Thermal anomaly at the Earth's surface associated with a lava tube

Antonello Piombo*

Dipartimento di Fisica e Astronomia, Alma Mater Studiorum - Università di Bologna, Viale Carlo Berti Pichat 8, 40127 Bologna, Italy

Marco Di Bari

Dipartimento di Scienze della Terra e Geoambientali, Università di Bari , "Aldo Moro" Via Edoardo Orabona 4, 70125 Bari, Italy

Andrea Tallarico

Dipartimento di Scienze della Terra e Geoambientali, Università di Bari, "Aldo Moro" Via Edoardo Orabona 4, 70125 Bari, Italy

Michele Dragoni

Dipartimento di Fisica e Astronomia, Alma Mater Studiorum - Università di Bologna, Viale Carlo Berti Pichat 8, 40127 Bologna, Italy

Abstract

Lava tubes are frequently encountered in volcanic areas. The formation of lava tubes has strong implications on the volcanic hazard during effusive eruptions. The thermal dissipation of lava flowing in a tube is reduced in respect to the lava flowing in an open channel so the lava may threaten areas that would not be reached by flows in open channels: for this reason it is important to detect the presence of lava tubes.

In this work we propose a model to detect the presence and the characteristics of lava tubes by their thermal footprint at the surface. We model numerically the temperature distribution and the heat flow, both in the steady and the transient state, and we take into account the principal thermal effects

*Corresponding author

Email addresses: antonello.piombo@unibo.it (Antonello Piombo), andrea.tallarico@uniba.it (Andrea Tallarico), michele.dragoni@unibo.it (Michele Dragoni)

due to the presence of an active lava tube, i.e. the conduction to the ground and the atmosphere, the convection and the radiation in the atmosphere. We assume that lava fluid is at high temperature, in motion inside a sloping tube under the gravity force.

The thermal profile across the tube direction, in particular the width of the temperature curve, allows to evaluate the depth of the tube. The values of maximum temperature and of tube depth allow to estimate the area of the tube section. The shape of the temperature curve and its asymmetry can give information about the geometry of the tube.

If we observe volcanic areas at different times by thermal cameras, we can detect anomalies and evaluate their causes during an eruption; in particular, we can evaluate whether they are due to active lava flows or not and what is their state. For lava tubes, we can connect thermal anomalies with lava tube position, characteristics and state.
Keywords: **physics of volcanism – lava tube – thermal anomaly – lava flow.**

---

1. Introduction

Lava tubes, tunnel-like structures formed beneath the surface of a lava flow, thermally insulate lava within the tube. The formation of lava tubes is a common feature of many volcanic eruptions both on the Earth and on the other terrestrial planets and was described by several authors (Ponte, 1949; Greeley, 1971a; Peterson and Swanson, 1974; Guest et al., 1980; Greeley, 1987; Peterson et al., 1994; Dragoni et al., 1995; Sakimoto et al., 1997; Kauahikaua et al., 1998; Calvari and Pinkerton, 1999). In many cases the tubes drain after an eruption and are refilled by lava in a subsequent eruption. In sloping tubes the motion of lava is driven by the gravity force.

The formation of lava tubes is one of the most significant factors controlling the emplacement of lava flows.

Lava tubes have strong implications for hazards in volcanic areas: because of the formation of tubes, lava flows may threaten areas which would not be reached by flows in open channels. Because the walls and roofs of tubes are good thermal insulators, lava flowing through tubes can remain hot and thin much longer than flows in open channels. Tube-fed lava can be transported for great distances from the eruption sites. Indeed, it has been observed that tube-fed flows tend to be longer than channel-fed or simple flows (e.g., Malin, 1980; Pieri and Baloga, 1986; Keszthelyi, 1995; Harris et al., 2005; Kilburn, 2000).

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). Lava tubes are seen in submarine flows (Applegate and Embley, 1992) and in the longest Quaternary flows (Stephenson and Griffin, 1967) and are reported on the Moon (e.g., Greeley, 1971b) and possibly Mars (Greeley and Spudis, 1981; Sakimoto et al., 1997). 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 it would have been possible if all the flows were 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).

The formation of a tube from an open channel is the consequence of progressive growth of the surface crust, which eventually becomes a solid roof welded to the channel levées. The mechanisms of formation of the tubes (Peterson and Swanson, 1974; Greeley, 1987; Peterson et al., 1994; Dragoni et al., 1995; Calvari and Pinkerton, 1998, 1999; Valerio et al., 2010), their spatial and temporal evolution (Kilburn and Luongo, 1993), their dynamics and their thermal behavior (Dragoni et al., 2002; Pinkerton et al., 2002; Dragoni and Tallarico, 2008; Dragoni and Piombo, 2009; Witter and Harris, 2007) were systematically studied. As the flow advances, a tube may plunge into the ground reaching depths in the order of tens of meters from the surface and its path may be difficult to follow. In general, lava tubes have irregular cross sections (Calvari and Pinkerton, 1999). However, in modeling the dynamical and thermal aspects of lava tubes, cylindrical tubes with circular cross sections are usually considered in the literature, owing to their simpler mathematical treatment (e.g. Sakimoto and Zuber, 1998; Dragoni et al., 2002). 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.

Volcanologists are used to map the distribution of ephemeral vents or breakouts, and from this they reconstruct the hidden path of lava tubes (e.g. Mattox et al., 1993; Calvari and Pinkerton, 1998). However, extents and structures of lava tubes are typically not precisely known due to the difficulty in finding lava tubes in the field. Thus, a clear and practical geophysical method is crucial for detecting the existence of lava tubes and for mapping their sizes and distributions.

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, if visible lava tubes are carefully investigated, there is a possibility that large numbers of lava tubes still remain undiscovered. Several geophysical methods have been applied to identify lava tubes, including the detection of magnetic-field perturbations, thermal radiation, seismicity, low-frequency sound associated with tube-fed flows, microgravity, electromagnetic induction, and ground penetrating radar system (e.g., Budetta and Del Negro, 1995; Flynn et al., 2001; Hoblitt et al., 2002; Garces et al., 2003; Miyamoto et al., 2005; Gómez-Ortiz et al., 2014; Carling et al., 2015). Some of these methods measure the perturbations related to moving lavas. However, although these methods can suggest the locations of active lava tubes, it is difficult to measure the sizes of lava tubes.

The presence of lava tubes may have surface evidences as the thermal anomalies, closely connected to the physical and geometrical characteristics of the tube. The use of analytical methods to calculate the temperature field associated with a lava tube is limited by the necessity of considering simple geometries for the tube section, deep tubes and steady conditions (Sakimoto and Zuber, 1998; Dragoni and Tallarico, 2008; Valerio et al., 2008).

In this paper we propose a numerical approach to study temperature and heat flow associated with lava tubes having cross-sections of different shapes and different depth. We first consider the temperature anomaly in the steady-state. Then we consider the time evolution of temperature after the refilling of an empty tube by lava. The model provides a useful tool to evaluate the tube characteristics from thermal data measured during an eruption.

2. Temperature and heat flow associated with a lava tube

We consider an infinitely long tube (in the y-direction), filled with lava. We assume that lava fluid is at high-temperatures, in motion inside a sloping tube under the gravity force.

The wall of the tube, embedded in a conductive, homogeneous and isotropic medium is assumed at temperature T_1 of the lava flowing inside the tube. We consider tubes of elliptic cross-section in the xz plane, with a the major semi-axis and b the minor semi-axis, and with eccentricity

$$e = \sqrt{\frac{a^2 - b^2}{a^2}} \tag{1}$$

The center of the tube is at depth h. The problem is two-dimensional. In the steady state the thermal field $T(x, z)$ satisfies the Laplace equation:

$$\nabla^2 T(x, z) = 0 \tag{2}$$

under given boundary conditions. Carslaw and Jaeger (1959) and Dragoni and Tallarico (2008) solved this case for an infinite medium imposing prescribed conditions at the wall of the tube and on an arbitrary peripheral confocal elliptical surface, both assumed isothermal at temperatures T_1 and T_2, respectively. The results show that inside the region delimited by these two boundaries, the steady-state thermal field is described by a set of elliptical isotherms, confocal with the wall of the tube, whose temperatures decrease from T_1 to T_2. In addition Dragoni and Tallarico (2008) solved the problem in a half-space by the image method, so assuming implicitly that the cross-section of the tube is point-like. This condition gives rise to an approximate solution which holds only for deep lava tubes, i.e. when the ratio between the depth h and the major axis a of the ellipse is large.

3. Numerical solution

In this work we propose a numerical approach by the Comsol Multiphysics® finite elements commercial software. In order to validate this numerical method we consider the steady-state cases already examined by Dragoni and Tallarico (2008): a lava tube embedded in an infinite or in a semi-infinite solid medium. First we calculated numerically the solution of Dragoni and Tallarico (2008) in an infinite medium, under the same boundary conditions. The resulting thermal field around the tube is identical to the analytical one.

The further step concerned the study of temperature distribution in a semi-infinite medium. The free surface simulate the Earth's surface, assumed isothermal at the temperature T_0. We adopt a space domain very large respect to the cross-sectional area of the tube. The boundaries of the domain are maintained at temperature T_2.

We calculate the temperature field around the tube and the heat flow density

$$\mathbf{q} = -\kappa \nabla T \tag{3}$$

where κ is the thermal conductivity that is taken constant. The results are shown in Fig.s 1 and 2 for a choice of values of parameters and two values of tube depth. The solution is very similar in the case of a deep tube (Fig. 1) while a remarkable difference can be seen in the case of shallow tube (Fig. 2). As the assumed boundary conditions force the Earth's surface to be at the prescribed temperature T_0, the thermal field at the surface does not give information on the thermal field at depth. This is in contrast with observations, especially when the lava tube is placed at shallow depth (Pinkerton et al., 2002). The condition of constant temperature at the Earth's surface will be relaxed in the numerical model.

The simultaneous effect of several processes such as heat conduction to the ground and the atmosphere, convection and radiation in the atmosphere is not generally considered in analytical modeling, but can be considered in a numerical model.

The rate at which the surface cools down by convection in the atmosphere is given by the vertical flux

$$q_c = h_c\,(T_s - T_a) \tag{4}$$

where T_s is the surface temperature and T_a is the temperature of the atmosphere at large distance from the tube. The constant of proportionality h_c is the (convection) heat transfer coefficient. It depends on the thermal properties of the air in the boundary layer, surface geometry and the air motion. In a well-stirred atmosphere a thin layer of undisturbed air is present in the vicinity of the surface. Since this layer is not in motion, h_c is relatively low ($h_c = 0.1 - 1.0$ W m^{-2} K^{-1}). In this case the heat transfer from the surface into the atmosphere occurs quasi conductively. Low values of h_c, but slightly higher than the previous one ($h_c = 2 - 25$ W m^{-2} K^{-1}), occur under the free (or natural) convection in a stable atmosphere when the turbulence is absent or weak, and very high values when the air turbulence is intense. In forced convection the value of h_c rises by a factor ranging from 10 to 100 with respect to the free convection ones. On the basis of field experiments above cooling pahoehoe lava, Keszthelyi and Denlinger (1996) suggest a broad and higher range of variation, from 35 to 150 W m^{-2} K^{-1}. Keszthelyi et al. (2003) suggested 45-50 W m^{-2} K^{-1} for pahoehoe temperature surface at 400-550 °C cooled by a wind speed of about 10 m s^{-1}.

The value of T_a depends on the atmospheric conditions, ranging from lower values under clear sky to higher values under warm, cloudy conditions and it changes from day to night. We assume that the atmosphere above the surface is at constant temperature $T_a = 20$ °C.

The heat flux associated with radiation at $z = 0$ is

$$q_r = \sigma\varepsilon\left(T_s^4 - T_a^4\right) \tag{5}$$

where σ is the Stefan-Boltzmann constant and ε is the emissivity; atmosphere and ground radiate at their respective absolute temperatures T_a and T_s. We assume equal atmosphere and ground emissivities. We assume ε in the range 0.8 - 1.0. The surface temperature T_s is part of the solution of the problem.

In general, thermal conductivity κ and heat capacity at constant pressure c_p are functions of the temperature T. We consider empirical functions given for basaltic lava by Mebed (1983) (Fig. 3).

Considering the effects of convection and radiation in the atmosphere, expressed by relations (4) and (5), the temperature T and the heat flow components q_x and q_z at the Earth's surface ($z = 0$) along the x-axis are shown in Fig. 4. Differently from what observed in Fig. 2, now the isotherms intersect the Earth's surface, producing a thermal anomaly. The heat flow has also a horizontal component q_x.

A noteworthy result concerns the relationships between the width of the temperature curve and the depth of the source. Berthelote et al. (2008) by laboratory measurements showed that a narrow anomaly is related to a shallow source, while a broad anomaly is related to a deeper source. As a measure of width we considered the half-distance between the points x_1 e x_2 where the horizontal straight line $T = T_{max}/2$ intersects the temperature curve of the thermal anomaly (Fig. 4):

$$x_{1/2} = \frac{1}{2}\left(|x_1| + |x_2|\right) \tag{6}$$

If we compare the values of $x_{1/2}$ as a function of h for different values of a and e, we note that the set of points are well fitted by a straight line of equation $h = x_{1/2}$. This means that $x_{1/2}$ is nearly equal to the depth of the tube and is fairly independent of the size of the tube.

Fig. 5 shows the relation between maximum temperature and tube depth for a choice of values of semi-axis (i.e. tube cross section area if e is fixed). We can infer that, for a given semi-axis a, the maximum temperature T_{max} rises with decreasing depth, but if the depth increases, the difference in the peak temperature curves vanishes and T_{max} tends asymptotically to the ambient temperature T_0.

Lava tubes may have irregular cross sections that can be approximated by an elliptical section with semi major axis horizontal or not perfectly horizontal. In Fig. 6 the thermal field is shown with different orientation φ of the semi major axis of the ellipse respect to the horizontal plane: the peak temperature T_{max} shifts toward the point of the surface nearest to the wall of the tube and the temperature anomaly becomes asymmetrical. The greatest asymmetry occurs when $\varphi = \pi/4$. The maximum values of temperature and of heat flow occur when the major semi-axis a of the ellipse becomes vertical, i.e. for $\varphi = \pi/2$, because in this case the distance between the wall and the Earth's surface is minimum.

We consider tubes having different cross-sectional shapes and study their thermal fields. In Fig. 7 we show the heat flow and the thermal anomaly at the Earth's surface and in a vertical cross section. The results do not differ significantly from the ones found for elliptical tubes. Asymmetry of the curve is related to a stronger asymmetry in the geometry of the tube, with the peak temperature shifted toward the point of the surface nearest to the tube. These results show that the thermal anomaly on the Earth's surface is sensitive to the shape of the tube; in particular, the rectangular shape produces a remarkable change in the thermal profile.

We consider an empty cylindrical conduit having an elliptical cross-section, and suppose that this conduit refills with lava at temperature T_1. Refilling takes place in a short time with respect to the characteristic time for heat diffusion. Starting from the time of the replenishment, the host medium around the tube at temperature T_0 progressively warms up at a rate which depends on its thermal parameters and the temperature T_1.

The thermal field around the tube and the thermal anomaly generated at the Earth's surface can be studied by the heat conduction equation in the transient state:

$$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho c_p} \nabla^2 T(x, z) \tag{7}$$

Just as in the steady state case, the solution searched out satisfies conditions (4) and (5) on the Earth's surface and $T = T_1$ at the tube wall. The initial condition is $T = T_0$ at $t = 0$ at any point of the surroundings. For a choice of values of parameters ($T_1 = 1000$°C at $t = 0$, $a = 1$ m, $e = 0.5$, $h_c = 40$ W m^{-2} K^{-1}, $\varepsilon = 0.9$), Fig. 8 shows that the temperature at the Earth's surface reaches the steady state, in a time after the replenishment of the tube, that depends on the depth h.

4. Conclusions

Observations of active volcanism with high-resolution thermal detectors allow to better understanding active volcanic processes. Thermal data, especially when used together with other monitoring techniques, help to determine the nature of potential volcanic hazards.

If we observe volcanic areas at different times by thermal cameras, we can detect anomalies and evaluate their causes during an eruption; in particular, we can evaluate whether they are due to active lava flows or not and what is their state. For lava tubes, our model shows that we can connect thermal anomalies with lava tube position, characteristics and state, i.e. we can reconstruct its features and whether it is still active or not, and whether it is refilling or cooling.

The numerical model shows how the surface thermal anomalies allow to estimate direction, depth, and shape of a potential active lava tube. The surface distribution of maximum values of surface temperatures can reveal the tube direction. The model takes into account the principal thermal effects due to the presence of an active lava tube, i.e. the conduction to the ground and the atmosphere, the convection and the radiation in the atmosphere. If the temperature values, in particular the maximum ones, are time dependent, the model can give informations about the distance from steady-state conditions.

If we fix a reasonable value of lava temperature, the thermal profile across the tube direction, in particular the width of the temperature curve, allows to evaluate the depth of the tube. The values of maximum temperature and of the tube depth allow to estimate the tube dimension. The shape of the temperature curve and its asymmetry can give informations about the geometry of the tube, i.e. if its section is elliptical, with a semi-axis horizontal or not, or if the section is different.

Acknowledgments

We are grateful to the editor Heidy M. Mader and to Ciro Del Negro and Sonia Calvari for constructive and helpful comments on the first version of the paper.

References

Berthelote, A. R., Prakash, A., Dehn, J., 2008. An empirical function to estimate the depths of linear hot sources: Laboratory modeling and field measurements of lava tubes. B. Volcanol. 70, 813-824.

Budetta, G., Del Negro, C., 1995. Magnetic field changes on lava flow to detect lava tubes. J. Volcanol. Geotherm. Res. 65, 237-248.

Calvari, S., Pinkerton, H., 1998. Formation of lava tubes and extensive flow field during the 1991-1993 eruption of Mount Etna. J. Geophys. Res. 103, 27291-27301.

Calvari, S., Pinkerton, H., 1999. Lava tube morphology on Etna and evidence for lava flow emplacement mechanisms. J. Volcanol. Geotherm. Res. 90, 263-280.

Carling, G.T., Radebaugh, J., Saito, T., Lorenz, R.D., Dangerfield, A., Tingey, D.G., Keith, J.D., South, J.V., Lopes R.M., Diniega, S., 2015. Temperatures, thermal structure, and behavior of eruptions at Kilauea and Erta Ale volcanoes using a consumer digital camcorder. GeoResJ 5, 47-56, doi: 10.1016/j.grj.2015.01.001.

Carslaw, H. S., Jaeger, J. C., 1959. Conduction of heat in solids. Clarendon Press, Oxford.

Dragoni M., Piombo, A., Tallarico, A., 1995. A model for the formation of lava tubes by roofing over a channel. J. Geophys. Res. 100, 8435-8447.

Dragoni M., D'Onza, F., Tallarico, A., 2002. Temperature distribution inside and outside a lava tube. J. Volcanol. Geotherm. Res. 115, 43-51.

Dragoni, M., Tallarico, A., 2008. Temperature field and heat flow around an elliptical lava tube. J. Volcanol. Geotherm. Res. 169, 145-153.

Dragoni, M., Piombo, A., 2009. Thermoelastic deformation associated with a lava tube. B. Volcanol. 71, 409-418.

Flynn, L. P., Harris, A.J.L., Wright, R., 2001. Improved identification of volcanic features using Landsat 7 ETM+, Remote Sens. Environ. 78, 180-193.

Garces, M., Harris, A., Hetzer, C., Johnson, J., Rowland, S., Marchetti, E., Okubo, P., 2003. Infrasonic tremor observed at Kīlauea Volcano, Hawai?i, Geophys. Res. Lett. 30, 2023-2027, doi:10.1029/2003GL018038.

Gómez-Ortiz, D., Montesinos, F.G., Mart?n-Crespo, T., Solla, M., Arnoso, J., V?lez, E., 2014. Combination of geophysical prospecting techniques into areas of high protection value: Identification of shallow volcanic structures, J. Appl. Geophys. 109, doi:10.1016/j.jappgeo.2014.07.009.

Greeley, R., 1971a. Observations of actively forming lava tubes and associated structures, Hawaii. Modern Geology 2, 207-223.

Greeley, R., 1971b. Lava tubes and channels in the Lunar Marius Hills, Earth Moon Planets, 3, 289-314.

Greeley, R. and Spudis, P., 1981, Volcanism on Mars, Rev. Geophys. Space Phys., 19, 13-41.

Greeley, R., 1987. The role of lava tubes in Hawaiian volcanoes. U.S. Geol.

Surv. Prof. Paper 1350, 1589-1602.

Guest, J.E., Underwood, J.E., Greeley, R., 1980. Role of lava tubes in flows from the Observatory Vent, 1971 eruption on Mount Etna. Geol. Mag. 117, 601-606.

Harris, A., Bailey, J., Calvari, S., and Dehn, J., 2005. Heat loss measured at a lava channel and its implications for down-channel cooling and rheology, in Manga, M., and Ventura, G., Eds., Kinematics and Dynamics of Lava Flows: Geological Society of America, Special Paper 396, 125-146.

Hoblitt, R.P., Battaglia, J., Kauahikaua, J.P., Okubo, P.G., 2002. Lava tube seismicity at Kilauea, Eos Trans. AGU 83, Fall Meet. Suppl., Abstract V71A-1259

Holcomb, R. T., 1987. Eruptive history and long-term behavior of Kilauea Volcano, in Volcanism in Hawaii by R. W. Decker, T. L. Wright, and P. H. Stauffer (eds.), U.S. Geol. Surv. Prof. Pap., 1350, 261-350.

Hon, K., Kauahikaua, J. P., Denlinger, R., Mackay, K., 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.

Kauahikaua, J.P., Cashman, K.V., Mattox, T.N., Heliker, C.C., Hon, K.A., Mangan, M.T., Thornber, C.R., 1998. Observations of the basaltic lava streams in tubes from Kilauea Volcano, Island of Hawaii. J. Geophys. Res. 103, 27303-27323.

Keszthelyi, L., 1995. A preliminary thermal budget for lava tubes on the Earth and planets. Geophys. Res. 100, 20411-20420.

Keszthelyi, L., Denlinger, R., 1996. The initial cooling of pahoehoe flow lobes. B. Volcanol. 58, 5-18.

Keszthelyi, L., Harris, A. J. L., Dehn, J., 2003. Observations of the effect of wind on the cooling of active lava flows. J. Geophys. Res. Lett. 30, doi: 10.1029/2003GL017994.

Kilburn, C.R.J., Luongo, G., (eds.) 1993. Active lavas: Monitoring and Modelling, UCL Press, London.

Kilburn, C.R.J., 2000. Lava flows and flow fields, in Sigurdsson, H., Houghton, B.F., McNutt, S.R., Rymer, H., and Stix, J., Eds., Encyclopaedia of Volcanoes, Academic Press, 291-306.

Malin, M., 1980. Lengths of Hawaiian lava flows. Geology 8, 306-308.

Mattox, T. N., Heliker, C., Kauahikaua, J., Hon, K., 1993. Development of the 1990 Kalapana flow field, Kilauea volcano, Hawaii, Bull. Volcanol. 55, 407- 413.

Mebed M.M., 1983. Thermal properties of rocks at high temperatures, High Temperatures-High Pressures, 15, 113-118.

Miyamoto, H., Haruyama, J., Kobayashi, T., Suzuki, K., Okada, T., Nishibori, T., Showman, A.P., Lorenz, R., Mogi, K., Crown, D.A., Rodriguez, J.A.P., Rokugawa, S., Tokunaga, T., and Masumoto, K., 2005. Mapping the structure and depth of lava tubes using ground penetrating radar. Geophys. Res. Lett. 32, L21316, doi:10.1029/2005GL024159

Peterson, D.W., Swanson, D.A., 1974. Observed formation of lava tubes during 1970-1971 at Kilauea volcano, Hawaii. Stud. Speleol. 2, 209-222.

Peterson, D.W., Holcomb, R.T., Tilling, R.I., Christiansen, R.L., 1994. Development of lava tubes in the light of observations at Mauna Ulu, Kilauea Volcano, Hawaii. Bull. Volcanol. 56, 343-360.

Pieri, D.C., Baloga, S.M., 1986. Eruption rate, area and length relationships for some Hawaiian lava flows. J. Volcanol. Geotherm. Res. 30, 29-45.

Pinkerton, H., James M., Jones, A., 2002. Surface temperature measurements of active lava flows on Kilauea volcano, Hawai'i. J. Volcanol. Geotherm. Res. 113, 159-176.

Ponte, G., 1949. Riassunto delle principali osservazioni e ricerche fatte sull'Etna. Bull. Volcanol. 9, 65-80.

Sakimoto, S.E.H., Crisp, J., Baloga, S.M., 1997. Eruption constraints on tube-fed planetary lava flows. J. Geophys. Res. 102, 6567-6613.

Sakimoto, S.E.H., Zuber, M.T., 1998. Flow and convective cooling in lava tubes. J. Geophys. Res. 103, 27465-27487.

Self, S., Thordarson, T., Keszthelyi, L., Walker, G.P.L., Hon, K., Murphy, M.T., Long, P., Finnemore, S., 1996. A new model for the emplacement of Columbia River basalts as large, inflated pahoehoe lava flow fields, Geophys. Res. Lett., 23, 2689-2692.

Valerio, A., Tallarico, A., Dragoni, M., 2008. Mechanisms of formation of lava tubes. Journal of Geophysical Research, 113, B08209, doi:10.1029/2007JB005435.

Valerio, A., Tallarico, A., Dragoni, M., 2010. A model for the formation of lava tubes by the growth of the crust from the levees. J. Geophys. Res. 115, B09208, doi:10.1029/2009JB006598.

Witter, J.B., Harris, A.J.L., 2007. Field measurements of heat loss from skylights and lava tube systems. J. Geophys. Res. 112, B01203. doi:10.1029/2005JB003800.

Table 1: List of the used symbols.

Symbol	Quantity
a	major semi-axis
b	minor semi-axis
c_p	specific heat
e	eccentricity
h	tube depth
h_c	turbulent heat transfer coefficient in the atmosphere
$\mathbf{q}$	heat flow density
t	time
T	temperature
ε	thermal emissivity
κ	thermal conductivity
σ	Stefan-Boltzmann constant
φ	polar angle in respect to x axis

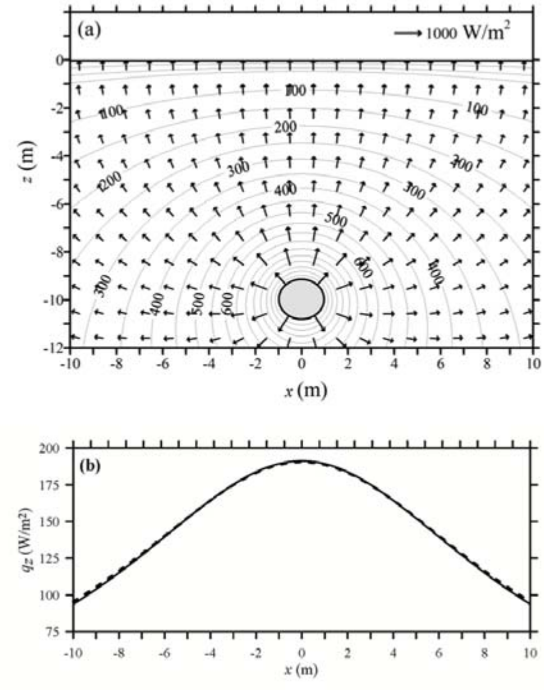

Figure 1: a) Isotherms (full lines) and heat flux (arrows) around a lava tube with $T_1 = 1000$ °C, $a = 1$ m, $e = 0.5$, $T_0 = 20$ °C, $h = 10$ m, $\kappa = 3$ W m^{-1} K^{-1}. b) Numerical (solid line) and analytical solution (dashed line) for z-components of the surface heat flux.

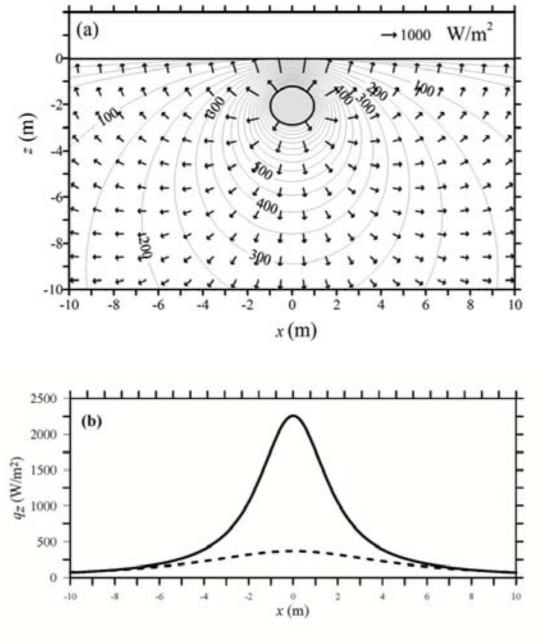

Figure 2: The same as Fig. 1 with $h = 2$ m.

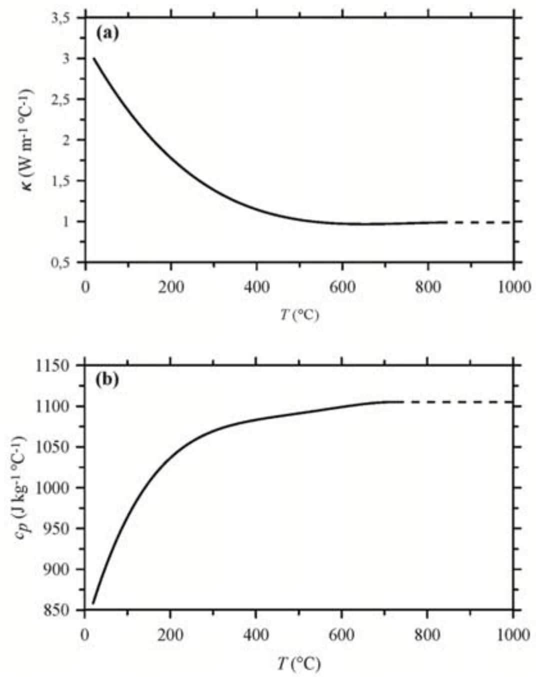

Figure 3: Thermal conductivity κ (a) and heat capacity at constant pressure c_p (b) of basalt (andesitic), as function of the temperature T from Mebed (1983); dashed lines indicate extrapolated values.

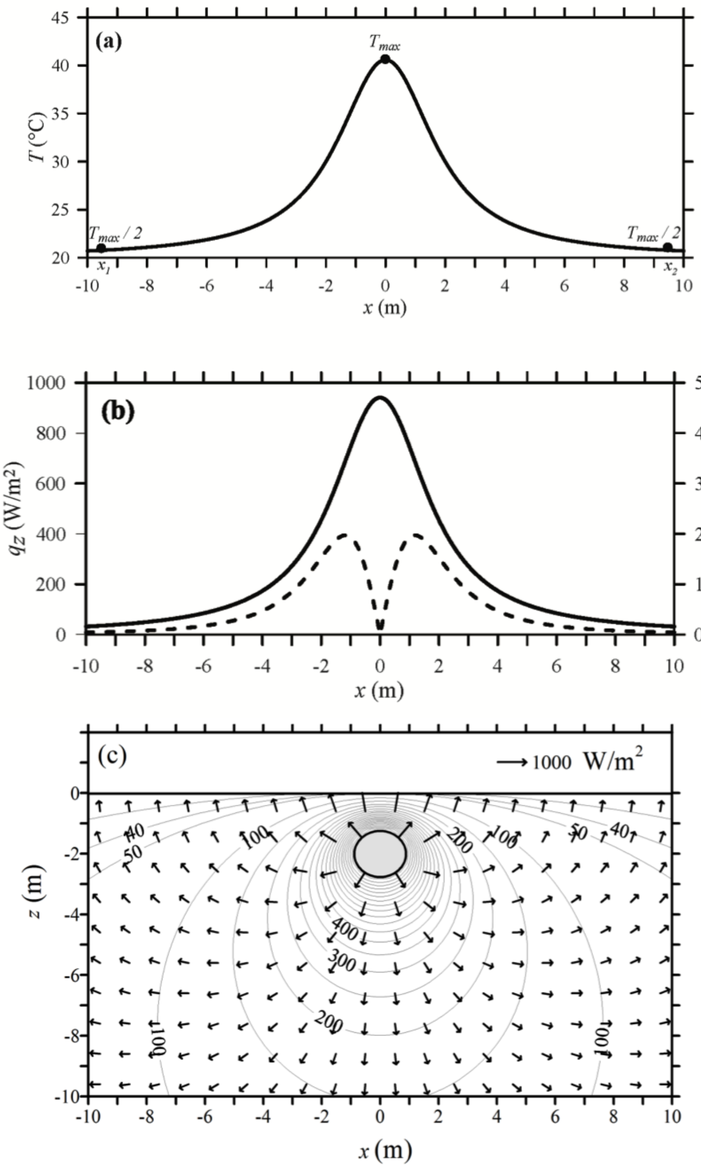

Figure 4: Effects of convection and radiation in the atmosphere on surface temperature T (a) and on x and z-component of the surface heat flux (b) (q_x full line and and q_z dashed line). (c) Isotherms (full lines) and heat flux (vectors) in the surrounding of a lava tube. ($h = 2$ m, $T_1 = 1000$ °C, $a = 1$ m, $e = 0.5$, $h_c = 40$ W m^{-2} K^{-1}, $\varepsilon = 0.9$).

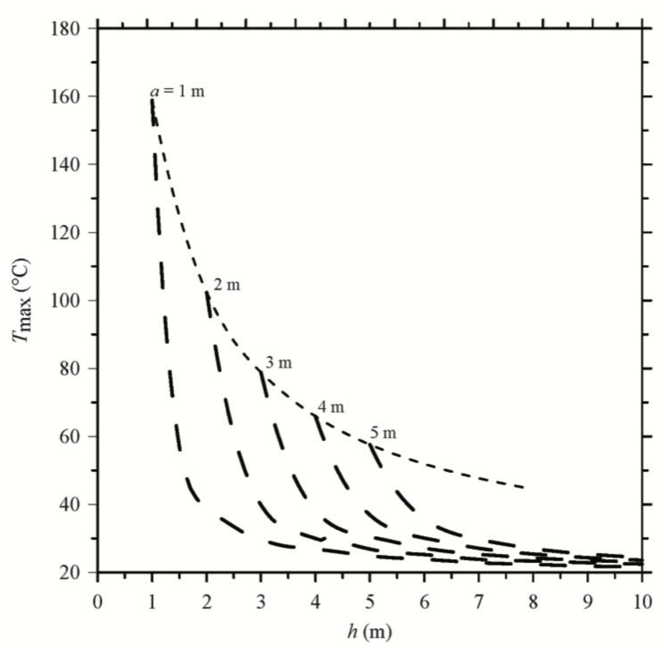

Figure 5: The relation between maximum temperature T_{max} and tube depth h for a choice of values of semi-axis a ($T_1 = 1000$ °C, $T_0 = 20$ °C, $e = 0.5$, $h_c = 40$ W m^{-2} K^{-1}, $\varepsilon = 0.9$).

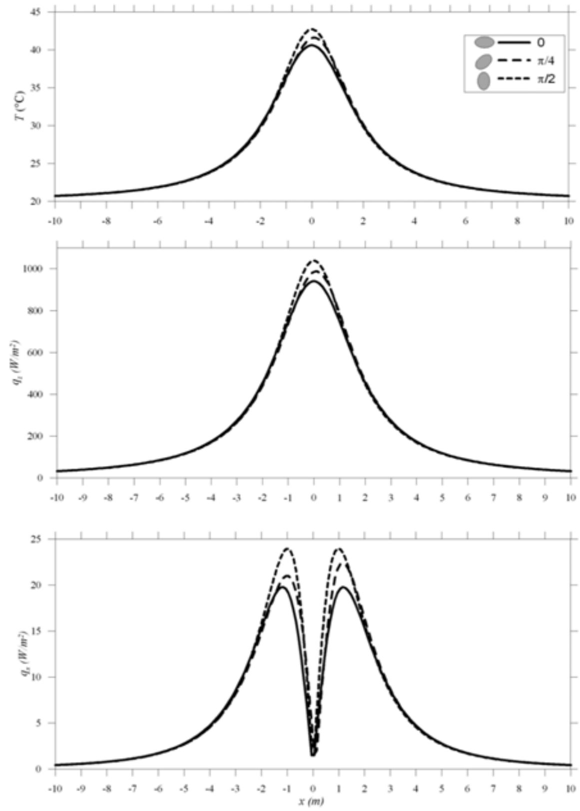

Figure 6: Thermal field at Earth's surface for different values of the angle φ. ($h = 2$ m, $T_1 = 1000$ °C, $a = 1$ m, $e = 0.5$, $h_c = 40$ W m^{-2} K^{-1}, $\varepsilon = 0.9$)

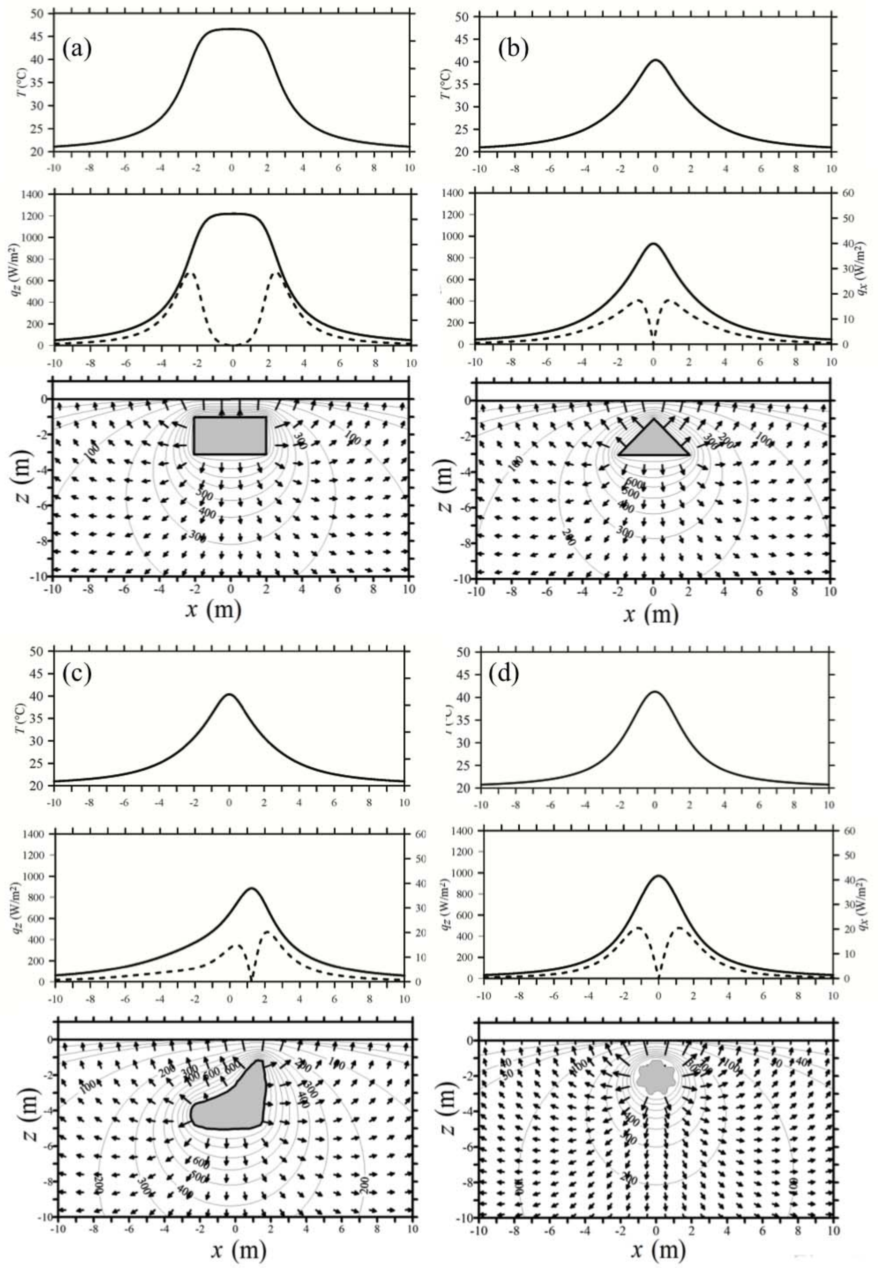

Figure 7: Isotherms (full lines), heat flux (vectors) and the corresponding surface heat flux and temperature in the surrounding of a lava tube with a) rectangular, b) triangular, c) asymmetric, and d) corrugated cross-section shape. (h = 2 m, T_1 = 1000 °C, a = 1 m, $e = 0.5$, $h_c = 40$ W m^{-2} K^{-1}, $\varepsilon = 0.9$)

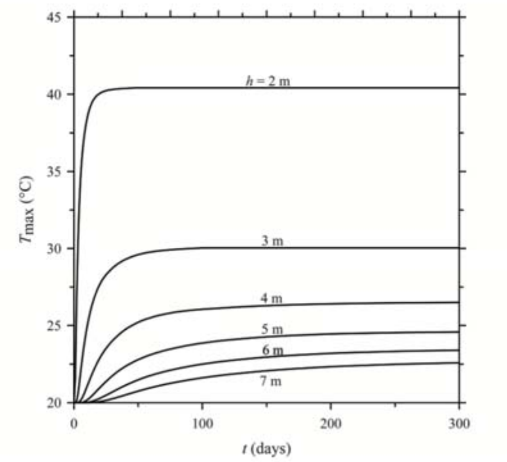

Figure 8: The maximum temperature T_{max} of the thermal anomaly versus the time t after the tube refills by lava at $T_1 = 1000$ °C at $t = 0$ for different values of h ($a = 1$ m, $e = 0.5$, $h_c = 40$ W m^{-2} K^{-1}, $\varepsilon = 0.9$).