

THE LAVA CAVES IN THE ETNA TERRITORY

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Introduction

Since ancient times, the lava caves of Etna have been one of the main attractions of this volcano, and have had an important role in Sicilian society throughout its development. Initially used as habitations, as places for worship or burial, they have also provided hiding places for bandits, safe shelters for wayfarers, and lastly have been used as storage chambers for snow, a characteristic Etnean economy. Etna in fact, in so far as an active volcano, has always been a different mountain to others. A long time before the Age of Enlightenment, therefore also before the start of mountaineering, when the Alps were visited only by a few intrepid hunters, Etna was already the favoured destination of travellers and students who made it an obligatory stop on their stay in Italy. It is thanks to these numerous cultured travellers that the multiple descriptions of the *fires* of Etna, with details and precious information for the reconstruction of the past eruptive activity of the volcano, have come down to us.

At the end of the last century, the spread of the passion for mountaineering and the knowledge of the mountain as exploration of both nature and Man himself, provoked new interest in the hypogeal ambient. With some decades of delay with respect to the areas of the Carso in the Trieste region and southern France, where Boegan and Martell respectively led the first speleological research into karstic caves, a methodical and scientific work of exploring of the caves of volcanic origin by the first Catanese speleologists began on Etna between the two world-wars. Among these, a special place is held by Francesco Miceli (1906-1978). Gradually, the location, description and topographical survey of numerous caves of volcanic origin was undertaken. At the beginnings of the 1970s, the known Etnean caves already numbered more than a hundred, and currently they amount to more than two hundred and fifty cavities.

Classification

The caves that are formed on volcanoes are created at the same time as the rocks that contain them, namely during the expansion of the lava flows, taking a period of time that may vary from a week to some months (Mattox et al., 1993; Calvari and Pinkerton, 1998). It is therefore possible to date their formation exactly, as long as the age of the eruption that has given rise to the flow in which they have developed is known. This characteristic is of fundamental importance to distinguish them from karstic caves, that form as a result of chemical and physical action of excavating the rock (limestone) and whose time of evolution can be in the order of the hundreds of thousands or even millions of years. There are examples of caves produced by the erosive action of water or wind also in volcanic areas, but these are by far a minority (Fig. 1).

The systematic work of surveying the lava caves has led to the formulation of numerous classifications of the cavities of volcanic origin.

Regarding an early classification of the volcanic caves, proposed by Licitra in 1978, two major groups can be distinguished:

1 surface rheogenetic caves

2 fracture caves

The first have largely developed on level ground and mainly parallel to the external surface of the flow. The name itself, deriving from the Greek (ρεω = flow and γεννητικός = that which generates) indicates that these caves are formed as a result of the flowing of lava. Fracture cavities instead extend vertically until remarkable depths, and often need a considerable speleological preparation by those wishing to explore them.

The processes that produce these two groups of caves are significantly different to each other. The genesis of the surface rheogenetic caves is tied to the formation of lava tubes, while fracture cavities are formed as a result of earthquakes during which the ground is cracked by the pressure of the magma

as it rises towards the surface. The surface rheogenetic caves are also commonly called lava flow tubes, since they are formed as a result of the flow of lava over the ground. The fracture caves instead extend to depth beginning from the apex part of an eruptive fracture that has intersected the surface. There are also obviously intermediate terms, namely cavities that are formed at the passage between a fracture cave and a lava flow tunnel. Finding these connections is rather unusual, but an example of exceptional beauty is surely that between the eruptive fractures of 1792, that continues to the base with the famous lava tube called “Tre Livelli” (Corsaro et al., 1990).

Lava tubes

The expansion of a lava flow is governed by several factors. Some are connected to the environment in which the flow expands; others are due to the interaction between the intrinsic chemical-physical characteristics of the lava, or *rheology*, and the modality with which it is emitted, scientifically defined as the eruptive dynamics.

Since the moment of its emission from the vent, the lava flow loses heat and begins to cool. The heat dispersion is greater on the surface, where the flow is directly in contact with the atmosphere. This heat exchange between lava and atmosphere is manifested with the formation of a solid crust, that becomes more rigid and thicker with time, and thus with the continuation of cooling. The surface of a lava flow, that on Etna, close to the point of emission, has a maximum temperature of 1080°C (Calvari et al., 1994), solidifies quickly as the flow expands. Walker (1973) was the first to notice that the length of the flows is proportional to the effusion rate. Indeed, high effusion rates produce very long flows. Later studies (Calvari and Pinkerton, 1998) have highlighted that, for an effusion rate of approximately twenty cubic meters per second, a typical value during the main phase of the 1991-93 eruption that threatened Zafferana Etnea (Calvari et al, 1994), a lava flow stops after having covered the maximum distance of five kilometers. In order to explain the remarkable lengths that may also exceed sixteen kilometers, as in the case of 1669, without cooling and thus not stopping, it is necessary to consider the existence of lava tubes inside the main body of the active flows that represent the most efficient way to transport lava from the point of emission to the front with minimal thermal energy loss, thanks to the high insulating potential of the solid walls of lava encasing the tube. This solid shell grows gradually, beginning from zones of stagnation of lava along the channel, until becoming a continuous roof. It protects the lava, that flows inside, from further heat dispersion, acting like a water conduit that transports the liquid to great distances without losing it in streams along the way.

Lava flows and lava tubes

Various authors have put forward hypotheses on the processes that cause the construction of a lava tube on the basis of observations made in volcanic caves, but also on active lava flows in Hawaii, on the two volcanoes Kilauea and Mauna Loa, as well as on Etna. However, there are significant differences between Hawaiian volcanoes and Etna, differences that we can substantially trace back to the composition of lava. The Hawaiian eruptions mostly produce highly fluid lavas with smooth and vitreous surfaces. In volcanology these are called lavas with a *pahoehoe* morphology, a Hawaiian word indicating the possibility to walk barefoot on the surface of these flows without difficulty, provided they have cooled down. Etna instead produces highly viscous flows, which while flowing become fragmented in large blocks, producing a very uneven surface. Also in Hawaii there are these kinds of flows, but they are a minority. And the scientific term is once again Hawaiian to define them: flows of type *aa*, evidently an onomatopoeic name that indicates the pain felt by anyone crossing them on barefoot, even when cold.

The *pahoehoe* flows are also typical of volcanoes on Iceland and some parts of Australia, and most knowledge in the volcanological field on caves formed in these lavas has led to erroneously believe that the formation of lava tubes was a typical phenomenon of pahoehoe lava, and a rare or at least unusual event in *aa* lavas. The exploration of the caves of Etna, and above all the correlation between the morphology of the lava caves and the surface structure of the flows that host them, has instead highlighted just how common the lava tubes are also inside flows of the *aa* type (Calvari and Pinkerton,

1998).

How a lava tube is formed

Recently, three mechanisms of lava tube formation lava in *aa* type flows have been recognized on Etna (Calvari and Pinkerton, 1998).

Sketch of the three main mechanisms of lava tube formation. In the inset (a) on the left a typical *aa* flow and on the right the sections of the zones close to the vent (A-A') median (B-B') and at the front or toe zone (C-C'). The two sections for each zone show the mechanism of a sector of lava tube formation. Sections 1 and 2 indicate the growth of the banks towards the inside of the channel that occurs in narrow channels and in zones close to the source. Sections 3 and 4 show the accumulation of blocks and gradual growth of a surface crust that occurs in wide channels and zones with a medium slope. Sections 5 and 6 show the swelling of the frontal zone of the flow that produces very broad tube sections. The inset (b) represents the partial collapse of the front zone following the opening of an ephemeral vent when the surface crust of this sector of the lava tube still has not completely solidified (modified from Calvari and Pinkerton, 1998, ed. A. Liotta).

When a lava flow runs over the land, the cooling of the marginal portion means that it is quickly bounded by solid and cooler lateral banks that form the channel within which the fluid lava may flow. The banks can grow upwards, that is towards the surface part of the lava channel, until joining together in the middle section. This happens as a result of the progressive accumulation of layers in the inner and upper portion of the very same banks, and is caused by small fluctuations in the level of the lava inside the channel.

This mechanism may more readily be found in narrow lava channels, namely channels of less than five meters wide. In this situation, slight fluctuations of the level of lava in the channel produce bridge-like structures that gradually propagate along the lava channel both up and downstream to make up the lava tube. Any abrupt increase in the speed of the flow can lead to a momentary or definitive destruction of these delicate structures. At that point, the process must then start again. An incomplete welding of the various sectors of the lava tube will leave openings in the roof, called windows, from which it is sometimes possible to observe, measure and sample the lava flow within the tube.

The second mechanism of genesis of a lava tube has been observed in channeled flows with widths greater than five meters (wide channels). In this case, the joining up of opposite banks is more difficult owing to the intrinsic instability of such a broad roof. However, the gradual slowing down of the surface flow caused by cooling produces a progressive accumulation of cold scoriaceous blocks. Peterson and Swanson (1974) have described numerous mechanisms of accumulation of blocks observed during Hawaiian eruptions. These blocks build up on the lava flow that continues running beneath them, and they form a continuous carpet that gradually solidifies. The infiltration of the fluid lava below in the interstices between one block and another acts as a kind of adhesive. The interstitial lava is cooled on contact with the air, and becomes a veritable cement binding the blocks firmly to form a continuous and rigid roof.

The third mechanism, never previously found, has recently been individuated on Etna for the first time (Calvari and Pinkerton, 1998), using data coming from the 1991-93 eruption. This process acts in the frontal zones of lava flows with *aa* surface that expand over a slightly sloping substrate. We may picture an input of continuous and stationary magma from the source, and a lava flow that has reached the maximum distance allowed by the limiting effect of the formation of a solid crust. In this situation, the accumulation of lava in the frontal zone of the flow will produce a progressive swelling with plastic deformation of the crust. When the pressure of the lava that is accumulating inside has exceeded the resistance of the crust, the opening of an ephemeral vent occurs that drains the fluid in the flow and forms a new flow. If this process takes place slowly enough to allow the cooling and hardening of the surface crust of the first flow, another sector of a lava tube will form in the peripheral zone (front) of the flow.

Lava tubes and lava flow caves

A lava tube is therefore a kind of “conduit” that quickly channels the lava from the main vent to the furthest parts of a lava field. But its existence, albeit necessary, is not sufficient to explain the presence of one or more caves inside a flow. In fact, at the end of an eruption the lava inside the tube may solidify, obstructing it totally. In this case it will not be possible to find the existence of the tube unless on occasion of excavation work for the construction of roads or buildings. Splendid examples of small un-drained lava tubes are observable along the edges of the road from Nicolosi to Rifugio Sapienza, or along the road leading from Rifugio Sapienza to the summit craters of the volcano (Figs. 3-4). The dimensions of a lava cave depend on both primary factors, those which have determined the width of the host tube, or on secondary processes, for example the drainage, collapse, or coalescence, namely the confluence of adjacent or overlapping tubes.

Among the primary factors, that concerning the erosion of the base of the lava tubes is much debated. This process is considered normal and frequent in Hawaii, and it is precisely there that it has been possible to measure, through highly advanced techniques, the speed of erosion of the bottom due to the lava flowing in a tube. This speed has proved to be as much as 10 centimeters a day, and suggests that the main Hawaiian lava tubes sink deeper at a speed in the order of a meter every ten days (Kauahikaua et al., 1998). On the basis of these measurements and previous observations, it is thought that the oldest lava tubes in Hawaii, that is those which were formed early on in the course of an eruption and that remained active over a longer time span, are also those of the greater dimensions (Cooper and Kauahikaua, 1992; Kauahikaua et al., 1998). This has still not been demonstrated for Etna, although various proposals of erosion of the lava tube base have been formulated also in the recent past (Licitra, 1981; Greeley et al., 1998). Not only has no evidence of erosion of the bottom been found on Etna to date, but the sizes of the Etnean lava tubes seem to be tied to various processes concerning the corresponding Hawaiian terms. Observations in drained and inactive lava tubes (Calvari and Pinkerton, 1999) have evidenced how the process of “capture” or coalescence of adjacent or overlapping lava tubes is extremely common in the Etnean caves. Splendid examples are observable in many caves of Etna such as those of Intraleo (Fig. 5) and of the Diavolo (Fig. 6), but also in Petralia. [add Petralia]

In order that a lava tube produces a lava cave, it is necessary that the partial or total drainage of the tube occurs. Evidently this speleogenetic process is as equally important and necessary as that of the formation of the lava tube. There are a number of causes of draining, due to factors both previous to the very eruption as those determined during its course or also at its termination. Once again there are various hypotheses, all true for specific cases but none of them generally applicable.

One cause of drainage is determined by the existence of a greater angle of the substrate downslope of the stretch with the cave. This leads to an increase of the pressure of the internal fluid mass towards the front of the flow, making the flow continue advancing for a period also after the source feeding has stopped (Rittmann, 1975; Wood, 1975). Evidently this cause is linked to topographical factors, generally existing before the eruption. The mechanism with which this happens is evident and would seem to be generally applicable, but so that the drainage takes place then other conditions must also occur. The existing lava in the tube at the end of the eruption must still be fluid enough to be able to move by gravity alone. There are therefore conditions of limited equilibrium between the slope of the tube and viscosity of lava beyond which drainage cannot happen.

The fracture caves

These cavities have been the object of careful speleological research only during the last decade. In the past, the difficulties of access and progression along the fracture caves severely limited their exploration. However, for a kind of irony of history, among the first cavities studied at Etna, and certainly the earliest to be mapped, is a fracture cave: the Grotta delle Palombe, in the eruptive apparatus of 1669. In the 19th century, this cave was explored separately by two famous students of Etna, Sartorius von

Wartershausen and Mario Gemmellaro. Both reached the base of the well of seventeen meters located inside the cave, and Sartorius also produced an accurate topograph.

Also in the case of fracture caves, we can distinguish two speleogenetic moments. The first corresponds to the episode of opening of the fracture on the ground, and the second to the phase of draining the lava with successive creation of the cave environments.

The opening of the eruptive fracture on the ground is clearly linked to the dynamics of the volcano.

One of the characteristics of Etna is that of having on its flanks numerous cones of scoriae and eruptive apparatuses, testimonies of what Rittmann has defined lateral eruptions. The systems of feeding these eruptions, more or less directly connected to those of the summit craters, are magma intrusions that on traversing the volcanic edifice break the structure being formed along the flanks of the volcano. The eruption of 1669 described above is an example of this type of activity.

Unlike lava flow caves, the drainage in the fracture caves can take place only at the end of the eruption or immediately after. However, not all lateral eruptive apparatuses on Etna have fracture caves; at the moment this fact has no unequivocal explanation. As a rough guideline, it may be thought that in some cases there is a reflux of the magma inside the same eruptive fracture, and that this is accompanied by the collapse of the inner walls and therefore the closure of the eventual cavity. However, it is still unknown why this phenomenon does not always happen and what exactly are its causes. The fact remains that whereas in lava flow caves the drainage happens mostly with horizontal movements, in the fracture caves it is essentially vertical and creates cavities with dimensions that extend to depth for some tens of meters. Often the walls of these cavities are made up of the same embedding rock or by a thin plastering of lava that has remained attached at the moment of the outflow. The existence of the so-called peeling-off and rolling-over structures at the base of some wells and along stretches of these eruptive fractures testifies finally to the extreme rapidity of the final drainage (Figs. 7-8). Taken together, these characteristics render fracture caves extremely unstable, short-lived, destined to become blocked by the collapse of their own sides, and therefore difficult to study (Fig. 9). Normally, none of these has ever been visited by man, unless for speleological or scientific reasons in modern times.

Main forms of volcanic caves

The unseen mechanisms acting on the ground inside the moving lava flows are more clearly expressed underground in the form and structure of the lava tubes, lending them variegated and peculiar morphologies. Among these, we may note some more common structures observable inside lava tubes, for example the striations etched into the walls from the passage of the lava, the lateral benches produced by the prolonged halting of the flow, the rolling-over structures that testify to fast drainage, but also narrow passages or abrupt closures of the vault that indicate instead the opening of an ephemeral vent.

By observing the topography of a lava tube it is possible to put forward some hypotheses on its origin. For instance, the presence of many overlapping or adjacent tubes immediately leads to think of the co-existence of a number of flows during the eruption. The lateral coalescence of flows is a rare phenomenon on Etna, and seems mainly tied to the emplacement of *pahoehoe* lava fields, as for example the Micio Conti cave in prehistoric lavas of this kind (Fig. 10). Vice versa, the vertical capturing of a flow by one beneath is an extremely common process on Etna, and above all in *aa* type lavas. The capture mechanism contributes significantly to the maintenance of a main feeding tube in the lava field. Deep tubes would become inactive if buried by successive flows already with lava tubes. However, they continue to drain lava towards the more distant parts of the lava field thanks to the continuous input from the capture of successive and overlying flows.

Important indications on the mechanisms operating inside lava tubes derive from the observation of the various cross sectional forms that the tubes take. Caves created inside narrow channels often have a bell shaped section and generally reduced dimensions. A splendid example of this type is La Fenice cave, which can be observed a little way from the Emmaus hotel, on the outskirts of Zafferana Etnea (Fig.11). Caves that are formed from wider channels (more than 5-6 m) will have broader sections with a "Norman arch" shape and a generally constant size. An example is the very well known Cassone

cave, whose entrance is along the road between Zafferana Etnea and Rifugio Sapienza (Fig. 12). Some particular cross-sections of lava tubes have a key-hole shape. These are characterized by benches that run longitudinally along much of the tubes on one or both sides. These morphologies can be found inside narrow or wider tubes (Fig. 13) and can be due to either phenomena of capture or more frequently halting of the flow at a constant height during the drainage of the lava tube (Figs. 14-15). Another type of morphology often found along the walls of the volcanic caves is that of the so-called rolling-over structures, already mentioned in the case of the fracture caves but also in various flow tubes. The coils are formed during the final phase of drainage of the main mass of the flow, when this happens suddenly. In this case, the lava covering, still plastic and attached to the walls, collapses towards the inside of the gallery (Fig. 16).

In greater detail, it is possible to observe a series of morphologies linked to the movement of the lava inside the volcanic caves. These are *stria* (streaks or faint ridges) of the flow, from which the type of emptying of the tube can be determined: mostly horizontal stria indicate a gradual lowering of the level of the flow, while more accentuated vertical components mean rapid drainage or even collapse of parts of the tubes at the end of the eruption (Fig. 17).

A last morphology entirely typical of the volcanic caves is the lava stalactite. This is a large drop of lava that may be some centimetres in length on Etna, hanging from the roof of the tube. Its origin is much debated, and there are two differing explanations for its formation. The first indicates dripping of the lava that forms the roof of the tube owing to the remelting of the low-melting portion. The second suggests that they are drops of lava remaining attached to the roof following fluctuations in the level of lava in the tube (Jaggard, 1931). Recently (Calvari and Pinkerton, 1999), it has been observed how both processes are plausible, and how they correspond to slightly different kinds of stalactites. The stalactites from remelting have a highly smooth and reddish surface; those due to lava remaining stuck to the walls are instead black and jagged.

The various morphologies described explain how lava tubes, even though generally accessible, have areas that may readily be penetrated while others are particularly arduous, since they are narrow or have very jagged surfaces. Nonetheless, this has not prevented them from being visited, probably for different purposes apart from simple habitations since prehistory.

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Fig.1 - Pitagora cave: example of cave produced by differential erosion of the loose material under a dyke-flow (Photo by M. Pompilio).

Fig.2 - Monte Nero pit. Example of eruptive fracture cave with walls that in this case still have the

scoriae of the eruptive apparatus (Photo G. Giudice - CSE Archives).

Fig. 3 - Example of small tumulus in the lava field of the 1983 eruption. Four small tubes can be seen, of which three are partially drained and one, in the centre, undrained (1983 flow) (Photo S. Calvari).

Fig. 4 - Detail of the former, showing the undrained tube (S. Calvari).

Fig. 5 – Intraleo cave. Example of lateral capture (Photo G. Giudice - CSE Archives).

Fig. 6 – Devil's cave (Grotta del Diavolo), formed during the eruption of 1614-24 (two overlapping tubes). In the image two levels of overlapping tubes can be seen, the upper one entirely drained (Photo G. Tomasello - CSE Archives).

Fig. 7 - Monte Nero pit. Example of cave in the eruptive fracture of 1923. Note the deep vertical form typical of fracture caves. At the base the rolling-over structures formed as a result of the rapid draining and successive collapse of the lava walls, can be observed (Photo G. Tomasello – CSE Archives).

Fig. 8 – Ice pit (Abisso del Ghiaccio), opened in the eruptive fracture of 1947. Example of rolling-over structures in a lava tube (Photo G. Giudice - CSE Archives).

Fig. 9 - Marinite cave (Grotta della Marinite). Other example of cave in eruptive fracture, formed in the eruption of 1928. At the bottom the accumulation of blocks from collapse are evident (Photo - CSE Archives).

Fig.10 - Micio Conti tube (Grotta Micio Conti), prehistoric flows: example of horizontal coalescence between parallel lava tubes (Photo A. Amantia).

Fig.11 - La Fenice tube (Grotta La Fenice), eruption 1792-93: example of cave with bell shaped section (Photo S. Calvari).

Fig. 12 - Cassone tube (Grotta Cassone), eruption of 1792-93. In this stretch of the tube one may observe the typical Norman arch section (Photo G. Giudice - CSE Archives).

Fig. 13 – Three Levels tube (Grotta Tre Livelli), eruption 1792-93: example of vertical capture of overlying lava tubes (Photo S. Calvari).

Fig. 14 - Three Levels tube (Grotta Tre Livelli), eruption of 1792-93. Prominent lateral benches on both sides of the tube may be seen (Photo G. Giudice - CSE Archives).

Fig. 15 – KTM cave (Grotta KTM), eruption of 1792-93. In this case, the lateral benches have developed on one side of the tube owing to the curve. This condition led to the accumulation of solidified lava on the inner side of the curve, a similar mechanism to that of the formation of banks in rivers (Photo G. Giudice - CSE Archives).

Fig. 16 - Cassone tube (Grotta Cassone), eruption of 1792-93: example of a segmented conical rolling-over structure (Photo A. Amantia)

Fig. 17 - Intraleo tube (Grotta Intraleo). Bottom left, vertical striations that indicate the collapse of the overlying tube occurring when the wall was still in a plastic state (Photo A. Marino - CSE Archives).

Fig. 18 - Micio Conti tube (Grotta Micio Conti), in prehistoric flows. The roof of the tube is covered by remelted stalactites, aligned in the direction of the flow to form small ridges (Photo N. Barone - CSE Archives).