

EFFECTS OF PRESSURE AND WATER ON THE MELTING OF BASALT

By

Mitsuhiko SHIMADA

(Received November 2, 1966)

Abstract

Melting of natural olivine basalt was measured at pressures up to 35 kilobars by using the differential thermal analysis as well as the quenching method.

Melting relations of basalt were classified into four cases according to the water contents in the samples: those were (1) the total pressure was equal to the water pressure, (2) 1.60 wt% of water was contained in the samples, (3) 0.98 wt% of water was in the samples, and (4) no water in the samples.

Melting temperatures are found to be the highest in the case (4) and the lowest in case (1). In the case (4) the melting temperatures increase with pressure but in the case (1) decrease with pressure, and the cases (2) and (3) correspond to the melting relations when the water pressures are less than the total pressures.

These melting relations were compared with the temperature distribution in the upper mantle. The results suggest the existence of the molten zone in the upper mantle, assuming the presence of basaltic composition and water (even to the extent of water of crystallization).

1. Introduction

The nature of the earth's upper mantle has been discussed by many authors. On the nature of the Mohorovičić discontinuity (Moho), especially since Lovering [1958] revived the basalt-eclogite transition hypothesis, there have appeared many discussions on the two opposite hypotheses: (1) Moho is caused by the change of chemical composition and (2) by the phase change. Recently a compromise seems to be accepted: the continental Moho is caused by the phase change and the oceanic one by change of chemical composition (Stishov [1963], Wyllie [1963]).

Ringwood [1962a, 1962b] and Clark and Ringwood [1964] proposed a model of the upper mantle which consisted of the mixture of one part of basalt and four parts of dunite, called "pyrolyte".

Anyhow, it is likely that basaltic composition is present in the upper mantle. Accordingly, the experimental investigations of the basaltic composition have

the important geophysical and petrological implications.

The melting temperatures of most solids increase with pressure. But it is well known that in the presence of volatile materials like water, the melting temperatures of silicate systems decrease with pressure. Such cases on natural minerals and rocks have been shown by many authors using the hydrothermal experiments (e. g. Yoder and Tilley [1962], Luth *et al.* [1964], Khitarov [1964]).

Though the presence of water in the upper mantle is not clear, there is no reason for believing that water (in any state) does not exist at all in the upper mantle. In the present work, the change of melting temperature of natural basalt with varying water contents was measured at high pressures up to 35 kilobars, and compared with the temperature distributions of the upper mantle.

2. Experimental procedures

The high pressure chamber used for this study was a single-stage piston-cylinder apparatus. Melting was detected by means of differential thermal analysis (DTA) as well as quenching method. Temperatures were measured with Pt/Pt-Rh 13 % thermocouples. The experimental apparatus and method were previously described in detail (Shimada [1966]).

Recently, Green *et al.* [1966] measured with an excellent way the friction in a piston-cylinder apparatus at high pressures and temperatures. They stated that after applying a -10 % pressure correction to a compression run at pressure greater than 15 Kb an accuracy of $\pm 3\%$ can be expected. In our experience, the pressure rise from heating and an outward piston movement were observed at the same time at pressures. Thus this pressure rise is considered to compensate for the in-stroke piston friction, but it may not compensate for their "reversible" friction. In this article, data were plotted on a load pressure diagram without friction correction.

Yakuno olivine basalt was used as the starting material for each run. This is a typical olivine basalt which is composed of olivine, augite, plagioclase and small amount of magnetite. About 50 to 70 mg of powdered rock samples were used. Four kinds of samples were prepared, which were classified according to the water contents in the rock samples as follows :

- 1) Undried samples—The powdered rock samples and the pressure transmitting medium were used without drying. The samples were not sealed within the platinum tubes, so that the volatile could run away. Thus the runs are considered to be carried out in the open system as to water at pressures. It was assumed that the samples contained enough water for the total pressure to be equal to the water pressure at least in the range of pressures up to 20 Kb, in comparison with Yoder and Tilley [1962]'s results of hydrothermal ex-

Table 1. Results of runs on melting of natural olivine basalt not sealed within platinum tubes

Pressure, Kb	Temperature, °C	Time, hr	Products
0*	1260±5	1	melt
0*	1243	1	melt
0*	1233	1	melt+crystal
0*	1208	1	melt+crystal
3.1±0.3	1218±15	3/4	glass
3.1	1148±5	1	glass
3.1	1103±10	1	glass+crystal (no pl.)
3.2	998±5	1	crystal
7.6	1146±10	1	glass
7.6	1050±5	1	glass
7.9	1000	1	glass+crystal (only ol.)
7.6	948	1	crystal
11.4	1094	1	glass
11.5	1049	1 <td glass+crystal (no pl.)	
11.5	998	1	glass+crystal
14.6	1029	1	glass+crystal
15.3	1030±25	6	glass
17.8	981±5	1/2	glass (little)+crystal

* Samples were heated in crucibles at atmospheric pressure.

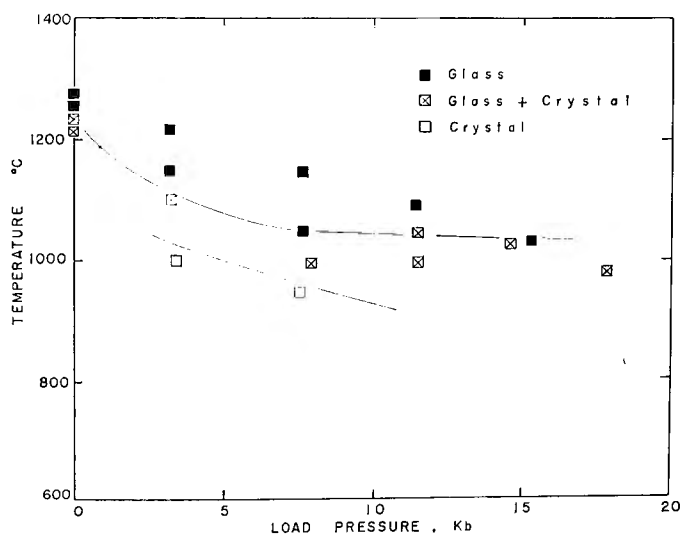


Fig. 1. Effects of pressure on the melting relations of natural olivine basalt determined by quenching method when total pressure is equal to water pressure.

periments on natural tholeiite.

2) Samples with 1.60 wt% of water—These samples contain 0.62 wt% of adsorbed water and 0.98 wt% of water of crystallization.

3) Samples with 0.98 wt% of water—These samples were dried at 100~110°C for 24 hours. Thus they contain no adsorbed water and are considered to contain only water of crystallization.

4) Dried samples—Powdered samples were dried at 100~110°C overnight and further dried at 800°C for an hour or more. Thus these samples are considered to contain no water.

Table 2. Results of runs of melting of natural olivine basalt sealed within platinum tubes

Pressure, Kb	Temperature, °C	Time, hr	Products
1.60 wt% of water			
11.2±0.3	1047±5	1/2	glass+crystal
16.2	1150	1/2	glass (+trace ol.)
16.2	1002±8	1	glass (little)+crystal
24.0	1150±5	1/2	glass+crystal (no pl.)
26.3	1000	1	crystal (+trace glass)
29.9	1200	1/2	glass+crystal (no pl.)
0.98 wt% of water			
12.2±0.3	1200±5	1/2	glass
11.5	1150	1/2	glass+crystal (no pl.)
11.6	1100	1/2	glass+crystal (no pl.)
11.5	1048±8	1	glass (little)+crystal
17.6	1200±5	1/2	glass
20.0	1000±6	3	crystal
23.5	1200±5	1/2	glass+crystal (no pl.)
25.8	1047	1/2	crystal
Dry			
10.8±0.3	1251±6	1/2	glass (+trace ol.)
9.7	1100±8	1	glass+crystal
16.4	1257	1/2	glass
16.4	1202±5	1/2	glass+crystal (no pl.)
16.2	1105±8	1/2	glass (little)+crystal
15.7	1050±5	1/2	crystal
24.0	1330	1/2	glass
24.2	1251±7	1/6	glass+crystal (no pl., bearing gr.?)
23.5	1186	1/2	glass+crystal (bearing gr.?)
30.8	1365±6	1/2	glass (+trace ol.)
33.0	1329±5	1/2	glass+crystal (no pl., bearing gr.?)

In the last three cases, samples were sealed within platinum tubes (in the cases 3 and 4, immediately after drying) and the pressure transmitting medium were also preliminarily dried.

3. Melting relations of basalt

(1) Total pressure=water pressure. In this case, melting relation was determined by the quenching method. The quenched samples were examined optically. The results are shown in Table 1 and Fig. 1. As mentioned above, the shape of the melting curve coincides well with that of the results of hydrothermal experiments on natural tholeiite described by Yoder and Tilley (1962).

(2) 1.60 wt% of water in the samples. The results of quenched samples are shown in Table 2. Beginning and completion temperatures of the melting determined by DTA are illustrated in Fig. 2 by circles and the results of the quenched samples by squares. The melting relations determined by two different methods are found to be well consistent with each other. Liquidus curve when total pressure is equal to water pressure (Fig. 1) is also illustrated in Fig. 2.

Yoder and Tilley (1962) also discussed melting relations with water pressure less than total pressure. Fig. 3 illustrates their schematical curves of the solid-liquid equilibrium for olivine tholeiite-water system when the water pressure is fixed at values less than the total pressure.

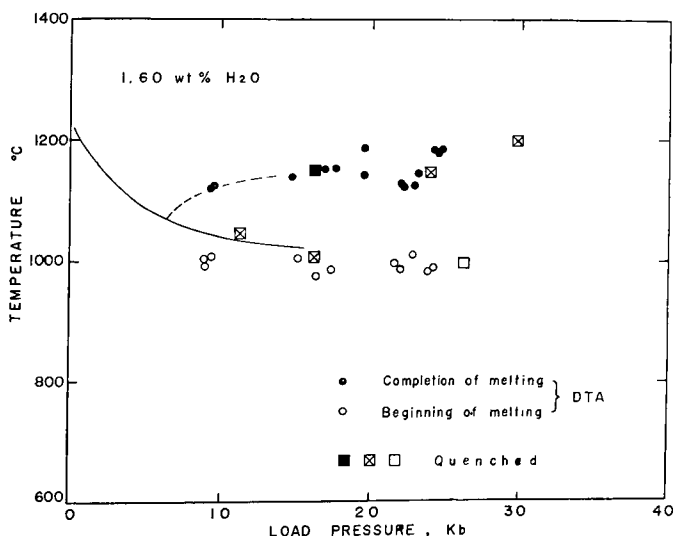


Fig. 2. Effects of pressure on the melting relations of natural olivine basalt including 1.60 wt% of water. Circles illustrate the results by DTA, and squares by quenching method. Solid line illustrates liquidus curve when total pressure is water pressure.

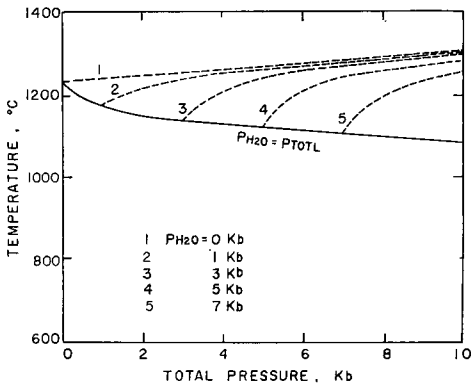


Fig. 3 Silicate liquidus curve in natural olivine tholeiite water system when water pressure is total pressure. Dashed lines illustrate schematically the new equilibrium curves effected when the water pressure is fixed at values less than the total pressure (after Yoder and Tilley [1962]).

quenched samples are given in Table 2. The water pressure in this case is estimated about 5 Kb.

(4) No water in the samples. Melting relations are shown in Fig. 5. The results of quenched samples are given in Table 2. This results of the "dry"

It is clearly seen that Fig. 2 gives the situation when the water pressure is fixed at a certain value less than the total pressure. Then if the liquidus curve is drawn until it reaches the "total pressure = water pressure" liquidus curve (dashed line in Fig. 2), the pressure of intersection point gives the water pressure inherent in the water containing samples. The "1.60 wt% of water" sample is found to give about 7 Kb of water pressure.

(3) 0.98 wt% of water in the samples. Melting relations are shown in Fig. 4. The results of

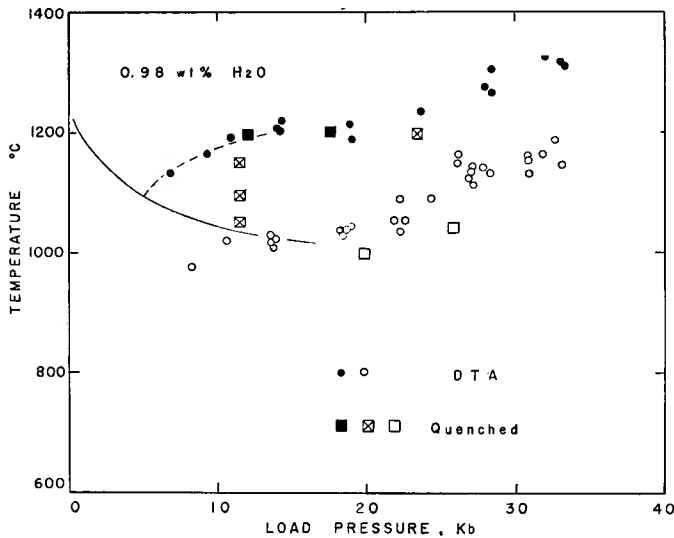


Fig. 4. Melting relations of "0.98 wt% of water" samples. Solid line illustrates liquidus curve when total pressure is water pressure.

samples should be consistent with the results of the zero pressure runs because those runs ought to be carried out in dry states (Table 1). They are also plotted in Fig. 5.

In Fig. 5, the relations of transition between basalt and eclogite and the melting relations of them after Yoder and Tilley [1962] are illustrated by dashed lines. The experimental basalt-eclogite transition interval after Ringwood and Green [1964] are also illustrated by an arrow. According to Yoder and Tilley's, the effect of the transition on the melting relations is characterized by the change of the gradient of melting curve and the change of melting

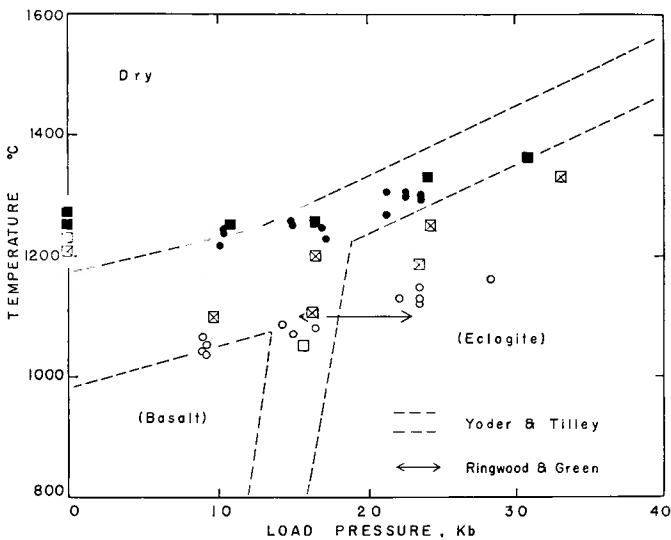


Fig. 5. Melting relations of "dry" samples. Dashed lines illustrate the relations of transition between basalt and eclogite and of melting of them after Yoder and Tilley [1962]. The arrow illustrates the experimental basalt-eclogite transition interval after Ringwood and Green [1964].

interval. In the present work, no change of melting interval was found. In a few quenched samples garnet phases seemed to appear (Table 2), which are uncertain (the detailed examinations of quenched samples are now undergone). The change of the gradient is seen at about 18 Kb (Fig. 5). In the cases 2 (Fig. 2) and 3 (Fig. 4), such changes are also seen at about 21 and 23 Kb, respectively. From this, it follows that Figs. 2, 4 and 5 (cf. Fig. 6) also shows the effect of water on the basalt-eclogite transition if the changes of the gradients are surely caused by the transition.

4. Geophysical discussions

The results above mentioned are summarized in Fig. 6. In order to apply

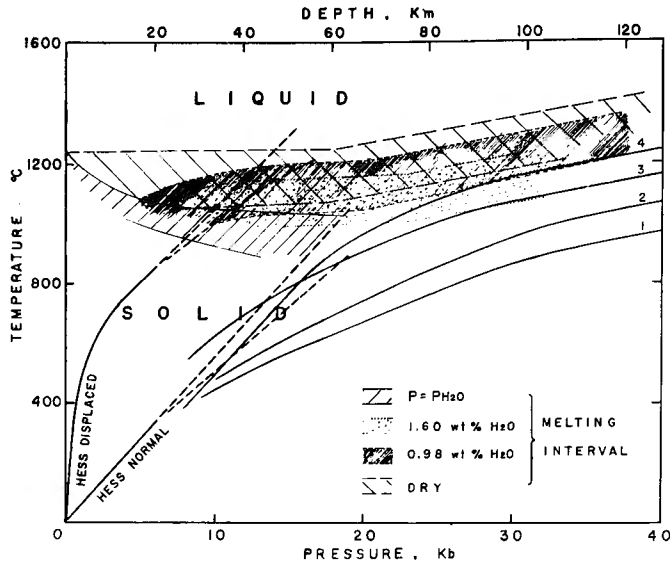


Fig. 6. Effects of pressure and water on the melting relations of natural olivine basalt. The temperature distributions after Clark and Ringwood [1964] are shown (1: P. C. shield; 2 and 3: continental upper mantle; 4: oceanic upper mantle). Hess' normal and displaced gradients are also shown (from Nicholls [1965]).

these results to the earth's upper mantle, we must refer to the temperature distribution of the upper mantle. There is no accepted distribution, but various distributions published by many authors have a similar tendency except ones of special locality. Clark and Ringwood [1964]'s and Hess' (Nicholls [1965]) distributions are shown in Fig. 6. According to Nicholls [1965] in high heat flow regions like the mid-ocean ridge areas thermal gradient probably closes to "Hess displaced gradient".

Fig. 6 shows that the melting curves intersect the geotherms. As mentioned above, the presence of water in the upper mantle is not clear. Assuming the presence of water to the extent of 1 to 2 percents, however, it is suggested that the molten (or partly molten) zone starts from 80~100 km depth and at some greater depth the molten zone disappear. Heretofore there have been many discussions on the molten zone in the upper mantle in connection with the low velocity layer (e.g. Subbotin *et al.*, [1965]).

Murase and Suzuki [1966] succeeded in the measurement of ultrasonic velocities of molten rocks. Their results show that longitudinal velocity decreases almost linearly in the melting interval as temperature increases. Thus only if the geotherm traverses the lower part of the melting interval, a low velocity layer will be formed.

In the oceanic region temperature gradient is greater than in the continental one. The low velocity layer caused by the presence of molten zone would be in wider range of depth in the oceanic region, which has been deduced from seismic observations.

In the high heat flow region, assuming the "Hess displaced gradient", the presence of enough water will have basalt begin to melt at about 900°C in the pressure ranges corresponding to the lower crust. The effect of water on melting may also explain the behaviour of magma and the mechanism of volcanic activities.

Acknowledgment

The author is indebted to Prof. H. Miki and Dr. S. Matsushima of Kyoto University for their valuable advices and encouragements.

References

- Clark, S. P. and A. E. Ringwood, 1964; Density distribution and constitution of the mantle, *Rev. Geophys.*, 2, 35-88.
- Green, H. G., A. E. Ringwood and A. Major, 1966; Friction effects and pressure calibration in a piston-cylinder apparatus at high pressure and temperature, *J. Geophys. Res.*, 71, 3589-3594.
- Khitrov, N. I., 1964; Questions dealing with concepts of the transition zone of the upper mantle to the Earth's crust, as indicated by some experimental data, *Tectonophys.*, 1, 175-178.
- Lovering, J. F., 1958; The nature of the Mohorovicic discontinuity, *Trans. Amer. Geophys. Union*, 39, 947-955.
- Luth, W. C., R. H. Jahns and O. F. Tuttle, 1964; The granite system at pressures of 4 to 10 kilobars, *J. Geophys. Res.*, 69, 759-773.
- Murase, T. and T. Suzuki, 1966; Ultrasonic velocity of longitudinal waves in molten rocks, *J. Fac. Sci. Hokkaido Univ.*, Ser. VII, 2, 273-285.
- Nicholls, G. D., 1965; Petrological and geochemical evidence for convection in the Earth's mantle. A Symposium on Continental Drift (ed. Blackett, P. M. S. *et al.*), Royal Society, London, 168-179.
- Ringwood, A. E., 1962a; A model for the upper mantle, *J. Geophys. Res.*, 67, 857-867.
- Ringwood, A. E., 1962b; A model for the upper mantle 2, *J. Geophys. Res.*, 67, 4473-4477.
- Ringwood, A. E. and D. H. Green, 1964; Experimental investigations bearing on the nature of the Mohorovičić discontinuity, *Nature*, 201, 566-567.
- Shimada, M., 1966; Melting of basalt at high pressures, *ZISIN (J. Seis. Soc. Japan)*, Ser. II, 19, 167-175.
- Stishov, S. M., 1963; The nature of the Mohorovičić discontinuity, *Izv. Geophys. Ser.*, No. 1, 42-48 (Engl. transl., 28-31).
- Subbotin, S. I., G. L. Naumchik and I. Sh. Rakimova, 1965; Structure of the Earth's crust and upper mantle, *Tectonophys.*, 2, 111-150.
- Wyllie, P. J., 1963; The nature of the Mohorovicic discontinuity, a compromise, *J. Geophys. Res.*, 68, 4611-4619.
- Yoder, H. S. and C. E. Tilley, 1962; Origin of basalt magma: An experimental study of natural and synthetic rock system, *J. Petr.*, 3, 342-532.