Formation Mechanism of Cave Systems Based on the Joining of Unit Caves

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Abstract

A formation mechanism of horizontally complex tunnel-shaped lava cave systems without traces of lava flows related to cave formation was proposed. The formation mechanism was discussed qualitatively in consideration of rheological properties of lava and morphology of lava caves (growth direction of unit caves, inside morphology of unit caves at a joining point, a state of collapse of unit caves at a joining point). The formation mechanism was discussed using the cave crust hypothesis because traditional theories cannot explain the lava cave systems. In order to establish the formation mechanism, only tunnel-shaped lava caves formed owing to cave crust were dealt with. Moreover, to simplify discussion of it, this paper studied the lava cave systems composed of two unit caves.

The formation mechanism is composed of coupling joining, penetration joining, buoyancy joining, and fracture joining. Furthermore, a T-shaped passage, an X-shaped passage, and a K-shaped passage can be explained by the four kinds of joining.

1. Introduction

The purpose of this paper is to propose a formation mechanism of horizontally complex tunnel-shaped lava cave systems.

The coalescing drainage model is responsible for some small three-dimensionally complex lava caves and some braided but not vertically complex lava caves (J.W. Harter, 1974). In this model, there are traces of lava flows inside lava caves because the caves are formed by lava flows. In Japan and South Korea, however, there are horizontally complex tunnel-shaped lava cave systems without traces of lava flows related to cave formation. Consequently, a new lava cave formation mechanism is necessary to explain the horizontally complex tunnel-shaped lava cave systems because the coalescing drainage model cannot explain them.

To establish the formation mechanism of the horizontally complex tunnel-shaped lava cave systems without traces of lava flows, the idea of a cave crust proposed by Ohsako (1982, 1986) is used as a precondition of discussion. Moreover, to simplify the discussion, this paper studies the formation mechanism of lava cave systems composed of two unit caves.

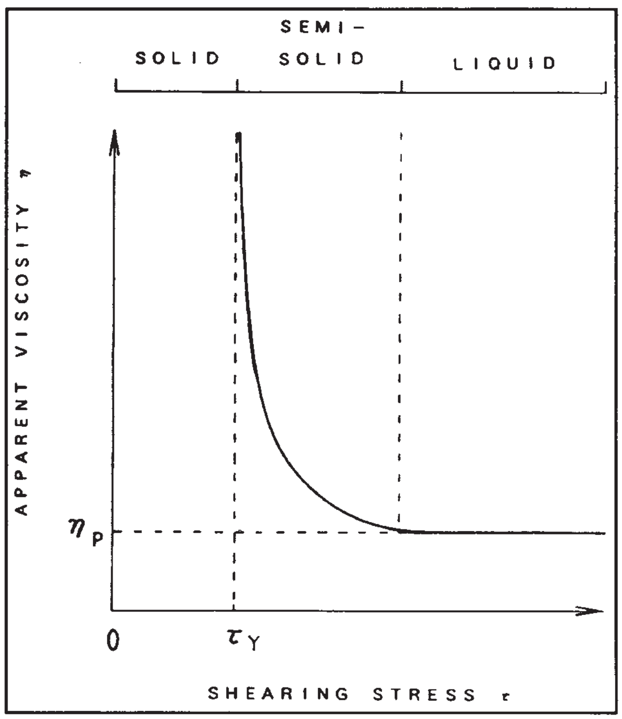

Figure 1 — Ideal Behavior of a plasto-visco-elastic fluid.

2. Idea of a Cave Crust

The assumptions used in the idea of a cave crust will be described below.

(1) Lava flows have rheological properties such as viscosity, plasticity, and elasticity (Pinkerton and Sparks, 1978). That is, lava flows may be regarded as plasto-visco-elastic fluids.

As shown in Figure 1, a plasto-visco-elastic fluid behaves as a solid, a semi-solid, or liquid according to shearing stress (M. Reiner, 1969). Figure 1 shows that a solid lava crust (a cave crust) can be formed in a flowing lava region where the stress is below the yield value.

This assumption is the necessary condition to form a cave crust and a cave cap (a shell-shaped lava ball at the tip of a cave crust).

(2) A no-slip condition is satisfied on the boundary between a lava flow and a cave cap.

This assumption is the necessary condition to form a semi-solid lava layer around a cave cap. The advance of a cave cap transforms the semi-solid lava layer to a cave crust owing to degassing.

(3) There is local topography capable of forming a cave cap in a lava flow (K. Adachi and N. Yoshioka, 1973).

(4) Lava is moving during the formation of a tunnel-shaped lava cave (a unit cave).

This assumption is the necessary condition to advance a cave cap mainly on account of the visco-elasticity of a lava flow and thereby to grow a cave crust behind the cave cap.

As described above, the idea of a cave crust (the cave crust hypothesis) has a distinctive feature that does not require the solidification of lava based on cooling for the formation of tunnel-shaped caves.

3. Observations of Joining Morphology and Four Kinds of Joining

The joining morphology of unit caves was observed from the point of view of growth direction of unit caves, inside morphology of unit caves at a joining point, and a state of collapse of the unit caves at a joining point. Consequently, from observation, I see that the formation mechanism of the horizontally complex tunnel-shaped lava cave systems is composed of coupling joining, penetration joining, buoyancy joining, and fracture joining.

3.1 Coupling Joining

3.1.1 Growth direction of the unit caves.

- The lines of growth of the two unit caves lie on a curve.
- Two unit caves join in coupling. The unit cave on the upstream side joined at the starting point of growth of the unit cave on the downstream side.

3.1.2 Inside morphology of the unit caves at a joining point

(1) Morphology in a horizontal plane

- Some passages narrow at the joining point.
- Some passages widen on the upstream side of the joining point.
- The lines of growth of the unit caves sometimes break at the joining point.

(2) Morphology in a vertical plane

- There are some sharp drops in cave floor level and ceiling level.
- The remains of a cave cap are sometimes left on the floor of the unit cave on the downstream side.
- The lava of the unit cave on the upstream side sometimes flows into the part near the joining point of the unit cave on the downstream side.
- At the joining point, the unit cave has a low ceiling and/or a high floor when there are no sharp drops in cave floor level and ceiling level.

3.1.3 State of collapse of the unit caves at a joining point

- Collapse tends to be found when the two unit caves do not lie on a curve at the joining point.

3.2 Penetration Joining

3.2.1 Growth direction of the unit caves

- The two unit caves join in grade crossing.
- There is the joining point between a starting point and an ending point of the formation of the unit cave.

3.2.2 Inside morphology of the unit caves at a joining point.

(1) Morphology in a horizontal plane

- A T-shaped passage is formed when the cave cap of one unit cave approaches the other unit cave from about 90°.
- A K-shaped passage is formed when the cave cap of one unit cave approaches the other unit cave from about 0°.
- Figure 2 shows an instance of a K-shaped passage.

(2) Morphology in a vertical plane

- Sharp drops in cave floor level and ceiling level are formed when two unit caves with different passage widths join.
- Sharp drops in cave floor level or ceiling level are formed when the floor of one unit cave and the ceiling of the other unit cave join partially.

3.2.3 State of collapse of the unit caves at a joining point

- A cave cap tends to be found when collapse of the unit caves does not exist.

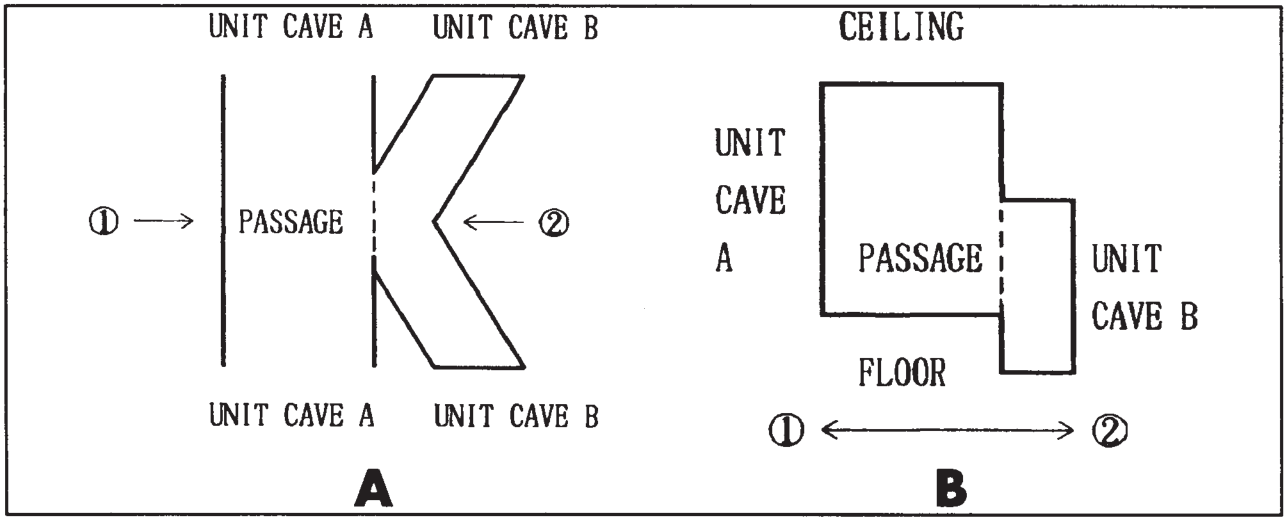

Figure 2—An instance of a K-shaped passage. (A) a schematic plan. (B) A schematic cross-section

3.3 Buoyancy Joining

3.3.1 Growth direction of the unit caves

- The two unit caves join in grade crossing.
- There is the joining point between a starting point and an ending point of the growth of the unit cave.

3.3.2 Inside morphology of the unit caves at a joining point

(1) Morphology in a horizontal plane

- A T-shaped passage is formed when one of the passages on the stretched side is separated.
- An X-shaped passage is formed when the passages on the stretched side are not separated.

3.3.3 State of collapse of the unit caves at a joining point.

3.4 Fracture Joining

- In the above three joinings the joinings with collapse are defined as fracture joinings.
- Items 3.1.3, 3.2.3, and 3.3.3 show that the deformation rate of the cave crusts is larger than the relaxation rate of the cave crusts. That is, a plastic flow of the joining part changes into ductile fracture under this condition (M. Reiner, 1969).

4. Joining Mechanisms of Unit Caves

I will propose four kinds of joining mechanisms of unit caves in consideration of the observations described in Section 3.

4.1 Mechanism of Coupling Joining

Figure 3 shows the mechanism of coupling joining.

(1) A unit cave A is formed in a lava flow on the basis of the cave crust hypothesis described in Section 2.

(2) Another unit cave B develops in a lava flow located on the upstream side of unit cave A.

(3) The local topography is eroded by the semi-solid region of unit cave B and the thickness of the topography is reduced gradually as a result.

(4) The cave cap of unit cave B collides against the local topography. We assume here that deformation rates of the cave cap and the local topography are slower than their relaxation rates.

(5) A shearing stress is thereby set up in the collision area. We assume here that the shearing stress is beyond the yield stresses of the local topography and the cave cap.

(6) The plastic flow part of the cave cap extends to the upstream side as the cave cap of unit cave B advances downstream. On the other hand, the plastic flow part of the local topography extends from the upstream side to the downstream side.

(7) The cave cap goes through the local topography with the length of the cap shortened by the above process.

(8) Unit cave B will join unit cave A when the cave cap can wholly go through the local topography.

4.2 Mechanism of Penetration Joining

Figure 4 shows the mechanism of penetration joining.

(1) There is a unit cave A in lava.

(2) A unit cave B approaches unit cave A.

(3) The cave cap of unit cave B collides against a cave crust (a side wall, a ceiling, or a floor) of unit cave

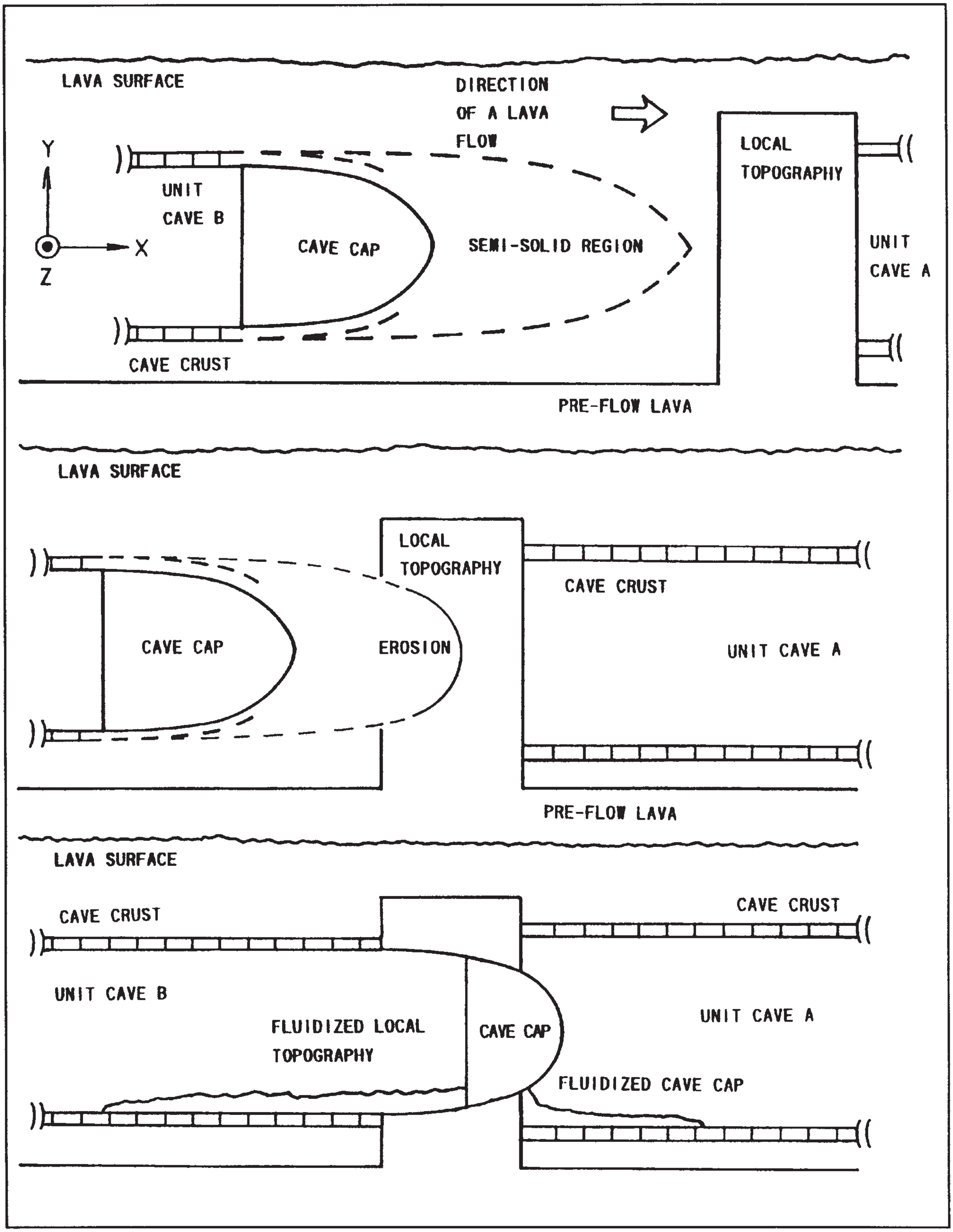

Figure 3 — Coupling joining

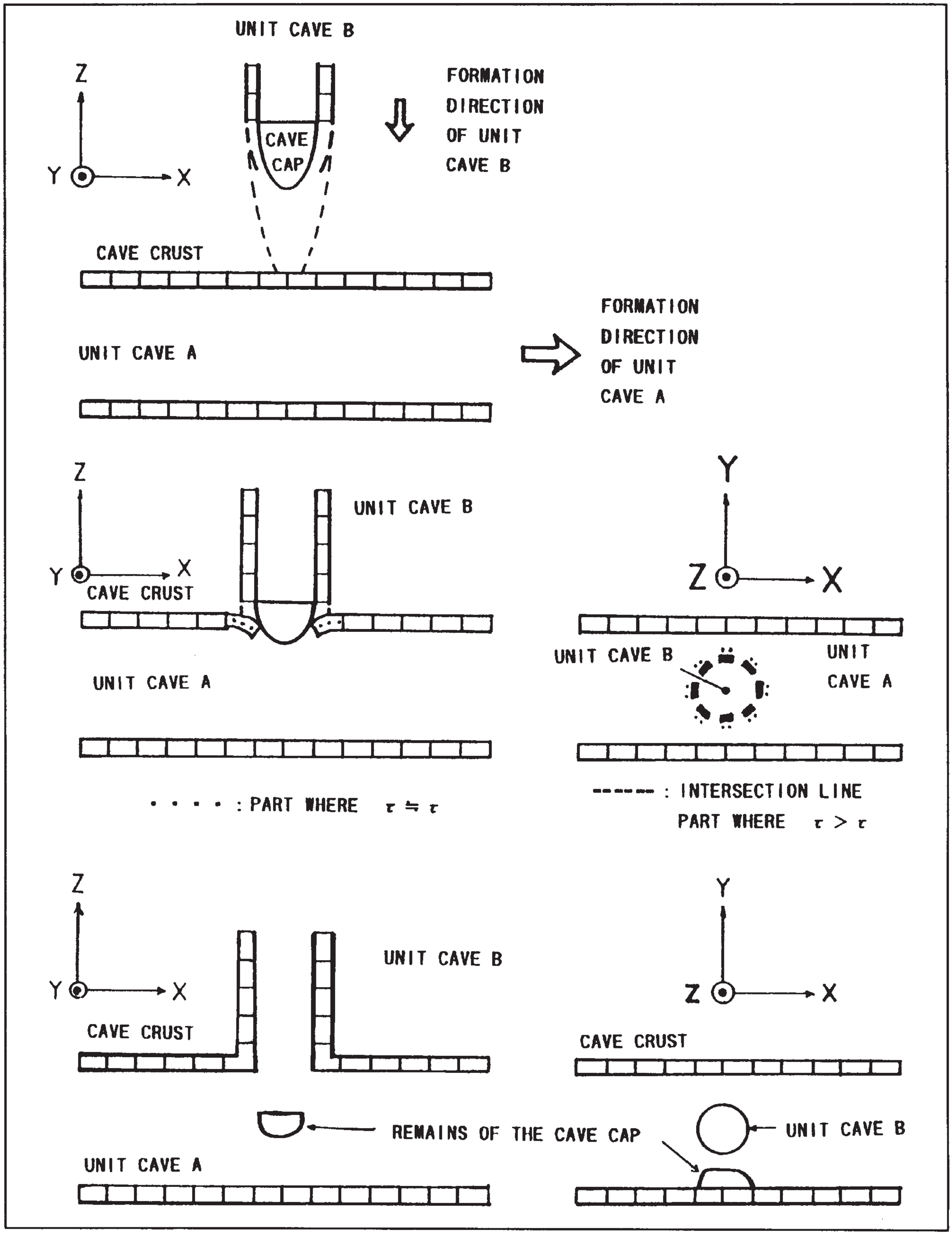

Figure 4—Penetration joining

A with deformation rates of the cave cap and the cave crust being slower than their relaxation rates.

(4) A shearing stress is thereby set up in the collision area. We assume here that the shearing stress is beyond the yield stresses of the cave can and the cave crust.

(5) Slip-lines penetrate the cave crust because the cave crust is thin compared to the local topography, and, as a result, plastic flow occurs more easily in the cave crust than in the case of coupling joining.

(6) The collision parts undergo plastic flow, so that the cave cap makes a hole in the cave crust of unit cave A.

(7) Part of the crust where the shearing stress is equal to nearly the yield stresses is bent inward at the same time. This bend is due to the visco-elastic properties of the cave crust.

(8) This bent part prevents molten lava from flowing into the unit caves by a bandlike constriction around the cave cap.

(9) This bent part acts as an adhesive agent in joining the two unit caves.

(10) This bent part solidifies again after the cave cap has penetrated because the shearing stress is below the yield stresses.

(11) Unit cave B will join unit cave A in this way.

(12) The cave cap of unit cave B cannot make a second hole in the other cave crust (side wall) of unit cave A because the passage increases rapidly in volume through the joining, so that degassing will not occur.

4.3 Mechanism of Buoyancy Joining

4.3.1 Formation of an X-shaped passage

Figures 5(a) 5(b) and 5(c) show the formation of an X-shaped passage.

(1) A crust of solidified lava flow is formed on the surface of a stationary lava flow.

(2) A unit cave A can rise in the stationary lava (by buoyancy) to come in touch with the surface crust if the buoyancy force is superior to the power of resistance due to the apparent viscosity of the stationary lava.

(3) We assume here that the deformation rates of the cave crusts (ceiling, side wall, floor) are slower than their relaxation rates.

(4) A plastic flow does not occur between the cave crust and the surface crust because the touch is not in the condition of point contact but in the condition of line contact, hence the shearing stress is not large enough to generate plastic flow.

(5) The buoyancy is generated when a tensile force due to the advance force of the cave cap decreases.

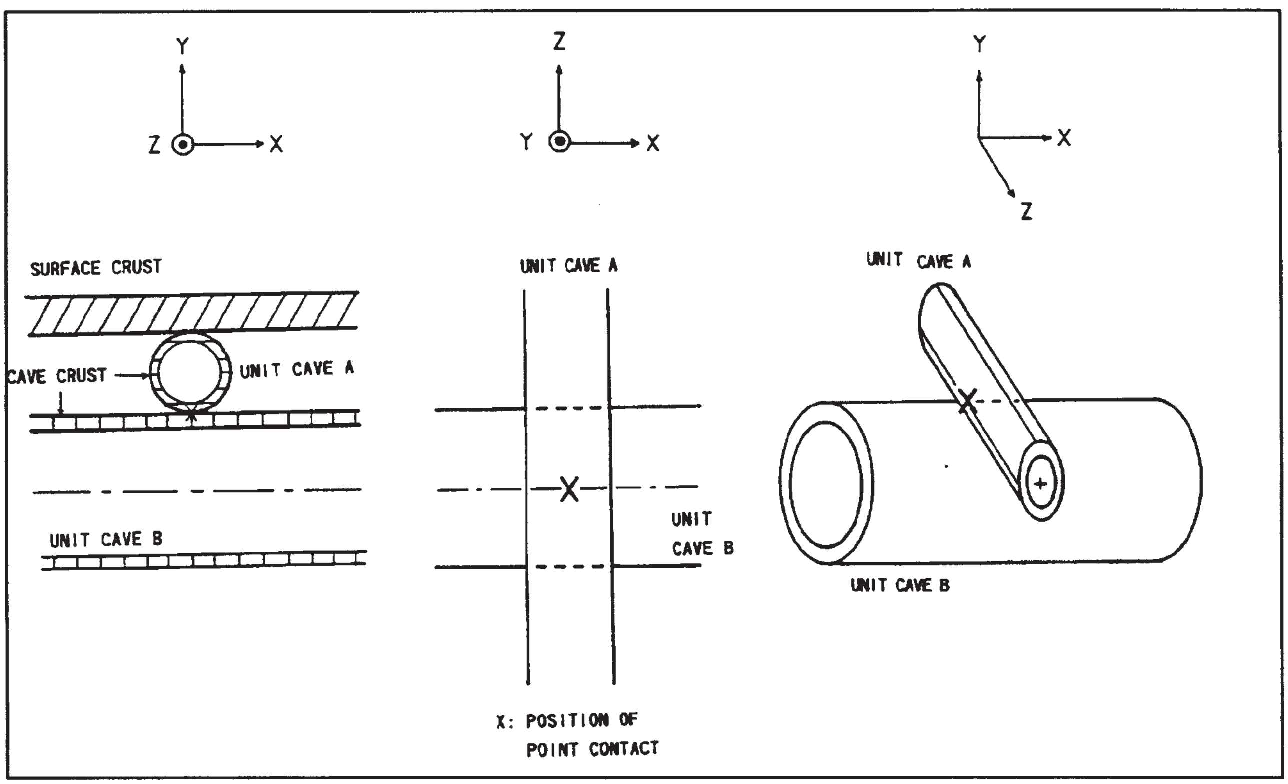

Figure 5(a) – Formation of an X-shaped passage – Initial stage

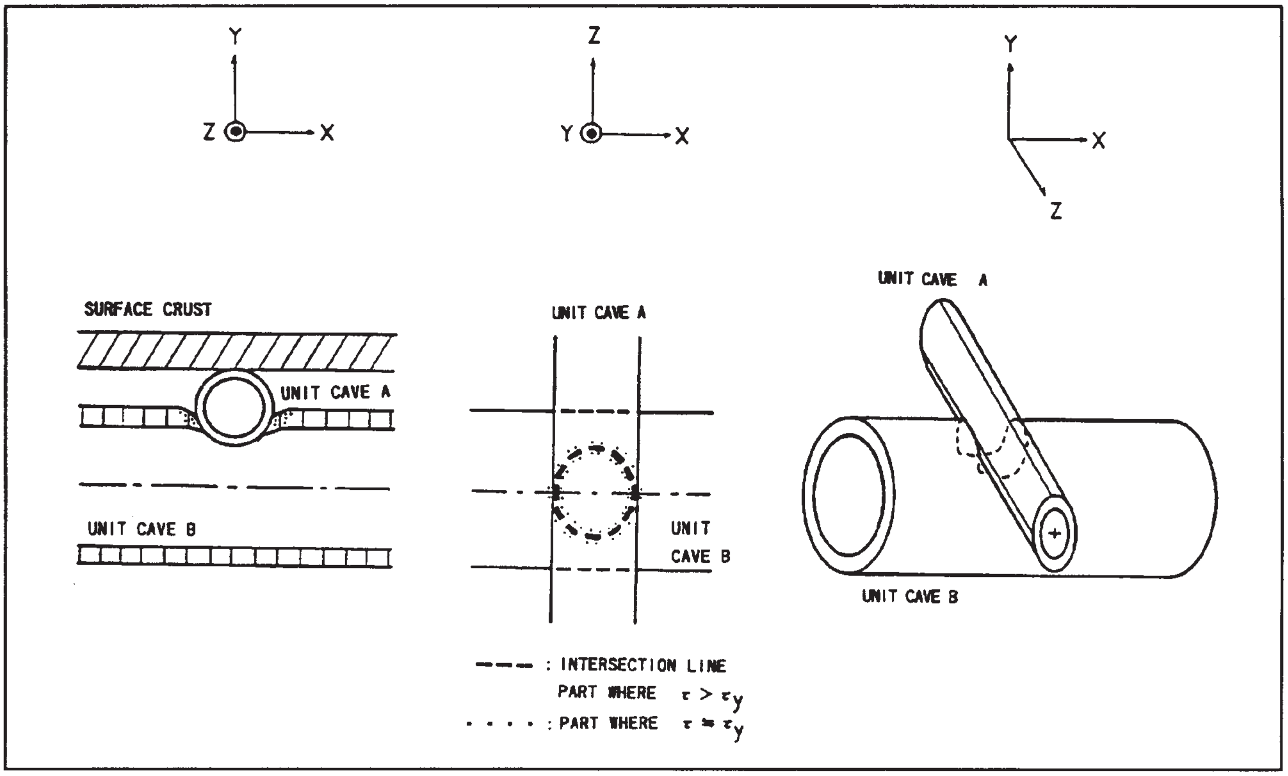

Figure 5(b)—Formation of an X-shaped passage—Intermediate stage

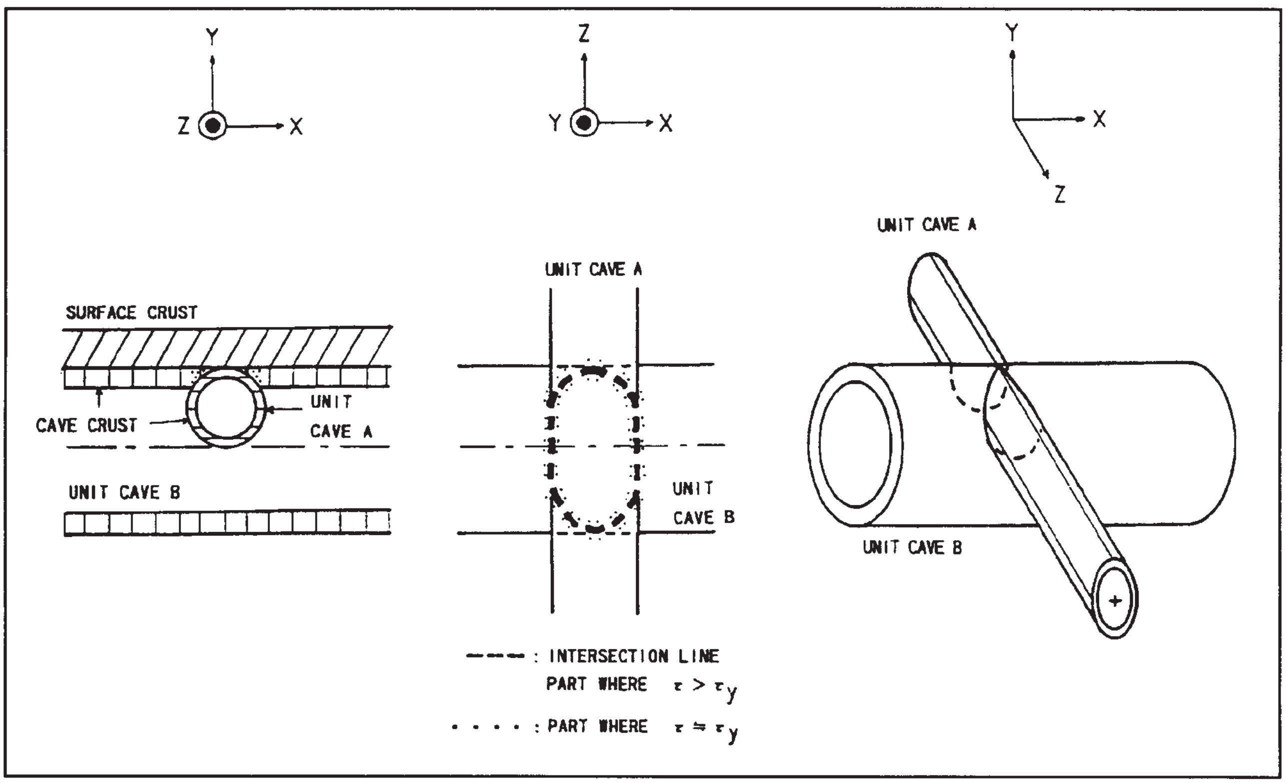

Figure 5(c)—Formation of an X-shaped passage—Final stage

(6) Unit cave A and unit cave B will overlap each other crosswise.

(7) Unit cave B rises because of buoyancy and collides against unit cave A.

(8) We assume here that shear force acts on the collision parts of the crusts (the floor of unit cave A and the ceiling of unit cave B), so that the shearing stress is beyond the yield stresses of the crusts of the two unit caves.

(9) Plastic flow occurs on the intersection line.

(10) The intersection line obtained by the crossing of the two unit caves develops with forming a closed curve.

(11) The part where the shearing stress is nearly equal to the yield stress is bent downward by the rise of unit cave B. This bend is due to visco-elastic properties of the cave crust.

(12) The bent crust of unit cave B returns to its original shape. That is the elastic recoil of the cave crust due to the visco-elastic property.

(13) This bent part acts as an adhesive agent in joining the two unit caves.

(14) The bent crust solidifies again after the unit cave has penetrated because the shearing stress is below the yield stresses.

(15) Furthermore this bent part prevents molten lava from flowing into the unit caves.

(16) Unit cave B comes in touch with the surface crust so that the buoyancy joining is finished.

4.3.2 Formation of a T-shaped passage.

Figure 6 shows the formation of a T-shaped passage.

(1) We assume here that unit cave A is stretched in the direction of the X-axis and unit cave B is not stretched in the direction of the Z-axis. Unit cave A may be regarded as a tube with one end fixed and the other end free.

(2) There is a fixed end of unit cave A in the negative range of X values. Let the origin (o) be a joining point of unit cave A and unit cave B.

(3) Items (1) through (9) in Section 4.3.1 occur.

(4) Unit Cave A is sandwiched between a surface crust and unit cave B, so that the cave crust in the positive range of X values is stretched, while the cave crust in the negative range of X values does not come to be stretched.

(5) In the positive range of X values, a higher shearing stress is set up in the cave crust of unit cave A compared to the shearing stress in the cave crust of unit cave B because the compression stress lies in the cave crust of unit cave A while the tensile stress is applied perpendicular to the compression stress (S.P. Timoshenko, 1952).

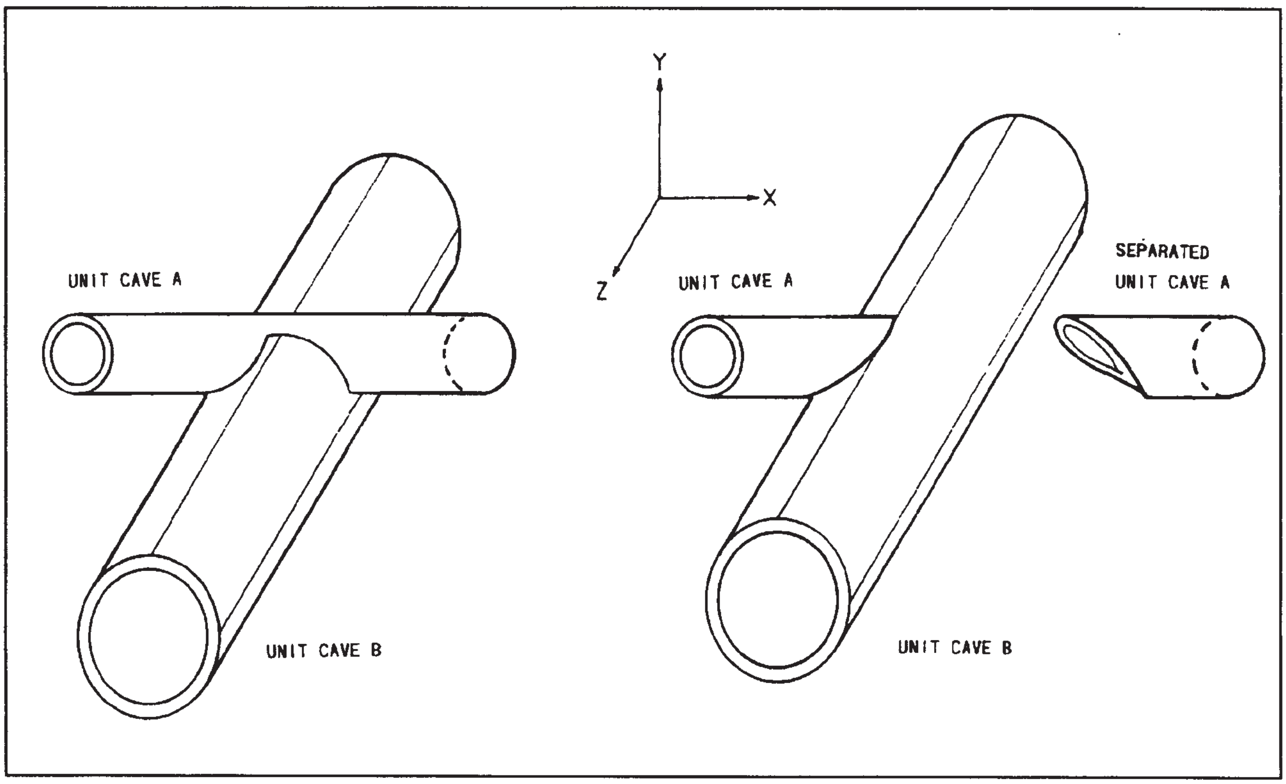

Figure 6 — Formation of an T-shaped passage

(6) In the negative range of X values, the shearing stress in the cave crust of cave A is equal to one in the cave crust of cave B.

(7) In the positive range of X values, an apparent viscosity η_A of unit cave A decreases with increasing shearing stress as is evident from Figure 1. On the other hand, there is no change in an apparent viscosity η_B of unit cave B. Consequently, η_B will be bigger than η_A.

(8) Unit cave A in the positive range of X values is separated from unit cave B, while unit caves A and B in the negative range of X values join in the same way as the formation of an X-shaped passage.

4.4 Mechanism of Fracture Joining

4.4.1 Fracture joining in coupling joining

When the local topography is stressed rapidly by a cave cap and thereby deformation rates of the local topography and the cave cap exceed their relaxation rates, elastic energy cannot be used up in such a short time through a plastic flow and hence ductile fracture occurs in the joining part (M. Reiner, 1969).

4.4.2 Fracture Joining in Penetration Joining

When a cave crust is stressed rapidly by a cave cap, ductile fracture occurs in the joining part in the same way as stated above.

4.4.3 Fracture Joining in Buoyancy Joining

When a cave crust is stressed rapidly by another cave crust, ductile fracture occurs in the joining part in the same way as stated above. When the shearing stress is beyond the yield stress, the unit caves are destroyed by the buoyancy force acting on the cave crusts because ductile fracture cannot form the joining so that lava around the caves cam not flow into the unit caves. Accordingly, it is necessary for the shearing stress to be nearly equal to the yield stress.

5. Discussion

I discuss qualitatively the formation mechanism of horizontally complex tunnel-shaped lava cave systems without traces of lava flows related to the cave formation in consideration of the rheological properties of lava. Consequently, four kinds of joining (coupling joining, penetration joining, buoyancy joining, and fracture joining) can be interpreted as the factors in the present formation mechanism from three points of view (growth direction of caves, inside morphology of unit caves at a joining point, and a state of collapse of unit caves at a joining point) as shown in Table 1. That is, two unit caves join without collapse when a plastic flow occurs at the joining point. On the other hand, two unit caves join with collapse when ductile fracture

Table 1 Conditions of four kinds of joining

DIRECTIONS OF 2 UNIT CAVES	SHEARING STRESS τ	DEFORMATION-RATE VERSUS RELAXATION-RATE	FLOW / FRACTURE	KINDS OF JOINING
PARALLEL	$\tau > \tau_Y$	D < R	PLASTIC	COUPLING JOINING
		D > R	DUCTILE	FRACTURE JOINING
GRADE CROSSING	$\tau > \tau_Y$	D < R	PLASTIC	PENETRATION JOIN
		D > R	DUCTILE	FRACTURE JOINING
TWO LEVEL CROSSING ⇩ GRADE CROSSING	$\tau > \tau_Y$	D < R	PLASTIC	BUOYANCY JOINING
	$\tau \fallingdotseq \tau_Y$	D > R	DUCTILE	FRACTURE JOINING

occurs at the joining point. Furthermore, I interpret that the general formation mechanism of the horizontally complex tunnel-shaped lava cave systems without traces of lava flows is formed by repetition of the same factor and/or different factors in the present formation mechanism.

Up to now we do not know how to interpret collapse in a passage within the range of traditional theories of lava cave formation. Collapse in a passage can be partially interpreted by the present formation mechanism. Furthermore, we can now explain a K-shaped passage, a T-shaped passage, and an X-shaped passage, while only a Y-shaped passage has been explained by traditional theories.

6. Conclusion

In the present paper, I discuss only tunnel-shaped lava cave systems formed on the basis of the cave crust hypothesis. Furthermore, I deal with lava cave systems composed of two unit caves to simplify the discussion. Under these conditions, I propose that the formation mechanism of the horizontally complex tunnel-shaped lava cave systems without traces of lava flows related to the cave formation is composed of coupling joining, penetration joining, buoyancy joining, and fracture joining. The present formation mechanism will be a great help in explaining structures of other horizontally complex tunnel-shaped lava cave systems. The next stage is to determine whether the cave crust hypothesis is applicable to an L-shaped passage.

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