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# Ultrasonic Velocity of Longitudinal Waves in Molten Rocks

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**Abstract**

Ultrasonic velocity of longitudinal waves in *molten rocks* has been measured by the method of ultrasonic impulse transmission technique. The values obtained of the wave-velocity lie between 2–3 km/sec. The geophysical significance of these results is discussed.

## 1. Introduction

On the question of the existence of molten parts in the earth's crust and upper mantle, many papers have been published in volcanology and seismology. Reasoning about the molten parts required a knowledge of the way in which the physical properties, especially seismological properties, of molten rocks vary under combined high temperature and high pressure because the direct evidence of the existence of molten parts is expected to be due to seismology.

Although some physical properties at high temperature and high pressure have been widely explored for rocks, little experimental work has been performed on molten rocks except viscosity and electrical conductivity[1),2)].

Ultrasonic velocity of longitudinal wave has been measured for the liquid $LiO_2$-$SiO_2$ system over the composition range 24–55% $LiO_2$ at 1150° to 1300°C by Bloom and Bockris[3)] and for the molten alkali (30%) silicate at 600° to 900°C by Kumazawa et al[4)]. So far as the authors are aware, no investigator has yet succeed in the measurement of *molten rocks*. Ultrasonic impulse transmission technique for measuring longitudinal velocities has been adapted in the temperature range from ca. 800° to 1400°C.

The results of measurements made on six different rocks and one glass are reported, in the hope that some light may be cast on volcanological and seismological problems.

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## 2. Method

Ultrasonic velocity measurements were made by time-distance relations. The experimental arrangement and cell are shown schematically in Figs. 1 and 2. Propagation of the longitudinal waves into and out of the molten rock at temperature up to ca. 1400°C was by means of vitreous silica rods to which

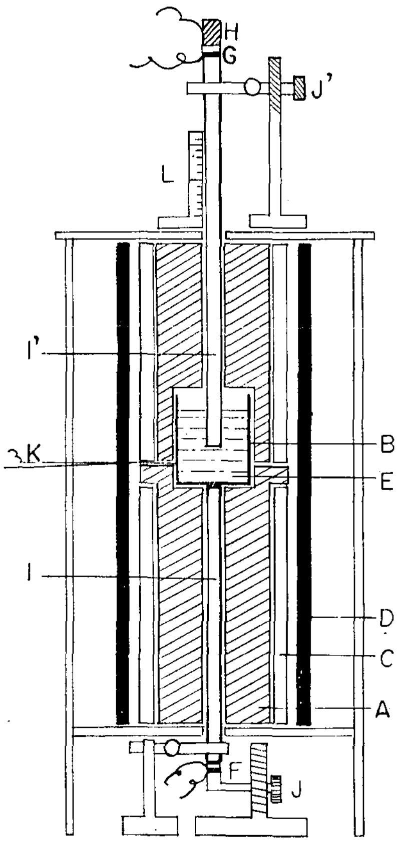



Fig. 1.

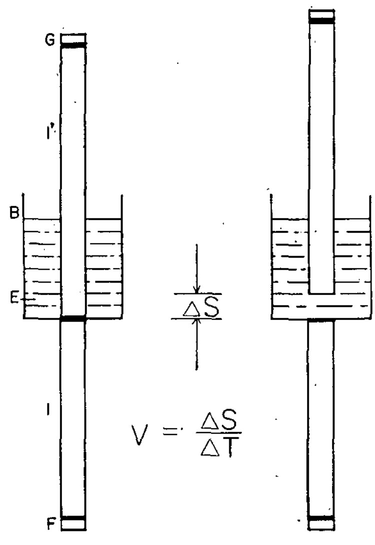



Fig. 2.

Fig. 1. Furnace and cell for the measurement of ultrasonic velocities in molten rocks by the double transducer method. A; alumina guide tube, B; Pt crucible, C; alumina furnace tube, D; EREMA, E; molten rock, F; generating tranceducer, G; receiving tranceducer, H; brass block, I&I'; lower and upper vitreous silica transmission rods, J&J'; lower and upper adjustable clamps, K; thermocouple, L; scale.

Fig. 2. Cell for the measurement of ultrasonic velocities in molten rocks. $v$ (velocity) $= \Delta s$ (distance) $/ \Delta t$ (time).

barium titanate transducers, 0.5 cm in diameter and 0.1 cm in thickness, were cemented. The rods were circular in cross-section, 0.5 cm diameter by 100 cm long, with flat ends. During a run the rods were supported in two clamps and they could be advanced or retracted in the furnace. The use of vitreous silica as a transmission line was highly advantageous because of the low attenuation of acoustic energy even at 1400°C. A little brass block, moreover, is mounted on the transducer to get a good effect of pulse. The cement, a liquid called ARALDITE, required 48 hours to become completely dry at room temperature.

The first transducer converts the electrical pulse into a mechanical pulse which travels through a vitreous silica rod and the molten rock in a Pt crucible and is picked up by the second transducer. The mechanical pulse reconverted into an electrical pulse by the receiver is displayed on the oscilloscope and the trace photographed with a camera. Typical oscilloscope traces of the event for eight distances of Oshima 1950 lava at 1310°C are reproduced in Fig. 3. In this figure the phase which represents ca. 6 km/sec appears apparently at distance 2–3.8 cm. This phase is due to the refraction wave propagating the wall of a little vitreous silica container. The container was destroyed because of the difference in thermal expansion between the container and molten rock at a cooling process. Pt crucible, 6.5 cm high, 4.2 cm in diameter and 0.25 mm in thickness, was used in the later experiments. To avoid errors due to reflection and refraction from the crucible walls the diameter of the container was nine times that of rod. The Pt crucible was supported on the guide tube, sealed through the outer tube. This method has a disadvantage. Unless the base of the crucible is very flat, it is sometimes difficult to establish good acoustical contact between the face of the lower rod and the melt in the crucible. This disadvantage was avoided by placing on the lower rod a little of the rock powder to be investigated. The rock powder melts at ca. 1400°C completely. Heating was carried out in a "EREMA" furnace. Though two holes disturbed the uniformity of temperature in both radial and axial directions in the furnace, the actual difference in temperature was found to be less than ±10°C within the space which was to be occupied by the specimen itself. The temperature of the specimen was measured with a Pt-PtRh thermocouple which was in contact with the Pt crucible. Control of furnace temperature could be obtained by automatic adjustment to ±10°C over 20 minutes and then measurements of the wave-velocity were begun. The reproducibility of velocity measurements at each temperature

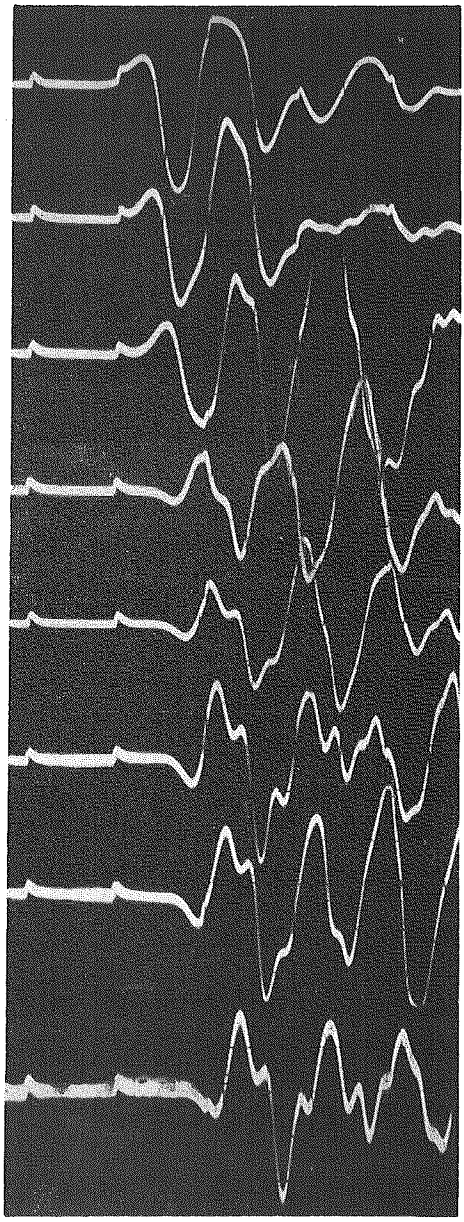



Fig. 3. Typical oscilloscope traces of the event for eight different distances of Oshima 1950 lava at 1310°C. Time scale indicates 10 $\mu$ sec. apart.

was less than ±0.3 km/sec. Most of the error in velocity measurements arises primarily from errors in identification of the first motion on the records and the error of the velocity determined by time-distance curve was less than ± 0.1 km/sec.

In order to compare the results for the wave-velocity given by this method with results obtained previously by other methods the velocity for mercury has been measured at room temperature. The time-distance curve for mercury at room temperature is given in Fig. 4. The reading of time taken to propagate the waves through the liquid and two silica rods are plotted in the ordinate. The wave-velocity obtained for mercury is 1.45 km/sec. Hubbard and Loomis' value obtained by the sonic interferometer is 1.4510 km/sec at 20°C.[5] The agreement between the two values is good. The agreement is the same with water.

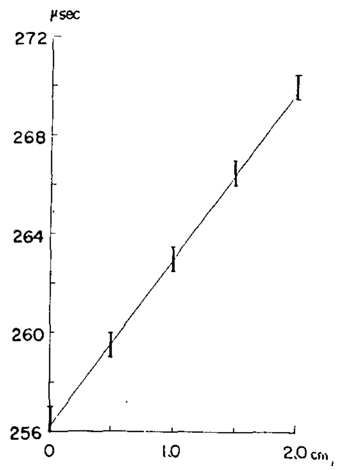



Fig. 4. Time-distance curve for mercury at room temperature.

## 3. Specimens

The chemical compositions of the specimens used in this experiment are given in Table 1. One can find petrographical descriptions referring to literatures. The locality of each rock is as follows:

1) (k); Kilauea Caldera, Hawaii. This rock is kindly supplied from Dr. K. Yagi, Professor of Hokkaido University. The chemical composition of the rock is unknown, but Prof. Yagi suggests to the authors that the composition is similar to that of Ref. (7).
2) (o); Oshima volcano, Izu Oshima, Seven Izu island (1950–lava)[6].

Table 1. Chemical compositions of specimens.

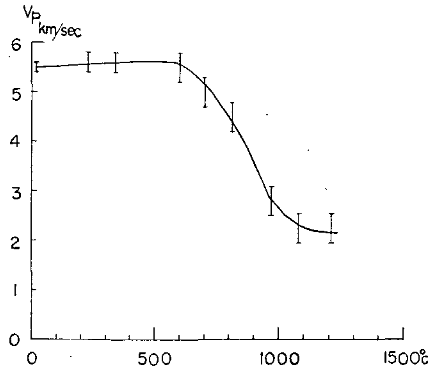
| | k | o | t | as | sa | sh | ag |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 46.59 | 52.02 | 57.40 | 59.90 | 60.80 | 69.74 | 71.5 |
| $Al_2O_3$ | 7.69 | 15.83 | 16.84 | 15.99 | 16.04 | 15.59 | 1.6 |
| $Fe_2O_3$ | 2.20 | 2.28 | 3.68 | 2.86 | 2.89 | 1.52 | 0.1 |
| FeO | 10.46 | 10.80 | 5.96 | 4.77 | 4.63 | 2.59 | |
| MgO | 21.79 | 4.47 | 3.28 | 4.68 | 3.50 | 0.85 | 3.9 |
| CaO | 7.41 | 9.48 | 6.60 | 6.08 | 4.74 | 3.63 | 8.0 |
| $Na_2O$ | 1.33 | 1.58 | 2.88 | 3.39 | 3.74 | 3.43 | 14.3 ($Na_2O$ + $K_2O$) |
| $K_2O$ | 0.28 | 0.29 | 1.21 | 1.28 | 1.75 | 1.36 | |
| $H_2O+$ | 0.37 | 0.99 | 0.36 ($H_2O+$ and $H_2O-$) | 0.58 ($H_2O+$ and $H_2O-$) | 0.74 ($H_2O+$ and $H_2O-$) | 0.67 | |
| $H_2O-$ | 0.04 | 0.24 | | | | 0.23 | |
| $TiO_2$ | 1.83 | 1.52 | 0.65 | 0.05 | 0.87 | 0.45 | 0.3 |
| $P_2O_5$ | 0.11 | n.d. | Tr. | n.d. | Tr. | 0.22 | |
| MnO | 0.18 | 0.09 | 1.08 | 0.89 | 0.33 | 0.08 | |
| S | 0.00 | | 0.02 | Tr. | 0.01 | | |
| $SO_3$ | | | | | | | 0.3 |
| Total | 100.53 | 99.59 | 99.96 | 100.47 | 100.04 | 100.36 | 100.0 |

3) (t); Tarumai volcano, Hokkaido (1909–dome lava)[8),9)].
4) (as); Asama volcano, Nagano and Gunma Pref. (Onioshidashi, 1783–lava)[8),10)].
5) (sa); Sakurajima, Kagoshima Pref. (1914–lava)[8)].
6) (sh); Showa-shinzan, Hokkaido (Dome lava)[11)].
7) (ag); Asahi glass which is supplied from Asahi Glass Co.

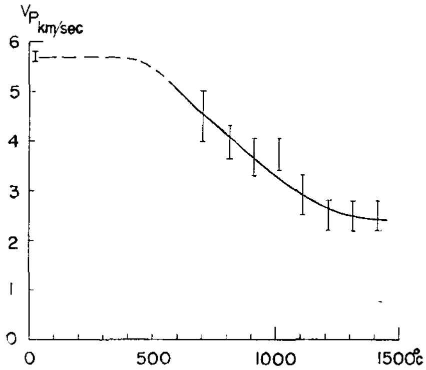
## 4. Results and Discussion

The measurements of the wave-velocity in molten glass and rocks as a function of temperature are graphically shown in Figs. 5a-f. Fig. 6 is overall diagram for the present and other authors' results[12),13)]. The wave-velocity in molten glass and rocks is ca. 2–3 km/sec and shows a increase as temperature decreases, and the rate of the increase of the wave-velocity becomes gradually greater. The curve of velocity against temperature is thus convex towards the origin at high temperature. The velocity increases two or three times, 6 km/sec, as temperature decreases to ca. 900°–1000°C and the curve becomes concave towards the origin at lower temperature. The sharp increase of velocity of molten rocks may result from the solidifying of the specimens. The sample of Asahi glass shows a decrease in the wave-velocity with decreasing temperature at low temperatures. This effect was observed in silica glass and Pyrex chemical resistance glass by Ide[12)]. The effect may be expected the same with other rock glasses. In addition to this, it should also be noticed that the velocity of molten rocks below the liquidus temperature

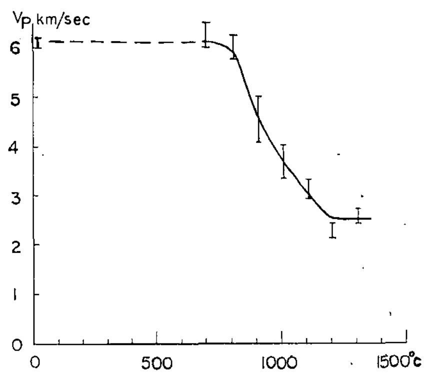
Fig. 5. Velocity of longitudinal wave in molten glass and rocks ($V_P$) as a function of temperature. Vertical lines in figures indicate the range of the reproducibility of velocity measurements.



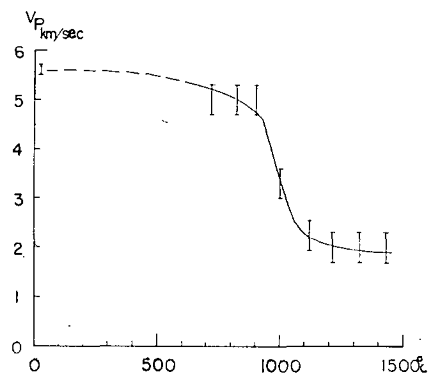

a) Asahi glass (ag)



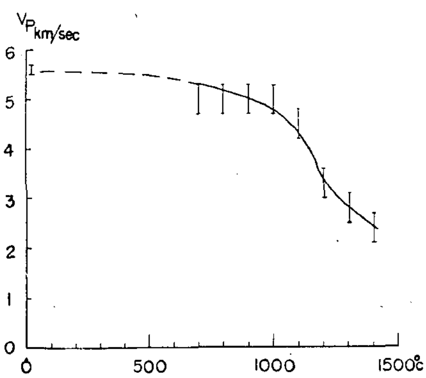

b) Kilauea lava (k)



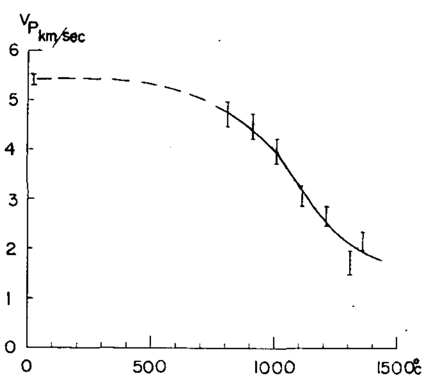

c) Oshima 1950 lava (o)



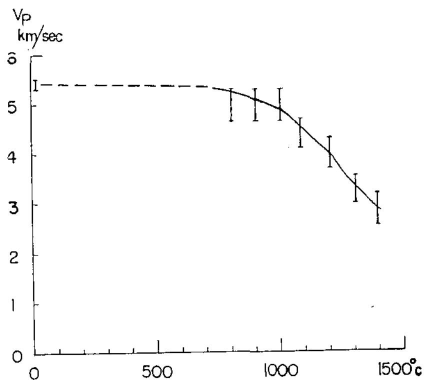

d) Tarumai 1909 dome lava (t)




e) Asama Onioshidashi 1783 lava (as)




f) Sakurajima 1914 lava (sa)




g) Showa-shinzan dome lave (sh).

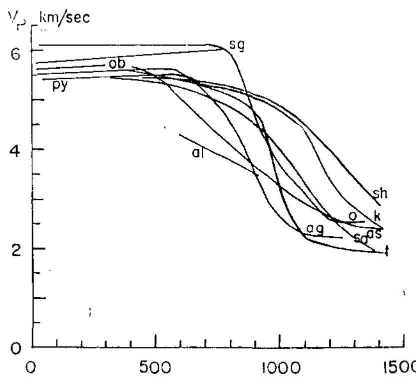



Fig. 6. Overall diagram for molten glasses and rocks.
sg; silica glass
ob; obsidian (after IDE)
py; pyrex glass
al; alkali (30%) silicate (after KUMAZAWA et al).

depends on the cooling rate during measurements of the wave-velocity. The wave-velocity increases during measurements at a constant temperature, because of the effect due to crystallization of minerals below the melting point.

Fig. 7 shows the ratio of $v$ to $v_0$ (the velocity at room temperature) as a function of temperature. The temperature coefficient of the ratio is nearly constant. The temperatures at which $v/v_0=1$ are plotted as a function of silica content in Fig. 8, where it is seen that the temperature increases with increasing silica content.

Fig. 9 shows the relation between $v/v_0$ and log viscosity obtained

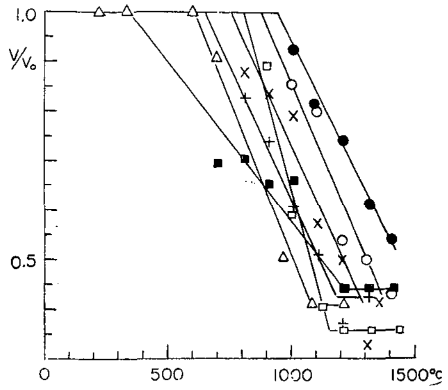



Fig. 7.

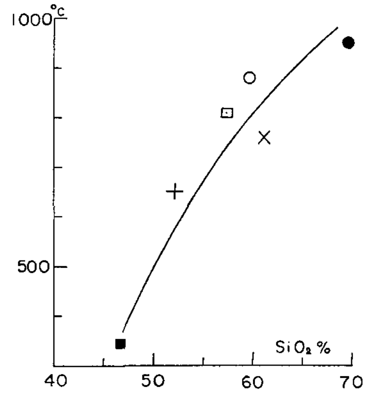



Fig. 8.

Fig. 7. Ratio of $v/v_0$ as a function of temperature.
△; ag, ■; k, +; o, □; t, ○; as, ×; sa, ●; sh.

Fig. 8. Temperatures at which $v/v_0=1$ as a function of silica content.
■; k, +; o, □; t, ○; as, ×; sa, ●; sh.

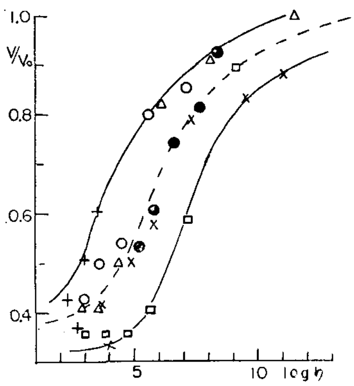



Fig. 9.

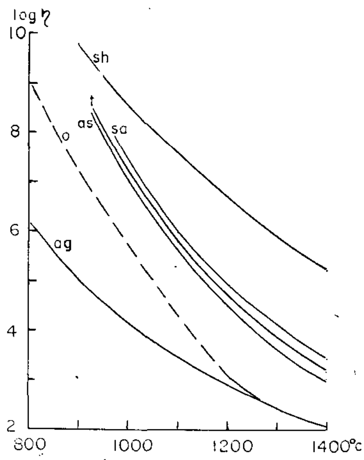



Fig. 10.

Fig. 9. Relation between $v/v_0$ and log viscosity ($\log\eta$).
△; ag, +; o, □; t, ○; as, ×; sa, ●; sh.

Fig. 10. Relation between log viscosity and temperature.
o; dotted part is an extrapolated value.

previously by one of the present authors[2] and Kani and Hosokawa[8] as shown in Fig. 10. The ratio $v/v_0$ shows an increase as viscosity increases.

It has already been pointed out that there is a possibility to investigate the elastic responce of magma with a low frequency excitation such as seismic waves, by a high frequency experiment in laboratory[4]. Kumazawa et al converted the ultrasonic wave velocity of molten silicate into the seismic wave velocity by the method on the basis of the viscosity elasticity interaction. They applied a simple Maxwell model to the conversion, and expressed the velocities of body waves in a visco-elastic medium as a function of $f\tau$, where $f$ is the frequency and $\tau$ the relaxation time ($\eta$ (viscosity)/$\mu$ (rigidity)).

At the present paper the similar conversion into the seismic wave velocity is applied to the ultrasonic wave velocity of molten rocks, but average $v/v_0$-viscosity relation in Fig. 9 (dotted line) for frequency of ca. $10^5$ cycles/sec is applied to the conversion. If rigidity is assumed to be constant and frequency varies to keep $f\eta/\mu$ constant with changing viscosity, $v/v_0$-frequency diagram in Fig. 11 is obtained. This diagram shows the variation over the frequency range $10^{-1}$-$10^5$ cycles/sec.

The diagram obtained above is applied to the seismic waves of the molten Oshima lava as an example and the results for three frequencies $10^0$, $10^1$ and $10^2$ cycles/sec are obtained as shown in Fig. 12. In any case the velocity of longitudinal wave in molten rocks at 1000° to 1400°C seems to be 2–3km/sec.

The adiabatic compressibility ($\beta$) of the molten rocks (calculated from the general equation $v^2=1/\rho\beta$ where the density $\rho$=ca. 2.5 and $v$=2.5 km/sec)

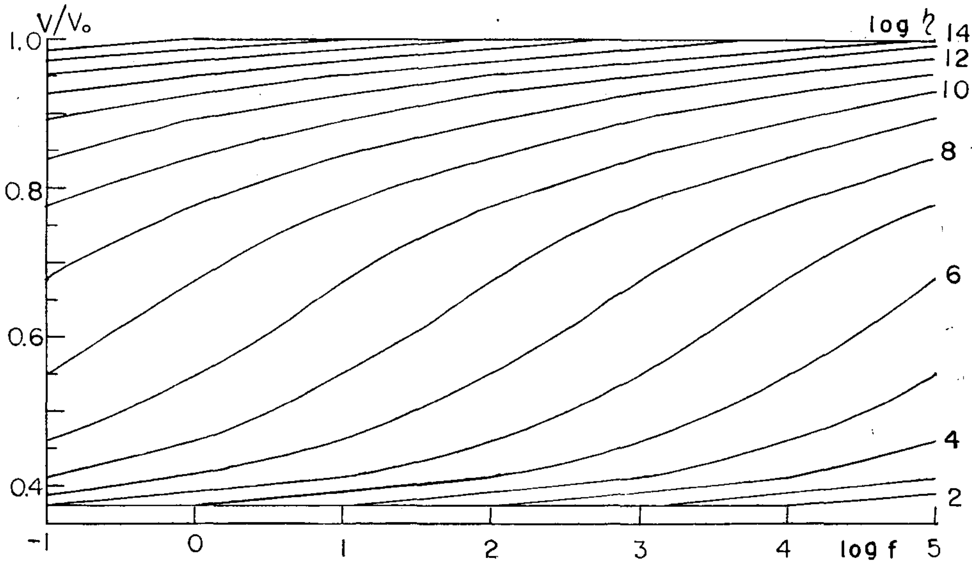



Fig. 11. $v/v_0$ for various log viscosities as a function of log frequency.

is ca. $6\times10^{-12}\,cm^2/dyne$. This result agrees approximately with $\beta$ of $30LiO_270SiO_2$ (molar percentage)[3] and that of a substance in a magmatic reservoir estimated by Gorshkov[13].

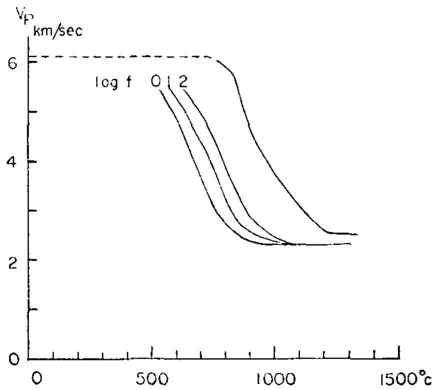



Fig. 12. Wave-velocities of Oshima 1950 lava for various frequencies as a function of temperature.

## 5. Conclusion

The original object of the present research was to measure temperature coefficient of the wave-velocity for molten rocks at atmospheric pressure. The results obtained are 2–3 km/sec in molten state of rocks.

Sassa[14] calculated the velocity of propagation of soundshocks in gas-riched molten lava in the volcanic vent at about 790 m/sec on the basis of the observed time differences between eruption-earthquakes and sound-shocks. Also Gorshkov[13] determined the velocity of the composite wave in the magmatic reservoir at 1.6–1.8 km/sec by the difference in the time of arrival of direct and composite waves.

In cases where molten rocks are subject to high pressure, the pressure effect must increase the wave-velocity of the molten rocks, while in cases where the molten rocks contain a gas, the gas content must decrease the velocity. It is interesting to raise the problem how the wave-velocity of molten rocks varies with increasing pressure and gas content.

If the velocity of longitudinal wave in molten rocks may be taken as a function of $f\tau$ as mentioned above, it is necessary for us to know the effect of pressure on $\tau$. The values of $\tau$ for molten rocks even at atmospheric pressure, however, have never been subjected to investigation. Since it is impossible to obtain the values of $\tau$ for molten rocks at the present step of experimental work, only the variation of viscosity of molten rocks with pressure is considered below. The order estimation of the variation was predicted on the basis of the fundamental rate process for viscous flow in molten rocks[15]. The results suggest that the viscosity of molten olvine varies from $10^2$ poises (1 atm) to ca. $10^6$ poises ($10^5$ atm) at 1500°C and from ca. $10^3$ poises (1 atm) to ca. $10^8$ poises ($10^5$ atm) at 1200°C. According to the estimation made by means of the diagram of Fig. 11 $v/v_0$ varies from 0.38 to 0.41 in $f=1$ cycles/sec, to 0.46 in $f=10$ cycles/sec and to 0.55 in $f=10^2$ cycles/sec at 1200°C. These values correspond to the change of velocity from 2.3 km/sec to 2.5, 2.8 and 3.3 km/sec respectively when $v_0=6$ km/sec. In the case of 1500°C, the effect of pressure on the velocity is estimated to be smaller than that of 1200°C.

It is probable that the change of $\tau$ with pressure must be diminished because rigidity ($\mu$) of molten rocks is expected to be increased with increasing pressure and velocity of molten rocks must be therefore little affected by pressure.

Thus, an important conclusion derivable from the present measurements on molten rocks is that there is a possibility of the detecting of molten parts in crystalline crust or mantle of the earth, if we have any method to observe the difference in seismic wave-velocity between them.

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