

28. *Elastic and Viscous Properties of Volcanic Rocks at High Temperatures. Part 3. Oosima lava.*

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Introduction.

Enormous volume of hot lava was given out during the recent activities of Volcano Oosima in 1950–51. Most of the ejected materials were in the form of lava-flows which were belched out of the pit crater, filled up the inner somma, overflowed it, then ran down the flank as streams of several metres' width, and at last spread over the wide area of the atrio. Incandescent lava, above 1100°C at the time of ejection, was so fluidal that phenomena like lava-fountains and lava-pools could be seen. The lava started as incandescent fluidal streams, and became more and more viscous at downstreams with stiff skins on them, by loss of heat through radiation as well as through liberating gases. Many vesicles of a little distorted form, the diametre of which ranges from several centimetres to about a millimeter, scatter in the solidified rock especially densely near its clinkery surface. Most of the solidified lava-flows may be classified into the aa type because of their clinkery, jagged or fragmental surface¹⁾. But there were seen in places ropy flows which may be classified more properly as the pahoehoe type although the surface was not so smooth. Beneath the fragmental surface of the aa type flow, we can often see a continuous layer of non-fragmental rock. Investigations on viscosity and temperature of flowing lava were carried out by T. Minakami and others²⁾. The mode of flowing was also described by T. Minakami. It appears very interesting as well as useful to study the relations existing among such volcanic phenomena as fountain and flow, physical and petrographical properties of the lava. The present writer has been interested in the laboratory experiments of rocks at high temperatures, and intended to investigate the lava from Oosima too.

1) G. A. MACDONALD, *Am. J. Sci.*, **251** (1953), 169.

2) T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **29** (1951), 427.
Jour. Geography, Tokyo, **60** (1951) (in Japanese).

Method.

As stated in the previous papers³⁾, the bending or sagging method of experiment was adopted. A thin plate of lava-specimen (ca. 0.3 cm × 8 cm × 1 cm) is supported between two knife-edges of fused silica and is loaded at the centre through another knife-edge or sags due to its own weight. The whole contrivance, chiefly made of special porcelain, is inserted in an electric furnace. The electric furnace of platinum wire was used only for the experiments above 1100°C and most of the experiments were carried out in the electric furnace of nichrome wire. The uniformity of temperature in the furnace was satisfactory. The temperature was indicated by a Pt-PtRh thermocouple inserted closely to the specimen, and the temperature was raised and lowered through manual regulation of electric supply always slowly enough to render the difference of temperature less than ±5°C between the surface and inside of the specimen. The specimen was heated and cooled nearly quasi-stationarily, and in addition, it was kept in a constant temperature from at least ten minutes before to the end of one series of measurements.

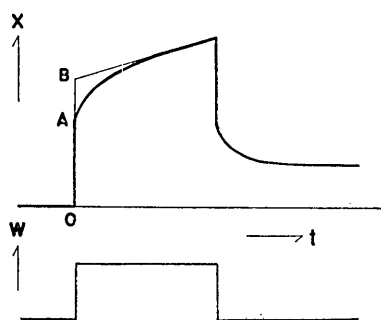


Fig. 1. Deformation (X) of a viscoelastic body under constant load (W).

Thus the experiments were done under nearly constant and uniform temperatures. Various constant load, less than 600 gr, were applied to the specimens. When a load is applied, the specimens show more or less visco-elastic behaviours as shown on Fig. 1. That is, after a sudden elastic deformation, there takes place anelastic relaxation with decreasing velocity which tends to be constant as time goes on, representing the viscous flow of material.

Amount of deformation is measured by doubly reflected light through two prisms on both ends of the specimen. As mentioned in the previous report, the observed subsidence at the centre (x) is expressed as follows,

$$x = \left(\frac{Wl^3g}{4bd^3} + \frac{5wl^4g}{32bd^3} \right) \left\{ \frac{1}{E_V} \left(1 + \frac{t}{\tau} \right) + \left(\frac{1}{E_R} - \frac{1}{E_V} \right) \left(1 - e^{-\frac{t}{\tau}} \right) \right\},$$

where W : applied weight,

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

- w : weight of specimen of unit length,
 b & d : width and thickness of specimen,
 l : distance between knife-edges,
 E_U : unrelaxed Young's modulus,
 E_R : relaxed Young's modulus,
 τ & τ' : relaxation times.

Viscosity is derived from the following equation which is based on the assumption of incompressible viscous liquid.

$$\eta = \frac{\tau E_U}{3} .$$

τ can be calculated on the basis of the terminal velocity of deformation under constant load.

As a dimensionless measure of anelasticity, another quantity $\Delta_B = \frac{E_U - E_R}{E_R}$ is introduced after Zener⁴⁾. This quantity may be correlated to other physical constants such as thermal expansion coefficient, as has been done in the field of metallurgy.

Specimens.

The following three kinds of lava specimens were examined. (Fig. 9. a-c.)

(1) Glassy lava. (G). Collected on the top of the inner somma. The lava was one of the most fluidal flows in the 1951 activity. The detailed descriptions of this flow which went through the windows of Kakô-Jaya was given by H. Foster⁵⁾. The specimen was taken from a side of the flow near the Kakô-Jaya. Beneath the clinkery surface, there was a comparatively uniform layer with many vesicles. The largest of the vesicles was about one centimeter and most of them were smooth but a little distorted. Colour of the rock is dark black. Glass in the groundmass is the richest among the tested three kinds. Three specimens of this kind were tested in the laboratory.

(2) Lava of high crystallinity (H). Collected from a crack in the typical massive phase of aa. There are many deep cracks in the 1951 lava-flows which buried the inner somma, especially around the former pit crater. The present specimens were collected from the bottom of one of those cracks which were several metres deep. The surface of

4) C. M. ZENER, "*Elasticity and Anelasticity of Metals*", 1952, Chicago.

5) H. L. FOSTER & A. C. MASON, *Am. J. Sci.*, **251** (1953), 249.

the flow is not so clinkery. The rock is of light black colour and contains fine vesicles only scarcely. Glass can be seen in the groundmass very rarely. Plagioclase as phenocryst is more equigranular than G. Two specimens of this kind were tested in the laboratory.

(3) Intermediate lava (I). It was collected and described by R. Morimoto and others, and was afforded to the writer. Quantity of glass is intermediate between the two described above. To be more precise, however, the glass is slightly less than the G and far more than the H. Three specimens of this kind were treated in the laboratory. These kind of specimens were formerly⁶⁾ tested under various conditions such as repeated heat-treatments.

Generally speaking, though the three kinds of specimens differ in their quantity of glass and regularity of microlites in the groundmass, the difference is rather little. All of the lava-flows where the specimens were taken may be classified at the aa type, in spite of the above-mentioned difference in appearance. The area of crystalline part distinguishable on the respective photomicrographs (Fig. 9) was measured. It gave the results of 50%~60% glass for G, 40%~50% glass for I, and about 10% glass for H. These numbers are not so exact, because extremely small crystallites and some crystallites in extinction-angle were omitted. But difference of crystallinity is fairly reflected.

Petrographical features of the 1950-51 lava were studied by H. Tsuya, R. Morimoto and J. Ossaka⁷⁾. According to them, fixed constituents of the lavas and fragmental ejecta are the same during the changing phase of the activities, and they are identified as an uniform augite-hypersthene-bytownite basalt. This basalt contains anorthite, bytownite, hypersthene and augite as porphyritic minerals scattered in the groundmass composed of bytownite, pigeonite, iron ores and glass. Porphyritic structure is not so remarkable; phenocrysts occupy 5-10% of the rock in volume, they are seriate to the groundmass minerals in size in the higher crystalline portion of the rock.

The specimens which were heated up to 1150°C and cooled slowly or quenched into water suffered no remarkable petrographical changes, but glass in the groundmass became black owing to oxidation of iron. Further development of crystallization by heating was not ascertained microscopically. But more minute studies should be done in this connection.

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

7) H. TSUYA & others, *Bull. Earthq. Res. Inst.*, 29 (1951), 563; 30 (1952), 231.

The necessitated size for the present method of experiment restricted the available kind of specimen. Specimens of different petrographic properties and of different type of flow, as various as possible, were to be tested. But we could not examine the specimen from the most glassy part of the flows because of its smallness in dimension. Some specimens were abandoned because of their fragileness due to rapid cooling and to too much included gas bubbles. Thus the available sort of specimen was restricted to some extent.

Results of Experiments.

A part of this series of experiments has been made public in which the intermediate lava in the temperature range of 0°–1100°C was treated. The points which were stressed in the paper were as follows.

(1) Young's modulus increases with temperature up to a certain critical temperature (T_c) at the first heating, and it decreases abruptly at a higher temperature. (Fig. 2)

(2) Young's modulus in cooling differs from that in heating. It also varies with the highest temperature (T_M) which the specimen was treated with in the laboratory.

(3) Repeated heating and cooling of one specimen result in elevation of T_c .

(4) Viscosity coefficient decreases with the rise of temperature, but its value is exceedingly higher than that observed in the field in its natural molten state.

(5) Viscosity increases as heat-treatment is repeated.

Concerning the unrelaxed Young's modulus, the tendency of increasing elasticity in heating was found to be common to all of the present three types. However, the critical temperature T_c at which the modulus shows a decrease differs from one another (Fig. 2–5). The following fact should also be noticed. The T_c of the glassy specimen is nearly the same as that of the intermediate one in the initial heating stage, and the T_c of the intermediate one in the second and third heating falls close to the T_c of the lava of high crystallinity. The temperature at which E_V is maximum is adopted as T_c in the Table I. Another temperature of the same curve is listed for reference, where $\left| \frac{\partial^2 E_V}{\partial T^2} \right|$ is maximum. The relaxed Young's modulus changes in the similar way as the unrelaxed modulus, though the value of E_R is less accurate.

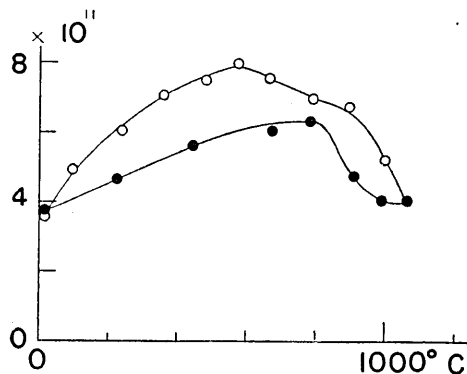


Fig. 2.

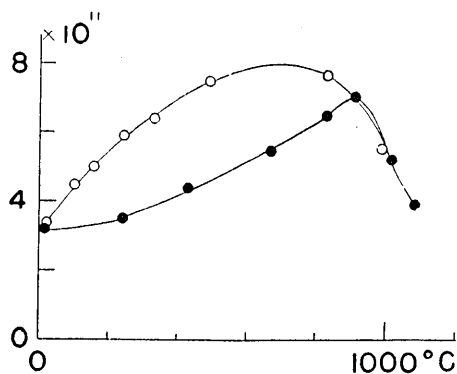


Fig. 3.

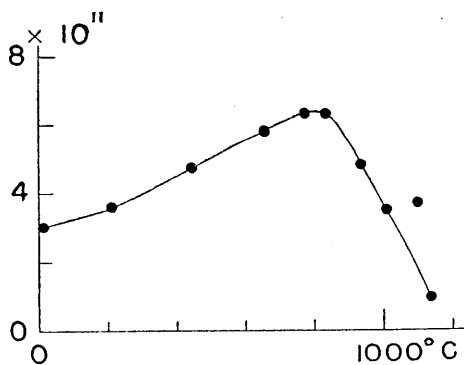


Fig. 4.

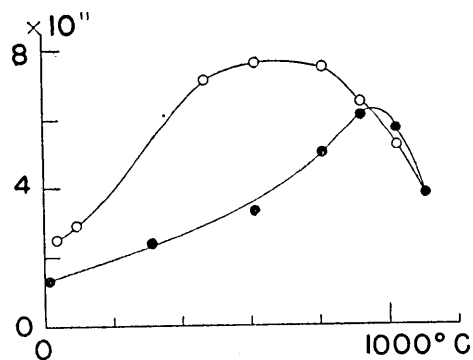


Fig. 5.

Fig. 2. Unrelaxed Young's modulus (in dyne/cm²) of intermediate lava at the first run. filled circles: heating, open circles: cooling.

Fig. 3. Unrelaxed Young's modulus of intermediate lava at the second run. filled circles: heating, open circles: cooling.

Fig. 4. Unrelaxed Young's modulus of glassy lava.

Fig. 5. Unrelaxed Young's modulus of the highly crystalline lava. filled circles: heating, open circles: cooling.

Table I. Critical Temperature for Elasticity of Oosima-lava.

Specimen	$\frac{\partial E_U}{\partial T} = 0$	$\frac{\partial E_R}{\partial T} = 0$	$\left \frac{\partial^2 E_U}{\partial T^2} \right = \text{max.}$
Glassy	790°C	760°C	800°C
Intermediate 1st heat	800	680 (?)	830
Intermediate 2nd "	910	950	940
Intermediate 3rd "	930	820	950
High crystallinity	950	920	950

Difference in the critical temperature of elasticity among various kind of lavas is also reflected in Δ_E . Glassy lava is distinctly more anelastic than the crystalline lava. Δ_E of the intermediate one is intermediate, but it is omitted on the Fig. 6 for simplicity's sake. Concerning the relaxation time τ' of strain under constant stress, there is found little decisive difference among the various specimens. (Fig. 7)

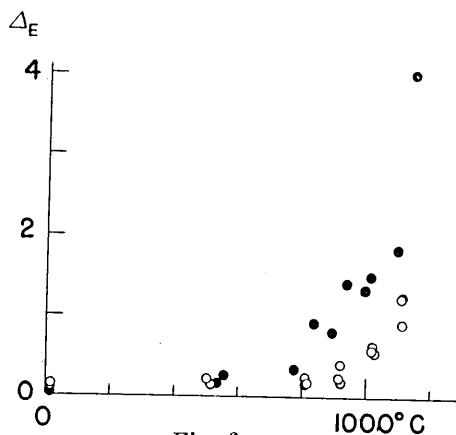


Fig. 6.

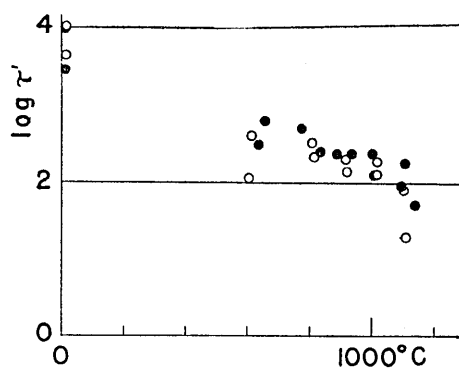


Fig. 7.

Fig. 6. Variation of Δ_E with rising temperature.

filled circles: glassy lava, open circles: crystalline lava.

Fig. 7. Variation of relaxation time (τ') with temperature (in seconds).

filled circles: glassy lava, open circles: crystalline lava.

Table II. Chemical Composition of Specimens.

Specimen Experi- menter	1950 lava ⁸⁾ (Intermediate)	Somma lava
	Sakuma	Kani
SiO ₂	52.02	51.80
Al ₂ O ₃	15.83	15.00
Fe ₂ O ₃	2.28	3.68
FeO	10.80	10.14
MgO	4.47	5.36
CaO	9.48	9.77
Na ₂ O	1.58	1.76
K ₂ O	0.29	0.32
H ₂ O ₊	0.99	0.62
H ₂ O ₋	0.24	
TiO ₂	1.52	0.60
P ₂ O ₅	n.d.	0.31
MnO	0.09	0.20
Total	99.59	100.56

8) H. TSUYA & others, *loc. cit.*, 7).

Remarkable difference could not be found among the viscosity coefficients of various specimens. The coefficient η of the *H*-lava looks only a little greater than that of *G*-lava. One very significant fact was found concerning viscosity, however. (Fig. 8) That is the abrupt decrease

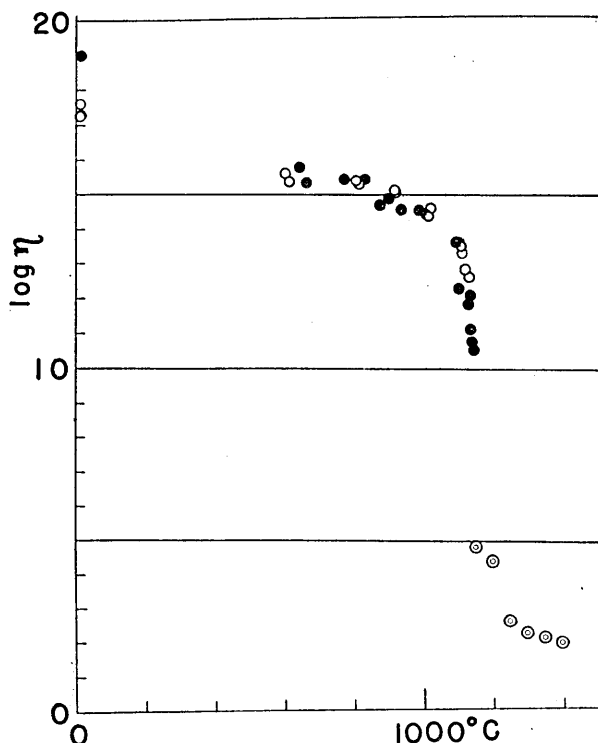


Fig. 8. Viscosity coefficient of remolten lavas (in poises).

filled circles: glassy lava,

open circles: crystalline lava,

double circles: somma lava (from K. Kani's experiment).

of viscosity, or increase of fluidity, within the narrow limits of 30~70 degrees above 1100°C. The present bending or sagging method failed above the temperature where η became less than 10^{10} poises. Fortunately, the results of K. Kani's experiments can be cited.⁹⁾ He had remolten the lava of the outer somma of Oosima between two concentric cylinders and had measured its viscosity from 1400°C down to 1150°C. Its chemical composition is not so much different from those used in the present experiments. His results are also illustrated on Fig. 8. A glance at this

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

figure will be sufficient to convince us of the existence not of the discrepancy between the two different experiment but of some discontinuity in physical properties caused by some phase change. T. Nagata¹⁰⁾ also found out a discontinuity in the electric conductivity of remolten Oosima lava at about 1130°C. Accordingly, it leaves no doubt that the Oosima lava "melts" at about 1130°C when it is reheated in laboratory. Kani ascribed the sudden increase of viscosity below 1250°C to crystallization of plagioclase and magnetite.

The viscosity coefficients which were estimated in the field in its natural molten state by several authors¹¹⁾ were exceedingly lower than the present results. Measurement of viscosity of the same specimen could not be repeated after it was heated above 1130°C, for the reason that the specimen suffered too much deformation to be tested again. It can be inferred, however, from the experiences in the former experiments up to 1100°C, that the repeated heat-treatment always renders the lava more and more viscous. Even the initial heating in the laboratory should correspond to the reheating of the specimen which had already experienced heat in its natural state. Accordingly, one cannot reproduce the state of matters in the natural molten lava-flow exactly by simply reheating the solidified lava.

Discussions.

The writer would like to refer to the following three problems on the basis of the experiments. They are: (1) Can we infer the dynamical properties of the natural molten lava from the result of the laboratory experiments?, (2) What part of the mentioned physical properties of the specimens can be correlated with their petrographical features?, (3) Can we explain the origin of various forms of lavas, such as aa or pahoehoe, on the basis of their respective dynamical properties?

Major characteristics of the dynamical properties were found to be common to all of the tested specimens. They were the increase of elasticity with rising temperature, the decrease of elasticity above T_c and the decrease of viscosity with temperature especially abrupt above 1100°C. Difference among the three kinds were rather small, but none the less important. Difference itself, if any, even it be small, is a precious key. The difference was comparatively remarkable in T_c and Δ_B .

10) T. NAGATA, *Bull. Earthq. Res. Inst.*, **15** (1937), 663.

11) T. MINAKAMI, *loc. cit.*, 2).

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

The difference in T_c should have been caused by the quantity as well as quality of glass in the groundmass, because all of the specimens are similar in their phenocrysts and microlites. When the glassy rock is reheated and recooled in the laboratory, the dissolved gases may probably escape and incipient crystallization may be hastened. Such phenomena like devitrification are frequently met in glass techniques. If we assume that the mentioned process of crystallization can take place submicroscopically as well, it will be naturally accepted that the G-specimen behaves like the crystalline one in the second heating run.

Another consideration should be taken before inferring how the elasticity of the natural molten lava varies with cooling. The "cooling" experiment in the laboratory has one essential defect. All cooling experiments must inevitably be conducted after the cooling in the nature and the first heating in the laboratory. And in consequence, the experimental values of elasticity in cooling are very much affected by the highest temperature T_M . Subsequently the present writer cannot help hesitating in applying the result of cooling experiment directly to the lava in the natural state. It seems more reasonable to suppose that the essential feature of change of elasticity in nature would be better reflected in its change in the first "heating" in the laboratory, especially as regards the glassy specimens. There is no doubt that the cooling lava in the field contains much more gases in its liquor and is of lower crystallinity than the tested glassy specimen at the same temperature. Accordingly we may well infer the most probable change of elasticity in the cooling natural lava by extrapolating the character and its change of the glassy specimen. We come to imagine naturally that the T_c must have been lower in the natural lava than that observed in the laboratory.

After all, elasticity of the Oosima lava in its natural state would have varied as follows. Elasticity is very faint above 1250°C, with scattered phenocrysts in fluidal liquor. The lava becomes slightly elastic below 1150°C with abrupt development of crystallization. A part of the separated gases is dissolved in the liquid phase and lessens the viscosity as well as the elasticity of it. Other part of the gases forms vesicles and decreases the apparent viscosity and elasticity of the flow, until it is liberated at last in the air. The liberation of gases has a threefold effect. It increases apparent elasticity and viscosity, develops crystallization and deprives heat. The temperature thus decreasing, elasticity increases down to around 700°–800°C, where the elastic modulus is at least nearly same as the value at the room-temperature. Elasticity

may probably increase a little further at lower temperature, because the internal stress increases due to the forced crystallization in highly viscous liquid which has long relaxation times for stress. The modulus tends to decrease, however, near the room-temperature because of release of stress due to thermal contraction of constituent minerals. The solidified lava is not under perfect thermodynamical equilibrium, but remains as the aeolotropic mixture of crystals and highly viscous quenched liquid with gases. When the specimen is heated again in the laboratory, its elasticity increases at first because of stress by expansion of crystals, and then decreases at the temperature where the thermal stress relaxes rapidly and some part of material comes to melt. Heat-treatment in the laboratory always develops crystallization and liberates dissolved gases and results in the approach of its elasticity to that of the highly crystalline lava.

τ' , the time of anelastic relaxation, is a result of various diffusions within the specimen. Δ_B has a similar character. It is related to the change of entropy in specimen. But increase of Δ_B may possibly have more intimate relations to randomness of arrangement of crystallites than to that of atomic scale. Both τ' and Δ_B are undoubtedly connected also to the liquid viscosity η implicitly, but they do not always vary in parallel, as shown in the previous report of the writer. Judging from the distinct higher value of Δ_B of G than H , we can expect more higher Δ_B for the natural molten lava, which means poorer relaxed elastic modulus in the natural state.

We will next discuss the most important part, that is, the viscosity of the lava. The abrupt change of viscosity at about 1130°C is remarkable in itself and distinguishes the Oosima lava from the other formerly tested rocks such as obsidian. But the viscosity of the natural molten lava is believed to be less than the value obtained in the laboratory. Similar state of matters, as mentioned above under the item of natural elasticity, should have occurred concerning viscosity as well. The irreversible physico-chemical processes, such as liberation of gases and resulting crystallization, is not reproduced perfectly in the experiment. The temperature of 1130°C must be a kind of eutectic point, but it is the eutectic point under a certain definite circumstance. If the circumstance, the quantity of gases dissolved in the liquor phase for instance, changes the temperature will shift inevitably. Although the observed difference in viscosity between the glassy and crystalline specimens was rather small, it seems more proper to think that the critical temperature

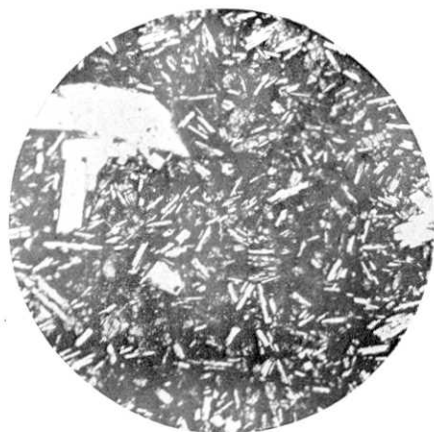
for viscosity also would be somewhat lower than 1130°C in the natural molten lava. Besides the just mentioned physico-chemical condition, the apparent viscosity of lava as a mass is expected to be reduced much more, if more vesicles are included.

Other factors like the cooling velocity or quantity of remnant gas also affect the physical properties of rocks considerably. The crystallinity, or the quantity of glass, was adopted here as a parameter including these factors. The relations of crystallinity itself to the physical properties should be discussed after more detailed studies subsequently.

The writer wishes to make some remarks on the possible cause of formation of aa and pahoehoe, though the specimen of typical pahoehoe was not treated in the present experiments. The main differences of pahoehoe from aa are its smoothness of the surface, smooth spheroidal vesicles inside and the lower crystallinity at least near its surface. The cause of such differences has been ascribed to the circumstance when the lava is solifying. The undistorted vesicles in pahoehoe might possibly imply also the existence of part or all of the following factors, i. e. high internal pressure of gas, more fluidity just before consolidation and greater gradient of increase of viscosity with cooling. The present experiment, however, could reveal any distinct difference between glassy and crystalline specimens neither in their absolute value nor in the critical temperature of change of viscosity. Consequently, possibility of existence of original difference in viscous properties between the aa-making lava and pahoehoe-making lava seems to be rather small, and the rôle of mechanical disturbance around the critical temperature was proved as a result to be of more importance, as already pointed out by many authors¹²⁾. Turbulent motion inside the lava-flow, due to topography for instance, causes liberation of more gases, develops crystallization and increases viscosity in parallel. The jagged surface and distorted vesicles which are the feature of aa, are considered to have resulted from further movement such highly viscous lava. Another experimental fact, i. e. the fact that the elasticity of glassy lava is less at some range of temperature than that of crystalline lava, should be recollected too. It means that glassy surface is much more extensible at around 800°-900°C than the surface of the crystalline lava. Even though the skin must be broken by the stress greater than the tensile strength of the material, the higher extensibility of glassy skin may also contribute to the for-

12) G. A. MACDONALD, *loc. cit.*, 1).

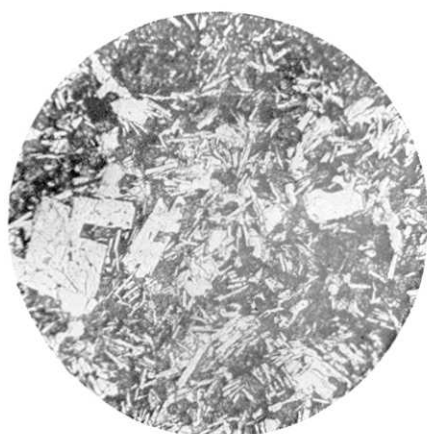
O. H. EMERSON, *Am. J. Sci.*, Ser. 5, 12 (1926), 109.



(a) Glassy lava ($\times 36$)



(b) Intermediate lava ($\times 36$)



(c) Crystalline lava ($\times 34$)

Fig. 9 a.-c. Photomicrographs of lava-specimens.

mation of pahoehoe lava to some extent.

We have here tried to infer the characters of the natural fresh lava from the results of experiments in the laboratory. The results of experiments are useful in the study of volcanic phenomena, though we should be careful enough in applying the results to the natural phenomena.

In concluding, the writer wishes to express his cordial thanks to Dr. T. Minakami, Dr. R. Morimoto and Mr. J. Osaka for their kind advices and criticisms as well as for the facilities given to the writer.

28. 高温に於ける火山岩の粘性及び弾性 第3報 大島熔岩

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前と同じ撓み法で、室温から約 1150°C 迄の領域で下記 3 種の大島熔岩を徐々に加熱した場合の力学的性質の変化をしらべた。

その一 (*G*) は流動的であつた熔岩流の表面近くにあり、石基にガラス分をやや多くふくみ、その二 (*H*) は熔岩池深部で固結し、石基の結晶度が高い。その三 (*I*) は第 1 報にものべてある試料で、前二者の中間にあたる。

加熱するとヤング率は徐に増し、或温度 (T_0) 以上では急に減少する。 T_0 の値は *G* が最も低く約 790°C、*H* では約 950°C であるが、*I* では第 1 回加熱では *G* にちかく第 2 回以後は *H* にちかい値となる。即ち加熱によつて T_0 は上昇する。

Anelasticity の度をあらわす量 $\Delta E = (E_U - E_R) / E_R$ については *G* が *H* より明かに大い。至緩和時間 τ' については大差がない。粘性係数 η についても各種熔岩の間の差異は著しくないが、1130°C 附近に於て融解と考えられる粘性の急変が見出された。

自然の熔岩流は、結晶度や、液相に溶解し或は分離して気相となつている gas 量の点で実験試料と全く同じではないであろう。しかし実験室で得られた上述の力学的性質を、よりガラス質且より気体の多い状態に外挿することにより、自然の熔岩流の力学的性質を想像し得るであろう。

尚、800~900°C 附近に於てガラス質熔岩の弾性が結晶質熔岩のそれより小さい、即ち伸び易いことは、pahoehoe 型、aa 型など熔岩流の型の成生に若干の関係があると思われる。