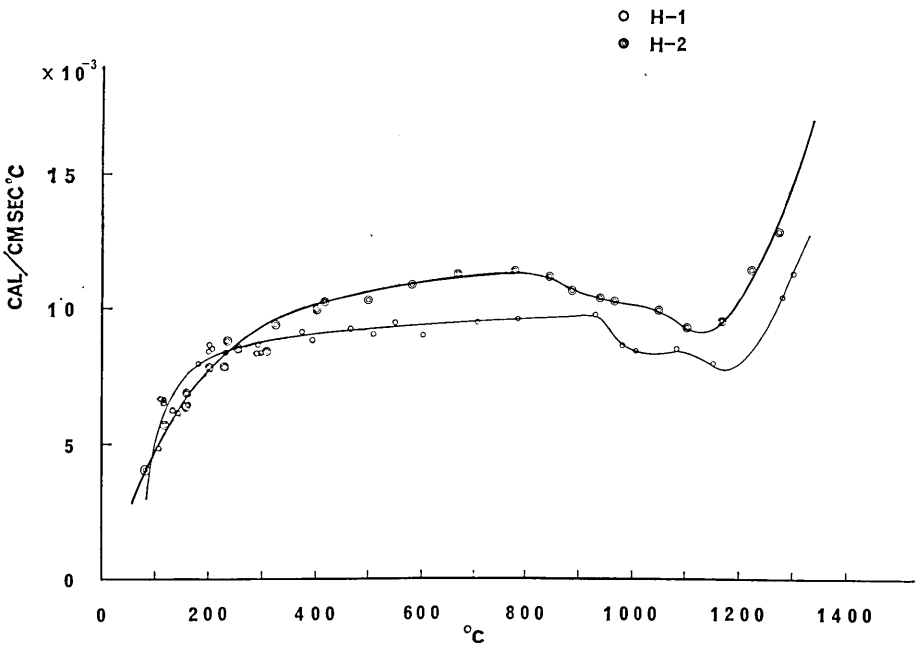

Fig. 7. Thermal conductivity of Horoman lherzolite.

Table 5. Thermal conductivity of Horoman lherzolite.

Specimen *H*-1			Specimen *H*-2		
Temperature °*C.*	Conductivity *cal/sec. cm. °C.*	Resistivity	Temperature °*C.*	Conductivity *cal/sec. cm. °C.*	Resistivity
108	4.88×10^{-3}	204.9	84	4.04×10^{-3}	247.5
112	4.69	213.2	114	5.70	175.4
118	6.55	152.7	161	6.83	146.4
121	6.51	153.6	202	7.83	127.7
122	6.66	150.2	230	7.89	126.7
134	6.22	160.8	236	8.82	113.4
143	6.15	162.6	256	8.55	117.0
163	6.41	156.0	309	8.04	119.0
181	7.99	125.2	326	9.41	106.3
201	8.45	118.3	403	9.96	100.4
204	8.63	115.9	418	10.29	97.2
208	8.55	117.0	500	10.32	96.9
234	8.35	119.8	580	10.91	91.7
293	8.67	115.3	667	11.31	88.4
293	8.32	120.2	778	11.48	87.1
297	8.31	120.3	844	11.29	88.6
375	9.16	109.2	885	10.76	92.9
394	8.84	113.1	937	10.50	95.2
466	9.27	107.9	963	10.31	97.0
508	9.06	110.4	1046	10.07	99.3
602	9.06	110.4	1100	9.41	106.3
704	9.49	105.4	1165	9.62	104.0
784	9.69	103.2	1219	11.55	86.6
928	9.89	101.1	1270	12.95	77.2
979	8.71	114.8			
1005	8.57	116.7			
1080	8.61	116.1			
1150	8.08	123.8			
1275	10.53	95.0			
1296	11.41	87.6			

then decreased by about 20% to approach a mininum value. After that, conductivity started to increase suddenly with the temperature just as other specimens did. Initial increase of the conductivity is a phenomenon peculiar to the Horoman specimen.

V. Conclusions

The thermal conduction in such amorphous substance, as fused silica, follows quite a different law from the usual phonon conduction law, that is, the thermal conductivity of fused silica increases with increasing temperature.

The thermal conductivity of α-quartz decreases with temperature. At the transition point between α- and β-quartz, the thermal conductivities make abrupt changes. Thermal conductivity in the direction of the C-axis is higher than that in the direction of the X-axis in α-quartz, but in β-quartz the conductivity in the direction of the C-axis is lower than that in the direction of the X-axis.

Thermal conductivity of β-quartz varies almost linearly with temperature. At β-quartz--tridymite transition, there is no abrupt change or inversion phenomenon. Thermal conductivity of tridymite increases with increasing temperature.

Thermal conductivities of all the specimen used in the present experiment, except Karatsu dunite, increase with the temperature above 1100°C —1200°C, This phenomenon may be the radiative or the excitonic effect as pointed out by Clark, Lubimova and Lawson and Jamieson.

Thermal conductivity of all specimens decreases from a small amount to 20% approaching to a minimum value at 1100°C—1300°C, before the above-mentioned sharp increase starts.

The behaviour of thermal conductivity of ultrabasic rocks at temperatures below 1000°C is very complicated. In investigating the behaviour of the phonon part, it is convenient to construct a plot of the reciprocal of the thermal conductivity (thermal resistivity) versus temperature. Such plots for specimens are shown in Figs. 8, 9 and 10. In figures, it is fairly difficult to show these results by one straight line.

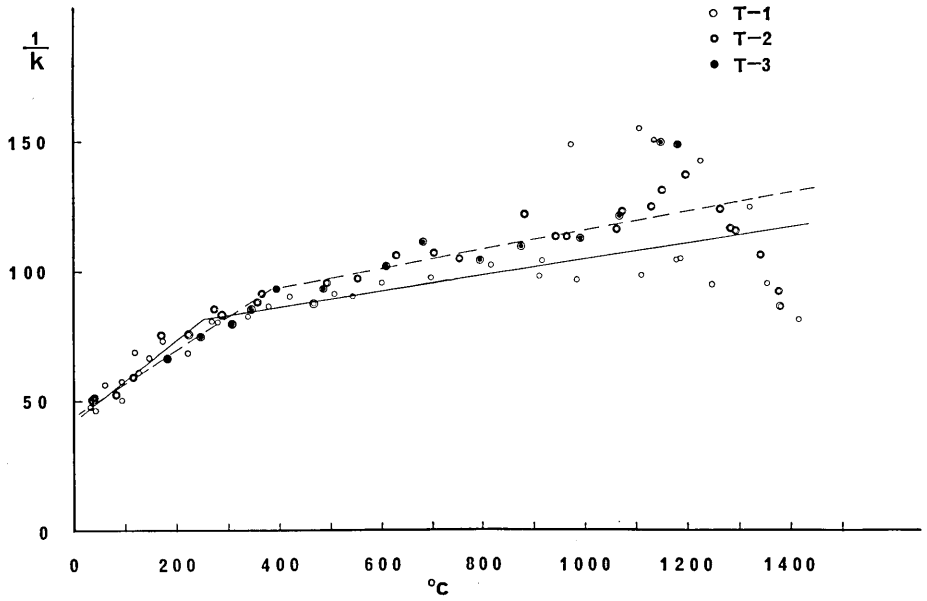

Fig. 8. Reciprocal of the thermal conductivity of Twin Sisters Mountain hurz burgite.

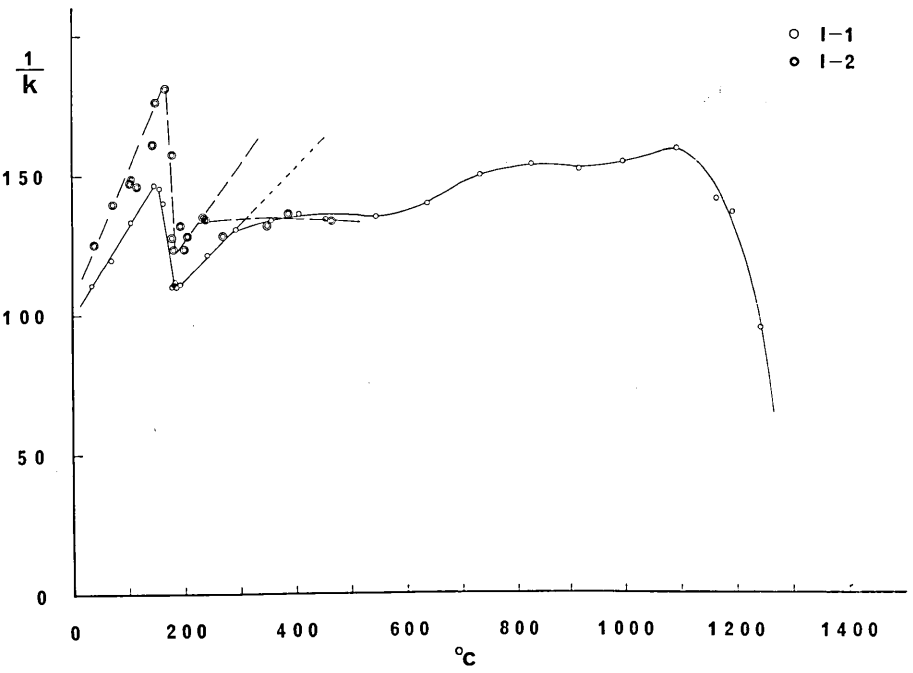

Fig. 9. Reciprocal of the thermal conductivity of Ichinomegata lherzolite.

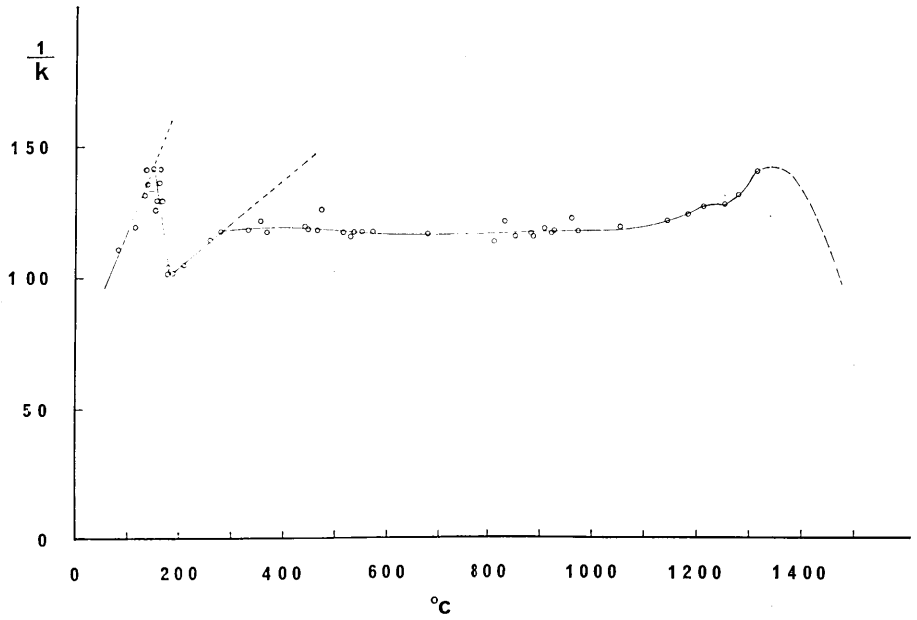

Fig. 10. Reciprocal of the thermal conductivity of Karatsu dunite.

The anomaly of thermal conductivity was found at about 170°C for Ichinomegata and Kartsu samples. Specimen from Horoman revealed completely different temperature variations of thermal conductivity. To ascertain such anomalous behaviour, thermal conductivities of Ichinomegata, Karatsu and Horoman will be remeasured also by the divided bar method.

The measurements of thermal diffusivity ($\kappa = K/c\rho$) of rock-forming minerals and rocks have been carried out by H. Kanamori, N. Fujii and H. Mizutani[13] independent of the present study of the thermal conductivity. Their experiments have been made in the temperature range from about 100°C to 800°C. According to their results, the thermal diffusivity of olivine starts to deviate from the $1/T$-relation significantly at about 500°C, whereas our experiments on hurz burgite do not show such deviations below 1100°C. At present it is hard to conclude whether the discrepancy is real due perhaps to the differences in the nature of specimens used, or only apparent due to experimental procedures.

13) H. KANAMORI, N. FUJII and H. MIZUTANI, in press A.G.U.

Fused silica and crystalline quartz are the specimens common to both studies. Their results on fused silica and crystalline quartz agree with our data below about 500°*C*, but above 500°*C* the values of Kanamori et al., are much higher than those of the author's. That is, the radiative or the excitonic effect seems to begin to appear in the temperature above 500°*C*. Inversion phenomenon between α- and β-quartz (at 573°*C*) was not in their experiment.

Intensive investigation on the possible cause of these disagreements is now underway.

Acknowledgment

The author would like to express his thanks to Prof. T. Rikitake and Dr. S. Uyeda by whose constant advice, discussion and encouragement the present study has been made. Thanks are extended to Prof. H. Kuno for his kind offering of samples and investigation of rocks under microscope.

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53. 地球熱学 第17報
岩石の熱伝導率の温度変化 その 2

地震研究所 川 田 薫

溶融石英，石英，かんらん岩，オリビンノジュール，ダンかんらん岩の熱伝導率を Kingery の方法を改良して室温から約 1400°C の温度範囲で測定した．

溶融石英の熱伝導率は温度上昇と共に一様に増加する．

α-石英の熱伝導率は温度上昇と共に一様に減少し，C 軸の方向の熱伝導率は X 軸の方向の値より高いが，α-石英と β-石英の転移点 (573°C) において逆転し，X 軸の方向の値が C 軸の方向の値より高くなる。この β-石英の熱伝導率は温度上昇と共に程んど直線的に増加する．β-石英と鱗珪石の転移点 (870°C) においては，α-石英と β-石英の転移点におけるような逆転は起らず，鱗珪石の熱伝導率は温度上昇と共に急激に増加する．

Twin Sisters のかんらん岩，幌満のかんらん岩，一の目潟のオリビンノジュールの熱伝導率は約1200°C 位から温度上昇と共に急激に増加する．これは Clark, Lubimova, Lawson, Jamieson 等が指摘していた輻射伝導又はエキサイトン伝導のためと思われる．今回の実験に使用したすべての岩石の熱伝導率は 1100°C から 1300°C で最小値を持つが，この最小値に近ずくと熱伝導率は数%から 20% 減少する．1000°C 以下の温度範囲における岩石の熱伝導率はかなり複雑な温度変化を示す．Twin Sisters のかんらん岩においては温度上昇と共に熱伝導率は減少するが，phonon 伝導から期待される一本の直線 (熱抵抗と温度の関係を示す直線) では近似できない．唐津のダンかんらん岩と一の目潟のオリビンノジュール，幌満のかんらん岩にいたっては，さらにこの近似は困難である．唐津のダンかんらん岩と一の目潟のオリビンノジュールは 170°C 附近に熱伝導率の異常がみいだされた．すなわち，室温から 150°C 位までは温度上昇と共に熱伝導率は直線的に減少し，170°C 附近ではこれが急激に上昇する．さらに幌満のかんらん岩は温度上昇と共に熱伝導率は増加する．

今回の実験では予想もしていなかった種々の現象が現われたために，これらの結果をそのまま地球内部に応用することはできないので今後さらに多くの試料について測定を行う必要がある．