

16. Effect of Thermal History on Viscosity of Oosima-lavas.

(Elastic and Viscous Properties of Volcanic Rocks. Part 4.)

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Introduction.

One of the factors which characterize volcanic activities is the viscosity of the intruding, extruding and flowing lavas during the course of the respective activities. The scale of upheaval and subsidence around the volcanoes, the frequency and magnitude of volcanic earthquakes as well as the intensity of explosions are affected without exception by the viscosity of lavas. Lava is the product of magma at its last stage of evolution. The viscosity of magma varies with the development of crystallization in it, and crystallization is a certain complicated function of temperature and the rate of cooling. Accordingly, viscosity will be influenced seriously by the thermal state in which the magma has been placed to the present. Especially, when the lava is ejected to the earth's surface and has to cool in the air, the rate of nucleation and growth of crystals cannot keep up with the rapid rate of cooling, and the lava remains as a heterogeneous mixture of crystals and glass.

The viscosity of flowing lavas of various volcanoes has been estimated by many investigators. However, we do not know how the character of extruding lava is affected by various complicated parameters in such transient circumstances. The question, which arose as to the mode of development of dynamical properties in the interior of lava, leads the writer to conduct the present experimental study concerning the effect of thermal history on the viscosity of Oosima-lavas.

It was already pointed out in the previous papers¹⁾ that heat treatment of Oosima-lava in the laboratory causes irreversible changes both in Young's modulus and in the viscosity. It was found that the viscosity always increases with the repetition of heating experiment, but the previous procedures of experiments need some alterations.

1) S. SAKUMA, *Bull. Earthq. Res. Inst.*, **30** (1952), 269; **31** (1953), 63 and 291.

Method.

The fundamental principle of experiment remains the same. Specimens are cut from lava blocks, ground and polished into thin plates of ca. 0.3 cm × 1 cm × 8 cm. The lava-plate is supported on two knife-edges at its ends and is loaded at the centre through another knife-edge, and the specimen continues to sag by the constant load. The whole contrivance is inserted in the electric furnace. In the previous experiments, elasticity and viscosity were measured at constant temperatures by the deformation of specimen due to application and removal of load. The load was not applied while the temperature was being raised and lowered to the next constant temperature. But such step-by-step procedure is not suitable for the present purpose to find the effect of thermal history, for the reason that the step-by-step heating complicates the history of the specimen. In the present studies, the temperature is raised not step by step but at a constant and definite rate and the load is applied from long before the commencement to the end of heating, to avoid the above-mentioned defect.

However, this method of experiment has still some other defects, which shall be discussed here.

1) Possible lag of temperature in the specimen.

Because the temperature in the furnace increases with time and is not kept constant, the distribution of temperature in the specimen as well as in the furnace is not perfectly uniform and constant. Accordingly, the temperature in the specimen will lag more or less behind the temperature which the thermocouple indicates. If we regard the specimen as an infinite plate with thickness l for mathematical simplicity, and assume the temperature at the surface as

$$T = \beta t \quad (\text{at } x=0 \text{ and } x=l),$$

the temperature in the specimen is given from the theory of conduction of heat by

$$T = \frac{4\beta}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin \frac{n\pi}{l} x \left\{ t - \frac{l^2}{\kappa n^2 \pi^2} \left(1 - \exp \left(-\frac{\kappa n^2 \pi^2}{l^2} t \right) \right) \right\}, \quad (1)$$

in which κ is the thermal diffusivity and n the odd integer. Put $x = \frac{l}{2}$, and

$$T = \beta t - \frac{\beta l^2}{8\kappa} + \frac{4\beta l^2}{\kappa \pi^3} \left\{ \exp \left(-\frac{\kappa \pi^2}{l^2} t \right) - \frac{1}{3^3} \exp \left(-\frac{9\kappa \pi^2}{l^2} t \right) + \dots \right\}. \quad (2)$$

Put $\kappa=3 \times 10^{-3}$ cm²/sec and $\beta=600^\circ/\text{h}$, and we find that the lag is only 0.7°C even at the centre. Subsequently, this kind of lag can be neglected.

2) Lag of deformation due to elastic after-effect.

If the specimen is the Newtonian viscous liquid, the velocity of deformation will represent its viscosity for the temperature at the very instant. But the actual lava has been proved to be a visco-elastic material except at high temperatures. Put

$$\tau' \ddot{e} + \dot{e} = \frac{P}{3\eta} \quad (3)$$

for the present specimen, where P and e are stress and strain, E is Young's modulus, η is viscosity and τ' is the relaxation time for strain under constant stress. τ' is the cause of the lag in question. The approximate value of τ' was given in the previous report. If the temperature increases as $T=\beta t$, and $\eta=\eta_0$ at $t=0$, the equation (3) becomes

$$\dot{e} = \exp\left(-\int \frac{dt}{\tau'}\right) \left\{ C + \int \frac{P}{3\eta\tau'} \exp\left(\int \frac{dt}{\tau'}\right) dt \right\}. \quad (4)$$

If we assume that $1/\eta = M \exp(mT - kt')$, on the basis of the result of experiment which will be seen on Figs. 2(a)-(b), and that, for simplicity's sake, $\tau' = \bar{\tau}' = \text{constant}$, we obtain

$$\dot{e} = \frac{PM}{3} \left\{ \frac{m\beta\bar{\tau}'}{1+m\beta\bar{\tau}'} \exp\left(-\frac{T}{\beta\bar{\tau}'}\right) + \frac{1}{\bar{\tau}'\beta} \cdot \frac{\exp(kT_0/\beta)}{m-k/\beta+1/\beta\bar{\tau}'} \cdot \exp\left(mT - \frac{kT}{\beta}\right) \right\}. \quad (5)$$

$$(t' = t - T_0/\beta)$$

After some approximate numerical calculations ($T_0=150^\circ\text{C}$, $k=10^{-4}$, $\beta=600^\circ/\text{h}$, $m=2 \times 10^{-2}$), we find that the first term, which includes the delayed elasticity principally, is of the same order of magnitude of the second term at 600°C and is not negligible, and that it vanishes at above 800°C owing to the decrease of $\bar{\tau}'$ at higher temperatures. If $\beta=100^\circ/\text{h}$, the first term vanishes even at 600°C . In short, the present method of experiment is trustworthy at least at temperatures higher than 800°C .

Tested Specimens.

Three kinds of new lavas²⁾ from Oosima were compared with one another. The three were already described with photo-micrographs in

2) H. TSUYA, R. MORIMOTO & J. OSSAKA, *Bull. Earthq. Res. Inst.*, **29** (1951), 563; **30** (1952), 231.

the preceding paper³⁾ on the elasticity at high temperatures.

One was found at the side of a fluidal lava-flow and remains glassy, one was in a deep crevice in the slowly solidified lava-pool and is highly crystalline, and the other is of an intermediate character of the above two.

Comparison of grain-size among the specimens were done by a modified method of volumetry. Petrographical constituents on photomicrographs were classified into three groups: (1) light-colored minerals (2) gray (on black and white photo)-colored minerals (3) dark-colored minerals and glass. Preliminary inspection by microscope showed that group (1) consists largely of plagioclases, (2) of pyroxynes and (3) of glass and few magnetites. Straight lines are drawn on the photomicrographs in cross-stripes. Length of every segment (x) of line which crosses a mineral or glass is regarded as the size of the part. The distribution of grain-size of minerals and the relative area occupied by the respective groups could be estimated roughly by this procedure.

More exactly, however, the average length which is occupied by one mineral differs from every one of its sides. An example will be shown in the followings. Assume the cross-section of a mineral to be a rectangle the sides of which are A and qA . The average length of the segments for all possible orientation of the rectangle to straight lines is given by

$$\bar{x} = \frac{2qA}{\pi\sqrt{1+q^2}} \log \frac{\tan\left(\frac{\pi}{4} + \frac{\lambda}{2}\right)}{\tan \frac{\lambda}{2}}, \quad (\tan \lambda = 1/q) \quad (6)$$

$$\therefore \bar{x} = \begin{cases} 0.80a & \text{for } q=1 \\ 0.78a & \text{,, } q=2 \\ 0.63a & \text{,, } q=10. \end{cases}$$

where a is the geometrical mean of the sides. Subsequently, it is not accurate to regard the length of the segment as the grain-size and the abscissae of Figs. 1 (a) and 1 (b) should be corrected.

In spite of that, the difference between the glassy and the crystalline lavas shown by this method deserves notice. The area of glass is about 50% for the glassy one and about 20% for the crystalline one. The difference was found to have been caused by the abundant presence of fine grains of minerals in the groundmass of crystalline lava. Phenocrysts occupy about 10% of total area in common. They are omitted from the figures.

3) S. SAKUMA, *loc. cit.*, 1).

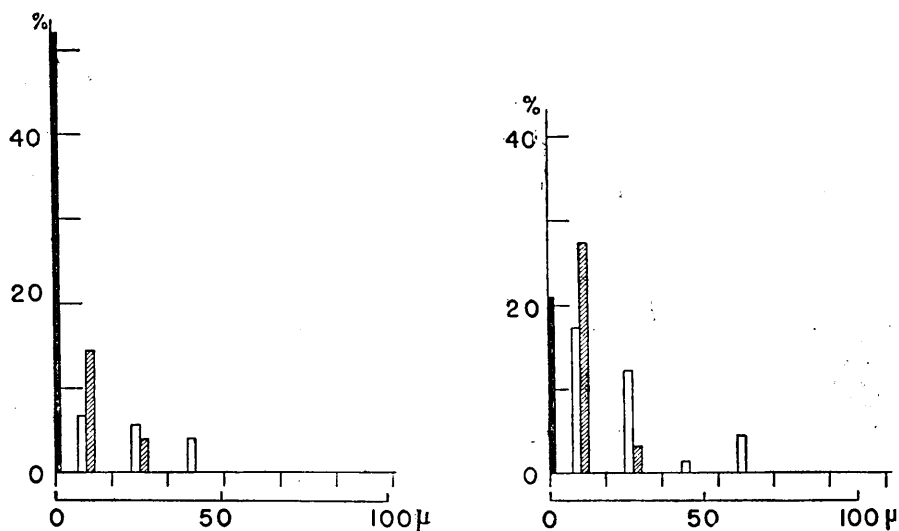


Fig. 1(a). Glassy lava. (phenocrysts (14%) are omitted from the figure.)

Fig. 1(b). Crystalline lava. (phenocrysts (13%) are omitted from the figure.)

Fig. 1. Area (in %) occupied by the minerals of various grain-size.

White columns: plagioclases,
Hatched columns: pyroxynes,
Black column: glass and magnetites.

Results of Experiments.

Viscous flow of specimens was studied by measuring its deformation every few minutes or every thirty seconds. The specimens were dealt

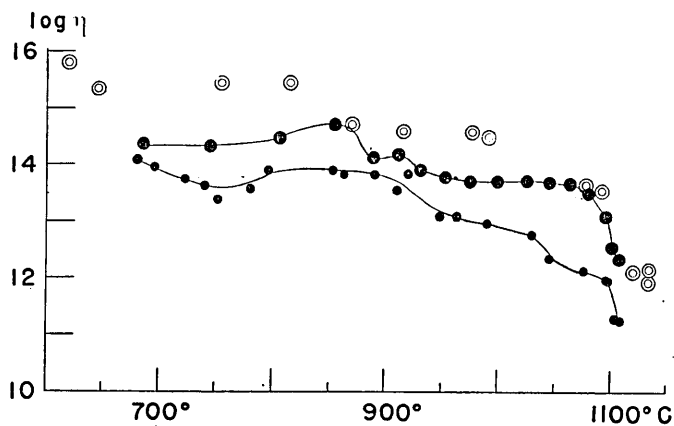


Fig. 2(a). Glassy lava.
Small circles: 600°/h,
Big circles: 100°/h.

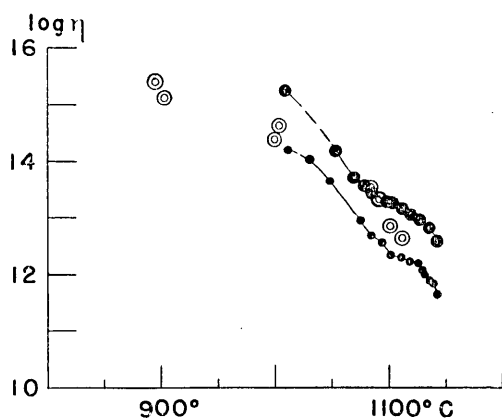


Fig. 2(b). Crystalline lava.
 Small circles: 600°/h,
 Big circles; 100°/h.

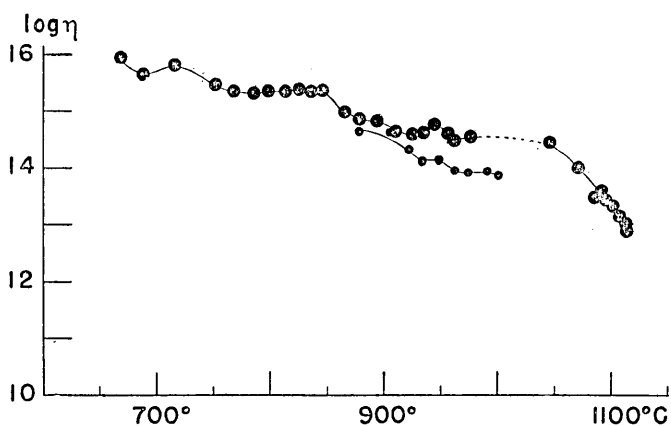


Fig. 2(c). Intermediate lava.
 Small circles: 100°/h,
 Big circles: 30°/h.

Fig. 2. Viscosity versus temperature with different rates of heating.
 Double circles: stepwise method. (for reference)

with under various rates of increase of temperature, i.e. 600°/h, 100°/h and 30°/h. The applied stress is kept same for all experiments so that

the structural viscosity, if any, may not affect the results. The results of experiments were found to be reproducible within the error of about 20%, in spite of the non-equilibrium character of the experiments.

Results are summarized as follows.

(1) The more rapidly the specimens are brought to high temperature, the more fluidal they become. Viscosity depends not only on T , but on T' . This shows merely the effect of thermal history in the laboratory, and it will be discussed later. Experiments under constant temperatures, after heated rapidly to the temperatures, were also conducted to prove the dependence of viscosity on time. Viscosity increases with time. (Fig. 3)

(2) The more glassy the specimens are, the more fluidal they behave without exception, under the same condition of experiment. This fact means that the lavas of Oosima are always affected by their respective thermal histories, which they have experienced under natural conditions.

The previous experiments by increasing the temperature step by step failed to show the transient character in viscosity of lavas. The remarkable discontinuity in viscosity which was observed in the previous experiments at about 1130°C will perhaps correspond to one of eutectics under nearly equilibrium conditions.

Analysis, Discussions and Application.

The dependence of viscosity upon the thermal history of lava is one of the keys to clarify the character of volcanic rocks, although it complicates our experimental studies of their physical properties. The writer wishes to throw some light on the complicated phenomenon through the following discussions.

The lavas cannot be imagined to be under perfect thermodynamical equilibrium. Crystallization under perfect thermodynamical equilibrium, under high pressure and gradually decreasing temperature, would have rendered the magma a different igneous rock.

At first, let us consider the lava cooling under natural conditions.

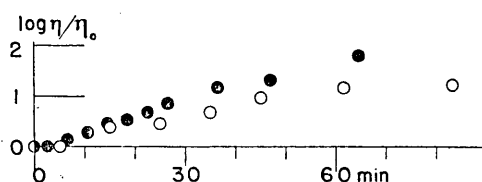


Fig. 3. Change of viscosity with time at constant high temperatures.

Closed circles:

1130°C ± 4°C, crystalline lava,

Open circles:

1000°C ± 3°C, intermediate lava.

Because it is not in equilibrium and the reactions lag behind cooling, the quantity of crystalline phase is inevitably less than that which may be expected under equilibrium conditions. The existence of the super-cooled glass will be the main cause of the phenomenon to be examined here. The quantity as well as quality of the phase which is not in thermodynamical equilibrium is a function not only of temperature but of time. Let us assume secondly that the fluidity, or the reciprocal of viscosity, can be divided into two parts, which correspond to the stable and unstable phases respectively.

$$\frac{1}{\eta} = c(T) + b'(T, t). \quad (7)$$

$b'(T, t)$, which is the unstable part, will vary in the following manner.

$$\frac{\partial b'}{\partial t} = -k'(T)b'. \quad (8)$$

$$\therefore b' = b_0(T) \exp \left\{ - \int k'(T) dt \right\}. \quad (9)$$

And $T = T(t)$ in general,

$$\therefore \frac{1}{\eta} = c(T) + b_0(T) \exp \left\{ - \int_{T_0}^T \frac{k'(T)}{T} dT \right\}. \quad (T_0 > T) \quad (10)$$

$c(T)$ and $b_0(T)$ may depend partly on the quality of the liquid phase at the temperature and partly on the quantity of it, as well as the mode of aggregation of the crystals. More precisely, $b'(T, t)$ may consist of more than one component. But only one main term is to be discussed here, because of the limited accuracy of the present experiment and because the reactions can be supposed to be eutectic, in which various minerals crystallize together.

When we heat the specimens in the laboratory, the change of viscosity with time will be similar to (7) and

$$\frac{\partial b}{\partial t} = -k(T)b. \quad (11)$$

In the last place, viscosity at heating in the laboratory is given approximately by

$$\frac{1}{\eta} = c(T) + b'_0(T) \exp \left\{ - \int_0^t k(T) dt \right\} \quad (12)$$

where the origin of time is taken at the beginning of the experiment. The initial state of (12) is the final state of (10).

$$\therefore \left\{ \frac{1}{\eta} = c(T) + I(T) \exp \left\{ - \int_0^T \frac{k(T)}{T} dT \right\}, \right. \quad (13)$$

$$\left. \begin{matrix} I(T) \equiv b_0(T) \exp \left\{ - \int_{T_0}^0 \frac{k'(T)}{T} dT \right\}. \end{matrix} \right. \quad (14)$$

Then we enter into analysis of the results of experiments on the basis of the above-mentioned assumptions.

(A) Evaluation of k .

A-1) Experiments under linearly increasing temperatures, in which $T = \alpha_n t$, $\alpha_n = 600^\circ/\text{h}$, $100^\circ/\text{h}$ and $30^\circ/\text{h}$.

$$\therefore \frac{1}{\eta_n} = c(T) + I(T) \exp \left\{ - \frac{1}{\alpha_n} \int_0^T k dT \right\}. \quad (15)$$

At first we compare the viscosity with one another among the same kind of specimens, which has the same history in the nature, i.e. $I(T)$ is common.

$$\frac{1}{\eta_1} - \frac{1}{\eta_3} = I(T) \left\{ \exp \left(- \frac{1}{\alpha_1} \int_0^T k dT \right) - \exp \left(- \frac{1}{\alpha_3} \int_0^T k dT \right) \right\}$$

$$\frac{1}{\eta_2} - \frac{1}{\eta_3} = I(T) \left\{ \exp \left(- \frac{1}{\alpha_2} \int_0^T k dT \right) - \exp \left(- \frac{1}{\alpha_3} \int_0^T k dT \right) \right\}.$$

If we take $\alpha_3 \ll \alpha_1$ and α_2 , we can put as follows approximately, because $c(T)$ is far less than $b(T)$ below 1100°C .

$$\ln \frac{\eta_2}{\eta_1} = \left(\frac{1}{\alpha_2} - \frac{1}{\alpha_1} \right) \int_0^T k dT. \quad (16)$$

Then we get $\int_0^T k dT$ as a function of T , as far as the assumptions

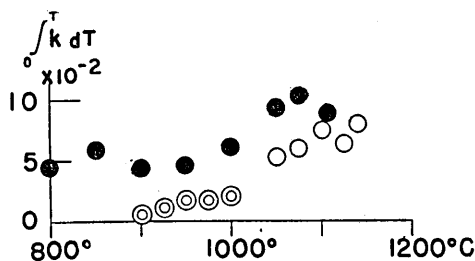


Fig. 4. $\int_0^T k(T) dT$ as a function of T .
 Closed circles: glassy lava,
 Open circles: crystalline lava,
 Double circles: intermediate lava.

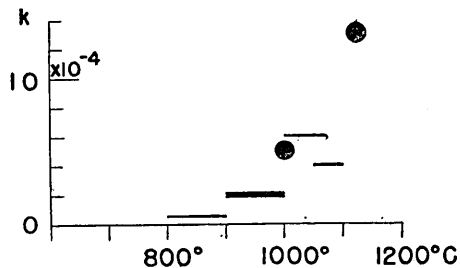


Fig. 5. k versus temperature.
 Circles: obtained from Fig. 3.
 Segments: obtained from Fig. 4.

stand right. The probable error of k is estimated at about 60% for the observed fluctuation in viscosity (20%).

A-2) Experiments under constant temperatures.

Specimens are heated in the same way as in 1), i.e. $T=\alpha t$, and then the temperature is kept constant at a definite temperature. In this case,

$$\frac{1}{\eta} = c(T) + I(T) \exp \left\{ -\frac{1}{\alpha} \int_0^T k dT \right\} \exp (-k(T)t), \quad (17)$$

in which t is the time elapsed at the constant temperature T . We can obtain k by this method too. If we could observe η for a long enough time, we would obtain $c(T)$ also.

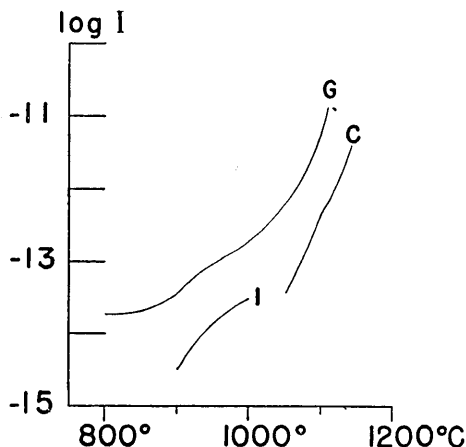


Fig. 6. I versus temperature. (suffixes G , C and I are for glassy, crystalline and intermediate lavas respectively.)

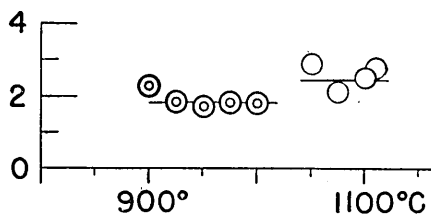


Fig. 7. $\Delta \ln I$.
Open circles: $\ln I_G - \ln I_C$,
Double circles: $\ln I_G - \ln I_I$.

As will be seen in Fig. 5, k is not remarkable at lower than 800°C, and it appears to increase at higher temperatures. The general tendency is common among the crystalline, intermediate and glassy lavas, even though there are some differences in details. Viscosity increases as much as ca. 2.7 times in $1/k$ seconds under constant temperature, so far as $c(T)$ is small. This is quite a remarkable fact.

(B) We can estimate $I(T)$ also by availing ourselves of k .

$I(T)$ includes the thermal history of the lava in the field, as well as the quantity and quality of the unstable non-crystalline phase. $I(T)$ shows the character of the relative change of viscosity with temperature. When we compare the $I(T)$ s of the crystalline and the glassy one, we find that

$$\ln \frac{I_G}{I_C} = \ln \frac{b_{0G}}{b_{0C}} + \left\{ - \int_{T_0}^0 \frac{k'_G}{T} dT + \int_{T_0}^0 \frac{k'_C}{T} dT \right\}. \quad (18)$$

Fig. 7 shows that the logarithms of the ratio of I_G to other lavas are positive and nearly constant respectively. This fact is consistent with the prevailing idea that the glassy lava has cooled faster than the others. The rates of cooling cannot be estimated from the present data, because of the integrated form of the equation (18), even if we assume $k=k'_G=(k'_C)$ and $b_{0G}=b_{0C}$. But the obtained ratios are not unreasonable quantitatively.

(C) Let us consider the meaning of k and suppose the mode of change of viscosity with temperature and time, on the basis of the experiments. In the writer's opinion, the increase of k at high temperatures may imply mainly the increase of velocity of crystallization from the supercooled glass in the groundmass. The $k-T$ curve on Fig. 5 can be expressed approximately by the equation:

$$k=C \exp(-W/RT_K) \quad (19)$$

where T_K is the absolute temperature, and the activation energy W is estimated at about 30 kcal/mol.

When we heat the specimens in the laboratory, velocity of crystallization of the supercooled part will get larger with rise of temperature, and a part of the supercooled glass is transformed into the crystalline phase. This increase of solid phase will surpass the decrease due to remelting of crystals, when the unstable part is predominant. This may be the main cause of the observed irreversibility in viscosity and elasticity. This progress of crystallization should be accompanied with separation and escape of volatile constituents too, as in the natural process of cooling.

Some of the crystals, which should have been remolten, possibly remain in the solid state in case of too rapid heating, and result in opposite change in viscosity. However, the effect of the phenomenon was found to be far less than the effect of the "recrystallization" in the present experiments. This may be explained from the increase of viscosity, instead of decrease, under constant temperatures at lower than 1130°C.

The state of matters in the interior of the specimens is, of course, not perfectly the same as that which occurred in its natural process of cooling. Crystallization in its natural state should have taken place in

the hydrothermal conditions. However, it was found that bubbles and fine vesicles grew up in the specimens during the present experiments too. This fact suggests that the lava still includes some volatile constituents. Consequently, it is not so unreasonable to infer that the changes in the properties of lavas in the laboratory are similar, at least qualitatively, to those in the natural cooling. We should be careful, of course, in extrapolating the present results to the phenomena in the nature.

(D) We have discussed hitherto the effects of crystallization upon viscosity. We must now try to infer the viscosity of lavas under natural conditions. If we assume that the equation (10) can be applied to nature and that $k=k'$, the necessary quantity to be determined further is the rate of cooling in the field.

T. Minakami⁴⁾ measured the flowing velocity, temperature and the dimension of one of the 1951 lava-flows of Oosima, and estimated its viscosity. He did not measure the cooling rate of lava, but it can be calculated from his published data. Because the quantity of the flowing mass (Q) through every cross-section of the flow is nearly constant, the flow can be duly regarded as steady. And we can put (cooling rate)=(space-gradient of T) \times (velocity of flow). Thus the rate of cooling was estimated as a function of temperature, within the range of 1125°-950°C. Then we can calculate $\exp\left(-\int_{950}^{1125} \frac{k}{\dot{T}} dT\right)$, but $\exp\left(-\int_0^{950} \frac{k}{\dot{T}} dT\right)$ remains unknown and this should be treated as a constant term in the calculation. η is calculated by availing ourselves of the observed I_G and k . A glance at Fig. 8 will be sufficient to convince us that the gradients of

Table I.
Cooling rate of the lava in the field.

T (°C)	Distance (m)	Q (cc/sec)	\dot{T} (°C/sec)
1125	140	3.5×10^5	-8.3×10^{-2}
1108	110	2.8	-5.7
1083	200	2.4	-2.6
1038	500	2.6	-1.4
(950)			

4) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **29** (1951), 427.

T. MINAKAMI and S. SAKUMA, *Bull. Volcanol.*, **14** (1953), 79.

the increase in viscosity with the decrease in temperature resemble each other satisfactorily, i.e. between the calculated and the observed ones.

Accordingly, we will be able to tell the viscosity of lavas in its natural molten state by k and I obtained in the laboratory, if we can assume their rates of cooling in the field, although it is not permitted without limit.

(E) There remains two essential problems to be solved. One is: what petrographical changes correspond to the changes in viscosity? The other is: in what manner does the viscous flow take place in the specimens?

The changes in viscosity, reversible or irreversible, must be accompanied by changes in the quantity of minerals and in the mode of aggregation of them. The difference between the crystalline and the glassy specimens are fairly distinct, as mentioned in the preceding paragraph. But petrographical change in the specimens by heating in the laboratory was found to be less distinct at least below 1130°C. Significant increase or decrease in the quantity of mineral grains could not be ascertained by microscopic studies, except increase of fine grains of magnetite in the glassy part. There is little ground at present to decide whether the physico-chemical process which produces magnetite as a result is the main cause of the observed change in viscosity, or not. More detailed and precise studies on the crystallinity and the mode of aggregation of constituent minerals under various conditions will be useful in this connection.

The origin of viscous flow in the mixture of crystals of various size and intercrystalline materials is also still vague at present. The recent progress in the physics of liquid state revealed that liquids can

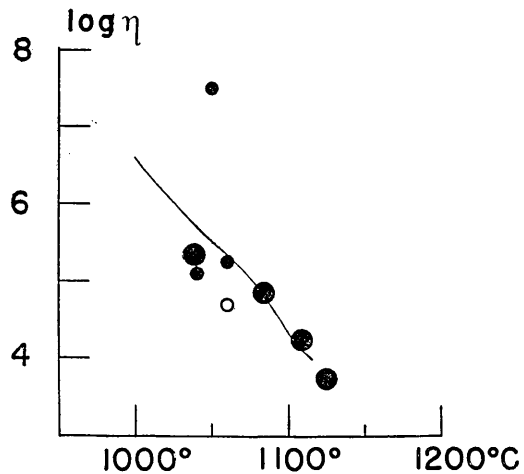


Fig. 8. Viscosity of Oosima-lava cooling in the field.

Line: calculated from \dot{T} in Table I,

Circles: observed in the field,

(big closed ones: T. Minakami, small closed ones: S. Murauchi and A. Sugimura, open one: R. Takahasi and T. Nagata⁵⁾.)

5) R. TAKAHASI and T. NAGATA, *Bull. Earthq. Res. Inst.*, **15** (1937), 1047.

be regarded as aggregates of fine, unstable crystallites. This idea may be accepted as quite reasonable for lavas too. Accordingly, the viscous flow will be realized as the result of slips at boundaries of grains of

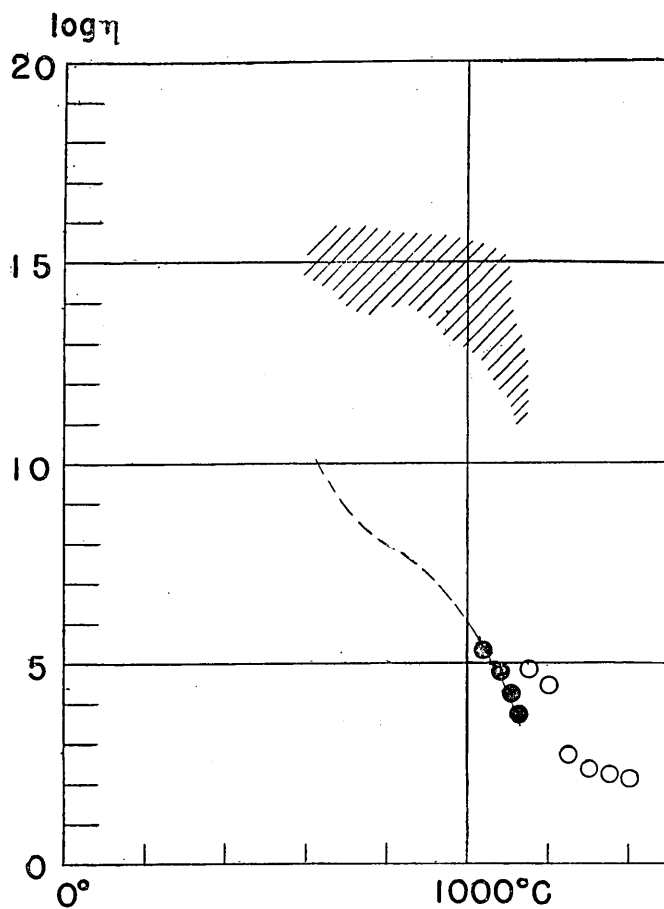


Fig. 9. Comparison of viscosity-coefficients obtained in the field and in the laboratory.

Hatched area: range of viscosity by the present experiment,

Open circles: K. Kani's experiment⁶⁾,

Closed circles: observed viscosity in the field (T. Minakami),

Broken line: calculated viscosity for an assumed cooling rate.

various sizes and forms macroscopically as well as microscopically. Those experimental studies will be of great use which deal with the

6) K. KANI, *Proc. Imp. Acad. Japan*, **10** (1934), 79.

apparent viscosity of the mixture of solid grains and viscous liquid, in order to clarify the functional relation of viscosity to the mode of aggregation of grains.

Conclusion.

The character of viscosity of lava should be realized as transient essentially. The lavas are always not in thermodynamical equilibrium, both in the field and in the laboratory. The present paper dealt with the specimens from Volcano Oosima, and showed that the viscosity is a function of the history of the lava, i.e. that of the degree of the development of crystallization. Viscosity of lavas of other volcanoes at the time of their ejection may also be inferred from similar experiments.

The variety in viscosity of lavas among volcanoes, or even in one volcano, might have been caused chiefly by the original difference in the chemical compositions among their magmas concerned.⁷⁾ But partly it must have been caused by the difference in their stage of development of crystallization at the time when the magmas obtained sufficient energy for them to struggle ahead to the earth's surface.

In concluding, the writer wishes to express his cordial thanks to Dr. T. Minakami, Dr. T. Nagata and Mr. J. Ossaka for the facilities and advices given to him.

16. 大島新熔岩の粘性の熱履歴について

地震研究所 佐久間修三

前報では熔岩試料の温度を徐々に段階的に変えて実験していた。しかしその実験により、熔岩の粘性には加熱により増加する傾向があることが判つたので、試料の加熱速度を系統的に変えて実験した。これによつて判明した粘性の熱履歴の性質は次の通りである。(第 2-3 図)。

- (1) 速かに高温に至らせれば粘性はより小となる。
- (2) 試料が玻璃を多く含む程粘性は小さい。
- (3) 一定温度下では粘性は時間と共に増す。

熔岩中にある過冷却非晶質部分が加熱により更に晶出することがこの熱履歴の主因であると考えたと実験事実をよく説明出来る。この考えで実験結果を整理して、この再晶出の速度は温度が高いほ

7) T. MINAKAMI, *Bull. Volcanol.*, **10** (1950), 59.

T. MINAKAMI and S. SAKUMA, *loc. cit.*, 4).

M. P. VOLAROVIC and others, *Comp. Rend. Acad. Sci.*, No. 9 (1934), 561; **1** (1936), 321.

ど大きいことを示した。(第 5 図)

実験によつてこのような晶出に伴う粘性の変化の性質を知れば、その熔岩が自然で冷えて来た途中での粘性をも或程度推定出来る。但し冷却速度をも知らなければならない。大島熔岩流について計算した 1 例 (第 8-9 図) を示す。

一言にしていえば、熔岩の粘性は温度のみの函数ではなく、本質的に過渡現象として考察されねばならない。
