Tube coalescence in the Jingfudong lava tube and implications for lava flow hazard of Tengchong volcanism

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Abstract: Tube-fed structure occurs as a general phenomenon in Tengchong basic lavas, such as lava tubes, lava plugs and tube-related collapse depressions. We deduced the development of Laoguiipo lava flows, which is the longest lava tube (Jingfudong lava tube) evolved in Tengchong volcanic area. Following the detailed documentation of the tube morphology of the Jingfudong lava tube, we propose that the Jingfudong lava tube was formed through vertical coalescence of at least three tubes. The coalescence and bifurcation process is reconstructed by the interpretation of tube floor continuity, the distribution of remnant tubes and the scales of lava tube branches (shapes of cross sections).

Keywords: Tengchong volcanism, Laoguiipo volcano, field investigation, lava tube, tube coalescence

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INTRODUCTION

Lava tubes are among the most common features in low viscosity/high effusion rate lava flow, not only on Earth, but also on other planets in the solar system (Greeley, 1992). As a type of cave, lava tubes provide a long-term stability environment, where diverse flora and fauna adapted to the unique ecosystems (e.g., Clarke, 2010; Novak et al., 2012; Pérez-Moreno et al., 2016) and complex aggregation of different minerals could take place (Onac & Forti, 2011). Lava tubes are observed in both Pahoehoe and aa lava flows (Halliday, 2002; Cashman & Mangan, 2014), their formation and development processes have been widely documented by investigating the basaltic lava flow fields (e.g., Wentworth & Macdonald, 1953; Ollier & Brown, 1965; Greeley, 1971; Hatheway, 1972; Peterson & Swanson, 1974).

Walker et al. (1973) suggested that the key parameter controlling the length of lava flow is effusion rate. Harris & Rowland (2009) reasserted this view and emphasized that cooling rates play an important role in lava flow length. Dietterich & Cashman (2014) summarized that the emplacement of lava flow was controlled primarily by effusion rate, underlying slope and rheology of lava (e.g., Dragoni et al. 2002, 2008; Honda, 2004), and proposed that the effusion rate at the vent could not record the lava supply to the

flow front in accuracy. Furthermore, the branching, merging and slope also played important roles in lava emplacement and are affected strongly by topography.

In the context of lava rheology, the formation of lava tubes should be taken into account when correlation set up between lava flow length and effusion rate. The role of tube-fed structures in enhancing lava transport in large lava fields has been widely recognized (e.g., Guest et al., 1980; Greeley, 1987; Peterson et al., 1994; Calvari & Pinkerton, 1998; Cashman & Mangan, 2014). Once the lava tube is successfully formed, it provides an efficient path for the transportation of following lava flows. Lavas has been inferred to flow to long distances in tube-fed transportation, due to efficient thermal insulation in lava tubes (e.g., Helz et al., 2003; Harris & Rowland, 2009; Cashman & Mangan, 2014). Furthermore, drained lava tubes could also act as a transportation path for later lava flows (Schmincke, 2005; Greeley, 1987).

Lava flow could intrude into the older lava tubes by eroding their ceiling or wall, and this is termed as *tube coalescence* (Calvari & Pinkerton, 1999). We herein report the tube-fed features in the Tengchong volcanoes, Southwest China, and focus on the tube morphology of Jingfudong lava tube, which is the longest lava tube (812 m) known in this volcanic area and developed within the lava flow of Laoguiipo volcano. This paper documents the important changes

of Jingfudong morphology, which is helpful for reconstructing the process of tube coalescence and bifurcation. This tube is formed by vertically stack of at least three tubes, which means tube coalescence is very important in tube forming processes. The tube morphology changes dramatically with the trend and slope of the lava tube, which has important implication for lava flow behaviors.

GEOLOGICAL BACKGROUND

The Tengchong volcanic field is located in Southwestern China (Fig. 1), along the Southeastern margin of the Tibetan plateau. There are several active faults and frequent earthquakes occur in this region as consequence (Lei et al., 2013). Three active magma chambers with size about 19–28 km (horizontal extent) are located at depth 4–12 km under the ground (Zhao et al., 2006).

The origin of Tengchong volcanic field remains controversial and several mechanisms have been proposed. Early researches showed that the eruptions in Tengchong area derived from the subduction-

collision (Zhu et al., 1983; Mu et al., 1987), or the post-collision or delayed arc-volcanism in the southeast margin of the Tibetan plateau (Zhao & Chen, 1992), or the mature island-arc area (Cong et al., 1994). Wang et al. (2007) proposed that the source of the Tengchong volcanic rocks ascended from an intracontinental tectonic setting, rather than a subduction or collision zone between Indian and Eurasian plates, on the basis of petrological, geochemical and tectonic investigations. Recent research suggests that the volcanic activity is caused by deep subduction of the Burma microplate (or the Indian plate), revealed by high-resolution tomography (Wei et al., 2012).

Tengchong volcanic field consists of 68 volcanic edifices, and 25 of them are preserved cones with clear crater (Fig. 1). Volcanic activities and the products can be divided into three stages: (1) Miocene-Pliocene basalt (5.5–0.9 Ma); (2) Pleistocene dacitic ignimbrite and intermediate-acid lava flows (0.8–0.01 Ma); and (3) Holocene basaltic andesites (0.01–0.007 Ma) (Jiang, 1998; Wei et al., 2003; Wang et al., 2007).

The most intensive eruption was the explosive eruption of Daliuchong volcano in the Pleistocene, with major products of strongly welded dacitic ignimbrites (Li et al., 2014). Monogenetic volcanic activities continued from the Pleistocene to Holocene, and erupted basalt to trachyandesite (Fan et al., 1999). The eruptions in Holocene were from the Heikongshan, Dayingshan and Ma'anshan volcanoes (Jiang, 1998; Wei et al., 2003; Zhao et al., 2012), which formed three scoria cones and lava flows covered an area of about 90 km². Many villages are now located in this area. The youngest eruption in this area is supposedly the eruption of Dayingshan volcano in 1609, which was described more like a forest fire in *Travels of Xu Xiake* (Xu, 1642) (whose official name is Xu Hongzu), and recorded in Simkin & Siebert (1994). However, the existence of this event is still under debate.

TUBE RELATED FEATURES IN TENGCHONG LAVA FLOW

Many tube-fed structures could be recognized in the Tengchong lava flows. There are Dapengdong ("Shelter Cave"), Bianfudong ("Bat Cave"), Yemaodong ("Wildcat Cave") lava tubes (Zhao et al., 2009) and other unnamed tubes in the lava flow of Ma'anshan volcano (e.g., Zhao et al., 2012). Some lava tubes are exposed in the Heikongshan lava flows and were used as refuges by Chinese citizens in World War II. Furthermore, many collapse depressions appear on the Heikongshan lava flows (Fig. 2A and B). As far as we know, no drained tubes have been found in the Dayingshan lava flows, but instead of many plugs in the eastern lava fronts (Fig. 2C). The diameter of these structures ranges from 8 m to 12 m, with lengths in excess of 60 m. They are characterized by concentric-circled cleavages formed by shear stress, and the interval between cleavages ranges from 5 cm to 15 cm.

The scoria cone of Laoguipo volcano is located about 5 km west of Tengchong city at an altitude of 1842 m above sea level. The lava flows cover an area of 15

Fig. 1. Distribution of volcanoes in Tengchong volcanic field. Sixty-eight volcanic edifices, three stages of volcanic activities of eruption and their products are present in the map [Modified from HuangFu & Jiang (2000), Wei et al. (2003) and Zhao et al. (2012)].

Fig. 2. Tube-related depressions in Tengchong lava flows. A) Collapse depressions in Heikongshan lava flow; B) Serval small pits in Heikongshan lava flow; C) A tube-like feature in the Dayingshan lava flow front.

km², with southern parts overlapped by later lava effusion from the Ma'anshan lava flow (Fig. 3A). The K-Ar dating results of lavas from Laoguipo lava flow show that the Laoguipo erupted in the late Pleistocene (0.165 ± 0.08 and 0.204 ± 0.136 Ma, Jiang (1998); 0.239 ± 0.029 Ma, Li et al. (2000)).

Two vents are recognized and shown in Fig. 3. The south vent erupted lavas flowing mainly to south parts, where the Jingfudong lava tube evolved (Fig. 3A). The northwest vent supplied the northern parts of lava flows and the highest ridge in this lava flow field (Fig. 3B, dashed ellipse in Fig. 3A).

Four collapse depressions recognized in the north part of Laoguipo lava flows (Fig. 3A). In the dashed rectangular in Fig. 3, different scale collapse depressions occurred in the lava flow and a remnant lava tube connected with the small pit (Fig. 4A). The lava tube has an entrance with 3 m in width and 2 m in height (Fig. 4B). The walls of the collapses are nearly vertical (Fig. 4C).

INVESTIGATION OF JINGFUDONG LAVA TUBE

Method

A systematic field speleological survey of Jingfudong lava tube was carried out by using conventional techniques and instruments, including compass and tape measure. The tube has been divided to dozens of segments in observation and documentation. The observation points depended on the morphology changes. In each point, width and height of the tube are measured, and photos of the profile of this segment have been taken while the shape parameters of each profile have been particularly recorded.

The chemical compositions of whole rocks were analyzed by X-ray Fluorescence Spectrometer (AB104-L, PW2404). The compositions of representative minerals were analyzed by JXA-8100 Electron Probe Microanalyzer with the standard of GB/T 15074-2008.

Results

Field measurements are plotted in plan view and as profiles (Fig. 5A and B), while the cross sections were obtained from the photos of the same segments, and then scaled by measurement of width and height of the same segment.

The volcanic rocks are black and vesicular. The rocks exhibit porphyritic textures in thin sections. The phenocrysts consist mainly of plagioclase, clinopyroxene and a small amount of olivine. The groundmass consists of volcanic glass and amounts of plagioclase, clinopyroxene and titanomagnetite microlite (Fig. 6A). Some plagioclase phenocrysts are euhedral and have the resorbed sieve core and hyperplasia edges (Fig. 6B).

The An of plagioclase phenocrysts are in the labradorite range. The pyroxene phenocrysts have Mg[#] values of 71.75 to 81.89 and their end member compositions ($\text{Wo}_{30.08-41.15}\text{En}_{42.12-53.88}\text{Fs}_{10.93-17.11}$) locate in the augite region according to pyroxene nomenclature scheme (Morimoto et al., 1988). Two olivine phenocrysts have chrysolite values of Fo = 76.85 and Fo = 81.41, respectively. Mineral compositions are shown in Table 1.

Three whole-rock major elements analyses in this work are shown in Table 2, together with five whole-rock analyses from Xiang et al. (2000). The Laoguipo lavas show a range of SiO₂ from

Fig. 3. A) The lava flow direction of Laoguipo volcano, the locations of vents and the Jingfudong lava tube; B) The profile of the highest ridge of Laoguipo lava field, formed by the latest lava flows. Terrain data from SRTM database in Chinese Academy of Sciences.

Fig. 4. A) Collapse depressions and remnant in Laoguipo lava field; B) Entrance of the remnant tube, which is connected with the small pit; C) Vertical wall of the large collapse depression.

51.12 wt % to 54.8 wt %. The lava compositions of Laoguipo volcano fall in a narrow range of basalt-andesite in TAS plot and a region of subalkali series.

CONFIGURATION AND FEATURES OF JINGFUDONG LAVA TUBE

Configuration of Jingfudong lava tube

The Jingfudong lava tube is the longest known in the Tengchong volcanic field. The measured length of the tube is 812 m, and the end of the tube is sealed by road construction. The tube extends forward and is exposed in a private timber mill on the other side of the road. The starting point of the Jingfudong lava tube is characterized by two lava inlets (① in Fig. 5B), which have height less than 50 cm. Lots of raft breakdowns with

diameter of ~10 cm were observed on the floor of the lower tube.

The average width of tube floor is 3.6 m, while the first 500 m in upstream has average width of 3.2 m and the downstream (from 500 to 812 m) has a width of 4.5 m. The overall height difference between floors of starting and ending is 119 m, giving out the average slope of tube floor is 8.9° to the horizontal.

The rapid changes of tube width and slope between cross-sections No. 18 and No. 24 are notable. From cross-sections No. 18 to No. 21, the average width is 2.8 m. The average inclination of this segment is 2.3°. The average width from cross-sections No. 22 to No. 24 is 5.8 m, much larger than the average width of the entire tube. After cross section No. 24, the average width of tube is 3.5 m. The average inclination of segment from cross section No. 22 to No. 24 is 18.6°,

Fig. 5. Map of the Jingfudong lava tube with 32 cross sections. A) Plan view of the lava tube; B) Profile of the lava tube. Scales: equal ratio between length and width in plan view; height is shown with 3× exaggeration in profile. The cross sections have appropriately equal ratio exaggeration. Tube coalescence evidence is marked by circled number.

Fig. 6. Microphotographs of Jingfudong volcanic rocks (crossed polarized light). A) typical plagioclase, pyroxene and olivine phenocrysts; B) plagioclase phenocryst with resorbed sieve core and hyperplasia edge, and matrix plagioclase.

Table 1. Electron microprobe analyses of crystals in Jingfudong rocks (in wt%).

Mineral	OI-1	OI-2	PI-1	PI-2	PI-3	PI-4	PI-5	PI-6	PI-7	PI-8	PI-9	Cpx-1	Cpx-2	Cpx-3	Cpx-4	Cpx-5
SiO ₂	39.40	38.58	51.87	53.36	53.62	53.90	54.17	53.65	53.47	54.35	53.34	49.51	49.38	50.81	51.95	52.90
K ₂ O	0.00	0.00	0.26	0.51	0.40	0.40	0.40	0.42	0.39	0.44	0.44	0.02	0.00	0.05	0.04	0.03
Na ₂ O	0.00	0.00	3.78	4.51	4.55	4.62	4.12	4.36	4.17	4.65	4.38	0.36	0.28	1.07	0.30	0.21
CaO	0.18	0.15	13.35	11.51	12.00	11.81	12.15	11.75	12.34	11.86	12.23	18.90	18.39	20.66	14.84	17.66
Al ₂ O ₃	0.03	0.01	29.24	27.84	27.84	27.87	27.54	27.92	28.18	27.81	28.02	3.56	3.53	1.14	2.21	1.39
MgO	43.13	40.06	0.15	0.07	0.18	0.14	0.15	0.16	0.13	0.12	0.16	13.91	14.68	16.09	19.11	18.03
MnO	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.09	0.42	0.27	0.48
FeO	17.55	21.50	0.45	0.42	0.54	0.47	0.53	0.40	0.43	0.39	0.51	9.76	10.17	6.34	9.86	8.46
TiO ₂	0.33	0.43	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.22	0.27	0.16	0.31	0.34
Cr ₂ O ₃	0.04	0.00	0.10	0.02	0.11	0.09	0.06	0.06	0.04	0.09	0.09	1.78	1.87	0.46	0.98	0.67
NiO	0.12	0.08	0.02	0.00	0.06	0.00	0.00	0.00	0.00	0.03	0.05	0.00	0.00	0.07	0.00	0.03
P ₂ O ₅	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.04	0.07	0.00	0.00	0.00	0.06	0.06	0.07
Total	100.76	100.86	99.23	98.24	99.30	99.33	99.14	98.73	99.18	99.80	99.21	98.08	98.65	97.35	99.94	100.26
Fo	81.41	76.85														
Or			1.51	2.99	2.30	2.31	2.37	2.48	2.28	2.52	2.53					
Ab			33.37	40.25	39.76	40.49	37.13	39.18	37.08	40.46	38.33					
An			65.12	56.76	57.94	57.20	60.50	58.34	60.64	57.02	59.14					
Mg#												71.75	72.01	81.89	77.55	79.16
Wo												41.15	39.28	42.76	30.08	35.52
En												42.12	43.61	46.31	53.88	50.44
Fs												16.72	17.11	10.93	16.03	14.04

Table 2. Major element analyses of samples from Laoguiipo lava flow.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	ΣFeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	LOI	Total
lf-1	54.58	1.41	17.63	8.10	0.12	5.07	7.56	3.39	1.89	0.20	-	99.95
lf-2	54.56	1.38	17.50	8.23	0.20	3.31	8.75	2.90	2.16	0.44	-	99.43
lf-3	54.74	1.24	16.83	7.83	0.15	4.59	7.80	3.78	2.35	0.43	-	100.74
lf-4	52.35	1.64	16.68	8.68	0.09	6.06	7.44	3.17	1.76	0.20	1.34	99.64
lf-5	52.07	1.21	18.10	8.35	0.14	5.30	7.00	3.36	1.89	0.31	0.40	99.58
lt-1	52.35	1.70	16.05	10.29	0.150	6.18	7.06	2.82	1.88	0.371	1.12	98.85
lt-2	50.72	1.75	16.13	10.59	0.147	5.49	7.56	3.03	1.7	0.633	2.23	97.75
lt-3	50.08	1.71	16.65	10.55	0.150	6.29	7.73	2.92	1.53	0.35	2.00	97.96

Note: prefix **lf** stands for samples from lava flow, obtained from Xiang et al. (2000). They collected the data from different publications which used different analytical facilities. **lt** stands for samples from lava tube in this study, analyzed in the Analytical Laboratory of BRIUG.

significantly steeper than the average inclination of the tube. Dramatic orientation changes also occur between cross section No. 21 to No. 24.

Features in Jingfudong lava tube

Typical lava tube features have developed in the Jingfudong lava tube, including *lava stalactites*, *lava levees* and *lava shelf*, etc. (Larson, 1992). Some mineral deposits have been observed in the lava tube as well, such as carbonate *stalactite*, *stalagmite* and *coralloid*. We present below some different scale features in Jingfudong lava tube.

Lava stalactites

Some lava stalactites are preserved well on Jingfudong tube ceiling. A few scattered on the tube ceiling, while most of them concentrated between cross section No. 22 and No. 23. The stalactites have V-like shape, with typical length of about 5 cm. A drip-like accumulation of lava occurred on the sharp ends of some lava stalactites (Fig. 7A).

Linings

A lot of linings remain on the tube wall. Thickness of the linings ranges from 1 cm to 6 cm. A small gap

less than 0.5 cm separated the linings and the tube walls. The surfaces of these linings are very smooth (Fig. 7B).

Lava levee

A twenty meter long lava levee was identified near the No.18 cross section in Fig. 4B. The height of this levee is about 70 cm, inclining to the tube floor with an angle of about 70°. The width of gap between the lava levee and the tube wall is about 5–8 cm. This lava levee has rough surface, and flow structures could be recognized on the levee (Fig. 7C).

Coralloid

Coralloid is a nodular-like speleothem (Larson, 1992) and forms during sublimation processes (Onac & Forti, 2011). A concentrated cluster of coralroid occurring on the tube wall in Jingfudong lava tube has scale of 20×10 cm, with typical silicate nodule with diameter of 0.5–1 cm (Fig. 7D).

Stalactite and stalagmite

Few carbonate deposits (calcite) and one stalactite with 5 cm length and 3 cm diameter (Fig. 7E) was found on the tube wall. In another part of the tube, a

10 cm long stalagmite (Fig. 7F) is growing on the lower part of tube wall, with 2.5 cm diameter.

Cupola

A few *cupolas* are found on the ceiling of the Jingfudong lava tube. They have an ellipsoidal shape, and remnant lava shows that they flow down from the upper layer (Fig. 8A). In the central of the recesses of these cupolas, small holes are observed, with diameters of few centimeters. These holes connect with upper layer lava tube. The cupola we show in Fig. 8A is located near cross-section No. 16 in Fig. 5.

Skylight

There are two skylights in the Jingfudong lava tube. One is the tube entrance, with scale of 2×4 m, located near cross-section No. 23 in Fig. 5. Layered lava forms the wall of the entrance. A few breakdowns were found on the floor beneath this entrance. Another skylight of size about 2×3 m is located at cross-section No. 31 in Fig. 5, which is the connecting part of two parallel tubes of approximately similar size. Large breakdowns could be found on the floor, and has the same scale with the skylight.

Lava shelf

A lava shelf overhangs on the tube wall between the cross-sections No. 17 to 18. This lava shelf is about 10 m long, and aligned parallel with the lava tube floor (Fig. 8B). The surface of the shelf inclines toward the tube centerline, with angle of about 10°. There is no evidence of molten lava flow down along the inclination, and the edge of shelf is quite sharp.

A large number of breakdowns are observed on the shelf surface.

TUBE COALESCENCE OF JINGFUDONG LAVA TUBE

In the case of Jingfudong lava tube, remnants of former tube vault (e.g. the lava shelf) and tube branch (Fig. 8C and D) are evidence of tube coalescence. The variation of cross section shapes in the Jingfudong lava tube (Fig. 5) and the presence of lava falls also indicate the process of tube coalescence. Jingfudong lava tube consists of several stacked tube branches, which are independent or coalesced at certain locations. We found that the tube heights and shapes of cross-sections varied significantly, for example, the heights near the cross-section No. 8, 16, 17, and 27 were nearly doubled compared to the typical height of the main tube (Fig. 5B). Evidence of the intrusion of lava from upper tube into lower tube, such as lava falls and copulas, are common features at these segments (e.g., Fig. 8D).

There are two lava inlets at the start of the lava tube (① in Fig. 5B). The upper inlet is smaller than the lower one. The tube floor of the lower tube continues for 500 m from the inlets. Remnants of upper tube could be found in segment ①, ②, ③ and ④ (Fig. 5B) and most of the lower tube ceilings were eroded. The diameter of the first 500 m of the upper tube is smaller than the lower one (see cross sections and Fig. 8C). In summary, in the first 500 m segment, the tube consists of two parallel lava tubes, and the upper one is smaller.

Fig. 7. Landscape features in Jingfudong lava tube. A) Lava stalactites; B) Lining; C) Lava levee; D) Silicate coralloid; E and F) Calcite stalactite and stalagmite.

Fig. 8. Tube coalescence features in the Jingfudong lava tube. A) Cupola, located near cross-section No. 16 in Fig. 5; B) Lava shelf, located between the cross-sections No.17-18 in Fig. 5; C) A small remnant tube branch at cross-section No. 20. D) Tube vault eroded by lava flow from upper tube branch, located at cross-section No. 28.

The tube floor is not continuous between the cross-section No. 21, 23. Instead, there is a lava sump (⑤ in Fig. 5B) and there is a branch emerging from the lower level. This branch extends in the upstream direction for 15 m, where it is blocked by breakdowns. It could be observed that the tube elongated further for about 10 m upstream through the gaps between blocks. The scale of this branch is similar to the upper one. The tube floor of this branch extends to the end of the entire tube.

After 500 m (downstream), the tube clearly consists of two tubes. The tube floor/vault is partially continuous from cross-section No. 23 to 30 (e.g., remnant of tube vault and large breakdowns could be observed at cross-sections No. 29-30). After cross-section No. 30, the tube consists of two independent tubes, connected by a skylight formed at cross-section No. 31, with breakdown deposits on the lower tube floor. The dimensions of these two tubes are similar (see cross sections).

DISSUSION

Potential volcanic hazards in Tengchong area

Tengchong area is a scattered volcanic field, characterized by tens of monogenetic vents and associated features (Fig. 1). The petrology and K-Ar dating results (e.g., Fan et al., 1999; Li et al., 2000)

suggest the volcanism resembles the relict subduction zone/post-collisional model (cf., Keskin, 2007; Dabiri et al., 2011), and the initial eruptions occurred in southeastern and northwestern ends of the Tengchong basin, then distributed in the basin. Since the early Pleistocene, volcanism occurred along a NS-trending belt and finally focused on three Holocene volcanoes in the west. This means new volcanism will likely form new vents within the field.

We note that the consideration of lava transport in tubes must be taken into account in assessing the lava flow hazard in the Tengchong volcanic area. The development of new lava tubes and tube coalescence, as well as the existing lava tubes will likely play important roles in future eruptions. We also suggest that unstable lava tube ceiling could suddenly collapse, which could induce accidents in local farm and construction works.

Lava transportation from Laoguiipo volcano

The development of Laoguiipo lava field could be inferred from Fig. 3. Overflows occurred in the initial stages and formed the lava field, followed by the flow of main directions in Fig. 3A (dashed arrows) which delivered new lava to the flow fronts. The topography shows that the initial lavas flowed to the north and then turned to the west, where the two collapse

depressions and remnant tube system evolved. The other early flow direction of lava is represented by Jingfudong lava tube. The latest flow directions are represented by the solid arrow in Fig. 3, and the highest ridge on this lava field (Fig. 3B) was formed during the latest stage.

Evolution of the Jingfudong Lava Tube

Lava tube coalescence can be recognized either from the compound shapes of the tube cross sections or features such as lava falls, breached levees and other structures (Calvari & Pinkerton, 1999). In this section, we infer the evolution of tube branches in the Jingfudong lava tube, by considering the tube floor/vault continuity, remnant tube branches, and tube features such as lava falls, lava shelves and copulas. These latter features are shown to provide key evidence for the lava tube being intruded by upper layer lava flows.

The segment between cross-sections No. 20, 23 is complex. There are three distinctive tube branches. The lowest tube has a similar diameter to the main tube, which is blocked by ceiling collapse. We call this branch the “initial tube”. The floor of this tube is continuous to the end of the entire tube. Above the “initial tube” is the “main tube”. This branch has its own inlet (lower inlet) and has a continuous floor from its inlet to cross-section No. 22. The “initial tube” and the “main tube” have similar dimensions. There is another small tube uppermost in this segment (area ④ in Fig. 5B). It has an independent inlet, and intermittent floor (①–④ in Fig. 5B). These evidences suggest that there were at least three tubes comprising the Jingfudong lava tube.

The tube floor from cross-sections No. 18 to No. 22 is gently sloped and then there is a significant step from cross-sections No. 22 to 24. We infer that the lava flows in cross-sections No. 18 to 22 ponded or merged, caused by underlying topography. After ponding, the lava accumulated until its surface became higher than surroundings, where the lava flows could move rapidly (due to the steep slope from cross-sections No. 22 to 24). According to Cashman & Mangan (2014), formation of a skylight is controlled by underlying slope and stability of lava supply, which suggesting that the steeper slope and unsteady lava supply promote the formation of skylights. So, we could infer that the entrance of Jingfudong lava tube is a skylight caused by slope. In the Jingfudong lava tube, few breakdowns exist on the floor beneath the entrance skylight, which suggests it was formed while the tube was active.

We suggest that the Jingfudong lava tube was formed in three stages. The “initial tube” developed in an early lava flow. This flow ponded near cross-sections No. 22, where there were the gentlest slopes (Fig. 5B). After ponding, it flowed rapidly when advancing, which is implied by the steepest tube floor between cross-sections No. 23 and 24. The initial tube floor is continuous from the cross-section No. 21 to the end of the tube.

The next lava flow, which effused from the lower inlet, followed this path and developed another lava tube (the “main tube”). The tube floor was continuous

from its start to beyond cross-section No. 22. We suggest that this tube branch remains continuous and was fed only from the lower inlet, because of the distinct two-layer structure and the presence of the remnant floor at ⑥ and ⑦ in Fig. 5B. This tube intruded into the “initial tube” at the lava sump (⑤ in Fig. 5B), and the two layer structure continues after this point (e.g., ⑥ and ⑦ in Fig. 5B).

Finally, a lava tube evolved from a lava flow from the upper inlet. This tube branch is represented by the remnant of tube floor (② and ③ in Fig. 5B) and small tube branch (④ in Fig. 5B). It was small in scale and fully developed, but almost totally intruded into the main tube.

Implications for flow behavior

Dietterich & Cashman (2014) proposed that braiding index had a positive correlation with underlying slope and channel width, and flow thickness had a negative correlation with slope. Jingfudong lava tube provides a case for applying their model to the vertical case. In vertically stack tubes, the braiding index is now represented by the stacked tubes, then the more tubes coalesced implying the higher braiding index. Two or three stack tubes were identified at ② and ⑤ in Fig. 5, where the floor slopes are clearly higher than other parts. This suggests that in the vertical direction, vertical braiding has a trend of coalescence. Cross section No. 18–21 has a significant small scale. The gentle slopes and the narrowest tube suggest the horizontal braiding index is high in this segment, which implies that the bifurcation has taken place in these segments.

Another interesting thing is the orientation change near No. 22 and 24 cross section in Fig. 5A, which could be the restraint of pre-existing topography. In Fig. 3A, the topographic contour lines show a depression change. The area of cross section No. 22 is the largest in the tube, and the most complicate coalescence occurs there. Areas of cross sections after No. 24 are obviously less than No. 22 cross section, and tube direction changes again from this point. These indicate that tube bifurcation occurs in these segments. From all above, we suggest that tube coalescence and bifurcation play important roles in Jingfudong evolution.

CONCLUSION

On the basis of the well-developed lava tubes in the Laoguiipo lava flows, lava tubes in Ma'anshan volcano, lava tubes and collapsing pits in Heikongshan lava flows and tube-like features in Dayingshan volcano, the tube-fed mechanism is important for lava transport in Tengchong eruptions. Lava tubes could significantly enhance lava transportation in active eruptions (see references above).

Detailed morphology of Jingfudong lava tube in Laoguiipo volcano lava field was documented, and the tube evolutions were interpreted from the morphology changes. At least three lava tubes evolved well and used the same path. The interpretation of tube coalescence and bifurcation were based on the shape,

slope and orientation changes within the lava tube, which are helpful for understanding the lava flow behavior.

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