FORMATION OF LAVA CAVES IN JAPAN AND KOREA

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ABSTRACT

This paper consists of qualitative considerations of lava cave formation on the basis of interior observations of lava caves in Japan and Korea. The observations suggest that most lava caves are composed of unit caves, and cavities formed by floor flows with sinking. Each unit cave consists of gas bubbles that formed under cool skins of lava.

The lava cave formation theory proposed here can be explained in terms of rheological properties of lava flows and mixed phase flows in lava flows. In this theory, plasticity of lava is necessary for morphological maintenance and vertical development of lava caves. In addition the gases, the liquid, and the semi-solid lava in the mixed phase flows area regarded as volatiles in lava, molten basaltic lava and crusts of lava, respectively. It is considered that there are two main modes of lava cave formation. One is formation due to coalescence of unit caves in Newtonian lava flows. The other is formation due to floor flows with sinking in Bingham plastic lava flows.

1. Introduction

In this paper, the author proposes a mechanism of formation of huge lava caves such as Manjang-Kul (Lava Cave) on Cheju Island in Korea. When a huge lava cave is formed it is difficult to believe that the whole cave is formed instantaneously. Moreover, it is important to know how morphology is maintained in a cave which is in molten lava. It is necessary to discuss these problems when lava cave formation is considered more generally.

Theories of lava cave formation which have been proposed to date do not deal clearly with these considerations. It is apparent that in those theories, mixed phase flow of lava and rheology of lava area not considered simultaneously. Ogawa (1980) deduced from interior observations of lava caves that most of them are complexes of many smaller cavities. This is important in development of hugh lava caves. But in his report, a clear explanation of the mechanism was not made systematically. Moreover, contrary to his inference, it can be observed in Japan and Korea that a lava cave can be reformed as a single cavity.

The purpose of this paper is to describe qualitatively the formation mechanism of a lava cave in a closed system based on interior observation of lava caves in Japan and Korea. A closed system is defined by the presence of large gas bubbles in molten lava, out of contact with the atmosphere and the ground during the formative stage of lava cave development. These large gas bubbles are named unit caves in the sense that a larger lava cave is composed of many large gas bubbles.

As mentioned above, it is assumed in this paper that lava flows are the mixed phase flow, and the development of unit caves depends on the rheology of lava flows.

2. Interior observations.

Features illustrating the formation of lava caves are demonstrated by photographs taken inside lava caves in Japan and Korea.

Figure 1.

2.1 The mixed phase flow in lava flows.

The cross section of lava caves is worth notice because it is reminiscent of the motion of underwater gas bubbles.

Fig. 1 shows the example of a large circular cross section in Suisan-Kul (Lava Cave) on Cheju Island in Korea. This type of cross section is rare in Japan and Korea.

Fig. 2[1] shows a semicircular cross section in Mitsuike-Ana (Lava Cave) at the foot of Mount Fuji. This type of cross section is observed widely in Japan and Korea.

Fig. 3[1] shows a "shell-shaped" cross section in Megane-Ana (Lava Cave) at the foot of Mount Fuji. It is rare that this type of cross section is observed in Japan and Korea.

Fig. 4[1] shows a dome-shaped space, Banba-Ana (Lava Cave) at the foot of Mount Fuji.

Fig. 5[1] shows lava stalactites which all are bent in one direction, in Mujina-Ana (Lava Cave) at the foot of Mount Fuji. This suggest that gas passed through the lava cave when the lava stalactites had not completely solidified. In other words, the cave was filled with gas during this stage of lava cave development.

Fig. 6 shows a lava cave with a semi-circular cross section. It was formed parallel to Yoshida-Tainai Lava Tree Mold at the foot of Mount Fuji. It seems that a tree mold was the source of gas supply to the lava cave.

From all this, it seems to suggest that gas in lava flows plays a very important role in the formation of lava caves. That is to say, some lava flow should be considered as a gas-liquid two-phase flow.

2.2 Lava flow lines.

Fig. 7 shows a very large cave wall in Manjang-Kul (Lava Cave). Judging from

[1] Editor's Note: This illustration could not be reproduced with adequate clarity for this publication.

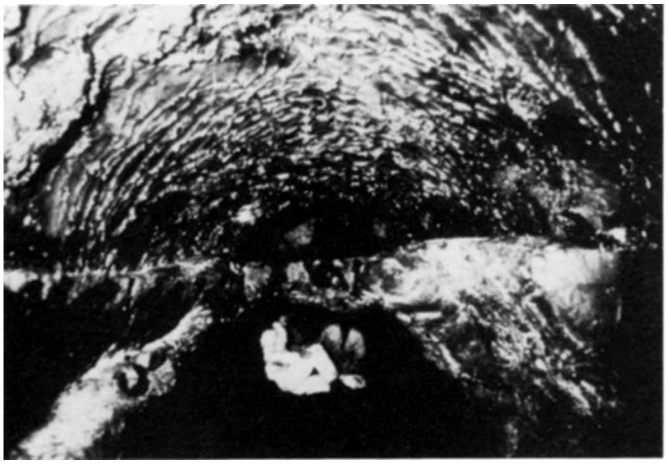

Figure 6

the morphology and the scale of the cross section, the wall seems to be influenced by factors different from the action of gas in lava flows. Fig. 8[1] shows lava flow lines on the side wall in Hundle-Kul (Lava Cave) on Cheju Island. Lava flow lines are not observed on the ceiling, but are observed on the side wall. This phenomenon is observed widely in Japan and Korea. From these facts it can be considered that formation of lava caves in a closed system is composed of two main modes.

2.3 Crust on the inner cave wall.

According to my observations of roof collapse and wall collapse in lava caves, there are some cases where something like a cave lining (termed *crust* here) is observed on the inner cave wall.

Fig. 9 [appearing as photo #24 in the accompanying paper by T. Ogawa] shows the crust on the ceiling in Mitsuike Ana (Lava Cave). Layered lava is observed on the right side. The crust is one thing, and the cave lining another. The crust is formed during lava cave formation. On the other hand, the ceiling is formed when lava caves serve as conduits for subsequent lava flows.

Fig. 10 shows crust on the side wall in Manjang-Kul (Lava Cave). From these two examples, it is considered that the morphology of the lava cave in a closed system is maintained by the crust.

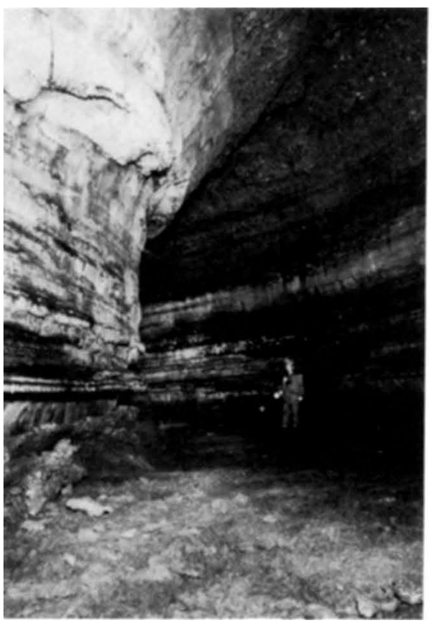

Figure 7.

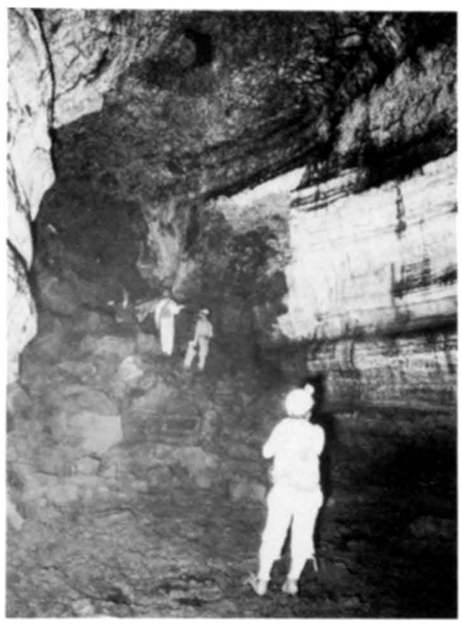

Figure 10.

Figure 13.

Figure 12

Fig. 11[1] shows crust with columnar joints in Megane-Ana (Lava Cave). Most of the joints in lava flows result from the strain that arises in the rock during cooling (Mcdonald and Abbot 1979). On the other hand, columnar joints cannot be observed in the crust on the inner cave wall. From this fact, it is considered that the crust on the inner cave wall is formed by another reason, different from the temperature difference.

2.4 Interconnection of unit caves.

Following the initial level of the lava flow lines visually, numerous discontinuous points of initial lava flow lines can be observed. The discontinuous points are the interconnection points of unit caves.

Fig. 12 shows interconnection points in Manjang-Kul (Lava Cave). The initial floor level of the rear unit cave is A, and that of the front unit cave is B; the level B is higher than A. When the floor level B sank to level A, these unit caves interconnected. This phenomenon seems to be very important to explain lava cave formation.

Fig. 13 shows scratch marks on the ceiling at the interconnection point in Manjang-Kul (Lava Cave). This photograph also supports the concept of floor flow with sinking.

3. Formation mechanism of lava caves.

It is reported (Sparks and Pinkerton 1978) that basaltic lava which, on eruption behaves as a Newtonian fluid will change to a Bingham plastic fluid. Moreover, the development of gas bubbles in each fluid will be described by using the concept of mixed phase flow that is widely observed in the field of chemical engineering and hydraulic engineering.

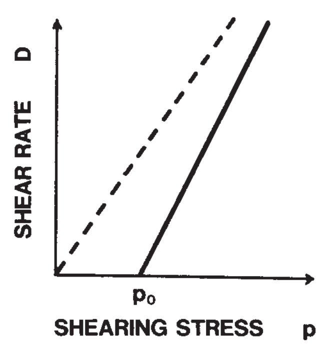

Fig.16 The ideal relation between shearing stress and shear rate.
p_0 : yield stress.
Solid line : a Bingham plastic fluid.
Broken line : a Newtonian fluid.

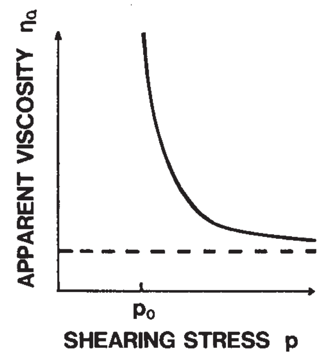

Fig.17 The ideal relation between apparent viscosity and shearing stress or shear rate.
Solid line : a Bingham plastic fluid.
Broken line : a Newtonian fluid.

3.1 Lava cave formation in a Newtonian fluid.

If a lava flow is a Newtonian lava fluid, the lava flow is regarded as a gas-liquid two-phase flow from the point of view described in section 2.1. That is to say, gases are volatiles in lava flows, and the liquid is molten basaltic lava.

Fig. 14 shows flow patterns for Newtonian gas-liquid two-phase flow in horizontal pipes (Wallis 1969). The flow patterns change from bubble flow to slug flow through plug flow as the gas flow rate is increased under a condition of constant liquid flow rate. In this paper it is assumed that the change of these flow patterns corresponds to the development of unit caves in lava flows.

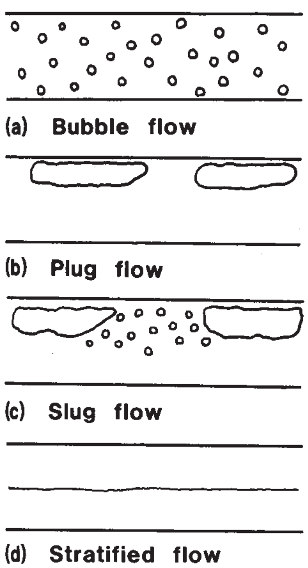

Fig.14 The flow patterns for the gas-liquid two-phase flow in horizontal pipes.

The flow pattern of lava flows near eruption vents may be bubble flow because it is difficult for gas bubbles in lava to accumulate into larger gas bubbles because of the influence of the morphology of country rocks under the lava flows, and also because of the difference between lava and country rock and atmospheric temperature. In this condition, the lava flows may be turbulent as in Fig. 15(a).

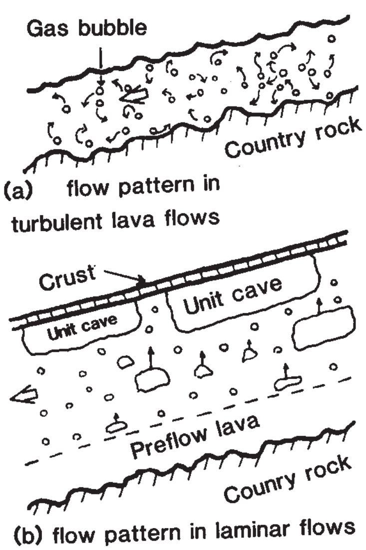

Fig.15 THE FORMATION OF UNIT CAVES

On the other hand, at the foot of a mountain the surface of country rocks is leveled by preflow lava, and the inside of the lava flow loses very little heat. In addition, the lava flow rate is decreased because of an increase of viscosity of lava and a gently-sloping mountainside. As a result, the lava flows change from turbulent flow to laminar flow.

In this stage, large numbers of gas bubbles that are supplied by subsequent lava flows coalesce into larger gas bubbles. Although the large gas bubbles rise because of the buoyancy of gas, the crust of the lava surface prevents the gas bubbles from escaping into the atmosphere. Meanwhile, the lava flow changes from bubble flow to plug flow and slug flow as in Fig. 15(b). The large bubbles in the gas-liquid two-phase flow grow to be unit caves as described above; unit caves in subsequent lava flows coalesce into those in previous lava flows. As a result, a large, long lava cave or a bigger unit cave is formed in a closed system. Where lava flows stagnate at depressions, dome-shaped lava caves are formed.

3.2 Lava cave formation in a Bingham plastic lava flow.

Pinkerton and Sparks (1978) reported that the 1975 Etna lava was a plastic fluid. In this paper, it is assumed that a lava flow is regarded as a Bingham plastic fluid which is an ideal plastic fluid.

As time passes, lava flows change in rheology from a Newtonian fluid to a Bingham plastic fluid. Crust (as in Figs. 9 and 10) is formed on the inner cave wall. The process of formation of the crust will be explained using the basic rheological properties of a Bingham plastic fluid as in Figs.16, 17 and 18 (Eirich 1956). The rheological properties of a Newtonian fluid are also shown in those figures.

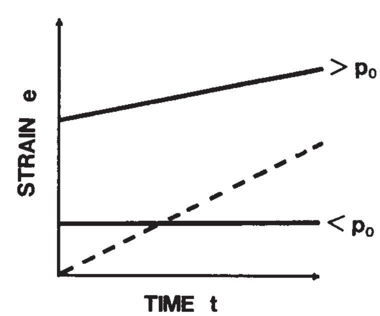

Fig.18 The ideal relation between time and strain.

Solid line : a Bingham plastic fluid.
Broken line : a Newtonian fluid.

Fig. 19(a) is a schematic drawing of a lava cave in layered lava. In the early stages of lava cave formation, the floor of

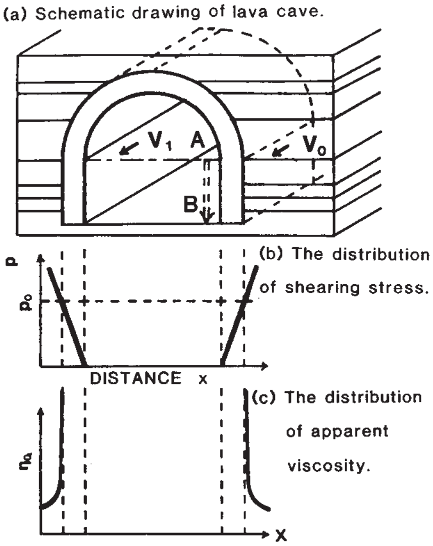

Fig.19 The formation of crust on the inner wall.

the unit cave is at the level of surface A. As time passes, the floor sinks to the level of surface B. Fig. 19(a) shows also that crust is formed on both the ceiling and the side wall.

Fig. 19(b) shows distribution of shearing stress at the level of surface A. This relationship is anologized from the plug flow in laminar flows of a Bingham plastic fluid in a circular pipe (Eirich 1956). The shearing stress is not established on the cave floor since there is no lava on it. The thickness of the crust depends on a yield stress for constant slope of the shearing stress. As evident from Fig. 16, since the shearing stress of the crust partition is under a yield stress, permanent deformation does not originate in the crust.

Fig. 19(c) shows the distribution of the apparent viscosity at the level of surface A. This relationship can be obtained from Fig. 17 and Fig. 19(b). Fig. 19(c) leads to the following: the crust partition acts as if it were a solid. And, as in Fig. 18, strain is constant with respect to time under the yield stress. It is considered, from the relationship described above, that the crust which has once been formed is stable to change with passage of time. This means that crust plays an important role in the morphological maintenance of lava caves in molten lava so that a hugh lava cave is completely formed. From the point of view described above, Bingham plastic lava flows are regarded as the gas-liquid three-phase flow. That is to say, gases are the volatiles in lava, the liquid is the molten lava, and the solid is the crust.

The floor flow with sinking is a unique phenomenon in Bingham plastic lava flows. Such a phenomenon can be explained as follows: since the shearing stress is not established on the floor surface of lava caves, the flow rate, V_1, of the floor is faster than that, V_0, in layered lava, namely the vertical component of V_1 is larger than that of V_0, and then floor flows with sinking are generated. At the same time, since the crusts on both side walls are formed continuously (by similar reasoning to that described above), the cave walls are extended vertically, and then the cross section of a lava cave is elongated. As a result, separate lava caves in lava flows will interconnect due to floor flow with sinking, and consequently a lava cave in a closed system is developed in the direction of the lava flows as in Fig. 20.

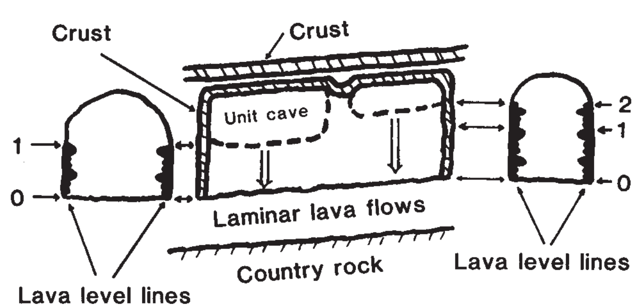

Fig.20 lava cave formation due to floor flow with sinking.

In addition, the crust is formed on the floor partition at the same time, but it may be destroyed generally by vertical vibration of the free surface.

4. Consideration.

The outline of the discussion about the formation of a lava cave in a closed system is summarized in Table 1. As indicated there are four combinations of factors influencing the formation of lava caves. In this table, both rheological properties and states of motion of lava flows are considered as factors in cave formation.

4.1 The case of a fixed mode.

The first mode in this case represents lava flows which are Newtonian fluids and stagnate. It is considered, for example, that when lava flows stagnate at a depression, dome-shaped lava caves are formed. Banba-Ana (Lava Cave), Fig. 4 is an example.

The second mode is the case where lava flows are Newtonian fluids and flow. In this case, tunnel-shaped lava caves are formed, without lava flow lines. These are sometimes observed in Japan and Korea.

Table 1 The modes of lava cave formation in a closed system.

THE STATE OF MOTION OF LAVA FLOWS		RHEOLOGICAL PROPERTIES OF LAVA FLOWS: A NEWTONIAN FLOW (TWO-PHASE FLOW)	RHEOLOGICAL PROPERTIES OF LAVA FLOWS: A BINGHAM PLASTIC FLOW (THREE-PHASE FLOW)
	STAGNATION	Bubble flow → Slug flow or Plug flow (Formation of unit caves) ▽ Dome shaped lava caves	No development of unit caves; Sporadic lava caves
	FLOWAGE	Bubble flow → Slug flow or Plug flow (Formation of unit caves) ▽ Tunnel shaped lava caves	Lava caves due to the floor flow with sinking

The third mode is where lava flows have been Bingham plastic fluids since the lava was erupted, and stagnate. In this case the unit cave is not formed because of the crust; and then a lava cave cannot be formed in Bingham plastic lava.

4.2 Cases of changing from one mode to the other.

In this section, cave formation will be described when a mode changes in the direction of the arrow indicated on the border among each mode in Table 1. From my interior observations of lava caves in Japan and Korea, there are numerous cases in which the second mode changes the fourth mode. In this case, lava flow lines could be observed on both side walls, if it were not for the cave ceiling.

It is seen in Fig. 7 that it is necessary to change from the second mode (formation of the ceiling partition) in order to form such a huge cave as Manjang-Kul (Lava Cave).

Next, the morphological maintenance of lava caves in Newtonian lava flows will be considered. In this case, since the crust cannot be formed, quench hardening of the whole lava flow is necessary for morphological maintenance. However, this quench hardening may not be effective for cases which are located in thick lava with very low thermal conductivity (Swanson 1973). Moreover, quick cooling due to the atmosphere from skylights is also considerable, but this effect may be restricted locally, and then the cave partition distant from the skylights will be destroyed due to the decompression of the internal pressure of the cave.

In order to overcome this difficulty, it would be advisable to assume plasticization of the inner cave wall in Newtonian lava on the basis of the idea of the reference 3. In this case, since the floor flow with sinking is not generated, lava may hardly flow. But crust has not yet been discovered in a cave which may be formed in a Newtonian lava flow such as Suisan-Kul (Lava Cave).

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