LAVA TUBES: THEIR MORPHOGENESIS AND ROLE IN FLOW FORMATION.

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy at the University of Leicester.

LAVA TUBES: THEIR MORPHOGENESIS AND ROLE IN FLOW FORMATION.

Christopher Wood.

Abstract.

An attempt is made to understand the morphology, formation and operation of lava tube systems in pahoehoe lava flows from evidence contained in lava tube caves (landforms resulting from the segmental drainage of lava tube systems). Twelve caves from five contrasting lava flows in Tenerife, Iceland and Sicily (Mt.Etna) are described and the morphogenesis of each is worked out from relationships between flow structure and cave form. The structural evidence adds support to the tube-forming processes previously observed by volcanologists during periods of effusive volcanic activity. No evidence is found to support the currently popular 'layered lava' theory of cave genesis; instead, each cave is seen to be derived from a lava tube system which is a network of varying tube types.

Knowledge of cave forms enables a visualization of the morphology of lava tube systems and the dynamics of the lava rivers they transport. Ideally, each system is sinuous and partly braided along the flow axis and terminates at a delta-like front, though complexities frequently arise as a result of such processes as stream piracy, the development of overflow tubes and the extension of the axial tube across former deltaic regions of the flow. Discussion of channel forms, comparison with other fluvial systems and knowledge of the efficiency of lava tubes in maintaining flow temperature and mobility suggests that lava tube systems are 'adjusted' forms: it is only through their construction that temperature and mobility are maintained sufficiently to enable the continued advance of the flow front downslope. At the front lava emerges from the tube system as a jet flow. As a result, it is argued that the development of pahoehoe lava flows is predictable and amenable to future quantification through the application of jet theory.
Frontispiece: Third roof collapse, Surtshellir.

The camera was pointing downflow. The photograph clearly shows the glazed lining of the cave and the apparent, thinly bedded roof rock. Note also the flat surface of the lava flow on either side of the collapse and the well-formed tumulus overlying the cave passage. The left hand wall of the collapse is 7m high.
Introduction.

Lava tubes are enclosed lava river channels and function as the arteries of active pahoehoe lava flows. They occur singly, occupying the axes of individual flow units, or they combine with others in structurally complex lava flows to form an internal conduit system, whose role is the efficient transportation of fluid lava between the vent and the advancing flow front. The development of lava tube systems appears to be essential to the formation of long lava flows and to the growth of Hawaiian type shield volcanoes (Peterson and Swanson, 1974), but because they function internally their morphology, formation and operation are poorly understood. Fortunately, at the cessation of effusive vent activity, the variability of the slope of the pre-flow surface may cause a part of a lava tube system to drain, forming a lava tube cave that can be explored and mapped. It is evidence from lava tube caves that forms the basis of the present study of lava tube systems.

It is not commonly known that a lava tube cave may be just as extensive, as complex in form and as beautiful in internal decoration as a limestone cave. Some are single, vast, meandering tunnels, though most are
complicated passage networks, each consisting of a long sinuous
and partly braided axial throughway, linking a number of branch passages
or lateral complexes. Many caves are extensive (ranging up to 11.5km
in length) and some are technically difficult to explore, with squeezes,
crawls, exposed roof traverses and wall climbs, lakes, ice slopes and
superimposed passage levels separated by pitches up to 20m deep. These
caves are far from the featureless tunnels depicted in the geological
literature; instead, varying passage forms and flow features diversify
all caves, and many are lined with a black-brown vitreous glaze that
flowed at the time of its formation and developed long, delicate, rod
and straw stalactites and tall, globular stalagmites.

The serious exploration of lava tube caves began only 10-15 years ago,
but today it represents a new and expanding branch of speleology, known
as vulcanospeleology. Caving groups in regions of the world with an
abundance of recent volcanic rocks and a lack of limestone have come to
specialize in vulcanospeleology, and are currently exploring and mapping
the lava tube caves and other volcanic cavities (vents, rifts, spatter
cones, etc.) that lie within their respective territories. Groups such
as the Cave Exploration Group of East Africa, Gruppo Grotte Catania
(Sez. Etna, Club Alpino Italiano) and the Cascade Grotto of the National
Speleological Society (Pacific N.W. of the U.S.A.) have had notable
successes in the discovery and exploration of new caves. These groups,
and others like them, have contributed enormously to the cumulative
knowledge of the forms and occurrences of lava tube caves.

Geological research has followed on from the exploration of lava tube
caves and has been undertaken by both speleologists and geologists. To
one group, lava tube caves are speleological landforms ranking in importance with limestone caves, while to the other, these cave represent one of the largest and most complex landform types in recent basaltic terrains and are terrestrial analogies to the sinuous rilles of the lunar and martian surfaces. There have been many investigations of the morphogenesis of lava tube caves as a result of these different interests, and specific observations of tube-forming processes were also undertaken during the 1969-71 Mauna Ulu eruption, Kilauea volcano, Hawaii. However, the history of research is one of controversy. There has been an inability to equate the complex morphologies of lava tube caves with either the traditional explanation, entailing the drainage of the axial flow of a partly congealed lava flow or flow unit, or the tube-forming processes of channel closure and toe-budding observed during the Mauna Ulu eruption. Researchers have mainly fallen back on previous, highly speculative, all-embracing theories of internal lava flow and tube formation, even though these are at variance with the observational evidence. The result is that there is still no generally accepted theory on the genesis of lava tubes or lava tube caves.

The present study considers this problem of the morphogenesis of lava tube caves and discusses the evidence these caves contain relating to the morphology, formation and operation of lava tube systems. The study is based mainly upon field investigations of lava tube caves in Tenerife, Iceland and Sicily (Mt.Etna), but also calls upon descriptions of other lava tube caves in the speleological literature and reports of the observations of tube-forming processes operative during the Mauna Ulu eruption.
Acknowledgements.

This thesis is the result of geological fieldwork undertaken during seven expeditions to lava tube caves in Tenerife, Iceland and Sicily (Mt.Etna). I am particularly grateful for the support of my companions on these expeditions, for each not only struggled with surveying instruments in frequently wet and cold conditions, but also contributed a part of the cost of the expedition in which he participated. My friend Martin Mills especially shared much of the responsibility of the surveying, survey calculations and survey drawing. Other members of the various expeditions were Messrs. Butcher, Brown, Carmen, Dodding, Dunk, Illingworth, Lynch, Trenchard, Warren, Wilkinson, Wilson, Wood and students from St.Albans College of Further Education. Members of Gruppo Grotte Catania (Sez. Etna, Club Alpino Italiano) also participated in the fieldwork on the 1614-24 lava flow and I am extremely grateful for the help and friendship offered by this group. All of the expeditions were undertaken in the name of the Shepton Mallet Caving Club and the use of caving and surveying equipment from this club is acknowledged. External financial support was raised for many of the expeditions from the Royal Geographical Society (Iceland, 1970, 1972 and Etna, 1976), the Ghar Parau Fund of the British Cave Research Association (Iceland, 1972 and Etna, 1976), the Sports Council (Etna, 1976), St.Albans College of Further Education Principal's Fund (Heimaey, 1973), the Sports Council of St.Albans College of Further Education (Etna, 1976) and the Students' Union of St.Albans College of Further Education (Etna, 1976). The Royal Geographical Society also kindly loaned a theodolite and folding staff for the 1970 and 1972 Iceland expedition and the 1976 Etna project. I also thank the following individuals and organisations for their help:
Dr. P. F. Brandon, who provided continued support for the expeditions; Dr. J. E. Guest, who first suggested the idea of a project on the 1614-24 lava flow, Mt. Etna; Prof. Sigurdur Thorarinsson, for his encouragement of the Gullborg project and for supplying information on the chemistry of the Leitahraun; B. M. Ellis, who built, maintained and modified the cave theodolites and allowed the use of his survey of Raufarhólshellir; the Icelandic National Research Council, for permission to carry out research in the Icelandic caves. Lastly, I am particularly grateful for the help and encouragement offered by my long-suffering supervisor, Dr. T. D. Ford.

Note on the spelling and use of Icelandic place-names.

It has not been possible to provide one of the characters specific to the Icelandic alphabet. As a result it has been necessary to transliterate 'Þ' for 'th' (e.g., Thorlakshavn). No authority can be given for this transliteration, though it is common practice.

It is also important to note the geological inference of some of the Icelandic place-names used herein:

'borg' literally means a castle or fort, but this element is frequently used to denote craters (e.g., Gullborg).

'eldborg' is the Icelandic name for low lava shields which possess a summit crater and has come into general vulcanological use as the term describing Icelandic type shield volcanoes.

'gjá' signifies an eruptive or non-eruptive fissure (e.g., Thvergjá).

'hellir' signifies a cave (e.g., Raufarhólshellir, Vegghellir, etc.).

'hraun' signifies lava - usually a lava flow (e.g., Leitahraun).
Contents.

Abstract. p.1

Introduction. p.9

1. Résumé of present knowledge of the forms and occurrences of lava tube caves. p.22

2. Previous research. p.39

3. Fieldwork. p.58

4. Methods of tube construction. p.93

5. Morphogenesis of the lava tube caves around Icod de los Vinos, Tenerife. p.123

6. Morphogenesis of Raufarhólshellir, S.W.Iceland. p.145


8. Morphogenesis of the lava tube caves of the Hallmundarhraun, W.C.Iceland. p.188


10. Discussion: (a) Morphology and evolution of lava tube networks in pahoehoe lava flows and implications regarding flow formation. p.244

11. Discussion: (b) Morphogenesis of lava tube caves. p.254

12. Conclusion. p.265

References. p.275

Appendix A: Glossary of technical terms. p.287

Appendix B: List of publications and supporting material.
LIST OF LAVA TUBE CAVES INVESTIGATED.

<table>
<thead>
<tr>
<th>Name of cave</th>
<th>Name of lava flow</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cueva del Viento</td>
<td>unnamed lava flow</td>
<td>Icod de los Vinos, N.Tenerife.</td>
</tr>
<tr>
<td>(Cueva de las Breveritas - Cueva de los Piquetes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cueva de San Marcos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raufarhóllshellir</td>
<td>Leitahraun</td>
<td>S.W.Iceland.</td>
</tr>
<tr>
<td>Borgarhellir</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegghellir</td>
<td>Gullborgarhraun</td>
<td>Snaefellsnes, W.Iceland.</td>
</tr>
<tr>
<td>Thrihellir</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Íshellir</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vidgelmir</td>
<td>Hallmundarhraun</td>
<td>W.C.Iceland</td>
</tr>
<tr>
<td>Surtshellir</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stephánshellir</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grotta dei Lamponi</td>
<td>1614-24 lava flow</td>
<td>Mt.Etna, Sicily.</td>
</tr>
<tr>
<td>Grotta degli Inglesi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grotta del Labirinto-Pozzo Superiore</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Distribution of lava erupted by Mauna Ulu from 1969 to 1971 (abstracted from Peterson and Swanson, 1974). Lava tubes are represented diagrammatically.

Reference map.
1. Résumé of present knowledge of the forms and occurrences of lava tube caves.

Lava tube caves are known to exist in many of the world's recent volcanic regions and are particularly common in, though not exclusive to, basaltic pahoehoe lava flows. One cave that does not occur in basaltic pahoehoe, for example, is the extremely complicated, 8km long Mount Suswa Lava Cave, Kenya, which Williams (1963) notes occurs in lava of phonolitic or trachytic composition. Other less extensive caves are known from basaltic aa lava flows. It has been suggested that lava tube caves occur on slopes falling within a limited range (Hatheway and Herring, 1970; Greeley, 1971), but in the writer's experience the range of gradients is wide, from less than \( \frac{1}{2}^\circ \) to more than \( 15^\circ \), and it appears that for short distances lava tubes will form on slopes approaching \( 60^\circ \) (Peterson and Swanson, 1974, p.216).

Continuous and long cave segments are difficult to find because drainage of a lava tube system is frequently only segmental and, also, the thin, fragile roof readily collapses both during active flow (the resulting collapse hole then being known as a window or skylight) and during or after drainage. Caves tend to occur in groups, both as
a result of segmental drainage and/or collapse of a single lava tube system, and as a result of tube drainage in successively overlapping lava flows or large flow units. Thus, caves in tongue-shaped lava flows or flow units are aligned along the axis, while caves in more complex lava flows or lava fields are randomly distributed. Partly collapsed lava tube systems can be immensely long, as is shown by the caves and collapses resulting from a lava tube which may have extended for more than 100km from the Undara Volcano, North Queensland, Australia (Atkinson, Griffin and Stephenson, 1977) (Fig. 1.1.). To date, however, the longest known continuous lava tube cave segment is the 11.5km long Leviathan Cave, situated in the Chyulu Hills, Kenya (Simons, 1976), while the Cueva del Viento, Tenerife (described in Chapter 5), Kazumura Cave, Hawaii, and possibly Manjang Gul, Korea, each possess a length of 10km.

Maps of lava tube caves reveal great differences in the configurations of passage networks (Fig. 1.2.). There is a great variability of form even within the limited number of caves surveyed for this study. The Cueva del Viento, Tenerife, for example, comprises a fantastic complex of small, interconnecting passages at various levels in the lava flow. This cave contrasts with some Icelandic caves, such as the Surtshellir-Stephánshellir system of interconnecting spacious passages all occurring on a single plane, or the single, vast meandering passage of Vidgelmír cave. The caves also vary both in distance and position relative to the vent, apparently due in part to the variability of the underlying topography and its control on the drainage of the tube network. Some caves, like one of the Gullborgarhraun caves in Iceland, may be entered through the wall of the vent crater, while other caves seem to originate considerable distances below the vent, such as
Fig. 12. Contrasting cave forms.
(Note different scales)
Plate 1.1. A view of the main passage of Stephánshellir.

A typical passage form. Features which may be identified in the photograph are an ice floor, roof breakdown, a lateral bench, wall striations (flow grooves), straw stalactites and horizontal roof structures.
Surtshellir–Stephánsshellir and Raufarhólshellir, Iceland, which occur 28km and 10km below their respective vents.

This writer recognises in lava tube caves forms and features which have developed in three quite separate stages of cave evolution. The first stage involves the construction of a conduit (lava tube) network beneath the congealed surface of the lava flow, through which liquid lava is transmitted during the course of the eruption from the vent to the advancing flow front. In the second stage, activity at the vent ceases, the conduit network drains and is modified by the deposition of cooled lava to the walls. This is followed by collapse and breakdown resulting from sub-aerial attack, which represents the third stage. All three stages are responsible for complexities in the morphology of a lava tube cave.

Cave passages vary in diameter from less than 1m to more than 15m. Passage profiles are also variable. In straight passages the profile is nearly circular if it has drained completely, though for a variety of reasons the perfect form is rarely attained and a more typical profile is one with an arched roof and a flat floor (Plate 1.1.). Bends possess an asymmetrical form, with the highest part of the passage situated on the outside of the bend, and this profile is comparable with the channel form at bends in other fluvial systems. Such passage profiles are products of the first genetic stage and the majority are subsequently modified as the flow through them diminishes. Lowering of the lava level within a passage may proceed spasmodically, with individual stands being marked by paired longitudinal deposits known as lateral benches (Fig. 1.3.). If the lowering of the lava level is arrested for a time, it sometimes happens that a crust
Fig. 1.3. **Section of a lava tube as envisaged by Bravo (1954).**

will form over the stream, so that with further lowering of the lava level a horizontal partition, or false floor, may remain spanning the passage. This process may be repeated on numerous occasions, the partitions remaining whole to give the passage what appears to be superimposed tube levels, or they may collapse to leave shelf-like ledges, known as lateral shelves, that protrude from either wall. Occasionally, as at Surtshellir, the crust was still plastic when the lava drained from beneath it and it sagged beneath its own weight. Many passages are also lined with a thick crust, which is a deposit left by the lava stream, and this is termed a lava tube crust.

Flow features ornament the walls and floor of lava tube caves. Blocks of solid crust which became incorporated in the liquid flow gauged the walls of the conduit and produced horizontal striation, known as flow grooves. In multi-level caves, solidified cascades of lava, termed lavafalls, are the result of one level capturing the flow of a higher level. The floor of a cave may show a wealth of interesting flow features. The common, rough, clinkery floor is caused by gases escaping from the surface as the lava cools, while flows broken into polygonal or irregularly shaped slabs are the result of jointing due to contraction upon solidification. The usual pahoehoe ropy or folded surface may be exhibited and crustal slabs may be tilted at varying angles by the flow. In some caves there are miniature floor channels, complete with high lateral levees. Sometimes blocks of solid crust have fallen from the roof of the lava tube while the floor was still plastic and the resulting ripples have become frozen and preserved as a floor formation. Much rounded relic blocks of older lava which fell into the lava stream may also sometimes be discovered.
During the lowering of the lava level, burning gases maintain temperatures in the interior of the lava tube at 1200°C. Jagger (1947) observed this phenomenon through a window in the roof of the Postal Rift Tube, Hawaii, and attributed the maintenance of such high temperatures to a blast furnace effect. More recently Peterson and Swanson (1974) have recorded similar observations. As a result, lava tube caves are lined with a black vitreous glaze that was sufficiently fluid at the time of its formation to trickle and to produce decorations on the walls and ceiling. The observations of Peterson and Swanson (1974, p.220) of these developments in a tube are as follows:

'Abundant lava stalactites several tens of centimetres long hang from the ceiling of tube portals at skylights. These stalactites are thick bodied and were observed to form when lava splashed from the stream, stuck to the roof, and dripped down. They have subsequently oxidized red, like the rock from which they hang.

Long, slender, very fragile stalactites hang from a thin glaze on the roof deep inside the lava tubes. These stalactites are rarely more than 1cm in diameter and commonly show contorted shapes that record a complex history of formation. They formed as viscous glaze in the ceiling slowly dripped downward; indeed, some of these stalactites have matching stalagmites rooted to the floor beneath them, just as in limestone caves. The lower end of many stalactites is bent towards the nearest skylight, probably reflecting the draft created as heat and gas left the tube through the skylight'.

Fig. 1.4. Lava speleothems from Vidgelmýr.
Usually cave walls exhibit a rippled glazed structure, but if the glaze was highly fluid and flowed down the walls, vertical ridges or corrugations resulted, producing minute gour-like features where each corrugation passed over a wall striation. Commonly, remelting of the ceiling of the tube caused blistering, though blisters may have burst before solidification, leaving circular ridges a few centimetres across (plate 6.3.).

In many lava tube caves lava stalactites and stalagmites are common (Fig. 1.4.), though it is strange that some caves are completely devoid of them. The larger forms usually hang from the outer edges of wall protuberances and are the result of the initial draining of the tube or, as described by Peterson and Swanson (1974), of lava flung as spatter onto the walls and ceiling. Smaller forms are made of glaze and possess a greater variety of shapes. Many are delicate rod- or straw-like features, no thicker than a pencil, while others may be tapered or tear-drop in shape. Some straw stalactites possess an erratic form and these probably correspond with Jagger's 'worm stalactites' (Jagger, 1931), resembling a piece of knotted string. Still other straws are partly crushed like a pipestem, or delicately ornamented with flow patterns. In Vidgelmír cave in Iceland forests of stalagmites lie beneath walls covered with dense clusters of rod and straw stalactites (Plate 1.2.). The stalagmites consist of tiny globules of glaze which have piled one above the other, so that heights of 30cm are not uncommon (Plate 1.3.). In another Icelandic cave, Borgarhellir, straw stalactites are united with globular stalagmites to form erratic columns over 1.5m high, and individual straws exceed lengths of 1m (Thorarinsson, 1957). Some interesting speleothems described by Jagger (1931) were 'barnacle stalactites'
Plate 1.2. Well-developed wall glaze, rod and straw stalactites and globular stalagmites in Vidgelmir. Tallest stalagmites 22cm+ high.

Plate 1.3. A large globular stalagmite in Borgarhellir (now stolen). Pencil 15cm long.
which originate as extrusions of molten lava through the pores in
the walls of the cave. Similar extrusions which oozed through
cracks to form papery thin curtains have been described by others
and are known as ribbon stalactites.

The examination of the chemistry and petrology of lava stalactites
has been undertaken by several workers (Hjelmquist, 1932; Williams,
1963; Ollier and Brown, 1965). There is an outer crust on most
speleothems which is ½-1mm wide and composed of a silvery magnetic
oxide of iron (a similar thin crust also lines the interior of many
caves). Internally, there are vesicles which are elongated vertically.
These also possess a crust, but it is thinner than the outside crust.
The vesicles are lined with freely formed crystals of plagioclase,
augite and magnetite. In thin section, the solid part is crystalline,
but with a different texture than crystalline basalt, and it is composed
mainly of plagioclase and augite.

In Government Cave, Arizona, Harter (1971) distinguished between
'drip pendants' and 'lavacicle stalactites'. He noted that lava drip
pendants were only rarely responsible for the formation of lava
stalagmites, and he separated the two stalactitic forms on the basis of
vesicle arrangement. Drip pendants were observed to possess many small
vesicles and were slightly denser than the roof rock, while lavacicle
stalactites possessed only a few large vesicles and were much less dense
than the roof rock.
2. Previous research.

Previous works on lava tubes and lava tube caves have been many and varied. The most prolific writers have been speleologists and this group, through its exploration and mapping activities, has been responsible for the present considerable knowledge of cave forms and occurrences world-wide. Professional geologists, on the other hand, appear to have looked upon lava tubes merely as curiosities, of limited application, until the need arose for terrestrial analogies of the volcanic landforms of the lunar surface. Smaller lunar sinuous rilles, and possibly examples on Mars, were thought to have probably originated from lava tube collapse, and research was therefore stimulated into the geology of terrestrial lava tube caves and, subsequently, into the processes of lava tube formation during the recent effusive volcanic activity on Hawaii (1969-71 Mauna Ulu eruption, Kilauea volcano). Experienced vulcanologists participating in the programme of observations of active lava tube formation during the emplacement of large pahoehoe lava flows on Hawaii were, in turn, struck with the importance of lava tubes in the transportation of fluid lava to sites distant from the vents and, generally, in the
building of Hawaiian type shield volcanoes. Thus, with many interested parties, and with reports of research on lava tubes or on lava tube caves occurring in diverse and sometimes even obscure publications, it is not surprising that there has been, and still are, gaps in communications between the parties. This chapter attempts to bring together in an historic framework both the recent observations and the more important older contributions on lava tube genesis, many of the latter group having previously gone unnoticed, but nevertheless are positive contributions to the discussion.

In Iceland, an early interest in lava caves (invariably lava tube caves) was shown by Victorian scientists and travellers during their 'Grand Tour'. Many formed an opinion of the origin of a particular cave they visited, though many of their theories were often as fantastic as the landscape in which they were conceived. Two popular explanations are notable, however. An earlier view held that lava caves (lava tube caves) were formed by blistering as gas escaped from the lava during its consolidation (Mackenzie, 1812), and some authors (Forbes, 1860; Baring-Gould, 1863) believed that the famous Surtshellir consisted of a chain of linked gas bubbles. The theory was based upon the apparently billowed and blistered flow surface. A little later some observers noted horizontal striations on the walls of Icelandic caves (Holland, 1862; Paijkull, 1868; Hartwig, 1891) and regarded these features as indicative of flow of hot magma through the cave. A new theory then became popular and involved the draining of fluid magma from beneath the congealed crust of the lava flow during the later stages of its emplacement. This last idea has persisted to the present day and forms the basis of the modern theories, though since these early days this traditional explanation has taken many different forms.
In Hawaii, lava tubes on the floor of Kilauea Crater had been well advertised since the visit of Ellis (1923), but possibly the first recorded exploration of a lava tube cave was by a party led by L.A. Thurston in a large lava tube leading from the bottom of Kalvaiki Crater (pit crater) (Anon., 1913). Thurston's Tube, as it became known, was later subjected to a more thorough investigation by Powers (1920). Other Hawaiian tubes were also described by Powers, such as the Kaumana Tubes (like Thurston's Tube, today a tourist attraction), and he also discussed the hypothesis put forward by Hobbs (1914), that buried lava tubes were important in draining Hawaiian craters: which concept, although not applicable to the Halemaumau and Makeuaweoweo (Mauna Loa) example cited, was proven during the recent eruption of Mauna Ulu and was quite an insight for it time. Powers did not offer an explanation of the origin of lava tubes. Generally, lava tubes must have been common occurrences on Hawaii but, unlike the well-developed lava tube caves on the mainland U.S.A., they were not well documented in this early period.

Early scientists and travellers also reported of lava caves on Mt. Etna, Sicily. Sir Charles Lyell (1855), for example, noted that conduits and caves were characteristic of the Etnean lavas, while Malladra (1917) described a lava tube cave from the Vesuvian lava of 1858. Ponte (1922) made the first serious study of lava tube caves on Mt. Etna. He described work in the caves of the 1669 lava flow carried out by Gurrieri (then unpublished), discussed and rejected the applicability of Hobbs' (1914) hypothesis to the drainage of Etnean craters and noted that the 'onion-skin' layering described by Malladra about the cave passages on Vesuvius could also be recognised in the Grotte delle Colombe on Etna. Ponte used the last observation to suggest that caves formed as a result of the progressive cooling of
a lava flow from the outside, so that a natural conduit was formed internally, being lined with successive layers of plastic lava as the flow through it diminished. Gurrieri (1933), in a monograph on the lava tube caves of the 1669 flow, Mt. Etna, noted that such caves were a characteristic of basaltic lava flows and suggested a relationship between open lava channels and lava tubes. He cited observations by earlier workers on Etna (Dolomeiu, 1778; Recupero, 1815), describing how tubes originated through the crusting over of a lava channel through the gradual inward growth of marginal levees.

During the 1947-8 eruption of Mt. Hekla, Iceland, Kjartansson (1949) was fortunate to observe the formation of a lava tube cave which was subsequently named Karelshellir (now unfortunately buried beneath later lava). His observations were of lava which was extruded from beneath a flat apalhraun (aa) crust and flowed west down a slope of 1 in 8 with a velocity of 20 cm/sec. The lava was confined to a narrow channel and Kjartansson described how marginal levees developed by the progressive welding of crustal fragments, so that the levees grew both upward and inward towards the centre of the channel until, ultimately, the channel became completely covered over.

A little later Bravo (1954) noticed how common were drained lava tubes in the superimposed basaltic lava flows of the cliff sections of the Valle de Orotava, Tenerife. He described the mode of advance and evolution of a lava flow, with a lava tube forming internally by the traditional method. As the lava flow proceeds down varying gradients it alternatively ponds and elongates and this is represented in lava tube caves, according to Bravo, by spacious chambers alternating with narrow linking passages. On other occasions, Bravo suggested, a low part of the tube may not drain of its fluid load and the subsequent
cave passage is obstructed by a solid plug of lava. Macau-Vilar (1957) took up the points made by Bravo when describing lava tube caves from the post-Miocene lavas of Gran Canaria. These caves, however, were frequently dissected by deep barrancas (ravines), but made excellent water catchment features.

A very notable publication at this time was a report by Wentworth and Macdonald (1953) which summarized many years of observations of active basaltic lava flows on Hawaii. Citing Stearn's observations of the 1935 eruption of Mauna Loa and Macdonald's observations of the 1942 eruption, they showed how the flow near the vent was confined to a narrow channel, where levee construction proceeded by spattering and overflow, and where a roof could be formed across the channel by the jamming of crustal slabs carried along by the lava stream. Farther from the vent, Wentworth and Macdonald envisaged the margins of the flow to be fed by a myriad of small distributary tubes which branched from the main feeder tube. They offered an alternative explanation of tube formation by describing how small flow units, or pahoehoe toes, could be elongated by repeated outbursts of lava from the front, and how each toe subsequently developed a shell by chilling, which gave, if drained, a small lava tube cave.

Cucuzza-Silvestri (1957) described lava tube formation from the evidence of flow structures in the lava of the 1819 eruption, Valle del Bove, Mt. Etna. He noted horizontal layering in the walls of the lava channel in this flow and described how an accompanying lava tube originated as a result of periodic overflow from the channel gradually building inward leaning walls, which eventually merged and formed a roof across the channel. At a slightly later date Poli (1959) attempted to catalogue the various types of caves which had formed on Mt. Etna.
She ascribed tube formation to the traditional method, but also noted the concentric layering in the walls of caves, as described by Ponte (1922) and Gurrieri (1933), suggesting that the flows enclosing the caves were made up of many successively enclosed cylinders whose viscosity increased externally. At the cessation of activity the more fluid internal layers drained of lava, leaving a tube-like cave.

Another variation of the traditional theme was offered by Bravo (1964) as an explanation of the origin of the Cueva de los Verdes, Lanzarote. He thought the cross-sectional form of the cave indicated two phases of formation. In the first phase extensive flooding of lava erupted from the volcano 'la Corona' formed the lava field 'Malpais de la Corona'. During the second phase, lava continued to be erupted, but in diminished quantity, so that it was confined to a channel eroded across the pre-existing lava field. Levees were developed along the borders of the channel by the ejection of spatter and during a momentary cessation of flow a crust formed over the lava. Bravo then envisaged a deepening of the conduit by lava melting the floor, until total cessation of the flow led to the draining of the remaining fluid magma. One year later Macua-Vilar (1965) published an outstanding descriptive work on the Cueva de los Verdes, but no comment was made on the cave's origin or of Bravo's explanation. A further report was written on the cave by Montoriol-Pous and de Mier (1969), though again this was mainly a descriptive work.

As new lava fields and lava tube caves were being discovered and explored by speleologists and geologists, it was realized that lava tube caves were much more common and possessed a greater diversity of size and form than was formerly believed, and many workers became discontented with the traditional explanation. In his 'Caves of
Thin pahoehoe lava flow in an open channel and covering stream alluvium. Surface spatter caused by steam from trapped water.

Decrease in lava supply forms tube, shelves, and benches with gutters against the walls. Stalactites hang from the ceiling.

Crusted slab pahoehoe forms on thicker flows. Slabs are continually formed, jostled and sunk. Carpet of scoriaceous rubble underneath.

Temporary increase in lava supply, and therefore heat, engulfs previous forms and enlarges the diameter of the tube — thermal erosion.

Successive pulses in the lava supply produce thin, layered levees.

Rapid decrease in lava supply causes rolls of plastic lava to arch down from the ceiling and walls. Festoon ridges develop on the floor.

Fig. 2.1. Model of lava tube formation after Kermode (1970).
Washington*, one of the most important regional surveys of lava tube caves, Halliday (1963, p.5), for example, noted 'as a group, these caves do not seem entirely in accord with the traditional concept of these caves as simple conduits with distal ramifications'. Similarly, Ollier and Brown (1965, p.225) noted that the traditional concept 'does not account for all the observed shapes and structural features encountered in lava tubes'. In order to explain the wide diversity of forms met with in the lava tube caves of Victoria, Australia, Ollier and Brown advocated a more elaborate explanation involving the mechanism of laminar flow, which was based upon discernable structures within the flow and the cave. They recognised in lava flows layers up to several feet thick which lay parallel with the flow surface. The layers were of compact basalt separated by trains of vesicles, buckles and partings. This 'layered lava' was said to result from differential movement within one thick lava flow along shear planes. In consideration of the caves and the lava structure, Ollier and Brown suggested the following mechanism of internal flow. The liquid lava concentrated between laminae during the formation of the layered lava became segregated and came to occupy tubes running through the lava. This mobile lava eventually became concentrated into a few major channels that were a continuing source of heat, so that the earlier layered lava was eroded. The end result was cylinders of liquid lava flowing through tubes cut in virtually solid rock.

In later years this theory found a great deal of support, particularly from North America, though it has become a controversial topic. Also, geologists and speleologists still expounded on hypotheses that followed traditional lines (Kermode, 1970; Macdonald and Abbott, 1970) as shown in Figs. 2.1. and 2.2. Most recently, however, the problems
Model of lava tube formation after Macdonald and Abbott (1970). (a) A lava flow (confined in a valley) develops a thin crust and starts to freeze inward from the edges, but the centre remains fluid and continues to flow. (b) The active movement of liquid becomes restricted to a more or less cylindrical, pipelike zone near the axis of the flow. (c) The supply of liquid lava diminishes and the liquid no longer entirely fills the pipe. Burning gas above the liquid heats the roof of the pipe and causes it to melt and drip. (d) Further diminution of the supply lowers the level of the surface of the liquid, which eventually congeals to form a flat floor in the tube.

Fig. 2.2.
of planetary landform evolution has provided an added impetus to the study of terrestrial lava tubes. Suddenly, lava tubes became important volcanic landforms because of the believed close analogy between lava channels and tubes and sinuous rilles. Vulcanologists were also taking an interest and were impressed at the considerable role lava tubes play in the growth of Hawaiian type volcanoes (Peterson and Swanson, 1974).

One of the first important studies of this nature was on the Bandera lava tube caves of New Mexico by Hatheway (1971, 1971a 1976 and also Hatheway and Herring, 1970). The study was of an impressive complex of lava channels and lava tube caves situated in eleven distinct basalt formations. All of the caves appeared to have formed in single flow units, except the Bandera Crater Tube (Fig. 10.3.), traceable for 28.5km, which was common to three flow units and had a more complicated origin. Three alternative methods of formation of the Bandera Crater Tube were discussed. It was concluded that the model proposed by Ollier and Brown (1965), if modified, adequately explained the formation of very long lava tubes, while the processes of tube formation observed by Wentworth and Macdonald (1953) were regarded as applying only to shorter caves, say less than about 1km in length (it was argued that the channel closure method of tube formation could not account for the origin of very long lava tubes, such as the Undara lava tube). Hatheway's model takes as its starting point the segregation of liquid and solid lava along shear planes, as proposed by Ollier and Brown (1965). Hydrostatic pressure of the liquid causes the formation of an effluent tongue, within which is a cylindrical tube, and this elongates as the tongue advances away from the flow front. It is argued that a 'mobile cylinder', or supply conduit, filled with fluid lava, must be present
upflow in order to continue the supply to the effluent tongue. This mobile cylinder naturally propagates in an upflow direction, following the line of maximum gradient of the flow unit. Fluid supply is segregated continually from the layered lava and the mobile cylinder eventually reaches the source area. At this time the cylinder ceases to grow in length and then drains as a result of lava spilling out of the toe at the front. In consideration of the planetary implications of lava tube caves, bend sinuosity, gradient and roof collapse were also analysed.

Following this study Greeley (1971a, 1971b and 1972) and Greeley and Hyde (1971) made a large contribution to the discussion on tube genesis as a result of interests in sinuous rilles. In his study of the lava tube caves of the Bend area of Oregon, Greeley (1971a) agreed that his fieldwork in general confirmed the 'layered lava' hypothesis of Ollier and Brown (1965). Greeley also agreed with Hatheway and Herring (1970) that two tube types were recognisable: minor and major lava tube caves. Minor lava tube caves were described as less than 10m wide and a few hundred metres long, which formed in small, single flow units and often occupied the entire flow (Fig. 2.3.). They were often feeders from larger tubes, or they formed in discrete lava flows which emanated straight from the vent. Most caves in the Bend area, however, were said to be major lava tube caves, 'of the type described by Ollier and Brown', and these were found in flows several kilometres long. Like Hatheway and Herring, Greeley also discussed sinuosity and gradient, and he concluded that the greater degree of complexity of the Horse System was attributable to a lesser gradient. Greeley (1971b and 1972) was also fortunate enough to observe actively forming lava channels and tubes during the 1969-71 eruption of Mauna Ulu, Hawaii. His observations showed that roofs over open channels were constructed by
Fig. 2.3. Diagram of a 'minor lava tube system' in northern California, showing the relationship of the lava tube to the lava flow, (after Greeley, 1971a).

Fig. 2.4. Formation and modification of lava structures as a result of subsequent lava flows (after Greeley, 1971b).
simple crusting, by the jamming and fusing together of crustal slabs and by ingrowing levee construction through spatter and overflow. He also noted multiple flow along rifts and suggested that this may be a mechanism leading to the formation of unusual cross-sections seen in some lava tube caves (Fig. 2.4.). Greeley noted that a single channel could display braided channel flow, open flow, mobile crustal plates and roofed channel along its length. These observations were of use in the study of 833m of lava tube cave in the Cave Basalt, Mt. St. Helens (Fig. 10.2.) (Greeley and Hyde, 1971), where it was thought the caves had formed by two processes. Some segments were developed in 'layered lava' and appeared to have resulted from laminar flow. Other segments were thought to have formed through spatter accretion leading to the formation of arched levees and eventually to a complete roof. Greeley and Hyde thought that laminar flow was a product of lesser gradients, while spatter accretion was the result of more turbulent flow on steeper gradients. They made the important point that subsequent lava flows could modify quite extensively earlier formed tubes by filling or partially filling, remelting the tube's roof to form vertically elongated tubes, reshaping and eroding the tube's walls, stacking additional tube levels above the first, or any combination of these.

Cruikshank and Wood (1972) also observed the development of lava conduits in the Mauna Ulu lavas, as part of a study concerned with the terrestrial analogies of sinuous rilles. They examined lava channels left at various stages of development and they were able to recognise stages in the roofing of channels to form tubes. They provided two examples of channel closure (Fig. 2.5.). Common to both examples, they proposed, a thin flow developed marginal levees by spatter along
The development of covering roofs on lava channels after Cruikshank and Wood (1972). 'In 1-3, a thin flow develops marginal levees by spatter along the flow boundary and by slowly undercutting the channel walls. In stages 4a-6a, marginal spatter grows until it fuses and is later covered by surface flows. In stages 4b-6b, a surface crust on the flowing lava fuses and grows by the method described by Wentworth and Macdonald (1953), later to be covered by surface flows. Stage 7 shows one form of breakdown of a lava tube roof often seen in Hawaii resulting in long trenches with debris floors, or chains of circular or elongated craterlets'.

Fig. 2.5.
the flow boundary and by slow undercutting of the channel's walls. Later stages of development, however, either involved the formation of roofs by marginal spatter, so that arched levees fused and became reinforced by surface lava flows or, alternatively, a surface crust on the flowing lava in the channel fused and grew, later also to be reinforced by surface flows. Cruikshank and Wood recognised that channels closed by spatter and overflow lay on topographic highs orientated along the tube's axis and caused by repeated lateral flows of lava overflowing the channel before closure (also independently recognised by Greeley, 1971b). They also noted several factors that governed the method of channel closure. Proximity to the vent, for example, was held to be important with regard to the loss of gases to the atmosphere, so that once sufficient gas had been removed from the magma, spatter was reduced and one method of levee construction was lost. Thus, this method of channel closure could not be expected far from the vent. An important observation that confirmed earlier speculation was the deepening of lava channels, with the result that older routes would capture newer ones. Cruikshank and Wood could not apply the explanation of Ollier and Brown (1965), or of Hatheway (1971) to the formation of lava tubes in the Mauna Ulu lava flows, but suggested instead that tubes resulted from the crusting over of surface streams by the fusion of floating crustal fragments and/or by the joining of spatter built lateral levees. Other observations also held to be important were bi-level conduits, fluvial-like processes of meandering, bank-cutting, channel capture and channel deepening in active tubes through melting and plucking of the wall rock.

Yet other observations of the Mauna Ulu activity were recorded by Peterson and Swanson (1974). Their observations agreed with those made by Wentworth and Macdonald (1953), Greeley (1971b and 1972) and
Cruikshank and Wood (1972), though they saw no evidence to support the proposal by Ollier and Brown (1965) that lava tubes are the result of the internal shearing of thick flows. Unlike the other observers, Peterson and Swanson described the budding of pahoehoe toes at the flow front, suggesting another tube forming process operating in these finely anastomosing distributaries. They also observed through skylights spectacular underground lavafalls which were formed when lava from a higher level plunged into a lower tube. It seemed that this occurred when the young lava emptied into the skylight of an older tube, or when a weakened roof of a lower tube collapsed beneath a stream of an overlying tube. It was also seen at times that there was a tendency for a flowing lava stream to develop a lower level roof beneath a skylight and at some skylights, if this process was repeated at successively lower levels, three- or four-tiered tubes developed. Peterson and Swanson were also convinced that the lowering of the lava level beneath skylights was not caused as a result of diminished flow, but resulted from bed erosion of the tube by the lava stream within.

Meanwhile, active exploration of new lava tube caves and new investigations of older known caves has continued. A Spanish group has investigated numerous lava tube caves from Iceland (Montoriol-Pous and de Mier, 1970 and 1971; Montoriol-Pous, 1972), the Canary Islands (Montoriol-Pous and de Mier, 1969 and 1974) and the Galapagos Islands (Montoriol-Pous and Escola, 1975), though these reports have only been concerned with descriptions of the caves' morphologies. Recently Simons (1976) described a most exciting discovery of an 11.5km+ long lava tube cave from the Chyulu Hills, Kenya, and this new find adds to the already impressive collection of lava tube caves in this area (Simons, 1974). Atkinson, Griffin and Stephenson (1977) have recently described an incredible, partly collapsed lava tube from the
Undara Volcano, N. Queensland, which system may have been operative over a total distance of 100 km. Most recently Ireton and Wilson (1977) have described over 7 km of lava tube cave from a single lava flow in the Snake River Group, Idaho. Eight separate caves were examined and they were divided into primary, secondary and tertiary types. The primary tubes were the segments of the main axial feeder tube of this lava flow, while the secondary and tertiary tubes were distributaries that fed lava from the axial tube to the margins and flow front. The characteristics of each type were described.

Although, as this review has shown, new observations of active tube-forming processes are available to aid interpretations of lava tube caves, controversy over the proposed methods of cave formation still exists. It is said that these recent observations contribute little towards an understanding of the complexity of lava tube cave networks, while the theoretical models which were designed specifically to explain long or complex caves lie beyond the bounds of observed processes and therefore lack credibility. This problem of the evolution of lava tube networks is considered in the following chapters. The approach is first to determine the various methods of conduit construction (i.e., construction of a single, unbranched tube or cave passage) which may be operative in a pahoehoe lava flow, and then to investigate the spatial relationships between these various conduit types in selected cave complexes. The applicability of the observed tube-forming processes to the evolution of complex lava tube caves is demonstrated and the theoretical models are discounted.
3. Fieldwork.

As a result of the relative inaccessibility of the areas in which the fieldwork was carried out, all of the field project were of necessity organised on expedition lines. Seven expeditions left the U.K. and Table 3.1. shows the areas visited, the lava tube caves investigated and the nature of the work accomplished. In total, 27km of lava tube cave, comprising twelve separate caves in five contrasting basaltic pahoehoe lava flows from Tenerife, Iceland and Sicily (Mt. Etna), were surveyed and investigated. The research areas are located on Fig. 3.1.

The nature and location of the fieldwork presented logistical difficulties and placed certain limitations upon the amount and standard of the fieldwork that could be done.

(1) It was not always possible to secure adequate funds, placing limitations upon the amount of time that could be spent in a research area and upon the amount of equipment that could be transported. In fact, a third expedition to Tenerife proposed for 1977 was cancelled as a direct result of a lack of funds.
Fig. 3.1. LOCATION OF THE STUDY AREAS.

- Iceland
- Leitahraun
- Gullborgarhraun
- Hallmundarhraun

- Tenerife
- Caves around Icod de los Vinos
- P. Teide (3,710m)

- Mt. Etna, Sicily
- Etna summit craters

1923 lava flow
1614-24 lava flow

Lava younger than 1150 A.D. shown.
<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Fieldwork accomplished</th>
<th>Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Heimaey)</td>
<td></td>
<td></td>
<td>b. Jour. SMCC, 5 (9), 21-34.</td>
</tr>
</tbody>
</table>

Unpublished report.
(2) As time was invariably in short supply whilst in the field, surveying standards inevitably suffered. This was particularly important with respect to the Tenerife expeditions, where 12.5km of frequently very narrow and awkward cave passage could not have been surveyed in the time available unless hand-held instruments and the 'leap-frogging' techniques were used. Also, the surveying programme took a disproportionate part of the time available in the field and on some occasions geological observations had to be noted simultaneously with survey figures.

(3) In Iceland, it was not always possible to obtain a research permit for a selected area. This was particularly important with regard to work in the Hallmundarhraun caves, for no permit was allowed. (The writer was keen to investigate these caves as they are the best developed in Iceland). The result was that it was not possible to carry out a detailed survey of these lava tube caves.

(4) There were severe limitations upon the amount of equipment that could be carried on expeditions, as travel was invariably by air and hired Landrover or car. In Iceland, a now defunct boat service at first allowed heavy tripods and theodolites to be transported, along with the camping and caving equipment and the food, which meant that surveys of Raufarholshellir and the Gullborg caves could be made to very high standards. The weight limit on an aircraft to Tenerife, however, meant that the heavy surveying equipment had to be removed in favour of lighter, hand-held instruments.

(5) Fieldwork had to be organised on a party basis as this was dictated by the nature of the work - (a) one had to have companions in the caves
for safety reasons; (b) companions were needed to help with the surveying. It was not always possible to find companions with the ready funds who wished to spend their annual vacation surveying in Iceland:

**ACCOMPLISHED OBJECTIVES.**

Each study area was initially reconnoitred with a view to: (a) determining the extent and the relationships of the caves; (b) locating all collapse depressions, particularly those definitely occurring through the collapse of the roof of an underlying cave; (c) identifying the important surface features of the lava flow around the caves. All caves were surveyed in order that their plan, long profile and passage cross-profiles might be drawn up. In addition, in order to determine the thickness of the roofs of some of the caves (Raufarhólsheggerir, the Gullborg caves, the Mt.Etna caves), the line traverse through the cave was plotted on the surface and levelled. Cave entrances and collapse depressions were related one to another through surface triangulation and tacheometry. Traverses between cave entrances closed similar underground traverses, thereby increasing the accuracy of the survey. The major features of the flow surface were also located in the surface triangulation in some cases: (a) the positions of the lava tube caves of the Gullborg volcano, Iceland, were located relative to the vent crater and the western lava channel; (b) the relationship between the lava tube caves and large terrace-like features on the 1614-24 lava flow, Mt.Etna, was determined; (c) the position of Raufarhólsheggerir relative to the position of buried fossil cliff-lines was similarly determined. In the greatly collapsed Raufarhólsheggerir, it was found possible to estimate the position of the original lava
tube by measuring the highest points of the glazed lining relative to the survey stations through the cave. In all caves passage cross-profiles were regularly surveyed at every, or every other, survey station. Many profiles were also selected for measurement because they illustrated particular cave forms. In all caves the direction of flow was determined and in the case of the Cueva de San Marcos a map showing the flow directions through the cave was drawn up. Interesting geological features were noted throughout the caves and particular attention was paid to establishing the relationship between passage form and flow structure. A search was made for sectional exposures of the lava flow both inside and outside of the lava tube caves (the latter being mainly unsuccessful) and structures were noted. An attempt was made in all cases except on Tenerife to locate the lava source, so that the relative positions of the caves could be ascertained. The chemical and mineralogical properties of the enclosing basaltic country rock in each study area was not attempted because chemistry was not held to be a particularly important factors for a cave's morphological evolution, though a search through the literature for such analyses was made (this was unsuccessful).

MAPS AND AIR PHOTO COVERAGE.

Topographical and geological maps and aerial photographs were available for all of the Icelandic study areas from the Icelandic Survey Department (Landmaelingsar Islands). Topographical maps published by the Geodaetisk Institut, Copenhagen, proved to be quite accurate, though the 1:100,000 maps was preferred to the 1:50,000 as the latter was only an enlargement of the former and possessed no additional information. These maps showed the outlines of all the post-glacial lava flows in
the study areas, distinguished between apalhraun and helluhraun (aa and pahoehoe) lava flows, frequently located source vents and provided the locations of spot heights and bench marks. In the case of the Raufarholshellir area it was found possible to purchase a 1:50,000 map published by the U.S. Army (sheet 1612/1), which was superior to the corresponding map of the Geodaetisk Institut. Two map sheet of the geological series of maps at 1:250,000 compiled by G. Kjartansson and published through Landmaelingar Íslands were found useful in locating source vents and in determining the relative ages of the lava flows. Aerial photographs of the Raufarholshellir and Gullborg areas were also purchased, the latter proving to be most useful in plotting the extent of flow units and flow direction in the Gullborgarhraun (Fig. 7.1.), though unfortunately air photographs of the Hallmundarhraun could not be purchased without a research permit.

Maps of Tenerife were difficult to obtain, but use was made of the a topographical map sheet at a scale of 1:100,000 (sheet 1103) published by the Instituto Geografica, Madrid, and a geological map at the same scale (sheet 1103) published by the Instituto Geologico y Minero de España. Air photographs were not available.

Extensive use was made of the excellent 1:25,000 topographical map of Mt. Etna Nord (sheet 262 111 N.O.) published by the Instituto Geografico Militare, Rome. The location of spot heights in the study area was particularly useful. Dr. J. E. Guest kindly loaned an unpublished geological map based upon the 1:25,000 topographical map and also satellite photographs (of unknown origin) of the study area, the latter proving to be extremely useful in locating surface features on the lava flow.
SURVEYING.

The surveying methods employed were based upon the experiences gained by members of the Shepton Mallet Caving Club from their survey of Raufarhólshellir in 1970 (Ellis, 1971; Bowler, 1971). This group, of which the writer was a member, investigated the severity of magnetic anomalies around Raufarhólshellir and found them to invalidate magnetic survey readings.

The first preliminary traverse in Raufarhólshellir was surveyed along the first 100m of cave and was closed by taking the survey line out through the last of the roof collapses and back over the surface to the cave entrance. Both magnetic and theodolite (i.e., non-magnetic) measurements were made at the same time. On calculation of the results it was found that while the theodolite had a misclosure of 0.84%, the magnetic traverse failed to close by 6.24%. The theodolite traverse was said to be better than expected, whereas the magnetic survey had to be compared with a misclosure of less than 0.5% that would have been expected with the same instruments in a limestone terrain. In this case, it was found upon investigation of the figures that forward and backward compass bearings along the same survey leg could differ by up to 16.5°, whereas under normal conditions the differences would not be expected to be more than 2°. Further investigations were carried out which showed that the results of the first traverse were typical. Thus, it was decided by the Raufarhólshellir survey team that maximum accuracy in a lava tube cave could only result from a theodolite traverse, as this technique utilized the included angle at every survey station. A specially constructed cave theodolite was used, though it was later realised that such measurements could be made with a compass (tripod mounted or hand held) providing that forward
Survey traverses and magnetic anomalies about Raufarhólshellir shown in relation to local physical features (drawn by B.M. Ellis).
and backward readings were taken at each station to obtain the
included angle (Mills and Ellis, 1971). Thus, it was understood that
although the magnetic attraction of the wall rock will vary from
place to place throughout the cave, this attraction is constant at
any one point.

The reasons for the variable attractions of the basaltic country
rock were not fully understood, but some suggestions were made, based
upon the results of four closed traverses (Bowler, 1971) (Fig. 3.2.). Some
relationship was found between the compass needle deviation and
surrounding physical features. Three of the traverses, carried out
at the entrance of Raufarhólshellir, showed a degree of consistency
and gave the following results:

1. stations more than 5m from the cave remained unaffected by any
   magnetic attraction, except stations near an area of disturbed
   ground (man made) and stations over one particular thin strip
   of ground near the furthest roof collapse from the entrance;

2. anomalies above or inside of the cave varied greatly and rapidly
   and did not appear to depend on whether the station was situated
   underground or on the surface - the total range was -14.75° to
   +29.50°.

Inside of Raufarhólshellir it seemed that a very rapidly varying
magnetic field was to be expected.

There are a number of possible reasons for magnetic anomalies around
and inside of lava tube caves, some of which were briefly touched
upon by Bowler (1971):

1. there may be local pockets of basalt rock which are rich or
   poor in magnetic minerals, such as magnetite;

2. the basalt will possess remainant magnetic orientation from the
time of its formation.

(3) the glaze that forms the lining of many lava tube caves, and which is particularly well developed in Raufarhólshellir, is magnetic and if collapse has taken place there will be a variation in its strength throughout the cave;

(4) a random magnetic attraction in caves may be the result of a random orientation of fallen blocks of roof or wall rock.

With reference to other surveys of lava tube caves, other workers appear to have appreciated the fact of magnetic anomalies, but had not bothered to investigate them. This is true of the individuals approached by the SMCC before the Raufarhólshellir expedition (Ellis, 1971). Greeley (1971a) appears to have considered the problem and suggested that the deviation is apparently about the same for both surface and sub-surface azimuths. He surveyed caves in the Bend area of Oregon with a Bruunton compass and a check on the accuracy of his method was a traverse through two entrances about half a mile apart; the surface survey ending within 50 feet of the second entrance.

In other lava tube caves surveyed during this study the magnetic deviation of the compass needle has not been found to be so marked as in Raufarhólshellir. For example, the Cueva del Viento was surveyed magnetically and a large closed traverse across the surface between the two entrances and through the cave from respective entrances to either side of a separating choke (a distance of about 1km) failed to close by 0.2m vertically and 10.5m horizontally (the choke was thought to be 8-10m wide). However, as the Raufarhólshellir survey showed, magnetic anomalies in lava tube caves cannot be ignored and so all of the caves surveyed for this study, except the Tenerife caves
and Vidgelmir (Hallmundarhraun) were surveyed with a cave theodolite and tripod and the included angle was utilized.

**Instruments and techniques employed in the cave surveys.**

**Azimuth: Cave theodolite** - comprised of a horizontal arm with a locking screw, 'T' levelling bubbles and transparent plastic pointer, with a sighting tube and attached clinometer mounted above. This unit was mounted on a 15cm (6 inch) diameter bakelite horizontal circle graduated to 0.5°. Readings were made to the nearest 0.25° by estimation. This instrument was constructed by B.M. Ellis as a direct result of the Raufarholshellir experience (Ellis, 1970).

**Azimuth: Magnetic** - comprised a Suunto compass, type KB-14/360, hand held and read to the nearest 0.5°.

**Elevation: Abney Level** - the readings being made to the nearest 0.5°. The Abney Level was mounted with the theodolite as a single unit on a tripod.

**Elevation: Suunto clinometer** - type PM-5/360 PC, read to the nearest 0.5° and hand held.

**Distance** - all distances were measured with a 30m 'Fibron' tape to the nearest 0.05m. The distance between stations was always less than the full length of the tape.

**Target lamps** - generally carbide lamps or candles mounted on tripods, or carbide lamps hand held.
Tripods - ex-WD wooden tripods for robustness.

Techniques - the two surveying techniques employed in this study were those normally employed in cave surveying in which a simple traverse (i.e., not polygonal) was made along the length of the cave passage.

(1) Where possible a non-magnetic theodolite traverse was made because of its greater accuracy. At each survey station the following readings were recorded: horizontal bearings to both the backward and forward station to enable the included angle to be calculated, the angle of inclination to the forward station, the distance to the forward station, the height of the instrument above the floor, the roof height above the instrument (tape attached to aluminium poles or estimated) and distances left and right of the instrument to the passage walls. In order that the survey could be orientated relative to true north, bearings were taken to prominent landscape features which could be located on the relevant topographical map of the area. The method proved to be extremely slow as readings were taken at every station and the instrument had to be re-levelled on each occasion, though accuracy was greatly improved through the loss of station movement. This method was employed in the surveys of Raufarhólshellir (SMCC in 1970), the Gullborg caves, the Surtshellir-Stephanshellir line traverse and the lava tube caves of the 1614-24 lava flow, Mt. Etna.

(2) Where time was limited, as on Tenerife, a more rapid surveying method was employed, entailing the use of hand held magnetic surveying instruments and the 'leap-frogging' technique. The Suunto compass and clinometer proved to be exceptional lightweight surveying instruments, though the use of these meant losses in accuracy because of the variable
<table>
<thead>
<tr>
<th>TRAVERSE</th>
<th>DETAIL</th>
<th>PASSAGE</th>
<th>DETAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>READINGS</td>
<td>COMPASS</td>
<td>SLOPE</td>
<td>STA.</td>
</tr>
<tr>
<td>FROM STA.</td>
<td>FROM STA.</td>
<td>DISTANCE</td>
<td>No.</td>
</tr>
<tr>
<td>No.</td>
<td>Direction</td>
<td>Reading</td>
<td>±</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
<td>294.0</td>
<td>-</td>
</tr>
<tr>
<td>33</td>
<td>3</td>
<td>229.0</td>
<td>-</td>
</tr>
<tr>
<td>34</td>
<td>33</td>
<td>174.0</td>
<td>-</td>
</tr>
<tr>
<td>35</td>
<td>34</td>
<td>257.8</td>
<td>-</td>
</tr>
<tr>
<td>36</td>
<td>36</td>
<td>181.0</td>
<td>-</td>
</tr>
<tr>
<td>37</td>
<td>37</td>
<td>158.0</td>
<td>-</td>
</tr>
<tr>
<td>38</td>
<td>38</td>
<td>158.0</td>
<td>-</td>
</tr>
<tr>
<td>39</td>
<td>39</td>
<td>126.0</td>
<td>-</td>
</tr>
</tbody>
</table>

**Sketches & additional notes:**

```
[Diagram of survey Party positions and notes]

Fig. 3.3A.
```
<table>
<thead>
<tr>
<th>No.</th>
<th>Direction</th>
<th>COMPASS READING</th>
<th>CLINO</th>
<th>SLOPE DISTANCE</th>
<th>STA. No.</th>
<th>L-o-S DISTANCE</th>
<th>STA. HEIGHT above floor</th>
<th>ROOF HEIGHT above sta</th>
<th>WALL DISTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>104</td>
<td>15</td>
<td>178.5</td>
<td>-7.5</td>
<td>11.0</td>
<td>104</td>
<td>4.0</td>
<td>(6-14)</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>105</td>
<td>15</td>
<td>92.0</td>
<td>-3.0</td>
<td>12.0</td>
<td>105</td>
<td>3.0</td>
<td>(6-14)</td>
<td>0.5</td>
<td>4.0</td>
</tr>
<tr>
<td>106</td>
<td>15</td>
<td>32.0</td>
<td>-10.0</td>
<td>4.5</td>
<td>106</td>
<td>1.5</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>107</td>
<td>15</td>
<td>27.0</td>
<td>0.0</td>
<td>5.4</td>
<td>107</td>
<td>--</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>108</td>
<td>15</td>
<td>227.0</td>
<td>15.0</td>
<td>7.0</td>
<td>108</td>
<td>0.8</td>
<td>0.6</td>
<td>0.8</td>
<td>2.5</td>
</tr>
<tr>
<td>109</td>
<td>15</td>
<td>99.0</td>
<td>-1.0</td>
<td>10.0</td>
<td>109</td>
<td>--</td>
<td>0.1</td>
<td>5.0</td>
<td>3.1</td>
</tr>
<tr>
<td>110</td>
<td>15</td>
<td>8.0</td>
<td>-6.0</td>
<td>7.8</td>
<td>110</td>
<td>0.8</td>
<td>1.2</td>
<td>1.9</td>
<td>0.5</td>
</tr>
<tr>
<td>111</td>
<td>15</td>
<td>93.0</td>
<td>-7.0</td>
<td>20.0</td>
<td>111</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>112</td>
<td>15</td>
<td>25.0</td>
<td>-2.0</td>
<td>8.0</td>
<td>112</td>
<td>--</td>
<td>1.2</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>113</td>
<td>15</td>
<td>52.0</td>
<td>-2.5</td>
<td>8.0</td>
<td>113</td>
<td>--</td>
<td>1.0</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>114</td>
<td>15</td>
<td>32.0</td>
<td>-11.0</td>
<td>9.6</td>
<td>114</td>
<td>--</td>
<td>1.6</td>
<td>3.2</td>
<td>--</td>
</tr>
<tr>
<td>115</td>
<td>15</td>
<td>55.0</td>
<td>2.0</td>
<td>5.0</td>
<td>115</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Fig. 3.3B.**

**Sketches & additional notes:**

- 2m wide
- 1.2m step
- Squeeze + 1.2m step
- 2.5m step
- Jawbreak

**Date log:**

- Sheet No. 24

**Survey Party:**

1. Instrument readings by Cave
2. Recorder readings by Cave
3. Other readings by Cave

**Cave & Species:**

- Cave 320.0

---
magnetic attraction of the wall rock and because of a certain amount of station movement. Every other station was leapfrogged and the readings recorded in the caves were: compass bearing and angle of inclination at every other station to both the backward and forward station, and at every station, the tape distance to the forward station, the height of the instrument above the floor, the height of the roof above the instrument (tape attached to aluminium poles or estimated) and distances left and right of the instrument to the passage walls. This method was employed in the surveys of the Cueva del Viento, the Cueva de San Marcos, Vidgelmir and an early survey of Surtshellir.

A comparison of the recordings taken by both methods is shown in Fig. 3.3.; figure 'A' being abstracted from the survey notes of Grotta degli Inglese and figure 'B' being abstracted from the survey notes of the Cueva de San Marcos.

In all the surveys stations were marked by a number written on white adhesive PVC tape stuck to the rock. Although placed in a position for the benefit of the surveyors, station markers were found to be useful reference points in often relatively featureless passages, particularly when describing the location of geological features, and provided a check on one's position in the cave. As a result, station markers were left in position until the end of the study and then removed from the cave.

Representative passage profiles were drawn from all cave passages as described previously. In all caves except the Cueva de las Breveritas and Vidgelmir, the survey of the cave was roughly plotted in the field and a copy of this plot was taken into the cave to check for any errors
in the centre line and of the passage detail, and the amended drawings were used for the final plots.

**Instruments and techniques employed in the surface surveys.**

Some surface surveying was done with the cave theodolite and a tape, particularly when plotting the line of the cave on the surface in order to determine the thickness of the roof of a cave. On most expeditions surface surveys were accomplished with the use of a theodolite and folding staff kindly loaned by the Royal Geographical Society. Two theodolites were used over the study period: one manufactured by Cooke, Troughton and Simms and the other manufactured by Hilger and Watts. On each, both the horizontal and vertical scales could be read by verniers to one minute of arc and could be estimated to 30 seconds of arc. The telescopes included stadia lines and the factor was checked and found to be 100. The theodolites were provided with a tubular compass which the makers claimed could be gauged to within one minute of arc. A 4m folding Carr staff was used with the theodolite.

The thickness of the rock above the caves was measured by plotting out on the surface the traverse line taken through the cave and then measuring the relative height of points above the cave survey stations. The surface points were plotted with the cave theodolite and the scale readings obtained in the cave, together with the horizontal equivalents of the slope distance measured underground. The heights of these points relative to the prime survey points at the cave entrance was the determined.

The relative positions of the cave entrances and the major morphological features of the lava flow surface were determined by triangulation and
<table>
<thead>
<tr>
<th>Name of cave</th>
<th>Details of survey sheets</th>
<th>Scale</th>
<th>Survey sheets in this study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CUEVA DEL VIENTO</strong>  (3 sheets):</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:2000</td>
<td>Full survey at reduced scale</td>
</tr>
<tr>
<td>Sheet No.1 Cueva de las Breveritas</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:2000</td>
<td>Full survey at reduced scale</td>
</tr>
<tr>
<td>Sheet No.2 Cueva de los Piquetes</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:2000</td>
<td>Full survey at reduced scale</td>
</tr>
<tr>
<td>Sheet No.3 Cueva del Viento</td>
<td>Full plan only with lower cave displaced</td>
<td>1:2000</td>
<td></td>
</tr>
<tr>
<td><strong>CUEVA DE SAN MARCOS</strong>  (1 sheet)</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:1000</td>
<td>Full survey at reduced scale</td>
</tr>
<tr>
<td><strong>RAUFARHÖLSHELLIR</strong>  (1 sheet)</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:1000</td>
<td>Original survey</td>
</tr>
<tr>
<td><strong>SURTHELLIR-STEPHÁNSHELLIR</strong>  (unpublished)</td>
<td>Line plan only</td>
<td>1:2000</td>
<td>Original survey</td>
</tr>
<tr>
<td><strong>VIDGEÐÓLIR</strong>  (1 sheet)</td>
<td>Plan, Ext. Section, Cross-section</td>
<td>1:2000</td>
<td>Original survey</td>
</tr>
<tr>
<td><strong>CAVES OF THE 1614-24 LAVA FLOW, MT. ETNA</strong> (5 sheets - some still in preparation):</td>
<td>Plan of caves in relation to surface details 1:1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheet No.1 General topographic map</td>
<td>Plan of caves in relation to surface details 1:1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheet No.2 Grotta dei Lamponi</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:1000</td>
<td>Original topographic plan and two extended sections</td>
</tr>
<tr>
<td>Sheet No.3 Grotta degli Inglesi</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:1000</td>
<td></td>
</tr>
<tr>
<td>Sheet No.4 Grotta del Labirinto</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:1000</td>
<td></td>
</tr>
<tr>
<td>Sheet No.5 Extended Section</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:1000</td>
<td></td>
</tr>
<tr>
<td>(Survey of Grotta del Labirinto incomplete - none of these surveys have been published)</td>
<td>Plan, Ext. Section, Cross-sections</td>
<td>1:1000</td>
<td></td>
</tr>
</tbody>
</table>
tacheometry with the theodolite and folding staff.

Plotting.

On return to the U.K. after every expedition the survey figures were reduced to rectangular co-ordinates and plotted either at a scale of 1:1000 or 1:2000, depending upon the extent of the cave system. All of the surveys so drawn show the plan, long profile (extended section) and passage cross-profiles of the cave, and many surveys run into several sheets. Table 3.2 lists the maps and surveys produced from this work and the derivation of the surveys enclosed in the back of this study.
4. **Methods of tube construction.**

It was realised quite early in this study that individual lava tube cave passages could be grouped into general types according to their size, shape and structure, and that these passage types probably reflected varying methods of tube formation. Accordingly, research was carried out into the relationships between passage forms and flow structures. Although descriptions of the emplacement of Hawaiian pahoehoe lava flows are numerous, little previous research on the structures of these flows could be found in the literature. In particular, the definition and description of a flow unit was found hopelessly inadequate in the light of the field evidence and some time was spent re-defining this fundamental structural division before the main investigation proceeded. This chapter describes the many types of conduits, or lava tubes, developed in pahoehoe lava and confirms the tube-forming processes observed during the recent Hawaiian activity.
Résumé of present knowledge of the emplacement, morphology and structure of basaltic pahoehoe lava flows.

Basaltic pahoehoe lava flows have been extensively described in the literature (for example: Dutton, 1884; Jones, 1937 and 1943; Macdonald, 1953, 1967 and 1972; Macdonald and Abbott, 1970; Wentworth and Macdonald, 1953 and Swanson, 1973) and an attempt is made here to précis the present knowledge of their structures and forms. This discussion is concerned with the large pahoehoe lava flows which are composed of many flow units and excludes the great flows of flood eruptions which commonly consist of single vast sheets. The surface forms and internal structure of cooled pahoehoe lava flows are quite distinct from those of other types of lava flows, though there is a gradation, of course, between pahoehoe and aa.

Generally, pahoehoe is characterised by a smooth, hummocky or ropy surface, by spheroidal vesicles and by the presence of lava tubes, either open or filled. However, this is a general definition and pahoehoe lava flows may be divided qualitatively into a number of varieties depending upon the relative gas content and method of flow of the lava (Macdonald, 1953; Wentworth and Macdonald, 1953; Swanson, 1973).

Most typically forming large flows is the variety termed by Swanson (1973) 'hummocky or tube-fed pahoehoe'. This is a relatively dense type, formed when largely degassed lava issues from lava tubes after flowing many kilometres underground and it gives rise to a hummocky surface of tumuli (domical swellings of the flow surface up to 4m high formed above clogged distributary tubes) and overlapping toes and flow lobes. After the initial outburst the flow becomes restricted to a
Fig. 4.1. Idealised cross-section of pahoehoe toes after Macdonald (1967).
narrow channel of its own making which gradually crusts over, and
from then on movement of liquid lava is completely internal, through
a resulting complex of lava tubes. In mature flows the feeding river
is enclosed in lava tubes almost continually from the vent to the
actively advancing flow margins and liquid is visible only at the
flow front or where the surface is broken, such as at a skylight.
Because the feeding river is so seldom seen, its morphology is poorly
understood. In these larger flows of moderate to low mobility, the
internal feeder tube apparently divides and further sub-divides into
a network of smaller tubes, with the streamlets carried in each branch
feeding a lobe of lava at the moving front. The front advances by the
protrusion of one small tongue, or 'pahoehoe toe', after another, and
the advance is said to resemble that of an amoeba, pushing out successive
pseudopodia. These toes advance either with a rolling motion, like
the endless track of a tractor, or through inflation, until after a
short distance they chill and lose their mobility. The process, known
as 'toe-budding', is repeated time and time again, ultimately
constructing one compound sheet of superimposed tongue-shaped units,
each perhaps only 0.1m - 1m across, and each being molded to the shape
of the underlying toes. Such compound sheets appear to resemble pillow
lava in cross-sectional exposures, though such ellipsoidal structures are
distinct from true pillows and may be recognised by their concentric
rows of vesicles and filled, partly drained or drained small lava tubes
at their cores (Fig. 4.1.).

Another type of pahoehoe that develops close to some vents is
'shelly pahoehoe' (Jones, 1943; Macdonald, 1953; Wentworth and Macdonald,
1953; Swanson, 1973). Structurally this consists of a mass of hollow,
gas-inflated toes and tubes in severely buckled, very thin sheet of
lava which originated as vent overflow. The formation of shelly pahoehoe has been attributed to an apparently gas-driven rise-fall cycle in the vent, causing periodic overflows of very mobile, gas-charged lava (Swanson, 1973). Two types have been recognised depending upon the local relief surrounding the edge of the vent. When relief is high (over 1m), the lava spills out in several narrow tongues, each confined to a topographical low, though these often merge to advance downslope along an eventual lobate front. This type of shelly pahoehoe has been termed the 'amoeboid variety' by Swanson (1973) and it differs slightly from the 'sheet flood variety'. The latter forms when the local relief is low (less than 1m) and the lava advances as a crusted thin sheet along a broad front. Each type of flow may develop structures transitional to both varieties and the separation of one variety from the other from structural evidence is practically impossible.

Yet another type of pahoehoe is 'smooth-surfaced pahoehoe' (Swanson, 1973), which is a dense type, characterised by surface channels and very few large cavities, and is formed from voluminous flows of partly degassed fallout away from the foot of lava fountains more than 100m high (fountains less than 100m high do not appear to produce the same pahoehoe). These flows develop from the degassed, molten spatter and move as rapidly flowing broad rivers, building channels, levees and meanders, rather than small, slowly moving toes and lobes as is typical of other types of pahoehoe. This type of flow does exhibit most of the usual features of pahoehoe, except tumuli. Large volumed flows of smooth-surfaced pahoehoe change to aa within a very narrow transitional zone.

In general, thin pahoehoe flows and the upper parts of thick flows are characterised by an abundance of vesicles. These are typically
Plate 4.1. A view of the entrance collapse of Vidgelmir.

Thin sheeting of the horizontally bedded flow units and arched cavities are exhibited in the upper parts of the walls. The lower part of the far wall is the original glazed wall of the cave and the upper 5m or so originally formed the roof.
spheroidal, or composed of clusters of distorted spheroids, and some pahoehoe may contain more than 50% vesicles (though 20% is normal). Also, most pahoehoe lava flows are covered with a glassy skin, which is mostly a mere film. This skin commonly confines just below it a layer of vesicles risen from the underlying fluid. Frequently, the skin of an active pahoehoe flow remains so plastic as to be dragged into twisted ropes and folds by the movement of the lava beneath, though the convexity of such forms rarely indicates the general flow direction. On some pahoehoe flows a thickened crust has been broken up and the surface of the flow consists of many slabs tilted at varying angles. This type of pahoehoe flow surface has been called 'slab lava' by Jones (1943) and Wentworth and Macdonald (1953).

Thin pahoehoe lava flows are typically broken into innumerable joint blocks. One group of joints lie parallel with the flow surface, giving the appearance of sheeting, while another lies at right angles to the flow surface and tends towards a regular polygonal arrangement, though joint blocks are mainly cubic (Frontispiece and Plate 4.1.) The orientation of joints normal to the cooling surfaces of the flow suggests that they are primarily due to shrinkage on cooling.

Flow units defined.

The writer finds confusion and ambiguity in the literature with regard to the conception and description of flow units and an attempt is made here to clarify the situation with regard to the divisions and sub-divisions found in the pahoehoe lava flows investigated.

The term flow unit was introduced by Nichols (1936). He recognised within parts of the Laguna and Suwanee lava flows of the San Jose
Valley, New Mexico, lensoid and sheet structures, one piled on the other, each resembling a separate and distinct lava flow. These lenses and sheets, however, possessed no great continuity and merged into the main bodies of the flows. Nichols thus arrived at the conclusion that a single lava flow may be multiple and composed of divisions, which he called 'flow units'. Units were described as lenticular bodies, 30.5m wide, 3-6m thick and more than 800m long, whose formation took place in the following manner (p.625)(Fig. 4.2.):

'The progress of a flow is often not uniform but irregular, owing to the fact that at times the crust acts as an effective dam. With increasing hydrostatic pressure the dam, where the crust is weak, is broken and the lava is free to move. In the cases under consideration, tongues a few hundred feet wide broke out from the front and sides of a flow and flowed on for considerable distances. Crusts appeared on these lava tongues, and solidification proceeded until a degree of rigidity was attained; these tongues were buried by later tongues, which in turn were buried by others'.

Several criteria for recognising flow units were put forward by Nichols, the important visual diagnostic features being: identifiable and close fitting contacts; no weathering or erosion of the flow unit surface and no soil band at the contact; sheet jointing is more common in flow units than is columnar jointing; flow units possess only limited sizes.

Wentworth and Macdonald (1953, p.32-33) have also described how many pahoehoe lava flows on Hawaii comprise of two or more parts that poured over one another during the course of a single eruption, each nearly
Development of flow units after Nichols (1936). Fig. 4.2.

Horizontally bedded flow units in the wall of the roof collapse of Vidgelmir. Fig. 4.3.
contemporaneous division being termed a flow unit. In Hawaii, units were said to range from a few centimetres to 3m or more in thickness. Their extent is variable, ranging from local gushes that move a few metres over the earlier surface of a major flow, to sheets that flow for 1000m or more over an earlier lava of the same eruption. Repeated flow units occur both in aa and in pahoehoe lava flows, but are most common in the latter. In some exposures of the lava flows, Wentworth and Macdonald could identify scores of pahoehoe units, 5-10cm thick, making up individual lava flows 3-6m thick. They point out that thicker flow units in pahoehoe may be further sub-divided in cross-section into smaller ellipsoidal structures, each of which is a small, filled tube.

It appears to the writer from a search of the literature that there have been varying interpretations of the term flow unit:

(1) Nichols' concept was 'a tongue-shaped structure within a flow' that originated as a lobate extension of the flow front;

(2) to other writers a flow unit represents a division of a lava flow that originates from a single discharge of lava from the vent;

(3) still other writers infer that a lava flow is made up of flow units originating from both (1) and (2).

In consideration of the field evidence this writer agrees with the third point of view.

Flow units in the lava flows investigated were identified from sectional exposures and from aerial photographs (for example, Plate 7.1. and Fig. 7.1.). In exposures, the principal criterion for distinguishing flow units was the identification of successive glassy, oxidized and ropy surfaces. Flow units varied enormously in size and
shape, though two basic morphological types were recognized: (1) sheet flow units and (2) tongue-shaped flow units.

(1) **Sheet flow units.** These ranged from 6cm to over 2.5m thick and possessed variable lateral extent. They appeared to have resulted from diffuse flow originating from periodic vent overflow and/or periodic channel overflow. Thus, large sheet units surrounded many vents, while less extensive sheets bordered many of the open lava channels and lava tubes (which probably originated from open lava channels). Sheets of each type probably overlay one another in places near the vent, but they were indistinguishable in exposures of the lava flow. Exposures of sheet units were composed of many horizontally bedded layers of variable thicknesses, the crusts of some layers being arched up above gas cavities (Fig. 4.3.). Drainage of the fluid interior of surface sheet units appeared to be the origin of the broad swells and shallow depressions which were characteristic of many of the pahoehoe surfaces. Sheet units did not form lava tubes.

(2) **Tongue-shaped units.** These flow units appeared to be the products of channelized flow rather than diffuse flow and were therefore exclusively tube-fed. Larger tongues, such as the 38km long Hallmundarhraun or the long, north-western arm of the Gullborgarhraun (Fig. 7.1.), were complex and composed themselves of many tongues and sheets of varying sizes. The large tongues were the products of a continued vent discharge transported through a complex, partly internal channel system. They were probably active throughout most of the effusive period of the eruption, unlike sheet units which were probably short-lived. Tongues of intermediate size, ranging down to, say, 1.5m-3m high, 6m wide and 20m long, were interpreted as lobate extensions of the fronts of the major tongues and some also appeared to have
originated as channel overflow, as depicted in Fig. 4.4. Even smaller flow units were, in turn, lobate extensions of the intermediate tongues. The smallest units of flow described in the Hawaiian literature are known as pahoehoe toes and perhaps only 0.1-1.0m across and 2m long, though the smallest tongues observed during this present study were 0.5m-1.5m high, 1-3m wide and of unknown length. Individual intermediate and small tongues were easily identified in cross-sections of the lava flow by their ellipsoidal forms and by the presence of axial lava tubes. At the margins of the major tongues exposures exhibited many superimposed ellipsoidal structures which were the sections of piled small units (Plate 4.6.). These exposures contrasted with exposures along the axes of major tongues, which consisted of superimposed sheets related to the axial lava channels and tubes. In the only located exposure of the cross-section of a major unit away from axial lava channels and tubes the structure was a combination of sheets and tongues.

PREVIOUS DESCRIPTIONS OF FLOW STRUCTURES RELATED TO LAVA TUBES.

(1) Structures related to lava tubes greater than, say, 1.5m high.

Wall structures noted by Wentworth and Macdonald (1953) in large lava tubes in Hawaii were described as being composed of several thin flow units which originated as repeated overflows of the lava river before it crusted over. In the walls of lava tube caves in Victoria, Australia, Ollier and Brown (1965) noted layers up to several feet thick lying parallel with the flow surface. Individual layers were of compact basalt separated by trains of vesicles or partings and sometimes the layers could be buckled, leaving cavities between them. The inner surfaces of the cavities showed drip features and in smaller ones vertical threads of lava were drawn out between the upper and lower surfaces,
apparently as the layers parted. This 'layered lava' was thought to result from differential movement within one thick flow through the development of shear planes and the horizontal segregation of the solid and liquid phases. The liquid continued to segregate downslope, occupying tubes eroded through the stratified flow. Hatheway (1971, 1971a and 1976) and Hatheway and Herring (1970) agreed with Ollier and Brown that differentiation by flow layering does exist within single flow and flow units. Greeley (1971a) showed photographs of lava structures he interpreted as layered lava of the Ollier and Brown type, though he did note a difficulty in distinguishing layered lava from multiple flow. In another publication Greeley and Hyde (1971) noted a contrast between tubes formed in layered lava on less steep slopes and those formed by spatter accretion on steeper slopes, and the evolution of a lava tube during the formation of layered lava was shown diagrammatically. Peterson and Swanson (1974) observed that 'layered lava similar to that name and discussed by Ollier and Brown (1965) occurs in the walls of the 1970-71 tubes, but our observations of flowage and deposition of the lava indicates that this layered lava represents successive thin flow units and near surface zones of vesiculation within the flow units, not internal shearing in thick flows as envisaged by Ollier and Brown' (p.221). A discordant relationship between the cave walls and adjacent horizontally layered lava was also observed in the Undara lava tube caves (Atkinson, Griffin and Stephenson, 1977), though several thin flow units were identified at roof level and the mechanism proposed by Ollier and Brown was not considered applicable.

(2) Structures related to lava tubes less than, say, 1.5m high.

Observations of structures about smaller lava tube caves have not been noted in the literature, perhaps because collapse does not occur in such small passages. Small tubes are seen in cross-sectional
exposures of some lava flows (Macdonald, 1967, p.11 and 1972, p.101), however, where they represent the drained cores of small ellipsoidal flow units (Fig. 4.1.).

FLOW STRUCTURES RELATED TO THE LAVA TUBE CAVERNS INVESTIGATED.

Although many tube-forming processes were recognised from the investigation, only two main varieties of lava structures were distinguished about the lava tube caves, each type depending upon whether the passage originated as an axial feeder tube or as a distributary tube.

(la) Exposures in the walls of the principal passages of Raufarholshellir, Surtshellir-Stephánsshellir and Víðgelmir (Iceland), the Cueva de San Marcos (Tenerife) and the Grotta dei Lamponi (Mt. Etna) showed surprising little variation. Individual exposures varied in size, but generally they were extensive and ranged up to 75m long and 15m high (Vídgelmir entrance collapse). At first glance these exposures give a false impression of being composed of thinly bedded (15cm-30cm thick) horizontal divisions: an impression accentuated by the occurrence of arched cavities between false divisions (Frontispiece and Plate 4.1.). In fact, on closer inspection, true divisions were seen to be thicker (up to 1.5m) and these had been fractured into horizontal thin sheets (Fig. 4.3.). Each division was of dense basalt and showed a heterogenous vesicle distribution. At the top was a zone, up to 30cm thick, of high vesicle density, separated from the rest of the division below by a continuous horizontal fracture or a line of concentrated or coalescing vesicles. This upper part of the division was normally fractured vertically and frequently polygonally, and carried an oxidized
Plate 4.2. (above) Flow unit contact at Roof Collapse 1, Surtshellir.

The ropy surface structure of the lower sheet flow unit is plainly visible.

Plate 4.3. (right) Flow unit contacts and gas cavity in Raufarhólshellir.

Two contacts are shown in this photograph: the model is standing on the surface of one unit, while the other occurs level with his head. The cavity is ovoid in plan. Note the spheroidal jointing of the overlying thick sheet.
Plate 4.4. Thin, contorted sheets of shelly pahoehoe exposed in the wall of the east channel of the Gullborgarhraun.

The exposure illustrates all of the general characteristics of shelly pahoehoe: thin sheet flow units greatly distorted by buckles, gas cavities and small uncollapsed or collapsed lava tubes. The upper part of the exposure is most typical of shelly pahoehoe, while the lower part more nearly approaches the type of structure exhibited about the lava tube caves of other lava flows.
glassy skin that was frequently ropy or folded (Plate 4.2.). Arched cavities sometimes occurred along the horizontal fracture line, ranging up to 0.5m high, buckling the surface of the division into a gentle wave (Plate 4.3.). Below, the division was seen to be composed of massive, little fractured and little vesiculated basalt, rarely up to 1.2m thick, but normally a little thicker than the upper zone. In the bottom 10cm or so was a concentration of vesicles, some being vertically elongated and drawn out in the direction of flow. The lower surface of most divisions bore 'sole marks', which were the impressions of the ropy or folded surface of the division below. Typically, a wall exposure would carry many thin divisions, each of which were continuous over great distances laterally. The surface expression of this structural type, most typified by the terrain around Raufarhólshellir and on the Hallmundarhraun, was a relatively flat terrain, diversified by low, wide flow lobes, surface lava tubes, tumuli, broad swellings and regions of extensive, though shallow, crustal subsidence.

(1b) Excellent exposures were investigated on the Gullborg volcano, Iceland, and comparable structures were visible in the collapsed walls of two quite separate lava channels (Fig. 7.1) and in the walls of the caves. Structures differed from those about other feeder caves. Exposures consistently showed great thicknesses, up to 5m, of thinly bedded divisions which were greatly distorted by gas cavities, buckles and collapsed small tubes (Plate 4.4.). Individual sub-horizontal divisions varied in thickness from 8-50cm, were continuous to the edges of each exposure, possessed an upper glassy skin and almost always contained a continuous parting of coalescing large vesicles interspersed with larger gas cavities along their centre line. Cavities abounded, ranging in size from large vesicles a few cm long to large cavities
Plate 4.5. The cross-section of an undrained lava tube exposed in the west wall of the Borgarhellir entrance collapse, Gullborg.

The following points are of particular note:

(1) the cavity overlying the tube is part of a breakdown dome, for it is irregularly shaped, blind, possesses no flow marks, yet is internally glazed;

(2) the tube itself is triangular-shaped in cross-section and differential erosion has picked out the successively enclosed cylinders of the flow (best observed in the bottom right hand corner);

(3) there is an abrupt discordant contact between the walls of the tube and the near horizontal structure of the walls;

(4) the walls of the tube are composed of thinly bedded shelly pahoehoe, with a general dip away from the tube on either side - thus the tube probably originated through the gradual inward growth of the walls of an open channel resulting from successive overflows;

(5) the overlying flow unit is massive and thick and totally different in character than the shelly pahoehoe of the walls.
30 cm high. The larger gas cavities were lined internally with a glassy skin, with small drips hanging from their roofs or thin threads stretched out between the top and the bottom. Other cavities were small, partially collapsed or uncollapsed lava tubes or were formed in the core of large buckles. A bed would be almost continuously horizontal or it would be quite severely contorted by gas cavities and large buckles, though successively higher beds would fit snugly onto the undulations of the lower beds. The surface expression of this lava type, which occurred principally around the vent region and the borders of the lava channels, is one in which surface lava tubes predominate, whole groups running parallel with one another, each arched above a surface littered with thin fragmental, crustal sheets derived from weathering of the top surface units.

An excellent exposure of an undrained lava tube and its surrounding flow structure was observed in the west wall of the Borgarhellir entrance collapse (Borgarhellir had been buried at this point to a depth of at least 16 m). The various elements exhibited in this section are explained in Plate 4.5. The cavity that occurs on the top of the filled tube structure is blind and irregularly shaped. It most likely formed through partial collapse of the roof unit during active flow (the cavity possesses a glazed lining), the debris having been removed by continued flow. A very slight lowering of the lava level in the tube has produced a flat floor. Relationships similar to those found at this exposure occur in all other caves on the Gullborg volcano.

The two lava types described correspond with tube-fed pahoehoe (la) and shelly pahoehoe (lb) described by Swanson (1973) from Mauna Ulu, Hawaii. Structural differences in the newly erupted lava flows from Mauna Ulu were seen by Swanson to be related to differences in the
volatile content and flow method of the lava, as described above. A relatively dense type, characterized by a hummocky surface with abundant low tumuli and overlapping pahoehoe toes and lobes, formed when largely degassed lava issued from tubes after flowing underground for several kilometres or more. This tube-fed lava corresponds with the lava type surrounding most of the lava tube caves studied (type la), all of which are situated considerable distances below their respective vents. A cavernous type of lava, Swanson noted, called shelly pahoehoe, was characterized by fragile gas cavities, small tubes and buckled fragments of surface crust and was deposited when gas-charged lava welled out of the source fissure during rise-fall cycles, with little or no accompanying fountaining. This type of lava closely corresponds with the lava type (type lb) deposited around the lava channels and lava tubes in the vent region of the Gullborg volcano, Iceland. It is interesting to note here that the long, outstretching flow units emanating from the lava channel and tubes are characterized by features diagnostic of tube-fed flow.

The structures exhibited in the walls of the larger cave passages are all regarded as being composed of thin flow units formed as lava periodically overflowed the walls of an open channel as the lava delivery pulsated. That lava tubes originate through the roofing of open lava channels accords with observations of actively forming lava tubes from Hawaii (Wentworth and Macdonald, 1953; Greeley 1971b and 1972; Cruikshank and Wood, 1972; Peterson and Swanson, 1974). The methods of channel closure remains conjectural as roof structures have either collapsed or are hidden by a glaze lining. Flow units are seen to overlie the roof of all of the caves, for their sole marks may be identified in situ or upon collapsed blocks. Many of these units may
Plate 4.6. A view downflow of the partially drained lava channel of the 1923 lava flow, Mt. Etna.

This channel possesses many of the features characteristic of lava tube caves: a triangular cross-section, a lava lining and a discordant relationship between the walls and the horizontally bedded wall rock. Some layering of the wall rock is visible on the extreme left of the photograph. Of especial note is the inward leaning walls of the main channel and the triangular shape of the lava tube in the far wall (this is a loop and re-enters the main channel downflow). The channel is 3m deep.

Plate 4.7. A detail of the structure of the wall of the channel of the 1923 lava flow, Mt. Etna.
also have formed through overflows from openings (skylights) in the roof of an active tube.

In order to verify and understand the mechanism of channel construction further, comparison was made between the wall structures of the lava tube caves and those of the lava channel in the 1923 lava flow, Mt. Etna (an aa flow). A similar comparison between the structures in the caves and lava channels of the Gullborgarhraun, Iceland, has already been inferred above. In both cases a horizontal stratification of flow units bearing a discordant relationship with the walls of the channel was recognised. Details of this relationship in the lava channel of the 1923 flow are shown in Plates 4.6. and 4.7. Descriptions of wall structures of other lava channels were sought for in the literature, though with little success. Russell (1905), Finch (1943), Baker and Harris (1963) and Sparks, Pinkerton and Hulme (1976) all agree that channel walls and levees may be built up by the solidification of lava overflowing from an enclosed stream, though structures are not described. The present writer did observe overflow from one of the lava channels of the 1973 Heimaey eruption, Iceland, when lava periodically flooded the areas bordering the channel to a depth of 30-50 cm (Plate 4.8.), but any resulting structures so formed could not be examined. Overflow from the open lava channels from which the lava tube caves investigated originated was probably very mobile, forming thin, broad sheets of pahoehoe on angles of perhaps less than 1°.

(2) Smaller lava tubes, usually occurring as branch passages or distributaries of the larger feeder tubes, were seen mainly to occupy the axes of intermediate to small sized flow units, which in cross-section were of ellipsoidal form (Fig. 4.5.). Frequently these passages
FIELD SKETCH OF SEA-CLIFF, PUERTO DE SAN MARCOS.

Fig. 4.4.

Lavas of the Ancient Basaltic Series
were only of crawling dimensions, though they did possibly range up to 1.5m high. This passage type was abundantly present in the Tenerife, Mt.Etna and Gullborg caves, was demonstrably important to the morphogenesis of Raufarhólshellir, but was not identified as a constituent passage type of the Hallmundarhraun caves. In all of the study areas, however, small surface, or near surface tubes possessed an identical range of sizes, forms and structures as the small cave passages.

These passage types were best exposed where the Cueva de San Marcos has been truncated through cliff recession. Fig. 4.4. shows the general succession of the lava flows making up the high sea-cliff at Puerto de San Marcos, on the north coast of Tenerife: the Cueva de San Marcos occurs in flow 8. Structurally, these lava flows are divisible into two contrasting groups:

(a) lava flows numbered 1, 2, 3, 6, 7 and 9 are recognisable for their strong columnar jointing or massive appearance;
(b) lava flows numbered 4, 5 and 8 are recognisable for their apparent horizontal jointing.

Lava tube caves were observed in the lava flows only exhibiting the apparent horizontal jointing.

Closer examination of flows 5 and 8 revealed them to be composed of small flow units or pahoehoe toes, whose jointing pattern explained the overall apparent horizontal jointing. A detail of flow 5, illustrating its structural characteristics is shown in Fig. 4.5. In general, flows 5 and 8 ranged in thickness from 6-18m, being made up of as many as 10 ellipsoidal units vertically. The units were thin and wide and were difficult to recognise, though detailed
Detail of superimposed small flow units in the cliff section at Puerto de San Marcos, Tenerife.

Fig. 4.5.
Plate 4.8. Channel overflow on Heimaey, Iceland, during the 1973 eruption.

Periodic surges of lava from the vent caused the channel to frequently overflow, sending thin, wide lobes across the bordering areas. Such thin deposits are probably the cause of the horizontally bedded flow units which make up the walls of lava channels.

Plate 4.9. A deformed tube at the axis of a small, tongue-shaped flow unit in flow 5, cliff section, Puerto de San Marcos, Tenerife.

The contacts of the flow units are plainly visible. The roof of the tube was probably still plastic when the higher tongue was emplaced, causing it to sag.
inspection revealed the usual diagnostic features: an external narrow zone of high vesicle density; a distinguishable external ropy surface, frequently oxidized to a chocolate-brown colour; concentric zones of vesicle accumulation; jointing lying parallel with the exothermic surfaces; an internal region of little jointed lava with a light vesicle density or, alternatively, a small lava tube (Plate 4.9.).

Tubes varied in size from 15cm to 5.5m high (Cueva de San Marcos and neighbouring cave were large and opened directly onto the cliff-face), and by crawling into some of the smaller tubes it was possible to observe them branch off the larger tubes: for example, at Cave B on the Cueva de San Marcos survey the smaller entrance occurring high in the cliff-face lies along the axis of a small ellipsoidal unit.

The ability of the pahoehoe toe-budding process to form small tubes has been discussed by Wentworth and Macdonald (1953), Macdonald (1967 and 1972) and Peterson and Swanson (1974), though speleologists have failed to describe cave forms associated with toes and small tongues. These small flow units extend from the crusted front of large, slow moving pahoehoe flow units and one would expect many of the smaller passages in lava tube caves to have originated from them.

MODES OF CONDUIT (LAVA TUBE) CONSTRUCTION.

No evidence was found during this investigation to support the theory put forward by Ollier and Brown (1965), and others, that conduits are eroded through layered lava by segregated liquid. Descriptions and photographs suggest that the 'layered lava' structure is very similar to the structure of superimposed sheet flow units observed
about the large cave passages described herein, and the writer suggests that structures composed of sheet flow units are common about all large lava tube caves. Not only does the layered lava theory appear to be based upon erroneous interpretations of flow structure, but it also involves flow mechanisms which are not feasible. Lava segregating out from between congealed layers in the flow must lose much of its heat and therefore its capacity to erode. The idea that liquid lava may remelt solid lava is an important one, but if such an hypothesis is invoked care must be taken in establishing a perpetual source of heat, which in this writer's opinion can only come from a lava stream that is fed directly and continually with hot, liquid lava from the vent. Viewed in this light, the proposal by Hatheway (1970, 1971a and 1976) and Hatheway and Herring (1970) that lava tubes propagate back up the flow towards the vent is hardly credible. As a further objection to the layered lava theory, it is difficult to envisage a horizontal arrangement of laminae and shear planes in relation to the lava tube, rather than a concentric arrangement as proposed by workers on Mt. Etna, unless erosion has considerably enlarged the conduit vertically through several flow units.

In consideration of the structural evidence two main tube-forming processes are believed to have been operative in the pahoehoe lava flows investigated:

(1) tube formation through the roofing of an open lava channel;
(2) tube formation through the maintenance of axial flow within intermediate-small tongue-shaped flow units.

There appears to be many variations of the channel closure mechanism. These tube-forming processes in general correspond with the processes observed during the recent Mauna Ulu activity (Greeley, 1971b and 1972;
(1) Single lava tube cave passages aligned along the axis of a lava flow or large flow unit, and the major throughways of the more complex cave networks, appear to have originated as open lava channels. A horizontal stratification of the wall rock was exhibited in all of the cave passages of this type. A similar stratification was observed in the walls of open lava channels and is regarded as successively deposited thin sheet flow units, formed as a result of a pulsatory lava delivery and periodic channel overflow. The method of channel closure in many cases remains equivocal because: (1) the inner lining of a cave had not collapsed and it hid all roof structures from sight; (2) where this lining had collapsed during active flow through the tube the exposed roof structures had subsequently been glazed over; (3) roof collapse in some caves was so extensive as to have completely destroyed all important roof structures. However, three methods of channel closure are regarded as having been important.

(a) As some horizontal layering of the roof beneath the surface flow units was visible in the big Icelandic caves (Raufarholshellir, Surtshellir-Stephanshellir and Vidgelmir), and as all of these lay considerable distances below the vent, thereby excluding the possibility of roof construction through the accretion of welded spatter (Cruikshank and Wood, 1972), the principal roofing method is regarded to have been the surface crusting of the lava river. A thin, continuous crust appears to have formed over the Grotta dei Lamponi (Mt.Etna) also. In some cases (for example, Surtshellir), roofing appears to have been incomplete and secondary roof levels, now subsequently collapsed, developed beneath skylights. Such a
Plate 4.10. A tube formed of welded spatter near the source vents of the 1923 lava flow, Mt. Etna. This tube was not investigated internally as it was unstable, though it appeared to extend for a considerable distance.
development was described by Peterson and Swanson (1974) from the Mauna Ulu tubes.

(b) Some welded spatter was observed in the roof and walls of the Thrihellir caves in the Gullborgarhraun, Iceland. This observation, together with considerations of the gas-charged nature of the magma inferred by the structure of the shelly pahoehoe and the close proximity of the caves to the vent outlet, suggests that some roofing may have occurred through the construction of arched levees of welded spatter. A lava tube cave of this type, developed in spatter, was observed near the source vents of the 1923 lava flow, Mt. Etna (Plate 4.10.), though it was not investigated because of its unstable nature.

(c) Many cave passages, both axial and non-axial, of a variety of sizes, appear to have originated as the result of the inward growth of the walls of an open lava channel as lava periodically overtopped them. Cave passages of this type bear a distinctive triangular or gothic-arch shape in cross-section, as seen in Vegghellir (Thorarinsson, 1957) in the Gullborgarhraun, Iceland, in the Tenerife caves (Plate 4.11.) and on Mt. Etna (Plate 4.12.). This process was described previously by Kjartansson (1949), Bravo (1954 - Fig. 4.6.) and Cucuzza-Sylvestri (1957).

(2) Many lava tubes certainly originate as a result of axial flow through flow units of intermediate to small sizes. No large passages in the caves investigated appeared to have formed in this way, though a cave of large diameter (3m) was observed in a large aa flow unit which had become confined in a narrow valley on the northern flank

Fig. 4.6.
Plates 4.11, (left) and 4.12, (right) Triangular-shaped passage profiles indicative of tube formation by the channel closure method in which lateral overflow causes the gradual inward growth of the walls of the channel. Plate 4.11 is a small loop tube in the channel of the 1923 lava flow, Mt. Etna. Plate 4.12 is of the main passage, Cueva de los Piquetes (Cueva del Viento), Tenerife. The tube in Plate 4.11 is 1.3m high.
of Mt. Etna. This feature showed no wall stratification, only successively enclosed, concentrically arranged lines of vesicles and radiating joints. This observation supports descriptions by Gurrieri (1933), Poli (1959) and Macdonald and Abbott (1970). However, numerous passages in the caves investigated were demonstrably the drained axes of smaller lava tongues. Such lava tubes generally possessed a diameter of less than 1.5m.

Thus, it appears that there are many methods of tube construction in pahoehoe lava flows, though it must be remembered that none of these mechanisms alone is capable of forming the complex lava tube systems from which most lava tube caves are derived. As will be shown in the following chapters, cave evidence suggests that these networks are composed of a variety of lava tube types.
Morphogenetic studies of selected cave groups.

General comment.

It will be noted that in each of the following cave studies the stages of cave development (outlined in Chapter 1) are described in reverse order. This procedure has been adopted because knowledge of the modifications caused by the later genetic stages aids an interpretation of the earlier developed forms.
5. Morphogenesis of the lava tube caves around Icod de los Vinos, Tenerife.

The lava tube caves discussed in this chapter lie near the northern coast of Tenerife, around the small town of Icod de los Vinos (Fig. 5.1.), 47km west of the capital Santa Cruz de Tenerife. Three principal caves lie within the study area:

1. the Cueva del Viento is the most extensive cave complex, with 10km of mapped passage, and its upper entrance is located 2km WSW of Icod de los Vinos;

2. the Cueva de San Marcos, with neighbouring shorter caves, possesses over 2km of mapped passage and is located 1.5km north of Icod de los Vinos in the basalt sea-cliff overlooking the little beach at the village of Puerto de San Marcos;

3. the Cueva de Felipe Reventon, not located or explored by the writer, has a reputed length of over 2km and is thought to lie beneath part of Icod de los Vinos.

There are reputed to be shorter caves lying parallel with the Cueva del Viento and, no-doubt, with the other two caves, but difficult terrain, vineyards and banana plantations makes location difficult. In total, these caves form one of the longest and most complicated lava tube
SKETCH MAP OF THE GEOLOGY AND LAVA CAVES.

(Based on Mapa Geologica de España & Instituto Geografica topographical map, No.II03)
cave networks in the world: the whole area around Icod de los Vinos being underlain by an enormous, shallow, segmented cave complex. The fieldwork was carried out during August, 1973 and April, 1974.

PREVIOUS EXPLORATION AND RESEARCH.

The first recorded exploration of the Cueva del Viento took place in 1969-70 and was carried out by the Sección de Esploraciones Vulcanoespeleológicas de la Guancha (SEVG) del Grupo Montañero de Tenerife and Sección de Esploraciones Subterráneas de la Agrupación Excursionista de Etnografía y Folklore de Barcelona, under the direction of Carlos Teigell. As a result of this work the cave was claimed as the longest lava tube cave in the world (Teigell, 1970), for its length of 6.18km exceeded the length of the Cueva de los Verdes on Lanzarote which, according to the Spanish, formerly held the title. In his description of the cave, Teigell commented upon its archaeology, meteorology and biology and confirmed that it possessed two entrances; the upper (giving access to the Cueva de las Breveritas) lying at an altitude of 640m and the lower (giving access to the Cueva de los Piquetes) at 580m. Other articles on the cave appeared the same year (Trogoblio, 1970; Anon., 1970 and 1970a). The following year Grupo de Esploraciones Subterráneas del Club Montañés Barcelona (GES) visited the cave and quoted a length of 6.2km and a vertical range of 580m (Montoriol-Pous, 1971). The full report of this expedition subsequently appeared (Montoriol-Pous and de Mier, 1974) and contained a survey (plan only at a scale of 1:1000), a description of the cave's morphology and a discussion on its secondary mineralization. The cave was also visited in 1971 by a U.S. caver, W.R. Halliday, who described it as an extensive labyrinth, divided into two parts by a 'sink' (roof collapse) (Halliday,
1972 and 1972b). Later, Montoriol-Pous (1972) repeated the figure of 6.211km for the total length of the cave, but stated that the figure of 580m for the vertical range was a preliminary figure only and was subject to verification (Spanish: 'a comprobar'). This important qualification appears to have been overlooked by most other writers interested in the cave and, as a result of a much lower figure of 478m for the vertical range of the cave obtained by the survey for this thesis, the present writer became involved in a certain amount of argument about the extent of the cave, particularly with P. Courbon (French caver) who had obviously misquoted the cave's true size (Courbon, 1972 and 1974).

The Cueva de San Marcos, formerly known as the Cueva de Guanches (it is assumed that these are the same cave from their similar descriptions), was a celebrated burial cave of the Guanches, who were the pre-conquest inhabitants of Tenerife. Stone (1880) stated that the cave was 11,000 ft. (3.353km) long and Brown (1932) suggested that the cave (known at the time as the Guanche Burial Cave) would be an exciting holiday excursion from Icod de los Vinos. Halliday (1972a, 1972b and 1972c) visited the cave in November, 1971, and reported that it contained 2.200km of surveyed passage, still going in the direction of the Cueva del Viento. He noted two entrances; one in a banana plantation and one in the sea-cliff at Puerto de San Narcos.

There is very little literature on the Cueva de Felipe Reventon, other than brief mentions and vague locations. For example, Montoriol-Pous and de Mier (1969) gave its length in a footnote in one paper, but had more to say in the report of their 1971 expedition to the Cueva del Viento (Montoriol-Pous and de Mier, 1974), when they stated that caves of minor importance were also examined by them. The biggest was
the Cueva de Felipe Reventon, estimated to be about 2km long and situated like the Cueva del Viento in the district of Icod de los Vinos.

**DETAILS OF THE CAVES.**

Details of the caves found from independent survey work in 1973 and 1974 are as follows:

<table>
<thead>
<tr>
<th>Cueva de las Breveritas</th>
<th>580m approx</th>
<th>7,922m</th>
<th>261m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cueva de los Piquetes</td>
<td>487m approx</td>
<td>2,080m</td>
<td>217m</td>
</tr>
<tr>
<td><strong>Total Cueva del Viento</strong></td>
<td>10,000m</td>
<td>478m</td>
<td></td>
</tr>
<tr>
<td>Lower cave, Cueva de las Breveritas</td>
<td>2,340m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cueva de San Marcos</td>
<td>36m approx</td>
<td>2,130m</td>
<td>69m</td>
</tr>
</tbody>
</table>

**N.B.**

(1) An altitude of 580m a.s.l. at the entrance of the Cueva de las Breveritas (highest entrance of Cueva del Viento) was determined by averaging two descents to sea-level using a Thommen pocket barometric altimeter (Swiss manufacture) reading direct to 10m and by estimation to 5m.

(2) A comparison between the plan of the Cueva del Viento prepared by the SEVG and the plan prepared for this thesis reveals a similar form to the cave (excluding the lower cave in the Cueva de las Breveritas which, at the time of the present survey, had not been discovered by the Spanish), though the former is elongated and comparison of the length of the cave between its north and south extremities gives a variation of at most 5% between the two
(3) The Cueva de las Breveritas and the Cueva de los Piquetes are separated by what was at first believed to be an impenetrable collapse about 8-10m wide, but this is now thought to be the foundations of a wine vat sunk into the cave (P. Courbon, personal communication).

**GEOLOGY OF THE STUDY AREA.**

The geology of the area around the lava tube caves is shown in Fig. 5.1., which utilizes information abstracted from Mapa Geologico de España, Sheet 1103 (Inst. Geologico y Minero de España), 1968. The place of the local geology in the volcanic succession of the island as a whole is shown below:

Recent Series Basalts & Trachybasalts (IV & Historical) ..... Recent Salic Series
Series III Basalts ........................................... Trachyte and Trachybasalt Series
......................................................... Upper Canadas Series
Lower Canadas Series Basalts ........................ Lower Canadas Salic Series
Ancient Basalt Series .................................................................

The geological evolution of the island is summarized after Hausen (1956), Fuster, et.al. (1968) and Borley (1974) as follows. Overlying a basement complex which is not seen are rocks of the Ancient Basalt Series. These are mainly found in two parts of the island: the oldest rocks forming the Anaga peninsula in the north-east, while younger lavas form the Teno peninsula in the north-west. Rocks of the Ancient Basalt Series are considered to have been erupted from fissures, forming lava shields, and comprise alkalic basalt and ankaramitic lavas and pyroclasts.
Abdel-Monem, Watkins and Gast (1967) gave an age of 15.2 Ma - 7.2 Ma for these early lavas. Volcanic activity then became more centralized with the production of the Lower Canadas and Upper Canadas Series and the Trachyte and Trachybasalt Series. A number of volcanoes produced large amounts of pyroclastic material and lavas, ranging from alkali basalt through trachybasalt to phonolite, and ultimately formed a volcanic complex believed by some to have risen 5000m a.s.l. At a later stage (late Pleistocene) emptying of a high level magma chamber and faulting caused the summit region to collapse and slip northward, forming the depression of Las Canadas: the stratified deposits of Bandas del Sur represent the final phase of activity of this period. Contemporaneously, and a little later, vulcanicity produced the Series III basalts and pyroclastics which overflowed the walls of the depression in many places. Vulcanicity of the Recent Period was mainly restricted to the Las Canadas depression, within which the two central volcanoes Pico Teide and Pico Viejo emerged, composed of lavas ranging from trachybasalt to phonolite. A final phase of activity was represented by the growth of clustered adventive cones over the island which erupted lavas of alkali basalt, trachybasalt and phonolite. This phase of vulcanicity passed into the Historic Period with the last eruption on Tenerife being that of Chinyero in 1909.

The most authoritative geological map of Tenerife, Mapa Geologico de España, Sheet 1103, in the 1:100,000 series shows the lavas upon which Icod de los Vinos stands as Series III Basalt, while the area of the cliffs at Puerto de San Marcos are shown as basalts of the Ancient Basaltic Series (Fig. 5.1.). Without access to the memoir describing this map sheet, the writer is reluctant to accept this view as it contradicts the belief that the lava tube caves constitute parts of a single complex that formed either in one large lava flow, or in lava flows
much closer in age than the duration of time between the Ancient Basaltic Series and Series III. Confirmation of this idea will come from further mapping and an analysis of the form and situation of the Cueva de Felipe Reventon, which is possibly the missing link between the Cueva de San Marcos and the Cueva del Viento.

The lavas regarded as basalts of the Ancient Series exhibited in the sea-cliff at Puerto de San Marcos, which hold the Cueva de San Marcos and a variety of smaller caves, were cursorily examined in April, 1974. These lavas were described in Chapter 4, where it was shown that the caves occurred only in the flows which exhibited an apparent horizontal jointing, resulting from each flow being composed of piled ellipsoidal units (Figs. 4.4. and 4.5. and Plate 4.9.).

In their study of the Cueva del Viento, Montoriol-Pous and de Mier (1974) accepted that this cave formed in basalt of Series III age and stated it to be an olivine-augite basalt with porphyritic texture. The lava flow fills the broad descending valley in which Icod de los Vinos stands and houses the main cave complexes of the Cueva del Viento and the Cueva de Felipe Reventon. The source of the lava is not known, nor the area, thickness or volume of the lava flow, for much of it is buried beneath later lava flows and nowhere is the base of the flow seen. Structurally, this lava flow resembles flows 5 and 8 at the cliff at Puerto de San Marcos. Where exposures are seen, such as beside the road above Icod de los Vinos, small tubes occur in ellipsoidal units. Surface tubes abound and bare rock surfaces exhibit excellent ropy structures indicative of high magma mobility, though it is felt that this mobility was more a consequence of a high effusion rate and a very steep gradient (averaging 14°-15°), rather than a high magma fluidity.
GEOLOGY OF THE CUEVA DEL VIENTO.

The Cueva del Viento is of especial note, for not only does it possess a complexity of form that, to the writer's knowledge is not repeated to anything like the same degree in any other cave of this type, but also, with a length of 10km, it ranks only after Leviathan Cave, Kenya, and possibly Kazumura Cave, Hawaii, as the world's longest lava tube cave.

Morphology.

The survey shows the form of the Cueva del Viento in plan, long profile and cross-profile. The cave comprises two main parts: (a) an upper cave totalling 7.66 km, dominated by the long, meandering main tube of the Cueva de las Breveritas and the Cueva de los Piquetes, linking a number of (today) unconnected passage complexes; (b) a lower cave that partly trends beneath the line of the upper cave in the Cueva de las Breveritas, comprising 2.34 km of passages in two main branches. The lower cave is joined to the upper cave in only one place, via a small 4m high pot and lavafall.

Features of the cave's morphology which deserve further description are: (1) the unusually complex planimetric form; (2) the sinuosity of the main passage; (3) the steep, multi-level long profile; (4) the great variety of constituent passage forms.

(1) Cave complexity. The Cueva del Viento exhibits an unusually high degree of passage complexity for a lava tube cave. Montoriol-Pous and de Mier (1974) thought that there might be some relationship between the form of the cave and the very steep gradient upon which cave genesis occurred. In order to compare and contrast the planimetric forms of the
caves they had investigated in Iceland and the Canary Islands, they devised an 'indices planimetrico' - \( I_p = \frac{L_p}{P_e} \) - where \( I_p \) was the indices planimetrico, \( L_p \) was the total length of the cave, and \( P_e \) was the distance between the two furthest points in the cave. The figure representing the form of each cave was then plotted against their respective gradients. As a result of this exercise, Montoriol-Pous and de Mier concluded that (a) a high degree of passage complexity in lava tube caves correlated with a high slope angle, as is the case at the Cueva del Viento and, (b) within the Cueva del Viento itself, areas of greater complexity correlated with areas of higher gradient.

Although the idea of comparative quantitative analysis seems to the present writer to be a most useful means of assessing the relative contributions of the controlling factors on the morphogenesis of caves, at this stage the writer is reluctant to agree with the conclusions reached by Montoriol-Pous and de Mier for the following reasons:

(a) firm conclusions cannot be based upon a limited sample of five caves;
(b) the genesis of a lava tube cave is a function of unique and complex relationships between a number of highly variable factors of which gradient is but one example, and the contribution of gradient to cave genesis (albeit in this case a very important contribution) must be viewed in the light of its influence, along with other factors, in the maintenance of the mobility of the lava - gradient alone cannot be responsible for cave complexity;
(c) visual interpretation of the writer's own survey and analysis of the survey notes do not support the contention that the most complex parts of the Cueva del Viento correlate with areas of steeper gradient.

At the moment the writer offers no reason for the complexity of the
Cueva del Viento, other than to suggest that it may be the result of a special combination of factors, possibly a very high and constant effusion rate, emplacement over a broad surface with a steep gradient, with consequent extreme magma mobility. Comparative quantitative analysis will eventually provide the answer, but this must wait until sufficient data is available. Meanwhile, we remain with the cave survey as a qualitative statement of the cave’s complexity.

(2) Sinuosity of the main passage. In plan, the main passage of the Cueva del Viento, particularly between the two entrances, exhibits pronounced sinuosity. Sinuous bends in lava tube caves will be discussed in detail in Chapter 10.

(3) Long profile and gradient. Lava tube caves may possess great lateral extent, but they lack the vertical development of limestone caves. When multi-level lava tube caves are found, it is usual that the lower part of the cave has captured the flow of an upper part through the roof collapse of the lower, and the two caves are linked via one or more lavafalls. This is the case in the Cueva del Viento where, in the Cueva de las Breveritas, the lower cave is linked with the upper cave via a single 4m lavafall.

The total vertical range of the Cueva del Viento is 478m by this survey, giving a mean gradient of 11°. This gradient is fairly constant, apart from the occasional step where the gradient may rise locally to 30°. The average gradient of the Cueva del Viento must be one of the highest known and it must have been a very important factor in cave genesis: for example, in the maintenance of mobility of the lava draining from the tube.
GENESIS OF MAJOR PASSAGE FORMS.

Fig. 5.2.

Key:
- Liquid lava
- Congealed lava phase 2
- Congealed lava phase 1

Cross-sections abstracted from surveys of Cueva del Viento and Cueva de San Marcos.

Approx Scale
Passage profiles. The survey shows the 81 passage cross-profiles surveyed in the Cueva del Viento during 1973 and 1974. Most of the profiles were measured in order to provide regular documentation of passage forms, though some were selected because they illustrated a characteristic or unusual shape.

As in the study of limestone caves, an analysis of passage profiles in lava tube caves allows an interpretation of the genetic history of the cave. Even the casual observer in the Cueva del Viento cannot fail to notice the recurrence of certain passage forms, though there is a gradation between one form and another. Thus, it was possible to group the surveyed profiles into eight general types and two representatives of each type are illustrated in Fig. 5.2.

Morphogenesis.

The modifications caused by each of the genetic stages are easily recognised in the Cueva del Viento and, as stated at the beginning of this section, form the basis of morphogenetic interpretation.

Breakdown and collapse. The cave has not been significantly altered by collapse. The two entrances were formed through roof collapse and there are a few areas of breakdown in the Cueva de las Breveritas. As a result of so few exposures of the lava flow, no generalizations are possible on the relationship between passage forms and flow structure.

Conduit drainage. Modifications of the lava tube caused by its drainage, with subsequent adherence of cooled lava to the walls and floor of the original conduit, are extensive in the Cueva del Viento. Such modifications are seen in the passage profiles identified in Fig. 5.2. It was found possible to explain the variety of passage forms in the
Cueva del Viento by constructing a theoretical model in which a cylinder, filled with fluid lava, was spasmodically drained. Individual still-stands of the fluid level in the conduit were marked by the growth of lateral benches and surface crusting, while diminution of the flow led to a gradual reduction in conduit dimensions. This is shown in Fig. 5.2. One particular feature of the cave's morphology worthy of special mention is the occurrence of tiered passages that result from the convergence of lateral benches. Recurrence of this feature throughout the cave results in many flat-out crawls through tiny triangular-shaped passages.

**Conduit network evolution.** Evidence of the developments that occurred in this stage must be looked for in the planimetric form of the cave, for this suffered least modification during the later stages.

(a) It appears that the lower cave (i.e., the cave lying beneath the Cueva de las Breveritas) formed before the lava flow, or flow unit, containing the upper cave was emplaced, and the lower cave pirated some of the active flow from the upper cave via the 4m pot. This point of view is supported by the following:
(i) the lower cave trends across the line of the upper cave;
(ii) the lower cave possesses a character and size not reflected by the upper cave;
(iii) flow features in the passages surrounding the 4m pot, which is a lavafall, indicate a flow direction into the lower cave.

It is suggested that the lower cave formed within a lava flow that was later buried by the Series III basalt, or it formed in an early unit of the Series III lava, there having been a break in effusive activity before a later unit containing the upper cave was emplaced.
Fig. 5.3.
PASSAGE COMPLEXES IN THE CUEVA DE LAS BREVERITAS.
In either case, collapse of the roof of the lower cave in the region of the 4m pot today, before the emplacement of the upper lava flow, or flow unit, was necessary for the capture of some of the drainage of the upper tube. It appears, however, that the main flow in the upper cave was never captured by the lower and the lower cave possibly only received additions of fluid lava during periods of high surges when the main route overflowed.

(b) Some of the passage forms of the complexes of the higher part of the Cueva de las Breveritas are anomalous and cannot be explained in the terms of Fig. 5.2. These passage complexes appear to have formed from a pattern of sub-parallel, or braided, open channels, which periodically flooded, causing the development of spillways or escape routes for the excess fluid.

Enlargements of the two main passage complexes in the higher part of the Cueva de las Breveritas are shown in Fig. 5.3. A traverse of the main route (shaded on the figure) through each of these complexes involves alternate crawling through triangular-shaped passages and walking through narrow trenched sections, where high lateral benches cause the passage to assume a 'T' shape. These alternating passage profiles would be adequately explained by Fig. 5.2., but for the fact that as many as six subsidiary passages may radiate off from any one point above the lateral benches. Similar features are found in the large passages lying parallel with the main route, to which the main route is connected via the higher level subsidiary network.

Obviously, if the main route and the parallel routes formed as enclosed conduits, connections would not be possible, and so it is suggested
that the higher level connecting tubes formed before this part of the Cueva de las Breveritas was completely roofed. The connecting tubes probably originated in flow units caused through either lava overflowing the banks of sub-parallel, or braided, open channels during successive high lava surges, or as overflow through skylights from a similar sub-parallel, or braided lava tube network. Thus, once formed, these subsidiary tubes may have only been used periodically, facilitating the transportation of excess liquid lava during periods of flooding in the main tube.

It is interesting to note also that as a result of such flooding, a tongue of lava spread across the area underlain by the lower cave and was captured by it at the roof collapse where the 4m pot is situated today, forming yet another outlet for overflow.

(c) Some smaller passage complexes, and parts of the larger complexes, formed as a result of the superimposition, convergence and divergence of tubes carried in individual small flow units: for example, the complex around Galeria Barroso. Such flow units are easily identified at surface exposures of the lava flow above the cave and mini lava tube networks are found by crawling into units with hollow cores. There is clear evidence in the cave also, particularly in the smaller complexes, of the lateral convergence of the flows carried in some passages, causing the removal of the separating wall and leaving a distinctive \( \eta \)-shaped section.

(d) Superimposed flow routes appear to have converged in the central part of the Cueva de los Piquetes. The upper route meanders across the line of the lower route and is today segmented as a result of partial drainage into the lower route. The lower route is today represented by
the main passage. Superimposition of the upper route may have been the result of overflows before the lower was roofed or, alternatively, the lower tube was subsequently buried by a higher, later flow unit and tube network, only parts of which have drained.

(e) Although wall structures on which a method of tube construction can be based are not exposed in the cave, frequent triangular-shaped passage cross-profiles (Plate 4.11) are those typically resulting from the gradual inward growth of the walls of an open lava channel. As described previously, smaller scale triangular-shaped passages similarly result from the convergence of lateral benches within the cave and this may form what speleologists call a 'tube-in-tube' structure.

Summary of the genetic history of the Cueva del Viento.

(1) Either the emplacement of a lava flow older than Series III, or the first effusive phase of Series III basalt flow, forming a large flow unit, in which the lower cave of the Cueva de las Breveritas was formed, probably originating as a large open channel which eventually became roofed.

(2) A period of little- or non-activity in the region, drainage of the lower cave, cooling of the lava flow and collapse of a small roof section of the cave in the region of (today) the 4m pot.

(3) Renewal of voluminous and continuous effusive activity with a new flow, or flow unit, causing the formation of a system of long, braided, or sub-parallel channel down the steep slope above Icod de los Vinos and across the line of the older tube.

(4) Selection of the most favourable flow routes. Erosion
by hot, flowing lava, causing modifications to the original channel forms and patterns (e.g., enlargement of the channel, meandering, etc.). Fluctuations in the lava level caused the channel to overflow periodically, particularly higher up the slope, and lava spread away from the main routes. Continued periodic flooding resulted in the formation and maintenance of 'flood tubes' or 'overflow tubes', connecting the main feeder routes and occupying the centres of surface units slowly advancing away from the main feeder tubes. Roofing of the main tubes progressed, apparently through the convergence of the walls of the channel, though some parts remained unroofed, through which fluid lava escaped onto the surface of the flow during high surges. Overflow crossing the line of the lower cave was captured at the roof collapse and formed the 4m pot and lavafall.

(5) Continued advance of the lava flow, with periodic surges now being mainly accommodated internally via the newly formed 'overflow tubes'. Surface flows strengthened the roof and later tubes formed across the line of the main tube and were captured by it (e.g., Cueva de los Piquetes).

(6) Cessation of effusive activity at the vent. Gradual, sluggish drainage of fairly viscous residual lava in the tube, causing its subsequent modification and diversity of passage forms.

(7) Cooling of the flow and collapse of the roof of the tube in two, or possibly three, places. Some collapse of the walls and ceiling of the cave.
Survey of Cueva de San Marcos.

- Plan
- Extended Section
- Cross Sections

In investigation of the rocky neck of the Cueva de San Marcos has been made in April 1974, as part of a comprehensive survey of the cliff-face at this point in the Rio Valley. The cliff-face overlying the cave is a narrow, steep, and narrow passage, lying behind the cliff. The rock is a banded sandstone, with a layer of sandstone overlying the cliff-face. The passage is narrow and restricted in passage. The higher entrance to the cave is through a lower entrance, which is a small opening in the ground. This entrance is located in the middle of the cave, and is the size of a small room.

Cross Sections

- 1 2 3 4 5 6
- 7 8 9 10 11 12
- 13 14 15 16 17 18 19

Extended Section

- 20 21 22 23 24 25 26 27 28 29 30

Notes:
- The survey was conducted in April 1974.
- The cliff-face overlying the cave is narrow and steep.
- The higher entrance to the cave is through a lower entrance.
- The cave passage is restricted in passage.
- The rock is a banded sandstone.

The survey was conducted at every station, with measurements taken at each point along the cliff-face. The survey was conducted by the authors of the paper, who used a combination of aerial photography and ground surveys to map the cave system.

In conclusion, the Cueva de San Marcos is an impressive cave system, with a variety of unique features. The cave is located in the Rio Valley, and is a popular destination for spelunkers and geologists. The survey conducted in April 1974 provides a valuable insight into the cave system, and will be used to guide future research and exploration.
GEOLOGY OF THE CUEVA DE SAN MARCOS.

An investigation of the geology of the Cueva de San Marcos was carried out in April, 1974. The cave is of outstanding scientific interest because it has been truncated at the cliff-face at Puerto de San Marcos, offering a unique opportunity of relating the cave form to the flow structure so well exposed in the cliff.

Morphology.

The form of the cave in plan, long profile and cross-profile is shown by the cave survey. There are two entrances: one lying in the cliff-face overlooking the beach at Puerto de San Marcos and the other, higher entrance, resulting from a roof collapse, lying behind the cliff in a banana plantation. In plan the cave possesses two main passages which converge downflow about halfway through the cave. The northerly branch passage possesses large dimensions, a sandy floor and connects with higher level passages overlying the point of confluence of the two main passages. The southerly passage is more restricted in its dimensions, but is a classical asymmetrical tube with an 'aa' floor. In addition, some 200m of passage lies behind (i.e., to the north of-) the higher entrance. The average gradient of the cave is 6°.

Passage forms in the Cueva de San Marcos group into the same types that occur in the Cueva del Viento, though some passages in the Cueva de San Marcos are very spacious and breakdown is of much greater importance.

Tiered tubes (i.e., tube-in-tube) of the type discussed in the previous section, caused by the convergence of lateral benches, are ubiquitous in the Cueva de San Marcos. Other unusual features are impressive
An investigation of the geology of the Cueva de San Marcos was carried out in April, 1974. The cave is of outstanding scientific interest because it has been truncated at the cliff-face at Puerto de San Marcos, offering a unique opportunity of relating the cave form to the flow structure so well exposed in the cliff.

**Morphology.**

The form of the cave in plan, long profile and cross-profile is shown by the cave survey. There are two entrances: one lying in the cliff-face overlooking the beach at Puerto de San Marcos and the other, higher entrance, resulting from a roof collapse, lying behind the cliff in a banana plantation. In plan the cave possesses two main passages which converge downflow about halfway through the cave. The northerly branch passage possesses large dimensions, a sandy floor and connects with higher level passages overlying the point of confluence of the two main passages. The southerly passage is more restricted in its dimensions, but is a classical asymmetrical tube with an 'aa' floor. In addition, some 200m of passage lies behind (i.e., to the north of-) the higher entrance. The average gradient of the cave is 6°.

Passage forms in the Cueva de San Marcos group into the same types that occur in the Cueva del Viento, though some passages in the Cueva de San Marcos are very spacious and breakdown is of much greater importance.

Tiered tubes (i.e., tube-in-tube) of the type discussed in the previous section, caused by the convergence of lateral benches, are ubiquitous in the Cueva de San Marcos. Other unusual features are impressive
lateral benches near the higher entrance, which are the result of converging lava flows; a series of stepped benches and a deep trench in the region of Section No. 16, which are the remains of an underground lava lake; and a funnel-like depression in the floor of the upper level passage.

The internal drainage pattern.

Fig. 5.4. is a diagram showing the pattern of flow through the lava tube just prior to the cessation of effusive activity. It was constructed from data plotted in the cave. The direction of flow of the lava was partly determined by the overall (i.e., roof and floor) direction of passage gradient, and partly by analysis of fossil flow features. Points of origin of the flow in the cave were easily recognised at 'lava springs' and are shown on the diagram as open circles. Points where the liquid lava sumped the passage, eventually congealing and blocking it, were recognised as 'lava seals' and are shown on the diagram as open squares. The diagram illustrates the complexity of flow through the lava tube and is a very useful aid in morphogenetic interpretation.

Morphogenesis.

Following the example of the previous section on the Cueva del Viento, evidence of the genetic stages will be described in the reverse sequence because later stage modifications hide, or frequently obliterate, evidence of the earlier stages.

Breakdown and collapse. Breakdown of the roof and walls is common in the Cueva de San Marcos, but only in three places does it significantly control the form of the cave:

(1) the form of the passage from which Section No. 20 was taken is
predominantly joint controlled and its floor is composed of collapsed roof blocks;

(2) across on the opposite side of the main northerly passage, a big loop has suffered extensive collapse and piled boulders form a raised platform along the side of the main tube;

(3) a large chamber, extensively modified by breakdown, lies above the confluence of the two main passages.

There are other areas of breakdown in the cave, particularly in the main northerly passage, and roof collapse has formed the higher entrance. The reason for collapse and breakdown is uncertain, though lava tube caves are particularly susceptible to collapse because of the abundance of joints, partings and flow unit contacts in the surrounding lava flow. All collapses in the Cueva de San Marcos occurred after the floor had solidified and may have resulted soon after this due to cooling and contraction of the surrounding flow. Some water does enter the cave in places through the roof, probably from irrigation ponds on the surface, and this may have encouraged some collapse. Similarly, earth tremors from volcanic activity on the island, and the vibrations caused by heavy traffic on the road over the far end on the cave, may have loosened the already fractured roof.

Exposures of the lava flow are not well displayed inside of the cave, but they do show a structure similar to that seen at the cliff-face.

**Conduit drainage.** As in the Cueva del Viento, passage forms in the Cueva de San Marcos are the result of modifications resulting from the drainage of the lava tube and are explained in Fig. 5.2. In addition, in the Cueva de San Marcos, it was found possible to construct a generalized 'morphogenetic map' by plotting the position of the dominant
passage types within the cave (Fig. 5.4B).

Conduit network evolution. Figs 5.4A. and 5.4B. clarify many of the problems of the formation of the Cueva de San Marcos.

(a) It is evident from Fig 5.4A. and from the structure of the flow exposed in the cliff-face (described in Chapter 4) and in the cave, that the main passage of the Cueva de San Marcos was the main feeder for a vast system of smaller distributary tubes in flow 8 (Fig. 4.4.) and the form and extent of the cave is the result of only partial drainage of this tube complex about the main feeder tubes. This is to be expected in an area through which the frontal wave of the lava flow passed, and through which the master axial feeder tube elongated. The main flow routes through the tube complex would have been the most sensitive to adjustments in the discharge of new lava from the vent, while the flow through the distributary tubes was controlled by the developments taking place in the feeder tubes. At the cessation of vent activity, the main routes would have been the most likely of the lava tubes in the complex to drain of residual lava. This is because: (i) they were directly connected with the vent; (ii) they carried a greater volume of fluid lava, which must have remained mobile longer than the lava in the smaller distributary tubes; (iii) drainage of the distributaries could not proceed without a sufficient head of liquid to force continued flow, which obviously they could not have had if the lava level of the main conduit had dropped below the level of the entrances to the distributaries (it will be noticed that entrances to the majority of side passages occur high in the walls of the main tube), and reverse drainage could not have taken place unless there was space to receive the residual lava from the distributaries as a result of the lava level in the main tube having lowered. Thus, one can speculate
that if the residual lava in the tube complex had remained mobile for a much longer period (i.e., if the lava was less viscous, or it cooled more slowly) then the extent of the cave network would have been much greater than it is today, for more of the tube system from which the cave originated would have drained.

(b) The complexity of the Cueva de San Marcos is a reflection of a large number of ingressive and egressive side passages and there are few closed loops as in the Cueva del Viento. These minor passages fall into three main types.

(i) Some pass across the line of the main route: for example, near the points from which Section No.7 and 13 were taken. Both cross the main route just under the roof and, in the Section No.7 example at least, access can only be made via a very exposed climb up the wall of the cave. The difference in the direction of the flow of the main route and the transverse route is shown in Fig. 5.4A. It is suggested that these transverse passages are later formations, having originated when lava was emplaced across the roof of an earlier formed tube which, during subsequent enlargement of the lower, caused the flow in the higher to be captured by the lower.

(ii) Other side passages are more difficult to account for, though there are two possible explanations: it may be found that enlargement of the main feeder tubes caused the capture of previously formed tubes and gave them permanence through new, continued flow (i.e., incision of the main tube across the line of divergent older routes) or, perhaps more likely, these side passages originated as overflows of an original open channel. The passages off the main route in the region of Section No.16 tend to support the latter view, for it appears that ponding of the flow took place here, with the passage from which Section No.22 was taken acting as an overflow route from this pond.
(iii) Some loops (for example, at Section No.28) appear to have originated simply as braiding in the main routeway.

(c) The upper level passage overlying the confluence of the two main routes appears to have formed as a result of ponding at Section No.16, when overflow flooded across the roof of the original lava tube below this point. An early outlet for this lava was the tube which today lies behind the higher entrance, though this flow was eventually captured again by the main route just downflow of the confluence. Other surface flows converged with the main higher level flow from the south-east. At some stage lava broke through the roof and was captured by the lower level tube in the region of Section No.24, as shown by the great funnel-like depression in the floor of the upper cave, and the corresponding lava spring in the lower cave.

(d) The branch passage emanating from the region behind the upper entrance is a very low passage involving flat-out crawling in many places. Fig. 5.4A. shows the flow direction of this passage to be toward the main tube and it may have been an important tributary, but is now filled with undrained lava. The reason for it remaining undrained is easy to explain: (i) the outlet was into the main tube where a larger flow caused the lava in the tributary to be held back; (ii) meanwhile, lava was invading the tributary from behind via the passage near Section No.13.

Summary of the genetic history of the Cueva de San Marcos.

(1) Advance of the flow front across the line of the present cliff-face through the protrusion of successive lobate tongues, constructing a lava flow composed of superimposed ellipsoidal units. Gradual lengthening of
the channel in sympathy with the forward advance of the front. This feeder system in the region of the cliff-face initially consisted of two small channels which converged.

(2) Stabilization of the channel, its gradual enlargement through bed erosion and levee construction. Overflows during high lava surges caused lateral lobes to advance across the surface away from the channel, thickening the flow. Some new tongues of lava emanating from the channel developed their own tubes and were maintained by continued flow from the main route. The channel gradually began to roof, though for a period the channel was incompletely roofed.

(3) In one place in the channel an obstruction caused the flow to pond and lava eventually escaped across the roofed part of the channel immediately downslope, causing the formation of a higher level tube. This lava eventually found its way back into the main feeder lower down the flow after crossing the line of the main tube.

(4) The channel was eventually fully roofed and the roof was strengthened by overflows and by the addition of new flow units, some of which held their own tube networks.

(5) Perhaps an enlargement of the main tube, or collapse of parts of its roof, caused the capture of lava carried in overlying tubes.

(6) Vent activity ceased and the tube partially drained. As the level in the main tube lowered, the tributary passages gradually drained, though their drainage was not extensive as their gradients were away from the main tube. Drainage of the lake near Section No.16 left pronounced shorelines and lateral benches. The nature of the drainage in the
different parts of the tube network controlled the eventual shape of the resulting cave passages, their being great variety throughout the cave.

(7) The lava flow cooled and contraction led to jointing and collapse of the walls and roof occurred. The sea eroded the coastline to produce the high cliff at Puerto de San Marcos and abruptly truncated the cave. Water dripping into the cave and the vibrations caused by heavy road traffic overhead continued to weaken the roof.

The lava tube cave Raufarhólshellir is situated in a post-glacial basaltic lava flow approximately 2.5km north of the farm Vindheimar, in the Ölfusá district of S.W.Iceland (Fig. 6.1.). A newly built road, designed to shorten the journey between Thorlakshavn and Reykjavík, passes across the line of the cave and within 100m of the entrance. Raufarhólshellir is an impressive cave, 1.35km long, containing spectacular secondary formations and composed of an enormous, greatly collapsed, sinuous main passage that divides upflow into three smaller branches. A continuation of the cave probably occurs downflow of the entrance collapse, but a way has not been forced in this direction.

The writer first visited the cave in 1970 as a member of an expedition which aimed to complete a full speleological study of Raufarhólshellir and some other lava tube caves in Iceland (Prior, et.al., 1971). A further visit was made in 1976 so that the evidence of the formation of Raufarhólshellir could be re-appraised in the light of subsequent experiences of other lava tube caves.
PREVIOUS EXPLORATION AND RESEARCH.

The first known recorded visit to Raufarhólshellir was in the summer of 1930, when Dr. G. Bardarsson retrieved some lava stalactites for the German petrologist Sven Hjelmquist to analyse. Hjelmquist subsequently published a very detailed account of the chemistry and mineralogy of these specimens (Hjelmquist, 1932), as was described in Chapter 1. Prof. H. Munger found great interest in the cave and made two expeditions during 1953-4, resulting in the publication of an article in an Icelandic newspaper (Munger, 1955) which contained a sketch survey and a description of the cave. About this time Raufarhólshellir was also visited by a party of French geologists (Bout, et al., 1955) and a little later by Corbel (1957), who described Raufarhólshellir as the longest cave of its type in the world (longer, incidentally, than Surtshellir, which was also visited by Corbel). The cave was subjected to another survey and geological investigation in 1967 by the Grupo de Esploraciones Subterráneas (GES) del Club Montañes Barcelones (Montoriol-Pous, 1972), but this group could not explore the whole cave because ice near the entrance blocked two large side passages. They made a magnetic survey of Raufarhólshellir, gave it a length of 1060m, described its morphological characteristics and discussed the origin of its secondary mineralization. Yet another survey and description of the cave was made by an expedition from Cambridgeshire College of Arts and Technology (Foreman, et al., 1970) in 1969 as an exercise whilst sheltering from the torrential rain they experienced whilst in Iceland! The Shepton Mallet Caving Club expedition, of which the writer was a member, carried out a full speleological study of Raufarhólshellir (survey, geological, biological and meteorological work) in July, 1970 (Prior, et al., 1971), from which a high grade survey of the cave was published (Ellis, 1971),
The post-glacial lava flows around Vindheimar, S.W. Iceland.

Fig. 6.1.
along with a theory on the cave's formation (Wood, 1971), the latter being modified for this chapter after further fieldwork was carried out in 1976.

GEOLOGY OF THE STUDY AREA.

Raufarhólshellir occurs in the S.W. Iceland Moberg zone. Rocks of the Moberg Series (principally hyaloclastites) were formed, it is believed, beneath the ice of the Riss glacial period (Kjartanssónn, 1959) and are given the local name Núpafjall Series in the study area. Here they are represented in the higher mountains of Skálabell (547m), Stóra-Sandfell (429m), Litli-Mytil (465m) and Sandfell (295m). Overlying the Núpafjall Series is the Young Grey Basalt, represented by the tuffs and breccias which were erupted from Trölladalur on the north side of Skálabell. This formation has been given the local name Skalafell Dolerite and Kjartanssónn (1959) believes it to be interglacial in origin. The Skálabell Dolerite overlies the moberg of Skálabell, Litli-Mytil and Krossfjöll (273m) and was subsequently glaciated during the Würm period.

Isostatic and eustatic adjustments in the study area since the Riss glacial period have led to the formation of two abandoned shore-lines, or raised beaches, both of which are backed by high sea-cliffs. The higher shore-line, which occurs at an altitude of approximately 110m (i.e., the top of the cliff), is formed in hyaloclastites of the Núpafjall Series and probably dates from the Riss/Würm interglacial (Foreman, et.al., 1970). During this time the Skálabell Dolerite was erupted from Trölladalur and spilled over the higher cliff to form a
Plate 6.1. Ellipsoidal structures above the main junction in Raufarhólshellir.

The easiest ellipsoidal form to identify in the photograph lies above the head of the model, though the whole exposure is made up of many interlocking ellipses. These structures are the cross-sections of small to intermediate sized tongue-shaped flow units.

Plate 6.2. Lavafall in tube 5, Raufarhólshellir.

The lavafall and walls of the passage are well glazed. Stalactites are to be observed in the roof.
low platform at its base. Before the onset of Würm times the lower shore-line, now approximately 70m a.s.l. was cut in the Skálafell Dolerite. After the Würm glaciation there was a rise in sea-level to 55m, before isostatic recoil began to outpace eustatic rising of sea-level, producing eventually stepped beach ridges. The formation of the shore-lines, or more particularly the high cliffs, across the line of the shallow valley between Skálafell and Krossfjöll, is demonstrably important to the formation of Raufarhólshellir.

Eruptive and non-eruptive fissures occur in the study area and are considered to be related to movements in the post-glacial period. The main bulk of the lava in the study area was erupted from the fissure Leitin, situated south-east of the mountain Bláfjöll (off the map), from which the lava flowed in a south-easterly direction, eventually becoming confined in the shallow valley between Skálafell and Krossfjöll, before tumbling over the fossil cliff-lines and onto the Ölfus plain. The Leita lava has been dated as younger than 3,420 B.C. (Foreman, et.al., 1969) and is partly overlain by a younger lava erupted in A.D. 1000 from the fissure situated at the south-east foot of Litli-Neitill. Raufarhólshellir occurs in the confined Leita lava and is situated immediately above the position of the fossil cliff-lines.

Because of the extensive amount of breakdown inside of the cave, there are many good exposures of the wall rock. Wall structures are seen to be made up of superimposed, horizontally bedded, thick flow units (Plate 4.3.), each regarded as having formed during a single period of overflow from an original open lava channel, as described in Chapter 4. In cross-section, the flow above the cave is composed partly of ellipsoidal units (Plate 6.1.), regarded as the cross-sections of small flow units. The surface of the flow shows all the characteristics of
NOTE ON THE CHEMISTRY OF THE LEITAHRAUN.

The following chemical analysis of the Leitahraun was received too late to be included in the text. It was kindly supplied by Prof. Sigurdur Thorarinsson and is abstracted from M. von Komorovics: Vulkanologische Studies auf einigen Inseln des Atlantischen Ozeans, Stuttgart, 1912.

\[\begin{align*}
\text{SiO}_2 &= 46.97; \\
\text{TiO}_2 &= 1.99; \\
\text{Al}_2\text{O}_3 &= 19.87; \\
\text{Fe}_2\text{O}_3 &= 8.23; \\
\text{FeO} &= 5.76; \\
\text{MnO} &= 1.20; \\
\text{MgO} &= 4.76; \\
\text{CaO} &= 14.46; \\
\text{Na}_2\text{O} &= 1.75; \\
\text{K}_2\text{O} &= 0.45; \\
\text{Si} &= 99.48.
\end{align*}\]

The Leitahraun is tholeiite basalt.
N.B. This survey is a reduction of the survey located in the back pocket.

RAUFARHÓLSELLIR, SOUTH-WEST ICELAND.

Lat: 63° 56' 26" N. Long: 21° 23' 50" W. Alt: 165m.

PLAN

NOTE: The cave floor is fallen blocks of lava except where shown otherwise, viz.

Original tube
Sheet ice
Position of cross-section with direction of flow of ice
Reference points at 50 metre intervals

SCALE of PLAN & EXTENDED SECTION

EXTENDED SECTION

GROUND LEVEL

CROSS SECTIONS (Drawn at 10X the scale of the plan & extended section above)

This survey originally drawn at a scale of 1:1000 by N.M. Ems, January 1971. Copies of the original scans can be supplied on request to B.M.C.E.
tube-fed pahoehoe: abundant, well-formed tumuli; low flat-topped mounds; shallow depressions; small, near surface tubes and large areas of flat pahoehoe pavement, frequently with a ropy surface.

GEOLOGY OF THE CAVE.

Morphology.

The survey shows that the cave extends upflow from the entrance collapse, generally in a north-westerly direction. In plan it consists of a long, sinuous tube, 1,100m long and up to 18m wide, with six tributary/distributary passages.

In long profile, the cave is inclined away from the lava source with a gradient of approximately 4°. The main tube has an average height of 11m, though occasionally it may reach 16m in height. Irregularities in the long profile are caused by piles of collapsed material and corresponding ceiling domes, so that in some places the height between the original floor and the roof is as much as 20m. At the lower end of the main tube collapse has been so great that only 2m of rock forms the roof and it is here that in four places the roof has collapsed completely. In the smaller passages there is no breakdown and the original form of the tube is seen. Here, the section is regular, though in tubes 4 and 5 lavafalls occur (Plate 6.2.), each emanating from a smaller tube above.

The shape of the tube varies along its length and the survey has shown that four passage profiles are characteristic (Fig. 6.2.):

(1) this passage profile occurs above the lavafalls in tubes 4 and 5 and tubes 2 and 3 are also of this type;
The four main passage types from Raufarhólshellir.

Fig. 6.2.
(2) this passage form is characteristic of the passage below the lavafalls in tubes 4 and 5 and tube 6 is also of this type;

(3) this passage profile occurs in the main tube, though the section in Fig. 6.2. was taken from tube 1;

(4) the main tube is characterised by a variable form, generally tall and narrow, with an arched roof and a flat floor (where seen), of which this section in Fig. 6.2. is an example.

**Secondary ornamentation.**

Although much of the original tube is destroyed in breakdown, Raufarhólshellir is well known for its internal decoration (today much vandalized). It carries the usual range of features formed during a sporadic evacuation of the lava from the tube (lateral benches, false floor, shelves, lava lining, patterned floor structures, etc.), but is particularly notable for its small scale decorative features which have resulted from the flow of a thin vitreous wall lining, and for its two spectacular lavafalls.

The vitreous lining in Raufarhólshellir is an extremely thin layer backed by a honeycombing produced by a concentration of vesicles. This makes it extremely brittle. Generally, it is a deep grey colour with a metallic lustre, though in places it is a startlingly bright orange-brown colour. Frequently it is rippled or it has formed over the horizontal wall striations left by previously transported crustal blocks that gauged the softened wall rock as they passed through the tube. There is a wealth of delicate rod- and straw stalactites, some minutely decorated, formed of the glaze material. These, together with small globular stalagmites, occur in the many deep recesses in the walls of the cave and are particularly well developed in the smaller branch passages. In tube 2, it can be seen how the lining blistered, and
Plate 6.3. Blistered glaze in the roof of tube 2, Raufarhólshellir.

Note also the small yellow-white stalactitic form in the centre right of the photograph. This is deposit of hydrated silica (opal).
cratered masses coat the ceiling (Plate 6.3.), from the rims of each hang a ring of tiny straw stalactites. In this tube also, as in parts of the other smaller passages, even the floor lava is covered with glaze material.

Most spectacular in Raufarhólshellir are its glazed lavafalls, one occurring in tube 4 and another in tube 5, each being about 2m high and each emptying from a higher level small tube (Plate 6.2.).

**Morphogenesis.**

Following the method described, the stages of the genesis of Raufarhólshellir will be discussed in the reverse order.

**Breakdown and collapse.** The form of the original tube has been modified to a considerable extent by breakdown and collapse. In order to locate the path of the original lava tube, sitings of the lava floor and glazed ceiling were recorded relative to the survey stations. The long section drawn from these figures was then superimposed upon the long section of the cave today, so that the amount of breakdown could be estimated and the relationship of the lava tube with the flow surface could be ascertained. The resulting profile is partly shown on the cave survey.

The area of greatest breakdown is in the main tube where it is estimated that as much as 10m thickness of roof rock has been removed in some places. Complete roof collapse has occurred in four places at the lower end of the cave, and at Pt.9 and between Pts.4 and 5, 10 and 11, 11 and 12, and especially 12 and 14, the roof of the cave is less than 3m thick. The width of the cave has also increased in the areas of greatest breakdown (for example, between Pts.4 and 5). Correspondingly,
huge mounds of debris in some places almost completely block the main passage.

Measurements of the thickness of the roof of Raufarhólshellir were not only carried out as an exercise in understanding the genesis of the cave, but were also carried out for practical reasons. It appeared that the new motor road, designed to shorten the journey between Thorlakshavn and Reykjavík for the heavy fish transporters, which took advantage of the lower gradient of the valley in which Raufarhólshellir is situated, was perilously close to collapsing through the roof of the cave. This possibility had not been considered by the Icelandic authorities. Re-survey of the roof in the area over which the road passed was carried out during the 1970 cave survey and the figures, together with a special report (Ellis, 1971) on the danger of the possible collapse of the Threngsli road was forwarded to the Icelandic Roads Authority. They, in turn, carried out another survey, which confirmed the first results, though the road was not re-aligned. Instead, the position of the road across the cave was located by drilling holes through the roof and hanging ropes from the road surface to the floor of the cave. With the danger area thus delineated within the cave, the Icelanders then laid out a net across the floor of the cave and a regular check was (and still is being—1976) made of the amount of debris accumulating on the net. However, one would think that as the roof is so thin (only 4.5m thick in some places) and so highly fractured in the danger area, and as it is subjected to constant vibrations by heavy traffic passing overhead, any collapse would be sudden rather than gradual.

Collapse of part of the roof of some lava tube caves may occur while the tube is still active, though this does not seem to have occurred
Fig. 6.3. Relationship between the cave and variable slope of the pre-flow topography.
in Raufarhólshellir. Instead, collapse occurred after draining and is attributed to weathering. Firstly, differential cooling of the flow units making up the country rock produces a kind of sheet jointing, which is crossed generally by vertical secondary joints, sometimes of a polygonal nature. Flow unit interfaces are further weaknesses in the country rock. Secondly, joints and interfaces are further weakened by the passage of water from the surface, with some resultant oxidation and hydration of the basaltic minerals. Chemical weathering is evident from the fact that where a drip is both strong and continuous, the rock is stained red-brown, or small white or yellow stalactites have formed (Plate 6.3.). When tested, it was found that these stalactites were of hydrated silica. Opal stalactites have been observed in many other lava tube caves and some of the best displays are known from the higher reaches of the Cueva del Viento, where individual stalactites may range up to 16cm in length. Thirdly, in the downflow regions of Raufarhólshellir, near the entrance, permanent ice has formed and the growth of ice crystals in the highly jointed basalt (perhaps a diurnal freezing) is probably the reason for the greater amount of breakdown in this part of the cave. 'Sole marks', visible in the ceiling on the base of roof units point to the interfaces as being the principal weaknesses in the country rock.

Conduit drainage. The proximity of Raufarhólshellir to the fossil cliff-lines, over which the lava had plunged, undoubtedly was of great influence in the drainage of the tube (Fig. 6.3.); for drainage could not have taken place unless there was space made available downslope for the draining residual lava, and the increased gradient of the cliff-lines provided such a space. Modifications to the lava tube during the draining stage was not extensive and the lava appears to have maintained a degree of mobility during the evacuation. There are some discontinuous lateral benches in the cave, and in one place a 1m
Relationship between passage form and lava structure in Tube 4.

Fig. 6.4.
high arched lava crust spans the floor of the main passage (Section 'G' on the survey).

Conduit network evolution. The configuration of the cave is problematical, for the small tubes above the lavafalls, which are the apparent source of lava for the tube, combined would not have contributed sufficient lava to have effectively maintained flow in the main tube, and one is led to suppose that other lava sources were never drained and lie hidden beneath the present floor level. Also, it is a strange coincidence that tubes 4, 5 and 6 have similar passage profiles and similar lengths.

The tributary tubes in the higher reaches of the cave appear to possess a common origin. Tube 4 is the best developed and is representative of the higher tributaries. The structural and morphological details of this passage are shown in Fig. 6.4.

The passage form appears to have originated from the coalescence of superimposed drainage levels resulting from the erosion of the separating sheet of solid lava. Spalling in the small tube above the lavafall has exposed a flow unit interface. Inspection of the collapsed lining of the tube, which here is 35cm thick, shows that its concealed surface is ropy, oxidized and glassy. In the roof of the larger tube downflow of the lavafall, similar features are recognisable and collapsed roof blocks on the floor also bear a ropy surface on one side and the cave glaze on the other. 2m lower are a pair of prominent lateral shelves, which appear continuous with the floor of the small tube above the lavafall. Lateral shelves are common in many lava tube caves and mainly represent the remnants of a collapsed false floor which formed through the crusting of the lava flow when it only
partially filled the tube: for example, the false floor in the main passage originated in this way (Section 'G' on the survey). The lateral shelf in tube 4, however, is not of this type, for it carried a continuous lava flow across its surface, as shown by the lavafall, and instead it appears to be the remnants of the floor of the small tube above the lavafall. It is suggested that this floor extended much further along the passage and headward erosion by the lavafall has caused the central part of the span to be cut away. Also, in two places, it was found that the underside of the lateral shelves had collapsed and a flow unit interface was exposed. The inference is that the tube above the lavafall is also underlain by a flow unit interface and is the drained core of a flow unit with an ellipsoidal cross-section. The sections of other similar undrained units are exposed in the roof overlying the greatly collapsed junction between tube 4 and the main passage and are shown in Plate 6.1. The lava flow overlying the cave in this region is generally regarded as being composed almost solely of these ellipsoidal units, each of which at the time of its formation represented a potential small lava tube.

Identical relationships are known from tubes 5 and 6, though tube 6 lacks a lavafall. They appear to have resulted from the capture at the lavafalls of flow carried in a higher level small conduit occupying the core of a single tongue, or 'toe', by the flow in the already established, perhaps much larger, lava tube beneath. Headward erosion of the lavafall by the melting and plucking of the country rock caused the enlargement of the passage. Thus, in each of the tributaries there appears to have been for a time a dual lava source, with fluid entering the system from both above and behind the lavafalls. It is supposed that the lowering of the floor level during drainage was insufficient to empty the lower conduit. However, why capture of the flow of roof
units occurred in these three passages, resulting in identical relationships and forms, remains unknown. The development of the tributary tubes of the higher reaches of Raufarhólshellir is shown diagrammatically in Fig. 6.5.

The wall structures in the main passage suggest that the main part of the cave originated as an open lava channel. The channel walls were built up through overflow of lava during periodic surges of flow through the channel as described in Chapter 4. The method by which the lava channel was roofed is not known, though the growth of lateral levees through spatter accretion must be ruled out as the cave occurs 10km below the vent and the lava must have mainly degassed by this point. Instead, roofing may have occurred through the growth of a surface crust across the lava stream. There is evidence to suggest that once the channel had roofed, the conduit was both deepened and widened through erosion of the wall rock. Deepening of lava tubes through bed erosion was observed by Peterson and Swanson (1974) and Cruikshank and Wood (1972) during the Mauna Ulu eruption in 1969-71, and the latter authors have subsequently pointed to the gorge-, or canyon-like cross-profiles of many large lava tube caves as evidence of bed erosion. Raufarhólshellir may have originally possessed such a passage profile, for a remnant is located in the narrow, uncollapsed section of the main passage just beyond tube 2 (Section 'E' of the survey). Evidence of tube widening is seen in some places where small wall tubes have been transversely, obliquely or longitudinally truncated by the flow.

Tubes 1 and 2 are regarded as a single loop passage and tube 2 in particular bears the characteristic shape of a tube formed through the drainage of the core of a single ellipsoidal flow unit (tube 1 is
Formation of a secondary tube, Raufarhólshellir - idealized.
(Compare with sections 'J', 'M' and 'N' of the survey)
greatly collapsed and such a form cannot be identified). The entrances
to both ends of this loop occur high in the west wall of the main tube
and it is thought that the loop originated either as a drained
overflow unit before the tube roofed over, or as a captured independent
small roof tube.

SUMMARY OF THE GENETIC HISTORY OF RAUFARHÖLSHELLIR.

(1) Emplacement of the Leita lava into the shallow valley between
Skálafell and Krossfjöll, across the fossil cliff-lines and onto the
Ölfus plain. Continued flow and the development and gradual extension
of an open channel system along the axis of the arm of the flow, with
some braiding over the position of the higher end of the cave today.

(2) Growth of the channel walls by overflow and possibly the
development of a loop tube in an overflow unit in the west wall.

(3) The gradual roofing of the channel through the growth of a
continuous crust or, alternatively, if the crust was continually being
broken up as a result of fluctuations in the lava level, through the
jamming of crustal sheets across the channel.

(4) The gradual burial of the lava tube by later flow units. Capture
of the flow carried in later lava tongues across the braided upper part
of the tube.

(5) Continued flow through the tube and steady enlargement through
bed erosion (elongating the profile vertically) and lateral melting
and plucking of the country rock. Formation of the glazed lining and
and stalactites through the remelting of the wall lining in the higher parts of the profile.

(6) Cessation of vent activity and the drainage of the tube; the amount of drainage being controlled by amount of space being made available at the cliff-lines and the mobility of the lava. Drainage only proceeded headward as far as the lavafalls and only parts of the braided tube became drained.

(7) Cooling of the lava and jointing. Attack by sub-aerial agents with subsequent breakdown and collapse. Total collapse in four places in the central part of the lava tube, the largest roof collapse completely filling the tube on the downflow side.

The lava tube caves Borgarhellir, Vegghellir, Thrihellir and Íshellir are radially located about the west side of the vent crater of the small lava shield known as Gullborg, in the Snaefells peninsula, Iceland. The caves were first discovered by local farmers in July, 1957, and subsequent investigations by a team led by Prof. Sigurður Thorarinsson (Thorarinsson, 1957) resulted in the discovery of unique lava formations in the largest cave, Borgarhellir. On Thorarinsson's recommendations, the Gullborgarhraun was designated a conservation area by the Icelandic government in order that features of scientific interest in the caves might be protected (as it turns out, this protection has proved unsuccessful and many fine lava formations have today been vandalized). Thorarinsson's team eventually found three caves - Borgarhellir, Vegghellir and Thrihellir - which they cursorily explored and surveyed, but no other study of this classical, small, monogenic lava shield was ever attempted.

The fieldwork for this study was carried out during July, 1972 and June, 1976, when it was seen that the morphology of the lava shield
could be related directly to the development of lava channels and lava tubes.

GEOLOGY OF THE STUDY AREA.

Gullborg lies some 50km north-west of Borganes in the post-glacial active volcanic zone that coincides with the Snaefells peninsula. The volcano is only one of six similar edifices located on the floor of Hnappadalur, a wide north-south trending valley opening onto the southern coastal strip of the peninsula. The valley is cut in rocks of the older Icelandic basaltic formations and, in some areas, in the hyaloclastic Moberg formation. Moberg appears to be the main rock underlying the Gullborgarhraun and small upstanding remnants occur as islands, or 'kipukas', within the lava flow. Locally, in the surrounding mountains, topographic highs exceed 600m.

All six volcanoes are of the classical, monogenic or monocyclic 'eldborg' (Icelandic: fort mountain) type, generally not more than 150m high (though one does exceed 200m) and between 2km and 4km in diameter in plan view. There is a certain amount of variety of form within the group, possibly relating to lava viscosity, ranging as they do from the well-known Eldborg itself, with its dominating narrow crater ramparts of welded spatter and overflow and its low, broad lava flow, to the higher Ytri Raudamelskúlur and Syðri-Raudamelsskúlur, with their higher, partly breached cinder and scoria cones and their less extensive, but stubbier, lava flows. As seen on the aerial photograph (Plate 7.1.), the four northern vents are very closely spaced, though their lavas have not overlapped. It is thought that these vents erupted almost
Gullborgarhraun, Iceland.
(Based upon USAF air photos 5277-5278)

Fig. 7.1.
contemporaneously. Lava from Sydri-Raudamelsskúlur, the volcano lying immediately to the west of Gullborg, was dated by Saemundsson (1966) using C14 methods as 649 BC. Gullborg was found to be the only volcano in the group to contain important lava tube caves (the official topographic map does mark a cave in the southern part of the Eldborgarhraun, but an attempt to locate this in 1976 was unsuccessful), but many of the other possess well-developed, radiating lava channels, plainly visible from the aerial photograph (Plate 7.1).

Gullborg (Icelandic: golden fortress) is similar in appearance to Eldborg. Its summit crater has an altitude of 143m at the centre of an irregularly shaped lava flow (Fig. 7.1.), characterized by long arms to the north. The lava flow has the form of an inverted saucer. Individual flow units are easily recognised from aerial photographs and are seen to have been fed from either open lava channels or from lava tubes. Much remains of the crater wall, which presents an impressive rampart to the observer in the lava flow, and structures of lava, scoria and welded spatter are visible in the several tens of metres of wall exhibited in the vent depression. This wall to the west is broken and it was from this point that lava escaped to a western channel and to the lava tubes. Aggradation around the breach has made this the highest part of the lava flow. Lava feeding another important lava channel on the east side probably escaped through a fissure beneath the wall of the crater. On the south side, escaping lava built small spatter cones, some of which are large enough to climb into.

The Gullborgarhraun exhibits a wide array of surface forms for its size. As discussed in Chapter 4, shelly pahoehoe characterizes the higher part of the lava flow surrounding the vent and bordering the
lava channels (Plate 7.2.). Here the surface is littered with masses of fragmental, thin crustal sheets, giving the appearance of frost shattered debris as seen on mountain tops. Winding across these areas are abundant, small surface tubes, each standing above the flow surface by a metre or more (Plate 7.3.). Surface tubes are important forms around the western channel, especially near the wall breach, and they obviously formed from overspill from the channel. They are thin arched pipes, whole families running parallel with one another, swinging away from the channel in a northerly direction for considerable distances, following the line of maximum gradient. Some of the debris of the surface of the flow is derived from the collapse of these surface tubes. As seen in exposures of the lava flow in the lava channels and the caves, great thicknesses of very thinly bedded shelly pahoehoe units were built up around the vent region, probably as a result of a rise-fall sequence of lava movement in the vent, causing periodic overflow both from the vent crater and from the lava channels. Observations of the formation of very similar shelly pahoehoe lava flows during the Mauna Ulu eruption, Hawaii, by Swanson (1973) suggest that the rise-fall cycle in the vent fissure was gas-driven and there was little or no accompanying fountaining: effusion of the Gullborg lava is believed to have been comparable.

Away from the vent region, the hummocky, dense pahoehoe characteristic of tube-fed flow prevails. At the outlet of the eastern channel is an extensive area of flat, pahoehoe pavement, while at the extremities of some large flow units, the surface crust has been broken, uptilted and pushed into transverse pressure ridges.
Plate 7.2. General view upflow of the east lava channel, Gullborg.

The model is standing beside a large block of the wall which appears to have calved off and become engulfed in the channel flow. Gullborg crater in the background. Note the horizontal lava structure exhibited in the walls of the channel and collapsed block.

Plate 7.3. Remnant of a surface tube near the west channel, Gullborg.
CAVES OF GULLBORGARHRAUN, Iceland.
Lat. 64°52'20"N. Long. 22°7'45"W. Alt. 86-125 m.

(N.B. This survey is a reduction of the survey located in the back pocket).

CROSS SECTIONS (drawn at 5 times scale of plan)

PLAN

EXTENDED SECTIONS

cave floor of fallen lava blocks except where shown otherwise viz:-

original lava tube
GEOLOGY OF THE CAVES.

The location of the caves is shown on Fig. 7.1, and their plans, long sections and passage cross-sections are shown on the survey. Details of the caves found from the survey work in 1972 are as follows:

<table>
<thead>
<tr>
<th>Cave</th>
<th>Altitude at Entrance</th>
<th>Length</th>
<th>Vertical Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrihellir</td>
<td>125.2m approx</td>
<td>365m</td>
<td>28m</td>
</tr>
<tr>
<td>Íshellir (new find 1972)</td>
<td>85.8m approx</td>
<td>120m</td>
<td>9m</td>
</tr>
<tr>
<td>Borgarhellir</td>
<td>118.3m approx</td>
<td>670m</td>
<td>32m</td>
</tr>
<tr>
<td>Vegghellir</td>
<td>118.6m approx</td>
<td>320m</td>
<td>19m</td>
</tr>
</tbody>
</table>

Figures for the length of Borgarhellir and Vegghellir are considerably in excess of figures given for the same caves by Thorarinsson (1957): his 430m for the former cave is in fact the approximate length from the edge of the roof collapse and excludes a large loop passage and a few smaller openings, while his 185m for the latter cave approximates to the length between the main roof collapse and the roof hole near the north end of the cave.

Thrihellir and Íshellir.

The survey shows Thrihellir to consist of five sub-parallel short caves and one isolated off-shoot, Íshellir. All of the caves except Íshellir may be entered through the floor of a branch of the main western channel, to which they are genetically related. The cave occurs in the southern flank of a cone of aggradation emanating from the breach in the west wall of the summit crater: the western channel occupies a position corresponding to the long axis of this cone. The caves trend generally south-easterly, apparently controlled by the position of the wall of the
Plate 7.4. Buried small tube exposed by the collapse of the roof of Íshellir, Gullborg.

Such small tubes are axial transport routes of tongue-shaped flow units and their flow has frequently been captured by the larger tubes. The passage in this photograph is 45-50 cm high and easily negotiated.
vent crater and, although they possess a common steep gradient (up to $17^\circ$), the relative heights of the caves within the cone do vary. There is a significant drop at the entrances of all the caves from the floor of the lava channel and in one case this amounts to a precarious 10m climbable pitch. Only one cave is of any significant length, though there are interesting forms and features in them all. Some caves are seen to reconnect laterally and some are composite forms, having developed through the capture of the flow in an overlying tube: a development which is splendidly displayed by a 2m high lavafall in one cave. The lava cone in which Thrihellir occurs is also riddled with smaller, unconnected lava tubes, for these are exposed through the collapse of flow units overlying the Thrihellir branches: for example, the tiny lava tube network shown on the survey overlying the central part of Íshellir (Plate 7.4.). Overflow of the channel above the entrances of the caves also produced small lava tubes which fed surface flow units. All of the caves possess a glazed lining and many are floored with sheet ice.

Later stage modifications have not significantly altered the original form of the lava tubes making up Thrihellir. Breakdown is locally important and is perhaps most extensive in the longest branch cave. Collapse appears to have been important in forming the surface trench from which the caves originate and this may have initially been a lava tube, for part of the roof remains in position beyond the first cave entrance. Breakdown and collapse in Thrihellir, as in the rest of the Gullborg caves, is attributed to the very thinly bedded and fractured country rock and to the cold cave climate. Some branches were modified during drainage and now exhibit well-formed lateral benches and floor channels, though generally an arched roof and flat floor is a more typical passage profile in Thrihellir.
The form of the cave (including Íshellir) and the structure it has built is analogous to an alluvial fan. As Wentworth (1954) noted, a lava flow has the character of an overloaded and aggrading stream and aggradation about vent outlets is not unusual. Similarly, Peterson and Swanson (1974) noted the formation of multiple layers of intersecting tubes in areas near the vent of Mauna Ulu, Hawaii, where completely new sets of small tubes apparently developed in successive, unrelated new layers of lava. The shape of Thrihellir suggests that as lava welled out through the breached western rim of the Gullborg vent, successively higher levels of lava tubes developed, forming a three-dimensional fan-shaped network of distributaries. Thrihellir today must represent only a small part of the total distributary system. Such a network was continually being enlarged as the rim of the summit crater and of the outlet gradually increased in height, and new networks of large and small tubes and surface channels were constructed across the roofs of older tubes. Lava tubes formed either through the roofing of surface channels, probably from the inward growth of the walls of the channel as a result of periodic overspills, or through spatter accretion forming inwardly arching levees, or they formed as the drained cores of smaller flow units derived directly from the breach or as channel overflow. Many of the older tubes gradually became extinct as aggradation continued at higher levels, though some were possibly fed directly through the wall of the vent below the overflow level at the breach and appear to have had continuous activity. Continued flow through some of the older tubes captured the flow carried in higher tubes, as is shown at the entrances of the present caves. Thus, while the surface of the lava flow around the breached western rim of the vent crater was growing in height gradually through aggradation caused by periodic overflow from the main western channel, lava was also being transported at depth through a complex,
fan-like distributary network of lava tubes; this lava perhaps eventually feeding the advancing flow units further away in the southern part of the lava flow.

**Borgarhellir.**

The location, general orientation and form of this cave is shown on the survey. Collapse of the roof of the cave has left an enormous pit in the surface of the lava field 50m long, 8m wide and 5-6m deep, revealing the sections of thick flow units that overlie the roof of the cave. The small cavity shown on the survey in the west wall of the collapse occurs over an undrained lava tube trending across the line of Borgarhellir, as was described in Chapter 4 (Plate 4.5.). The glazed walls of the lava tube proper are not seen until some 150m into the cave, for until this point is reached the traverse is a climb down through very large collapse debris. This illustrates the quite considerable depth of the cave: it is estimated that some 16m+ of rock overlies the roof of Borgarhellir near the entrance collapse. Once into the cave the wall structure alters from thick, massive, little jointed flow units, to very thinly bedded, contorted and cavernous layers, such as was described in Chapter 4. Here, wall structures are brick-red in colour and conspicuous against the dark, glazed lining. The interesting features of the cave are:

(a) an intrusive lava tongue, 1m high, with a surface of welded crustal slabs, that terminates just before the main passage junction is reached (Plate 7.5.);

(b) at the start of the eastern loop passage the cross-profile is asymmetrical, illustrating how the flow of lava modified the conduit around the bend in a way analogous to bends in other river channels (Plate 10.1.).

(c) interesting floor formations occur in the wide chamber in the eastern
Plate 7.5. The front of the intrusive tongue in Borgarhellir, Gullborg.
loop passage, where a surface crust has remained attached to the walls of the tube, but sagged during drainage of the fluid beneath;

(d) everywhere throughout the cave is a well-developed, rippled, chocolate-brown, glazed lining;

(e) there is an incredible display, particularly near the far end of the cave, of delicate, long (up to 1.5m long) erratically shaped lava stalactites, frequently occurring with groups of tall (up to 1m high) globular stalagmites;

(f) frozen into the floor throughout the cave are rounded and glazed lava blocks, possibly derived from roof and wall breakdown.

Breakdown inside the cave is limited in occurrence except in the first 200m or so from the entrance, where the cave is formed completely as a result of spalling of the roof and walls. Near the entrance the passage cross-profile is one dictated by the horizontal and vertical jointing of the country rock. Total collapse at the entrance has, of course, buried the lava tube beneath more than 16m of debris.

Away from the entrance breakdown, passage profiles are typically arched with a flat floor, and modifications caused during the drainage of the tube are negligible. No generalizations on the drainage history of the lava tube can therefore be made, other than to say that to have vacated the tube with so little modification, the residual lava must have drained rapidly and remained extremely mobile.

Borgarhellir possesses large passage dimensions and this fact, together with the depth, orientation and location of the cave within an elongated ridge at the stem of the large north-west lava tongue (Fig. 7.1.), suggests that it operated as the main supply conduit for this part of the lava field. Breakdown of the walls of the cave shows thicknesses of thinly
bedded units of shelly pahoehoe, as is characteristic of the channels and tubes of the Gullborgarhraun, and Borgarhellir is considered to have originated as an open lava channel which possessed almost the same planimetric form as the cave today. Before roofing a subsidiary loop channel or tube may have developed, branching from the western main passage and eventually rejoining the main route near the end of the cave. Such a passage is suggested from considerations of the formation of the small loop recess shown by the survey in the wall of the main western loop. The mechanism of roofing remains uncertain because of the lack of visible roof evidence. It is regarded, however, that Borgarhellir originated early in the history of the lava flow, for it has been buried very deeply by later flow units.

Vegghellir.

Vegghellir lies close beside Borgarhellir, but possesses a slightly different orientation, is not as large and does not lie as deeply in the lava field as the other cave. Its orientation suggests that it may have fed lava into the long north-east arm of the lava flow (Fig. 7.1.). The cave has three entrances, with the two highest resulting from roof collapse and the lowest being a vertical pitch of 15m. Vegghellir consists of a single passage in which most of the original lava tube has been destroyed by breakdown. Two interesting features in the cave are:

1. a relic of the lava tube lining at the location of Section 'C' on the survey, which Thorarinsson (1957) described as resembling a 'gothic arch' in form, and which exhibits a discordant relationship with the thinly bedded, shelly pahoehoe wall units;

2. the irregularly shaped long profile of the cave which exhibits high roof domes and wide chimneys, one of which opens onto the surface of the lava flow and forms the lowest entrance.
The structure of the country rock about the gothic arch corresponds with the structure about the undrained lava tube in the entrance collapse of Borgarhellir (Plate 4.5.). Everywhere, the walls of Vegghellir exhibit the usual structure of large thicknesses of thin, shelly pahoehoe flow units and the cave is believed to have formed as a result of the inward growth of the walls of an open channel. The roof domes and chimneys are regarded as having initially formed as skylights over the active tube, one or two of which appear to have fed surface flows during very high lava surges in the tube, for small surface tube emanate from the various entrance of the cave.

SUMMARY OF THE GENETIC HISTORY OF THE LAVA TUBE CAVES OF GULLBORG VOLCANO.

Dating the events leading to the construction of the lava tube caves is difficult because so much appears to have taken place simultaneously. An attempt is made, however, to relate the evolution of the lava tubes to the growth of the lava flow as a whole.

(1) The upper parts of all the caves occur above an altitude of 100m and it is clear that there was a period of effusive activity, with the lava flow reaching a thickness of 30m+, before the formation of the lava tubes described took place (undoubtedly there are other, deeper lava tubes which remain unknown). Further, all of the caves are orientated about the western breach of the crater rim and this breach must therefore pre-date the caves.

(2) Both Borgarhellir and the deepest parts of Thrihellir were the first tubes to develop, possibly when the surface of the lava flow was some 20-25m lower than it is today above Borgarhellir. Borgarhellir
originated as an open lava channel, resembling the drained channels seen in the lava flow today, and fed lava into a steadily elongating north-west arm of the lava flow. It appears to have remained active as a lava tube throughout the rest of the life of the eruption.

(3) Growth of the walls of the vent crater continued through spatter and overflow during rise-fall lava cycles and the height of the lip of the breach correspondingly increased. A cone of aggradation was built up where the lava spilled through the breach and overflowed the walls of successively formed lava channels. Lava tubes, formed through the roofing of these surface channels and through the draining of surface overflow units, were periodically buried as the lip of the breach gradually heightened.

(4) Two new lava tubes were constructed (Vegghellir and the undrained tube) along a similar line to Borgarhellir, but in the flow units that buried this larger cave. Vegghellir possibly fed lava into the long north-east arm of the lava flow. Both caves appear to have originated from open lava channels which developed a roof through the gradual inward growth of the channel walls as a result of periodic depositions of overflow units.

(5) Lava continued to overtop the crater rim for only a short time before eventual overflow was confined only to the breach in the west wall. The cone of aggradation about the breach continued to heighten, possibly until the end of the eruption. Lava was fed simultaneously through lava tubes at depth and through a continuously changing channel network on the surface. Flow through surface channels and through later lava tubes was constantly captured by
the roof collapse of lower tubes, further complicating the network in the cone. A new, large lava channel was developed down the long axis of the cone and this carried lava to the western part of the lava flow. Flow through this channel also pulsated, periodically causing thin sheet of lava to overflow the surrounding area.

(6) It is not clear when the eastern channel formed, though for a time this channel appears to have been partly roofed. The tongue of lava fed by this channel is not large and appears to have been diverted to the south-east by a topographical obstruction.

(7) The activity ceased, the tubes drained (though some of the tubes may have drained before the cessation of vent activity) and sub-aerial attack ensued, causing the decay of the caves and the fragmentation of the surface of the lava flow.

The three lava tube caves described in this chapter - Vidgelmir, Surtshellir and Stephanshellir - are aligned along the axis of the 38km long Hallmundarhraun; a post-glacial basaltic lava flow situated west of the Langjökull, in the county of Myrasysla, west central Iceland. These are the best developed and most frequently visited of all the Icelandic caves. The well-known Surtshellir and Stephanshellir are parts of a single, though not continuous, partly braided cave complex; while Vidgelmir consists of one vast, sinuous passage. Vidgelmir is particularly notable for its beautiful ice and lava formations. Today, the Hallmundarhraun caves are part of the regular tourist itinerary and well-signposted cross-country tracks, suitable for four-wheel drive vehicles, approach the caves from Hvitadalur, through the farms of Gilsbakki (for Vidgelmir) and Kalmanstunga (for Surtshellir-Stephanshellir) (Fig. 8.1.).
Fig. 8.1. SKETCH MAP OF THE GEOLOGY SURROUNDING THE LOWER 25KM OF THE HALLARÖNDARHRAUN (Based upon maps of the Geodaetisk Institute, Copenhagen and KjartanSSon's geological survey, Landmaelingar Islands, Reykjavík.)
The fieldwork was therefore done during short visits to the Hallmundarhraun. Two days were spent on the lava flow in 1970, when both Surtshellir and Stephánsfellir were briefly explored and a very low grade magnetic survey was made of Surtshellir. In 1972, during a six day camp on the Hallmundarhraun, use was made of the heavier surveying instruments carried to Iceland for the Gulborg project and a theodolite traverse of the middle line of Surtshellir-Stephánsfellir was completed, along with an exploration and low grade magnetic survey of Viðgelmir. A further brief visit to the area was made in 1976, when two days were spent walking through the caves in order to identify the features of geological interest within them. It must be pointed out that as the work of the group from the U.S.A. was a survey only (as far as is known), this most impressive group of caves still requires very thorough geological investigation.

Survey note.

All the cave maps surveyed and drawn by the present writer are included on a single large sheet enclosed in the back survey pocket.
This pocket contains in addition a copy of the map of Surtshellir-
Stephánshellir resulting from the survey work of the U.S. group.

**PREVIOUS EXPLORATION AND RESEARCH.**

Exploration of the caves has spanned many centuries. Surtshellir (home of Surtur, the 'black prince of fire' of Norse mythology) is mentioned in the Icelandic sagas (Landnama-bok and Sturlunga Saga) and appears to have been the home of a band of outlaws as early as the tenth century. Mills (1971) listed all of the earlier accounts of visits to the Hallmundarhraun caves. Notable amongst these are descriptions by Forbes (1860 - Fig. 8.2.) and Baring-Gould, 1863, who believed the caves consisted of a chain of linked bubbles; and a little later descriptions by Paijkull (1868) and Hartwig (1891), who were two of the first to propound the theory that lava caves originated from the drainage of fluid lava from beneath the solid crust of a lava flow.

Recent explorations of the Hallmundarhraun caves include a visit by the French geomorphologist Corbel, who subsequently published a description and a thumb-nail sketch plan of Surtshellir (Corbel, 1957). The main descriptive work on the caves is that by Thorsteinsson (c.1963), who also noted two additional caves higher up near the source region of the Hallmundarhraun, though these caves were not investigated by the present writer. Spanish cavers carried out the only serious, though somewhat brief, study of Surtshellir-Stephánshellir
Fig. 8.2. 1860 representation of the main passage of Surtshellir, from Forbes' *Iceland: Its Volcanoes, Geysirs and Glaciers*, (1860).

(N.B. Incorrect perspective)
in 1967 (Montoriol-Pous and de Mier, 1971), and their report contained a line survey of Surtshellir and descriptions of the morphology of both caves. Between 1970 and 1973 a speleological group from the U.S.A. carried out a high grade survey of Surtshellir-Stephánshellir (Reich, 1974). Also in the summers of 1970 and 1971 the Hallmundarhraun area was the venue of the British Schools Exploring Society's annual expedition and geological mapping was one of the main activities, though the lower lava flow and its caves were not investigated (Atkins, 1971 and pers. comm.).

**GEOLOGY OF THE STUDY AREA.**

The Hallmundarhraun occupies an area approaching 200km$^2$ and has been dated by Saemundsson (1966) with $^{14}$C methods as A.D. 775 $\pm$ 100 years. Atkins (1971) believed the Hallmundarhraun was erupted from two vents situated to the east of the large table-mountain Eiríksjökull, on the western edge of the Langjökull ice-cap. Because the lavas mixed and flowed together, it is considered that they were erupted from these two vents contemporaneously. Another vent may underlie lobate extensions of the Langjökull at Jökullsárlón. Lava from the northern vent constructed a shallow, but well defined shield-like edifice (average slope 3°) extending for a distance of about 3km to the north, west and south of the summit crater. Well defined sinuous lava channels up to 10m wide and 1.6km long trend away to the north from this larger crater.

The Hallmundarhraun possesses a total length of about 38km and for much of this distance is never more than 7km wide. Its margin is easily identified to the north, where it lies parallel with the
Plate 8.1. The flat surface of the Hallmundarhraun around Surtshellir.

Note the roof collapses and occasional tumulus. Tent (2m high) at the base of the hill in the centre background gives scale.

Plate 8.2. Collapse depression in the surface of the Hallmundarhraun.
Nordingarfljot river, but its southern margin is buried by recent
hyaloctastic scree and wind blown sand derived from the Eiríksjökull
escarpment (Fig. 8.1.). The lava tube caves are located in the
distal portion of the lava flow, some 28 km (Surtshellir-Stephánshellir)
and 33 km (Vidgelmir) below the source vents. The flow here is
restricted by the sides of the narrow Nordingarfljot valley, which
is never more than 2 km wide, and at its narrowest point between
Surtshellir and Vidgelmir is less than 1 km wide. The Nordingarfljot
crosses from the northern margin to the southern margin of the flow
between Vidgelmir and Surtshellir, and as it nears the flow front it
filters into the basalt, eventually emerging pouring out of the front
as the unusual and picturesque waterfall Hraunfoss. The hills
confining the distal parts of the lava flow rise to 933 m on the
south side, where they are composed of the older basaltic formations
and some acidic rocks (rhyolite, rhyolitic agglomerate, pitchstone
and felsite), while to the north the hills are lower and are composed
of Tertiary flood basalts.

The Hallmundarhraun is characterized by features that distinguishes
it as tube-fed pahoehoe (Swanson, 1973), and varying types of surface
terrain are determined by the varying gradients of the pre-flow
topography. Around the caves the gradient is negligible (less than
$\frac{1}{2}^\circ$ around Surtshellir-Stephánshellir and about $1^\circ$ around Vidgelmir)
and the surface relief is low, with only the occasional tumulus
exceeding a height of 1.5 m. Some parts here are great featureless
expanses, broken only by shallow downwarps of the surface and by
the fronts of low flow lobes (Plate 8.1.), while other parts are
characterized by quite extensive, bowl-shaped collapse structures
(Plate 8.2.). Tumuli are ubiquitous, ranging up to 2.5 m high
(Frontispiece), and folded and ropy surfaces are classically displayed over the large areas of the flow surface which have been eroded of moss. Collapse of the roofs of the lava tube caves has caused deep, vertical-sided pits in the flat surface of the lava flow, some of which are quite enormous (up to 75m long and 8m deep) (Frontispiece and Plate 8.3.). In contrast, where the gradient of the lava flow is relatively high, such as between Vidgelmir and Surtshellir, where the mean gradient is 2-3° (though it may reach 10° locally), the surface of the flow is thrown into a chaotic assemblage of collapse depressions and pressure ridges.

Exposures of the structure of the lava flow are best seen in the collapse pits. Surtshellir-Stephánnshellir possesses eleven such roof collapses and Vidgelmir possesses one enormous example. In some of the collapse pits a glazed lining is still attached to the walls and hides the structure of the lava flow behind, though in many there has been extensive spalling of the wall rock. There is less breakdown of the walls inside the caves than is to be expected in such open cave systems, though in general structures that are visible confirm the type of structure seen at the collapse pits. All exposures reveal the same general structure of superimposed, thin sheet flow units, as was described in Chapter 4. Some collapses have truncated surface tubes and these occur exclusively in structures with an ellipsoidal cross-section, which are interpreted as small, tongue-shaped flow units.
Plate 8.3. General view of the third roof collapse, Surtshellir.

Plate 8.4. Unusual passage form downflow of Roof Collapse 1, Surtshellir.

The floor of this part of Surtshellir probably originated as a false-floor which sagged on withdrawal of the fluid beneath.
SURTSHELLIR, Hallmundarhraun, Iceland.
Lat. 64° 47' N. Long. 20° 43' 25" W. Alt. 350 m.

(\(N.B.\) Magnetic survey during 1971)

- rocks
- sheet ice
- snow
- roof height in metres.
- changes of vertical height in metres.

SCALE

0 100 200 300 metres

0 500 1000 feet

PLAN

roof collapse 2
roof collapse 3
roof collapse 4
small holes in roof
stone wall
bones, robber's lair
ice columns and stalagmites

CROSS SECTIONS
(Drawn at 5 times the scale of the plan.)

water
lower section displaced
altar
**MORPHOLOGY OF THE CAVES.**

**Surtshellir-Stephánshellir.**

Surtshellir-Stephánshellir is a single, though not continuous, cave complex. It is broken beneath the highest roof collapse of Surtshellir, though the nature of the obstruction is not known because the lower termination of Stephánshellir was ice-filled when examined in 1972 (the survey by Reich suggests that this obstruction is a collapse). The cave complex trends diagonally across the lava flow from north to south, and terminates beneath the upper edge of the disturbed ground that coincides with the increase in gradient between Surtshellir and Vidgelmír. The surveys show the form of the cave in plan, long profile and cross-profile. The combined length of Surtshellir and Stephánshellir is 4.2km and the length of Surtshellir by the 1970 survey is 1.970km. As Surtshellir is the most interesting part of the cave complex, its morphology will be described along a traverse which begins at the lowest, most south-westerly roof collapse (No.1 on the surveys).

The lowest entrance collapse of Surtshellir is the normal entrance to the cave. Here debris rests upon a false floor which probably originally extended throughout the lower length of the cave. A cavity underlies this floor, but it is low (1.2m high) and extends only a short distance downflow. The first 200m of the main passage downflow is floored with sheet ice and partially blocked by huge ice formations, though the passage is typically arched and approximately 4m high. Beyond this ice section the roof very gradually loses height, until 520m beyond the entrance collapse it eventually meets the floor. The floor throughout is unusual in that it appears to have sagged along the centre-line, so that its attachments to either wall occurs at
head height when one stands in the centre of the passage (Plate 8.3.).
The feature is probably a part of the false floor observed at the
entrance collapse, though here the crust was still plastic when the
underlying fluid withdrew and it did not possess the rigidity to
remain upstanding. It is possible, therefore, that a lower cavity
also underlies the floor throughout this downflow part of the cave,
though it is nowhere seen.

Proceeding upflow (north-east) from the first entrance, further
remnants of the false floor border each wall. These remnants occur
as opposing ledges, 1.2m high, bent over at the top toward the centre
of the passage, with deep gutters where each ledge leans away from the
wall. The tube here is arcuate, with a flat floor and an average
height of 8m (Plate 8.5.). Breakdown is extensive in this part of
the cave and it increases significantly toward each roof collapse.

The next roof collapse is very impressive. Collapse has taken place
at the junction of the main passage and two smaller side routes,
resulting in an enormous hole, 40m long, 15m wide and more than 7m
deep, with vertical and often overhanging walls. Leading off
immediately to the east is a tube whose floor is at a higher level
than the main tube, and whose dimensions are smaller. This passage
rapidly closes down from a height of 3m to crawling dimensions and
shortly leads to an area of roof breakdown. The way on is a crawl
through the collapse debris, either into a passage to the south
which soon becomes impenetrable, or into a passage to the north which
leads back upflow to the main passage between the second and third
collapses. The cross-section of both the north and the south passage
is low and wide, and often the passage is not high enough to stand
upright in. There is very little breakdown and the floor is generally covered with sheet ice which, when covered with a film of water in summer months, is extremely treacherous underfoot. These passages are featureless and relieved only by ice formations.

The passage trending toward the north opens out and eventually bifurcates as the main passage is approached once more. The sight into the main passage at the passage intersection is most spectacular, for one emerges onto a platform, some 4.3m above the floor of the larger passage. In front, trending from right to left, is the great tunnel of the main tube, approximately 15m in diameter. Along either side of this run narrow ledges, widening to large platforms where the side passages emerge, while across in the opposite wall are continuations of the tributary passages of the south side. Climbing down to the floor of the main passage is made easy by a series of 14 thin ledges spaced vertically 20-30cm apart. Each ledge is only 4-5cm thick, and juts out from the wall by up to 40cm. They coincide with similar features on the opposite wall and probably originated as thin crusts developed over the surface of the lava stream during a gradual lowering of the lava level in the main tube. The passages in the north wall of the main passage shows signs of late stage invasion of lava from the main stream, for the congealed front of an intrusive tongue is visible in the terminal chamber, and is 0.6-1m high. The core of this tongue drained back into the main tube and the remnants of the thick crust that formed over its surface remain today spanning the widths of the smaller loop passages.

The third roof collapse is also large, being some 52m long, 15m wide and 5.5m deep (Plate 8.3.). To the north-east, a low dry-stone
wall has been built across the cave, beyond which breakdown of the walls and roof of the cave is very extensive. The last collapse of Surtshellir upflow is relatively small and debris has buried any continuation of the passage there may have been beyond.

The surveys do little justice to the relative complexity of Stephánshellir, which to the explorer between the 8th and 10th roof collapses is quite bewildering. This part of the cave is a labyrinth developed on a single plane (i.e., it is not multi-level). In many parts of the cave intersecting passages have left only pillars 1-2m diameter to support the roof. However, apart from this complexity, Stephánshellir is a very featureless cave and a traverse through it is much less interesting than a traverse through Surtshellir. Its passage profiles are typically arched (Plate 1.1.) and rather uniform in height (from 2-3m), though some passages are nearly circular in cross-section. There is a dull, uniform grey lining throughout, and there are no outstanding secondary formations, except what appears to be an accretionary lava ball (Macdonald, 1972, p.89), 1.5m in diameter, which has become wedged in a passage near the 11th roof collapse. Roof collapses, although of infrequent occurrence, tend to block passages completely. An additional difficulty is experienced in traversing the cave in summer, when sheet ice, which covers much of the floor of the cave, has partially melted in crawlways. Of most interest in Stephánshellir is the sixth entrance (Plate 8.6.), which probably originated as a skylight. This is a vertical cylinder with smooth, glazed walls and vertical flow marks. It is partly overlain on the surface by a flow unit which contains a tube. Drainage lines link the cylinder and the surface tube and the two appears to be genetically related. Thus, it is probable that the surface unit was
Plate 8.7. Ice stalagmites in Vidgelmir. The tallest ice formations are 1.5m high. Note the vastness of the cave and the massive wall rock exposed in the left hand wall.
N.B. This survey is a reduction of the survey located in the back pocket.

PLAN

scale

0 1000 feet

0 300 metres

0-5m. step in floor

entrance

ice formations

CROSS SECTIONS (drawn at 5 times scale of plan)

a b c d e f g h i

cave floor of fallen lava blocks except where shown otherwise viz:-

original lava tube sheet ice/water

squeezes roof collapses

EXTENDED SECTION

a b c d e f g h i

displaced 50m. down
derived from, and fed periodically by, fluid lava welling up through the skylight as large surges passed through the tube system below.

Vidgelmír.

The accompanying survey of Vidgelmír is a reduction of the survey enclosed in the back pocket. Vidgelmír is the most spectacular of all the lava tube caves investigated. It is an immense cave and it possesses an incredible display of ice and lava formations. Unfortunately, the cave is rapidly becoming vandalized and the writer is concerned for its preservation. This concern was expressed in a special report sent to the Icelandic National Research Council after the fieldwork in the cave in 1972 (Mills and Wood, 1972). As far as is known, however, the recommendations that the cave be placed under a conservation order (like the Gullborg caves) and/or it be gated, have not been taken up.

Vidgelmír is situated approximately 5km downstream of the lowest entrance collapse of Surtshellir and 33km below the vents. It occupies the axial part of the flow, which is here known as the Grahraun. The survey shows Vidgelmír to be a long, sinuous cave, with two small loop passages in the lower third of its length. It possesses a mean gradient of approximately $1.5^\circ$ and a total traverse length of 1.585km. The overall impression of the cave is one of vastness, and some dimensions illustrating the size of the cave are listed below:

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean height</td>
<td>9.15m</td>
<td>(29 feet)</td>
</tr>
<tr>
<td>Max. height</td>
<td>15.80m</td>
<td>(53 feet)</td>
</tr>
<tr>
<td>Mean width</td>
<td>10.20m</td>
<td>(33½ feet)</td>
</tr>
</tbody>
</table>
Plate 8.8. A detail of the wall glaze and delicate rod and straw stalactites in Vidgelmir. The longest stalactites are 30cm long.
Max width .................. 16.50m (55 feet)
Area of largest cross-section 137.60m$^2$ (1,479.76 sq. feet)

Entrance to Vidgelmír is made through a roof collapse in the east (upflow) end of the cave. The collapse is enormous, being some 75m long and in one place 15m deep. A part of the roof spans the collapse pit as a natural bridge (Plate 4.1.).

A very tight squeeze occurs 45m downflow of the entrance collapse (in 1972 ice partially blocking this squeeze had to be chipped away before the cave could be entered, and in 1976 there was so much ice that the squeeze could not be located at all), and for the first 150-200m beyond the squeeze, the cave is ice-filled (Plate 8.7.). However, with further progress into the cave, the ice gradually disappears and it becomes an easy walk to the end of the cave. The walls beyond the ice section are well glazed, frequently of a chocolate-brown colour, and forests of tall, globular stalagmites litter the floor. Alcoves and recesses are frequently covered with delicate rod and straw stalactites, many ranging up to one metre in length (Plates 1.3. and 8.8.). The most spectacular display of lava speleothems is in the larger loop passage, but speleothems are well developed throughout the lower part of the cave generally. Although the cave is so vast and its internal temperature so cold, breakdown of the walls and roof is not of great importance, though some large breakdown piles have developed in the lower end of the cave. Interestingly, frost shattering, as well as frost wedging, appears to have been operative in the cave, for thin flakes of shattered wall rock litter the floor ice. Another interesting feature is the wildly fluctuating roof heights, as reflected by the passage profiles of the survey. The
high points appear to be breakdown domes, but because they are glazed and there are no corresponding debris piles on the floor, breakdown must have occurred during the period of activity in the tube and the debris was carried away by the lava stream. It is unfortunate that roof thickness could not be surveyed, for it is felt that the roof of Vidgelmir must be very thin in places.

**SOME CONSIDERATIONS ON THE MORPHOGENESIS OF THE CAVES.**

A full morphogenetic interpretation of the Hallmundarhraun caves is not possible due to the limited amount of fieldwork carried out. However, the following points explain some of the features of the caves.

**General comments.**

(1) The caves occur considerable distances below the source vents (28km and 33km respectively) and flow through them could only have been maintained if hot, mobile lava was continually delivered into the system from the source vents. It is suggested that this lava was transported through a lava tube which originally extended throughout the whole length of the lava flow, of which the caves today represent only small drained segments. The caves mentioned by Thorsteinsson (c.1963) as occurring higher up the flow (Franzhellir and Hallmundarhellir) may represent other drained segments of this tube system.

(2) Segmental drainage of the original long lava tube system appears to have been the result of the variable gradient of the pre-flow
topography. The Hallmundarhraun in the Nordingarfljot valley is stepped (Fig. 8.1. and 11.3.). At the cessation of vent activity, the more rapid drainage of the tube on the fall of each step meant that space was made available for the drainage of the residual lava from the parts of the tube situated on each tread.

(3) The enormous volumes of the main passages of the caves, particularly of Viðgelmir, and their axial positions, suggests that they probably transported the bulk of the flow through the Nordingarfljot valley during the later stages of the eruption (it is interesting to compare the size of the passage forms of the Hallmundarhraun caves with the passage forms of the other caves depicted in Fig. 11.1.).

(4) The lava transported through the caves appears to have been extremely mobile, for some passages drained almost completely of their residual lava and there has been very little passage modification due to the deposition of cooled lava on the walls of the caves. It is thought, therefore, that the passages constituting the Hallmundarhraun caves are very close in form to the original tubes from which they were derived (again, it is interesting to compare the passage forms of the Hallmundarhraun caves with the passage forms of the other caves depicted in Figs. 11.1. and 11.2.).

(5) Passage forms in the Hallmundarhraun caves have only been significantly altered by breakdown either side of the roof collapses and between collapses 3 and 4 of Surtshellir.

(6) Horizontal layering of sheet flow units was consistently exhibited in wall exposures throughout all of the caves and this was taken to
indicate that the caves originated as open lava channels which subsequently became roofed. The method of roofing remains conjectural. As the structures of the smaller side passages were never seen, it is not known if these passages originated as the drained cores of tongue-shaped flow units or as roofed small lava channels.

Cave configuration.

(1) Sinuosity and braiding are important elements of the cave forms. Sinuosity is particularly well developed in the main tube of Surtshellir and Vidgelmir, while braiding is evident in Stephanshellir between roof collapses 8 and 10. A discussion of sinuosity and braiding in lava tube caves is left until Chapter 10.

(2) The complexity of Surtshellir between roof collapses 2 and 3 is a development of the intersection of the main tube by a smaller, higher-level tube. It will be noted that the routes to the north and south of the main passage are aligned N-S almost in a straight line and appear to lose height gradually in a southerly direction. Also, the entrances of these smaller passages occur 4.3m above the floor of the main passage. Thus, at some early stage in the history of the Hallmundarhraun in this region, it appears that a new tube was formed which trended diagonally across the roof of the main tube of Surtshellir, and its flow was subsequently captured by the lower. There is some evidence to suggest that the main tube was later enlarged, and flow was also sent down the newly captured southern loop, re-entering the main stream once more at the point of the second roof collapse today.

The three lava tube caves described in this chapter - Grotta del Labirinto-Pozzo Superiore, Grotta degli Inglesi and Grotta dei Lamponi - occur within a small area (approximately ¾km²) lying astride the forest track that runs between Casermetta and Villagio Turistico Mareneve, in the eastern part of the 1614-24 lava flow known as the Lava del Passo dei Dammusi, on the north slope of the volcano, Mt. Etna. One of the caves, Grotta dei Lamponi, is perhaps the best known and best developed lava tube cave on Mt. Etna, though no other caves were known to exist in the study area until the Grotta degli Inglesi was discovered by J.E. Guest and R. Greeley in 1975 and reconnaissance prior to this study in 1976 proved the existence of the Grotta del Labirinto-Pozzo Superiore complex. The combined length of the caves is almost 3km. The fieldwork was carried out in August, 1976, as a part of a continuing collaborative project with J.E. Guest, R. Greeley and R. Romano. Emphasis was placed upon understanding the role played by lava tubes in the construction of the major landforms on the 1614-24 lava flow. No previous other research on the geology of the lava flow, or of its caves, is known.
The terraces and lava tube caves of the eastern part of the 1614-24 lava flow, Mt. Etna (based mainly upon satellite photographs).

Fig. 9.1.
GEOLOGY OF THE STUDY AREA.

The 1614-24 lava flow is the oldest dated flow to have originated from flank eruptions in the N.E. rift zone on Mt.Etna (Guest and Romano, 1975) and it is estimated that it may possess a volume as high as 2km³. The eruption may have marked a period when activity migrated from the summit area to the N.E. rift and this was accompanied with caldera collapse in the summit region (Wadge, Walker and Guest, 1975). The flow is of Hawaïite composition and, unusual for Mt.Etna, is almost entirely pahoehoe. Its morphology is characterised by large terraces, which Guest and Romano (1975) suggested originated as lava lakes retained on the downslope side by a clinker dam. Lava tubes and cumulo-domes are also important landforms.

The study area exhibited all the landform types seen elsewhere on the 1614-24 lava flow and as such its geology may be regarded as being representative of the whole lava flow. The following landforms made up the surface of the flow in the study area.

Terraces.

The long profile of the eastern part of the 1614-24 lava flow is stepped, or terraced, and the part of the profile contained within the study area (Fig. 9.1) exhibits three of these terraces. Each is characterised by a lobate front that may range up to 60m in height (specifically terrace 'C', though outside of the study area the front of terrace 'A' may exceed 100m in height), that is composed of aa, scoriaceous and 'toey' lava (Plate 9.1.), lying at a very steep angle (ranging between15⁰ and 40⁰). In contrast, the tread of each terrace is composed of billowy pahoehoe pavement, frequently exhibiting beautifully formed ropy surfaces and other features indicative of extreme

Note that the pahoehoe toes appear to have been extruded through the clinker dam. The pahoehoe was probably derived from lava tubes.

Plate 9.2. General view of the large collapse depression on the tread of terrace 'E', 1614-24 lava flow.

Note the relatively undisturbed pahoehoe surrounding the depression and its upturned rim.
magma mobility. Tubes, filled or partially drained channels, collapse structures, tumuli, squeeze-ups and toes diversify the surface relief. Collapse structures, the result of the formation of a crust or roof from beneath which the lava drained away, the roof subsequently sagging or collapsing into the void, are very common and are sometimes developed on a spectacular scale. On terrace 'C' also, movement of sub-crustal fluid lava has caused a chaotic upheaval of thick crustal slabs, some thrust up vertically and measuring 8m across and 2m thick. On the other hand, parts of terrace 'E' possess completely undisturbed, relatively smooth, flat pavements.

The relative occurrence and distribution of clinker and pahoehoe is striking: pahoehoe occurs exclusively on the relatively flat tread of each terrace, while clinker occurs on the steeper slopes of the terrace fronts. The correlation between gradient and lava type suggests that the clinker formed as a result of the steeper gradient of the terrace front, for the sudden stirring of the lava as it tumbled down the front probably led to increased gas loss and crystallization. In fact, once formed, the angle of the slope of the front, which when at its maximum is possibly the angle of repose of the clinker material, may have been self-maintaining. This idea is borne out by the following observations: (i) lava tubes, which transported fluid lava, either terminate at a terrace front or on the slope itself (Fig. 9.1. and survey); (ii) the terrace fronts are made up of overlapping clinker lobes, some of which appear to originate from lava tubes on the tread (for example, from Grotta del Labirinto); (iii) there is an abrupt contact where the base of the front of one terrace rests upon the tread of the next lower terrace, illustrating that there was a steady forward advance of each terrace front. It appears, then, that the fronts acted as 'dams', holding back the progress of the more fluid pahoehoe behind, while they themselves
slowly advanced across the tread of the next lower terrace as lava fed from tubes periodically overtopped the lip of the dam. It is interesting to speculate on the growth of the terraces by this method: in order to overtop the clinker dam the lava flooding the tread of the terrace must slightly increase the height of that tread, while overspill contributed to the forward growth of the front. It could be argued, therefore, that the terraces with the highest fronts are the ones that have been in existence longest.

Generally, the terraces possess a flat tread and an arcuate to straight front that lies tranverse to the direction of flow. Two differ from this norm, however, in that they rise to significant high points and are circular, or semi-circular, in ground plan. One of these is Mt. Collabasso (Fig.9.1.), which is regarded as a cumulo-dome. The other is terrace 'C', whose form suggests that it may have a similar origin to Collabasso and may be transitional between a terrace and a cumulo-dome. It is interesting also that smaller terraces appear to have grown upon the surface of larger terraces: for example, terrace 'D' sits upon the tread of terrace 'E' (Fig. 9.1.) and its direction of frontal advance is almost 90° different to that of terrace 'E'.

Collapse depressions.

Three types of collapse depressions were recognised in the study area: (i) sags and collapses of the crustal sheet due to the wholesale evacuation of fluid lava from beneath the surface of a terrace; (ii) depressions caused by the collapse of the roof of lava tube caves; (iii) depressions caused by the collapse of large dome-like uplifts of unknown origin on evacuation of the fluid lava (Plate 9.2.). To some extent the forms (ii) and (iii) grade into one another, for on terrace 'C' areas of ponded sub-crustal flow, from which lava tube cave segments
Plate 9.3. (top) and 9.4. (bottom) Different types of tumuli, 1614-24 lava flow. Plate 9.3. illustrates the classical form, while Plate 9.4. shows a tumulus deformed by piled extrusions.
radiate, have caused oval or irregularly shaped collapses. The larger features, of which there are two examples in the study area, also exhibit signs of ponded flow, but evidence of their formation is hidden beneath collapse debris. The largest collapse occurs on the tread of terrace 'E' (Plate 9.2.) and lies 50m from the foot of terrace 'D', surrounded by relatively undisturbed, smooth, flat pahoehoe. The collapse resembles a huge bomb crater, with an upturned rim of pahoehoe crustal slabs and a central depression, some 35m across at its widest point, of a chaotic assemblage of collapsed crustal blocks. The second is the collapse from which Grotta degli Inglesi originates, situated 100m north of the base of the front of terrace 'C' on the fairly undisturbed surface of terrace 'D'. In form it resembles the collapse on terrace 'E', but is smaller and in this case it is possible to walk around beneath the upturned crust of the rim. There is little doubt that both of these features formed domical structures before collapse on evacuation of the fluid lava within, and both probably fed lava tubes. The intriguing question is, however, were they in turn fed by lava tubes? The feature on terrace 'D' was obviously a source of abundant fluid lava and may well have been the main source for the formation of terrace 'D'. But where did this lava come from? One can speculate that perhaps an escape route for fluid lava lay beneath the front of terrace 'C' and, as happened during the formation of Pozzo Superiore, a considerable hydrostatic pressure caused the surface of terrace 'D' to rupture and the lava to escape.

Tumuli.

Tumuli were difficult to recognise because they were frequently malformed. Some were of classical development, though squat (Plate 9.3.). Others were so malformed that they appeared as mounds, up to 3 or 4m high, composed of toes, squeeze-ups and crustal slabs, caused by pasty lava oozing through the surface crust (Plate 9.4.).
Open lava channels.

Because of the freshness of the lava surface, filled and semi-filled lava channels could be identified on the surfaces of terrace 'E' and terrace 'C'. Some exhibit walls 1m high and possess a floor of smooth, flat pahoehoe, with ponds ranging up to 12m across. The best example lies above the position of Grotta dei Lamponi, on the tread of terrace 'C', its source lying in the region of the foot of terrace 'B'.

Surface tubes.

Classically developed small surface tubes (i.e., from ½ - 2m high) abound. An excellent example lies above the Grotta dei Lamponi near its entrance A1 (Survey) and probably originated from overflow from a skylight in the roof of the larger tube. This small surface tube was described in Chapter 4.

The internal structure of the lava flow about the lava tube caves is only poorly displayed. The only reasonable section of the lava flow occurs in the terminal chambers of Grotta dei Lamponi, but this exposure exhibits structures overlying the line of the original lava tube; the drained tube having been subsequently buried beneath collapse debris in this region. The exposure, in fact, provides a cross-section of the deeper parts of terrace 'D', which is typically stratified. Elsewhere, for example, at the main entrance to Grotta dei Lamponi, overlying ellipsoidal units are visible and, at other collapses within this cave, horizontal stratification is apparent in the wall rock. However, there are so few good exposures of wall structures in the lava tube caves in the study area that any morphogenetic interpretation of the caves must rest mainly upon their morphologies.
GROTTO DEI LAMPOINI, MOUNT ETNA NORTH, SICILY.

LOCATION: LAT 37°15'04" N 31°57'40" W ALT 1728m

CAVE DETAILS: Total traverse length 742m; Vertical range 93m

CROSS-SECTIONS
Drawn at 1:5,000 scale of plan & extended section.

KEY
- Collapse doline on cave floor
- Break of slope
- Underlying passage
- Site and direction of cross-section

EXTENDED SECTION

This cave was surveyed on 22nd/23rd August 1975 by members of Gruppo Grotte Catane–Sicilia–Meloni Caving Club. Phoenix Exploration Club used a Suunto compass and clinometer (types KB-1/300P & PWS-300PC) and a 30m Tabor tape. Magnetic survey techniques were employed throughout. The survey drawn by W. Weir, 26th December, 1975.
GEOLOGY OF THE CAVES.

Three very different lava tube caves, with a combined length of almost 3 km, were mapped in varying positions relative to the terrace fronts. The location of the caves is shown on Fig. 9.1. and the plans and long sections of the Grotta dei Lamponi and Grotta degli Inglesi are drawn on two separate survey sheets. The Grotta del Labirinto-Pozzo Superiore complex was surveyed in August, 1976, by Italian members of the research party (Club Alpino Italiano), but their completed map of this cave is still awaited. From the surveys, the dimensions of the caves are as follows:

<table>
<thead>
<tr>
<th>Cave</th>
<th>Length</th>
<th>Vertical range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grotta del Labirinto - Pozzo Superiore</td>
<td>about 1.5km</td>
<td>not known</td>
</tr>
<tr>
<td>Grotta degli Inglesi</td>
<td>565.5m</td>
<td>30.06m</td>
</tr>
<tr>
<td>Grotta dei Lamponi</td>
<td>783.5m</td>
<td>52.16m</td>
</tr>
</tbody>
</table>

As will be shown, each of the caves formed quite independently of the others.

Grotta dei Lamponi.

This is the best developed cave and appears to have been an important feeder tube and a possible source for terrace 'E'. It originates at the foot of terrace 'B' and curves around the eastern flank of terrace 'C', eventually being buried at a considerable depth (approximately 44 m from the surface of the flow to the roof of the cave in the lowest part) beneath terrace 'D'. This great depth is a most unusual feature, as lava tube caves normally lie just below and parallel with the flow surface and it must be supposed that the lower half of the Grotta dei Lamponi has been buried by the emplacement of terrace 'D'.
Plate 9.5. (above) A view of the interior of Grotta dei Lamponi south of the forest track, 1614-24 lava flow.

Note the smooth, eroded walls and wall striations (flow grooves). The roof at this point is less than 2m thick.


The flow which formed this tube appears to have been intruded beneath an already thick surface crust, which was subsequently uparched. The rucbac sits on a new crust.
The form of the cave is shown in the survey. Upflow, south of the forest track, the cave has been slightly buried by clinker originating from a higher point on terrace 'C'. In general, however, in this area, the roof is thin and in one or two places comprises only a thin crust. Large and small surface tubes overlie the cave and one example appears to have deposited its load into the main tube via a skylight that is today the entrance 'Al' (Survey). Three loop passages occur in the upflow part of the cave, the lowest demanding a flat-out crawl in order for it to be negotiated. All of these loop passages begin their respective journeys at floor level in the main tube, though on re-entry their floors are elevated above the floor level of the main tube and a step is produced. In the higher parts of the main passage the profile is wide and low (Plate 9.5.), though the roof height gradually increases with loss of altitude. Downflow, north of the forest track, the cave becomes progressively more collapsed until the lowest 20% is completely buried beneath collapse debris; there being a cavity aligned along the route of the original lava tube which formed as a direct result of collapse. If the line of the cave is projected through the collapse debris in elevation (see extended section B on the survey), the roof of the original tube is seen to have lain some 10m below the present floor level of the overlying breakdown cavity. The most interesting feature in the cave below entrance 'Al' is the occurrence of a natural bridge, possibly originating from the progressive enlargement and eventual coalescence of lateral benches, as was described to explain similar features in the Cueva del Viento. Above the bridge is the entrance to a small side tube.

As wall exposures are frustratingly absent or incomplete, interpretation of the cave's genesis must rely mainly on morphological evidence. Breakdown and collapse has significantly altered the lower part of the
cave which, as described above, in the lowest 20% is a cave formed in collapse debris and is not a lava tube cave (the cave has formed by the collapse of the overlying rock into the tube). There are four areas of total roof collapse, though they are not large and the lowest (entrance 'Al') appears to have originated as a skylight. The differences in the nature of the passage profiles at the top end of the cave and where the complete lava tube cave is last seen just beyond the bridge - a transition from a low, wide, arched profile to a tall, gorge-like profile - suggests that residual lava remaining in the cave after the cessation of activity was drained from the bottom end of the tube at a faster rate than from the top. It appears that only a very small part of the cross-section of the upper part of the lava tube drained and much remains filled. Rapid drainage of the lower part of the cave produced a deep trench beyond the bridge.

There is evidence to suggest that the lava tube originated from an open lava channel. The channel did not possess the smaller loop tubes, or the bridge structure. The lateral benches in the cave would then have represented the banks of the channel, and the drainage of overspill flow units formed small surface tubes which were recaptured downflow by the main stream. Once established, these continued to carry periodic overflow. The bridge can be explained as a remnant of an early roof that formed over the channel. This roof was probably more extensive and appears to have broken up except in the bridge section, though even at this point it appears to have been engulfed during high lava surges. It was during a surge that lava escaped from the channel, forming a small surface tube on the east bank. At this stage, continued pulsation of the lava delivery caused the walls of the lava channel to be heightened and a new roof to be formed, enclosing the remnant of the lower roof (bearing in mind that the 1614-24 lava flow was emplaced over a period of 10 years,
it would not be improbable for the lava channel or tube—proto Lamponi—to have been modified during successive period of vigorous effusive activity), enclosing the now much remelted remnant of old roof and the entrance to the now buried surface tube. Because of the thinness of the roof in the upflow part of the cave, it is thought that this part of the channel may have remained open longer than the downflow part. Right up until very late in its activity, it appears that flow periodically escaped through the roof of the tube via skylights and formed surface units, some of which developed their own small tubes. The thin roof in the upflow part of the cave suggests that roofing here may have proceeded as a continuous surface crust across the lava stream.

Grotta degli Inglesi.

This cave originates from a large collapse depression situated on terrace 'D', 100m north of the base of the front of terrace 'C'. The survey shows the cave to be shaped like a letter Y, with the southerly arm lying at a slightly lower altitude than the northerly arm. Near the collapse depression the cave is of large dimensions, though the ceiling becomes progressively lower further into the cave as a result of a later invasion of a spinose lava tongue. The front of this tongue, 1m high, is situated in the stem of the Y, just before the bifurcation is reached. At the bifurcation a wide, low chamber floored with collapse debris gives access to either a small, well-formed tube trending to the ENE, or to a steep incline and into a larger tube whose orientation is eventually southerly (i.e., upflow). The direction of the flow of lava in the first mentioned branch is towards the terrace front and, as the cave/terrace profile shows (extended section 'A' on the survey), this tube may have fed fluid lava directly onto the front. As the other arm is lower in both altitude and depth within the flow it is presumed to be older than the rest of the cave. This passage also contains a spinose floor
which is also a later invasion, for floor lava cascades over and around chemically disintegrated blocks which obviously fell from the roof at an earlier date. Throughout this branch the ceiling is low and wide.

Breakdown is mainly of roof units in this cave and has resulted in the formation of two roof collapses, one at either end of the stem of the Y. Wall structures are not visible. Further difficulties in trying to understand the origin of the cave arise because the lava tube underwent almost negligible drainage of the lava it was transmitting and its cross-sectional volume may have been 5 or 6 times that of the passage cross-sections seen today. The source of the lava was the collapse depression which apparently originated as a large dome structure. Shorelines of ponded flow beneath the collapse debris of the dome are visible. The form of the cave also suggests that the southerly branch is part of a slightly older lava tube which may have captured some of the drainage of the younger tube which, in turn, is represented by the stem and the northerly branch of the Y. Such a capture would explain the partial burial of the collapsed roof blocks in the southerly passage.

Grotta del Labirinto.

This cave originates on the tread of terrace 'C', where it is a complex of interconnecting small passages lying just below the surface (Plate 9.6.), though where it passes down the terrace front in a north-westerly direction it reduces to a single tube of steadily diminishing dimensions and a steep gradient. Because this cave caused a certain amount of crustal upheaval during its emplacement, lies just below the surface of the terrace and possesses a form that is to some degree dictated by the shape of the terrace upon which it is situated, it is thought to have formed late in the history of the lava flow. The source of the lava which passed through the tube appears to lie at the foot of terrace 'B'.

Entrance to Pozzo Superiore is located at the very top (Plate 9.8). The largest crustal slab is 3-4m high and slabs were upturned as a result of the pressure in a lava tube beneath.

Plate 9.8. (right) Entrance to Pozzo Superiore, 1614-24 lava flow.

Note the bulbous squeeze-ups and striations. The hole gives access to a chamber 10m deep and some 15m wide.
Pozzo Superiore, a large, deep chamber entered through the roof, is also part of the same cave complex, as are short cave segments emanating from collapse features on the surface of terrace 'C'. The situation of Pozzo Superiore at the very highest point of the terrace, and the tremendous upheaval caused by the emplacement of the whole cave network, exemplified by the collapse depressions which probably originated as small domes, suggests that the network was the result of a late surge of lava, under considerable hydrostatic pressure, after a period of relative inactivity (on this terrace at least) when the surface of the terrace had solidified to a depth of 2m. Incredibly, this surge of lava at Pozzo Superiore caused crustal slabs 5-7m wide and 1.5m thick to be upturned vertically as the lava punched a hole through the crust. These slabs remain in position today (Plate 9.7.), welded by overflow and bulbous squeeze-ups, with a gaping hole, 10m deep, at the summit (Plate 9.8.), left when the lava withdrew into a lower level tube or escaped onto the front of the terrace. It seems likely also that the configuration of the Grotta del Labirinto-Pozzo Superiore complex was due partly to the formation of an anastomosing network of streamlets which forced routes beneath the surface crust, causing a certain amount of up-arching of the crust.

RELATIONSHIPS BETWEEN THE LAVA TUBE CAVES, THE TERRACES AND THE COLLAPSE DEPRESSIONS.

The mapping brought to light interesting relationships between the major landforms in the study area.

Relationships between the lava tube caves.

It appears from the surveys that each of the three main lava tube caves
originated quite independently of the others. It was originally thought that Grotta dei Lamponi connected with the southerly arm of Grotta degli Inglesi, for the terminations of these caves lie only 40m apart in plan view and they possess a common passage alignment. It is now regarded that this apparent connection is merely a coincidence: (i) no sound connection could be made between the two caves; (ii) the direction and angle of slope of the floors of the caves is opposite; (iii) the long section (Extended Section B on the survey) shows that the caves terminate 20m apart vertically or, if the projected line of the original lava tube is brought into the calculation, 25-30m apart. It is a strange coincidence, however, that the relevant passage in the Grotta degli Inglesi turns through $90^\circ$ to become aligned with the Grotta dei Lamponi and this may indicate some directional control, such as a buried valley in this region.

The relationships of the caves and the superimposition of the flow units in which they are contained allows an interpretation of their relative ages. The relative ages of the two parts of the Grotta degli Inglesi has already been inferred, as has the age relationship between the Grotta degli Inglesi and the Grotta dei Lamponi. In summary, there are three level of caves beneath terrace 'D': the deepest, and probably the oldest, is Grotta dei Lamponi, which appears from the extended section to pass beneath the base of terrace 'D' and into terrace 'E'; next oldest is the lower arm of Grotta degli Inglesi; youngest (highest) is the main part of Grotta degli Inglesi. Yet south of the forest track Lamponi is only slightly buried and it sits upon the same terrace as Grotta del Labirinto-Pozzo Superiore. It is suggested that Grotta del Labirinto-Pozzo Superiore, however, is much younger than Grotta dei Lamponi: (i) the Labirinto-Superiore complex occurs just below the surface of the terrace and appears to have been the origin of some of the clinker lobes that
make up the front of terrace 'C' which, in turn, sits upon the tread of terrace 'D' (Lamponi is, of course, partly buried by terrace 'D'); (ii) the formation of the Labirinto-Superiore complex caused considerable upheaval of the thick surface crust of terrace 'C' and this appears to have taken place late in the history of the terrace, while the emplacement of Grotta dei Lamponi caused no such upheaval and the cave is even partly buried by clinker that may have originated from the Labirinto-Superiore complex.

The following chronology of cave formation is therefore deduced:

(4) formation of Grotta del Labirinto-Pozzo Superiore;
(3) formation of Grotta degli Inglesi (stem and northern branch of the Y);
(2) formation of Grotta degli Inglesi (southern branch of the Y);
(1) formation of Grotta dei Lamponi.

It is interesting to note here that breakdown and collapse of the lower part of Grotta dei Lamponi occurred most probably after terrace 'D' was emplaced and probably involved the collapse of the base of this terrace into the lava tube. It must therefore be possible to identify the base of terrace 'D' in the section exposed by this collapse in the cave.

Relationship between the lava tube caves and the collapse depressions.

All of the collapse features, except the one situated on terrace 'E', possess lava tubes radiating from their rims. The problems of the formation of these features was discussed above where it was suggested that some, particularly those on terrace 'C', were the result of collapsed lava tube roofs in area where the flow had been ponded and subsequently drained. The role tubes played in the formation of the other two larger features is not known, other than the collapse on terrace 'D' was the source of the lava from which Grotta degli Inglesi was constructed, but
it is not known how the lava got to this source.

**Relationship between the lava tube caves and the terraces.**

Some interesting relationships were found between the position of the caves and the terraces.

(1) Grotta dei Lamponi was found to possess a shape that curves around the eastern flank of terrace 'C' before it is buried beneath terrace 'D'. The inference being that there was an obstruction on the site of terrace 'C', or terrace 'C' was already in existence in some form or another during the formation of the lava tube, on whose form it exerted a directional control.

(2) Grotta degli Inglesi lies in a small terrace and its attitude in the terrace suggests that it played an important part in terrace formation: (i) the arm of the cave extending to the ENE terminates actually in the terrace front and probably contributed to frontal advance; (ii) the cave occurs on two levels, each probably having been feeders for separate flow lobes, contributing to a thickening of the terrace. It is envisaged that terrace 'D' was constructed on the tread of terrace 'E' due to the formation of overriding flow units fed from lava tubes emanating from a new lava source over the position occupied by the collapse depression today. This lava source acted as a secondary bocca. It is doubtful if Grotta dei Lamponi, which plunges very deeply beneath terrace 'D', contributed to the formation of this higher terrace.

(3) Two caves are seen to terminate at the terrace fronts and another is seen to plunge over the side, then rapidly close down: no cave was found to pass from the tread of one terrace onto the tread of a lower terrace. Tubes appear to stop at a terrace front where they debouched their load,
causing frontal growth and steady advance. More fluid lava lower in the terrace, possibly fed through older formed tubes, pushed its way through the clinker and emerged on the terrace front as piled pahoehoe toes. The general picture is the simultaneous process of fluid lava pushing through the clinker at the terrace front while lava, rapidly changing to clinker, was being dumped over the top from surface tubes.

**INFERRED CHRONOLOGY OF EVENTS IN THE STUDY AREA.**

1. Advance of the lava flow as far as terrace 'C' and the growth of this terrace, perhaps at a stationary front;
2. Outbreak of new lava at the foot of terrace 'B', or higher, and the formation of an open lava channel which eventually roofed to form Grotta dei Lamponi, with its gradual extension around the base of terrace 'C' in a curve, feeding lava into the area now occupied by terrace 'E';
3. Growth of terrace 'E';
4. Outbreak of lava at the base of terrace 'C', or flow of new lava around the western side of terrace 'C', and the formation of terrace 'D' as flow units progressively overrode one another in a north-easterly direction across the tread of terrace 'E', fed from an ever changing tube system of which only the Grotta degli Inglesi remains accessible;
5. A period of inactivity (on 'C' at least);
6. Outbreak of lava at the base of terrace 'B' and the formation of the Grotta del Labirinto-Pozzo Superiore complex as anastomosing streamlets forced their way beneath the surface crust on terrace 'C', with consequent upheaval of the very thick crust and the forward growth of the front onto terrace 'D'.
**Discussion.**

The discussion is divided into two parts. The first part considers the evolution of lava tube networks and the evidence drained segments (lava tube caves) contain of the morphology and dynamics of the internal feeder river systems of pahoehoe lava flows. Lava rivers housed in lava channels and tubes are seen to be adjusted or equilibrium forms and the liquid lava emerging at the end of the tube system near the flow front is likened to a jet flow. As a result, it is argued that the development of pahoehoe lava flows is predictable and amenable to quantification through the application of jet theory. In the second part, the conclusions reached on the evolution of lava tube networks are incorporated in a new general theory on the morphogenesis of lava tube caves.

For the purpose of this discussion a lava tube cave is considered to be an abandoned segment of the channel once occupied by the internal feeder river of a pahoehoe lava flow. Accordingly, analysis of the variable planimetric morphologies and passage forms of lava tube caves is particularly valuable in visualizing the extent, morphology and dynamics of the ideal pahoehoe river system (a lava river is here defined as mobile flow confined between the banks of a narrow channel, as in an open lava channel or lava tube) and in confirming the processes of channel construction and channel maintenance described by vulcanologists during periods of active flow emplacement. Such an analysis is described here and is a comparative study of the fluvial forms and processes of lava and water. The writer has called extensively upon the works of Leopold, Wolman and Miller (1964) and Morisawa (1968) for descriptions of the forms and processes of aqueous river systems. The study is qualitative due to its embryonic form and to the limited opportunities for collecting quantitative data within the general fieldwork programme, though the ways and means for a quantitative approach are described.
CONTRASTS BETWEEN THE PHYSICAL PROPERTIES OF WATER AND LAVA AS LIQUIDS.

The contrasts between water and lava as liquids were previously discussed by Wentworth (1954) and his main points are incorporated in this present assessment.

A liquid is a substance capable of flowing, having molecules which easily change their relative positions without separation of the mass, enabling it to remain under the pull of gravity below an upper horizontal surface. Important additional properties include equal hydrostatic pressure in all directions at a given point, a viscosity sufficiently low to respond to the gravitational forces in short periods of time and slight compressibility, resulting in pressure being proportional to depth.

Water, within a certain temperature range, very nearly approaches a perfect liquid, and is the only liquid to flow in quantities comparable with lava. It exhibits a nearly straight line relationship between pressure and depth, viscosity, time and volumes of movement. The main non-linear behaviour of water is that of turbulent flow (flow in which the path lines of particles are irregular curves which continually cross each other, forming a complicated network which in aggregate represents forward motion).

Lava, on the other hand, is a very imperfect liquid, being inhomogeneous in temperature, density, viscosity, pressure and physical composition. In a liquid state it generally consists of bubbles of gas and solid crystals suspended in a liquid melt, and it is at all times close to the phase boundaries. Mobility of a sort, however, is frequently
Fig. 10.1. **Shear stress as a function of rate of strain for Newtonian and Bingham liquids.**
characteristic of its early life as a result of high temperatures and a high gas content by volume, and its behaviour at such times is amenable to some hydrostatic and hydrodynamic principles. Subsequently, by loss of gas and heat, lava is subject to the progressive loss of free molecular mobility that defines the perfect or near perfect liquid. With such a loss there is a great increase in viscosity and the growth of additional crystals.

The most fluid lavas possess viscosities of more than 100,000 times the viscosity of water (Macdonald, 1972, p.61). As a liquid with a general high viscosity a lava will flow with laminar motion and rarely, if ever, with turbulent motion (in laminar flow the flow paths of the individual particles of the fluid do not cross or intersect, but have path lines which are essentially parallel). It can be shown, however, that without exceeding the Reynolds number of about 2,300 which defines the lower limit of turbulent flow (Wentworth, 1954, p.430), very mobile lava is still capable of a much higher velocity than that of water.

Water is a Newtonian liquid and its behaviour is represented on a graph of stress versus rate of strain by a straight line through the origin. It contrasts with lava, which possesses a definite yield stress and behaves as a Bingham liquid. That is, for stresses below a certain value - the yield stress - the strain rate is zero and the lava does not flow. These relationships are shown in Fig. 10.1. Having said this, however, it appears that at least the hottest and most fluid lava near the vent during an eruption may show Newtonian characteristics, but that during its course to the flow front it develops Bingham properties. This behaviour was reported by Booth and Self (1973) during the 1970 eruption of Mt. Etna, Sicily, and others have described flow
Flow in lavas is a function of complex inter-relationships between a number of highly variable factors resulting from the physical properties of the lava, the characteristics of the extrusion and the characteristics of the external environment. Not all factors are of equal importance. Also, some are completely independent of the others, while others interact and are partly or even wholly dependent upon the independent factors.

The principal factors influencing the physical behaviour of lavas are:

(1) the chemical composition of the lava,
(2) the amount and condition of the gas held in the lava,
(3) the temperature of the lava,
(4) the solid load carried in the lava,
(5) the volume of the lava discharged,
(6) the rate of discharge from the vent,
(7) the gradient of the slope down which the lava flows,
(8) the topography of the surface over which the flow takes place,
(9) the external temperature and pressure and the local gravity field (all of which are normally regarded as constant).

A principal physical property of a lava is its viscosity. This is controlled by the chemical composition of the lava, the amount and condition of the gas present in it, its temperature and its solid load.
Lava is composed of partly molten silicates containing volatiles either in solution or present as bubbles in the melt. Chemically, the control over viscosity is influenced by the relative proportion of silica to bases in the melt. In general, the more silica a magma contains in proportion to the bases the higher is its viscosity (Macdonald, 1972, p. 61). Acid lavas have higher viscosities, therefore, because it is thought that the spare bonds of the silica tetrahedra not taken up by the bases, link to other tetrahedra and form three-dimensional polymer networks that restrict the freedom of flow. If, however, the proportion of bases is large, then these basic atoms will take up the spare bonds on the tetrahedra, and the bonding of one tetrahedron to another is less extensive. In this case the liquid consists more nearly of independent units with interconnecting bonds, making flow easier.

The amount of gas dissolved in the lava is the result of the relationship of the rest of the lava and its temperature and pressure. Nearly all magma contains more gas at depth than it can hold in solution when pressure is reduced as it reaches the surface. Separation of excess gas therefore takes place in newly erupted lava and may be seen as bubbles in the liquid (vesicles in consolidated lava). The effect of gas on the viscosity of the lava is complicated, for if a large amount of gas remains in solution, viscosity remains low, and if the gas has separated into bubbles in the melt, then viscosity also remains low if the bubbles are not too numerous, but if they are abundant and whipped into a foam, then viscosity is increased.

Temperature has a simple, yet important control over viscosity, for the higher the temperature of the lava, the lower its viscosity. Heat is lost through radiation and conduction to the air and the ground,
and temperature is subject to changes throughout the length and cross-section of a lava flow. Also, there is an intimate relationship between the mobility of the lava and the maintenance of temperature, which must be a fundamental consideration in the later discussion.

The solid load of the lava is determined by the gas content and the temperature of the lava, for a reduction in either, or both, will cause crystallization. The solid load is normally made up of crystals suspended in the melt, together with crustal fragments engulfed by the flow. Viscosity is increased by the process of thickening the liquid through frictional drag between the grains.

Although lavas in general possess high viscosities when considered against other liquids, they do nevertheless display a significant range and vary in viscosity from one type of lava to another. Viscosity is defined here as that property of a fluid which determines its resistance to a shearing stress. The reciprocal of viscosity is mobility. As pointed out earlier, as a liquid with a general high viscosity, a lava will flow with laminar motion and rarely with turbulent motion. In lavas of very high viscosity, the fluid portion of the flow results in a greater amount of internal shearing than more fluid flows, and hence affects mobility.

Factors linked with the character of the extrusion and the external environment include the amount and rate of discharge, the gradient of the slope over which the flow passes and the local topography. Discharge is important simply in determining the size of the lava flow (Walker, 1973) and maintaining the mobility of the flow by the continual addition of hot lava from the vent. Slope also has a control over the mobility of the flow, both in terms of flow velocity and in the maintenance of
mobility. Slope is an important factor to consider in the drainage of lava tubes. The topography of the pre-flow surface may cause the lava to be confined within a narrow valley, or to spread upon a wide plain, or to flow with different velocities over variable gradients, or to become ponded. Under these varying circumstances flow mechanisms are affected.

The magma is subject to change even while it is in the vent, for the temperature and pressure of the external environment are significantly less than the temperature and pressure at depth. In a response to regain equilibrium with the new environment, both at the vent and during flow, the lava suffers losses in temperature and gas which leads to progressive crystallization, an increase in viscosity and a loss of mobility. Account, therefore, must also be taken in this discussion of the dimensions of distance and time.

**ENERGY LOSSES IN CHANNEL FLOW.**

A flowing liquid, be it water or lava, is subject to two principal external forces: a gravitational impelling force and resistance to downward movement as a result of friction along the channel boundaries. In lava, however, the liquid behaviour near the vent is the result of a high gas content by volume and a high temperature. With the progressive loss of gas and temperature downslope, there is a growth of additional crystals and an increase in viscosity, resulting in an additional internal flow resistance. Thus, as pointed out by Booth and Self (1973), there is in most lava flows between the vent and the flow front an exchange from a high heat/low mechanical energy regime to a
low heat/high mechanical energy regime. The same authors also speculated that the non-Newtonian regime (Bingham flow) may be coincidental with the high mechanical energy regime; the necessary shear stress required to maintain flow being provided by the mass of the molten material flowing downslope from the vents.

It appears that such energy losses are minimal in pahoehoe lava flows confined to a channel or lava tube system, as Swanson (1973, p. 622) observed during the 1969-71 Mauna Ulu eruption on Kilauea volcano, Hawaii:

'Tubes provided such efficient thermal insulation that the flowing lava maintained temperatures equal to, or only slightly less than, the eruption temperature of 1,165° ± 5° C. For example, a traverse from Alea Crater to a point near the ocean (a distance of about 10km - see reference map, p. 8) revealed that the highest optical pyrometer temperatures of lava visible in each window of the tube system were 1,150° to 1,155° C, with no recognisable tendency for progressive cooling downslope'.

One reason, it has been commonly stated, for the negligible loss of (heat) energy from the lava river within a lava tube is the low thermal conductivity of the enclosing vesicular basalt (Robertson and Peck, 1969). This is certainly true, but it cannot be the main reason for the maintenance of high temperatures and mobility of flow over such considerable distances. Instead, it is argued here that lava channel-lava tube systems in pahoehoe lava flows are, like their aqueous counterparts, adjusted or equilibrium forms: it is through their construction that enough mechanical energy is conveyed to overcome the friction of the
slope, and the thermal energy losses to the air and the ground are reduced sufficiently to maintain temperatures which allow continued flow. Indeed, as Wentworth (1954) noted, there appears to be an intimate relationship between lava movement and the retention of heat, for convection rather than conduction accounts for the principal method of heat transfer, and the mobility of the lava depends upon the maintenance of high temperatures. Thus, mobility increases with temperature and, in turn, the temperature is more fully maintained by an increase or maintenance of movement.

Consider this principle during the early stages of flow emplacement: here the lava is subject to thermal and mechanical energy losses and the marginal parts of the flow fail and cease motion for lack of heat. As seen on Mauna Ulu, this process took place as follows:

'Most of the lava that flowed away from the newly opened vents on Mauna Ulu's east flank spread out in wide, thin sheets that, upon cooling, quickly developed a surface crust. No significant channels or tubes appeared as long as the flow retained this wide, flat form. However, with continued movement for several tens of minutes, such flows almost invariably concentrated into shallow but distinct, co-ordinated channelways. ...... the channel gradually deepened and perpetuated itself, and after several hours of flowage, the channel was well established' (Peterson and Swanson, 1974, p.211).

The situation is one where initially very hot and mobile lava is in contact with a cold surface and there is a sharp transition between the two. This is not a steady condition and a transitional zone of temperature and viscosity is produced, resulting in a velocity change
towards the edge of the active flow. This, in turn, through its reduced flow of heat to the outside of the mass, tends toward congealing and causes the active flow to narrow. Mobility is maintained along the paths of most active movement and eventually a well-defined channel is produced in which there is a steady state of thermal and flow conditions, with a zone of transition of temperature and viscosity from the central thread outward and downward to the wall rock.

Such behaviour was partly explained by Hulme (1974), who argued that it is the non-Newtonian behaviour of lavas and the existence of a yield stress which chiefly determines the morphology of flows. He showed through calculations and experiments that after flowing a short distance the width and depth of a lava flow stabilizes as long as conditions such as slope and effusion rate do not change, and the active part of the flow becomes confined between initial marginal levees. Later work on Etnan lava flows, however, by Sparks, Pinkerton and Hulme (1976) showed that later developments, such as channel construction, could not be predicted by Hulme's model and that the theory was best applied to flows of very low aspect ratio (low height when compared with width) and to parts of flows where cooling is of secondary importance.

In any open channel the maximum temperature loss is to the air, but the velocity of the flow and heat delivery through the channel are such that the temperature in the channel is kept nearly constant. However, as the velocity and the delivery of heat is reduced, perhaps through a reduction in discharge or slope, or because the flow has suffered excessive heat loss through prolonged flow, the maximum temperature filament drops below the surface and the top of the lava stream begins to solidify. Eventually, through increased viscosity, the top velocity
of the lava stream will be reduced and the channel may become completely roofed, with relatively rapid flow now continuing in a lava tube beneath. There is thus a change downslope from channel flow to tube-fed flow, which takes place when the rate of thermal delivery falls below the rate of thermal loss to the sides and the bottom of the channel and from the surface to the air.

Such ideas provide a theoretical framework supporting the tube-forming processes described in Chapter 4. As observed by geologists in Hawaii, there are many ways in which lava channels are roofed. Near the vent flow appears turbulent, and splashing and spattering may lead to the construction of arched levees which eventually join across the river. Alternatively, the channel may become covered by a stationary crust which is thickened by overflow, or crustal slabs carried in the river may jam across the channel. These processes are not necessarily confined to pahoehoe, but may also take place in aa channels. However, in aa and more viscous flows, areas of surface crust are broken up by the drag of the thick fluid beneath, and roofs over open channels may only develop where resulting debris piles up at an obstruction, as froth piles up at a weir.

MORPHOLOGY OF PAHOEHOE LAVA RIVER SYSTEMS.

Larger pahoehoe lava flows are known to be fed by a complex of internal streams, but because liquid lava is visible only at the front of the flow or where the roof of a lava tube has collapsed, the extent and morphology of this arterial system is difficult to visualize. For example, Macdonald's conception of pahoehoe feeder systems is as
Almost all the larger tubes branch and rejoin repeatedly, sometimes with several parallel stream paths, in the manner of a braided river. Many small tubes branch from the larger ones. The internal feeding system of an active pahoehoe flow is an exceedingly complicated maze of a vast number of anastomosing small tubes supplied by one or more larger tubes, and in turn supplying lava to the spreading flow margins.

Although this description is limited, it does provide a framework upon which a more detailed model of the morphology of pahoehoe lava rivers can be built from the morphological evidence of lava tube caves. Such a model must represent the form of the arterial system just prior to the cessation of effusive vent activity: up to this time it is envisaged that the system undergoes constant adjustment as the lava flow elongates.

The use of cave morphology as the basis for this reconstruction has limitations.

1. No lava tube system will have ever drained completely, for the lava with residual mobility left in the system at the cessation of vent activity will drain towards the lower reaches of the lava flow and must fill the conduits of the front region. It is a pity that cave evidence in this most important part of the flow is lost, though processes and forms of the frontal region are fairly well known from observations made during active flow emplacement and from structures exhibited in the exposures of the fronts of older flows.
(2) Drainage of the lava tube system is usually segmental and related to local variations of the pre-flow topography: for example, as seen in the Hallmundarhraun and at Raufarhólshellir. This means that cave segments lie randomly along the axes of lava flows. Also, as roof collapse is the only way of knowing that a cave exists, only one or two segments may be accessible for mapping in an otherwise quite extensively drained lava tube system. However, there are some systems, such as the Bandera Crater Tube, New Mexico (Fig. 10.2.) and the Cave Basalt system, Mt. St. Helens (Fig. 10.3.), which have drained extensively, with a greater proportion accessible for mapping.

(3) As demonstrated in the Cueva de San Marcos, the shape of a cave does not necessarily correspond with the pattern of lava tubes active just prior to the cessation of vent activity in that particular segment of the flow. To drain efficiently, all constituent tubes must drain downslope. The gradient of most side tubes is away from the main tube and, as there is no space available for draining lava at the end of blind, minor branch tubes, it is usually found that only those side tubes re-entering the main passage downflow drain of their residual lava. There is some drainage of side tubes in a reverse direction into the main tube, but such drainage only leaves short, blind passages or wall recesses.

The best mapped example of a lava tube system in relation to the shape of its parent flow is the Mount St. Helens system (Fig. 10.3.) With reference to caves with a complex passage pattern that occur along the axes of major flow; these are not strictly true channel forms, for the lava river during normal flow only uses the main throughway, and side complexes only function as active channels during periods of flooding, as described in the Cueva del Viento.
The distributary network at the front of active pahoehoe lava flows, which cannot be described from cave evidence, has been described by Hawaiian vulcanologists. The observation made by Peterson and Swanson (1974, p.215) of the front of the advancing flow units from Mauna Ulu, Kilauea volcano, during 1970-71 is typical:

"The flows advanced chiefly by the budding of pahoehoe toes from the flow front ...... Channels that did develop within new surface flows were relatively narrow, usually 1-3m across, and the lava streams travelled at rates of 1 to 6km/hr except where slopes were locally steep. Lava spread away from the main channels through complex distributaries, much like the artery system that branches into smaller arteries and finally into capillaries. The lava channels not only branched, however, but also rejoined each other, forming a braided pattern like that of some glacial meltwater rivers.

In addition to the roofing processes near the vent, another tube-forming process .... operated in these finely anastomosing distributaries. As a pahoehoe toe budded from the flow front, a skin chilled around it. The skin inflated like a balloon as more lava oozed into it. Eventually, the skin broke open owing to excess fluid pressure, and lava emerged as a new toe that rapidly became encased in its own skin. Repetitions of this budding process gradually lengthened the flow and developed a small tube, whose overlying crust thickened to form a rigid shell. In this way, the exceedingly complex and intricate distributary system that is the major means for developing broad fields of pahoehoe was slowly formed".
A model of the arterial system of a large basaltic pahoehoe lava flow, based upon evidence of cave forms and observations of active lava flows, is one resembling a long, sinuous, partly braided river lying along the axis of the lava flow, terminating at a delta-like front. Like aqueous systems, as the delta front advances through continued aggradation, the lava river elongates behind.

**THE DYNAMICS OF AXIAL FLOW.**

Axial flow is confined mainly within a long lava tube. The tube, in fact, is a covered lava river channel and it exhibits forms which are also characteristic of water-built channels: a specially shaped cross-profile built by the accretion of lava layers from periodic overflow and perhaps some erosive downcutting into a softened bed, sinuosity and braiding.

In the caves investigated, the main through-tubes of Raufarhólshellir, Vidgelmír, Surtshellir-Stephánshellir, Borgarhellir, the Cueva del Viento and the Cueva de San Marcos were identified as parts of axial feeder tubes. A particularly well-drained axial tube is represented by the caves of the Cave Basalt, Mt.St.Helens (Fig. 10.3.), while the Bandera Crater Tube (Fig. 10.2.) is partly a reconstruction based upon surface channels and collapses (Hatheway and Herring, 1970). Relatively unconfined flows may consist of several parallel long flow units with a more complex branching feeder tube system, such as that envisaged to have formed within the pahoehoe flow units erupted from Mauna Ulu (reference map, p.8.).
Like water rivers, the ability of lava rivers to build channels by degradational and aggradational processes depends upon the relationship between the forces impelling downward flow and the resisting forces. The resisting forces exerted by the fluid on the bed and the banks of the channel is a shearing stress. If there is no acceleration, the downchannel or tangential stress which the fluid exerts on the channel boundary is equal to, and opposite to, the parallel resisting stress exerted by the bed and banks on the moving liquid. The shearing stress is transmitted from one layer to another through the medium of viscous or turbulent exchange (mainly the former in lavas) of momentum as a result of a gradient of velocity. An 'adjusted' or stable form which a channel can assume, therefore, is one in which shear stress at every point on the perimeter of the channel is just balanced by the resisting stress of the bed and banks at each point. In water-built channels with moveable bed and banks, however, the channel must be able to transmit the flow and maintain the stability of the banks. Such channels are known as 'threshold' channels because each point on the perimeter is at the threshold of movement. In this condition a channel could not transport sediment because the required increase in stress would cause erosion of the banks. In fact, the natural water-built channel not only carries sediment, but migrates laterally by erosion of one bank, maintaining on average a constant channel cross-section by deposition on the opposite bank. There is thus an equilibrium between erosion and deposition and the form of the cross-section is stable, but the position of the channel is not.

Lava channels must also satisfy the two principal conditions of the efficient transmission of the flow and the maintenance of bank stability. Transmission of flow of fluid lava, however, infers not only a maintenance
Fig. 10.4. Tall, gorge-like passage profiles which may indicate incision of the lava stream.
of velocity (mobility), but also of temperature. Their success in this respect in itself suggests that lava channel/lava tube systems are adjusted forms. Cruikshank and Wood (1972, p.424) noticed lateral migration of lava channels by the degradational process of bank cutting and meandering during the Mauna Ulu eruption, though the extent to which the channel form remained stable was not known because the lava channel soon acquired a roof.

Wentworth (1954) has speculated upon the most efficient channel cross-section for the transmission of fluid lava under steady flow conditions. On theoretical grounds, the most efficient shape for reducing heat loss would be when the least surface area is exposed, as in a cylindrical conduit. In the higher reaches of a lava river, however, initial temperatures are maintained sufficiently by the bed and walls of an open channel. Here, heat loss to the air is probably greater than heat loss to the sides and bottom, and the optimum channel shape would be deeper and less wide than the shape determined by hydraulic considerations alone. This shape is maintained as channels become roofed over to form lava tubes. Further vertical elongation of the channel cross-section is thought to result from bed erosion during later flow (Cruikshank and Wood, 1972, p.425; Peterson and Swanson, 1974, p.219). Thus, the characteristic profile of the axial feeder tubes upon draining is a tall, gorge-like form (Fig. 10.4.), caused partly through the gradual incision of a lava river which had only ever partially filled the profile (estimates of discharges of fluid lava based upon dimensions of axial feeder tubes would therefore be completely erroneous).
As in water rivers, a lava river must exhibit a zone of transition of velocity, and hence temperature and viscosity, from the central part of the stream outward and downward to the wall rock. Velocity at the bed of the channel will be zero and the transition will be extremely gradual. The temperature of the lava of the stationary bed is not known, though two basaltic lava flows have been known to cease motion on a gentle slope when their internal temperatures reached 760°C (Macdonald and Finch, 1950) and 785°C (Macdonald, 1972, p. 60), respectively. Correspondingly, there must be a range of temperatures from the bed of the channel to the central mass of more than 250°C, and such a transitional temperature/velocity profile is probably many tens of centimetres thick. The rate of increase of velocity from the bed upwards to the central, most mobile thread is governed by the way mixing takes place between the slower moving elements nearer the bottom and the faster moving elements above. In non-turbulent or laminar flow mixing is molecular and by viscous forces. Lava streams must therefore represent successively enclosed thin cylinders shearing over one another as temperature and mobility are reduced towards the bed. This concept was correctly used by Italian workers (Malladra, 1917; Ponte, 1922; Gurrieri, 1933; Poli, 1959) to explain the concentrically arranged layers of lining in lava tube caves on Vesuvius and Etna. Similarly, concentric flow structures are visible in cross-sections of drained or partly drained lava tubes, as exemplified in the exposure of the undrained tube at the Borgarhellir entrance collapse (Fig. 4.5.).

Lava linings (lava tube crusts) occur in most caves, but they range greatly in thickness. In Icelandic caves, for example, a lining may be only 8-10 cm thick, while in the Tenerife caves linings ranged up to 20-30 cm thick. This lining must by definition represent lava which
was not fluid enough to drain out of the conduit and viscous enough to stay in place even on walls and ceilings (though crusts have been observed which have sagged on withdrawal of the fluid interior of the tube). The temperature of the outer edge of the crust must have been very close to the temperature at which lava movement ceased and the variation in the thickness between crusts of different caves must therefore reflect variations in channel adjustment through aggradation around the perimeter. Linings abut against horizontally bedded sheet flow units and, because of the abrupt discordant contact between the two in the caves where this contact is seen, it is believed that channel widening and deepening (probably through such processes as plucking of the wall rock and melting by the lava stream) took place before the channel stabilized. Thus, wall linings are also evidence that lava rivers possess the capacity for self-adjustment.

Investigations have shown that not only is the channel cross-section of water rivers adjusted to environmental controls of load and discharge, but so also is the channel plan. Such adjustments are sinuosity and braiding. Axial lava channel/lava tube systems similarly exhibit sinuosity and braiding, but whether these are also adjusted forms remains equivocal.

The sinuosity of the main passage of the Cueva del Viento was pointed out in Chapter 5, and sinuosity is easily identified from the plans of the other caves investigated. Sinuous bends in lava tube caves have been recognised by other authors: for example, Hatheway and Herring (1970) attempted a quantification of sinuous bends in the Bandera lava tube caves based upon the methods employed in the measurement of meanders in water-built channels. Such studies, however, were carried
Fig. 10.5.

AN EXAMPLE OF BRAIDING IN A LAVA TUBE CAVE.
Part of Labyrinth System, Lava Beds National Monument, California.
Surveyed by Peck, Soper and Modafferi (National Park Service), 1963.
out in order to compare the forms of lava tube caves and lunar sinuous rilles, which were believed to be analogous features, rather than to attempt an explanation of sinuosity in lava tube caves. Greeley and Hyde (1971) noticed that some sections of the lava tube caves in the Cave Basalt, Mt. St. Helens, occupied, and were probably controlled by, the bed of an ancient stream, and other lava tubes may similarly be topographically guided. This latter explanation does not explain the regularity of bends in the lava tube caves presently under discussion, however. Cruikshank and Wood (1972) have shown that fluvial-like processes of bed erosion and bank cutting (lateral melting and plucking of the wall rock, particularly on the outer walls of bends) may be operative in both open and closed lava channels. Asymmetrical passage profiles analogous to cross-profiles from bends in water-built channels are also common in many caves (Plate 10.1.). If this is the case, then sinuosity in lava tubes - like sinuosity in water-built channels - is an equilibrium condition resulting from adjustments amongst the many controlling variable of the flow.

Flow through braided channels in lava tubes also appears to be very common. Braiding is the division of a single channel into two or more anastomosing channelways. It can frequently be seen in photographs of Hawaiian effusive activity and Fig. 10.5. illustrates braiding in a lava tube cave (other examples may be observed in the enclosed surveys). Braiding of water rivers has been attributed to the incompetency and incapacity of the river: that is, the river can transport neither the amount of debris nor the size of debris that is supplied to it as bed load. Braiding in water rivers occurs under conditions of highly variable discharge in rivers with easily erodable banks which can supply an abundant bed load. These factors lead to the necessity of
local high velocities to enable the river to do its work. Lava rivers also are overloaded and are subject to a wildly fluctuating discharge, and one could speculate that similarly, through sub-dividing the lava channel, velocity and fluidity is maintained, ensuring the efficient transmission of the lava flow. However, the relationship between flow conditions and braiding in lava channels and lava tubes remains unknown for certain.

**THE DYNAMICS OF TUBE-FED FLOW AT PAHOEHOE FRONTS.**

It was suggested in the preceding section through comparison with aqueous systems that pahoehoe lava rivers occupying axial lava tubes tend towards equilibrium forms, enabling the efficient transfer of fluid lava from the vent to the flow front without significant loss of temperature or mobility. At the front, however, there is an abrupt change in flow pattern, reflecting an adjustment to flow resistance and energy expenditure. Technically, the 'wetted perimeter' increases and there is a larger frictional drag, with subsequent loss of both heat energy and mechanical energy. The front is an area of rapid aggradation, where channels and tubes become choked and an ever-changing pattern of interconnecting small tubes and channels develops as the flow advances.

A particularly good description of the mechanism of advance of a large pahoehoe lava flow from the Mauna Ulu eruption, Kilauea volcano, was given by Swanson (1973, p.621):

'Gradually, however, the pahoehoe tube system extended itself, in part by a continuing flow of lava through interconnecting pahoehoe
toes and in part by the crusting over of small surface channels. The formation of the crust slowed cooling, so that hot, relatively fluid pahoehoe encroached on and eventually covered slightly older aa flows. As each pahoehoe lobe broke onto the surface from the end of the new tube and advanced downslope, it changed gradually to aa that was covered shortly afterward by still newer pahoehoe that emerged at the surface from the ever-lengthening tube system. This process - pahoehoe changing to aa, only to be covered by slightly younger pahoehoe as the tube system advanced - was repeated over and over again throughout the next few weeks.

Analogies of flow fronts which are fed by a stream flowing under equilibrium conditions in an adjusted channel are deltas and alluvial fans. In fact, the 'bird-foot' delta of the Mississippi River is very close in form to the shape and distributary pattern of a pahoehoe lava flow (Fig. 10.6.). Water-built deltas are formed when a stream contained in a channel of its own making debouches into a body of standing water as a jet flow, and as a result of the velocity of the stream water being checked, the sediment load is dropped and continual frontal aggradation takes place as the river elongates its channel behind.

A quantitative theoretical approach to the formation of water-built deltas was carried out by Bates (1953) in terms of 'jet theory' as described first by Tollmein (1926). Bates considered that a stream of turbulent fluid discharging into a large basin through a well-defined and stable orifice was a free jet and jet flow therefore existed whenever a major river discharged directly into a lake or ocean. He described the pattern of deposition established by jet flow as follows.
Firstly, stream deposits form in areas lateral to the threads of maximum turbulence and natural levee formation becomes highly developed along the flanks of the jet to a distance of four diameters from the orifice. Throughout this distance there would be no deposition in the core zone, since there is no deceleration of the flow along the axis. However, in the transitional zone four to eight diameters out from the orifice, deposition of bed load and suspended load takes place from the core of the jet because axial deceleration now begins. This deposition develops a transverse bar across the channel, more sediment being transported into the area than is being transported out. The linking of the transverse bar to the submerged flanking levees then creates a lunate bar blocking the mouth of the outlet. As the deposit continues to build upward, new outlets must form, cutting the bar or natural levee deposit if stream flow is to continue unimpeded into the basin. It is this requisite splitting of the main channel, Bates suggested, into a system of distributaries that leads directly to the typical pattern of delta formation found at stream mouths.

Bates recognised that the mechanisms of inflow into a still basin assumes that there are three possible types of inflow, two of which have the characteristics of the 'plane jet', in which the mixing takes place only in two dimensions (e.g., along a horizontal plane), and one the characteristics of the 'axial jet', in which the mixing is three-dimensional:

1. **Hyperpycnal** - if the flow is more dense and sediment laden fluid flows down the side and bottom of the basin as a turbidity current, then vertical mixing is inhibited and the flow pattern is that of a plane jet;
(2) **Homopycnal** - if the flow is equally as dense, where sediment-laden fluid enters a basin filled with fluid of comparable density as in a stream entering a fresh water lake, the mixing takes place in three-dimensions and the flow pattern is of an axial jet;

(3) **Hypopycnal** - if the inflow is less dense, where sediment-laden fluid moves out over the surface of a denser fluid filling the basin, as in the case of a stream discharging into an ocean, then mixing in inhibited and the flow pattern is that of a plane jet.

In the last case, if the magnitude of discharge of this type of inflow in water is small, a lunate bar forms off the outlet, but if the discharge is moderate to large, then a cuspatel, arcuate or bird-foot delta will form.

By analogy, the frontal growth of pahoehoe lava flows may be interpreted in terms of jet flow. Clearly, fluid lava confined within a narrow channel (lava tube) in which its temperature and mobility are efficiently maintained, debouching across new ground (the hypothetical basin), is not capable of vertical mixing and exhibits characteristics of hypopycnal flow of the plane jet. The very exciting possibility now exists in the future of predicting the growth pattern of pahoehoe lava flows through the application of jet theory.

**THE EVOLUTION OF CONDUIT NETWORKS IN PAHOEHOE LAVA FLOWS.**

Surveys of the more extensive lava tube cave systems, such as the Cueva del Viento and Surtshellir-Stephánsbær, show that the axial feeder river of an active pahoehoe lava flow frequently only occupies a single route through what may be an extremely complex internal, partly drained, conduit network. Such networks may be developed in
both the vertical and the horizontal planes. The investigations of the morphogenesis of selected lava tube caves described in the preceding chapters suggest that conduit network evolution is the result of any combination of the following developments: (1) braiding in the main channel, (2) stream piracy and the abandonment of flow routes, (3) the development of conduits to carry overflow during periods of flooding of the main channel, (4) elongation of the axial feeder tube across former frontal deltaic zones.

(1) **Braiding.**

Braiding has already been discussed in the preceding section and is seen in the lava tube caves investigated as interconnecting loops along the main channelway. Braiding is best displayed in Stephánshellir.

(2) **Stream piracy.**

There is considerable evidence of stream piracy in the lava tube caves investigated, in both the horizontal and the vertical planes. In the Galleria Barroso, Cueva del Viento, for example, lateral migration of the bends of two small tubes towards one another through erosion of the walls on the outside of each bend, has caused capture along the horizontal plane by the stronger (larger) of the two tubes, and has produced a distinctive \( \bigcap \)-shaped profile at the point of capture. In the vertical plane, capture of a higher lava stream by the channel of a lower one is always marked by a lava fall and is therefore easily identified. The writer distinguishes between 'active' and 'passive' vertical capture in lava tube caves. In the caves investigated, **active** stream piracy, through the bed erosion of the higher of the two tubes involved, or enlargement of the lower, may be recognised in Raufarhólshellir, at the 'funnel' and elsewhere in the Cueva de San Marcos, and in many
small captures in the Cueva del Viento. Frequently, however, capture is passive, when a new lava stream crossing older ground plunges through the skylight of a lower active or extinct lava tube. Passive capture is believed to have taken place between part of the upper cave and the lower cave in the Cueva de las Breveritas (i.e., at the 4m pot).

(3) Development of overflow or flood conduits.

Due to wild fluctuations in the effusion rate of most eruptions, the delivery of fluid lava through a channel or tube pulsates. In open lava channels high pulses can cause overflow and extensive lateral flooding, increasing the thickness of the lava flow and leading to the construction of levees. In lava tubes, such flooding appears to be accommodated in tube complexes that lie above the general level of, and to either side of, the main channelway. These overflow or flood conduits were first recognised in the Cueva de las Breveritas, when it was thought that they formed initially from overflow units while the main route was still an open channel, but it is now recognised that many of the small lateral conduits in all of the more complex systems are of this type. Thus, as with aqueous systems, even within large pahoehoe lava flows channel width is increased significantly during periods of high discharge. During low or normal flow conditions, the lava river comes to occupy the main channelway again and the flood conduits, which lie above lateral benches, drain and remain open until the next surge.

(4) Elongation of the axial feeder tube.

It appears that as the lava front advances, the axial feeder tube elongates across earlier formed frontal deltaic zones. The mechanism of this elongation is not known, though it is clear that very few of the vast number of distributary tubes of the old delta region are
utilized by the extending active tube complex, for competition between routes must cause most to clog. The Cueva de San Marcos appears to occupy a part of a lava flow through which such a frontal wave had passed and it was shown previously how this cave occupies only a small portion of the formerly extensive conduit network. The complexity of this cave may have been controlled to some extent by pre-existing conduits of the old delta front.
Consideration of the foregoing case studies and the preceding discussion enables a new general theory on the morphogenesis of lava tube caves to be formulated. The theory describes the common, multi-stage development of lava tube caves and explains how morphological diversity is an inevitable result of caves evolving in widely differing environmental situations.

The evolution of a lava tube cave occurs in three stages: (1) conduit (lava tube) network construction, (2) conduit (lava tube) network drainage, (3) breakdown and collapse.

(1) **Conduit (lava tube) network construction.**

Developments occurring in this genetic stage were discussed in the preceding chapter and only need to be summarized here. Cave development commences with the construction of a complicated network of conduits, or lava tubes, beneath the congealed surface of the lava flow, through which liquid lava is transmitted between the vent and the advancing front. Conflict over the validity of models depicting the formation of lava
tubes was partly resolved by observations of actively forming lava
tubes on Hawaii (Wentworth and Macdonald, 1953; Greeley, 1971b and
1972; Cruikshank and Wood, 1972; Peterson and Swanson, 1974). Field
investigations of flow structures related to lava tube caves undertaken
in this study confirmed that conduits, or lava tubes, in pahoehoe lava
flows evolve in two ways: (a) through the roofing of open lava channels,
(b) through the maintenance of axial flow within intermediate to small-
sized, tongue-shaped flow units.

(a) Major feeder tubes aligned along the axes of lava flows result
from the roofing of lava rivers carried in open lava channels. Roofing
may be accomplished in a variety of ways: through the accumulation and
fusing of crustal plates; through the accumulation and fusing of a
surface scum; through the growth of a stable surface crust from the
sides to the centre of the channel; through the agglutination of welded
spatter to form arched levees which eventually fuse with their opposite
number; or through the inward growth of channel walls as a result of
deposition of lava from periodic overflows.

(b) Some large, independent, unbranched tubes may occur through the
maintenance of axial flow in intermediate sized flow units which have
become confined within a narrow valley, as has been suggested by
Macdonald and Abbott (1970). Smaller tubes are constructed within
small, tongue-shaped flow units originating as channel overflow
(as depicted by Greeley, 1971a), or as a part of the toe budding process
at the front of overriding large flow units. Toes and small flow units
are amoeboid-like tongues of liquid lava which override one another as
they push out from the front of a major tongue. They develop a skin
through chilling, this is inflated by the addition of new lava behind,
the skin ruptures, liquid lava breaks out and a new toe or flow unit is formed as the process is repeated. In this way small tubes become elongated along the axes of small flow units.

Although the full extent of a lava tube network in a large basaltic pahoehoe lava flow is never seen, the composite picture is envisaged as resembling a vast number of anastomosing small tubes ramifying from one or more larger feeder tubes aligned along the axis of the flow. The axial tube is long and in its simplest form it may be sinuous and partly braided. Frequently, however, the axial tube is a complicated network comprising of one or more of the following elements: stream piracy (causing multi-level systems), the formation of overflow conduits either side of the main routeway, or the extension of the active tube across former frontal detaic regions of the lava flow.

(2) Conduit (lava tube) network drainage.

It does not necessarily follow that because lava tube networks develop in pahoehoe lava flows they will form caves, for the conduit network may not drain off the fluid which it is transporting. The transition in the genetic stages, from a lava tube to a lava tube cave, must, by definition, take place when the discharge of lava to the tube declines and eventually ceases. This occurs when discharge to one lava tube system is captured by a more favourable flow route during the period of active vent effusion (analogous to stream pirating and 'misfit' streams), or when activity at the vent ceases completely.

Drainage takes place when two conditions are fulfilled:
(a) when discharge wanes the lava within the tube must retain a degree
Fig. 11.1

PASSAGE PROFILES OF SELECTED LAVA TUBE CAVES.

Christopher WOOD

CUEVA DEL VIENTO

RAFAEL O. DELLA MONTE
Fig. 11.2.
GENESIS OF COMMON PASSAGE FORMS IN LAVA TUBES.

Fluid lava
Congealed lava
Collapse debris

(Not to scale)
of mobility on the existing slope;
(b) there must be a space into which the residual lava can drain.

(a) Drainage depends upon the mobility of the residual lava in the conduit, and this, as it was shown in the preceding chapter, is a function of its viscosity, which in turn is controlled mainly by temperature and the gradient of the slope down which it flows. Returning to the discussion on the relationship between temperature and mobility; the mobility of the lava within the lava tube must depend principally on the maintenance of high temperatures, and the temperature is more fully retained by a maintenance of movement. During active flow, movement is a function of a continuing discharge and gravity. When discharge to the tube diminishes or ceases, movement takes place only as a response to gravity. Temperatures are not maintained, viscosity increases and a feedback effect, because of diminishing temperatures, tends toward cessation of movement altogether. Residual lava in a tube will therefore possess a greater viscosity than the lava of active flow. This means that it is rare for a tube to drain fully of its residual lava, and generally movement ceases before a lava tube has completely emptied. Considerable modifications to the original tube form result from this response to an environmental change: (i) the original tube network becomes segmented and, (ii) varying cross-sections are produced within the tube due to the accretion of cooled lava to the walls (Figs. 11.1. and 11.2.). For the evacuation of very viscous flow the slope must be steep. For example, the Cueva del Viento possesses extremely spinose aa floors which could only have retained movement because of the very high gradient of the cave (averaging 11°). In contrast, some Icelandic caves, such as the Hallmundarhraun caves, appear to have drained on almost negligible slopes, and presumably their residual lava must have
Fig. 11.3. Maps illustrating the influence of topography on cave genesis.
remained extremely mobile. The contrast may be carried further and is even more striking with regard to passage cross-sections (Fig. 11.1.), for the passages in the Cueva del Viento appear to have drained with difficulty because of the more viscous flow, resulting in low tortuous cave passages which are often flat-out crawls over spinose aa, but in the Icelandic caves just mentioned passages are vast and the amount of modification of the original tube form is minimal. The study of some Icelandic caves has also shown that details of the pre-flow topography are also important factors in the drainage of lava tube systems, for they show that selected segments of long lava tubes drain only where topographic detail is favourable. This is illustrated in Fig. 11.3. The drainage of Raufarhólshellir, for example, was controlled by the position of fossil cliffs lying immediately downslope of the lava tubes. Similarly, Surtshellir-Stephánshellir and Vidgelmir in the Hallmundarhraun each occur on the tread of steps in the long profile of the lava flow and, because the steeper gradient of the fall of each step encouraged the complete evacuation of the fluid residual lava from the tube on the tread above, the length of each cave bears a relationship to the size (extent) of the tread of the step upon which it is situated.

(b) The other condition which must be fulfilled before lava tube drainage commences is that there must be a space into which the residual lava can flow. During active flow the lava passing through the conduit causes a build-up of hydrostatic pressure behind the flow front, and as long as the pressure is great enough to rupture the crusted front, advance of the flow will continue. It may be in very fluid lava flows that this process continues for a short while after discharge at the vent has ceased. An alternative may be that space for residual lava
is provided in an underlying cave, leaving a segment of tube abandoned (stream piracy). Another alternative results because most lava tubes during their active life are not filled to the roof with mobile lava, either because discharge has diminished since the construction of the roof, or the lava river has eroded the floor and caused the lava level in the conduit to be lowered (Peterson and Swanson, 1974, p.219). In any case, at the cessation of vent activity, residual lava will drain under the pull of gravity to the lower part of the flow, entirely filling the conduit here and leaving the higher part near the vent empty. This process explains the vast tunnels of caves like Vidgelmir closing down completely in only a few metres.

(3) Breakdown and collapse.
A lava tube cave is further modified as a result of yet another change of environment. Breakdown and collapse may occur in the earlier genetic stages, but these processes are mainly confined to the period succeeding drainage, when the lava cools and is eventually open to sub-aerial attack. Lava tube caves are particularly prone to collapse because of the abundance of flow unit contacts, partings and joints in the surrounding lava flow. Many caves collapse because the roof could not support its own weight during or after evacuation of the liquid core (Hatheway and Herring, 1970). In colder climates frost wedging is an obvious process leading to extensive breakdown and collapse, as in the Icelandic caves. Commonly whole caves may collapse to leave long, sinuous trenches in the surface of the lava flow, such as is found in the Undara flow, Queensland (Atkinson, Griffin and Stephenson, 1977), or cave systems become further segmented through roof collapse. As well as these modifications to the plan form of a cave, passage profile may become
extensively modified as a result of breakdown of the walls and ceiling. The lava lining of passages peels away and a rectangular form develops that is dictated by the jointing pattern of the surrounding lava flow. In some caves the original passage form is completely destroyed (for example, as in Raufarholshellir), while in other caves it is buried beneath material spalled from the walls and ceiling (for example, as in the terminal chambers of Grotta dei Lamponi).

A paper summarizing this model of the genesis of lava tube caves, entitled 'The origin and morphological diversity of lava tube caves', is to be found in Appendix B.
12. Conclusion.

The present study has considered the problems of lava tube formation and the role of lava tubes in the emplacement of large basaltic pahoehoe lava flows. It was based upon field investigations of 27km of lava tube cave, consisting of 12 caves in 5 contrasting lava flows from Tenerife, Iceland and Sicily (Mt.Etna). A lava tube cave has been defined as a drained segment of a lava tube network. Reports of observations of the tube forming processes operating during the 1969-71 Mauna Ulu eruption, Kilauea volcano, Hawaii, have also been extensively called upon to support the arguments put forward.

The many previous studies throughout the world have shown that lava tube caves are quite common volcanic landforms and possess a wide diversity of sizes, forms and occurrences. They have been investigated mainly by speleologists and local geologists, though later more detailed investigations were stimulated because it was believed that partly collapsed lava tube caves were analogous with some lunar sinuous rilles. As a part of the same study a programme of observations of lava tube formation was carried out during the 1969-71 Mauna Ulu eruption,
Kilauea volcano, Hawaii, when it was realised by professional vulcanologists that the formation and functioning of lava tubes was essential to the continued advance of pahoehoe flow fronts and, perhaps, to the growth of Hawaiian type shield volcanoes.

Previously varied hypotheses never adequately explained the development of conduit systems in pahoehoe lava flows. The problem was that the complex cave morphologies encountered in the field could not be reconciled either with the traditional model of lava tube formation, entailing the drainage of the fluid core of a partly congealed lava flow, or with the tube-forming processes of channel closure and toe-budding observed during periods of active vent effusion. The present writer has never held this view and has shown in this study that the relationships between flow structures and passage forms in the caves investigated in general confirm the channel closure and toe-budding mechanisms. It also appears that the structures related to the caves investigated are similar to the structures related to all other lava tube caves and that some previously favoured, though controversial, theories on tube genesis are based upon erroneous interpretations of the structural evidence. Lava tube caves are recognised as compound forms, each being constructed of a variety of conduit types. The various methods of conduit genesis in pahoehoe lava flows have been demonstrated and the morphogenesis of selected caves have been worked out from the spatial relationships between their constituent passage types.

The caves investigated occur in small groups. On Tenerife three caves - the Cueva del Viento, Cueva de Felipe Reventon (this cave not investigated) and the Cueva de San Marcos - form part of a 15km long cave complex situated in a basaltic lava flow on the northern slope of the island. The Cueva del Viento, with a length of 10km, is one of
the longest known lava tube cave systems in the world. It consists of two parts, one part trending beneath the line of the other, though the two parts are connected as a result of lava stream piracy. Each part originated as a separate cave: they are housed either in separate lava flows or separate large flow units. The morphology of the Cueva del Viento was shown by the survey to be complex, but this complexity could be attributed to the abandonment of some passages and passage complexes as a result of various piracies of flow and to the development of 'overflow conduits' on either side of the main route. The Cueva de San Marcos, situated downflow of the Cueva del Viento, was recognised to be of great geological interest because it had been truncated by the retreating sea cliff at Puerto de San Marcos and offered a unique opportunity of relating cave form and flow structure. The flow was composed of many small flow units or pahoehoe toes, some of which housed small cave passages along their axes. The structure of the flow around the cave was regarded as typical of structure near the front of a large pahoehoe lava flow and it was demonstrated how the morphology of the cave originated through a modification of the conduit network as the feeder tube elongated in sympathy with the continued advance of the front downslope.

Raufarhólshellir, situated in the Leita lava, Iceland, and Vidgelímír and Surtshellir-Stephánshellir, situated in the Hallmundarhraun, Iceland, are enormous caves which originated from feeder conduits aligned along the axes of long lava flows confined by valley sides. The origin of Raufarhólshellir is problematical, for its apparent source is small lava tubes above lavafalls in the three main tributaries at the head of the cave, though these could not have contributed the volume of lava that was required to partly fill the main tube and it is believed that other, larger, sources never drained and today lie buried beneath the
floor deposit. The Hallmundarhraun caves are vast, sinuous tunnels, though Stephánsshellir is partly braided and this cave may have originated in an area subjected to periodic underground lava ponding. Vídgelmfr is a particularly splendid cave, with spectacular displays of ice and lava formations, while Surtshellir is relatively featureless, though exhibiting an interesting passage intersection in its higher reaches. All of these large Icelandic caves appear to have originated from open lava channels and they have all drained quite extensively of the very fluid lava they were transporting. Consequently these caves have undergone little secondary modification. Drainage of all of the caves was demonstrably related to variable gradients in the pre-flow topography.

Lava tube caves and open lava channels located about the vent crater of the small Icelandic lava shield, Gullborg, were constructed as feeders for the large flow units making up this compound lava flow. One group of caves, known as Thrihellir, was developed around the breach in the crater rim as a result of the rapid aggradation of the escaping fluid lava and probably compares with the multiple layers of intersecting tubes noted in the vent area of Mauna Ulu. Borgarhellir, the largest cave of the Gullborg group was particularly notable for its lava formations and its situation in a long flow unit trending to the north-west. Lava channels and tubes exhibited comparable wall structures and the relationship between passage form and lava structure was well exposed about an undrained tube in the wall of the entrance collapse of Borgarhellir, and about a remnant of the lava tube lining (the 'gothic arch' structure) in Vegghellir. Surveyed relationships between the positions of the caves, the vent crater, the open lava channels and the major flow units, enabled a reconstruction of the history of the lava flow.
The lava tube caves of the 1614-24 lava flow, Mt. Etna, were investigated primarily in order to assess the role they played in the formation of the large terrace-like features of this lava flow. Three very different caves — Grotta del Labirinto-Pozzo Superiore, Grotta degli Inglesi and Grotta dei Lamponi — occurred in varying positions relative to the terrace fronts and appeared to have originated from independent secondary boccas. Structures of the lava flow were rarely seen in the caves and morphogenetic interpretations were based upon the caves' morphologies. Spatial relationships between the caves provided details of their relative ages and the possible order of terrace formation. Caves were seen to have played some part in the growth of the terraces, which have been described as lakes held back by a rubble dam.

As a lava tube cave is a drained segment of the channel once occupied by the internal feeder river of a pahoehoe lava flow, the morphologies of caves were recognised as evidence upon which a model of the morphology of the feeder river system could be based. Using this evidence, together with observations of the emplacement of pahoehoe lava flows, the ideal arterial system is one described as resembling a long, sinuous, partly braided river lying along the axis of the lava flow, terminating at a delta-like front. The cave forms were rarely so simple (examples investigated are Vidgelmír, Surtshellir, Raufarhólshellir and Borgarhellir) and more often than not the lava river appears to have threaded its way through a complicated maze of open conduits within the axis of the lava flow (examples investigated are the Cueva del Viento, Cueva de San Marcos and Stephánshellir). The complexity of axial conduit networks was seen to originate from such processes as braiding in the main routeway, stream piracy, the
development of lateral conduit networks to carry overflow during periods of high discharge and the elongation of the tube system across former deltaic frontal regions. Lava rivers, it is argued, are comparable with other fluvial systems with regard to their dynamics and morphologies. They possess the capacity for self-adjustment. Such forms as open and closed channels (lava tubes), channel sinuosity and channel braiding are the developments of such aggradational and degradational processes as bank-cutting, bed erosion, stream piracy and delta formation. The lava tubes of the arterial system must be regarded as 'adjusted' or equilibrium forms because of their efficiency in maintaining the temperature and velocity of lava flow over quite considerable distances (40km +).

At the flow front, where the mobility of the lava passing out of the tube system is checked as a result of rapidly increasing energy losses, the stream divides and sub-divides into a system of smaller distributary tubes and channels, feeding lava to a broad delta-like front. As the front advances through continued aggradation, it is envisaged that the feeder river elongates behind (as demonstrated by the Cueva de San Marcos). Comparison with the work by Bates (1956) on river deltas suggests that lava emerging from the end of a lava tube at the front of a pahoehoe lava flow may be likened to a jet flow. Thus, the development of pahoehoe lava flows may be predictable and amenable to future quantification through the application of jet theory.

The principal conclusions reached by this study are:

(1) The development of lava tubes, with their ability through self-adjustment to maintain the temperature and mobility of the lava river
within, is the reason for the emplacement of long pahoehoe lava flows over regions of low gradients. As such, lava tubes must be considered important factors in the formation of the gentle slopes of basaltic shield volcanoes.

(2) The relationships between lava structures and passage forms in the caves investigated mainly support the observations of active tube-forming processes of channel closure and toe-budding. Lava tube networks are compound and constructed of a variety of conduit types. Some previously favoured theories on lava tube formation, particularly the 'layered lava' theory of Ollier and Brown (1965) and supported with modifications by Hatheway (1971, 1971a and 1976), Hatheway and Herring (1970), Greeley (1971a) and Greeley and Hyde (1971), are rejected as being based upon erroneous interpretations of flow structure and cave morphology.

(3) Lava tube systems in both active and ancient lava flows are frequently much more complicated than has been formerly envisaged by geologists and each may be composed of the following elements: a long, sinuous axial throughway which is the part usually occupied by the lava river; lateral tube complexes which carry flow periodically when surges from the vent cause the main route to overflow; higher tube complexes left vacant through the capture of their flow by an underlying, older routeway; a complex deltaic region of distributary tubes at the flow front.

(4) Ignoring secondary complexities, the ideal form of the arterial system in a pahoehoe lava flow consists of a long, sinuous, partly braided lava river housed mainly in lava tubes along the axis of the
flow, terminating at a delta-like front in which the flow divides and sub-divides into smaller anastomosing distributary open channels and lava tubes.

(5) The main axial feeder tube transmits the flow without significant loss of temperature or mobility, enabling the continual advance of the front as the tube system elongates behind. Because of the efficiency with which the fluid lava is transported, the flow will continue to lengthen indefinitely as long as vent discharge is maintained. Thus, it is possible to explain the emplacement of enormously long pahoehoe lava flows, such as the flows erupted from the Undara Volcano, N. Queensland (Atkinson, Griffin and Stephenson, 1977).

(6) Low thermal conductivity of the enclosing basalt of a lava tube is not the main reason for the maintenance of high temperatures and mobility of the lava river. Rather, it is because lava rivers possess the ability through aggradational and degradational processes for self-adjustment. They are seen to modify their channel forms in such a direction that thermal and mechanical energy losses are minimised and the transmission of the flow is maintained. Such adjustments to the varying flow conditions in time and space are seen firstly in open channel construction and then in channel closure (tube formation) and through the development of sinuosity and braiding.

(7) Because the efficiency of flow is so well maintained throughout the length of the lava flow, fluid lava eventually emerges from the end of the axial tube as a jet flow. Suddenly increased energy losses causes aggradation and the splitting of the flow into distributaries, as in a delta. As the delta front advances, through continued
aggradation, the axial tube elongates through the former deltaic regions. Thus, a new model of flow formation is introduced which is suitable for quantification and experimentation and will enable the prediction of the rate of frontal growth of the lava flow through the future application of jet theory.

(8) Some lava flows are not developed as single long flows, but are more complex. Parts of the 1614-24 lava flow, Mt. Etna, were probably built up as a result of aggradation from lava tubes originating from secondary boccas located throughout the length of the lava flow (though boccas and respective tubes do not appear to have been active simultaneously). In the Gullborg lava flow lava tubes and channels were developed radially about the vent, each feeding an independent flow unit and thus developing a compound lava flow.

(9) Lava tube caves are the drained and partly collapsed segments of lava tube networks. Their evolution consists of three stages. The first stage involves the construction of a conduit network beneath the congealed surface of the lava flow through which liquid lava is transported from the vent to feed the advancing flow front. The conduit network is complex and takes the form described in (3) above. In the second stage activity at the vent ceases, the conduit network drains and it is modified by the deposition of cooled lava to the walls. Such second stage modifications cause parts of the conduit network to become choked and therefore segmented and cause quite extensive modifications to the passage profile. The third genetic stage is characterised by breakdown and collapse of the walls and roof of the lava tube as a result of the destructive work of sub-aerial agents. Passage forms are further modified and the cave becomes
further segmented. Thus, because the rapidly changing environmental situation in which cave genesis is induced is unique to each cave forming locality, these cave exhibit an infinite variety of sizes, forms and occurrences.

**Future research based upon the results of this study.**

The model developed in this study requires confirmation both in the laboratory and in the field. In the laboratory, experiments with fluid analogous with basaltic pahoehoe lava (liquid paraffin wax, liquid metals, etc.) under conditions of jet flow (hypopycnal flow of the plane jet type) would provide a basis for the quantitative interpretation of the development of pahoehoe lava flows. In the field during periods of effusive volcanic activity, much needs to be known about the distribution of temperature, viscosity and velocity throughout the lengths and cross-sections of lava channels and lava tubes in order to confirm their efficiency as transportation systems and to better understand the dynamics of the lava river within. Further observations of tube-forming processes should also be concerned with the adjustability of the channel form by the lava river as a response to varying discharges and slopes. The dimensions, cross-sectional forms, channel patterns and slopes of lava tubes can be determined from lava tube caves. As a result of such work it may be possible in the future to be able to predict the rate of advance of the lava flow, the mechanisms of flow formation and the eventual form the flow will assume.

There is much regional work on the mapping and geological investigation of lava tube caves still to be done — in fact, such work has hardly begun. Many of the world's great classic lava tube caves remain unsurveyed: for example, surveys are required of the two great Kenyan systems of Mt. Suswa Lava Cave (over 8km) and Leviathan Cave (over
11.5km). Geologically, very few lava tube caves have been properly examined, though vast systems are known from the Western U.S.A., the Canary Islands, Hawaii, Korea and Kenya. To the writer's knowledge, even the now drained and segmented lava tubes of Mauna Ulu, Hawaii, have not as yet been entered to confirm the tube-forming processes observed during the eruption or to map the system, much of which must have remained unknown while the eruption was taking place. With further regional studies it will be possible to compare and contrast cave forms and their respective controlling factors quantitatively. As mentioned when discussing the complexity of the Cueva del Viento (p.8.), there is as yet very little information upon which to base comparative study, yet it is only through such study that many of the outstanding questions of lava tube and pahoehoe flow formation will be answered.
References.


Anon. 1970a. Sesenta y ocho montañeros han instalado, proximo a la Cueva del Viento, un Campamento Regional de Espeleologia: La Tarde (Newspaper), Santa Cruz de Tenerife, 7 Deciembre, p.10.


Baker, P.E. and Harris, P.G. 1963. Lava Channels on Tristan da Cunha: Geol Mag., 100, 345-351.


Bravo, T. 1964. En Volcan y el Malpais de la Corona. La 'Cueva de los Verdes' y 'Los Jameos': Publicaciones del Cabildo Insular de Lanzarote, Arrecife.


Ciesiel, R.F. and Wagner, N.S. 1969. Lava Tubes in the Saddle Butte Area of Malheur County, Oregon: The Ore Bin, 31 (8), (Aug.).


Foreman, I., et.al. 1970. Some Aspects of the Cambridgeshire Expedition to S.W.Iceland: Geophile, 70, 24-38. (Cambridgeshire College of Arts and Technology).


Lyell, C. c.1855 The Principles of Geology, p.150.


Montoriol-Pous, J. and de Mier, J. 1969 Estudio morfogenetico de las cavidades volcanicas desarrolladas en el Malpais de la Corona (Isla de Lanzarote, Canarias): Geo y Karst, 6 (22), 543-563.


Trogoblio (Pseud.). 1970. La Cueva del Viento y los espeleologos del Grupo Montañero de Tenerife: El Dia (Newspaper), Santa Cruz de Tenerife, 2 Mayo, p.4.


Appendix A:  
Glossary of technical terms.

This glossary is divided into four parts: vulcanological, speleological, surveying and general. The definitions not composed by the present writer have been abstracted from Green, J. and Short, N.M., Volcanic Landforms and Surface Features: A Photographic Atlas and Glossary, Springer-Verlag, Berlin, 1971.

Vulcanological terminology.

Aa: The Hawaiian word for solidified lava characterized by an exceedingly rough, jagged or spinose surface. The surface is covered with loose fragmental clinker grading into a central massive layer.

Accretionary lava ball: A rounded mass varying in size from a few centimetres to several metres diameter, formed on the surface of a lava flow such as aa by the molding of viscous lava around a core of already solidified lava.
Adventive cone: An ash or lava cone on the flank or foot of a major volcano, often on a radial crack.

Agglutinate: A deposit of flattened bombs and spatter that were still sufficiently fluid to stick together.

Aggradation: To build up by deposition (of cooled lava).

Anastomosing lava channel: Anastomosing is a term borrowed from medical usage, where it applies to dividing and rejoining blood vessels. It is synonymous with braiding.

Basaltic lava: A mass of molten igneous material erupted onto the surface of the earth. It is rather fluid and crystallizes to rocks containing mainly calcic plagioclase and pyroxene, with or without olivine. Because of the relatively low viscosity of basaltic lava, individual flows average 15m or less in thickness, but may extend over large areas. Basaltic lava may form a large cone (a shield volcano) or, if it flows from a number of fissures, an extensive plateau.

Bocca: A vent on the side or near the base of an active volcano from which lava issues.

Braided lava channel: A lava channel that divides into several smaller channelways, which successively meet and redivide. Braiding is synonymous with anastomosing.

Clinker: The fragmental portions of aa lava flows, resembling clinker formed in the grate of a furnace.

Collapse depression: A depression on the land surface, with or without a basal aperture, formed by the collapse of the roof of an underlying cavity or in lavas by the withdrawal of fluid lava from beneath a surface crust.

Columnar jointing: Parallel prismatic columns, either hexagonal or pentagonal in cross-section, in basaltic flows and
sometimes in other extrusive and intrusive rocks. It is formed as a result of contraction during cooling.

**Effusion:** The action or process of effusing, or being poured out.

**Effusive activity:** Activity of a volcano involving fluid outflow.

**Eruption:** The process by which solid, liquid and gaseous materials are extruded or emitted onto the earth's surface as a result of volcanic activity.

**Eruptive fissure:** A fracture in the earth's surface which is volcanically active.

**Festooned pahoehoe:** A type of pahoehoe, the ropy surface of which has been dragged by flow of the underlying molten lava into festooned patterns.

**Fissure:** A fracture or crack in a volcano, lava dome, or across volcanic terrain.

**Flood basalt:** An extensive, thick and smooth basaltic lava flow or successive flows of high temperature, fluid basalt from fissure eruptions accumulated to form a plateau. It is synonymous with plateau basalt.

**Flow unit:** A successive but essentially contemporaneous layer or portion constituting a single larger flow. Each flow unit either sheet or tongue shaped and represents a separate gush of liquid lava pouring over one another during the course of a single eruption.

**Hornito:** A small cone of agglutinate built on the surfaces of lava flows by escape of gas and clots of molten lava through cracks or other openings in the crust of the flow.

**Hyaloclastite:** Hydrated, tuff-like rock formed by granulation of lava flows in water typically composed wholly of angular fragments of palagonite 1-2 mm to a few cm across.
Kipuka: Hawaiian term for an island of older land not covered but surrounded by newer lava.

Laminar flow: In which the flow paths of the individual particles of the fluid do not cross or intersect, but have path lines which are essentially parallel.

Lava: A general term for molten rock poured out onto the surface of the earth by volcanoes and for the same material that has cooled and solidified as solid rock.

Lava channel: A linear depression that forms in lava flows and carries lava to the flow front.

Lava conduit: A pipe within a lava flow that transports liquid lava. It is synonymous with lava tube.

Lava field: A broad expanse of lava composed of many successive lava flows, with or without vent structures or pyroclastic cover.

Lava flow: A lateral, surficial outpouring of molten lava from a vent or a fissure during the course of a single eruption. Also the solidified body of rock that is so formed.

Lava levees: The scoriaceous sheets of lava that overflowed their natural channels of flow and solidified to form a levee, similar to a levee formed by overflowing sediment laden stream water.

Lava river: Mobile lava flow confined between the banks of a narrow channel, as in an open lava channel or lava tube.

Lava shield: A convex carapace of lava or assemblage of lava flows of variable size.

Lava tube: A linear conduit beneath the solidified surface of a lava flow through which liquid lava is transported. It forms through the roofing of open lava channels or through the maintenance of axial flow in tongue-shaped flow units.
Lava tube cave: Part of a lava tube system from which the molten lava has withdrawn after the cessation of effusive vent activity. A lava tube cave may be a complex passage network and may range up to and beyond 10 km in length.

Lava tube system: A complex system of many interconnecting and branching lava tubes formed throughout the length of a lava flow and transporting fluid lava from the vent to the advancing flow front.

Layered lava: A term introduced by Ollier and Brown (1965) describing the apparent horizontal stratification of basaltic lava flows.

Monogenetic volcano: A volcano formed in one, although sometimes long, eruptive period.

Pahoehoe: The Hawaiian word for solidified lava characterized by a glassy, smooth and billowy or undulating surface, spheroidal vesicles and lava tubes.

Pahoehoe toe: One of a series of small, bulbous projections that develop at the front of a moving pahoehoe flow or flow unit, formed by the rupturing of the crust and the emergence of fluid lava.

Palagonite: A sandstone-like brown tuff containing innumerable angular grains and fragments of a yellow-brown devitrified, basaltic glass. The rock also contains fragments of augite and olivine, microlites of plagioclase, and broken pieces of basalt.

Phonolite: An alkaline rock consisting of alkali feldspars and feldspathoids, with sodic pyroxenes and amphiboles. Phonolitic lava flows can form lava plateaus and exhibit pahoehoe structures and forms.
Pillow lava: A general term for those lavas displaying pillow structures and considered to have formed in a sub-aqueous environment.

Pit crater: A circular or ellipsoidal pit sunk below the gentle sloping surface of a volcano (shield volcano), resulting from collapse.

Pressure ridge: An elongated uplift of the congealed crust of a lava flow, lying transverse to the direction of flow and resulting from the ruckling of the crust by the movement of the liquid beneath.

Rift: A fissure or other opening in rock made by cracking or splitting.

Ropy pahoehoe: Congealed fluid lava, whose surface features resemble coils of ropes. The coils consist of lines of glassy scoria so arranged by surface currents in the lava stream.

Scoria: Rough, cinder-like, sometimes brightly coloured, more or less vesicular lava (pyroclasts) thrown out by an explosive eruption or appearing on a lava stream. The expansion of enclosed gases produces the typical structure.

Scoria cone: A cone built of scoria.

Shelly pahoehoe: A type of pahoehoe, which contains open tubes and blisters beneath a crust 1-30cm thick.

Shield volcano: A relatively low, broad volcano ranging up to many kilometres in diameter, built up almost entirely of lava, with slopes seldom more than 10° at the summit and 2° at the base, producing a shield-like profile.

Sinuous rille: Winding, linear depression of considerable length recognized in the surfaces of the Moon and Mars,
believed to be comparable with either terrestrial open lava channels or collapsed lava tube systems.

Skylight: A collapse hole in the roof of an active lava tube.

Slab pahoehoe: A type of pahoehoe, the surface crust of which has been fractured and fragmented, the fragments or slabs of crust being uptilted as a result of the continued movement of the underlying fluid.

Spatter: An accumulation of small pyroclastic fragments or blebs of plastic lava (cow-dung bombs).

Spatter cone: A mass of lava ejected violently from a volcano, which spatters and congeals as it hits the ground to form a small cone. Sometimes synonymous with hornito, driblet cone or agglutinate cone.

Squeeze-up: A small extrusion of lava from a fracture or opening on the solidified surface of a lava flow caused by pressure. It may be bulbous or linear in form.

Toe-budding: The process of flow advance through the continued formation of small lobate extensions of the flow front.

Tumulus: Domical swellings of the flow surface, up to 4m high, formed over clogged distributary tubes in pahoehoe.

Turbulent flow: In which the path lines of particles are irregular curves which continually cross each other, forming a complicated network which in aggregate represents forward motion.

Vent: An opening in the surface of the earth's crust, through which material is forced during a volcanic eruption.

Vesicle: A small cavity in congealed lava which originated as a gas bubble in the molten lava.
Volcanic gases: Gases escaping from the molten rock in the vent and during flow are variable, though a typical composition of Hawaiian volcanic gases is: \( \text{H}_2\text{O} = 79.31\% \); \( \text{CO}_2 = 11.61\% \); \( \text{SO}_2 = 6.48\% \); \( \text{N}_2 = 1.29\% \); \( \text{H}_2 = 0.58\% \); \( \text{CO} = 0.37\% \); \( \text{S}_2 = 0.24\% \); \( \text{Cl}_2 = 0.05\% \); and \( \text{Ar} = 0.04 \) (volume percent) (Poldervaart in Green and Short, 1971).

Speleological terminology (with reference to lava tube caves).

Breakdown: Both the process of spalling of the roof and wall rock of a cave and the debris derived therefrom.

Breakdown dome: A roof dome caused by breakdown of part of a cave roof.

False floor: A horizontal partition formed across a lava tube cave originating as a surface crust over a lava stream which later withdrew.

Flow lines: The horizontal striations in the walls of lava tube caves formed by the gouging of softened wall rock by crustal fragments carried by the flow in the former lava tube.

Gour: Small, cup-like deposits on the walls of lava tube caves formed as a result fluid glaze material trickling across flow lines (similar features in limestone caves are formed through secondary deposition around the edges of pools of water).

Lateral bench: A longitudinal deposit of lava caused by the narrowing (diminishing) of the flow through the tube.

Lateral shelf: A longitudinal cornice-like feature protruding from the wall of a cave, formed either through the partial
collapse of a false floor or through the erosion of the crust separating two vertically stacked tubes.

Lavafall: A solidified cascade of lava, usually signifying the piracy of the flow of a higher lava tube by a lower one.

Lava lining: A deposit of lava lining the inside of a lava tube cave. There may be several superimposed layers of variable thicknesses. It is synonymous with lava tube crust.

Lava seal: The termination of a lava tube cave, where the roof and the floor meet because the residual lava did not withdraw from this part of the lava tube.

Lava spring: A recess in the wall of a cave which was a source of lava for the internal flow.

Lava stalactite: A pendant cone, rod or straw formed by dripping of remelted lava from the roof of a lava tube.

Lava stalagmite: A cone or globular column on the floor of a lava tube cave built up of lava drips which fell from the stalactites above.

Lava tube: Defined in the vulcanological section.

Lava tube cave: Defined in the vulcanological section.

Lava tube crust: Synonymous with lava lining.

Lava tube glaze: An extremely thin, glassy lining in lava tube caves caused through the surface remelting of the lava lining by burning gases.

Lava tube system: Defined in the vulcanological section.

Roof collapse: Total collapse of a section of the roof of a lava tube cave.

Skylight: Defined in the vulcanological section.

Spalling: The disintegration and gradual collapse of roof and wall rock.
Speleogenesis: The formation of forms and features in an underground environment, particularly cave formation.

Speleology: The exploration and scientific study of caves.

Speleothems: Ornamentations in caves, particularly stalactites and stalagmites.

Tube-in-tube: Describing a small tube formed within the floor deposit of a larger tube.

Vulcanospeleology: A term originating in the U.S.A. describing the exploration and scientific study of caves in volcanic rocks.

Surveying terminology.

Azimuth: Referring to the horizontal bearings.

Closed traverse: A survey line taken through a cave which starts at and returns to the same point.

Leap-frogging: A surveying technique in which instruments are read only at every other station.

Levelling: The act of ascertaining relative elevation or of surveying profiles by taking levels with a theodolite and staff.

Line survey: The survey of only the centre-line of the feature (i.e., cave) under investigation.

Misclosure: When a traverse intended to but does not close on the first station.

Tacheometry: The rapid measurement of distance with a theodolite and staff.
Traverse: A survey by measuring straight lines from point to point and the angles between.

Triangulation: Surveying by means of a series of triangles.

General geological terminology.

Exothermic surface: The surface from which heat is lost.

Fluvial system: Describing flow in rivers of lava, water, or any other liquid or gas.

Hydration: Chemical weathering of a mineral involving the addition of the entire water molecule to the mineral structure. The disruptive effect of minerals expanding due to water incorporated by hydration is essentially mechanical and is an important factor in rock decomposition.

Hydrostatic pressure: The pressure exerted by the weight of the fluid above.

Jet flow: The flow of a substance at high velocity from an orifice.

Morphogenesis: The evolution of the morphology of a feature.

Oxidation: Although oxidation commonly involves the combination of iron or other elements with oxygen (usually dissolved in percolating rain water) as part of the weathering process, this is not always the case. By definition a substance is oxidized when it loses electrons and reduced when it takes on electrons. Combinations with oxygen weakens the original mineral structure, freeing the remaining minerals for participation in other chemical reactions.

Sinuosity: Winding or bending. For the purpose of defining sinuosity of aqueous river channels, Leopold, Wolman and Miller (1964)
used the ratio of channel length to downvalley distance as a criterion. The ratio was found to vary in rivers from a value of unity to a value of 4 or more; rivers having a sinuosity of 1.5 or greater were called meandering, and below 1.5 straight or sinuous.

Stream piracy: A term borrowed from geomorphology, describing the capture of the flow of water in one stream as a result of the headward erosion of a stronger neighbouring stream. It is synonymous with river capture.

Sole marks: A term usually applied to structures exhibited on the base of beds of sedimentary rock which are the impressions of the structures on the upper surface of the bed below.
Appendix B:
List of publications and supporting material.

The following references are to publications resulting from this present study. Those marked with an asterisk are included in this appendix in support of the main work.


Wood, C. 1973. Cueva del Viento confirmed to be the longest lava tube cave in the world: Jour. Shepton Mallet Caving Club, 5 (6), 3-7 (Autumn).


THE GENESIS AND CLASSIFICATION OF LAVA TUBE CAVES

by Christopher Wood

Summary

An attempt is made to resolve the current conflicts in volcano-speleology which result from the difficulties found in reconciling the complex three-dimensional lava tube networks with traditional models of speleogenesis in lavas. The important observations and models of lava tube cave genesis are described and discussed. It is found on observational and speculative grounds that the models may be reduced to two: the crusting of open lava channels and the chilling of a shell around flow units or pahoehoe toes. The popular theory of laminar flow and shear plane development as a pre-requisite for the evolution of complex tube forms is discussed and rejected. Instead, it is suggested that caves of a more complicated form may result from the crusting of braided channel flow or the coalescence of drainage channels carried in flow units or toes. Multi-level lava tube caves may be developed in a similar way and result from stacked conduits or flow units. In the light of these discussions it is seen that a genetic classification of lava tube caves is not practicable, for one cave may result from a combination of speleogenic processes. A descriptive classification is therefore proposed which is based on cave form as measured by the cave survey.

Current conflicts in volcano-speleology result from difficulties found in reconciling the often extremely complex three-dimensional lava tube cave networks with traditional models and observations of speleogenesis in basaltic lava flows. For some, the principal hypotheses on lava tube genesis lack credibility, for no one theory will suitably explain the wide range of lava tube morphologies encountered in the field. Others are attracted, somewhat blindly, to a single all-embracing theory of laminar flow and speleogenesis intimately linked with the formation of shear planes in lava, as an explanation for the origin of diverse morphologies, though they provide little evidence in support. The cause of this conflict, which has flavoured all recent discussions, appears to stem from the infant nature of volcanoespeleology, and results from unsystematic terminology, poor fieldwork, inadequate documentation, a general acceptance of unproved theories and, as yet, little observation of actively forming lava tubes. Conclusions have been drawn in the past without the foundation of sound descriptive material. This paper then, is an attempt to resolve the conflict. The information already available on speleogenesis in lavas will be summarised; much of it is, because of the obscure publications in which it is found, still unknown to the general worker. Proposed models of lava tube cave genesis will be reviewed in the light of known behavioural characteristics of basalt lava flows.

Models and observations of speleogenesis in lavas

General descriptive works on lava tube caves have in the past been numerous, but relatively little important evidence was cited which would contribute to a discussion on the origin of these features. The widely accepted traditional model which involved the simple crusting of a lava flow and its subsequent drainage did little to explain the often extremely complex forms of lava tube caves. Clearly, speleogenic processes at work in basalt flows were much more complicated. It was only recently, within the last few years, that important fieldwork was carried out both in ancient flows and in active extrusive volcanism. These observations are outlined below, together with the more important older contributions.

During the 1947-8 eruption of the Icelandic volcano 'Hekla', Kjartansson (1949) was fortunate to observe the formation of a lava tube cave which was subsequently named Karelshellir. His observations in December, 1947, were of new lava to the NNE of Haskuldbjalla, which was being extruded from beneath a flat aplanic crust (a) crust and flowed west down a slope of 1 in 8 with a velocity of 20 cm/sec. The lava was confined to a narrow channel, and Kjartansson described how it partially crusted over and how marginal levees developed by progressive welding of crustal fragments towards the centre of the channel until, ultimately, the channel became completely covered. Many years of observations of pahoehoe flow mechanisms in Hawaii were similarly summarised by Wentworth & Macdonald (1953). They showed that lava tubes formed under two contrasting situations. Citing Stearns' observations of the 1935 eruption of Mauna Loa and Macdonald's observations of the 1942 eruption, Wentworth & Macdonald showed how flow near the vent was confined to a narrow channel. Here, levee construction took place by spattering and overflow, and a roof was developed by the jamming of crustal slabs across the lava river. They envisaged the margins of the flow to be fed by a myriad of small distributary tubes which branched from the main tube. Thus, an alternative process of tube construction was the chilling of a shell around pahoehoe toes. Repeated outbursts lengthened the toes and small tubes were formed.

In his study of the lava caves on Mt. Etna, Poli (1959), possibly stimulated by Rittmann's speculations (Rittmann, 1958), believed that the wall structures in lava tube caves indicated laminar flow. The hypothesis was presented that a lava flow constituted many successively enclosed cylinders of lava whose viscosity increased externally. This features could be identified in a lava tube cave on Mt. Etna where the walls were composed of layered concentric structures (interpreted here as lava tube crusts). Thus, at the cessation of eruptive activity the more fluid internal cylinders drained of lava leaving a tube-like cave.

* The cover photograph of lava flowing in a tube as seen through a “skylight” on Hawaii was kindly supplied by D.W. Petersen, of the U.S. Geological Survey's Hawaiian Volcano Observatory. It is reproduced by permission of the editor of “Studies in Speleology” (Vol. 2, No. 6) in which Petersen and Swanson's account of this phenomenon is presented. Colour blocks by courtesy of Gilchrist Bros. of Leeds, and by Hawaiian Volcano Observatory.
FIG. 3

1 Thin pahoehoe lava flow in an open channel. Surface spatter caused by steam from trapped water.


3 Pulses in lava supply produce thin, layered levees.

4 Decrease in supply forms tube, shelves, and benches with gutters against the walls.

5 Temporary increase in supply, and therefore heat, engulfs previous forms and enlarges the diameter of tube - thermal erosion.

6 Rapid decrease in supply causes rolls of plastic lava to arch down. festoon ridges on floor.

MODEL OF SPELEOGENESIS IN LAVA AFTER KERMODE (1970)
Another European study which followed traditional lines was carried out by Bravo (1964) on the famous Cueva de los Verdes, Lanzarote. Bravo believed the cross-sectional form of this cave indicated both a primary and a secondary volcanic phase (Fig. 1). The primary phase consisted of the inundation by lava erupted from the volcano 'La Corona' to form the extensive lava field 'Malpais de la Corona'. During the secondary phase, lava continued to flow from the vent in diminished quantity over the recently solidified and, in places, still hot lava field, eroding a deep channel. Levees were formed along the borders of the channel by the throwing up of scoraceous material, and during a momentary cessation of the flow, a superficial crust was formed over the channel. Bravo envisaged that this conduit was deepened by melting of the floor, until total cessation of flow led to the draining of fluid lava. In a later work, Montoriol-Pous & de Mier (1969) agreed with Bravo that cross-sectional forms of the cave could, in some cases, have originated in the manner described.

An important work on the theory of speleogenesis in lava was stimulated by the survey of the Australian lava tube caves at Victoria (Ollier & Brown 1965). Field evidence of forms and structures of the caves and the lava flows was summarised and, because of the difficulty in reconciling this information with traditional concepts, a new general theory of lava tube cave genesis was proposed. The structure of the basalt flows around the caves was important to the hypothesis. Where cross-sections were exposed, flows were divided into layers up to several feet thick which lay parallel with the flow surface. Layers were of compact basalt separated by trains of vesicles or partings. Sometimes the layers were buckled, leaving open spaces between them, and at other times partings were not accompanied by buckling. The inner surface of the openings were often lined with stalactites and stalagmites, and in some of the smaller openings the upper and lower surfaces were connected by vertical threads of basalt, apparently stretched out when the layers parted. This 'layered lava', it was thought, resulted from differential movement within one thick flow by the formation of shear planes. The following arguments put forward by Ollier & Brown were also particularly relevant to their point of view:

a) The existence of caves indicated the withdrawal of magma, and this meant the lava had both a solid and a liquid phase within the same flow.

b) Cave shape suggested an abrupt passage from liquid to solid lava. This was also shown by the discordant contact between the inner lining of some caves and the surrounding basalt.

c) The discordance between the curved cave walls and the horizontally layered lava suggested erosion of the layered material.

d) The 'treacle' effect at partings between layers in the lava were thought to indicate that parts of the layered lava was still sticky at a late stage.

e) The 'hands' of stalactites in some caves indicated that there must have been some liquid in the interstices of the layered lava which was under pressure and was squirted into the caves from the walls.

Ollier & Brown believed the layering of the lava was connected with laminar flow and produced by its partial congelation. Individual layers were separated by partings of vesicles and liquid lava, and the thickness of the layers increased with increasing viscosity. It was said that when layered lava formed, the more congealed lava went into layers while the more liquid lava was concentrated between laminae. The liquid lava then became further segregated and came to occupy tubes running through the layered lava. Mobile lava eventually became concentrated in a few major channels, and these were a continuing source of heat and could erode some of the earlier layered lava. The end result was cylinders of liquid lava flowing through tubes cut in virtually solid layered lava.

A simpler model which summarised in diagrammatic form the processes which led to the formation of a lava tube cave in a flow confined in a narrow valley, was presented by Macdonald & Abbott (1970). This is reproduced in Fig. 2. It was common, they also noted, for minor tubes to develop at flow margins in pahoehoe toes.

In a slightly later work on lava tube caves in New Zealand, Kermode (1970) produced a similar model to that of Macdonald & Abbott's for flow confined in a valley (Fig. 3). Kermode, however, envisaged progressive enlargement and thickening of the flow, so that definite stratigraphical horizons could be identified, and tube enlargement took place by thermal erosion.

Interesting fieldwork was carried out by the writer (Wood 1971) in the Icelandic lava tube cave Raufarhólshellir. The smallest type of tube was generally found above lavafalls in the extremities of the cave and had a form consisting of a flat floor and an arched roof. A second type of tube, into which the first type passed below the lavafalls, carried three lateral benches, one of which was found above a lateral shelf and was continuous with the single lateral bench of the first tube type. A third type of tube was the joint controlled, rectangular, breakdown tube, and a fourth type was composed of a series of irregular forms of large size which constituted the main tube. Cross-sections of the lava flow were rarely observed in the smaller tubes, but it was observed that because of the natural weaknesses at flow unit contacts, ropy surfaces were sometimes exposed. By the identification of successive contacts, therefore, the relationship between flow structure and tube forms could be understood. It appeared that the smallest tubes represented the drained cores of single flow units, and that each flow unit represented a potential 'primary tube unit'. Larger tubes were seen to be constructed of multiples of this single unit, due to erosion and remelting of the crusts of the original flow units by the lava stream. The second type of tube, therefore, was observed to be made up of two flow units or primary tube units (Fig. 4), one situated above the other, whose dividing crust had been eliminated. Similarly, although evidence was stated to be difficult and inconclusive, it was envisaged that the main tube was made up of multiple, superimposed and adjacent units, due to the
accretion and overflow or by spattering and spattering. Peterson & Swanson described the formation of a crustal slabs, (c) the growth of a stationary crust over the flowing stream and (d) the growth of levees by roof construction observed comprised (a) growth inward of a crust from the banks, (b) the jamming together of crustal slabs, or they formed in discrete lava flows which emanated directly from the vent. There were few minor lava tube caves in the Bend area. Most were said to be major lava tube caves 'of the type described by Ollier & Brown', and these were found in flows several kilometres long. Greeley showed that thick flows in his study area were subdivided by horizontal discontinuous partings giving the effect of layered lava. He noted that it was unfortunate that it was often impossible to distinguish layered lava from multiple flow units. It was agreed, however, that shear planes and layered lava were essential to the formation of major lava tube caves. An interesting point made by Greeley in the study was that the degree of meandering of a tube may be attributable to the degree of fluidity of the mobile conduit within the flow body. Thus, he envisaged that tubes could migrate from one side of the flow to the other, until they were more firmly stabilized in position by the congealing lava. Further, from the surveys of the two lava tube cave systems, it was shown that the Arnold system comprised of large lava tube segments oriented along a single trend and interrupted by large collapse ponds, while Horse system was seen to be composed of smaller segments that lay parallel or branched and were often disconnected. The difference between the two were regarded by Greeley to result from a difference of gradient. Horse system formed in a flow with a more gentle gradient than the Arnold system.

Greeley & Hyde (1971) made a study of 833m of lava tube cave in the Cave Basalt, a pahoehoe basalt which originated on the SW flank of Mount St. Helens, Washington, and extended southward for 11km down a stream valley cut in pyroclastic deposits. They believed the cave system had two modes of formation. Some tube segments were seen to have formed by the accretion of spatter leading to the formation of arched levees and eventually a complete roof. Other tube segments were developed in layered lava and resulted from laminar flow. Greeley & Hyde thought that spatter accretion was a product of more turbulent flow on a steeper gradient, as shown in parts of Little Red River Cave, while laminar flow was a product of lesser gradients. The important point was also made in this work that subsequent lava flows could modify quite extensively the first formed tube by filling or partial filling, remelting the tube roof to form vertically elongated tubes, reshaping and eroding the tube walls, stacking additional tube levels above the first, or any combination of these.

The observations made by Greeley (1971b) of actively forming lava channels and lava tubes during the 1970 eruption along the Upper Eastern Rift Zone of Kilauea, are extremely important to the discussion on lava tube cave genesis. The report is also interesting because it summarises previous observations in Hawaii. Greeley's own observations showed that root-over roof over the flow body, by the jamming and fusing together of crustal slabs, and by levee formation resulting from accretion of lava through overflow and spattering. He also noted multiple flow along rifts and suggested this may be a mechanism leading to the formation of unusual cross-sections seen in some lava tube caves. Here, each flow or surge could produce a new upper level, with individual dimensions and characteristics dependent upon flow volume and velocity. Concerning this procedure, Greeley produced a diagram (Fig. 5) which bore similarities to the model drawn up by Wood for the origin of more complicated tube forms in Rauðhólsheiði. It was concluded by Greeley that a single lava channel could display braided channel flow, open flow, mobile crustal plates and roofed channel along its length. The difference in type appeared to be related, in part, to topographic slope and thus to flow velocity. Support was also found for the hypothesis put forward by Baldwin (1953) that tube formation may result from a complex system of overlapping and coalescing lobes of lava, each of which cools and becomes part of the tube roof.

The complex braided distributary system of lava tubes observed by Greeley on Kilauea during 1970-1 were also described by Peterson & Swanson (1974). They were impressed at the considerable role lava tubes play in the growth and importance of Hawaiian volcanoes. Frequent observations were made of the extensive and intricate system of lava tubes developed in the thin flows that slowly advanced down the south flank of Kilauea. The processes of tube development were seen to vary with distance from the source vents, but in general tubes were seen to form by the roofing of lava streams and by advancing lava toes becoming encased in chilled shells. Open channels were common near the vent and the various methods of roof construction observed comprised (a) growth inward of a crust from the banks, (b) the jamming together of crustal slabs, (c) the growth of a stationary crust over the flowing stream and (d) the growth of levees by accretion and overflow or by splashing and spattering. Peterson & Swanson described the formation of a master tube into Alea crater by the crushing of a south flowing channel, and showed how Alea became an underground holding tank and feeder reservoir for the extensive lava flows lower on the flank. Further away from the vent and below Alea crater, processes of tube formation were seen to be similar to those near the vent, though they were slightly modified because of different flow characteristics. Small, narrow channels
FIG. 4

EVIDENCE OF STACKED CONDUITS IN RAUFARHÓL SHELLIR
AFTER WOOD (1970)
FORMATION AND MODIFICATION OF LAVA STRUCTURES AS A RESULT OF SUBSEQUENT LAVA FLOWS AFTER GREELEY (1971b)

IDEALISED SECTION OF PAHOEHOE TOES AFTER MACDONALD (1967)
were seen to develop though they were only 1-3m across, and from the main channel ran a complex of distributaries in a braided pattern. Tubes developed at the front by chilling of a skin around pahoehoe toes. Sometimes, by looking through 'skylights' (collapsed portion of a tube roof), underground lava falls could be seen, formed when lava in a high level tube plunged into a deeper tube. It was thought this would occur when a younger tube emptied into a skylight of an older one, or when the weakened roof of a lower tube collapsed beneath a stream of an overlying tube. Sometimes, also, Peterson & Swanson observed the formation of lower level roofs beneath skylights. Layered lava similar to that described by Ollier & Brown was seen, but Peterson & Swanson believed it represented successive thin flow units and not internal shearing. "...we saw no evidence to support the currently fashionable proposal by Ollier & Brown that lava tubes are the result of internal shearing of thick flows'.

Discussion: flow mechanisms and speleogenesis in lavas

In order to evaluate the models and observations outlined in the previous section, it is pertinent to divide the discussion into two parts. In the first place, the concern of the volcanospeleologist must be with the genesis of the simple, primitive form of conduit, and the laws under which it forms in newly erupted pahoehoe lava, whether that form be the whole cave or branches within an intricate network. When such a basic model is realised the mechanism for the formation of complex morphological patterns of conduits may be discussed.

It has long been recognised that lava tubes are characteristic features of basaltic pahoehoe lava flows, and that the extrusion of the flow depends to a marked degree upon the early formation of tubes which, by conserving the heat of the lava river within, allows the flow front to progress further from its source than it would normally. Observations of surface phenomena by numerous volcanologists (in Hawaii, for example, by Jones, 1937; Jagger, 1947; MacDonald, 1967; Swanson et al., 1971) show that it is common during the early stages of an eruption when discharge is often greatest, and during later stages near the vent, for pahoehoe to flow in an open channel. Here, after the channel is established, particularly near the vent, more turbulent flow causes splashing and spattering along the channel margins, building high levees between which the stream flows commonly several feet down. It was recorded in the previous section how levees may become arched and a firm roof established under special circumstances across the channel. Flow through the channel is not generally uniform but pulsates, and during high pulses lava may escape the channel and spread laterally as minor units which cool quickly. Early formed channel roofs may either be strengthened or destroyed during such pulses. The author was fortunate to observe this phenomenon during the Heimaey eruption in the Vestmannaeyar Islands during April, 1973. Although flow here was viscous, a natural arch was seen to develop between two high pulses across part of a lava channel which was under observation. Once established, the arch was overridden by lava of subsequent pulses and appeared to be considerably strengthened by accretion above and below. This continued through six or seven large changes in lava level, until an extra large surge of lava swept away the apex of the arch.

Further from the vent the lava has cooled and degassed quite significantly, and the surface is observed generally to darken and to crust. The nature of the crust appears to vary from a thin grey skin, to pahoehoe slabs, or to irregular scoricious blocks, according to flow characteristics and viscosity. Numerous Hawaiian observers attached great importance to tube genesis through the jamming of crustal slabs. Blocks and slabs were seen to develop on Heimaey when the discharge dropped and movement generally slowed, and these were later swept downstream to be piled onto a roof and onto levees. Due to the nature of the lava on Heimaey, however, blocks did not become welded, but lay upon the channel as unconsolidated moraine-like material, as froth piles up at a weir, and this was strengthened by remelting and accretion beneath.

Near the flow front channel type flow changes to tongue type flow. Tubes predominate, and the flow front advances in a spasmodic fashion which has been described to resemble the advance of an amoeba 'by the protrusion of successive lobate toes'. Mobile lava, under hydrostatic pressure, may burst forth from the front and chill quickly with the result that a shell develops around the extending tongue. These become buried by later tongues. Cliff and roadside exposures in Hawaii often reveal superimposed pahoehoe toes (Fig. 6), some of which may be over 1m thick and contain small tubes.

Is it possible that these phenomena may be explained in terms of thermo-dynamic considerations? The argument has been put forward that thermo-dynamic principles are not applicable; 'Thermo-dynamics deals with equilibrium systems only; it cannot consider dis-equilibrium processes' (Tubbs, 1972, p.9). Practically all lava in a state sufficiently fluid to flow at all, must consist of a mixture of phases – bubbles of gas and solid crystals suspended in a liquid melt. It is true that lava is subject to rapid changes of temperature, is low in conductivity and inadequately mixed in relation to its dimensions, which means that it is unlikely to approach homogeneity in temperature, density, viscosity, pressure, or physical composition. However, certain valid conjectures may be made and speculated upon.

In the early stages of an eruption, very hot and fluid lava flows out from the vent over a cold surface. This is a situation that does not represent a steady condition, for there is a sharp transition between the newly erupted lava and the cold surface, and this is subject almost immediately to a rapid widening of the temperature slope and a corresponding decrease in its steepness. Flow of heat to the outer parts of the lava tends powerfully towards congelation resulting in a narrowing of the channel. Ultimately a restricted lava channel is formed which represents a condition where the velocities of flow and of heat delivery by the stream are nearly equal to the heat loss through the channel sides and to the air, and is sufficient to keep temperatures nearly constant. Thus, in a given lava channel there is a steady state of thermal and flow conditions.
The mobility of the lava appears to depend on the maintenance of high temperatures. It is important to consider that the internal transfer of heat by conduction is probably insignificant compared with convection, and there must therefore be a relationship between movement and the relationship of heat. If the moving lava is losing heat to the air and the ground, the faster flow will suffer a smaller temperature drop than a slower one and will more effectively maintain a higher mobility. Since mobility increases with temperature, and the rate of movement will increase with higher temperatures, the temperature, in turn, is more fully maintained by an increase or maintenance of movement.

The flow fails to overflow its margin and movement ceases, therefore, through lack of heat, and selection may take place amongst the several flow routes away from the vent. The great initial widths of lava flows are not maintained and, in the course of continued flow, something like a principle of thermal economy operates to narrow and thicken the flowing tongue. The hot liquid is cooled by heat transfer across what has been called a 'heated perimeter' (analogous to 'wetted perimeter' of flowing water) between the top lava-air surface and between the walls and floor. It is thought that solid channel walls which are sufficiently solid to stay in place are likely to be about 700°C, and the adjacent outer parts of the moving lava will have slightly higher temperatures, but these will be lower than the more rapidly moving central thread. In any lava channel, then, there must be a zone of transition of temperature and viscosity from the centre outwards and downwards to the wall rock. This transition of temperature may be as much as 200°C and take place over something like 1m of thickness. In maintained open channel flow greatest heat loss must be through the lava-air contact, but it appears at this stage that the velocity of flow and heat delivery by the stream keeps temperatures nearly constant. In this type of flow the maximum velocity and highest temperatures are at the top and in the centre of the channel.

As velocity and corresponding thermal delivery drop, perhaps because of the greater distance from the vent source or the slowing of the extrusive activity, the thread of maximum temperature and maximum velocity drop below the surface of the flow. The top now gradually becomes covered by solidified crustal blocks that move with the most rapid flow. Gradually, the increase in the continuity of crusting and the increased viscosity results in a decrease of top velocity. It is at this point that a channel may become completely bridged, while fairly rapid flow continues beneath in a lava tube. Thus, there is a change down-slope from channel flow to tongue flow. The subcrustal movement of lava results when the rate of thermal transfer by channel flow falls below the rate of thermal loss through the sides and bottom of the channel and loss from the surface of the lava to the air.

Thus, on observational and speculative grounds simple conduit formation in basalt lava flows is acceptable through the crusting of open channels and the chilling of a skin around pahoehoe toes. Additional models, such as those provided by Bravo, Poli, Macdonald and Kermode, are but variations upon a similar theme. The processes of conduit genesis in basalt flows may be summarised:

1. by the crusting of open lava channels;
   a) by spatter accretion
   b) by simple, wholesale crusting
   c) by the jamming and welding of crustal slabs
2. by the chilling of a skin or crust around
   a) thick, rapidly emplaced lava flows or lava flow units
   b) pahoehoe toes.

It must be remembered that each process is dependent upon particular flow conditions which may be a function of the physical properties of the basalt, the distance from the vent, and the nature of the topography over which the lava flows.

These conclusions are important, for they provide the foundation upon which the evolution of complex morphologies in lava tube caves may be understood. In order to account for such complicated lava tube cave systems as the Mt. Hamilton Lava Cave, Ollier & Brown proposed an hypothesis of layered lava. In seeking an explanation for these fantastic forms, they related lava structures to tube morphology. Unfortunately, their observations and conjectures may be flawed on a number of points. Their hypothesis hinges upon the concept of laminar flow and the development of shear planes. The writer has argued elsewhere (Wood, 1971) that the description provided by Ollier & Brown of layered lava would compare well with a description of a flow composed of thin, superimposed flow units. Peterson & Swanson also reached the same conclusion. The six accompanying photographs illustrate the range of lava structures found around lava tube caves in Iceland. They are shown here because the author believes 'layered lava' structures cannot be unique to Victoria or, indeed, the Bend area of Oregon, and if this structure be a pre-requisite to lava tube cave genesis, then it should be identifiable at all cave entrances and collapses. Instead, in Iceland, two basic structures are observed: multiple flows and a type of piled slab lava. Most typical is the structure of Plate 1., which is similar to that shown by Greeley (1971a) in Figs. 4a & 4b of 'layered lava' structures in Idaho and Washington. The extensive cave systems of Surthshellir/Stephanshellir, Vidgelmir and Raufarhöfshellir are formed in this type of lava, and in all cases buried, oxidised,ropy surfaces are identifiable at regular intervals throughout the vertical section, indicating flow unit contacts. Plate 2 shows such a contact at the roof collapse of the lava tube cave Borgarhellir. It is interesting to compare Plates 1 & 2 with the description of 'layered lava' given by Ollier & Brown. The alternate banding of compact lava and trains of vesicles can be shown to exist in superimposed flow units. Buckles were held to be important also by Ollier & Brown. Buckles are seen in Plate 1 and are the obvious result of movement below an already concealed and quite solid crust. Where flow units are buried by subsequent units, the buckles are preserved as shown in Plate 2. Commonly, the roof of cavities below crustal upwarps are adorned by lava stalactites,
1. Entrance to Surtshellir showing lava structures.

2. Contact of flow units in west wall of entrance to Borgarhellir.

3. Lava showing structures resulting from laminar flow.

5. Mouth of buried lava channel at entrance to Borgarhellir.

6. Three superimposed flow units in the west wall of the entrance to Borgarhellir.
and the cavities lie in a transverse direction to the lava flow. Partings identified by Ollier & Brown which show a ‘treacle effect’ may be small cavities formed by the coalescence of vesicles (see Plate 4). Lava which may be interpreted as resulting from laminar flow is shown in Plate 3. This shows narrow bands of highly vesicular lava and, in some places, fractures which might be interpreted as shear planes. This lava was seen at an entrance collapse of Stephanshellir, and formed part of the compact central mass of the uppermost flow unit. No cavities were found relating to this particular structure and it obviously played little parts in speleogenesis here.

The second type of lava structure observed about lava tube caves in Iceland is that shown in Plate 4, and perhaps these are more suited to the name ‘layered lava’. A structure very similar to this was observed by the author forming by means of unloading and overthrusting of thin crustal slabs onto levees by a lava stream during the Heimaey eruption. Plate 5 shows piled crustal slabs bordering a partially drained and buried lava channel. Plate 6 shows large thicknesses of slabs forming the upper part of three superimposed flow units at the entrance collapse of Borgarhellir. It is obvious here that cooling of a surface crust on units was sporadic and the crust continually broke up through movement of the mobile mass and through surges.

It appears that these two structural types in Iceland are a function of the viscosity of the lava. The lava of Heimaey fell intermediate between Hawaiiite and Mugearite, was erupted at low temperatures, (1030°C), and was estimated to contain some 47% crystals at the time of the eruption. This lava has affinities with the Snaefellnes lavas from which Plates 4, 5 & 6 are taken. Lavas of interior Iceland were generally more fluid and show more typical flow unit structures as in Plate 1.

Another objection to the theory of lava tube genesis by means of shear plane development, is that the lava during its passage through the congealed layers must lose much of its heat and therefore its capacity to erode. Once movement of lava through a given opening tends to slow down, there must be a powerful ‘feedback’ effect which, by diminishing temperatures, will tend towards cessation of movement altogether. Only an external addition of heat, such as increased temperature of lava passing through, or heating of the whole mass from outside, can lead to increased movement. As a further objection, it is difficult to envisage a horizontal arrangement of laminae and shear planes in relation to the lava tube, rather than a concentric one proposed by Poli, unless erosion has considerably enlarged the conduit through several flow units.

Greeley’s support for the hypothesis proposed by Ollier & Brown is inconsistent. The flow structures observed at Bend appear to be similar to well-jointed, thin, flow units. In addition, his concept of the hypothesis changes, so that there is little difference between his diagrammatic model shown in the Mount St. Helens paper and the model outlined by MacDonald.

In the light of recent observations, the hypothesis put forward by Ollier & Brown does not seem credible and in accordance with field evidence. Perhaps more reasonable models which could account for the genesis of more complex morphologies are to be found which treat individual tube segments as simple conduits formed under the laws and principles outlined above. Any lava tube cave segment, therefore, under this principle, developed either by the crusting of an open channel, or by the rapid chilling of a skin around a flow unit or smaller pahoehoe toe. Both are directly applicable to the genesis of complex tube patterns, either separately or combined. Greeley and Peterson & Swanson described how the Kilauea lava streams assumed intricate, braided networks, any of which if crusted and drained would form extremely complex lava tube cave systems. Greeley, Peterson & Swanson and the writer have all pointed to the importance of coalescing drainage channels carried in stacked conduits or flow units. It could be that complicated three-dimensional tube patterns are a combination of both processes. Here is scope, then, for improved field techniques in ancient flows, so that unit flows and tube segments may be identified and isolated.

Discussion: Classification of lava tube caves

In the light of the preceding discussion, it would seem ridiculous and pointless to attempt a classification of lava tube caves based upon genetic considerations, for it is obvious that throughout the length of a single lava tube cave numerous speleogenic processes may have been at work. Attempts have been made to classify lava tube caves, however, and these are reviewed here in the hope that some basis for a descriptive classification may be drawn up which will facilitate observation recording and further research on lava speleogenesis.

A descriptive classification of lava tube caves was found necessary by Halliday (1963) to compare morphologies of the caves of Washington. He found it necessary to refer to the planimetric and longitudinal form of the caves. They were either described as simple/unitary (unbranched) or complex (branched). Both types of cave could be vertically complex, and the complex varieties could possess re-entrant, confluent or effluent passages, or a combination of these. Greeley (1971a), however, agreed with Hatheway & Alika (1970) that there were two basic types of lava tube caves, minor and major caves, differentiated by their genetic characteristics. These have been outlined above. A vague, hypothetical genetic classification was presented by Harter & Harter (1970) which was based on wall stratification and thermodynamic principles. They found 5 basic classes of lava tube caves: surface tube, true trench, semi-trench, rift cave and interior tube.

Owing to the present limited knowledge of speleogenesis in lava any genetic classification is premature. We have already found difficulty with the concept of major and minor lava tube caves as described by Greeley, and the classification proposed by Harter & Harter is to a large extent hypothetical, bearing little comparison with examples in the field. Points of criticism of the latter classification have been published by Tubbs (1972), though Tubbs himself appears to be a little misguided over flow mechanisms prevalent in basalt lava flows.
Yet a means is needed to differentiate basic lava tube cave varieties, so that unified descriptions can be made and progress achieved towards an understanding of their origin. Halliday has shown that caves may be categorised on the basis of descriptive fact which becomes available on the measurement (survey) of the cave. Such solid facts as the planimetric and longitudinal morphologies form a sound basis for classification and there is no reason why Halliday’s system should not be taken up. Vulcanospeleologists should beware, however, that the morphology of the lava tube cave described is not the result of modifications of the original conduit formed during its draining, but is the form developed during the extrusive phase of volcanic activity. Multi-level caves may result, for example, from the formation of stacked conduits or from the formation of false floors and roofs during the draining of the conduit. Secondary features are extensively described in the literature and are easily identified by the experienced lava tube caver.

Thus, it is proposed here that lava tube caves be described as simple/unitary or complex. Simple or unitary lava tube caves should be unbranched, sinuous, elongated and uni-level in character. Perhaps they represent the simple conduit described above? Complex lava tube caves should bear predominantly ingressive tubes or more complicated anastomosing tube patterns. A preliminary examination of lava tube surveys in the literature suggests that aggressive patterns may be rare. Gradations between aggressive, ingressive and anastomosing forms most probably exist. Complex tube types may be formed at a common level or they may be multi-level. Multi-level caves are easy to identify in practise from caves divided by secondary features because of the occurrence of fall-falls.

It may be found that unitary forms develop in single, thick, rapidly emplaced and cooled lava flows. Tubes of more complex morphology in Iceland, such as the confluent Raufarfh Isheir and the more complicated anastomosing Surtshellir/Stephanshellir are found considerable distances from the vent (10km and 26km respectively), and obviously result from more complex flow mechanisms. It is of paramount importance, therefore, that cave forms be related to flow structure and the topographical situation in which lava tube cave genesis is induced.

Conclusions

The current conflicts in vulcanospeleology resulting from the difficulty found in reconciling complex cave forms with traditional models of lava tube cave genesis can now, in the light of recent observations, be resolved. Observational and speculative considerations show that models on speleogenesis in lava may be reduced to two: (a) the crusting of open channels by spatter accretion, by wholesale crusting, and by the jammimg and welding of crustal slabs or (b) the chilling of a shell around flow units or pahoehoe toes. Complex lava tube caves do not appear to result from laminar flow and the development of shear planes, but are most likely the result of a simple conduit described above? Complex lava tube caves should bear predominantly ingressive tubes or more complicated anastomosing tube patterns. Complex tube types may be formed at a common level or they may be multi-level. Multi-level tubes may result from the formation of stacked conduits or from the formation of false floors and roofs during the draining of the conduit. Secondary features are extensively described in the literature and are easily identified by the experienced lava tube caver.

Multi-level caves may result, for example, from the formation of stacked conduits or from the formation of false floors and roofs during the draining of the conduit. Secondary features are extensively described in the literature and are easily identified by the experienced lava tube caver.

Conclusions

The current conflicts in vulcanospeleology resulting from the difficulty found in reconciling complex cave forms with traditional models of lava tube cave genesis can now, in the light of recent observations, be resolved. Observational and speculative considerations show that models on speleogenesis in lava may be reduced to two: (a) the crusting of open channels by spatter accretion, by wholesale crusting, and by the jammimg and welding of crustal slabs or (b) the chilling of a shell around flow units or pahoehoe toes. Complex lava tube caves do not appear to result from laminar flow and the development of shear planes, but are most likely the result of crusted braided flow, or coalescence of drainage channels carried in flow units or smaller toes. Multi-level tubes may be the product of the last mechanism and may represent stacked conduits.

Genetic classification of lava tube caves does not appear to be a worthwhile exercise at the present time, for a single cave may be the product of more than one vulcanospeleogenic process. Grounds may be found for supporting a descriptive classification of tube forms based upon cave surveys, as used by Halliday in the ‘Caves of Washington’.

25th July, 1973. Christopher Wood,

12 Kenton Gardens,

St. Albans,

Hertfordshire.

References


CUEVA DEL VIENTO: THE WORLD'S LONGEST LAVA TUBE CAVE

C. Wood

As a result of survey work in the lava tube caves of Tenerife by members of the Shepton Mallet Caving Club during August, 1973, and April, 1974, the various world records claimed for different lava caves can now be classified. The information presented here is the best that is available at the present time.

The world's longest lava tube cave was, until recently, held to be the famous Ape Cave, situated on the flanks of Mount St Helens, Washington. The survey made by Halliday (1963) put the length of this cave at 3418 metres with a vertical range of approximately 213 metres. This may seem short in terms of the major limestone caves, but it must be remembered that by the very nature of lava tubes to form thin, fragile roofs, which readily collapse, it is often difficult to find long, continuous segments of cave passage. There are, indeed, many collapsed tubes in the U.S. and elsewhere that are as much as 24 kilometres in length. As an example, two lava tubes from the Undara Crater, Einasleigh-Mt. Surprise area, N. Queensland, can be traced for 38 kilometres, but even here the longest uncollapsed segment so far explored (Barker's Cave) is only 732 metres long (Watt, 1972; Grimes, 1973).

In 1964 Dr T. Bravo speculated that if the line of roof collapses ('jameos') located above the well-known Cueva de los Verdes be traced upon the surface, a total length of 10.8 kilometres could be given for this cave. Unfortunately entrance into the cave could not be gained through many of the collapses from the surface. During the preceding years of 1961 and 1962, however, successive expeditions to Lanzarote by members of the Grup de Exploraciones Subterraneas (GES) of the Sociedad de Ciencias Naturales Club Montanes Barcelona had forced a route through some of the boulder piles beneath the collapses, and claimed a continuous underground traverse of first 4280 metres, and later 6100 metres. The GES therefore claimed the Cueva de los Verdes as the longest lava tube cave in the world (Montoriol-Pous and de Mier, 1969), it also beat Ape Cave with a vertical range of 230 metres. Fired by their success on Lanzarote the GES spent part of 1967 in Iceland in the hope of beating their world record. They explored and surveyed thirteen lava caves and, although the length of the Cueva de los Verdes was not exceeded, this Spanish group claimed second and third places in the world order for Surtshellir and Raufarholshellir respectively (Armengou and Montoriol, 1968). These latter caves were resurveyed by the SMCC in the summer of 1970 and 1972, when the length of Raufarholshellir was shown to be 1350 metres, with a vertical range of 32 metres (Ellis, 1971); and the length of Surtshellir was given as 1970 metres. It was regarded by the SMCC members in 1972, as it was also by the GES, that the neighbouring caves Surtshellir and Stephanshellir were in fact one single complex and, although no connection was made between the two, a total length of 3490 metres could be quoted.

It seemed only a little later that the U.S. lava cavers became disconcerted by the 'claim jumping' going on in Europe. Halliday in particular decided to check the Spanish claims of long lava tube cave in the Canary Islands, and in November, 1971, he visited Lanzarote and Tenerife. He maintained before he left for the Canary Islands that, from correspondence with Montoriol, it did not seem possible for the Cueva de los Verdes to dethrone Ape Cave of its premier position, for the Lanzarote cave was described as segmented and not therefore in accord with the U.S. definition of one continuous lava tube cave section (Halliday, 1972b). Indeed, it was shown that the longest single cavernous segment of the Cueva de los Verdes was only 1600 metres long (Halliday, 1972c). It seemed on this basis also that none of the Iceland...
caves could compete for premiership. While on Tenerife, however, Halliday visited the little known lava tube cave called Cueva del Viento (Cave of the Wind) with Carlos Teigell and other members of the Seccion de Exploraciones Vulcanoespeleologicas (SEV) de la Guancha del GrupMontanero de Tenerife, and he was forced to admit that here 'the system has more footage than Ape Cave'. Actually the Cueva del Viento had been under continuous study by the SEV, and in 1970 a claim had been made to a length of 6181 metres (Teigell, 1970). The GES also visited the Cueva del Viento in 1971 (Montoriol, 1971) and in their expedition report also quoted a length of 6.2 kilometres, together with an amazing figure for the vertical range of 580 metres.

This was not the end of the story, for a little later Halliday (1972a) reported a cave named Manjung-gul on Chejudo Island, Korea, to have 5470 metres of cave passage surveyed, with the longest section 4600 metres long. It was said that there was also an upper level in the same cave estimated to be about 1800 metres long, but as yet unsurveyed. Peterson (1972) in another recent article, put the length of this Korean Cave at 7865 metres. Yet another cave, called Bilcino, on the same island, was reported by Halliday to have a length of 6000 metres, but no details are known as yet.

In his 'Atlas des Grands Gouffres du Monde' Courbon (1972) mentioned both the Oaeva de los Verdes and the Cueva del Viento. The length of 5 kilometres (+) is quoted for the Cueva de los Verdes, with a vertical range of 260 metres. No length is quoted for the Cueva del Viento but the extraordinary vertical range of 580 metres is given, as it is by the GES. This large vertical range, according to Courbon, put the Cueva del Viento as the fourth deepest cave in Spain in 1972. It is unfortunate that the source for these figures is not given.

This, then, was the state of the affair prior to our own visit to Tenerife in August, 1974. Three large lava tube caves were explored by us during the two week stay, but only one, which we believed to be the Cueva del Viento, was surveyed. Our own preliminary figure for the total length of the cave surveyed was 7920 metres. If we are to abide with the U.S. definition, however, then the length of the longest continuous cave segment, lying upflow of the single roof collapse, was 7690 metres. This beats any rival mentioned here.

On return to Britain where we could check references, our confidence that we had surveyed the whole of the Cueva del Viento was shaken. While on the island we had found difficulty initially locating the cave and this had only eventually been accomplished with the help of the local people. From the single collapse entrance the major part of the cave lay upflow and comprised an extremely complicated, interconnecting system of small tubes which, in the farthest extremities, was linked by a four metre drop to a larger, lower cave passage trending obliquely to the direction of the upper cave. The farthest point of the cave in the upflow direction terminated in a very tight squeeze which was not forced, and we had evidence to believe that it had never been forced. Downflow, after only a short distance from the entrance collapse, the cave was blocked by another roof collapse which, on examination, could not be passed either into the cave passage beyond, or out onto the surface of the flow.

Confusions arose because the various Spanish articles we retrieved while on Tenerife, and later translated, all gave different accounts and locations for the Cueva del Viento. The GES expedition report gave the cave two collapse entrances located in the central part and known as 'Cueva de los Piquetes' and 'Cueva de los Breveritas'. Another article in a local newspaper included a map of the area of the cave with a crude cave survey superimposed upon it. This showed two entrances in the central
part of the cave, breaking it into three segments, with one of the entrances corresponding with the entrance to our own cave. The most important article translated, which gives exact locations of the cave entrances, generates even more confusion, for these figures do not correspond with any others. The other references to the cave by Halliday (1970c) mentions the total length of 6.2 kilometres is broken into two caves with lengths of 4623 metres and 1578 metres respectively.

Had we attempted to locate the collapse at the lowest point in our cave upon the surface in August, we might well have been able to pass into more cave passage beyond. This thought had occurred to us at the time, but because of the intensive surveying programme we found no time to test this hypothesis. The conclusion to be drawn from these articles, however, was that we had no completed the whole of the cave, but only the upper two segments. It was for this reason that a second expedition was arranged to Tenerife in April, 1974. On this visit a lower cave was found that had a length of 2008 metres and was separated from the cave we had surveyed during the preceding August by the roof collapse at the lower end of that cave. Thus, the Cueva del Viento is in fact two caves separated by a single collapse, with entrances to each segments (Cueva de los Piquetes and Cueva de los Breveritas) being found in the central part of each. The total length of the original cave reached a magnificent length of 10.0 kilometers with a total vertical range of 478 metres.

The other anomaly in the literature is the reference to the large vertical range of the Cueva del Viento. Although we found the gradient extremely steep (a gradient of 1 in 6), the figure of 580 metres for the vertical range of the cave seems ridiculous, for the highest figure quoted in any of the articles is only 640 metres (Teigell, 1970) for the highest of the two entrances. Examination of the sketch map and survey in El Dia shows that even here the three combined cave segments cannot have a vertical range of more than 400 metres. In fact, we found it slightly more.

The last word comes from Halliday, who commented on my report of our trips to Tenerife in August, 1974, that was published in "Descent" No 26. In "Descent" No 28 Halliday reports two possible contenders to the Cueva del Viento as the world's longest lava tube cave: Kazumura Cave, on Hawaii, is reported to be over 5500 metres, and "a Korean lava cave" (presumably one of those mentioned above) has been emplaced to about the same general length.

Clearly, the outstanding fact is that the cave surveyed by SMCC members in August 1973, and April 1974, is a world beater. Our surveys figure for the longest (highest) cave segment far outdistances any rivals. It would be impracticable to arrange the world's longest lava tube cave in descending order, for data is inadequate and definitions are not international, but the best information available to us at the present time is as follows:-

<table>
<thead>
<tr>
<th>Cave Name</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cueva del Viento (Cueva de los Breveritas)</td>
<td>7690 metres</td>
</tr>
<tr>
<td>Kazumura Cave</td>
<td>5500 metres</td>
</tr>
<tr>
<td>Manjung-gul</td>
<td>4600 metres</td>
</tr>
<tr>
<td>Ape Cave</td>
<td>3418 metres</td>
</tr>
</tbody>
</table>

References
Bravo, T. 1964, En volcan y el malpais de la Corona. La 'Cueva de los Verdes' y los 'Jameos'; Publicaciones del Cabildo Insular de Lanzarote, Arrecife, 31p.
Footnote - Depths of lava caves

The Cueva del Viento has a surveyed depth of 478 metres, but it should be noted that the system consists of two caves separated by a few metres of impenetrable collapse - which renders this figure unacceptable by normal methods of calculating cave depths. It therefore appears that the world's deepest lava caves include:

- Cueva de los Breveritas, Tenerife, Canary Isles: 261 metres
- Cueva de los Piquetes, Tenerife, Canary Isles: 217 metres
- Ape Cave, Washington, U.S.A.: 213 metres

and almost certainly the Kazumura Cave on Hawaii has a depth of this order too.

A feature of most lava caves is that for these entire lengths they lie only a few metres below the surface - hence the common roof-collapse entrances and indeed tree roots hanging from the cave roofs. They obtain their great depths (or vertical ranges, which is perhaps a better term to use) by having fairly gentle gradients beneath very long hillsides. A rather unusual cave therefore is Dynamited Cave (Washington, U.S.A.) which attains a depth of 110 metres and involved pitches of 5, 12, 8 and 6 metres in a trip to the bottom.
Cristopher Wood

FACTORS CONTRIBUTING TO THE GENESIS
OF CAVES IN LAVA
Gruppo Grotte Catania

ATTI DEL
SEMINARIO SULLE GROTTE LAVICHE

Catania, 27-28 agosto 1975

Cristopher Wood

FACTORS CONTRIBUTING TO THE GENESIS
OF CAVES IN LAVA
Christopher Wood (*)

FACTORS CONTRIBUTING TO THE GENESIS OF CAVES IN LAVA

RIASSUNTO — I vari modi e le circostanze in cui si formano le cavità laviche riflettono varie condizioni e combinazioni di fattori che ne influenzano la genesi.

Questi fattori sono riconosciuti come componenti delle proprietà fisiche del magma, del carattere dell'attività effusiva, e delle condizioni ambientali esterne. Il loro ruolo nella genesi delle cavità è controverso, e si è visto che esse si formano solo quando questi fattori possiedono certe proprietà e mantengono certi rapporti.

Quei fattori che si possono valutare direttamente sul terreno sono la pendenza, la topografia e la quantità di lava emessa. Altri fattori che non possono essere misurati si manifestano attraverso le forme e le strutture osservate nelle stesse cavità laviche, e nelle colate che le hanno originate.

Si è fatto un elenco di osservazioni e rilevamenti che possono essere eseguiti sul terreno, ed è su questi che deve basarsi l'interpretazione dei fattori genetici e lo studio comparativo delle diverse forme di cavità.

SUMMARY — Varying forms and occurrences of lava tube caves reflect the varying relationships and combinations of factors controlling cave genesis.

These factors are recognised as components of the physical properties of the magma, the character of the effusive activity, and the external environment. Their roles in cave genesis is discussed and it is seen that caves result only where the controlling factors possess certain properties and hold special relationships. Those

(*) University of Leicester, Geology Dept.; B.C.R.A.
factors which may be measured directly in the field are identified as slope, topography and the amount of lava discharged. Other factors which cannot be measured are seen to have expression in the forms and structures found in lava tube caves and the parent lava flow.

A list is made of observations and measurements which may be made in the field, and it is upon these that interpretation of the genetic factors, and comparative study of diverse cave forms must rest.

A full understanding of the genesis of lava tube caves can only be accomplished through comparative study, for the variability of the forms and occurrences of caves must reflect variabilities in the nature, the relationships, and the combinations of the factors controlling cave genesis. In the analysis of an individual lava tube cave and its immediate environment, many of these factors are not subject to direct measurement, but must be deduced from the field evidence that is available. In considering this problem, this paper sets out to assess the roles that individual factors play in cave genesis in lava, and to suggest which pertinent structures and forms in lava flows are suitable for interpretation and comparative study.

Résumé of present knowledge of cave form and occurrence.

Lava tube caves are known on a world-wide scale, almost exclusively in basaltic lava fields, though in fact the lava of a great majority of such caves has never been analyzed. In basalts, they appear to be most common in the more fluid variety known as pahoehoe, where they are regarded as characteristic features and are believed to play an important role in the emplacement of the flow. Some are found in the more viscous variety known as aa, but their extent in this lava type is not known. Some workers have suggested that lava tube caves develop on slopes falling within a limited range of gradients but in the present writer's experience the range of gradients is wide.

Lava tube caves vary both in distance from, and position in, relation to the vent, or lava source, apparently due in part to the underlying relief. In form, caves range from simple, sinuous unbranched tunnels, to complicated braided labyrinths with superimposed levels connected by lava falls. In size they range from flat-out crawls to enormous tun-
nels over 20m diameter, while lengths vary from a few metres to over 10km, and if collapsed segments are included some caves are known to have had lengths in excess of 20km. They have a great diversity of cross-sectional form ranging from an almost perfect circle, a half circle with a flat floor, a crescent, a triangle, or to a shape resembling a wine glass. In most caves ornamentation lines many passages and is best seen in beautiful stalactitic and stalagmitic lava growths. For the majority of caves the structure of the lava flow in which they occur, and the relationship of the passage pattern and form to the lava structure, has never been determined. Where in has been examined, apparently similar lava structures have suffered different interpretations, resulting in contrasting genetic models.

Factors that contribute to cave genesis.

The surface morphology and internal structure of a lava flow is the result of complex relationships between a number of variable factors which are components of the physical properties of the magma, the character of the extrusion, and the external environment in which the flow takes place. As lava tube caves are characteristic geomorphic forms of some lava flows, then their origin too is controlled by these factors. However, not all these variable factors are of equal importance. Also, some are completely independent of the other factors, while others interact and are partly or even wholly dependent upon the independent factors.

1) Factors influencing the physical properties of the magma (viscosity):
   a) the chemical composition of the magma
   b) the amount and condition of the gas held in the magma
   c) the temperature of the magma
   d) the solid load carried in the magma

2) Factors determined by the character of the extrusion:
   e) the amount of magma discharged
   f) the rate of discharge

3) Factors determined by the external environment:
   g) the gradient of the slope beneath the flow
   h) the topography of the ground over which flow takes place.
   i) flow resistance
The principal physical property of the magma is viscosity, a fundamental factor in cave genesis. This is controlled in turn by the chemical composition of the magma, the amount and condition of the gas present in it, its temperature and its solid load.

Lava in general is composed of partly molten silicates containing volatiles either in solution or present as bubbles in the melt. Chemically, the control over viscosity is influenced by the relative proportions of silicon to bases in the melt. Generally speaking the smaller the proportion of bases, like iron and magnesium, to silicon the higher is its viscosity. Acid lavas have higher viscosities, therefore, because it is thought the spare bonds of the silica tetrahedra, not taken up by bases, link to other tetrahedra and form three-dimensional polymer networks, restricting the freedom of flow.

If, however, the proportion of bases is large, then these basic atoms will take up the spare bonds on the tetrahedra, and the bonding of one tetrahedron to another is less extensive. In this case the liquid consists more nearly of independent units with interconnecting bonds, making flow easier. Clearly, the most viscous flows are of acid lavas, like rhyolite or dacite, while the intermediate lava, andesite, is not as fluid as the basic lava known as basalt.

The amount of gas dissolved in the magma is the result of the relationship of the rest of the magma and its temperature and pressure. Nearly all magma contains more gas at depth than it can hold in solution when the pressure is reduced as it reaches the surface. Separation of excess gas therefore takes place in newly erupted magma and may be seen as bubbles in the liquid (vesicles in consolidated lava). The effect of gas on the viscosity of the magma is complicated for if a large amount of gas remains in solution, viscosity is low, and if the gas has separated into bubbles in the melt, then viscosity in also low if the bubbles are not too numerous, but if they are abundant and whipped into a foam, then viscosity is increased.

Temperature has a simple, yet important, control over viscosity, for the higher the temparture of a magma, the lower its viscosity. Heat is lost through radiation and conduction to the air and the ground, and temperature is subject to change throughout the length and cross-section of a lava flow. Also, there is an intimate relationship between the mobility of the lava and the maintenance of temperature, which must be a fundamental consideration in this discussion.

The solid load of the magma is determined by the gas content and the temperature of the magma, for a reduction in both, or either, will
cause crystallization. The solid load is normally made up of crystals suspended in the melt, together with crustal fragments engulfed during flow. Viscosity is increased by the process of thickening the liquid through frictional drag between the grains.

Although lavas in general have high viscosities when considered with other fluids, they do nevertheless possess a significant range of viscosities. Viscosity is defined here as that property of a fluid which determines its resistance to a shearing stress. The reciprocal of viscosity is mobility. Thus, liquids with low viscosity, or high fluidity, flow readily, while those of high viscosity, or low fluidity, flow slowly and with difficulty. As a fluid with a general high viscosity, a lava will flow with laminar motion and rarely, if ever, with turbulent motion. This means, in laminar flow, that the flow paths of the individual particles of the fluid do not cross or intersect, but have path lines which are essentially parallel. In lava flows of very high viscosity, the fluid portion of the flow results in a greater amount of internal shearing than more fluid flows, and hence affects mobility.

Factors linked with the character of the extrusion and the external environment include the amount and rate of discharge, the gradient of the slope over which the flow passes, and the local topography. Discharge is important simply in determining the size of the lava flow, and hence cave system, and maintaining the mobility of the flow by the addition of hot magma from the vent. Slope also has a control over the mobility of the flow, both in terms of flow velocity and in the maintenance of mobility. Slope is an important factor to consider in the drainage of lava tubes. The topography of the pre-flow surface may cause the lava to be confined within a narrow valley (Fig. 2), or to spread upon a wide plain, or to flow with a different velocity over variable gradients, or to become ponded. Under these varying circumstances, flow mechanisms are affected.

The magma is subject to change even while it is in the vent, for the temperature and pressure of the external environment are significantly lower than the temperature and pressure at depth. In a response to regain equilibrium with the new environment, both at the vent and during flow, the lava suffers losses in temperature and gas which lead to progressive crystallization. Account, therefore, must also be taken in this discussion of the dimensions of distance and time.

The processes of cave genesis in lava, to which these factors contribute, may be divisible into two distinct genetic stages, involving (a) the construction of a conduit, or lava tube, within the flow body
and (b) the drainage of the lava tube, usually after cessation of activity at the vent, to produce a lava tube cave. The discussion will therefore consider the role individual factors play in these separate genetic stages.

Circumstances inducing the growth of conduits in lava flows.

It is only when the determining factors possess certain properties and bear special relationships that internal conduits in lava develop. Lava tubes have been observed in lava flows characterized by a pahoehoe surface, in some aa flows, but never in block lava flows. These terms were introduced by geologists to designate the three common surface forms and internal structures which characterize the majority of lava flows. Pahoehoe is recognized by a smooth, billowy, or ropy surface; aa by a fragmental and spinose surface; and block lava by more regularly shaped fragments than aa, with less spinose surfaces. Observations have shown that the surface expression and internal structure of these lava flows is a result of its particular mode of emplacement, which in turn is determined by its viscosity.

Although chemical composition represents the major control of the viscosity of lavas, the other controlling properties make an important contribution to the relative viscosities of the lavas richer in bases, such as basalt. It has been observed, for example, that both pahoehoe and aa commonly form in the same flow, that a flow of pahoehoe may change aa downslope, that quiet effusion at the vent produces pahoehoe, and violent lava fountaining produces aa. It is therefore generally considered that the formation of aa instead of pahoehoe is largely the result of greater viscosity, resulting from lower temperatures, a smaller gas content, and a more advanced crystallization. Even more viscous than aa is block lava, which may be derived in a similar way to aa, but in general it appears that the principal determinant of flow of block type is the chemistry of the lava, for block lavas tend to occur in basalts richer in silica than aa and pahoehoe, and are most typical in andesites, lavas with an intermediate silica content. It is also interesting to note here that although the rock trachyte may contain nearly as much silicon as rhyolite, and more than dacite, it is commonly less viscous. This may be because of the larger amount of gas dissolved in the magma, or that trachyte contains less free silica, and hence has less polymeric bonding. Commonly, therefore, trachyte and phonolite tend to form thinner and broader flows than dacite or rhyolite, and it has been reported that they may even show pahoehoe structures as are usually formed in basalt.
There is, then, a basic difference between silica-rich and base-rich lava flows. Lavas rich in silica, like rhyolite and dacite, if they remain coherent and are not ripped into clouds of incandescent particles by the expanding gases, are always so stiff from the start that they congeal as thick tongues before they have travelled far. Lavas rich in bases, in contrast, have the appearance of great fluidity, travelling large distances and forming thin flows.

The fluid motion within the mobile central part of a flow of high viscosity tends to separate into a series of parallel sheets, slipping over one another, and lying parallel with the ground which causes frictional drag. In fact flow is often so viscous that towering masses from the central part of the lava flow are heaved up by the imperceptibly slow forward movement, only to collapse due to contraction on cooling to litter the flow surface with angular blocks. This type of movement is characteristic of block lavas, whose advance is generally so slow that only the fall of blocks down the scree covered front shows that it is taking place. The flow mechanism and mode of advance of an aa flow is similar to that of a block flow, but there are important differences related to the greater mobility of aa. Close to the vent an open stream is formed, generally moving along the middle line of the flow, while towards the front the river disappears beneath the spinose rubble of the flow surface. On a steep slope the front may advance at a rate of several kilometres per hour, advancing with a rolling motion, gradually burying the rubble which avalanches from the top surface and the flow front. The main mass of an aa flow is a very viscous paste, moving with less internal shearing than block lava. In some aa flows lava tube caves have been discovered, showing that in some cases internal flow becomes restricted to preferred parts of the flow. In very fluid lavas pahoehoe flow mechanisms prevail and are quite distinct from aa or block lavas, although gradations exist between the three types. Pahoehoe near the vent may consist of a single sheet moving as a unit, the front of the flow advancing with a rolling motion like aa. More typical, however, larger flows are fed by a complex of internal streams beneath the crust, liquid being visible only at the flow front or where the surface is broken. At the vent the mobile stream is soon confined in a channel between levees of its own construction, by splashing, spattering and overflow. The channel may be braided or simple, and extend for considerable distances, but sooner or later, as a result of heat loss to the air and the ground, the surface freezes over and the active flow becomes restricted to pipe-like zones of liquid movement, feeding the active flow front which may lie miles downslope. At the front the lava
does not flow as a unit, but rather by the protrusion of one small tongue after another, said to resemble the pseudopodia of an amoeba. These tongues advance only a short way before they chill and lose their mobility, though the process is repeated time and time again, ultimately constructing one compound sheet.

Recent observations of active flows in Hawaii have shown that internal conduits originate either as the result of the roofing of an open channel, or through the retention of movement within pahoehoe toes. Indeed, open lava channels appear to be essential prerequisites for the survival of active flow, for through their construction, enough mechanical energy is conveyed to overcome the friction of the slope, and thermal energy losses to the air and the ground are reduced sufficiently to maintain temperatures which allow continued flow. Indeed, there is an intimate relationship between movement and the retention of heat, for convection, rather than conduction, accounts for the principal method of heat transfer, and the mobility of the lava depends on the maintenance of high temperatures. Thus, mobility increases with temperature and, in turn, the temperature is more fully maintained by an increase or maintenance of movement.

Consider this principle during the early stages of emplacement: here the lava is subject to thermal and mechanical losses and the marginal parts of the flow fail and cease motion for lack of heat. Mobility will be retained along the paths of most active movement only. The situation is one where initially very hot and mobile lava is in contact with a cold surface and there is a sharp transition between the two. This is not a steady condition and a transitional zone of temperature and viscosity is produced, resulting in a velocity change towards the edge of the active flow. This, in turn, through its reduced flow of heat to the outside of the mass, tends towards congealing and causes the flow to narrow. In this way a well defined channel is produced in which there is a steady state of thermal and flow conditions, with a zone of transition of temperature and viscosity from the central thread outward and downward to the wall rock.

In any open channel the maximum temperature loss is to the air; but the velocity of the flow and heat delivery through the channel are such that the channel is kept nearly constant. However, as the velocity and the delivery of heat is reduced, perhaps through a reduction in discharge or slope, or because the flow has suffered excessive heat loss through prolonged flow, the maximum temperature filament drops below the surface and the top of the lava stream begins to solidify. Eventually, through increased viscosity, the top velocity of the
lava stream will be reduced and the channel may become completely bridged, with relatively rapid flow now continuing in a lava tube beneath. There is thus a change downslope from channel flow to tongue flow, which takes place when the rate of thermal delivery falls below the rate of thermal loss to the sides and bottom of the channel, and from the surface to the air.

As observed by geologists in Hawaii, there are many ways in which lava channels may be roofed. Near the vent flow is often turbulent, and splashing and spattering may lead to the construction of arched levees which eventually join across the stream. Alternatively, the channel may become covered by a stationary crust which is thickened by overflow, or crustal slabs carried in the stream may jam across the channel. These processes are not necessarily confined to pahoehoe, but may also take place in aa channels. However, in aa and more viscous flows, areas of surface crust are broken up by the drag of the thick fluid beneath, and roofs over open channels may only develop where the resulting debris piles up at an obstruction, as froth piles up at a weir. Although there is therefore a very high likelihood for conduits to form in aa, it may be that only the most fluid flows are capable of evacuating the tube, or even should evacuation take place, the unconsolidated rubble which forms the roof of the tube may not have the coherence to withstand collapse.

By their very nature also, toes which are peculiar to pahoehoe flow fronts hold small tubes. The advance of pahoehoe is by the outbreak of mobile magma through the crusted front which immediately develops an elastic skin which stretches as the new formed tongue elongates, until it has chilled sufficiently to arrest movement. Not only do these tongues accumulate side by side, but they pile one above the other also. Sections of pahoehoe may reveal stacks of conduits within the compound flow.

Circumstances inducing conduit drainage.

It does not necessarily follow that because lava tubes develop in some lava flows they will form caves, for the conduit may not drain off the fluid lava which it is transporting. The transition in the genetic stages, from a lava tube to a lava tube cave, must, by definition, take place when the discharge of lava to the tube declines and eventually ceases. This occurs when discharge to one lava tube is captured by a more favourable flow route during the period of active vent effusion.
(an analogy with stream piracy and «misfit» streams), or when activity at the vent ceases completely.

Drainage takes place when two conditions are fulfilled:

a) when discharge wanes the lava within the tube must retain a degree of mobility on the existing slope;
b) there is a space to which the residual lava can drain.

a) Drainage depends upon the mobility of the residual lava in the conduit, and this, as we have already recognized, is a function of its viscosity, controlled here mainly by temperature and the gradient of the slope down which it flows. Returning to the discussion on the relationship between temperature and mobility, the mobility of the lava within the lava tube must depend principally on the maintenance of high temperatures, and temperature is more fully retained by a maintenance of movement. Movement is normally, during active flow, provided by continuing discharge and gravity. When discharge to the tube diminishes or ceases, movement takes place only as a response to gravity. Temperatures are not maintained, viscosity increases, and a feedback effect, because of diminishing temperatures, will tend towards cessation of movement altogether. Residual lava in a tube will therefore have a greater viscosity than the lava during active flow. This means that it is very rare for a tube to drain fully of its residual lava, and generally movement ceases before a lava tube has completely emptied. This leads to the production of varying cross-sections within the cave (Fig. 1). For the evacuation of very viscous flow, the slope must be steep. For example, the Cueva del Viento has extremely spinose aa floors which could only have retained movement because of the very high gradient of 1 in 6. In contrast, some Icelandic caves in fluid pahoehoe, such as Vidgelmir or Surtshellir/Stephanshellir, appear to have drained on almost negligible slopes (Fig. 2). The contrast may be carried further and is even more striking with regard to passage form, for passages in the Cueva del Viento appear to have drained with difficulty because of the more viscous flow, resulting in low, tortuous cave passages which are often flat-out crawls over spinose aa, but in the Icelandic caves just mentioned passages are vast and the amount of congealed residual lava is small. The study of some Icelandic caves has also shown that details of the pre-flow topography is also an important factor, for they show that selected segments of long lava tubes drain only where topographic detail is favourable. The drainage of Raufarhólshellir, for example was controlled by the fossil cliffs lying downflow
of the lava tube, and similarly the caves of the Hallmundarhraun are separated by areas of steeper gradient (Fig. 2).
b) The other condition which must be fulfilled before lava tube drainage commences is that there must be a space into which the residual lava can flow. During active flow the lava passing through the conduit causes a build-up of hydrostatic pressure behind the flow front and as long as pressure is great enough to rupture the crusted front, advance of the flow will continue. It may be in very fluid flows that this process continues for a short while when discharge at the vent has ceased, causing the higher part of the conduit to empty. An alternative may be that space for residual lava is provided in an underlying cave, leaving a segment of the sube above empty of the lava it once transported. This may not seem the rare occurrence it seems, and the process is to some extent identified in caves which possess lavafalls. Another alternative, also very common, results because most large tubes during their active life are not filled to the roof with mobile lava, either because discharge has diminished since the construction of the roof, or the lava river has eroded the floor and lowered the lava level. In any case, at cessation of vent activity, residual lava will drain under the pull of gravity to the lower part of the flow, entirely filling the conduit here, and leaving the higher part near the vent empty. This process explains the very strange phenomena of vast tunnel-like lava tube caves closing down completely in only a few metres.

Measurement of the genetic factors in the field.

Because the work of the speleologist is restricted mainly to inactive lava fields, many of the factors contributing to cave genesis are not subject to direct measurement, but must be interpreted indirectly by means of the available field evidence. A case in point is viscosity. The viscosity of an active lava flow is accessible for precise measurement with special instruments, but in older lava fields the worker must deduce the general viscosity from such observations as the nature of the surface form of the lava, its length in relation to its thickness, its structure, its chemistry, and so on. This will act as a guide to mobility. However, factors which are available for more or less direct measurement in older lava flows, are slope, major topographic detail, and the amount, but not the rate, of discharge.

Observations and measurements which may be recorded in the field, suitable as interpretative data, are listed below:

1) the survey of the cave, to show plan, long profile and passage cross-sections;
2) the relationship of the cave profile with the profile of the flow surface and the pre-flow surface;
3) the analysis of the topographic situation of the cave;
4) the relationship of the cave to the vent;
5) the relationship of one cave segment to another;
6) the chemical and mineralogical analysis of the parent lava;
7) the analysis of the structures and forms seen on the surface of the flow, in exposures near the cave, and visible within the cave through spalling of the wall lining;
8) the analysis of the internal cave forms and features.

Thus, although we possess some knowledge of the contributions individual factors make, we do not know the whole range of properties, relationships and combinations which these factors hold in the genesis of caves. Varying combinations and relationships of factors must be reflected in the diverse types of lava tube caves present throughout the world. It is through the comparative study of these diverse forms that full understanding will be reached.

REFERENCES

Mill M. T., (1974): Survey Cueva del Viento, Sheet 1 (Cueva de los Breveritas); Published Shepton Mallet Caving Club.


Wood C. (1974): Survey Cueva del Viento, Sheet 2 (Cueva de los Piquetes); Published Shepton Mallet Caving Club.
In the last few years the volcano Mount Etna has shown quite vigorous activity. The last major eruption was in 1974, and in 1971 extensive lava flows poured down the 3323 m high mountain from a series of flank vents, cutting road communications and threatening the villages which cluster on the agriculturally rich lower slopes. In fact, Mount Etna is in a state of almost continuous activity, as even the most casual observer lower down the slope can see from the constant plume of white smoke hanging over the summit. Most recent activity was reported in December when new lava was seen to be overflowing the NE crater, one of the summit craters, and was spreading down the higher northern slopes. Sicilians naturally hold an especial interest in their volcano. On the one hand it poses a menace to the inhabitants upon its slopes; in the villages and hamlets, and in the city of Catania (pop. 387,939), itself built upon ancient lava flows and destroyed several times by eruptions of the volcano. On the other hand Sicilians look to Mount Etna for its beauty and grandeur, and its offer of such recreational pursuits as walking, camping and skiing. Cavers in Sicily are no exception, for being without extensive areas of limestone, they turn to their volcano in pursuit of their sport locally, and have here been very successful in the discovery of over 150 caves. Principals in the exploration of these caves are members of the Gruppo Grotte Catania. As a section of the Club Alpino Italiano, whose centenary year fell in 1975, Catanian cavers sought to celebrate the anniversary of the parent club at the end of last August with two weeks of caving on Mount Etna, culminating in a conference ('Seminario sulle Grotte Laviche') on lava tube caves both internationally and at home. As one of the contributors to the conference I took the opportunity to drive the 1500 miles to climb on Mount Etna and to sample the Sicilian caving scene at first hand.

I was impressed with Mount Etna and saw much of the northern slopes of the volcano during the week prior to the conference, though I was unable to take part in any of the organised excursions. From a camp at Villaggio Turistico Mareneve at 1450 m (the most suitable site for water, strangely a commodity in short supply on the volcano), daily expeditions on foot to the higher parts of the northern slopes had objectives of exploring individual groups of caves. Principal interest was in the enormous lava flow of pahoehoe basalt erupted between the years 1614-24. This particular flow was the only major pahoehoe lava flow on Mount Etna, most others being of the aa basalt variety which was more viscous when emplaced and today possesses a surface covered with extremely spiny cinder. Pahoehoe is generally more fluid when emplaced and one of its characteristics is the formation of lava tubes and surface features related to tube-fed flow. This is not to say that lava tubes do not occur in aa, for many small lava tube caves were seen during our short stay in this type of lava. One particular aa flow was erupted in 1923 from a fissure at 1880 m, lying just above our camp. This particular flow is famous for its deep lava channels, which on close examination yielded lava tube caves of varying shapes and sizes in their walls, illustrating well the genetic relationship between open and closed lava channels. The lava tube caves in the 1614-24 lava flow were much bigger, and the longest was visited by us first because of its close proximity to the forest track which skirts the mountain from Villaggio Turistico Mareneve (incidentally, providing one with magnificent vistas to the north). Grotta dei Lamponi lies at 1728 m in that part of the 1614-24 flow known as the Lava del Passo dei Dammusi, and although reputed to be Etna's longest cave, it had never been surveyed in its entirety. Helped by Alfio Cariola (our amiable guide and interpreter) and Blasco Scammacca, we felt
POZZO DEL M. DUE PIZZI INF.2 (N.W.)

LOCATION: Lat. 37° 47' 08" Long. 14° 59' 58" Alt. 2515m.
MOUNT ETNA NORTH, SICILY.

Section North-South

External wall of loose accumulated scoria
very unstable

Height of Station 6

Surveyed by Mr. R. T. 

Plan of hornito below Station 6

Extended Section A-B

The hornito was surveyed on 21st August 1975 by members of
Gruppo Grotte Catana Phoenix Exploration Club, Shepton Mallet
Caving Club. Hornito below Station 6 surveyed with a survey compass
(Rob 54/360) and compensator (RPA 415/360 PC) and a 30m Fison
tape. Hornito above mainly sketched.

This survey drawn by C. West on 1st January 1976.
could make our contribution by carrying out our own survey of this cave. Grotta dei Lamponi was of especial interest to us because the very end of the cave lay 55 m below the surface of the flow. This is most unusual, for lava tube caves normally only have thin roofs (hence the common roof collapses), and one must suppose that the lava flow was here buried by later units of the same flow. Another cave visited lay at a height of 2030 m in the 1614-24 lava, 4 km WSW of Grotta dei Lamponi, and because of the ice partly filling it, was known as Grotta del Gelo. It had an imposing entrance and a magnificent layering of the clear ice at the bottom of the cave. Still higher in the same flow at 2200 m was possibly the best preserved and most classically formed lava tube cave we visited on Mount Etna, Grotta Aci. Over 400 m in length, it had a tiny entrance roof collapse through which a 10 m ladder was slung. It was practically all uncollapsed tube, of perfect form, showing varying floor features with changes of gradient.

Another highlight of the week was the descent of a hormito. In fact it was intended to descend both the hormitos known as Due Pizzi, located at a height of 2515 m, but because of problems in belaying the ladder, and because a sketch survey was made of the northwest hormito, we were underground until early afternoon, and the attraction of a new lava tongue trundling past us not 250 m away took any ideas of exploring the second hormito from our minds. Hormitos are bee-hive shaped cones located on the surface of lava flows whose origin is due to gas-charged spatter from deeper in the lava flow escaping through cracks in the lava crust, building up cones of piled plastic clots. The hormitos on Mount Etna were the largest I had ever seen, towering above the surface of the flow by over 50 m. On eventual descent we found the ladder pitch to be 32 m, though the full depth of the central shaft was 50 m. At the bottom was a large chamber floored with boulders through which one could climb to find the remnants of a tube 10 m lower.

Returning off the volcano, the 'Seminario sulle Grotte Laviche' was held in the Dept of Biology at the University in Catania. It was extremely well planned and executed, and when the papers are published later this year they will represent the most up-to-date review on speleogenesis in lavas. The morning of the first day (27 August) was a greeting to participants and it was an opportunity to see the film of the 1971 eruption of Mount Etna made by Dr R. Romano (Inter. Inst. Vulcanology, Catania) - though I thought it very poor. The afternoon also began with a film entitled 'Etna, anatomia di un vulcano', made by Vincenzo Barbagallo, the principal guide on Mount Etna, and was a definite improvement on the last film, including good pictures of the latest eruptions. This was followed by a paper written by Prof. Alfred Rittmann (Inter. Inst. Vulcanology, Catania) on 'La formazione delle grotte laviche', in which he discussed the physical characteristics of flowing basalt, and the role of viscosity in tube formation, and firmly put the conference in a scientific frame of mind. My own paper followed on 'Factors contributing to the genesis of caves in lava', in which it was explained which variable factors contributed to cave genesis, which could be taken up for measurement in the field, and the need of comparative study.

It takes a lot of adjustment on the part of a British caver to attend a conference organised by Italian cavers, for I was beginning to learn after the first day that one never enters the conference hall until at least one hour after the advertised starting time - and even then proceedings may not begin until the hosts have turned up, shall we say 20 minutes later! Actually, the record was 2 hours after the advertised time of the start of proceedings on the second day! However, the long wait was eventually worth it when Dr. L. Villari (Inter. Inst. Vulcanology, Catania) on behalf of Dr. D. W. Peterson and Dr. D. A. Swanson, of the Hawaii Volcano Observatory, read a paper which sought to add more information to, and explain in more detail, the paper written by these authors for Studies in Speleology ('Observed formation of lava tubes during the 1970-71 eruption of Kilauea Volcano, Hawaii'). As one would expect,
excellently produced and highly pertinent photographs were shown of tubes
in formation, and views on lava tube genesis were discussed in the light of
recent work by other authors. This represented a most constructive
discussion. Then came the paper I have been particularly waiting for,
that of Prof Cliff Ollier, from Australia, on 'Lava caves, lava channels
and layered lava'. Prof Ollier, with M.C.Brown, published in 1965 a paper
which was the first major scientific interpretation of lava tube caves
('Lava caves of Victoria'). The theory they put forward in that paper linked
tube formation with internal shearing of thick lava flows. It had been
accepted by many authors as explaining many of the features lava tube caves,
but due to certain criticisms which could be made of the theory, I was
particularly interested to hear if any new evidence would be presented.
Interestingly, Prof Ollier did believe his theory still relevent in the light
of new work on lava tube caves, and explained in what context. Because of
the short discussion that followed, a note by Prof J.Montoriol Pous (Univ.
of Barcelona) and J.De Mier (Club Montanos Barcellones) was not read, though
these authors were unable to send a full paper. This was a pity, for they
have been leaders in the exploration of many of the world's longest lava
tube caves, and it would have been interesting to hear their views. I did
not really catch the gist of the paper read by Giorgio Pasquini (Univ. of
Genoa), because my interpreter (kindly supplied by Gruppo Grotte Catania)
leaned over to whisper after a few minutes 'He's mad!' (though I'm sure in the
nicest possible way), and refused to say more. It certainly led to animated
discussion, none of which I understood. When things calmed down, a short
paper by Dr Ronald Greeley (University of Santa Clara, California) was read,
entitled 'Lava tubes on other planets', showing us the evidence that lava
tubes may exist on the lunar surface, connected perhaps with simous riles
which may be partly collapsed tubes. Again, it is a pity that Dr Greeley did
not have time to prepare a longer, deeper paper, for he has enormous experience
and much to contribute to this field, and is one of those fortunate people who
have studied tubes in formation in Hawaii and been able to compare these
observation with structures of lava tube caves in ancient lava flows. A
short paper followed by A.Lucrezi (Gruppo Speleologica Aquilano) which was a
bibliographical history of lava tube caving, and the conference that morning
finished with Fabio Brunelli and Blasco Scammacca (Gruppo Grotte Catania)
discussing the variety of caves on Etna, with many good photographs.

After the usual late start, which I was now ready for, the afternoon session
started with Prof. D.Caruso (University of Catania) discussing 'La problematica
biologica delle cavita nelle lave'. This was followed by a paper on
archeological remains found in lava caves on Mount Etna by A.Larosa and E.Picone
(Centro Sicil. di Iniziativa Archeol., Siracusa), and Prof. S.Cucuzza Silvestri,
Director of the International Institute of Vulcanology in Catania, gathered
together the points raised in the conference, illustrated these with his own
observations, and opened a general discussion. Topics ranged from ice in
caves, airflow, hydrology, pseudokarst and lahars. The conference was closed
in true caving style at the local Yatching Club restaurant, after a very
successful two weeks of activities.
4. Caves in Rocks of Volcanic Origin

C. Wood

The superficial resemblance between the forms of limestone and of volcanic rocks is often striking. Features characteristic of karst—lapiés, solution and collapse dolines, swallow holes, extensive cave systems, gorges and natural bridges—may all be seen in regions of volcanic rocks. Solution is not, however, the dominant process of landform evolution in volcanic rocks, and the geomorphology of some volcanic tracts has been termed "pseudokarst" (Rosack, 1952; Haliday, 1954, 1960). Without examining the concept of pseudokarst in its entirety, caves in volcanic rocks will be discussed here within this context of karst-like landforms of non-solutional origin.

The investigation of caves in rocks of volcanic origin is known as "vulcanospeleology". Volcanic caves present as wide a diversity of size, morphology and origin as limestone caves, though they are somewhat restricted in occurrence to rocks which are of Tertiary age, or younger, because weathering agents destroy them relatively rapidly. Speleogenesis may occur both in lavas and in pyroclastic rocks.

In lavas, the special flow characteristics resulting in cave formation are a function of fluidity, which is determined in turn by the gas content, the chemical composition and the temperature of the lava. "Acid" lava rich in silica, such as rhyolite or dacite, is too viscous to form caves. Basaltic lava, on the other hand, has greater mobility and it is in this rock that volcanic caves attain their greatest significance. Even here, basaltic lava flows fall into three general types—pahoehoe (or "ropy"), aa (or "cindery") and block lava—depending upon the physical properties of the magma and the resulting forms produced by the flow, each type differing in importance as a cave-former.

In pahoehoe lava the volatiles remain trapped in solution, which results in slower congelation and a greater mobility than in aa or block lava.
Farther from the vent, however, the loss of gas and progressive cooling induces a loss in fluidity and a change to aa or block varieties. Pahoehoe is therefore regarded as the fundamental form of basaltic lava (Macdonald, 1967, p. 2). Flow continues beneath an elastic skin which becomes twisted intoropy wrinkles and congeals with a smooth glistening surface. The front advances by the protrusion of tongues of mobile magma through ruptures in its still half-consolidated skin.

Aa and block lava have a surface form and mechanism of advance which is distinct from pahoehoe. In aa, the rapid loss of volatiles leads to a sudden increase in viscosity and rapid consolidation. Spiny-surfaced masses of solidifying lava are ejected by the mobile magma, giving to the flow a characteristic rough, jagged, clinkery surface. The front of the flow advances with a rolling motion which has been described as resembling the front of the endless track of a tractor, sluggishly burying the blocks of cinder which avalanche down from the top of the flow. Block lava has a surface made up of fragments which are more regular than aa, lacking its rough, spinose character.

Although not common, lava tube caves and other minor cavities may form in aa lava flows (Powers, 1920). The rarity of such features may be due to the greater viscosity of aa and its inability to vacate tubes after cessation of activity at the vent. In pahoehoe, because lava tube caves are regarded as characteristic features, and because a whole variety of smaller cavities are associated with crustal forms upon its surface, discussion of lava caves will be restricted principally to this type of lava.

Accumulations of fragmentary rocks and minerals blown from the vent by the explosive discharge of volcanic gases are known as pyroclastic deposits. Larger and coarser fragments, including volcanic bombs, lumps of scoria or pumice, or blocks of older rocks, pile up near the vent to form roughly bedded volcanic breccia or agglomerate. Finer material that showers down from volcanic clouds as ash travels farther from the vent and, when more or less indurated, is known as tuff. Often beds of agglomerate and tuff alternate with lava flows, and it is in such situations that speleogenesis is most likely in pyroclastic rocks.

CATEGORIES OF VOLCANIC CAVES

The literature reveals few attempts to classify caves in volcanic rocks. In his classic work Ky erle (1923) recognized speleogenesis in lavas and in pyroclastic rocks, and listed two important types of lava caves: "blasen- holhen" and "lavaholhen", corresponding to gas pocket caves and lava tube caves respectively. An attempt was made by Poli (1959) to classify genetically the wide variety of caves he examined on the flanks of Mount Etna in Sicily. A more sophisticated classification was advocated by Montoriol-Pous and de Mier (1969). Caves formed during the period of consolidation of the rock in which they are found were termed "syngenetic", while caves formed after consolidation of the enclosing rock by weathering and erosion were termed "epigenetic". These two major categories were then subdivided into minor groups. Similarly Szentes (1971) classified the caves in the volcanic rocks of Hungary into two main groups, according to whether they formed through primary processes or by secondary processes. Concerned solely with lava caves, Lindsey (1966) listed the more important categories of lava caves, while Harter and Harter (1970) devised a classification of lava tube caves.

There is a wide diversity of speleological forms to be found within volcanic rocks. To avoid confusion the classification of the more important volcanic cavities will be divided into those landforms formed by processes which originate within the earth's crust (endogenic), and those formed by processes which originate on the outside of the Earth's crust (exogenic). Caves formed in volcanic rocks fall into both of these categories:

Endogenic: (a) cavities beneath pressure ridges; (b) cavities beneath spatter cones; (c) blister caves; (d) vent caves; (e) fissure caves; (f) lava tube caves.

Exogenic: (a) caves in bedded tuffs and agglomerate.

MINOR VOLCANIC CAVITIES OF ENDOGENETIC ORIGIN

Because the thickened pahoehoe crust is buckled by the movement of the mobile lava beneath, or by gases escaping from the depths, the surface of a lava flow is commonly diversified by features with a relatively strong relief. Many of these features, when ultimately vacated of liquid lava, contain cavities of variable sizes making the flow surface very cavernous in places.

Of larger order, ranging from 1 to 12 m in height, are long narrow ridges which lie transversely to the direction of flow, termed pressure ridges. They result from compression of the crust by the movement of the mobile magma beneath, and cavities are present in many. Caves are commonly 1-2 m in height, with a roughly triangular cross-section, extending unbroken for lengths of up to 800 m. Examples of cavities in pressure ridges were described by Russell (1902) from Cinder Buttes, Idaho.

Sometimes gases escaping from the lava carry liquid clots of lava
through cracks in the crusted surface of the flow to form steep-sided heaps of welded spatter known as spatter cones. Frequently withdrawal of the magma results in the formation of a dome-shaped chamber, and sometimes spatter cones afford entrance to lava tube caves. In the Craters of the Moon National Monument, Idaho, some cavities are 9 m in diameter and up to 20 m in depth (Peck, 1962). Ollier (1967) described a cavity in a spatter cone near Mt Eccles, Victoria, Australia, which was shaped like an inverted wineglass, with a depth of 30 m, and walls festooned with lava stalactites.

Some cavities develop from the true blister-like lifting of a lava sheet by pockets of steam or other gases trapped within the flow. Small cavities in the surface of McCarry's flow are only 1 m in length and 13 cm in depth, and clearly formed through the coalescence of vesicles (entrapped bubbles of gas) (Nichols, 1946). Larger features were described from Iceland (Mercer, 1966), though from their description they may have been confused with tumuli (domical upwellings of the flow surface by differential pressure on the crust from the mobile flow beneath) or spatter cones. Many of these domes were ruptured at the top revealing bell-chambers of large size, some of which had circular tunnels leading off. Some other interesting blister cavities formed in ignimbrite (welded ash) on the lower slopes of the Fantale volcano, Ethiopia (Sutcliffe, 1970; Gibbon, 1974). Many blisters held circular domed chambers 18-30 m across and about 3.5 m high. It was thought that the layered ignimbrite had become sufficiently plastic to dome up locally where gases had built up.

At the vent it is usual for the level of the magma chamber to subside after cessation of extrusive activity. A cavity formed in this way described by Lindsley (1966) from the crater of Mt Pisgah, California, consisted of a narrow passageway angling down for 3.5 m. A rather different feature was described from Auckland, New Zealand (Anon., 1957), with a depth of 14 m terminating in a choke. From its description this feature may be similar to the "mortars" examined by Stearns (1924) in the Craters of the Moon National Monument, Idaho, and developed by jets of steam or gas. Some mortars had several branches which united to form a main tube, though most were filled with debris 3.5 m below the surface.

Open fissures are common in lava fields and some formerly carried molten lava to the surface. They are mostly narrow cracks, only a few feet wide and not more than 6 m deep, though they may extend for considerable distances. One enormous fissure system, however, contributed much of the lava of the Snake River Plain, Idaho, and has a depth of several hundred feet (Halliday, 1959, 1966; Ross, 1969). The famous Grippa Djass fissure at Myvatn, NE Iceland, is celebrated for its caverns which contain a hot spring at a temperature of 384° C (105-5° F). Some 260 m of cave has been surveyed in this fissure (England, 1959).

Lava Tube Caves

The feeding rivers of basaltic lava flows, particularly pahoehoe, are extremely complicated. Flow patterns frequently consist of an internal network of interconnecting conduits which sometimes attain considerable vertical and horizontal complexity. The speleologist has an interest in these conduits, or lava tubes, for many are emptied of liquid lava, either wholly or partly, to form lava tube caves. These are speleological features which must rank in importance with limestone caves for size, beauty of internal decoration, complexity of form and detail of formation. They are not merely curious geological features of limited occurrence, for it seems the development of tubes is a characteristic of pahoehoe, and they play an important role in moving lava away from the vent during periods of extrusive activity. A few lava tube caves have been discovered in andesitic lavas.

In Europe, lava tube caves are found in Iceland, the Azores, the Canary Islands, and on some of the Mediterranean volcanoes, notably Mt Etna in Sicily. The Middle East has examples in Syria and Israel, while in Africa lava tube caves have been reported in the Cameroun Mountains, Malagasy, Ethiopia, Uganda, Kenya and are most probably to be found in other countries dissected by the African rift valley system, for example, Zaire. Australia and New Zealand have important locations, and some of the longest lava tube caves in the world are found in Korea. Japan has lava tube caves and so also have many of the Pacific islands, such as Easter Island, Galapagos and, of course, the Hawaiian Islands. References are coming to light of lava tube caves in Argentina, and undoubtedly other locations on that sub-continent will be discovered soon. The largest number of explored lava tube caves are in the western U.S.A. and in Mexico. There are notable exceptions to this list, but it is not regarded that such areas are devoid of lava tube caves, rather that the features are difficult to locate, or there is as yet insufficient local interest.

Even though long conduits are initially developed, the thin fragile roof of drained lava tubes readily collapse (see Plate 4.1), and continuous cave segments are difficult to find. To date, the longest lava tube cave is the Cueva del Viento, on the island of Tenerife, Canary Islands, but even here the total of 10 km is broken into two segments of 7.9 km and 2.1 km respectively. These lengths are short, however, in terms of partly
collapsed tube systems in the U.S.A. and Australia, which have lengths of nearly 40 km in some cases. There is a great diversity too in the nature of lava tube caves (see Fig. 4.1). The Cueva del Viento, for example, comprises a fantastic complex of small interconnecting passages on three different levels. It contrasts with some Icelandic caves, such as the Surtshellir/Stephanshellir system of interconnecting spacious passages formed at one level, or the beautiful Viðgelmir cave with its vast, single, meandering passage. It is interesting also that some caves may be entered through the wall of the crater at the vent, such as one of the Gullborgarhraun caves in Iceland; while other caves seem to originate considerable distances from the vent, such as the Surtshellir/Stephanshellir system and Rauðhólshekkur which lie 26 km and 10 km respectively below the vent.

In terms of speleogenesis, it is possible to distinguish in lava tube caves forms and features which have developed in two quite separate phases of development. The first phase involves the development of a conduit beneath the congealed surface of the flow, through which liquid lava is transmitted from the vent to the advancing flow front. In the second, activity at the vent ceases, the conduit drains and is modified by the adherence of cooled lava to the walls. Both phases are responsible for complexities in the morphology of the lava tube cave, and it is important not to confuse the two.

The cross-section of a lava tube cave is developed both by the mobile lava stream entirely filling the conduit, and by the degree of meandering which takes place within the flow. The diameter of caves is variable and
may range from 1 to 25 m. Commonly, in straight tube sections the cross-section is almost circular, though for a variety of reasons the perfect form is rarely attained. At meander bends the cross-section is asymmetrical with the highest part of the tube situated on the outside of the bend, a direct analogy with the form of a river meander. These cross-sectional forms, however, are developments of the first phase of speleogenesis, and the majority are subsequently modified from the moment draining of the tube commences.

![Image of a cave](image)

**Plate 4.2.** Lateral benches and roof collapse, Stefánshellir, Iceland (*Photo: D. J. Wilkinson*).

Lowering of the lava level within the tube may proceed spasmodically, with individual stands being marked by longitudinal deposits known as lateral benches (Plate 4.2). If the lowering of the lava level is arrested, it sometimes happens that a crust will form over the lava stream, so that with subsequent lowering of the lava level a horizontal partition, or false floor, may remain across the cave. This process may be repeated on numerous occasions, the partitions remaining whole to give the tube what appears to be superimposed tube levels, or they may collapse to leave shelf-like ledges that protrude from the walls. Occasionally, as at Surtshellir (*Mills and Wood, 1971*), the crust was still plastic when the lava stream left it, so that it sagged beneath its own weight.

Apart from modifying the cross-section of a tube, flow features ornament the walls and floors of the cave. Blocks of solid lava which have become incorporated in the liquid flow may gouge the walls of the conduit to produce flow grooves and flow ridges. In multi-level caves solidified cascades of lava, termed lava falls, may be the result of lava passing from level to level. The floor of a lava tube cave may show a wealth of interesting flow features. The more common rough, clinkery floor is caused by gases frothing to the surface as the lava cools, while flows broken into polygonal slabs are the result of jointing due to contraction upon solidification. Sometimes blocks of solid crust may fall from the roof of the cave while the floor is still plastic, and the resulting ripples may be "frozen" and preserved as a floor formation known as a splash concentric.

During the lowering of the lava level, burning gases maintain the temperature in the interior of the lava tube at 1200°C. Jagger (1947) observed this phenomenon through a "window" in the roof of the Postal Rift Tube, Hawaii, and attributed the maintenance of these high temperatures to a blast furnace effect. As a result, lava tube caves are lined with a black vitreous glaze that was sufficiently fluid at the time of its formation to trickle and produce decorations on the walls and ceiling. Usually cave walls exhibit a rippled structure, but if the glaze was highly fluid and flowed rapidly down the walls, vertical ridges or corrugations result, producing minute gourd-like formations where each corrugation passes across a flow ridge. Commonly remelting of the ceiling of the tube causes blistering, though blisters may have burst before solidification to leave circular ridges a few inches across, from which hang tiny glazed stalactites.

In most lava tube caves lava stalactites and stalagmites are common features (Plate 4.3), though it is strange that some tubes are completely devoid of them. The larger forms usually hang from the outer edges of wall protuberances and are the result of the initial draining of the tube, or of lava flung as spatter on to the walls and ceiling. Smaller forms are made of glaze and possess a greater variety of shapes. Many are delicate rod or straw-like features, 6-13 mm in diameter, while others may be tapered or tear-drop in shape. Some straw stalactites have an erratic form consisting of contorted spiral structures, and others are partly crushed like a pipe-stem. Some are delicately ornamented with flow patterns. In the Viðgelmir cave in Iceland forests of stalagmites lie beneath walls festooned with rod and straw stalactites (Fig. 4.2). These stalagmites consist of tiny globules of glaze which are piled one above the other, so that heights of 30 cm are sometimes reached. In another Icelandic cave, Borganhellei, straw stalactites are united with globular stalagmites to
form erratic columns over 1-2 m high and individual straws exceed lengths of 1 m (Thorarinsson, 1957). Some interesting speleothems described by Jagger (1931) were “barnacle stalactites” which were described as extrusions of molten lava through pores in the walls of the cave. Similar extrusions which oozed through cracks formed thin, papery, ribbon stalactites. The examination of the chemistry and structure of lava stalactites has been carried out by several workers (Hjelmenquist, 1932; Williams, 1963; Ollier and Brown, 1965). On many speleothems the outer skin was found to be coated with silvery magnetic oxide of iron. Internally the vesicles were elongated vertically and lined with crystals of augite and feldspar. In Government Cave, Arizona, Harter (1971a) distinguished between “lava drip pendants” and “lavacicle stalactites”. He noted that lava drip pendants were only rarely responsible for the formation of lava stalagmites, and he separated the two stalactitic forms on the basis of vesicle arrangement.

Plate 4.3. Straw stalactites and globular stalagmites of lava, Viðgelmir, Iceland. The stalagmites average 20 cm high (Photo: D. J. Wilkinson).

Fig. 4.2. Lava speleothems from Viðgelmir, Iceland.
The secondary features in lava tube caves obscure those details of the lava structures which provide evidence of the genesis of the original conduit. Only where roof segments or wall linings have collapsed are the important lava structures visible, but in many caves collapse is of infrequent occurrence. This meant in the past that models of tube genesis were highly speculative, and some even controversial. Today, new observations of lava tube systems in ancient lavas, and of tube formation during periods of active volcanicity, have contributed greatly to the discussion.

In Europe, an early interest in lava caves was shown by Victorian travellers in countries like Iceland and Sicily. Many formed an opinion of the origin of a particular cave, though the conception of some theories was often as fantastic as the weird landscape through which they travelled. Two popular explanations are notable. An earlier view held that lava caves were formed by blistering as gas escaped from the lava during its consolidation, and some authors believed the famous Surtshellir to consist of a chain of linked bubbles. The theory was based upon the apparently bellowed and blistered surface of pahoehoe, but a little later some observers noted horizontal striaions on the walls of the caves and regarded these features as evidence of flow of hot magma through the cave. A new theory then became popular and involved the draining of fluid magma from beneath the congealed crust of the lava flow during the later stages of its emplacement. This idea persists to the present day as an explanation for the genesis of lava tube caves, though it has taken many different forms.

In his study of the lava caves of Mt Etna, Sicily, Poli (1959), for example, believed that the wall structures in lava tube caves indicated laminar flow. The lava flows were thought to be constructed of many successively enclosed cylinders of lava whose viscosity increased externally. In the caves this was observed where the walls were composed of layered concentric structures (interpreted here as lava tube crusts). At the cessation of activity the more fluid internal cylinders drained of lava, leaving a tube-like cave.

Another variation of the traditional theme was suggested by Bravo (1964) as an explanation of the origin of the Cueva de los Verdes, Lanzarote. He thought the cross-sectional form of the cave indicated two phases of formation. In the first phase extensive flooding of lava erupted from the volcano "la Corona" formed the lava field "Malpais de la Corona". During the second phase, lava continued to be erupted, but in diminished quantity, so that it was confined to a channel eroded across the pre-existing lava field. Levees were developed along the borders of the channel by the ejection of scoriaceous material, and during a momentary cessation of flow a crust was formed over the lava. Bravo envisaged a deepening of the conduit by lava melting the floor, until total cessation of the flow led to the draining of the remaining fluid magma.

In many ways earlier observations of actively forming lava tubes in newly erupted pahoehoe supported the simple traditional concept. The Icelandic geologist Kjaransson, for example, was fortunate to observe the formation of a lava tube during the 1947-48 eruption of the Icelandic volcano "Hekla" (Kjaransson, 1949). He described how the lava was confined to a narrow channel which became partially crusted over, and how marginal levees developed by progressive welding of crustal fragments towards the centre of the channel until, ultimately, the channel became completely covered over. A similar process was also described by Wentworth and Macdonald (1953). Citing Stern's observations of the 1935 eruption of Mauna Loa, Hawaii, and Macdonald's observations of the 1942 eruption, Wentworth and Macdonald showed how the flow near the vent was confined to a narrow channel, where levee construction proceeded by spattering and overflow, and where a roof could be formed across the channel by the jamming of crustal slabs carried along by the lava stream. Farther from the vent, they envisaged the margins of the flow to be fed by a myriad of small distributary tubes which branched from the main tube. They offered an alternative explanation of tube formation by describing how small flow units, or pahoehoe toes, could be elongated by repeated outbursts of lava from the front, and how each toe subsequently developed a shell by chilling, which gave, if drained, a small lava tube cave.

As new lava fields were discovered and explored by speleologists and geologists, however, it was realized that lava tube caves were much more common and possessed a greater diversity of form and size than was formerly held, and many workers became discontented with the traditional explanation. In his Caves of Washington, one of the most important regional surveys of lava tube caves, Halliday (1963, p. 5), for example, noted "as a group, these caves do not seem entirely in accord with the traditional concept of these caves as simple conduits with distal ramifications". Similarly, Oliver and Brown (1965, p. 225) noted that the traditional concept "does not account for all the observed shapes and structural features encountered in lava tubes". In order to explain the wide diversity of form met with in the lava tube caves of Victoria, Australia, Oliver and Brown advocated a more elaborate explanation of laminar flow, which was based upon discernible structures within the flow and the cave. They
recognized in lava flows layers up to several feet thick which lay parallel with the flow surface. The layers were of compact basalt separated by trains of vesicles, buckles and partings. This "layered lava" was said to result from differential movement within one thick flow along shear planes. In consideration of the caves and the lava structure, Ollier and Brown suggested the following mechanism of internal flow. The liquid lava concentrated between laminae during the formation of the layered lava became segregated and came to occupy tubes running through the lava. This mobile lava eventually became concentrated in a few major channels that were a continuing source of heat, so that the earlier layered lava could be eroded. The end-result was cylinders of liquid lava flowing through tubes cut in virtually solid rock.

In later years this theory found a great deal of support, particularly from North American volcanospeleologists, though it has become a controversial topic even there. Also, geologists and speleologists were still expounding on hypotheses that followed traditional lines (Kermode, 1970; Macdonald and Abbot, 1970) (Fig. 4.3). There was a reluctance to reject the traditional explanation, and Wood (1971) found in a later study of the Icelandic lava tube cave Raufarholshollir that traditional concepts could still apply to more complicated cave systems. Like Ollier and Brown, Wood based his conclusions upon the relationship between flow structure and tube morphology. Cross-sections of the lava flow were identified in the main passage of Raufarholshollir, and at the collapse entrance. The structures were similar to those recognized by Ollier and Brown, but at Raufarholshollir it was felt the structural characteristics of the flow resulted from the superimposition of small flow units. In terms of tube morphology, Wood recognized four general passage types based upon detailed cross-sectional measurements. The smallest tube type was generally found above lava falls in the extremities of the cave and had a form consisting of a flat floor and an arched roof. A second tube type, into which the first type passed at the lava falls, carried three lateral benches, one of which was found above a lateral shelf and was continuous with the single lateral bench of the first tube type (Fig. 4.4). A third type of tube was the joint controlled, rectangular, breakdown tube, and a fourth was composed of a series of irregular forms of larger size that constituted the main tube. Cross-sections of the lava were rarely observed in the smaller tubes, but it was observed that because of the natural weaknesses at flow unit contacts, ropy surfaces were sometimes exposed. By the identification of successive contacts, therefore, the relationship between the flow structure and tube form could be understood. It appeared that the smallest

![Diagram of speleogenesis in lava](image-url)
tube passages represented the drained cores of single flow units, and that each flow unit represented a potential “primary tube unit”. Larger tubes were seen to be constructed of multiples of this single unit, due to erosion and remelting of the crusts of the original flow units by the lava stream. In one case, where one unit was seen to diverge and then re-enter the main conduit, a small loop passage had been established.

In latter years, the development of lunar geology and the problems of lunar landform evolution has given an impetus to the study of terrestrial lava tubes. The study has leapt from almost total insignificance to great importance, because of the believed close analogy between lava channels and tubes and lunar sinuous rilles. Vulcanologists are also taking interest and have been impressed at the considerable role lava tubes play in the growth and importance of Hawaiian type volcanoes (Peterson and Swanson, 1974).

One of the first important studies of this nature was on the Bandera lava tubes of New Mexico by Hatheway and Herring (1970). The study was of an impressive complex of lava channels and lava tubes situated in eleven distinct basalt formations. All the tubes appeared to have formed in single flow units, except the Bandera Crater tube, traceable for 28.5 km, which was common to three flow units and had a more complicated origin. Hatheway and Herring discussed three alternative modes of formation of the Bandera Crater tube, and quoted methods of tube formation after Wentworth and Macdonald and Ollier and Brown. They concluded that the model proposed by Ollier and Brown, if slightly modified, adequately explained the formation of very long tube systems, while they regarded the processes recorded by Wentworth and Macdonald to apply only to shorter tubes. In consideration of the lunar implications, Hatheway and Herring analysed bend sinuosity, gradient and roof collapse. On the basis of their study of gradients, they suggested that the production of long tubes in olivine basalts would take place if gradients lay between 0°21’ and 0°35’.

Following this study, Greeley (1971a and b; Greeley and Hyde, 1971) have recently made a large contribution to the discussion on tube genesis, as a result of interest in lunar sinuous rilles. In his study of the lava tube caves of the Bend area of Oregon (Greeley, 1971a), the fieldwork in general confirmed the “layered lava” hypothesis of Ollier and Brown. Greeley also agreed with Hatheway and Herring in that two tube types were recognizable: minor and major lava tube caves. Minor lava tube caves were described as less than 10 m wide and a few hundred metres long, which formed in small, single flow units and often occupied the entire flow.

They were often feeders for larger tubes, or they formed in discrete lava flows which emanated straight from the vent. Most caves in the Bend area, however, were said to be major lava tube caves “of the type described by Ollier and Brown”, and these were found in flows several kilometres long. Like Hatheway and Herring, Greeley also discussed sinuosity and gradient, and he concluded that the greater degree of complexity of the Horse system was attributable to a lesser gradient. Greeley (1971b) was also fortunate to observe actively forming lava channels and tubes during the 1970 eruption of Kilauea, Hawaii. His observations showed that roofs over open channels were constructed by simple crusting, by the jamming and fusing together of crustal slabs, and by levee formation through overflow and spatter. He also noted multiple flow along rifts and suggested that this may be a mechanism leading to the formation of unusual cross-sections seen in some lava tube caves (Fig. 4.5). Greeley noted that a single channel could display braided channel flow, open flow, mobile crustal plates and roofed channel along its length. These observations were of later use in the study of 833 m of lava tube in the Cave Basalt, Mount St Helens (Greeley and Hyde, 1971), where they believed the caves to have two modes of formation. Some tube segments were developed in “layered lava” and resulted from laminar flow. Other segments were thought to be due to spatter accretion leading to the formation of arch levees and eventually a complete roof. They thought that laminar flow was a product of lesser gradients, while spatter accretion was the result of more turbulent flow on steeper gradients. Greeley and Hyde made the important point that subsequent lava flows could modify quite extensively the first formed tube by filling or partially filling, remelting the tube roof to form vertically elongated tubes, reshaping and eroding the

![Fig. 4.4. Evidence of stacked conduits in Raufarholshöllir (after Wood, 1970).](image-url)
tube walls, stacking additional tube levels above the first, or any combination of these (Fig. 4.5).

Cruikshank and Wood (1972) also observed the development of lava conduits on Kilauea in 1969, as part of a study concerned with the terrestrial analogues of lunar sinuous rilles. They examined lava channels left at various stages of development, and they were able to recognize stages in the roofing of channels to form lava tubes. They provided two examples of channel closure. Common to both examples, they proposed, a thin flow developed marginal levees by spatter along the flow boundary

and by slowly undercutting the channel walls. Later stages of development, however, either involved the formation of roofs by marginal spatter, so that arched levees fused and became reinforced by surface flows or, alternatively, a surface crust on the flowing lava in the channel fused and grew, later to be reinforced by surface flows. Cruikshank and Wood recognized that channels closed by spatter and overflow lay on topographic highs orientated along the tube axis caused by repeated lateral flow of lava overflowing the channel before closure. They also noted several factors that governed the method of closure. Proximity to the vent, for example, was held to be important with regard to the loss of gases to the atmosphere, so that once the gas was removed from the magma, spatter was reduced and levee formation was lost. Thus this method of roof construction would not be expected farther from the

vent. Turbulence also caused evolvement of gases, and they suggested that roof construction by lateral spatter could only occur in narrow channels. An important observation that confirmed earlier speculation (e.g. Wood, 1971) was the deepening of lava channels, with the result that older routes could be captured by newer ones. Cruikshank and Wood could not apply the explanation of Ollier and Brown and Hatley and Herring to speleogenesis in the Hawaiian pahoehoe, but suggested instead that tubes developed by the crustling over of relatively fast-moving streams by fusion of floating crystal fragments and/or by the joining of spatter built laterally on to levees. Other observations also held to be important were bi-level conduits, fluvial-like processes of meandering, bank cutting, channel capture, and channel deepening in active tubes through melting and plucking of the country rock.

Yet other observations of the Kilauea activity were recorded by Peterson and Swanson (1974). Their observations agreed with those made by Wentworth and Macdonald, Greeley and Cruikshank and Wood, though they saw no evidence to support the proposal by Ollier and Brown that lava tubes are the result of the internal shearing of thick flows. Unlike the other observers, Peterson and Swanson described the budding of pahoehoe toes away from the vent, suggesting another tube-forming process operating in these finely anatomizing distributaries. They also observed through "skylights" spectacular glowing underground lavafalls, which were formed when lava from a high level tube plunged into a deeper tube. It seemed that this occurred when the young lava emptied into the skylight of an older tube, or when a weakened roof of a lower tube collapsed beneath a stream in an overlying tube. It was also seen at times that there was a tendency for a flowing lava stream to develop a lower level roof beneath skylights, and at some skylights, if this process was repeated at successively lower levels, three- or four-tiered tubes developed.

Although, as this review shows, new observational data of actively forming lava tubes is available to aid the interpretation of lava tube caves in ancient lava flows, controversy still reigns. In a recent review of the literature, Wood (1974) decided that the difficulties found by speleologists and geologists in interpreting lava cave development was the result of considering individual hypotheses as over-all explanations. In order to evaluate the past models, discussion should first centre upon the genesis of the primitive conduit, i.e. the simple tube passage, and then, with that knowledge to build upon, to construct a model of more complex tube varieties. The model proposed by Ollier and Brown was discounted by Wood as an explanation of more complex tube systems, and instead
suggested two alternatives based upon the established observational evidence. These alternatives took account of individual tube segments as simple conduits which could have formed either by the opening of an open channel or the chilling of a shell around a small flow unit or pahoehoe toe (Fig. 4.6). As a first alternative, Wood pointed to observations made in Hawaii which showed that lava streams assume intricate braided channel networks, any part of which, if crusted and drained, would form a complex lava tube cave. As his second alternative he pointed to the importance of coalescing drainage channels carried in stacked conduits or flow units (Fig. 4.4). He suggested that three-dimensional complexes like Mount Hamilton Lava Cave, or the Cueva del Viento, may be due to a combination of both processes.

Fig. 4.6. Idealized section of pahoehoe toes (after MacDonald, 1967).

Even with detailed mapping of more lava tube caves, and even with more observation of actively forming lava tubes, it will be a long time before adequate explanations are forthcoming. In fact, it may be that because of the large variety of controlling factors governing speleoogenesis in lavas, explanations may only account for individual lava tube caves. There remains great scope in this field of speleology.

LAVA CAVE MINERALIZATION

Some solution of magmatic rocks occurs and, in favoured localities, geomorphic features of solutional origin, such as lapis (Palmer, 1927) and solutional depressions (Le Grand, 1952) have been found. In general, however, solution of basalt by normal weathering processes cannot be regarded as wholly responsible for mineralization in lava caves. The most common mineral deposits to be found are calcite, quartz, opal, chalcedony, gypsum and zeolites. Hydrated silica and calcite in particular are often found in stalactitic forms up to 15 cm long, while gypsum occasionally coats cave walls and lava stalactites. More complicated structures of opal of coralloidal form were discussed in detail by Swartzlow and Keller (1937). These authors believed that solution of the basalt was greatly facilitated by chemical alteration by hot, moist gases during the cooling of the flow.

CAVES OF EXOGENETIC ORIGIN IN PYROCLASTIC ROCKS

Less common are large-scale speleogenie features formed in pyroclastic rocks. The volcanic caves of Mount Elgon, Uganda, fall into this category and serve as an example, having been described in detail by Ollier and Harrop (1958). Mount Elgon consists of layers of volcanic agglomerate which is interbedded with subsidiary lava flows, and the majority of the caves are associated with ash bands located within the agglomerate. One cave at Sipi was reported to be 122 m in length, while another visited by Sutcliffe (1970) was said to have an entrance 60 m in width. The caves occur in rows and are frequently located in cliff faces. The agglomerate which underlies the ash band in which the caves had formed was reported by Ollier and Harrop to have been a hard, baked soil layer, and it was believed that water percolating through the upper agglomerate was held above this impervious soil horizon, finding an easy outlet along the band of ash which it attacked chemically. Cave formation was therefore partly attributed to the solution of the ash, which possessed a high concentration of sodium salts, and partly to normal erosional processes carried out by the subterranean streams. Similar features have been described elsewhere in the world. In the caves of South Georgia, U.S.S.R., for example, Dsavriviili (1965) has shown how these speleogenie processes can lead to the collapse of the overlying basalt, while other features in the Carpathian Mountains of Rumania hold interesting speleothems of limonite, resulting from solution of concretions in the rock above the cave (Naum and Butnar, 1967). Szentes (1971) also listed this type of cave as present in Hungary. In the U.S.A., an interesting study by Parker, Shown and Ratlaff (1964) of Officer's Cave, Oregon, showed that solution was not necessarily of great importance to cave formation in pyroclastic rocks. Officer's Cave occurs in altered montmorillonite tuff and volcanic ash and constitutes the uppermost of four cave levels, with a cavern complex of 214 m depth. Although chemical analysis showed a high content of sodium in the tuff, solution was discounted as a major process of speleoogenesis. Rather, it was because the nature of the rock was to become disaggregated when wet, offering little resistance to erosion, that cave formation occurred.
CONCLUSION

In the preface of his early bibliography Harter (1971b) wrote: "The infant science of . . . volcanospeleology suffers greatly from fragmentation. Terms are not standardized. References are often difficult to acquire, and information may be unreliable." To this one must add that the study of volcanic caves has suffered most from a piecemeal approach which has lacked, until quite recently, any scientific method. To some extent these difficulties resulted because the areas of study are widely separated, and from the fact that cave research in volcanic rocks is only now being recognized as an exciting alternative to cave research in limestone. Over the past three years, for example, British cavers have contributed to the cumulative knowledge of lava tube caves by expeditions to Iceland and Tenerife, where detailed survey and geological work has shown remarkable contrasts in cave form and genesis. This type of speleological study from the world's active caving community, together with the new interest held by professional geologists, is certain to clarify many of the outstanding problems in volcanospeleology in the near future.

REFERENCES


THE ORIGIN AND MORPHOLOGICAL DIVERSITY OF LAVA TUBE CAVES

C. Wood
6 Trafalgar Road,
Long Eaton,
Nottingham,
England

This paper, based upon research carried out by the writer in Iceland, Tenerife and Sicily, describes the common, multi-stage development of lava tube caves and explains how morphological diversity inevitably results from these caves evolving in widely differing environmental situations.

The evolution of a lava tube cave occurs in three stages: (i) conduit (lava tube) construction, (ii) conduit drainage, (iii) breakdown and collapse.

Conduit (lava tube) construction

Cave development commences with the construction of a complicated network of conduits, or lava tubes, beneath the congealed surface of the lava flow, through which liquid lava is transmitted from the vent to the advancing front. Conflict over the validity of models depicting the formation of lava tubes (Wood, 1976) was recently resolved by observations of actively forming lava tubes in Hawaii (Greeley, 1971 & 1972; Cruikshank and Wood, 1972; Peterson and Swanson, 1974). These observations showed that lava tubes evolve from either (i) open lava channels, or (ii) small flow units and 'pahoehoe toes', depending upon the distance from the vent.

(i) Major feeder tubes result from the roofing of the lava river carried in open channels. Roofing may be accomplished in a variety of ways: through the accumulation and fusing of crustal plates; through the accumulation and fusing of a surface scum; through the growth of a stable crust
from the sides to the centre of the channel; or through the agglutination of spatter to form arched levees which eventually fuse with the opposing levee.

(ii) Smaller distributary tubes are constructed further from the vent as part of the process of ‘toe budding’, a frequent method of extension of fluid lava flows. Toes and small flow units are amoeboid-like tongues of liquid lava which override one another as they push out from the front of the flow. They develop a surface skin through chilling: this is inflated by the addition of new lava from behind, the skin ruptures, liquid lava breaks out and a new toe or flow unit is formed as the process is repeated.

Although the full extent of a lava tube network in a large basaltic flow is never seen, the composite picture is envisaged as resembling a vast number of anastomosing small tubes ramifying from one or more larger feeder tubes. (Wentworth and Macdonald, 1953).

Conduit drainage

The evacuation of lava from a lava tube commences with the cessation of effusive vent activity, or when flow in one lava tube has been ‘pirated’ by a more favourable flow route in another. In addition, for evacuation to proceed, two further conditions must be fulfilled: the residual lava must maintain mobility on the existing slope and there must be a space into which this lava can drain (Wood, 1975). These conditions are rarely met throughout the whole tube network and drainage is usually selectively related to favourable topographic situations. During drainage the lava in the tube may be lowered either constantly or sporadically, and the tube may be emptied either wholly or partially. This is accompanied by extensive passage modification caused by the accretion of cooled lava to the roof and walls of the conduit, forming such features as linings, benches, shelves, false floors, etc.

Breakdown and collapse

Modification through breakdown and collapse may occur in the earlier genetic stages but mainly it is confined to the period succeeding drainage, when the lava cools and is eventually open to sub-aerial attack. Lava tube caves are particularly prone to collapse because of the abundance of flow unit contacts, partings and joints in the parent lava flow. Many caves collapse because the roof cannot support its own weight during or after evacuation of the liquid core (Hatheway and Herring, 1970). In colder climates frost wedging is an obvious process leading to extensive breakdown and collapse (Wood, 1971).

As an inevitable consequence of the varying influences of the controlling factors on cave genesis in widely differing environments, each genetic stage offers a vast number of alternative morphogenetic routes (Wood, 1975). The result is that as a group lava tube caves exhibit enormous morphological variety, ranging as they do from the complicated, three-dimensional passage networks of caves like the Cueva del Viento, Tenerife, to the single, vast, meandering passages of cave like Vidgelmir, Iceland. Specifically, diversity may be recognised in the lengths and complexities of cave networks and in their constituent passage forms.

Diversity in the lengths (i.e. extent) of cave networks results because the factors controlling the drainage of lava tubes — principally, viscosity and gradient — vary in influence from flow to flow, or even from one part of a flow to another path, for example, the Icelandic caves Surstrheliir/Stephanshelliir (4km) and Vidgelmir (1.8km) each occur on the tread of steps in the long profile of the 34km long Hallmundarhraun ('hraun' = lava) and, because the steeper gradient of the fall of each step encouraged the complete evacuation of the fluid residual lava from the tube on the tread above: the length of each cave bears a relationship to the extent of the tread of the step upon which it is situated. In contrast, the considerable drainage of viscous residual lava from the lava tube network that is today the 10km long Cueva del Viento, Tenerife, is a consequence of both a constancy of slope and a very high slope angle of 11°.

Diversity in the complexities of lava tube caves mainly reflects a diversity in the complexities of the lava tube networks from which they originated. The reason for complicated internal flow patterns in fluid lava flows remains equivocal, but it is clear that the individuality of a pattern is a product of the particular environment in which it formed. Again, the controlling factors — for example, the period and rate of effusive vent activity, the viscosity of the lava, the nature of the pre-flow topography, etc. — vary from flow to flow. Something is known of the developments leading to the formation of complex lava tube networks from observation in Hawaii. It seems that lava channels may possess some complexity even before they are roofed over and the following confirmed processes are believed to add to this initial complexity: fluvial-like processes of bankcutting, meandering and channel deepening ('erosion'); stream 'pirating': breakout of lava from a higher to a lower lava tube; the convergence and divergence of flow accommodated in small flow units or toes. The picture is further complicated because only particularly favourable segments of the lava tube network drains of lava and then parts may collapse.

The diversity in passage forms in lava tube caves is illustrated in Fig. 1 and an explanation of some common forms in the caves studied by the writer is offered in Fig. 2. Differences in the size of a passage depend upon whether it carried a large or a small discharge, whether it originated as a feeder tube or as a distributary tube, whether ‘erosion’ has enlarged it, or whether it has been extensively modified by lava accretion. The passage profiles of the Icelandic caves (Raufarholshelliir and Vidgelmir), for example, are vast, for they carried an immense volume of fluid lava which, at the cessation of activity, drained almost completely from the tube and caused very little passage modification by accretion. In contrast, the passage profiles of the Cueva del Viento are smaller and more varied, and these resulted from extensive modification caused by the slow and difficult drainage of very viscous residual lava from the tube. There is some correlation between passage type and varying gradients in the Tenerife caves.
Fig. 1.

PASSAGE PROFILES OF SELECTED LAVA TUBE CAVES.

Christopher Wood

Cueva del Viento
Cueva del Viento

Vidulfer
Vidulfer

442
References


MORPHOGENETIC STUDY OF THE 1614-24 LAVA FLOW AND ITS LAVA TUBES

C. Wood (University of Leicester)

Studi morfogenetici della colata del 1614-24 e dei suoi tunnel di lava: Viene riportato un rilievo dettagliato su 3 km^2 della colata del 1614-24. Vengono descritti tre principali caratteri morfologici: terrazzi, tunnel di lava e collassi.

During August 1976, a large team completed a detailed topographic survey of a selected part of the 1614-24 lava flow, Mount Etna North, with the aim of shedding new light on the role played by lava tubes in the formation of the impressive terraces, cumulo-domes and after features of the flow. The surveying programme, entailing both underground and surface surveys, was carried out by students of St Albans College of Further Education and members of Club Alpino Italiano (Sezione dell' Etna).

The area selected for investigation comprised some 3 km^2 lying astride the forest track that runs between Casermetta and Villaggio Turistico Mareneve, in the eastern part of the flow known as the Lava del Passo dei Dammusi. Reconnaissance had shown this area to contain a large number of well-developed landforms, the most important being:

(i) Three large terraces, each characterised by a tread of hummocky pahoehoe pavements and a front up to 80 m high of aa, scoriaceous and 'toey' lava;
(ii) Four very different lava tube caves, with a combined length of 3.5 km located in varying positions relative to the terrace fronts;
(iii) Large ovoid or irregularly shaped 'collapse' features, ranging up to 35 m across, possessing an upraised rim of fractured, thick pahoehoe crust and a deep central depression of a chaotic assemblage of blocks, frequently with open lava tube passages radiating from them.

Underground surveys

Due to errors in previous magnetic surveys of lava tube caves in Iceland resulting from the variable attraction of the wall rock, non-magnetic techniques were employed in this survey. Use was made of a simple, tripod-mounted cave theodolite, comprising a 15 cm diameter horizontal graduated card, with a pointer, sighting tube and clinometer mounted above. At each survey station, the following readings were taken: horizontal bearings to both the backward and forward station to enable the included angle to be calculated, the angle of inclination to the forward station, the distance to the forward station, the tripod height, the roof height (though this was frequently estimated) and distances left and right to the passage walls. In addition, passage cross-sections were sketched and geological features which would aid an interpretation of the origin of the cave were noted. The thickness of the roof was measured by plotting out on the surface the line taken through the cave and making a surface survey. For two caves, this line was continued beyond the end of the cave at the surface and down the front of the terrace in which the cave was situated to a large collapse depression. This increased the accuracy of the survey in this area by forming a closed traverse and provided important data on the relative positions of the caves and the terrace fronts. The figures were roughly plotted in the field and the surveys so produced were taken into the caves and checked for errors.

Surface survey

The relative positions of the cave entrances, collapse depressions and terraces were determined by triangulation with a theodolite and folding staff. Horizontal bearings were also taken to prominent landscape features up to 4 km distant which were clearly identifiable on the 1:25 000
Figure 1. Terraces and lava tubes in the Grotta dei Lamponi area (sketched mainly from satellite photographs).
topographic map of Monte Etna Nord (Istituto Geographico Militare, Edition 2, 1969), so that both the surface triangulation and the cave surveys could be related to true north.

Plotting

On return to the United Kingdom the survey figures were reduced to rectangular co-ordinates and plotted at a scale of $1:1000$. Separate surveys were drawn of the three longest lava tube caves to show their plan, long profile and passage cross-profiles. In addition, the plans of the caves were drawn on a large topographic map of the study area, which also shows the position of the terraces, the collapse features, the distribution of aa or scoriaceous lava and pahoehoe, along with minor topographic and flow features (see figure 1).

Acknowledgements

The project was funded by generous grants from the Royal Geographical Society, The Ghar Parau Fund of the British Cave Research Association and the Sports Council. This work has been carried out as a part of a collaborative project with Dr R. Greeley, Dr J.E. Guest and Dr R. Romano.
Abstract

Three caves, the Cueva del Viento, Cueva de Felipe Reventon and Cueva de San Marcos, appear to form part of a vast lava tube cave network underlying the area around the small town of Icod de los Vinos, Tenerife. This paper describes the exploration and research carried out in two of these caves during 1973 and 1974. The Cueva del Viento was surveyed then to a length of 10 km. Its morphology is extremely complex, being made up of two cave labyrinths, one lying above the other, but features of the main genetic stages are recognisable and its genetic history deducible. The associated Cueva de San Marcos, over 2 km long, is of special scientific interest because the whole lava flow has been truncated by the cliff-face at Puerto de San Marcos, offering an unparalleled opportunity of relating cave morphology to flow structure. It is shown how the cave represents only a small part of the total distributory network of lava tubes.

Previous Exploration and Research

The first recorded exploration of the Cueva del Viento took place in 1969-70 and was carried out by the Secciôn de Esploraciones Vulcanoespeleologicas de la Guancha (SEVG) del Grupo Montañero de Tenerife and Secciôn de Esploraciones Subterráneas de la Agrupaciôn Excursionista de Etnografía y Folklore de Barcelona, under the direction of Carlos Teigell. As a result of this work the cave was claimed as the longest lava tube cave in the world (Teigell, 1970), for its length of 6.18 km exceeded the length of the Cueva de los Verdes on Lanzarote which, according to the Spanish, had formerly held this title. In his description of the cave, Teigell commented upon its archaeology, meteorology and biology and confirmed that it possessed two entrances, the upper (Cueva de las Breveritas) lying at an altitude of 640 m and the lower (Cueva de los Piquetes) at 580 m. Other articles on the cave appeared the same year (Trogoblio, 1970; Anon., 1970 and 1970a) and described regional caving camps which included the Cueva del Viento in their itineraries. The following year Grupo de Esploraciones Subterráneas del Club Montañas Barcelones visited the cave and quoted a length of 6.200 km and a vertical range of 580 m (Montoriol-Pous, 1971). The full report of this expedition subsequently appeared (Montoriol-Pous and de Mier, 1974) which repeated these figures and reported on the cave’s morphogenesis and secondary mineralization. In November, 1971, the U.S. caver W. R. Halliday, apparently concerned with claim-jumping going on in Europe, which had ousted Ape Cave on Mount St. Helens, Washington (variously quoted as 3.400 or 3.418 km) from what the North Americans regarded as the premier position as the world’s longest lava tube cave, made a point of visiting both the Cueva de los Verdes and the Cueva del Viento. His reports (Halliday, 1972 and 1972b) described the Cueva del Viento as an extensive labyrinth cave which, according to SEVG survey (a plan at a scale of 1:1000) possessed a total length of 6.211 km (though he noted that at least two passages remained unexplored). As near as he could calculate from the survey, a 9 m ‘collapse sink’ (an American term which we would like to discourage, because ‘sink’ is not applicable
flows comprising the cliff at Puerto de San Marcos and much of the study area was walked over in order to collect data for a map of the surface morphology of the flow and to find other caves. The Cueva de los Piquetes and the Cueva de San Marcos and, also in the latter, flow direction through to possess a length of 2.130 km and a vertical range of 69m. Passage forms were recorded both in the cliff at Puerto de San Marcos was successfully accomplished also in April, 1974, and was found what was initially thought to be an impenetrable choke, but we were later informed (pers. comm. P. Courbon) it was the foundations of a wine-vat sunk into the cave! The vertical range of the Cueva de las Breveritas of 261 m, gave a total of 478m. The survey of the Cueva de San Marcos and neighbour in this cave obtained from our own survey, was the reason for us being involved in a certain amount of argument, particularly with P. Courbon. He had previously quoted the 580m vertical range (Courbon, 1972 and 1974) and, in one article, did say that the survey was complete. Possibly this vertical range was never checked and as the SEVG survey is a plan only it did nothing to assist the researcher. In fact, the dimensions of the cave are still misquoted: for example, Aellan and Strinati (1975) quoted the length of the Cueva del Viento as 6.180 km and a vertical range of 580m. The Cueva de San Marcos, formerly known as the Cueva de Guanches (we assume this to be the same cave from its description), was a celebrated burial cave of the Guanches, who were the pre-conquest inhabitants of Tenerife. Stone (1880) stated that the cave was 11,000 feet (3.353 km) long and extended to the Ice Cavern in the Peak. Even in the 1930s (Brown, 1932) this cave (known at the time as the Guanche Burial Cave) was a recommended excursion from Icod de los Vinos, when one could enter the cave via an upper entrance and walk through a passage for 400 yards (365m) to a hole overlooking the sea. Halliday (1972a, 1972b and 1972c) visited this cave in November, 1971, and reported that it contained 2.200km of surveyed passage, still going in the direction of the Cueva del Viento. He noted two entrances: one in a banana plantation and one in the sea-cliff at Puerto de San Marcos. It was suggested that the cave was in the same flow as the Cueva del Viento, which appeared late pre-historic.

There is very little literature on the Cueva de Felipe Reventon other than brief mentions and vague locations. For example, Montoriol-Pous and de Mier (1969) gave its length in a footnote in one paper, but had more to say about this cave in the report of their 1971 expedition to the Cueva del Viento (Montoriol-Pous and de Mier, 1974), when they stated that caves of minor importance were also examined by them, the biggest being the Cueva de Felipe Reventon, estimated to be about 2km long and situated, like the Cueva del Viento, in the district of Icod de los Vinos. The location, exploration and survey of this cave remain prime objectives of any future expedition.

**Brief narrative of the expeditions**

30 days were spent in the field during August, 1973, and April, 1974, as the expeditions were organised around package tours each of two weeks duration. The first expedition used Puerto de la Cruz as a base, which entailed travelling daily the 20km or so to the caves. During the first week, much of the Cueva de las Breveritas was surveyed, though at the time we thought that this cave constituted the whole of the Cueva del Viento and we were not to learn of our mistake until many months later. On the 6th day in the cave the total surveyed length exceeded 5.500 km and one insignificant draughting passage was reluctantly left to be surveyed the next day. To our great surprise (and dismay) this passage eventually led to a 4m deep hole and lava-fall and into an extensive lower cave which, after an exhausting 8th day of surveying, was found to possess a length of 2.340 km. The total length of the cave at the end of that day amounted to 7.922 km, which exceeded the variously quoted 6.181 km for the whole of the Cueva del Viento, and this fact, together with the lack of evidence of previous visits by other people to the lower cave, led us to believe that the lower cave was a new discovery. Due to the time-consuming surveying programme on this expedition (the 5 expedition members worked continuously in two groups for eight days), little time was available for making geological observations in the cave or of the surrounding district, other than to catalogue characteristic cave forms and to examine the surface morphology of the flow around Icod de los Vinos and Puerto de San Marcos.

On return to England subsequent examination of a newspaper article by Teigell (1970), which we had only managed to retrieve on Tenerife, revealed that we had only surveyed the upflow part of the Cueva del Viento, known as the Cueva de las Breveritas. A second visit was made to Tenerife, therefore, in April, 1974, with the objectives of locating and surveying the downflow part of the Cueva del Viento (known as the Cueva de los Piquetes), surveying the Cueva de San Marcos and investigating the geology of the sea-cliff at Puerto de San Marcos, where interesting exposures of the lava flows were noticed in 1973. The Cueva de los Piquetes was surveyed in three days and was found to possess a length of 2.080 km which, when added to the length of the Cueva de las Breveritas, gave a total length for the Cueva del Viento of 10 km — a far cry from the variously quoted 6.181 km! The Cueva de las Breveritas and the Cueva de los Piquetes were found to be separated by what was initially thought to be an impenetrable choke, but we were later informed (pers. comm. P. Courbon) it was the foundations of a wine-vat sunk into the cave! The vertical range of the Cueva de los Piquetes was found to be 217m which, when added to the vertical range of the Cueva de las Breveritas of 261m, gave a total of 478m. The survey of the Cueva de San Marcos and neighbour in this cave (Puerto de San Marcos) was successfully accomplished also in April, 1974, and was found to possess a length of 2.130 km and a vertical range of 69m. Passage forms were recorded both in the Cueva de los Piquetes and the Cueva de San Marcos and, also in the latter, flow direction through the cave was ascertained. Some time was spent examining the structural characteristics of the lava flows comprising the cliff at Puerto de San Marcos and much of the study area was walked over in order to collect data for a map of the surface morphology of the flow and to find other caves.
SKETCH MAP OF THE GEOLOGY AND LAVA CAVES.

(Based on Mapa Geologica de España & Instituto Geografica topographical map, No II03)
Survey of Cueva de San Marcos.
The Cave Surveys

For the sake of consistency the same survey techniques were carried out on both of the expeditions. We were well aware from our own previous work in Iceland of the errors that could arise from the use of magnetic survey techniques in lava tube caves due to the variable attraction of the wall rock, but we chose to make a magnetic survey of the Cueva del Viento for the following reasons: (i) we were aware of the reputed length of the cave, and therefore the considerable time needed to survey it, before we arrived on Tenerife; (ii) the lightest surveying instruments had to be chosen because of the limited weight allowance on the aircraft; (iii) a survey by means of a cave theodolite utilizing the included angle at every station meant both backward and forward readings at every station and would have made the surveying time required three times longer than if we used a lead-frogging technique; (iv) it was felt that the attraction of the wall rock in the Cueva del Viento would be less than that of Icelandic caves because it was suspected (correctly) that it did not carry a glass lining (Bowler, 1971).

Magnetic survey techniques were therefore used, for it was believed that any loss in accuracy would be compensated by an assurance of the completion of the survey. The instruments used were 30m Fibron tapes read to the nearest 0.05m, Suunto compasses (type KB-14/360) and clinometers (type PM-5/360 PC) read to the nearest 0.5°, which were hand-held, although care was taken to minimize errors due to station movement. Survey stations in the main passages and often at junctions off the main route were marked with numbered white adhesive tape for reference during the period of the survey and removed from the cave before departure. Wall distances and roof heights were measured at every station and at significant points between them (though where the roof was too high it was estimated). The 'lead-frogging' technique was used throughout the survey.

Upon return to England the survey figures were reduced to rectangular co-ordinates using four figure logarithmic tables and surveys at the scale of 1:2000 (Cueva del Viento) and 1:1000 (Cueva de San Marcos) were plotted from these after checking against a line survey for any mathematical errors. Because of the complexity of the Cueva de las Breveritas some passages were not drawn on the plan in order to preserve clarity: for example, high recesses and chambers in the vicinity of cross-sections 27 and 28. Also in order to preserve clarity, only the principal side passages were drawn on the extended section of the Cueva del Viento. Twenty one closed traverses were made in the Cueva de las Breveritas and their closure errors were distributed proportionally to the slope distance between stations. The traverses varied in length from 37.65m to 211.90m and had closure errors of 0.48% to 7.80%. There were only two very small closed traverses in the Cueva de los Piquetes and four in the Cueva de San Marcos of 29.35m, 52.70m, 61.24m and 79.11m, with the largest closure error being 8.21%. A closed traverse across the surface between the two entrances and through the cave from respective entrances to either side of the separating choke in the Cueva del Viento failed to close by only 0.2m vertically and 10.5m horizontally: the thickness of the choke can only be guessed, but lies in the region of 10m.

The survey of the Cueva del Viento was drawn on three sheets at a scale of 1:2000. The survey of the Cueva de las Breveritas forms Sheet No. 1 and consists of plan, extended sections and cross-sections, with the outline of the upper cave superimposed upon the lower. Sheet No. 2 consists of a plan, extended section and cross-sections of the Cueva de los Piquetes. Sheet No. 3 consists of a full plan only (Breveritas and Piquetes) with the upper and lower caves of the Cueva de las Breveritas enlarged at twice the scale of the main plan. The survey of the Cueva de San Marcos was drawn at a scale of 1:1000 and consists of a plan, extended section and cross-sections. The surveys drawn for this paper (Figs. 2 and 3) are reductions of the original surveys. Note that the lower cave in the Cueva de las Breveritas, discovered by us in 1973, is shaded in Fig. 2 for clarity. A comparison between the plan of the Cueva del Viento prepared by the SEVG and our own plan reveals a similar form (excluding the lower cave which, at the time of our survey, had not been explored by the Spanish), though the former is elongated and comparison of the lengths of the cave between its north and south extremities gives a variation of at most 5% between the two surveys.

An altitude of 580m a.s.l. at the entrance of the Cueva de las Breveritas was determined by averaging two descents to sea-level using a Thommen pocket barometric altimeter (Swiss manufacture) reading direct to 10m and by estimation to 5m.

Space does not allow a full verbal description of the caves and this, together with a description of the routes through them and their exact locations, is to be published in the Shepton Mallet Caving Club Journal, Autumn, 1977.

The Geology of the Study Area

The geology of the area around the lava tube caves is shown in Fig. 1, using data abstracted from Mapa Geologico de España, Sheet 1103 (Inst. Geologico y Minero de España), 1968. The place of the local geology in the volcanic succession of the island as a whole is shown below:

Recent Series Basalts and Trachybasalts (IV & Historical) Recent Series Salic (= Acidic) Rocks
Series III Basalts Trachyte and Trachybasalt Series
..............................................................................Upper Canadas Series Rocks
Lower Canadas Series Basalts Lower Canadas Series Sodic Rocks
Ancient Basalt Series
The geological evolution of the island is summarized after Hausen (1956), Fuster, et al. (1968 — unfortunately, a second-hand reference, for according to the British Library this paper is out of print and not available in Britain) and Borley (1975) as follows. Overlying a basement complex which is not seen are rocks of the Ancient Basalt Series. These are mainly found in two parts of the island: the oldest rocks forming the Anaga peninsula in the north-east, while younger lavas form the Teno peninsula in the north-west. Rocks of the Ancient Basalt Series are considered to have been erupted from fissures, forming lava shields, and comprise alkaline basalt and ankeramitic lavas and pyroclastics. Abdel-Monem, Watkins and Gast (1968) gave an age of 15.2Ma-7.2Ma for these early lavas. Volcanic activity then became more centralized with the production of the Lower Canadas and Upper Canadas Series and the Trachyte and Trachybasalt Series. A number of volcanoes produced large amounts of pyroclastic material and lavas, ranging from alkali basalt through trachybasalt to phonolite, and ultimately formed a volcanic complex believed by some to have risen almost 5000m a.s.l. At a later stage (late Pleistocene) emptying of a high level magma chamber and faulting caused the summit region to collapse and slip northward, forming the depression of Las Cañadas: the stratified pyroclastic deposits of Bandas del Sur represent the final phase of activity of this period. Contemporaneously, and a little later, volcanic activity produced the Series III basalt at pyroclastics which overflowed the walls of the depression in many places. Vulcanicity of the Recent Period was mainly restricted to the Las Canadas depression, within which the two central volcanoes Pico Teide and Pico Viejo emerged, composed of lavas ranging from trachybasalt to phonolite. A final phase of activity was represented by the growth of clustered adventive cones over the island which erupted lavas of alkali basalt or trachybasalt and phonolite. This phase of vulcanicity passed into the historic period with the last eruption on Tenerife of Chinyero in 1909.

The most authoritative geological map of Tenerife, Mapa Geologico de España, Sheet 1103 in the 1:100,000 series shows the lavas upon which Icod de los Vinos stands as Series III Basalt, while the area of the cliffs at Puerto de San Marcos are shown as basalts of the Ancient Basalt Series (Fig. 1). Without access to the memoir describing this map (Fuster et al., 1968) the authors are reluctant to accept this view as it contradicts their belief that the lava tube caves constitute parts of a single complex that formed either in one large lava flow, or in two lava flows, much closer in age than the duration of time between the Ancient Basalt Series and Series III. Confirmation of this idea will come from an analysis of the form and situation of the Cueva de Felipe Reventon, which may be the missing link between the Cueva del Viento and the Cueva de San Marcos (Fig. 1).

The lavas regarded as basalts of the Ancient Series exhibited in the sea-cliff at Puerto de San Marcos, which hold the Cueva de San Marcos and a variety of smaller caves, were cursorily examined in April, 1974. Fig. 4 shows the general succession of the lava flows exposed in the cliff-face. As the authors were not equipped for exposed climbing only the flows lying behind the Amara Apartments were examined in any detail, though the general succession of the lava flows was easily worked out from the western headland of the San Marcos bay. Beneath the majority of the lava flows lies either a recognisable soil horizon or an extremely conspicuous brick-red tuff, which in many places has been eroded, leaving large rock shelters beneath the base of the lava flow. Structurally the lava flows are divisible into two contrasting groupings:

1. lava flows numbered 1, 2, 3, 6, 7 & 9 are recognisable for their strong columnar jointing or massive appearance;

2. lava flows numbered 4, 5 & 8 are recognisable for their (apparent) horizontal jointing.

Hand specimens were not obtained for laboratory study and any relationship between rock type and structure is not known and must be left for the future. Suffice it to say, lava tube caves were observed only in the flows exhibiting the apparent horizontal jointing.

Closer examination of flows 5 and 8 revealed them to be composed of small flow units or 'toes', whose jointing pattern explained the overall apparent horizontal jointing. A detail of flow 5, illustrating its structural characteristics, is shown on Plate 1. In general, flows 5 and 8 ranged in thickness from 6-18m, being made up of as many as 10 elliptical units vertically. The units were thin and wide and were difficult to recognise, though detailed inspection revealed typical characteristics: a distinguishable external ropy surface, frequently oxidized to a chocolate-brown colour; an external narrow zone of high vesicle density; jointing parallel with the exothermal surfaces; an internal core region of little jointed lava of light vesicle density or, alternatively, a small lava tube. Plates 2 and 3 show examples of small tubes carried in elliptical units of the flow and these tubes bear all the characteristics internally of the larger lava tube cave passages. Tubes varied in size from 15cm high to 5.5m high, though by crawling into some of the smaller tubes it was possible to observe them connecting with others, and occasionally they were seen to be branches of larger tubes: for example, at Cave B on the Cueva de San Marcos survey (Fig. 3) the smaller entrance occurs high in the cliff face and lies at the centre of a small flow unit.

In their study of the Cueva del Viento, Montoriol-Pous and de Mier (1974) accepted that this cave had formed in basalt of Series III age and stated it to be an olivine-augite basalt of porphyritic texture. The lava flow fills the broad descending valley in which Icod de los Vinos stands and houses the main cave complexes of the Cueva del Viento and the Cueva de Felipe Reventon. The source of the lava is not known, though this could probably be determined during future fieldwork. Nor is the area, thickness or volume of the lava flow known, for much of it is buried beneath later lava flows and nowhere is the base of the flow seen. Structurally, this lava flow resembles flows 5 and 8 at the cliff at Puerto de San Marcos. Where exposures are observed, as beside the road above Icod de los Vinos, small tubes occur in flow units. Surface tubes abound and bare rock surfaces exhibit excellent
ropy structures indicative of great magma mobility, though it is felt that this mobility was more a consequence of a high effusion rate and very steep gradient (averaging 14-15°), rather than high magma fluidity.

**Geology of the Cueva del Viento**

The Cueva del Viento is of especial note to the speleologist, for not only does it possess a complexity of form that, to the authors’ knowledge, is not repeated in anything like the same degree in any other cave of this type, but also, with a length of 10km, it ranks only after Leviathan Cave, Kenya, and possibly Kazumura Cave, Hawaii, in the list of the world’s longest lava tube caves.

**Morphology**

The survey (Fig. 2) shows the form of the Cueva del Viento in plan, long profile and cross profile. The cave comprises two main parts: (i) an upper cave totalling 7.86km, dominated by the long, meandering main tube of the Cueva de las Breveritas and the Cueva de los Piquetes, linking a number of (today) unconnected passage complexes; (ii) a lower cave that partly trends beneath the line of the upper cave in the Cueva de las Breveritas, comprising 2.34km of passages in two main branches. The lower cave is connected to the higher cave in only one place, via a small 4m high pot and lavafall.

Features of the cave’s morphology which deserve further description are: (1) the unusually complex planimetric form; (2) the sinuosity of the main passage; (3) the steep, multi-level long profile; (4) the great variety of constituent passage forms.

1. **Cave complexity.** The Cueva del Viento exhibits an unusually high degree of passage complexity for a lava tube cave. Montoriol-Pous and de Mier (1974) thought that there might be a relationship between the form of the cave and the very steep gradient upon which cave genesis had occurred. In order to compare the planimetric form of caves they had investigated in Iceland and the Canary Islands, they devised an ‘indices planimetrico’ — $Ip = \frac{Lp}{Pe}$ — where $Ip$ was the indices planimetrico, $Lp$ was the total length of the cave, and $Pe$ was the distance between the two furthest points in the cave. The figure representing the form of each cave was then plotted against their respective gradients. As a result of this study, Montoriol-Pous and de Mier concluded that (a) a high degree of passage complexity in lava tube caves correlated with a high slope angle, as is the case at the Cueva del Viento and, (b) within the Cueva del Viento itself, areas of greater complexity correlated with areas of higher gradient.

Although the idea of comparative quantitative analysis seems to the present authors to be a most useful means of assessing the relative contributions of the controlling factors on the morphogenesis of caves, at this stage they are reluctant to agree with the conclusions reached by Montoriol-Pous and de Mier for the following reasons:

(a) firm conclusions cannot be based upon a limited sample of five caves;

(b) the genesis of a lava tube cave is a function of unique and complex relationships between a number of highly variable factors of which gradient is but one example and the contribution of gradient to cave genesis (albeit in this case a very important contribution) must be viewed in the light of its influence, along with other factors, in the maintenance of the mobility of the lava — gradient alone cannot be responsible for cave complexity;

(c) Visual interpretation of our own survey and analysis of our survey notes do not support the contention that the most complex parts of the Cueva del Viento correlate with areas of steeper gradient.

At the moment the present authors offer no reason for the complexity of the Cueva del Viento, other than to suggest that it may be the result of a special combination of the controlling factors, possibly a very high and constant effusion rate, emplacement over a broad surface with a very steep gradient, with consequent extreme magma mobility. Comparative quantitative analysis will eventually provide the answer, but this must wait until sufficient data is available. Meanwhile, we remain with the cave survey as a qualitative statement of the cave’s complexity.

2. **Sinuosity of the main passage.** In plan, the main passage of the Cueva del Viento, particularly between the two entrances, exhibits pronounced sinuosity. Sinuous bends have been recognised in many other lava tube caves and some authors have attempted a quantification based upon the methods employed in the measurement of river meanders. Such studies, though, have been carried out in order to compare the forms of lava tubes and lunar sinuous rilles, which are believed to be analogous features (Hatheway and Herring, 1970), rather than to attempt an explanation of sinuosity in lava tubes. Greeley and Hyde (1971) noticed that some sections of the lava tubes in the Cave Basalt of Mount St. Helens occupied, and were probably controlled by, the bed of an ancient stream, and other lava tube caves may similarly be topographically guided. This does not explain the regularity of meander bends in caves like the Cueva del Viento, however, and observations of active lava flows in Hawaii by Cruikshank and Wood (1971) have shown that fluvial-like processes of bed ‘erosion’ and bank-cutting (lateral melting and plucking of softened wall rock, particularly on the outer walls of bends) may be operative in open- and closed lava channels. If this is the case, then sinuous bends in lava tube caves may be, like river meanders, an equilibrium condition resulting from adjustments among the controlling variables of the flow.

3. **Long profile and gradient.** Lava tube caves may possess great lateral extent, but they lack the vertical development of limestone caves. When multi-level lava tube caves are found, it is usual that the lower part of the cave has captured the flow of an upper cave through the roof of the lower
1. Detail of Flow 5.

2. Detailed structure of lava toes in Flow 5.


and the two caves are linked via one or more lava-falls. This is the case in the Cueva del Viento where, in the Cueva de las Breveritas, the lower cave is linked with the upper cave via a single 4m lava-fall.

The total vertical range of the Cueva del Viento is 478m by our survey, giving a mean gradient of 11°. This gradient is fairly constant, apart from the occasional small steps where the gradient may rise locally to 30°. The average gradient of the Cueva del Viento must be one of the highest known and it must have been a very important factor in cave genesis, for example, in the maintenance of magma mobility. In their study of the Bandera lava tube caves of New Mexico, Hatheway and Herring (1970) found mean gradients of 0°35’-0°48’ for the Bandera- and Twin Craters Tubes and suggested a lower limit of tube formation of about 0.5°. Perhaps the gradient of the Cueva del Viento of 11° lies near to the upper limit of tube formation?

(4) Passage profiles. The survey shows the 81 passage cross-profiles surveyed in the Cueva del Viento during 1973 and 1974. Most of the profiles were measured in order to provide regular documentation of passage forms, though some were specially selected because they illustrated a characteristic or unusual shape.

As in the study of limestone caves, an analysis of passage profiles in lava tube caves allows an interpretation of the genetic history of the cave. Even the casual observer in the Cueva del Viento cannot fail to notice that certain forms are very common, though there is a gradual gradation between one form and another. Thus, it was possible to group the surveyed profiles into eight general types and two representatives of each type are illustrated in Fig. 6.

Morphogenesis

The morphogenesis of a lava tube cave is complex and its interpretation is difficult. Wood (1975 and 1977) has shown that a lava tube cave is the cumulative result of developments occurring in successive genetic stages which he identified as: (1) conduit (lava tube) construction; (2) conduit drainage; (3) breakdown and collapse. Each cave is shown to be unique, because it evolved in a direction through the genetic stages dictated by the particular environmental situation in which cave genesis was induced. Unfortunately, we do not know what particular set of factors controlled the genesis of the Cueva del Viento, or how these factors differed from the factors which controlled the genesis of other caves, but the modifications caused by each of the genetic stages are easily recognised and are used here as the basis for morphogenetic interpretation.

Stage 3 The cave has not been significantly altered by collapse. The two entrances were formed through roof collapses and there are a few areas of collapse in the Cueva de las Breveritas. As a result of so few exposures of the lava flow, no generalizations are possible on the relationship between the passage forms and the flow structure.

Stage 2 Modifications of the lava tube caused by its drainage, with subsequent adherence of cooled lava to the walls and floor of the original conduit, are extensive in the Cueva del Viento. Such modifications are seen in the passage profiles identified in Fig. 6. It was found possible to explain the variety of passage forms in the Cueva del Viento by constructing a theoretical model in which a cylinder, filled with fluid lava, was spasmodically drained, with individual still-stands of the fluid level in the conduit being marked by the growth of lateral benches and surface crustng, while diminution of the flow led to a gradual reduction in conduit dimensions. This is shown in Fig. 6. One particular feature of the cave’s morphology worthy of special mention is the occurrence of tiered passages that result from the convergence of lateral benches. Recurrence of this feature throughout the cave results in many flat-out crawls through tiny triangular-shaped passages.

Stage 1 Evidence of the developments that occurred in Stage 1 must be looked for in the planimetric form of the cave, for this suffered least modification during the later stages.

(a) It appears that the lower cave (i.e., the cave lying beneath the Cueva de las Breveritas) formed before the lava flow, or flow unit, containing the upper cave was emplaced, and the lower cave ‘pirated’ some of the active flow from the upper cave via the 4m pot. This point of view is supported by the following:

(i) the lower cave trends across the line of the upper cave;
(ii) the lower cave possesses a character and size not reflected by the upper cave;
(iii) flow features in the passages surrounding the 4m pot, which is a laalfall, indicate a flow direction into the lower cave.

It is suggested that the lower cave formed within a lava flow that was later buried by the Series III basalt, or it formed in an early unit of the Series III lava, there having been a break in effusive activity before a later unit containing the upper cave was emplaced. In either case, collapse of the roof of the lower cave in the region of the 4m pot today, before the emplacement of the upper lava flow, or flow unit, was necessary for the capture of some of the drainage of the upper tube. It appears, however, that the main flow in the upper cave was never captured by the lower and the lower cave possibly only received additions of fluid lava during periods of high surges when the main route overflowed.

(b) Some of the passage forms of the complexes of the higher part of the Cueva de las Breveritas are anomalous and cannot be explained in the terms of Fig. 5. These passage complexes appear to have formed from a pattern of sub-parallel, or braided, open channels, which periodically flooded, causing the development of spillways or escape routes for the excess lava.
Enlargements of the two main passage complexes in the higher part of the Cueva de las Breveritas are shown in Fig. 6. A traverse of the main route through each of these complexes involves alternate crawling through triangular-shaped passages and walking through narrow, trenched sections, where high lateral benches cause the passage to assume a ‘T' shape. These alternating passage profiles would be adequately explained by Fig. 6, but for the fact that as many as six subsidiary passages may radiate off from any one point above the lateral benches. Similar features are found in the large passages lying parallel with the main route, to which the main route is connected via the higher level subsidiary network.

Obviously, if the main route and the parallel routes formed as enclosed conduits, connections would not be possible, and so it is suggested that the higher level connecting tubes formed before this part of the Cueva de las Breveritas was completely roofed. The connecting tubes probably originated in flow units caused through either lava overflowing the banks of sub-parallel, or braided, open channels during successive high surges, or overflow through ‘skylights' (areas where the roof of an active lava tube has collapsed) from a similar sub-parallel, or braided, lava tube network. Thus, once formed, these subsidiary tubes may have only been used periodically, facilitating the transportation of excess liquid lava during periods of flooding in the main tube.

It is interesting to note also that as a result of such flooding, a tongue of lava spread across the area underlain by the lower cave and was captured by it at the roof collapse where the 4m pot is situated today, forming yet another outlet for overflow.

(c) Some smaller passage complexes, and parts of the larger complexes, formed as a result of the superimposition, convergence and divergence of tubes carried in individual small flow units; for example, the complex around Galeria Barroso. Such flow units are easily identified at surface exposures of the lava flow above the cave and mini lava tube networks are found by crawling into units with hollow cores. There is clear evidence in the cave also of small scale tube networks, convergence of the flow in some passages having caused the removal of the separating wall to leave distinctive ‘M' shaped passages.

(d) Superimposed flow routes appear to have converged in the central section of the Cueva de los Piquetes. The upper route meanders across the line of lower route and is today segmented as a result of partial drainage into the lower route. The lower route is today represented by the main passage. Superimposition of the upper route may have been the result of overflows before the lower was roofed, or alternatively, the lower tube was subsequently buried by a higher, later flow unit and tube network, only parts of which have drained.

Summary of the genetic history of the Cueva del Viento

(1) Either emplacement of a lava flow older than Series III, or the first effusive phase of the Series III basalt flow, forming a large flow unit, in which the lower cave, Cueva de las Breveritas, was formed, originating first as a large open channel which eventually became roofed.

(2) A period of little- or non-activity in the region, drainage of the lower cave, cooling of the lava flow and collapse of a small roof section of the cave in the region of (today) the 4m pot.

(3) Renewal of voluminous and continuous effusive activity with a new flow, or flow unit, causing the formation of a system of long, braided or sub-parallel channels down the steep slope above Icod de los Vinos and across the line of the older tube.

(4) Selection of the most favourable flow routes: ‘erosion' of the tube by hot, flowing lava, causing modification of passage forms and patterns (e.g., enlargement of the conduit, meandering, etc.). Fluctuations in the lava level caused the channel to overflow periodically, particularly higher up the slope, and lava spread away from the main routes. Continued periodic flooding resulted in the formation and maintenance of ‘escape' or ‘overspill' tubes, connecting the main feeder routes and occupying surface units, slowly advancing away from the main feeder. Roofing of the main tubes progressed, with the ‘skylights' through which the lava escaped during high surges roofing last. Overflow, or a new flow unit, crossing the line of the lower cave was captured at the roof collapse and formed the 4m pot and lavafall.

(5) Continued advance of the lava flow, with periodic surges being accommodated now underground through the spillways. Surface flows strengthened the roof and later tubes formed across the line of the main tube and were captured by it (e.g., Cueva de los Piquetes).

(6) Cessation of effusive activity at the vent and gradual, sluggish drainage of very viscous lava from the tube, causing its subsequent modification and diversity of passage forms.

(7) Cooling of the flow and collapse of the roof in two, or possibly three places. Some collapse of the walls and ceiling of the cave.

Geology of the Cueva de San Marcos
An investigation of the geology of the Cueva de San Marcos was carried out in April, 1974. The cave is of outstanding scientific interest because it has been truncated at the cliff-face at Puerto de San Marcos, offering a unique opportunity of relating the cave form to the flow structure so well exposed in the cliff.

Morphology
The form of the cave in plan, long profile and cross-profile is shown by the cave survey (Fig. 3). There are two entrances; one lying in the cliff-face overlooking the beach at Puerto de San Marcos and the other, higher entrance, resulting from roof collapse, lying behind the cliff in a banana
Fig. 4. C. WOOD & M. T. MILLS  Tenerife

FIELD SKETCH OF SEA-CLIFF, PUERTO DE SAN MARCOS.

Lavas of the Ancient Basaltic Series

Pico Teide (3,715m)

CUEVA DE SAN MARCOS
Fig. 5.

C. WOOD & M. T. MILLS

Tenerife

GENESIS OF MAJOR PASSAGE FORMS.

Key:
- Liquid lava.
- Congealed lava phase 2.
- Congealed lava phase 1.

Cross-sections abstracted from surveys of Cueva del Viento and Cueva de San Marcos.
Fig. 6.

PASSAGE COMPLEXES IN THE CUEVA DE LAS BREVERITAS.

UNDERLYING PASSAGE
LATERAL BENCH
COLLAPSE DEBRIS
4 m POT TO LOWER CAVE

SCALE

0 25 50m

C. WOOD & M. T. MILLS
Tenerife
plantation. In plan the cave possesses two main passages which converge downflow about halfway through the cave. The northerly branch passage possesses large dimensions, a sandy floor and connects with higher level passages overlying the point of confluence of the two main passages. The southerly passage is more restricted in its dimensions, but is a classic asymmetrical tube with an "aa" (clinkery or spinose) floor. In addition, some 200m of passage lies behind (i.e., to the north of) the higher entrance. The average gradient of the cave is 6°.

Passage forms in the Cueva de San Marcos group into the same types that occur in the Cueva del Viento, though some passages in the Cueva de San Marcos are very spacious and breakdown is of much greater importance.

Tiered tubes of the type discussed in the previous section, caused by the convergence of lateral benches, are ubiquitous in the Cueva de San Marcos. Other unusual features are impressive lateral benches near the higher entrance, which are the result of converging lava flows; a series of stepped benches and a deep trench in the region of Section No. 16, which are the remains of an underground lava lake; and the funnel-like feature in the floor of the upper level passage.

The internal drainage pattern

Fig. 7A is a diagram showing the pattern of drainage of fluid lava during the active life of the lava tube. The diagram was constructed from data plotted in the cave. The direction of the flow of the lava was partly determined by the overall (i.e., roof and floor) direction of passage gradient, and partly by analysis of fossil flow features. Points of origin of the flow in the cave were easily recognised at 'lava springs' and are shown on the diagram as open circles. Points where the liquid lava sumped the passage, eventually congealing and blocking it, were recognised as 'lava seal' and are shown on the diagram as open squares. The diagram illustrates the complexity of the flow through the lava tube and is a very useful aid for morphogenetic interpretation.

Morphogenesis

Following the example of the previous section, evidence of the genetic stages will be described in the reverse sequence, because later stage modifications hide, or frequently obliterate, evidence of the earlier stages.

Stage 3 Breakdown of the roof and walls is common in the Cueva de San Marcos, but only in three places does it significantly control the form of the cave:
(1) the form of the passage from which Section No. 20 was taken is predominantly joint-controlled and its floor is composed of collapsed roof blocks;
(2) across on the opposite side of the main northerly passage, a big loop has suffered extensive collapse and piled boulders form a raised platform along the side of the main tube;
(3) a large chamber, extensively modified by collapse, lies above the confluence of the two main passages.

There are other areas of collapse in the cave, particularly in the main northerly passage, and roof collapse has formed the higher entrance. The reason for collapse and breakdown is uncertain, though lava tubes are particularly susceptible to collapse because of the abundance of joints, partings and flow units contacts in the surrounding lava flow. All collapses in the Cueva de San Marcos occurred after the floor had solidified and may have resulted soon after this due to cooling and contraction of the surrounding flow. Some water does enter the cave in places through the roof, probably from irrigation ponds on the surface, and this may have encouraged some collapse. Similarly, earth tremors from volcanic activity on the island, and the vibrations caused by heavy traffic on the road over the far end of the cave, may have loosened the already fractured roof.

Exposures of the lava flow are not well displayed inside the cave, but do show a structure similar to that seen at the cliff-face.

Stage 2 As in the Cueva del Viento, passage forms in the Cueva de San Marcos are the result of modifications resulting from the drainage of the lava tube and are explained in Fig. 6. In addition, in the Cueva de San Marcos, it was found possible to construct a generalized 'morphogenetic map' by plotting the position of dominant passage types through the cave (Fig. 7B).

Stage 1 Figs. 7A and 7B clarify many of the problems of the formation of the Cueva de San Marcos.

(a) It is evident from Fig. 7A and from the structure of the flow exposed in the cliff-face and in the cave, that the main passages of the Cueva de San Marcos were the feeder tubes for a vast system of smaller distributary tubes in Flow B, and the form and extent of the cave is the result of only partial drainage of this tube complex about the main feeders. The main flow routes through the tube complex would have been the most sensitive to adjustments in the discharge of new lava from the vent, while flow through the distributary routes was controlled by developments taking place in the feeder routes. At cessation of vent activity, the main routes would have been the most likely of the lava tubes in the complex to drain of residual lava because (a) they were directly connected with the vent, (b) they carried a greater volume of lava, which must have remained mobile for a longer period than the lava in the smaller distributary passages, and (c) drainage of the distributaries could not proceed without a sufficient head of liquid to force continued forward flow, which obviously they could not have had if the level of the main conduit had dropped below the level of the entrances to the distributaries (it will be noticed that entrances to the majority of side passages occur high in the walls of the main tube), and reverse drainage could not have taken place unless there was space to receive the residual lava from the side routes as a result of the lava level in the main route having
lowered. Thus, one can speculate that if the residual lava in the lava tube complex had remained mobile for a much longer period (i.e., the lava was less viscous, or there was a steeper gradient), then the extent of the cave network would have been much greater than it is today, for more of the tube system from which the cave originated would have drained.

(b) The complexity of the Cueva de San Marcos is a reflection of a large number of ingressive and egressive side passages and there are few closed loops as in the Cueva del Viento. These minor passages fall into three general types.

(i) Some pass across the line of the main route; for example, near the points from which Sections No. 7 and 13 were taken. Both cross the main route just under the roof and, in the Section No. 7 example at least, access can only be made via an exposed climb up the wall of the cave. The difference in the direction of the flow of the main route and the transverse route is shown in Fig. 7A. It is suggested that these transverse passages are later formations, having originated when lava was emplaced across the roof of an earlier formed tube which, during subsequent enlargement of the lower, caused the higher flow to be captured by the lower.

(ii) Other side passages are more difficult to account for, though there are two possible explanations; (a) it may be found that enlargement of the main feeder tubes caused the capture of previously formed tubes and gave them permanence through continued flow (i.e. incision of the main tube across the line of divergent older routes); (b) perhaps more likely, these side passages originated as overflows of the original channel (i.e., before roofing). The passages off the main route in the region of Section No. 16 tend to support the latter view, for it appears that ponding of the flow took place here, with the passage from which Section No. 22 was taken acting as an overflow route from this pond.

(iii) Some loops, for example, at Section No. 28, appear to have originated simply as part of the main channel.

(c) The upper level passage overlying the confluence of the two main routes appears to have formed partly as a result of the ponding at Section No. 16, when overflow flooded across the roof of the earlier formed tube. An early outlet for this lava was the tube which lies today behind the upper entrance, though this flow was eventually captured again by the main route just downstream of the confluence (at Section No. 13). Other surface flows converged with the main higher level flow from the south east. At some stage lava broke through the roof-, and was captured by, the lower level in the region of Section No. 24, as shown by the great funnel-like depression in the floor of the upper cave and the corresponding lava spring in the lower cave.

(d) The branch passage emanating from the region behind the upper entrance is a very low passage involving flat-out crawling in many places. Figure 7A shows the flow direction of this passage to be toward the main route and it may have been an important tributary, but is now filled with undrained lava. The reason for it remaining undrained is easy to explain: (i) the outlet was into the main tube where larger flow caused the lava in the tributary to be held back, or ponded; (ii) meanwhile, lava was invading the tributary from behind via the passage near Section No. 13.

Summary of the genetic history of the Cueva de San Marcos

(1) Advance of the flow front across the line of the cliff-face today by the ‘toe-budding’ process, causing the construction of a lava flow composed of small, piled elliptical units. Gradual lengthening of the channel network from which the small units emanated. This network in the region of the cliff-face initially consisted of two small channels which converged.

(2) Stabilization of the channel, its gradual enlargement through bed ‘erosion’ and leveé construction. Overflows during high surges causing lateral lobes to advance across the surface away from the channel, thickening the flow. Some new flow units emanating from the channel developed their own tubes and were maintained by continued flow from the main route. Gradual roofing of the channel network, though for a period the channel was incompletely roofed.

(3) In one place in the channel an obstruction caused the flow to pond and lava eventually escaped across the roofed part of the channel immediately downslope, causing the formation of a higher level tube. This lava eventually found its way back into the main channel lower down the flow after crossing the line of the main tube.

(4) The channel was eventually fully roofed and the roof was strengthened by overflows and by the addition of new flow units, some of which held their own tube networks.

(5) Enlargement of the main tube caused the capture of lava carried in overlying tubes.

(6) Vent activity ceased and the tube drained. As the level in the main tubes lowered, the tributary passages gradually drained, though their drainage was not extensive as their gradient was away from the main tube. Drainage of the lava lake near Section No. 16 left pronounced ‘shorelines’ or lateral benches. The nature of the drainage in the different parts of the tube network controlled the eventual shape of the resulting cave passage, there being great variety throughout the cave.

(7) The lava flow cooled and contraction led to jointing and collapse of the walls and roof occurred. The sea eroded the coastline to produce the high cliff at Puerto de San Marcos and abruptly truncated the cave. Water dripping into the cave and the vibrations caused by heavy road traffic overhead continue to weaken the roof.
The authors wish to express their thanks for help with the fieldwork carried out by the following SMCC members:


M.S. Received June 1977

C. Wood,
88 Skipton Road,
Harrogate.

M. T. Mills,
The Triangle,
Fenster Road,
Nailsworth,
Gloucestershire.

References

Abdel-Monem, A., Watkins, N. D. and Gast, P. W.
Aellan, V. and Strinati, P.
Anon.


1970. La “Cueva del Viento” (Icod), la mayor del mundo en terreno volcánico con 6.181 metros. La Tarde (newspaper, Santa Cruz de Tenerife), 28 Noviembre, p. 7.

1970a. Sesenta y ocho montañeros han instalado, próximo a la Cueva del Viento, un Campamento Regional de Espeleología. La Tarde (newspaper, Santa Cruz de Tenerife). 7 Diciembre, p. 10.


1972a. Lava Tube Opening in Cliff, Cascade Cave, 11 (2) p. 12 (February).


1972. Contribución al conocimiento de la Raufarhólsheilir (Hjalli, islandia), con un estudio sobre la tipología vulcanoespeleológica. Speleon, 19, p. 16.

1969. Estudio morfogenetico de las cavidades volcanicas desarrolladas en el malpais de la Corona (Isla de Lanzarote, Canarias). Barcelona, Geo y Karst, 6 (22), 543-563.


LIST OF ENCLOSED CAVE SURVEYS.

1. Survey of the Cueva del Viento, Tenerife.
2. Survey of the Cueva de San Marcos, Tenerife.
7. Part plan of the study area of the 1614-24 lava flow, Mt. Etna, Sicily.
C. WOOD  Ph.D.  THESIS  1978

LAVA TUBES: Their morphogenesis and role in flow formation

563450
C. WOOD  Ph.D. THESIS 1978

LAVA TUBES: their morphogenesis and role in flow formation

563450
LAVA TUBES: their morphogenesis and role in flow formation
LAVA TUBES: their morphogenesis and role in flow formation
LAVA TUBES: their morphogenesis and role in flow formation
LAVA TUBES: their morphogenesis and role in flow formation
LAVA TUBES: their morphogenesis and role in flow formation.
C. WOOD  Ph.D.  THESIS  1978

LAVA TUBES: their morphogenesis and role in flow formation
LAVA TUBES: THEIR MORPHOGENESIS AND ROLE IN FLOW FORMATION.
Christopher Wood.

Abstract.

An attempt is made to understand the morphology, formation and operation of lava tube systems in pahoehoe lava flows from the evidence contained in lava tube caves (landforms resulting from the segmental drainage of lava tube systems). Twelve caves from five contrasting lava flows in Tenerife, Iceland and Sicily (Mt. Etna) are described and the morphogenesis of each is worked out from relationships between flow structure and cave form. The structural evidence adds support to the tube-forming processes previously observed by vulcanologists during periods of effusive volcanic activity. No evidence is found to support the currently popular 'layered lava' theory of cave genesis; instead, each cave is seen to be derived from a lava tube system which is a network of varying tube types.

Knowledge of cave forms enables a visualization of the morphology of lava tube systems and the dynamics of the lava rivers they transport. Ideally, each system is sinuous and partly braided along the flow axis and terminates at a delta-like front, though complexities frequently arise as a result of such processes as stream piracy, the development of overflow tubes and the extension of the axial tube across former deltaic regions of the flow. Discussion of channel forms, comparison with other fluvial systems and knowledge of the efficiency of lava tubes in maintaining flow temperature and mobility suggests that lava tube systems are 'adjusted' forms: it is only through their construction that temperature and mobility are maintained sufficiently to enable the continued advance of the flow front downslope. At the front, lava emerges from the tube system as a jet flow. As a result, it is argued that the development of pahoehoe lava flows is predictable and amenable to future quantification through the application of jet theory.