45. *On the Temperature and Viscosity of the Fresh Lava Extruded in the 1951 Oo-sima Eruption.*

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1. Introduction.

It is well known that the nature of volcanic eruption depends closely on the chemical and petrological characters of extruded lavas, or in other words, on whether they are basalt, andesite or dacite etc.. In fact, the eruptions of the Hawaiian volcanoes, Oo-sima and Miyake-sima, Asama and Sakura-zima, and Usu show respective characteristics in the manner of extrusion of lava and in their subsequent phenomena, and on the other hand, their extruded lavas in recent years are respectively characterized by the olivine basalt, the oversaturated basalt (or tholeitic basalt), pyroxyne andesite and dacite. However, what seems to be an important clue for determining the nature of eruption is the viscosity of intruded and extruded lavas which vary greatly according to their chemical compositions including gas content and their temperature.

Although several experiments on this problem have been conducted up to the present, our knowledge concerning the fluidity of molten lava at the instant of extrusion is yet quite unsatisfactory, the experiment based on actual phenomena being not always simple in its method.

We can, however, obtain some information from laboratory experiments, though the nature of rocks dealt with in the laboratory does not always represent that of fresh lava at the moment of ejection, specially in respect to the volatile gas content.

In order to obtain data on this problem, the writer conducted measurements of the temperature and viscosity of molten lava which spurted out in the 1951 eruption of Oo-sima, which shall be the main subject of the present report.

2. The Nature of the 1951 Lava-Flows of Oo-sima.

In the 1950 eruption of Oo-sima which lasted for 70 days from July 16 to September 23, the molten lava which first buried the pit crater, 200 m in its depth, and then filled the atrio of the inner somma, overflowed at last from the two lower places of this somma forming several narrow streams. After a period of quiescence for four months, the Oo-sima volcano resumed its activity at the beginning of February 1951, when the molten lava spouted abundantly in the manner of fountain as was the case in the 1950 eruption and, forming several lava streams, descended the flank of the inner somma towards the sand sea or the caldera surrounded by the outer somma.

Since the sources of extruding lava and these lava flows were easy of approach, the writer, on March 19, 1951, carried out measurements of the temperature of fresh lava and obtained data necessary for determining its viscosity, including the flowing velocity of the lava flow. It will be needless to say that, for the determination of the relation between the two quantities, it is necessary to measure the temperature as precisely as possible, because the viscosity of lava depends remarkably on its temperature. For this purpose, the temperature measurements were carried out with the aid of two kinds of thermo-junctions, one being platinum—platinum-rhodium and the other copper—constantan.

Since the lava streams were in a molten and incandescent state, and we could easily poke a wooden stick into them, we were able to measure not only the temperature of the surface but also that of the interior part.

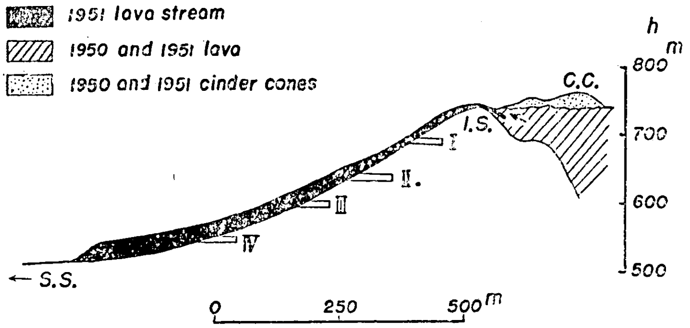

Fig. 1. The 1951 lava stream along the flank of the inner somma and the four positions for the present observation.

Since both ends of the junction used for the present investigation were protected by an unglazed porcelain tube, of which the end was closed, it took at least ten minutes to obtain the equilibrium temperature between the molten lava and the hot junction. However, we had to carry out the measurement within several seconds for the temperature of the lava which was flowing at a speed of over 50 cm per second. For this purpose, 5 cm of the closed end of the tube was cut off and the hot junction was put in direct contact with the molten lava. As the result of that, it was possible to reduce the time required for measurement to five seconds.

During the present investigation, four lava flows, each of which formed a narrow stream, were descending the western flank of the inner somma, of which the inclination is measured as 35° at the upper part and gradually decreases in steepness towards its base. Of these lava streams, the writer chose a stream flowing on the southern most side as the main object of the present investigation, and measured various elements at four positions of this flow including the upper stream near the source.

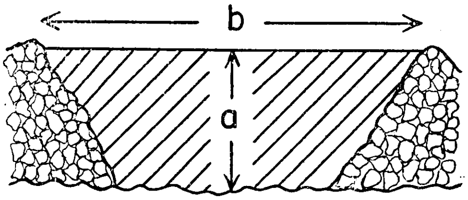

Fig. 2. The section of the flowing lava stream.

The thickness of various parts of this stream was measured by a wooden stick which we could easily poke into it. On the basis of the investigation just mentioned, the profile or the section of the stream was made as is shown in Fig. 2. In this figure, the banks at both sides of the stream were formed by accumulation of lava blocks of rather small sizes which fell off from the lava flow in its downward course.

The lava stream from its source to a distance of 300 m, including the upper three positions (I, II and III) was in a molten and jelly-like state. However, in the vicinity of position IV, its surface which is 5° or 7°C cooler than its interior, was covered by a thin layer, 2–3 cm in thickness, of gum-like character, and at the distance of more than 500 m from its origin, its surface came to be markedly cooled and covered by solidified lava blocks of small size, forming the aa-type flow, though the inner part was still fluidal and incandescent, being 1000°C–1030°C in its temperature. Therefore, the flowing velocity at the surface of the middle stream between 300 m and 500 m from its source was to some extent, reduced as compared with the flowing velocity at a slightly deeper part, and as is illustrated in Fig. 3, the velocity distribution of a section of the stream shows features varying in accordance to the distance from its source.

The elements necessary for determining the viscosity of lava, namely, the thickness, width, maximum flowing velocity and inclination of the slope, each of which was measured at the four positions mentioned above, are given in Table I.

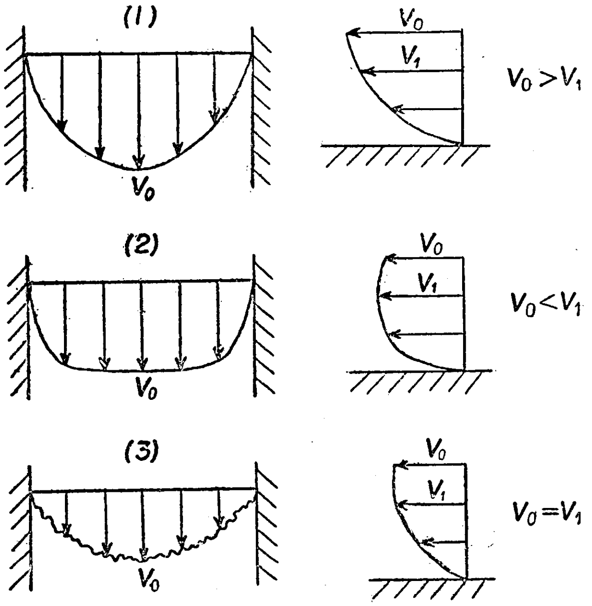

Fig. 3. Distribution of the flowing velocity of the lava stream.

V_0, surface velocity. V_1, inner velocity.
(1) upper stream. (2) middle stream.
(3) lower stream.

Table I. Elements for determining the viscosity of flowing lava.

Position	Thickness (a)	Width	Inclination (φ)	Max. flowing vel. (v)
I	31 cm	110 cm	35°	102±8 cm sec.
II	50	160	27	35±4
III	77	210	16	15±3
VI	130	250	11	8±2

3. The Viscosity and Temperature of the Fresh Lava Extruded in the 1951 Eruption of Oo-sima.

To simplify the calculation of the viscosity of lava, the problem is here dealed with as a two-dimensional flow, and with respect to the form of the section of the stream, the following two cases are considered. In the first case, in which the stream is remarkably wide and of a constant thickness, and therefore hardly affected by the internal friction given from both sides, the viscosity coefficient (η') is given by the following relation with the elements in Table I;

$$\eta' = \frac{\rho g \sin\varphi}{2v} a^2 .$$

In the other case, in which the form of the section is replaced by a semi-circle and its radius is taken similar to the thickness of the stream, the relation between the viscosity coefficient and the other elements is expressed by the following formula,

$$\eta = \frac{\rho g \sin\varphi}{4v} a^2 .$$

The values of the viscosity coefficient based on the above extreme cases are connected in the following relation,

$$\eta' = 2\eta .$$

Therefore, seeing that the present research is to examine the number of the figure of the viscosity coefficient, it will be sufficient for this purpose to apply either the former assumption or the other. Although, strictly speaking, the actual case assumes an intermediate character between the above two extreme cases, the latter assumption is naturally more adaptable to the 1951 lava stream dealt with in this paper than the former. Thus the values of the viscosity coefficient given in Table II are calculated by the latter formula.

Table II. The viscosity coefficient and temperature of the molten lava measured at a lava stream of the 1951 Oo-sima eruption.

Position	Vis. coef. (η)	Temperature (θ)
I	5.6×10^3 poises (C.G.S.)	1125°C
II	1.8×10^4 〃	1108 〃
III	7.1×10^4 〃	1083 〃
IV	2.3×10^5 〃	1038 〃

It must be added that each element concerning the lava flow given in Table I includes an observation error of about ten per cent, so the true value of the viscosity is estimated to range from twice to half of the obtained value.

As mentioned already, the temperature of the flowing lava was precisely measured at the four positions (I–IV), the result of which is shown in Table

II, together with the viscosity coefficient at the respective temperature. As will be seen clearly in Table II, the fresh lava at the position I, 10 m distant from its outpouring source shows 1125°C in its temperature and 5.6×10^{3} poises in its viscosity, and that at the lower position IV, 400 m distant from the origin, 1038°C and 2.3×10^{5} poises respectively.

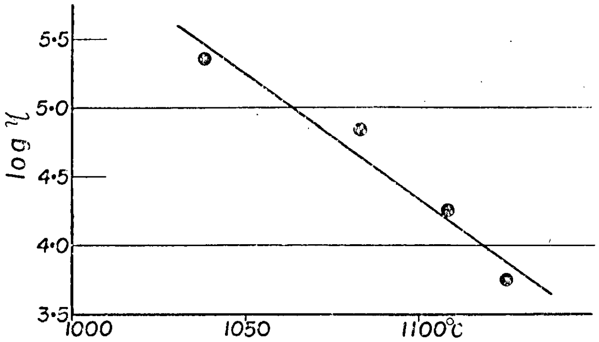

Fig. 4. Temperature and viscosity coefficient of the Oo-sima lava measured in the present investigation.

The relation between the two kinds of quantity, temperature and viscosity, based on the present investigation, is expressed by the following formula at the range of temperature (θ) from 1000°C to 1150°C;

$$\log\eta = 6.155-0.0181\ (\theta-1000),$$
$$1150^\circ\mathrm{C}\geq\theta\geq1000^\circ\mathrm{C}.$$

From the above relation, it becomes clear that the viscosity of the present Oo-sima lava is doubled when the temperature at 1100°C or 1000°C falls by 11°C or 16°C respectively.

On the basis of the present investigation, it may be concluded that the 1951 lava of Oo-sima was 1200°—1150°C in its temperature and nearly 10^{3} poises in its viscosity in the course of intrusion into the vent and at the instant of extrusion.

Regarding the 1950 lava of this volcano, S. Murauchi[1] and I. Murai with their associates[2] measured its temperature with the aid of an optical pyrometer and its viscosity from its flowing velocity, the result of which is as follows;

Table III.

Temp.	Vis. coef.
1060°	1.7×10^{5} C.G.S.
1050	3.3×10^{7} 〃
1040	1.3×10^{5} 〃

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1) S. MURAUCHI, *Natural Science and Museum*, **12** (1950), No. 3 and 4.

2) I. MURAI, N. NASU and A. SUGIMURA, *Read at the Meeting of E.R.I.* (Oct., 1950).

Since an optical pyrometer was used for their temperature measurement, and the result thus includes an observation error of 30°C or 50°C at least, it is impossible to compare the 1951 lava with the 1950 lava with respect to their temperature and viscosity. However, the 1950 lava, at least in form of its flow, which overflowed after it had filled the atrio of the inner somma, seems to have been of lower temperature and of larger viscosity than those of the 1951 flow.

It must be added that R. Takahasi and T. Nagata[3] in 1937, gave 5×10^4 poises at 1060°C for the molten lava in the Oo-sima pit creater, from the observation of standing gravity wave on its surface and from the temperature measurement by means of an optical pyrometer.

It will be necessary to refer to the chemical and petrological properties of the present Oo-sima lava. According to H. Tsuya, R. Morimoto and J. Osaka[4] the 1951 lava is chemically and petrologically almost similar to those which flowed out in our historical age including the 1950 lava, being all characterized by the oversaturated basalt (or tholeitic basalt) of 52–53% in silica content, bearing no olivine.

4. The Pressure which acted under the Oo-sima Volcano in its 1951 Eruption.

To what degree did the pressure act under the Oo-sima volcano or on the lower end of the vent in the present eruption?

During the period from March 10 to 31, 1951, the molten lava was outpouring incessantly in a fountain fashion from four sources located near the western summit of the inner somma, of which the diameter was estimated at 70 cm - 120 cm respectively. From the present field investigation, it may be assumed that these jet-like sources were connected one another under the ground at the depth not exceeding 300 m, and the main conduit had an estimated diameter of 2–3 m. Moreover, the elevating velocity of molten lava passing through the main conduit is also estimated at 2–3 m per second from the outpouring velocity at the four sources.

Moreover, on April 6, 1951, a fountain-like eruption as may be seen in Fig. 8, occurred in the central part of the inner-somma and the height of the lava fountain and the diameter of its jet were estimated at about 10 m and 3–4 m respectively.

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[3] R. Takahasi and T. Nagata, *Bull. Earthq. Res. Inst.*, **15** (1837), 1047.

[4] H. Tsuya, R. Morimoto and J. Osaka, *Personal Communication.*

However, the pressure exerted at the part slightly deeper than the lower end of the conduit and necessary in ejecting the molten lava in the manner just mentioned, may be approximately expressed as follows;

$$P = P_1 + P_2 ,$$

$$P_1 = \rho g l , \qquad P_2 = \frac{4\eta v l}{a^2} + \frac{1}{2}\rho v'^2 ,$$

$$\text{where} \quad v' \doteqdot \frac{2}{3} v \quad .$$

In the above expression, the first term (P_1) represents the normal ground pressure at the depth l and second (P_2) the pressure necessary for driving the lava with a velocity v at the central axis of the circular conduit.

The ratio of the second term to the first ranges from 1/10 to 1/100 for the present two cases according to the above relation. In other words, if the subterranean pressure increases by one tenth of the normal ground pressure, it will be possible enough to cause such an eruption as in the present Oo-sima.

On the other hand, noticeable forerunning phenomena including earthquakes originating from the Oo-sima volcano did not appear in the 1950 eruption as well as in the 1951 one, notwithstanding the fact that those eruptions were the most remarkable ones on record of this volcano. This fact may be reasonably interpreted by the marked fluidity of the intruded and extruded lava and accordingly by the moderate pressure acting under this volcano even at its eruption.

In addition, as regards eruptions caused by such moderate pressure, it also depends on whether a conduit through which the fresh lava may extrude, exists or not, namely, on the structure of the volcano.

However, we do not lack facts supporting the assumption mentioned above, which were made clear from observations of volcanic activities of various types in Japan as well as in the other parts of the world.

For examples, the 1944 eruption of Volcano Usu[5], in Hokkaido, was preceded not only by severe earthquakes localized near the active crater, but also by marked rise of the ground, which resulted in the birth of a new mountain. The extruded lava in this eruption is characterized by the dacite of 70% silica content and of extraordinary high viscosity, forming a lava dome 100 m high without flowing. Moreover, since this volcano had no opened

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[5] T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **25** (1947), 65, 71; **27** (1949), 123, 129; **8** (1950), 145.
T. MINAKAMI, T. ISHIKAWA and K. YAGI, *Bull. Volcanol.*, **11** (1951), 45.

crater through which the fresh lava could extrude, the 1944 as well as the 1910 eruption[6] both occurred from the newly opened craters at the base of this volcano. Judging from these phenomena, it is quite natural to assume that a remarkable pressure was at work under this volcano not only in the midst of eruption, but also in the course of intrusion or at the pre-volcanic stage.

According to the eminent work of A. Lacroix[7], local earthquakes lasting for about two weeks preceded the 1902 eruption of Volcano Pelée, which resulted in the total lost of 26000 habitants of Saint-Pierre. Seeing that the extruded lava forming a 'Spine' and the dome at this eruption were in an exceedingly viscous state and not in a fluidal state, it will be reasonable to infer that an enormous pressure brought forth the extrusion.

Mt. Asama is noted for its severe paroxysmal eruption of the Vulcanian type which is characterized by rapid ejection of a large amount of incandescent lava for a moment in form of lava-block and volcanic bomb including fine ejecta. Recent eruptions of Asama always occurred in the summit crater, at the bottom of which the fresh lava usually appeared. The Asama lava[8] extruded in our historical time, is characterized by the two pyroxyne andesite with 60-62% silica, and its viscosity at the moment of extrusion, has an intermediate character between the Usu and Oo-sima lavas. However, the forerunning phenomena of the Asama eruption[9] including earthquakes and topographical deformations both of volcanic origin were not so remarkable as in the case of Usu, but they have been observed manifestly through instrumental investigations.

Finally, we must touch on the Hawaiian volcanoes, of which the eruptions are characterized by abundant outflow of fluidal lava from their summit craters and sometimes from their flank fissures. According to chemical and petrological researches, the extruded lavas are mainly of the olivine basalt containing 48-50% silica.

T. A. Jaggar, R. H. Finch and G. A. Macdonald[10] of the Hawaiian Volcano Observatory have studied strenuously the volcanic phenomena of these volcanoes for about 70 years. By their researches, it may be said that the eruptions of Kilauea and Mauna-Loa are not always preceded by numerous earthquakes and marked land deformations so evidently as in the cases of Usu and Asama etc.,

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[6] F. OMORI, *Bull. Imp. Earthq. Inv. Comm.*, **5** (1911), 1 and **9** (1920), 41.

[7] A. LACROIX, *La Montagne Pelée et ses Eruption*, (1904).

[8] H. TSUYA, *Bull. Earthq. Res. Inst.*, **11** (1935), 575.

[9] T. MINAKAMI, *Bull. Earthq. Res. Inst.*, **20** (1942), 431; *Bull. Volcanol.*, **10** (1950), 59.

[10] T. A. JAGGAR, R. H. FINCH and G. A. MACDONALD, *Vol. Let. etc.*,

though T. A. Jagger and R. H. Finch[11] succeeded in predicting several eruptions of Mauna-Loa including the 1935, 1940 and 1942 eruptions on the basis of the periodic cycle of its volcanic activity and sometimes of predominant earthquakes.

On the other hand, R. L. Nichols[12] obtained the viscosity of the Alika and 1887 flows of Hawaii by means of their flowing velocities with the result of 4.3×10^4 poises for the former and 4.8×10^4 poises for the latter, though their exact temperature could not be made clear. However, it must be added that these values of viscosity given by Nicholas does not represent those just after the outflow from the crater or at the instant of eruption. Moreover, H. S. Palmer[13] gave the viscosity coefficient of 1.5×10^{-1} poises for the same lava flow, which differs too much from that given by the former investigator. For this problem, R. H. Finch[14] concluded from his steady observations concerning the features of the molten lava at Kilauea and Mauna-Loa, that its viscosity must range from 10^2 to 10^4 poises. Judging from the nature of their eruption and the chemical character of extruded lava, his estimation may be reasonable and harmonizes with our expectation.

If the erupting lava is so fluidal as to be less than 10^2 poises in its viscosity, the Hawaiian eruption may have been caused by a pressure only slightly larger than the normal ground pressure, and as the result, without any marked forerunning phenomena, as in the present case of Oo-sima.

Although we are lacking in the exact and abundant knowledge of the physical properties of intruding lava it would be safe to say that the richer the silica content is, the less fluidal the fresh lava at the moment of eruption and in the course of intrusion is.

In any case, it may be said that the fluidity of fresh lava is closely related not only with the nature of eruption but also with its forerunning and subsequent phenomena.

5. Comparison of the Present Result with the Laboratory Experiment.

Since we have not much opportunity available for investigating the character of the molten lava in field, several investigators have made the experiments of

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11) G. A. MACDONALD, *Am. Jour. Sc.*, **241** (1943), 241; P. E. SCHULZ, *Bull. Geol. Soc. Am.*, **54** (1943), No. 6.

12) R. L. NICHOLS, *Jour. Geol.*, **67** (1939), 290.

13) H. S. PALMER, *Bull. Hawaiian Vol. Obs.*, **15** (1927), 1.

14) R. H. FINCH, *Vol. Let.*, **480** (1943), 2.

viscosity and temperature of lava remolten in laboratory. Of these laboratory works, K. Kani[15] carried out one concerning various basaltic rocks including the Oo-sima lava forming the outer somma of this volcano, of which the chemical composition is almost similar to that of the 1951 lava.

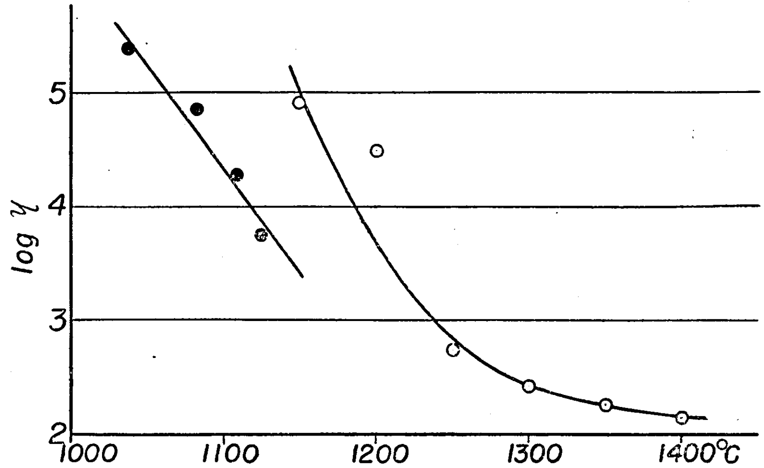

Fig. 5. Comparison of the present result with the Kani experiment: closed circle, the present result, opened circle, K. Kani's result.

In Fig. 5, the result of his experiment is compared with that of the 1951 lava in the natural state, with which the foregoing paragraphs dealt. A glance of this figure shows that the remolten lava is exceedingly viscous as compared with the lava in field as the same temperature, or to be more exact, the former is nearly 5×10^4 poises and the latter 4×10^3 poises both at the temperature of 1150°C.

It is, however, believed that the discrepancy between the above two cases, the one in the natural state and the other in laboratory, is mainly caused by the richer content of gas in the former. Although a more suitable interpretation is necessary for the result obtained in laboratory, valuable informations concerning the characters of the fresh lava will be surely supplied from experiments on remolten rocks.

In addition, the relation concerning the mobility or viscosity of various lavas and their chemical composition, specially their silica content as mentioned in the previous paragraph, is supported, at least in its qualitative character, by the

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[15] K. KANI, *Proc. Imp. Acad.*, **10** (1934), 79.

laboratory experiment made by M. Volarovic[16]. According to his research, the viscosity of basalt (49% silica), Techenite (51% silica) and andesite (64% silica) is 1.1×10^3, 1.3×10^4 and 4.0×10^4 poises respectively at the temperature of 1150°C.

The writer proposed in this report an hypothesis concerning the relation of the mobility of fresh lava with the nature of eruptions of respective volcanoes and their forerunning phenomena, but there must be many faults in this research. It is, however, his desire that this difficult but interesting problem be developed with the aid of precise and newly planned observations of the active volcanoes throughout the world.

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45. 1951 年に噴出した大島熔岩の溫度と粘性について

地震研究所　水　上　武

火山の噴火は各々の火山によつて夫れ夫れ著しい特性を示すことはよく知られている事實である。これを決定する重要な要素として噴出時の熔岩の粘性が著しく相異することを擧げることができる。

1951 年の大島の噴火に際して，噴出直後の熔岩流について，白金及び白金ロヂウムの熱電對を用いて熔岩流の表面及びその內部の溫度を測定し，同時に斜面を流れる速度から粘性係數を求め，兩者の關係を明かにした。その結果今回の大島熔岩の噴出時の或は噴出直前の溫度は 1150°C，その粘性係數は 10^3 poises (C. G. S.) 程度であつたことが明かになつた。これ位の小さい粘性の熔岩を地下から押し上げるために必要な壓力は安山岩質熔岩の場合に較べて桁外れに小さい事を示すものである。

一方ハワイ火山の噴出時の熔岩の溫度は 1200°C 位で大島のそれとは餘り相違しないが，その粘性は 1 poises 程度と推定されているから大島の約 1 千分の 1 に相當する。淺間山，櫻島等の安山岩質熔岩の噴出時の粘性は餘りよく測定されていないが，10^7 poises 以上，その溫度は 1100°〜1050° 位と推定されている。最近の有珠山の活動に於いて熔岩丘を形成した熔岩や，プレ火山の 1902 年のドームの熔岩は 10^{10} poises 程度と考えられる。

今迄に測定された結果によれば，玄武岩質の熔岩は酸性熔岩に較べてやや高い溫度で噴出している事を示してをり，從つてこの溫度の相異からその粘性が必然的に相異するわけではあるが，それだけでは以上に示した粘性が著しく相異する事實は量的には到底說明されない。從つて瓦斯含有量の多少を考慮に入れた噴出熔岩の物質的相異に基づくものと考えざるを得ない。この事はヴオラロヴイッチ氏の行つた熔融火山岩の溫度と粘性に關する實驗に於いても，同一溫度に於いてシリカ成分の少ないもの程粘性が小さい結果を得ている。

また可兒氏の大島元村熔岩についての實驗結果は，今回の熔岩の化學成分と殆んど同じであるにかかわらず 1150° の溫度に於いて今回の測定結果の數十倍の大きい粘性を示している。これは實驗室內に於ける再熔融岩石と新鮮な熔岩とでは瓦斯含有量が著しく異なることによるものであろう。

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[16] M. VOLAROVIC, *Comp. Rend. Acad. Sc. U.R.S.S.*, I (1932), 564.

Fig. 6. The lava streams flowing on the flank of the inner somma on March 19, 1951.
I, The lava stream dealt with in the present investigation.

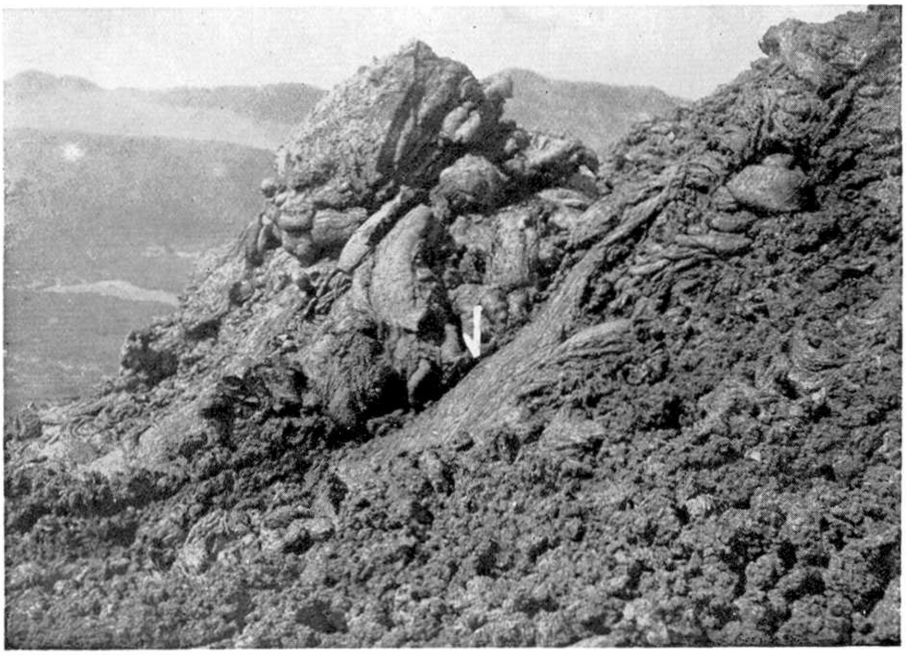

Fig. 7. The lava river near its source on March 18, 1951.
(arrow mark indicates the flowing lava.)

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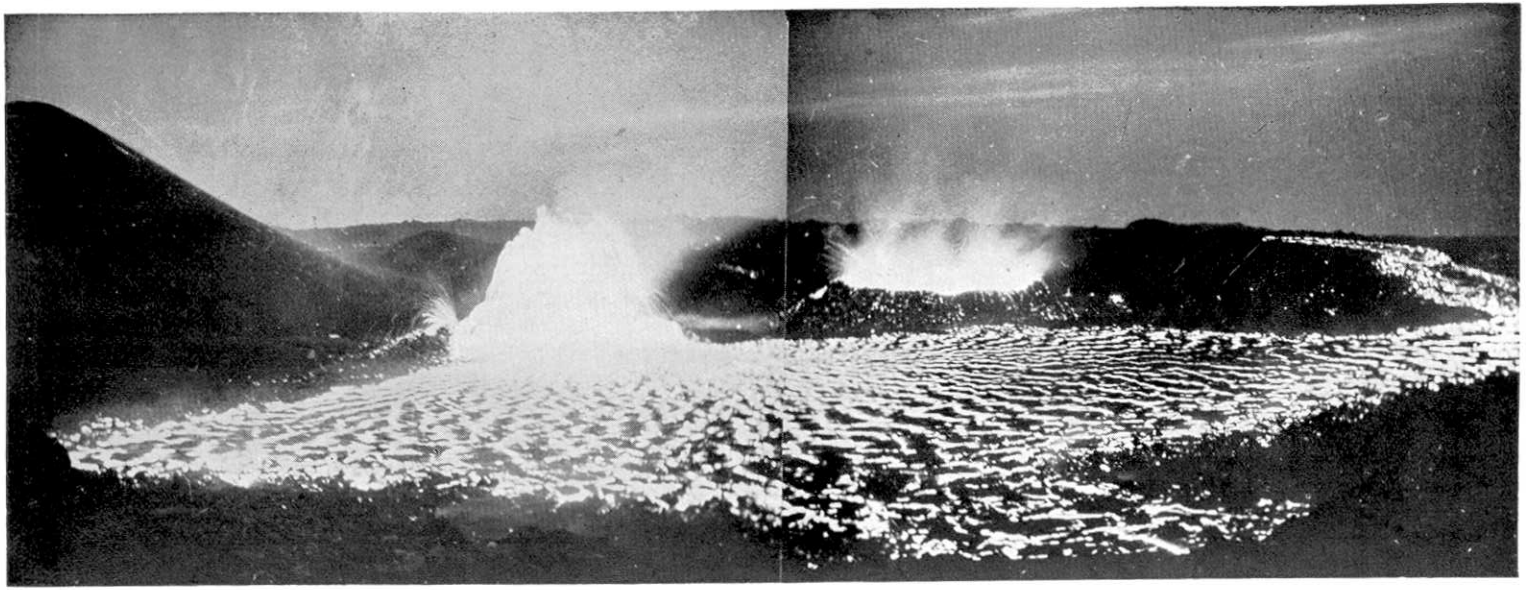

Fig. 8. The lava fountain and lava pool in the inner somma on May 7, 1951. (Photo. Y. Takagi.)