Mapping the structure and depth of lava tubes using ground penetrating radar

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[1] The formation of lava tubes is one of the most significant factors controlling the emplacement of lava flows. However, extents and structures of lava tubes are typically not precisely known due to the difficulty in finding lava tubes in the field. We developed a new stepped-frequency ground penetrating radar (GPR) system with shielded antennas, which allows measurements that have both high spatial resolution and large penetration depth. We performed two types of measurements over an inactive lava flow and show that this method can easily detect the existence of a lava tube. Importantly, phase reversals of the reflection signals can help identify reflections from a lava tube. Using these reflection patterns, we estimate the vertical dimension and the depth of a lava tube at Fuji volcano, which are validated by survey measurements. The presented method may be the most practical way to map terrestrial and perhaps extraterrestrial lava tubes. **Citation:** Miyamoto, H., et al. (2005), Mapping the structure and depth of lava tubes using ground penetrating radar, *Geophys. Res. Lett.*, *32*, L21316, doi:10.1029/2005GL024159.

1. Introduction

[2] Lava tubes, tunnel-like structures formed beneath the surface of a lava flow, thermally insulate lava within the tube, allowing it to be transported for long distances. Theoretical studies indicate that lava flowing in a tube can travel significantly further than analogous channel-fed or surface lava flows [e.g., *Keszthelyi*, 1995]. Once a lava tube is formed, it strongly controls subsequent flow emplacement and the resulting morphology of the associated flow or flow field [e.g., *Calvari and Pinkerton*, 1999].

[3] Lava tubes have been studied and characterized in general terms in basaltic flow fields [e.g., *Holcomb*, 1987; *Peterson et al.*, 1994; *Calvari and Pinkerton*, 1999], and they are postulated to be an explanation of the extensive lava flow lengths observed on other planetary surfaces [e.g., *Greeley*, 1971; *Sakimoto et al.*, 1997]. Previous work has typically focused on tubes or tube systems where collapsed roof segments allowed access to the subsurface. Given their abundance and importance in flow emplacement, much remains to be learned regarding lava tube distribution and network patterns, their roles in establishing flow lengths and emplacement of surface lavas, and tube system evolution. Recent detailed studies at Etna (Sicily, Italy) show that there appear to be significantly more lava tubes than previously expected [*Calvari and Pinkerton*, 1999]. This is likely true for many other volcanoes, including those in Hawaii [*Byrnes and Crown*, 2001].

[4] Lava tubes may dominate not only the formation of a single "simple" flow lobe but may also have significant effects on flow field development. Observations of pahoehoe sheet flows in Hawaii show features that are inflated by lava delivered from the tube system [e.g., *Hon et al.*, 1994]. Repeated or continuous use of lava tubes may produce a complex lava-tube network and a resulting flow field considerably more extensive than would have been possible if all the flows had been channel-fed [*Self et al.*, 1996]. Detailed observations of an active lava flow field at Etna have also shown that tube-fed flows are responsible for most of the widening, thickening, and lengthening of the flow field [*Calvari and Pinkerton*, 1999]. All of these studies strongly suggest that inflation and the formation of tubes are closely linked, and both play important roles in the emplacement of long-lived lava-flow fields. This has significant implications to the formation of flood basalt provinces, calling into question emplacement rate and flow duration estimates for these large volume eruptions [e.g., *Shaw and Swanson*, 1970; *Self et al.*, 1996].

[5] The above process may also help to resolve the long-standing controversy for what controls the length of lava flows [e.g., *Walker*, 1973; *Pinkerton and Wilson*, 1994; *Miyamoto and Sasaki*, 1998]. The unusually long lava flows on the Moon and Mars are unlikely to have been open (e.g., channel-fed) because their effusion rates would have had to have been implausibly large. Recent studies have instead invoked tube-fed flows, which can explain the great lengths of planetary lava flows with more realistic effusion rates [e.g., *Sakimoto et al.*, 1997].

[6] Precise understanding of flow inflation processes is now at the center of recent discussions on the emplacement

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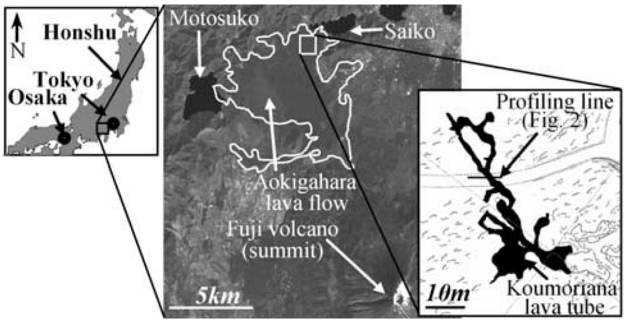

Figure 1. Landsat image shows the location of the Koumoriana lava tube in Aokigahara lava flow on the northern flank of Fuji volcano. Right inset shows the location of the Koumoriana lava tube based on the results of survey data. A solid line in this inset corresponds to the measured line for the result of the profiling measurement shown in Figure 2.

of most lava flow fields on the Earth, Moon, and Mars. Although inflation-related features are widely discussed in studies of many volcanic fields, the formation of lava tubes, which is necessary for significant inflation to occur, is rarely discussed except for some observations of active lava flows [*Kauahikaua et al.*, 1998]. Importantly, the evolution of lava tubes in long-lived volcanic fields may be much more complicated than those observed over relatively short timescales. For example, the lack of correlation between pahoehoe surface units and proximity to lava tubes in Hawaiian lava flows [*Byrnes and Crown*, 2001] may indicate the necessity of further investigations of relationships between inflation and lava tubes. Furthermore, lava-tube networks are rarely completely mapped in inactive lava flows, although the formation of lava tubes and their network structures are often suggested in active flow observations. These facts raise questions about the universality of the above inflation processes in terrestrial and extraterrestrial lava-flow fields.

[7] The reason why lava tubes are not generally systematically characterized may be simply due to the lack of a method to find and characterize them: Lava tubes are commonly identified by surface features, especially when a part of the tube collapses to allow observation from the surface (skylights) [*Mattox et al.*, 1993]. Therefore, even if visible lava tubes are carefully investigated, there is a possibility that large numbers of lava tubes still remain undiscovered. Thus, a clear and practical geophysical method is crucial for mapping sizes and distributions of lava tubes.

[8] Several geophysical methods have been applied to identify lava tubes, including the detection of magnetic-field perturbations [*Budetta and Negro*, 1995], thermal radiation [*Flynn et al.*, 2001], seismicity [*Hoblitt et al.*, 2002], and low-frequency sound [*Garces et al.*, 2003] associated with tube-fed flows. Since these methods measure the perturbations related to actively moving lavas, these methods cannot be directly applied to inactive lava tubes. In addition, although these methods can suggest the locations of active lava tubes, it is difficult to measure the sizes of lava tubes, which are good indicators of the highest effusion rates. Furthermore, the existence of a putative lava tube is usually not unambiguous until it is confirmed by other methods or a field study. Therefore, an alternative method is required for easy and clear identifications of both the existence and the size of inactive lava tubes.

[9] A variety of geophysical and engineering methods have been proposed for detecting shallow cavities; most commonly cited are the microgravity method and the seismic reflection and refraction method. These methods have vertical resolutions that do not normally meet the submeter resolution required for mapping lava tubes. Therefore, in this work, we develop a new ground penetrating radar (GPR) system to test its feasibility for mapping lava tubes.

2. Methodology

[10] GPR method is a technique to map shallow subsurface structures using electromagnetic (EM) reflection waves. GPR has been successfully applied to various problems in the geological, archaeological, and engineering fields [e.g., *Davis and Annan*, 1989; *Neal*, 2004]. Yet, little work has been done on the application of this technique for the detailed mapping of lava tubes. This may be because commercially available GPR systems usually do not have a sufficient penetration depth (>10 m; larger than typical thickness of a basaltic lavas) with fine-enough spatial resolution (<1 m) necessary to detect lava tubes. Thus, in conjunction with Kajima Corporation and Kawasaki Geological Engineering Co. Ltd., we have developed a new GPR system, which is based on a stepped-frequency radar system (for a penetration depth deeper than commonly-used pulse radar) with a frequency range from 50 MHz to 500 MHz. To minimize undesired clutter, we sealed the sides and top of both the transmitter (Tx) and the receiver (Rx) antennas with Ni-Cu-Zn ferrite, which efficiently absorbs VHF energy, providing up to 40 dB of attenuation. Though the shielding is usually not employed by commonly available commercial GPR systems, it helps minimize the signal associated with EM waves reflected from aboveground objects.

[11] Here, we employ two methods: (1) profiling, wherein the Tx and Rx are moved together across a flow field, maintaining a set distance between them, and (2) Common Midpoint (CMP) measurements, wherein the Tx and Rx are slowly moved apart, with their midpoint maintained at a fixed location.

3. Field Measurements and Discussion

[12] We performed GPR measurements at the Koumoriana lava tube in the Aokigahara lava flow, Fuji (Honshu, Japan) (Figure 1) both in summer (Aug., 2001) and winter (Jan., 2002; Dec., 2004; and Feb., 2005). We selected this lava tube as a test site since the structure of the lava tube had been mapped in detail by survey measurement (Figure 1) and we had performed a preliminary GPR measurement previously. The Aokigahara lava flow is a basaltic lava field that erupted in 864 A.D. and contains >30 lava tubes. See *Tsuya* [1968] for geological details.

[13] We collected >150 profiling and CMP measurements over a relatively flat area around the Koumoriana lava tube, including on both paved and unpaved roads and inside the

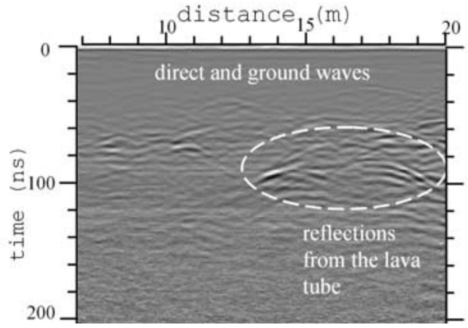

Figure 2. Example profiling result from the Koumoriana lava tube. Grayscale shows the received signal amplitude; horizontal axis gives horizontal position of the two antennas and vertical axis gives two-way signal travel time of the radar wave. White dotted line denotes several parabolic structures that are indicative of a lava tube, confirmed by survey measurement.

lava tube. In this paper we show results from the paved road because the road is a useful marker that allows us to compare the GPR results with the survey data.

[14] The initial investigation at the test site includes numerous reconnaissance GPR profiling measurements using a fixed Tx-Rx offset of 80 cm, 100 cm, and 120 cm as well as using a commercial pulse radar system (GSSI SIR 2 system with a 200 MHz antenna). A typical measurement profile is shown in Figure 2. The multiple hyperbolic patterns (hyperbolae) at around 70–100 ns and 13–19 m can be interpreted as an isolated structure. This hyperbolic pattern occurs because reflection time is roughly proportional to true distance between the antennas and the subsurface structure. In fact, we find similar hyperbolic patterns in several locations in the Aokigahara lava flow, which is consistent with the view that there are many undiscovered lava tubes in this lava flow [*Tsuya*, 1968].

[15] CMP measurements can provide further information. Figure 3 shows an example where the common midpoint was maintained at the position corresponding to the 16.5-m point in Figure 2. We interpret the prominent straight lines from 10–20 ns and 1–3 m as a surface wave (note that the uppermost prominent diagonal line nearly intersects the origin). The nearly straight lines from 30–80 ns and 1–6 m may correspond to waves reflected off the surface of the paved road. The hyperbolic patterns in Figure 3a marked with dashed white lines, however, display the characteristic pattern indicating subsurface structures. The existence of two such returns, separated by 14 ns, implies that two reflections have occurred.

[16] A detailed comparison of these two signals can shed light on the nature of these two reflections. Figure 3b shows traces of received amplitude vs time (called an A-scan plot) at CMP antenna separations of 3.4 and 8.0 m. Typical A-scan data over the lava tube shows that the first arrival is the surface wave, which travels directly through the ground between the Tx and the Rx (e.g., signals at 60–70 ns in the left trace in Figure 3b). Reflection from subsurface structures occurs at about 80 ns and 130 ns in the left and right traces of Figure 3b, respectively (circled regions); comparison with Figure 3a shows that these signals are contained in the hyperbolae marked by white dashed curves. Importantly, these two features have amplitudes with opposite sign (compare the circled regions in Figure 3b).

[17] It is a fundamental feature of EM wave propagation that when an interface to a material with a higher refractive index is encountered (i.e. at the bottom of the lava tube), the phase of the reflected wave is reversed. On the other hand, an 'internal reflection' from an interface with a higher dielectric constant material (i.e. at the top of the lava tube) does not have such a phase reversal [e.g., *Neal*, 2004]. Thus, we can interpret the upper reflection pattern in Figure 3 as coming from the lava-air boundary at the top of a lava tube, and the lower reflection as coming from the air-lava boundary at the base. This gives an important cross-check in interpreting the reflection data, and thus we can safely conclude that the diffraction pattern is not caused by a material which has larger dielectric constant, such as higher water concentration. However, with these data alone it is difficult to distinguish an empty (air-filled) tube from a lava tube filled with sand or other materials with low dielectric constant, although it may be noted that the reflection coefficient would be lower in magnitude in these cases. The reflection from the base is not apparent until around 5 m, which can be interpreted as due to the scattering from the irregular shape of the lava tube roof.

[18] The hyperbolae in the CMP profile allow an estimate of the average velocity of the reflected waves [e.g., *Neal*, 2004]: The average velocity of the EM wave is about 0.07 m/ns (thus the average dielectric constant is $\sim$16). We extrapolate the reflection patterns from the lava tube to the 0 m antenna offset as shown in Figure 3: The difference in two-way time between the reflections from the top and the bottom of the lava tube is about 14 ns, which suggests that the vertical dimension of the lava tube is about 2 m if it is air-filled lava tube. Also, the depth below ground of the lava tube roof is estimated $\sim$2.5 m.

[19] The profiling measurements suggest that the horizontal size of the lava tube is about 5 m, whereas the CMP measurements confirms the signal is from a lava tube and

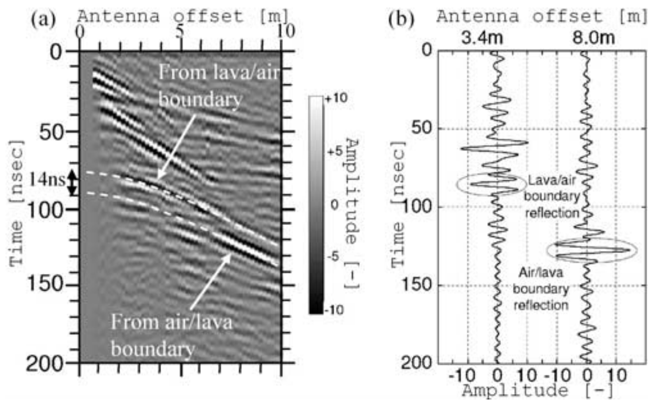

Figure 3. (a) Example CMP profiling result over the Koumoriana lava tube. Grayscale shows the received signal amplitude, horizontal axis gives horizontal distance between the two antennas, and vertical axis gives two-way signal travel time of the radar wave. Signals at antenna offsets smaller than 70 cm cannot be measured due to the size of the antenna shield. (b) Signal amplitude vs time of the CMP survey at antenna offsets of 3.4 m and 8.0 m.

suggests that the distance between the ground and the top of the tube is 2.5 m and the height (thickness) of the lava tube is about 2 m. We confirmed that these estimated values are all consistent with the survey measurement.

4. Implications and Conclusions

[20] We have developed a new step-frequency GPR system with shielded antenna to test the feasibility for detecting and mapping lava tubes. Our method has the following significant improvements relative to previous geophysical methods: (1) it can identify lava tubes in inactive (and perhaps active) lava flow fields; (2) it can map the vertical and horizontal dimensions of lava tubes; and (3) the existence of a lava tube can be confirmed by using the phase reversals of the reflection signals.

[21] We note that, with previous methods, inactive lava tubes can be recognized only when the roof of a tube collapses, or when new roads cut through tubes [*Calvari and Pinkerton*, 1999]. The method presented here is the first geophysical method for finding and mapping inactive lava tubes and perhaps the most practical technique for this purpose. We also note that little is known about the spatial distribution and evolution of lava tubes, and thus a systematic survey of lava tubes using our method would provide fundamental constraints in understanding the morphology and emplacement of lava flows. Important aspects include:

[22] (1) Mapping subsurface lava tubes: As stated above, constraints on the distributary patterns of lava tube networks would provide important information on the formation of long-lived lava flow fields.

[23] (2) Understanding the connectivity of subsurface lava tubes and surface breakouts: The lack of strong correlations between the surface units and major lava tube segments [*Byrnes and Crown*, 2001] suggests a more complex process for the tube formation and evolution than previously believed. Recently tube coalescence and formation of large chambers inside lava tubes have been observed at Etna, which suggest that multiple flows connected by secondary vents is essential for tube growth [*Calvari and Pinkerton*, 1999]. At this moment we do not know if this is a dominant process at many lava fields or not. Detailed mapping of the connectivity of the lava tubes would be useful to understand the unknown history and evolution of lava tubes.

[24] (3) Mapping the size distributions of lava tubes: Although air-filled lava tubes do not necessarily have the same cross section as that of the original tube-fed flow, the dimension of an air-filled lava tube is a potential indicator of the local effusion rate at the time of lava-tube formation. This is because the flow rate depends on fourth power of radius, for either pressure-driven or gravity-driven flows [e.g., *Sakimoto et al.*, 1997].

[25] These advances should be useful for proper assessments of volcanic hazards, to fully understand flow field growth, and to evaluate processes such as flow field inflation.

[26] The ability to locate lava tubes includes other important aspects. Lava tubes provide ideal insulation from cosmic radiation, meteoroids, and temperature fluctuations [*Hörz*, 1985]. These traits suggest that extraterrestrial lava tubes are good candidates for future planetary exploration, as both sites of possible astrobiological interest on Mars and potential sites for future astronaut bases on Mars or the Moon. The presented method does not require considerable data-acquisition time, high power, or direct contact of the instruments on the surface of the ground, and therefore, the method would be useful in future planetary explorations to find extraterrestrial lava tubes.

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References

Budetta, G., and C. D. Negro (1995), Magnetic field changes on lava flow to detect lava tubes, *J. Volcanol. Geotherm. Res.*, *65*, 237–248.
Byrnes, J. M., and D. A. Crown (2001), Relationships between pahoehoe surface units, topography, and lava tubes at Mauna Ulu, Kilauea Volcano, Hawaii, *J. Geophys. Res.*, *106*, 2139–2151.
Calvari, S., and H. Pinkerton (1999), Lava tube morphology on Etna and evidence for lava flow emplacement mechanisms, *J. Volcanol. Geotherm. Res.*, *90*, 263–280.
Davis, J. L., and A. P. Annan (1989), Ground penetrating radar for high resolution mapping of soil and rock stratigraphy, *Geophys. Prospect.*, *37*, 531–551.
Flynn, L. P., A. J. L. Harris, and R. Wright (2001), Improved identification of volcanic features using Landsat 7 ETM+, *Remote Sens. Environ.*, *78*, 180–193.
Garces, M., A. Harris, C. Hetzer, J. Johnson, S. Rowland, E. Marchetti, and P. Okubo (2003), Infrasonic tremor observed at K̃circ;lauea Volcano, Hawai'i, *Geophys. Res. Lett.*, *30*(20), 2023, doi:10.1029/2003GL018038.
Greeley, R. (1971), Lava tubes and channels in the Lunar Marius Hills, *Earth Moon Planets*, *3*, 289–314.
Hoblitt, R. P., J. Battaglia, J. P. Kauahikaua, and P. G. Okubo (2002), Lava tube seismicity at Kilauea, *Eos Trans. AGU*, *83*(47), Fall Meet. Suppl., Abstract V71A-1259.
Holcomb, R. T. (1987), Eruptive history and long-term behavior of Kilauea Volcano, in *Volcanism in Hawaii*, edited by R. W. Decker, T. L. Wright, and P. H. Stauffer, *U.S. Geol. Surv. Prof. Pap.*, *1350*, 261–350.
Hon, K., J. Kauahikaua, R. Denlinger, and K. Mackay (1994), Emplacement and inflation of pahoehoe sheet flows: Observations and measurements of active lava flows on Kilauea Volcano, Hawaii, *Geol. Soc. Am. Bull.*, *106*, 351–370.
Hörz, F. (1985), Lava tubes: Potential shelters for habitats, in *Lunar Bases and Space Activities in the 21st Century*, pp. 406–412, Lunar and Planet. Inst., Houston, Tex.
Kauahikaua, J., K. V. Cashman, T. N. Mattox, C. C. Heliker, K. A. Hon, M. T. Mangan, and C. R. Thornber (1998), Observations on basaltic lava streams in tubes from Kilauea Volcano, island of Hawaii, *J. Geophys. Res.*, *103*, 27,303–27,324.
Keszthelyi, L. (1995), A preliminary thermal budget for lava tubes, *J. Geophys. Res.*, *100*, 20,411–20,420.
Mattox, T. N., C. Heliker, J. Kauahikaua, and K. Hon (1993), Development of the 1990 Kalapana flow field, Kilauea volcano, Hawaii, *Bull. Volcanol.*, *55*, 407–413.
Miyamoto, H., and S. Sasaki (1998), Numerical simulations of flood basalt lava flows: Roles of parameters on lava flow morphologies, *J. Geophys. Res.*, *103*, 27,489–27,502.
Neal, A. (2004), Ground-penetrating radar and its use in sedimentology: Principles, problems and progress, *Earth Sci. Rev.*, *66*, 261–330.
Peterson, D. W., R. T. Holcomb, R. I. Tilling, and R. L. Christiansen (1994), Development of lava tubes in the light of observations at Mauna Ulu, Kilauea Volcano, Hawaii, *Bull. Volcanol.*, *56*, 343–360.
Pinkerton, H., and L. Wilson (1994), Factors controlling the lengths of channel-fed lava flows, *Bull. Volcanol.*, *56*, 108–120.
Sakimoto, S. E. H., J. Crisp, and S. M. Baloga (1997), Eruption constraints on tube-fed planetary lava flows, *J. Geophys. Res.*, *102*, 6597–6613.
Self, S., T. Thordarson, L. Keszthelyi, G. P. L. Walker, K. Hon, M. T. Murphy, P. Long, and S. Finnemore (1996), A new model for the emplacement of Columbia River basalts as large, inflated pahoehoe lava flow fields, *Geophys. Res. Lett.*, *23*, 2689–2692.
Shaw, H. R., and D. A. Swanson (1970), Eruption and flow rates of flood basalts, in *Proceedings of Second Columbia River Basalt Symposium*, edited by E. H. Glimour and D. Stradling, pp. 271–299, East Wash. State. Coll. Press, Cheney.
Tsuya, H. (1968), Geology of Mt. Fuji, 24 pp., Geolog. Surv. of Jpn., Tsukuba.

Walker, G. P. L. (1973), Lengths of lava flows, *Philos. Trans. R. Soc. London, Ser. A*, *274*, 107–118.

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