PROCEEDINGS OF THE X, XI, AND XII INTERNATIONAL SYMPOSIA ON VULCANOSPELEOLOGY

Edited by
Ramón Espinasa-Pereña and John Pint

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2002 SYMPOSIUM ABSTRACTS

Compiled by Sigurður S. Jónsson

Geology of Harrat Kishb, Saudi Arabia, in Relation to the Formation of Lava Tubes

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Basaltic lava fields cover 89,000 square kilometers of western Saudi Arabia. One of these lava fields, named Harrat Kishb, has an area of 5,890 square kilometers and is located 300kms northeast of Jeddah. The nature of lava found in this area and the thickness of the flows were propitious for the formation of lava tubes one million years ago.

The lava tubes of Harrat Kishb are found in three different structural and physical positions relative to their parent volcanic cones. The three-km-long lava tube associated with the Jebel Hil volcano was formed by the emptying of the arterial tube as the lava front advanced downslope. Instead, the Ghostly Cave and Kahf Mut'eb lava tubes are found 7km from the volcano which gave birth to them and were caused by blocking of the lava flow by an older cone. The third manner of formation is seen in Dahl Faisal, where a thin part of the roof of the lava tube was sucked down to form a funnel-shaped entrance for surface air.

More than 2000 basaltic volcanoes can be found in western Saudi Arabia and many of these are associated with multiple lava flows. Because of the discovery of caves in Harrat Kishb, it is likely that many of these volcanoes have also produced lava tubes.

Data Base on Icelandic Caves

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The first list of Icelandic lava caves was compiled by Hróarsson in 1990 in his book "*Hraunhellar á Íslandi*" (Lava caves in Iceland). The list comprised a geographically sorted list of about 170 caves, mostly caves mentioned or described in earlier publications but also several newly discovered caves and caves only known to locals in the vicinity of the caves. Hróarsson's list laid the foundation for a "*dbase IV*" table with cave names, lava flow, length and other relevant data and the "*dbase IV*" file was maintained for several years. Later that format was abandoned and the whole list was imported and maintained in a large "*Excel*" spreadsheet.

The author will present a whole new design of a cave database, running on Microsoft Access®, using data and data fields from the previously existing Excel spreadsheet. Attempt has been made to simplify data input, and general

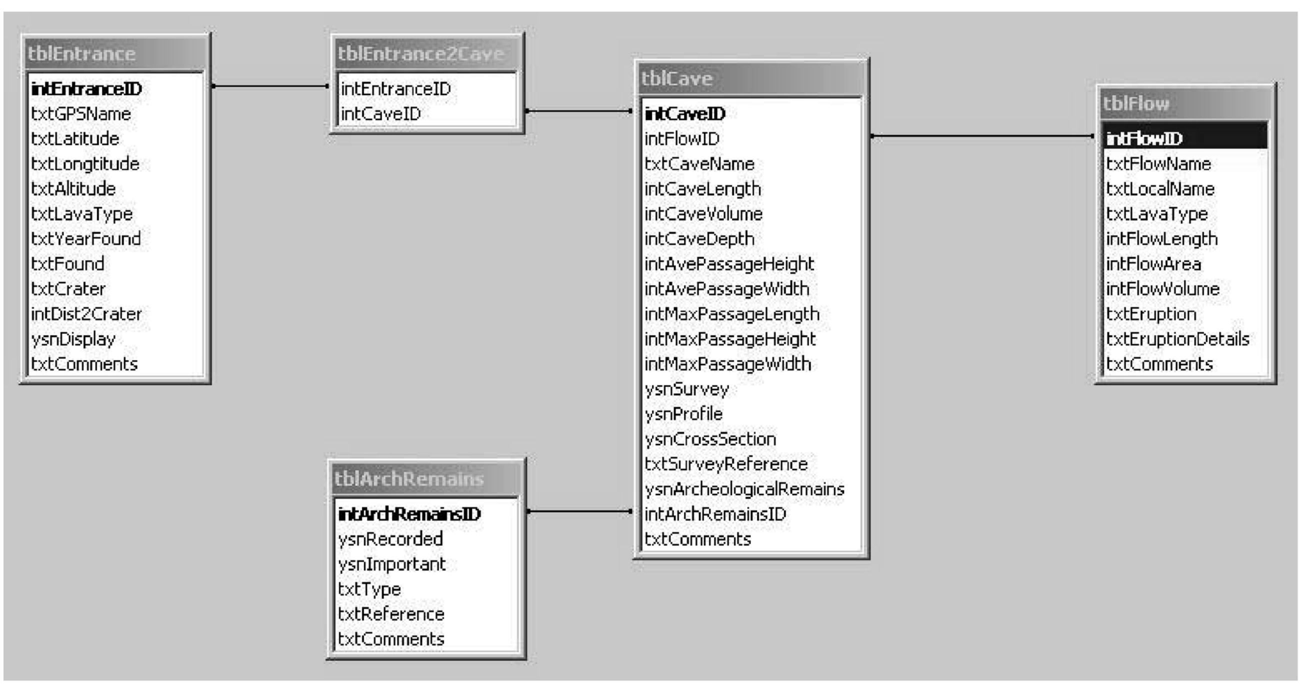

Figure 1 (Begley, "Data Base"). An example of ISS cave database table relations.

filtering, sorting and other data extraction capabilities. The ISS cave database now holds about 60 caves with known GPS-coordinates, but a large pile of data waits to be inserted into the ISS cave database.

Ranking Azorean Caves Based on Arthropod Fauna

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Endemic arthropods and in particular troglobian species were used to evaluate the conservation value of volcanic caves of the Azorean islands. For each of the 44 Azorean endemic species of arthropods recorded to caves, a rarity index was calculated, using distribution and abundance data obtained from the literature. In addition, several scoring indices based on diversity and rarity measures were used to rank 16 caves from which standardized sampling has been performed. About 47% of the 19 endemic troglobian arthropod species are "single cave endemics", that is, are known from only one cave. Based on the Jackknife estimator we estimated the occurrence of 28 (± 3) species of troglobian arthropods in the Azores, which implies that there is the need of further biospeleological surveys in these islands. The most beautiful caves based on a "Show Cave Index" are also the most diverse in troglobites ($r = 0.55$; $p = 0.01$), which means that geological diversity could be a good surrogate of fauna diversity. Moreover, there is more trogobite species on largest caves ($r = 0.66$; $p = 0.0099$). Based on the complementarity method, to preserve the Azorean arthropod troglobite biodiversity there is a need to protect at least 10 caves in order each species is represented at least once. However further caves will be needed to have each species represented at least twice. The standardized sampling provided valuable guidance for achieving the goals of practical conservation management of Azorean biological cave diversity, but further research is required to have better knowledge on the real diversity of Azorean troglobites and their distribution. There is also the need of special measures of protection for the aboveground native habitats in order to maintain the flux of nutrients for the cave environment. This study showed that cave fauna could be used to identify a network of caves for protection that are also of great geological interest.

A Data Base and Classification System for the Azorean Volcanic Caves

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The Azorean Regional Government, being aware of the importance of the volcanic caves and pits as elements of our natural heritage, created in 1998 a multidisciplinary task force to promote its study. One of the main objectives of this group was to act as a consultant to the government, by recommending initiatives concerning de conservation and preservation of these volcanic underground structures.

As a first priority, this group decided to develop a database, which could be used as a managing tool for the Azorean volcanic caves and pits. To achieve this goal it was found necessary to create a field form, to register as many data as possible, allowing a satisfactory description of the underground volcanic structures, and also that could provide the principles for the database structure.

Due to the geographical dispersion of the Azorean islands, and the number and diversity of the lava tubes, it was consider most relevant that managing decisions should be based on accurate knowledge. At that time it was settled the idea of an instrument that could organize the information, in a way it would be possible to evaluate among several parameters of each volcanic caves, to build different sorting accessions, and to produce meaningful lists. These fundaments gave origin to a computer application built over FileMaker Pro 4.0, combining both a database and a classification system.

The sorting and classifying systems presume an objectively chosen criteria set, so that the results are logical, coherent and reliable. It is also significant the possibility to generate diverse classifications based on different preset criteria, deduced from established objectives and aimed to real applications.

The Azorean Speleological Inventory and Classifying System (IPEA) incorporate six major classification issues, as follows: scientific value; potential for tourism; access; surrounding threats; available information and conservation status. Each classification comprises five classes (I to V) where the volcanic caves are sorted as a result of weight calculation upon the values given by nine criteria sets. These criteria are: biologic component; geologic features; accessibility; singularity and beauty; safety; caving progress; threats; integrity and available information. For each of these criteria were established six parameters, where 0 is the lack of information and the other five parameters are objective and clear statements that describe the cave within the criteria.

Each volcanic cave is than characterized by choosing one of the six parameters of the different criteria, that allows among other possibilities to sort the caves in many different ways and to produce relevant lists. It is expected that this application becomes a useful tool to managing Azorean caves for conservation, study and exploration.

Ranking Azorean Caves Based on Geological, Biological, and Conservation Attributes

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With the Azorean Speleological Inventory (IPEA) in a computer data base format it is possible to have a better characterization of the Azorean volcanic caves and pits, spread all over the nine islands of the archipelago. Once the existing data is often poor and incomplete, all the analysis and ranking should be considered, by now, as a preliminary approach.

The IPEA data base comprises 206 records that correspond to the Azorean caves and pits whose existence was confirmed by the team created form that purpose. It is also important to emphasise that there are several reports and bibliographic notes that allows to expect, in a near future, to raise up that number. Moreover, 57% of these 206 caves are unsatisfactorily described, in particular on their biological and geological features, and only 67 are mapped.

The Azorean volcanic caves are located at Pico (81), Terceira (66), São Miguel (17), São Jorge (16), Graciosa (11), Faial (8), Santa Maria (5), and Flores (2). About 63% are lava tubes, 13% pits, 4% fractures, 4% erosional caves and the remaining are combine or undetermined types.

Troglobic species were identified in 25 underground structures, namely the blind ground-beetle, *Thalassophillus azoricus*, which can only be seen in Água de Pau cave (São Miguel island) or the genus *Trechus* found in Pico caves. In 59 caves there are rare and uncommon geologic features, such as long lava stalagmites and sets of burst bubbles of lava, e. g. Soldão and Torres caves (Pico), and Natal and Agulhas caves (Terceira). In 12 caves severe threats were identified in the surrounding area, and thus prevention and protection measures are needed. It is recognized for 22 underground structures their high integrity status, for example Gruta dos Montanheiros (Pico), Gruta da Beira (São Jorge) and Furna do Enxofre (Graciosa).

"Gruta das Torres" Project

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In the Archipelago of the Azores there are a large quantity of lava tubes and pits, in almost every of the nine islands. At present, result of field work made during the last years by the Society of Speleologic Exploration "Os Montanheiros", by the Ecological Association "Amigos dos Açores", by the "Círculo de Amigos da Ilha do Pico", and by the Regional Services for Nature Conservation, there are 239 volcanic caves marked in the Azorean Archipelago.

This geological and biological richness lead the Regional Government of the Azores to promote, through its resolution nr. 149/98 of June 25, the creation of a working group responsible for the study of the Azorean volcanic caves. This group has already created a database and a classification system that will allow the raise of a management model for these caves. In this field of action, and taking into consideration the high speleologic value of "Gruta das Torres", its proximity to population centres and its great accessibility and therefore the facility of being visited, the Regional Environmental Services of the Azores has conceived this project and thus created a pilot experience in the Management and Exploration of volcanic caves in this Region.

"Gruta das Torres" is a volcanic cave, located in Criação Velha – Pico Island, that had its origin in *pahoehoe* lava flows expelled from Cabeço Bravo. It is the biggest lava tube known in the Azores with a total extension of 5 150m. It consists of a main tunnel of large dimensions, attaining in some areas more than 15m in height. There are also secondary ramifications of smaller dimensions where, at times, it is necessary to crawl. Its interior is full of interesting lava formations, such as lava stalactites and stalagmites, silica deposits, lateral benches, flow marks, ropy lava, and lava balls.

The walking tour inside the cave is 400m long and the access to its interior is attained through one of the cave's natural openings.

The improvements to make in the cave, namely to turn the access more easy, will be minima in order to keep the cave's aspect the most original as possible.

In the cave's interior only the ground will be cleaned, clearing out breakdown of the ceiling and walls so as to facilitate the passing through of visitors.

The visits will take place in small groups, with individual lightening system and in the presence of a guide who will give all the informations about the cave.

Besides the route inside the cave, one intends to familiarise visitors with the local geology, flora and fauna, through a briefing given at the cave's support installations, as well through the creation of complementary routes to be explored at surface near the site.

References:

Borges, P.A.V., Pereira, F. & Silva A., (1991), Caves and Pits from the Azores with some comments on their geological origin, distribution and fauna. 6th International Symposium on Vulcanospeleology. Hilo, Hawaii, pp. 121-151.

Nunes, J.C., (1999), A Actividade Vulcânica na ilha do Pico do Plistocénico Superior ao Holocénico: Mecanismo Eruptivo e Hazard Vulcânico, Tese de Doutoramento no Ramo de Geologia Especialidade de Vulcanologia, Departamento de Geociências, Universidade dos Açores, Ponta Delgada, pp. 239-241.

Costa, M.P. & Barcelos, P., (2001), Cavidades Vulcânicas dos Açores, Congresso Internacional sobre Património Geológico e Mineiro, Beja, Outubro, 2001.

Costa, M.P & Verissimo, E.F. (2002), Projecto Gruta das Torres, 2nd Pico Island Internacional Volcanological Meeting, Abril, 2002.

Subcrustal Drainage Lava Caves; Examples from Victoria, Australia

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Most documented lava caves are large, linear or anastomosing tubes formed by roofing of lava channels or development of major feeder tubes within a flow. However an increasing number of small shallow caves is being recorded that have simple to complex patterns of interconnected low chambers and small passages that form by a different process.

In reviews of active volcanoes in Hawaii, Peterson & others (1994) and Hon & others (1994) proposed two distinct models for the formation of lava tubes: firstly by the roofing over of linear surface lava channels; and secondly by the draining of still molten material from beneath the solidified crust of pahoehoe flow lobes. This paper will concentrate on the second type: the smaller, but occasionally complex, caves formed by localisation of flow beneath the crust of thin flow lobes or sheet-flows, and subsequent partial draining - as illustrated in Figure 1. More recently Halliday (1998a & b) has described two types of small lava cave: His "sheet flow caves' and 'hollow volcanic tumulus caves' which he regards as being distinct. I will argue that these are just two of several possible end-members of a continuum of forms which I will refer to as "Subcrustal drainage lava caves". Examples are drawn from the basaltic Newer Volcanic Province of Victoria, Australia.

Subcrustal drainage caves involve a broad array of styles ranging from simple single chambers (Figure 2) to multi-level, complexly-interconnecting systems of tubes and chambers (Figure 3). However, while we can identify distinctive types at the extremes, there are many that fall in the middle ground and are hard to classify. All members of the group have in common the dominance of shallow, low-roofed, irregular chambers and small-diameter tubes running just below the surface of the host flow. They also grade (and possibly evolve over time) into larger and more-linear tubes. In long-lasting lava-flow systems, continuing evolution of these small caves in the upstream parts of the flow could produce larger "feeder-tubes' which would converge on the form of, and be difficult to distinguish from, the large "roofed channel" type (eg. the proximal end of H-53, Figure 3).

The simplest caves are small chambers; typically only 1m high with a roof about 1m or less thick, that occur scattered through the stony rises and have been called "blister caves" in Victoria. These can be circular, elongate or irregular in plan; up to 20m or more across but grading down to small cavities only suitable for rabbits. In section, the outer edges of the chamber may be smoothly rounded or form a sharp angle with a flat lava floor. The ceiling may be arched or nearly flat, with lava drips, and can have a central "soft" sag that would have formed while the crust was still plastic. Alternatively, the thin central part of the roof has collapsed and we find only a peripheral remnant hidden behind rubble at the edge of a shallow collapse doline (e.g. H-78, Figure 2). The more elongate versions grade into small "tubes" (e.g. H-31). These caves generally are found beneath low rises (with or without the central fissure required to class them as "tumuli"!), though some have no surface relief at all.

Larger systems show more evidence of directed flow beneath the crust, either radially from a central feeder (H-33, Figure 2) or laterally from the breached levee of a lava channel (Figure 3). They are commonly branching systems with complexes of low passages that bifurcate and rejoin, or open out into broad low chambers. The form suggests draining from beneath the thin solidified roof of a series of coalesced flow lobes.

A Small Cave in a Basalt Dyke, Mt. Fyans, Victoria, Australia

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The Volcano: Mt. Fyans is a volcano within the Newer Volcanic Province of Victoria, Australia. The age of the province dates back at least 5 million years, but this is a youthful eruption, undated, but possibly less than 100,000 years old – judging by the well developed "stony rises" (remnants of the original hummocky lava surface) and minimum soil development. The volcano is a broad shield of basaltic lava with a low scoria cone at the summit and possibly a crater - though an extensive quarry in the scoria makes the original form difficult to deduce!

The scoria at the summit has a thin cap of basaltic lava, and ropy patterns on the underside of this are well-exposed on the southern margin of the quarry. The loose scoria has been intruded by two large basalt dykes up to 12 m across (which would have fed the lava cap) and a number of smaller pipe or finger-like basalt bodies, some of which have been partly drained to leave small cavities. The quarry operations have worked around the large dykes, but damaged the smaller intrusive features (which is how we know they are hollow!).

The dyke cave: A small horizontal cave occurs within the largest dyke. It lies close to the west edge of the dyke and runs parallel to it (see map). Entry is via a small hole broken into the roof. The cave is about 17 m long and generally less than one metre high. The roof and walls have numerous lava drips. The floor is a horizontal ropy pahoehoe surface which rises gently towards the northern end – but the ropy structures suggest a final flow direction from south to north. The drainage points for the lava are not obvious. Both roof and floor have common patches of pale-cream coatings over

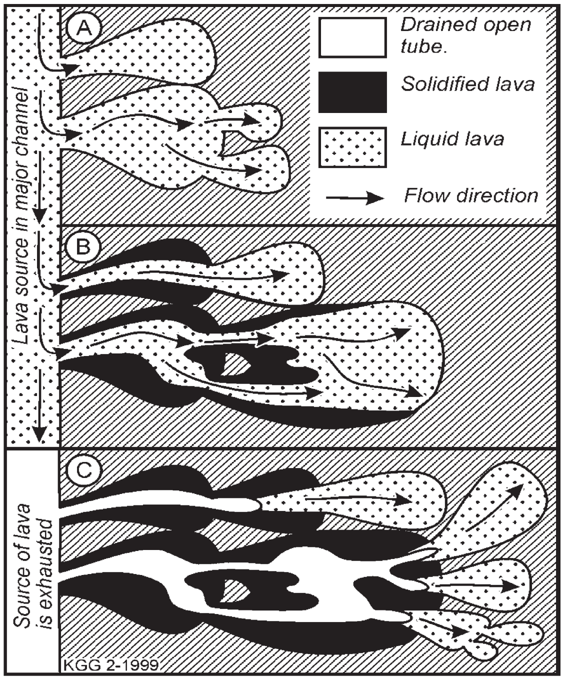


Figure 1: Development of subcrustal caves by partial drainage of successive lava lobes

Figure 2: Examples of small subcrustal caves.

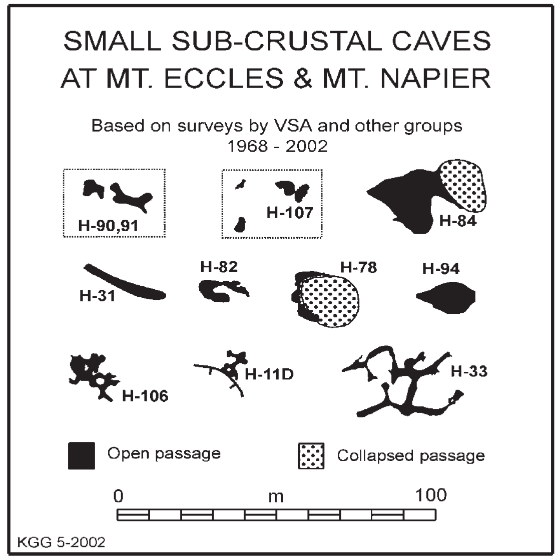
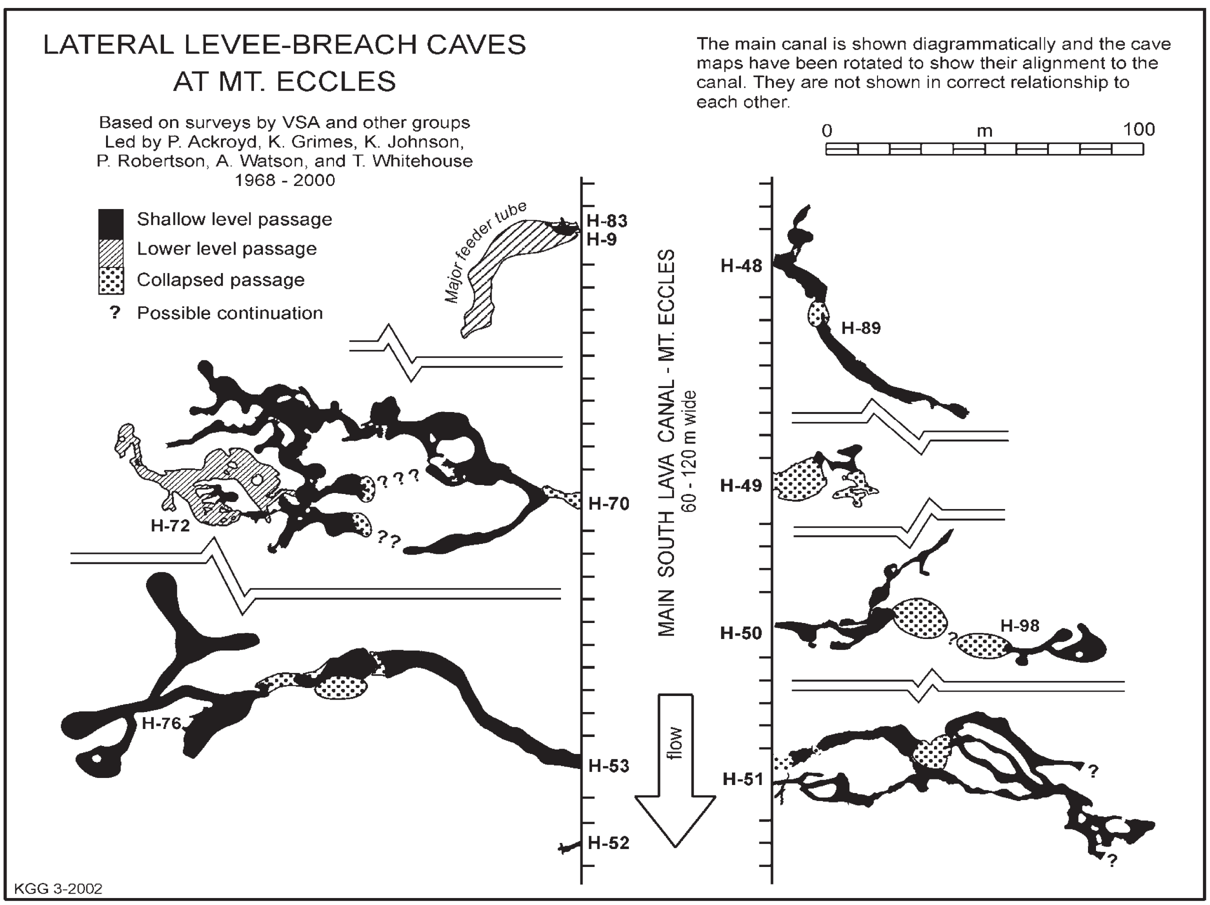


Figure 3: Examples of larger subcrustal caves formed in thin overflows from a lava channel.



Figures for Grimes “Subcrustal Drainage Lava Caves.”

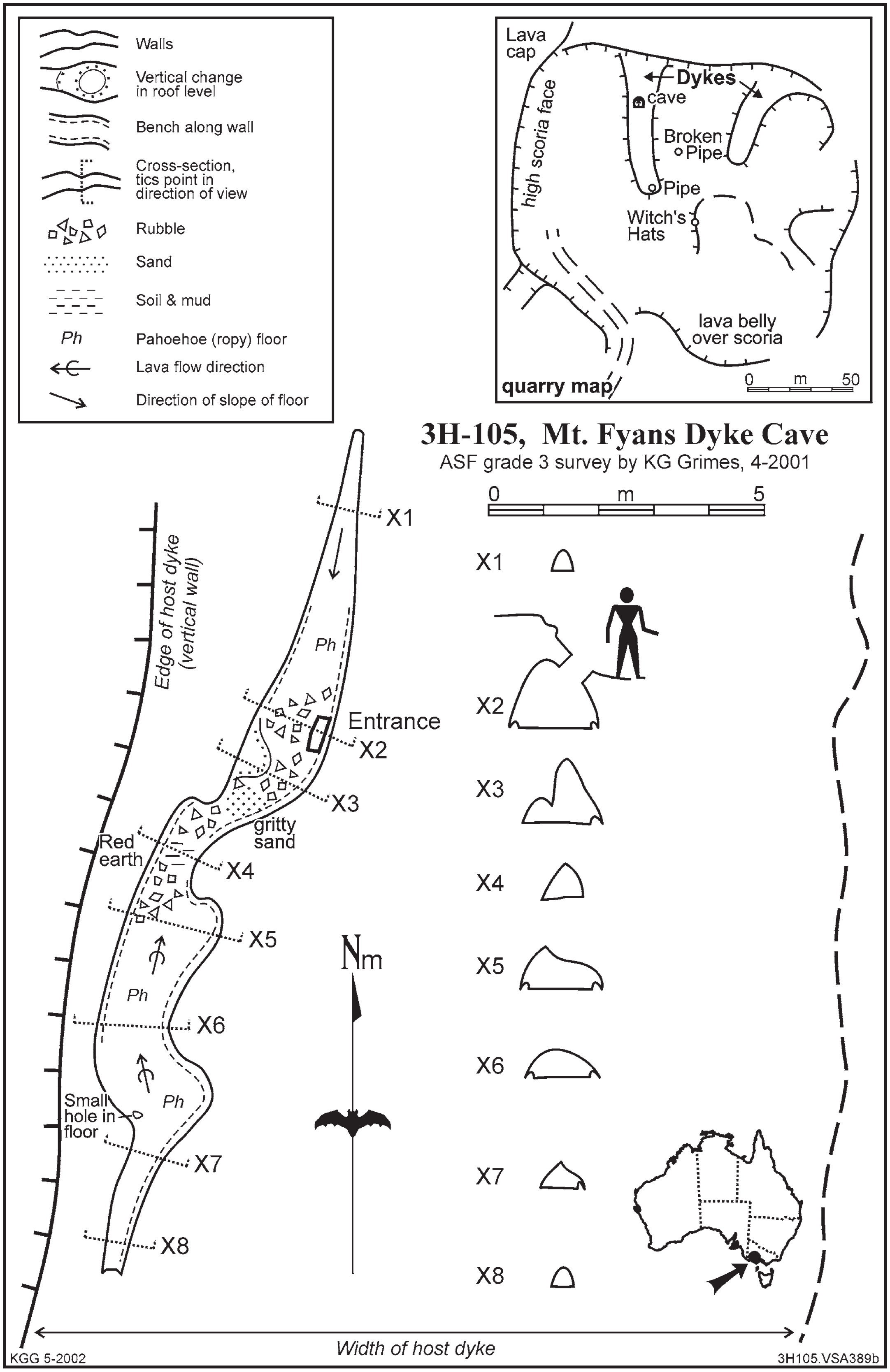


Figure for Grimes "Small Cave Mt. Fyans."

the basalt – possibly fumerolic alteration? There are well-developed rolled benches (10 cm diameter) along the edges of the floor. One small hole in the roof, near the entrance, opened into broken scoriaceous material.

Related features: As well as the cave, the main dyke also has a drained vertical pipe at its southern end – this has been broken into by the quarry operation and we found the upper part lying on its side 20 m to the NE. This pipe had spatter and dribble patterns on its inside walls. Elsewhere in the quarry there are intrusive pipes and smaller fingers of basalt that have pushed up through the loose scoria. Several of these have drained back after the outside had solidified so as to leave a hollow core, some with lava drips. Probably the most distinctive are conical "Witch's hat" structures.

No other volcanic caves formed in dykes have been reported in Australia, but a larger one has been reported from the Canary Islands (Socorro & Martin, 1992).

Genesis: The dykes and other bodies would have been intruded into the loose scoria towards the end of the eruption, would have cooled and partly solidified, and then as pressure was lost those liquid parts that were still connected to the main feeder channels would have drained a little way back to leave the cavities. There may have been some oscillation to form the rolled benches in the dyke cave.

Reference:

Socorro, JS., & Martin, JL., 1992: The Fajanita Cave (La Palma, Canary Islands): A volcanic cavity originated by partial draining of a dyke, in Rea, GT., [ed] *6th Int. Symp. Volcanospeleology*. National Speleol. Soc., Huntsville. pp 177-184 [in spanish].

Preliminary Data on Hyalocaves in Iceland: Location, Formation, and Secondary Mineralogy

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Hyalocave is a new type of volcanospeleological phenomena. *Hyalo*- is a word derived from Greek and means glass. Hyalocaves are associated with subglacial volcanic eruptions and are the result of entrapment of large ice-fragments inside or atop volcanically generated gravity flows and pillow lavas.

Evidence of basaltic subglacial eruptions have be found in Iceland, British Colombia in Canada and Antarctica. Subglacial eruptions form very distinctive geomorphological mountains called "*tindar*" (hyaloclastite ridges) and "*stapi*" (steep sided tuya). Interaction between magma and meltwater produces pillowlava or fragmented volcanic glass, depending on the hydraulic pressure inside the glacier. Scientist tend to associate subglacial eruptions with englacial lakes. Formation of basaltic subglacial eruption is often divided into three stages: 1) Magma under hydrostatic pressure, pillowbasalt is formed, 2) hydrostatic pressure is low - explosive face; volcanic glass is formed when magma comes into contact with water, gravity driven currents flow down the slopes of the mountain and 3) the main magma feeder is blocked from the water and subaerial lavas starts to flow. Lavas may flow into the englacial lake forming flowfoot- or foreset breccias.

Hyalocaves have been found on the Reykjanes peninsula (Stapafell), Mosfellssveit (Mosfell), Laugarvatn-area (Laugarvatnsfjall, Hlodufell, Mosaskardsfjall, Kalfstindar), Snaefellsnes (Songhellir in Stapafell), Eyjafjallajokull glacier and Thorsmork. Most of them are small: only few meters in length, width and height, although few are tens of meters in size.

These formations haven't been given much attention, due to lack of understanding of basaltic subglacial structures and their chaotic fashion. Hyalocaves are clear evidence of ice in the system. They can help scientists to estimate the waterlevel in the "englacial lake". They also indicate that the mountain was "roofed" by ice during the formation of the particular sediment- or pillow-pile. In the future hyalocaves might even help sedimentologist to estimate the density of gravity flows in subglacial environments.

Two new minerals in Iceland are associated with hyalocaves, these are *monohydrocalcite* ($CaCO_3$*H_2O) and *weddellite* (CaC_2O_4*$2H_2O$). Monohydrocalcite has been found in basaltic lava tubes in Hawaii, limestone caves and lake sediments in salty environment. Weddellite has been found in few limestone caves in Australia and Namibia in Africa. Weddellite is often associated with urea and feces of bats, birds, rats and other mammals. Ideally monohydrocalcite needs the following conditions to form: pH>8, Mg/Ca >1, temperature <40°C, water droplets or aerosol, salt, bacteria or algae. Formation of monohydrocalcite in Iceland is associated with oceanic originated precipitation (pH 5,4) that becomes isolated from the atmosphere as soon as the water seeps into the hyaloclastite and comes into contact with volcanic glass. Volcanic glass is ten times more easily dissolved then crystalline rock. Elements from the glass are dissolved by exchanging positive ions from the glass (Mg^{++}, Ca^{++} et. al.) while hydrogen ions go into the glass. Due to this hydrogen loss the pH increases and ends in 8-9. Micro-organism are know to exist in basaltic glass. Bacteria was seen in thin-sections made from the site where monohydrocalcite was found. Monohydrocalcite was only found in selected hyalocaves and only in the entrance with clear evidence of great leakage and moss growth (*Hymenostylium recuroirostrum*). Minerals formed only in the roof and on walls. The crystals are very small and form thin layer on pillow-fragments or 1-3 mm knobs on both the pillow-fragments and the glassy matrix. The color is white to light-brown. Weddellite is white and powdery. It is located both on walls and ceiling. Its occurrence is associated with sheep feces and urea, but they use the caves for shelter. Weddellite is the first organic mineral described from an Icelandic cave.

Proposals for Future Vulcanospeleological Research in Iceland

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Icelandic speleology has contributed enormously from foreign expedition during the last 3-4 decades. Prior to that, very scant information was available on Icelandic caves, and only the general public knew a few caves. Furthermore Icelandic geoscientists have always rather reluctantly approached speleological topics for whatever reasons. An accurate chronology of foreign cave-expeditions to Iceland is not available, but an effort can be made to expose the highlights.

The first expeditions are not very well known and it can be that the main purpose of those journeys was general travelling around Iceland. The British Shepton Mallet Caving Club was active in surveying the larger known Icelandic caves in the seventies, and so were Jay R. Reich and his associates. Spanish, Dutch and French cavers are also known to have visited the country and some have produced important data.

The highly successful expeditions to the eastern part of the Skaftáreldahraun (Eldhraun) in 2000 and 2001 were jointly planned by the Icelandic Speleological Society and foreign participants and organizers. (Wood 2002. this volume). Main role of the ISS was to propose a potentially prominent area for speleological studies with acceptable remoteness and road-access

The main purpose of the poster presented is to raise attention for two sites, considered to be of great vulcanospeleological interest, and offer cooperation in logistical planning and research program. The ISS has some preliminary information about the two sites.

The first site proposed is the western part of the Snæfellsnes peninsula, mostly Holocene lava flows on the flanks of the Snæfellsjökull glacier but also unexplored flows of similar age further ease along the peninsula. The ISS has conducted several short reconnaissance trips and small-scale surveying trips mostly in the Purkhólahraun and Neshraun lava flow in recent years, but also in Saxhólshraun and Klifhraun. Only few caves have been mapped, but a large number of caves and conduits await further research.

The other site is a large lava shield northeast of lake Thingvallavatn, called Þjófahraun (Thjófahraun). The ISS has organized two reconnaissance trips to the area in recent years and concluded that there is a wealth of speleological features to be explored and surveyed. Many un-surveyed caves are known, both braided tube systems and pit-like structures.

What Is a Lava Tube?

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Variances and imprecision in defiing the term LAVA TUBE have led to its application to a wide range of features, some of them far removed from the ordinary meaning of the word TUBE: "a hollow body, usually cylindrical, and long in proportion to its diameter..." The current American Geological Institute definition helpfully limits the term to roofed conduits and requires that they be formed in one of four accepted mechanisms. However it provides little guidance on whether a variety of injection structures traditionally termed LAVA TUBES actually are undrained or refilled examples or are entirely dfferent phenomena.

Ideally, lava tubes and lava tube caves should be defined as discrete structures with definable parameters which differentiate them from all other volcanic features, e.g., aa cores, lava tongues, tumuli, sills and related injection masses. The defining characteristics should be compatible with:

1) the common meanings of TUBE and CAVE;
2) the presence of solid, liquid, and/or gaseous matter within them;
3) observations of all phases of their complex speleogenesis, e.g., crustal and subcrustal accretion and erosion;
4) their tendency to form braided and distributory complexes, and multlevel structures of at least two types;
5) their propensity to combine with or produce other volcanic structures, e.g., lava trenches, rift crevices, tumuli, drained flow lobes, lava rises, dikes, etc.

The ideal may not be achievable at the present state of knowledge and technology. However, new concepts of flow field emplacement and drainage offer a notable opportunity to shape a clearer definition of this elusive term. I propose that the Commission on Volcanic Caves of the IUS develop such a definition, in collaboration with the AGI and other concerned agencies and organizations, for consideration at the 2005 International Congress of Speleology.

Caves of the Great Crack of Kilauea Volcano, Hawaii

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The Great Crack ("17 Mile Crack") is the most prominent feature of Kilauea volcano's Southwest Rift Zone. Rather than consisting of a single crevice, much of the "crack" consists of en echelon crevices of various widths in a strip locally more than 1 km wide. Numerous grabens and collapse pits are present.

Detailed studies of this complex have been begun only in the past decade. Some of the participating geologists have requested support and some leadership by speleologists in investigating cavernous pits at the bottom of steep talus slopes. The Hawaii Speleological Survey of the National Speleological Society consequently has cooperated with University of Hawaii and U.S. Geological Survey researchers in investigating cavernous pits in the principal axis of the crevice complex.

The first two such pits yielded minimal findings, but the third—labelled Pit H by University of Hawaii geologists—immediately was seen to require SRT expertise. In 2001 it was explored and mapped to a depth of 183 m. Despite extensive breakdown, accretion by laterally flowing lava was identified on several levels. A total of 600 m of passage was mapped.

In a similar crevice passage at the bottom of Wood Valley Pit Crater (which is nearby but off the principal axis of the rift zone), tube segments have been found along the crevice at a depth of almost 90 m.

No such tube segments have been found in Pit H Cave, but numerous other pits remain to be investigated along the Great Crack.

Investigation on Discharge Mechanism of Lava-Tube Cave

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Mt. Fuji Volcano-Speleological Society

Discharge mechanism of lava-cave has been proposed and discussed based on Bingham characteristics of lava flow in the tube(T.Honda,2000,2001). A simple model of steady state isothermal laminar flow in circular pipe were used for analysis.

Flow characteristics were studied as a function of parameters such as tube radius, viscosity, yield strength of lava and inclination of down slope. A critical condition was obtained for determining the discharge parameters in which the yield strength plays a dominant role. Some existing data base form the observation of lava cave were introduced to the critical condition and yield strength can be obtained. This model was applied to lava cave of Mt.Fuji, Etna, St.Helenes, Suchiooc, Kilauea, etc., and some deduced yield strength of lava of the caves for these area are found to be good accordance with yield strength estimated by other methods.

General flow equation of Bingham fluid can be shown as,

$$f(t)=(t-f_B)/v_B \quad (t>f_B, \text{ or } r>r_B),$$
$$f(t)=0 \quad (t<f_B, \text{ or } r<r_B).$$

Here, f_B is Bingham yield strength, v_B is Bingham viscosity, which takes specific value depending on the materials. t is shearing stress at r.

For laminar flow model in circular tube on the slope, the equation of the distribution of flow speed u of Bingham fluid are shown as follows:

For tw =(d g sin a)R/2>f_B,

$$u=(R-r_B)^2(d\ g \sin a)/4v_B \quad (r<r_B),$$
$$u=[R^2-r^2-2r_B(R-r)]\ (d\ g \sin a)/4v_B \quad (r>r_B).$$

For tw= (d g sin a)R/2<f_B, u=0.

Here, tw is shearing stress at wall, a is angle of slope or inclination of tube, d:density of the fluid, g: gravity acceleration, R :radius of the tube, r_B :radius of the flowing position where Bingham yield stress takes f_B.

Here, (d g sin a)R/2=f_B is the critical condition to determine if the fluid in the tube can be drained out. For given and known relation between slope angle and diameter (height)of the tube, this critical condition can give the yield strength f_B. This critical condition means that when the yield strength f_B of Bingham fluid is higher than the shear stress at the wall, there is no flow of fluid, as a consequence, no discharge of fluid from the tube. Relations between slope angle and height of cave for Mt. Fuji, Mt. Etna, and St. Helenes are shown in Table 1 – Table 3. Obtained yield stress from slope angle and height of some lava caves are shown in the Table 4 together with the yield stress obtained by other methods.

References:

T. Honda: "On the formation of Subashiri-Tainai cave in Mt. Fuji". The 26th annual meeting of the Speleological Society of Japan, 2000, August, p.64

T. Honda: "Investigation on the formation mechanism of lava tube cave". The 27th annual meeting of the Speleological Society of Japan, 2001, August, p.11

T. Honda and T. Ogawa: "On the formation process of Inusuzumi-yama lava cave ". The 27th annual meeting of the Speleological Society of Japan, 2001, August, p.37

T. Honda: "Formatin mechanism of lava tube caves in Mt. Fuji". The 2001 Fall meeting of the Volcanological Society of Japan, 2001, 0ctober, p.66

On Lava Stalactite Formation in the Hollow of Tree Molds of Mt. Fuji

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At the north-east flank of Mt.Fuji, lava stalactites are often found in the hollow located adjacent to the lava tree molds. These stalactites have a periodic distribution on the surface with 3–6 cm pitch on the roof of hollow and have almost same diameter (4–8mm) at the edge of the lava stalactites. There had been no scientific and systematic study on the formation process of this kind of stalactite in the hollow adjacent to the tree molds before long.

The author proposed a possible formation mechanism of this stalactite and a model to explain the final structure of stalactite (T.Honda, 2000). The author have investigated the initiation of the formation process of stalactite by stability/instability problem (H.Lamb, 1954) of melted liquid layer on the surface of hollow under the action of gravity force. Limit of stability/instability of this layer is determined by balance between surface tension and density of lava. Period of wave of small perturbation on this layer for this stability limit can be determined as, $Pc=2\pi(s / g\ d)^{1/2}$. Here, Pc is critical period of wave, s is surface tension, d is density of lava, g is gravity acceleration. This period is believed to be also a pitch of stalactite location .

As surface tension of lava (I.Yokoyama et al,1970): 10×10^{-2}Kg/m(1000deg) to 6.5×10^{-2}Kg/m (1400deg), and density of lava 1.5to2.5g/cm^3 are used for this study.

For surface tension s=6.5×10^{-2}Kg/m and d=1.5–2.5g/cm^3, Pc=3.2–4.1cm. For surface tension of lava s=10×10^{-2}Kg/m and d=1.5–2.5g/cm^3, Pc=5.1–6.6cm. Measurement by a scale shows 3cm–6cm pitch which has a good agreement with above estimation.

As for a study on the structure and diameter of lava stalactite, the author used the Bingham flow model to explain the formation mechanism and structure of lava stalactite. From the diameter of edge of stalactite, yield strength of lava was determined. From this yield strength, the temperature of this stalactite when it was formed can be estimated.

General flow equation of Bingham fluid can be shown as,

$$f(t)=(t-f_B)/v_B \quad (t>f_B, \text{ or } r>r_B),$$
$$f(t)=0 \quad (t<f_B, \text{ or } r<r_B).$$

Here, f_B is Bingham yield strength, v_B is Bingham viscosity, which takes specific value depending on the materials. t is shearing stress at r. For laminar flow model in vertical set circular tube with pressure difference P1-P2 for stalactite length L, the critical condition is $tw=(P1-P2)r/2L=f_B$. Here, (P1-P2)/L=dgL/L=d g. So the limiting radius for lava discharge is $r=2f_B/d$ g. For density d =2.5 g/cm^3, when r=2–4mm, f_B=2.5–5x10^2 dyn/cm^2. For density d=1.5g/cm^3, when r=2–4mm, f_B=1.5–3x10^2 dyn/cm^2. This low yield strenght suggests that the lava was in rather high temperature condition when surafce is re-melted before re-solidified.

References:

T. Honda: "The formation process of lava stalactite in the of tree molds of Mt. Fuji". The 26th annual meeting of the Speleological Society of Japan, 2000, August, p.4

T. Honda: "The investigation on the formation process of the lava tree-molds structure of Mt. Fuji". The 2000 Fall meeting of the Volcanogical Society of Japan, 2000, September, p.110

H. Lamb: Hydrodynamics, Dover 1945, p.19

I. Yokoyama et al: "Measurement of surface tension of volcanic rocks". Technical Report of Hokkaido University, 1970, p.56-61.

Table 1. *Relation between Slope angle and height of lava cave in Mt.Fuji.*

Name of lava cave	*Slope angle*	*Height*
Subashiri-Tainai Cave Upper area	20 degree	1m
Subashiri-Tainai Cave Lower area	15 degree	2m
Shoiko-Fuketsu Cave-1	10 degree	3.3m
Mujina-Ana Cave	8.5 degree	5m
Bannba-Ana Cave	4.8 degree	5m-10m
Mitsuike-Ana Cave	3.2 degree	10m

Table 2. *Relation between Slope angle and height of lava cave in Mt.Etna.*

Name of lava cave	*Slope angle*	*Height*
Tre Livelli Cave	15.3 degree	3m
Serracozzo Cave	9.8 degree	2m-3m
KTM Cave	8.9 degree	5m
Cutrona Cave	6.4 degree	6m
Immoacolatella-I Cave	3.8 degree	10m

Table 3. *Relation between Slope angle and height of lava cave in St.Helenes.*

Name of lava cave	*Slope angle*	*Height*
Little Red River Cave	4.5 degree	9.1m
Ape Cave	3.3 degree	11.6m
Lake Cave	2.6 degree	15.5m
Ole's Cave	2.1 degree	7.6m

Table 4. *Yield strength obtained from the critical condition.*

Name of volcano which has lava tube caves	*SiO_2 fraction of lava*	*Yield strength obtained from the limiting condition (yield strength obtained by other method in paranthesis)*	*References*
Mt.Fuji	49.09~51.3%*	2.5~5x10^{4}dyne/cm^2	*H.Tsuya(1971)
Mt.Etna	48%	5x10^{4}dyne/cm2 (7x10^{4}dyne/cm^2*)	*G.P.L.Walker et al(1967) *G.Hulme(1974)
Mt.St Helenes	50.12~50.28%*	1~2.5x10^{4}dyne/cm^2	*R.Greely&H.Hyde(1972)
Mt. Suchiooc	51.23~51.35%*	7.5 x10^4~1x10^{5}dyne/cm^2	*R.E.Perena(1999)
Mt.Kilauea	46.46~50%	1x10^{3}dyne/cm^2 (1x10^{3}dyne/cm^2*)	*H.R.Shaw et al(1968) *G.Hulme(1974)
Mt Piton de la Fournaise	47.98%*	5x10^{4}dyne/cm^2	*A.Lacroix(1936)
Mt.Cameroon	43.5%*	1x10^{5}dyne/cm^2 (~1x10^{5}dyne/cm^2*)	*J.G.Fitton et al(1983)

Tables for Honda "Discharge Mechanism"

Air Quality Measurements in Lava Tubes

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Air quality in lava tubes is not normally recorded or investigated. Thus in some instances discomfort from poor air quality may have been misinterpreted as resulting from stress from high temperatures or high humidity. Only two gases have been recorded are ammonia from bat caves and carbon dioxide. The former is unlikely to reach hazardous levels and later has been known to reach hazardous levels in at least one lava tube. This paper will focus on the possible sources, concentrations, distribution and movement both spatially and temporally within lava tubes. The importance of air analyses including oxygen, nitrogen and water vapour will be stressed in order to establish the source of carbon dioxide. Analysis of trace gases, for example, hydrogen sulfide and methane, can also give additional information as to a CO_2 source. Simple CO_2 tests available to the exploration caver will introduced and assessed. The practical aspects of the exploration lava tubes found to contain poor air quality will be discussed. The advantages and disadvantages of using scrubber gases, oxygen re-breathers and scuba will be presented. The paper will include examples of where poor air quality has been identified from volcanic activity and will feature the author's experience with the Chillagoe Caving Club in Bayliss Cave, Undara the longest lava tube found in Australia.

The Mapping History of the Surtshellir/Stefánshellir Cave System

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The nearly 2 km long cave Surtshellir is the best know lava tube in Iceland and is mentioned in many early manuscripts and publications of domestic and international origin. The cave is mentioned in the Icelandic Sagas and folklore and tales are associated with the cave. The cave has provoked many early travelers' attention and curiosity and many explorers visited the cave in past centuries. The first mappublished of the cave was the work of native explorers Eggert Ólafsson and Bjarni Pálsson and published in Denmark in 1772. Eggert and Bjarni's fieldwork is believed to have been carried out in the summer of 1755 but they also toured the same region in 1773. The next map that follows is the work of German traveler/explorer Zugmeyer published in 1902.

The presentation is an overview of the work carried out is Surtshellir and the adjacent and upflow continuation of Surtshellir, Stefánshellir but they upflow segment is divided from Surtshellir with an unpenetrateable boulder-choke which also contains perennial ice. The maps presented are both of Surtshellir and Stefánshellir individually and of the both. It can be concluded that early travelers were not aware of the upflow continuation since not mention is made of its presence.

Surtshellir is in the Hallmundarhraun lava flow in West-Iceland and was formed in historical times (10^{th} century), just after the settlement of Iceland in 874 AD. Surthellir bears large and extensive remains of human habitation, but the archaeological remains have not been cared for by Icelandic archaeological authorities, and are now more or less ruined – or at least seriously affected. The Icelandic novelist Halldor Laxness had pieces of bones ^{14}C-dated in the fifties, and the dating gave grounds to conclude that the remains where of 10^{th} century origin. This has recently been confirmed by later ^{14}C datings.

Altogether 11 maps of different grades and quality are presented and each map's history is briefly discussed.

25 Years of Icelandic Cave Surveying – Jay R. Reich's Maps

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The Pennsylvania born caver Jay R. Reich has contributed a lot to Icelandic speleology and his work on Icelandic caves is summarized. Four large and detailed maps are presented and light is cast on Jay's enthusiasm and fine work in cave mapping and drawing, as well as his enormous interest in Icelandic caves. His first visit to Iceland was early in 1969 when he made his first attempt to survey Surtshellir but hostile weather and other logistical problems prevented him from achieving his goal at that time. He was in Iceland three more times, and completed his map of Surtshellir/Stefánshellir in 1973. His next major project was the exploration and mapping of the extensive cave system of Kalmanshellir in 1993, also in the Hallmundarhraun lava flow. The map of the roughly 4 km cave system with vast details was finished the same year.

The Icelandic Speleological Society collaborated with Jay in the mapping of Víðgelmir, also in Hallmundarhraun, and fieldwork was carried out in 1996. The map was drawn by Jay Reich, checked and corrected by ISS members and it was finished in 1998. During the Kalmanshellir expedition Jay had in collaboration with ISS members and US cavers completed a map of the recently discovered nearly 1 km long cave of Leiðarendi in 1993. In the last 30 years Jay and his collaborators have surveyed all three of the big caves of the Hallmundarhraun lava flow in Western Iceland and Jay has completed maps of over 10 km of cave passage.

Conservation of Volcanic caves in Iceland – Status and Update

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Since the founding of the Icelandic Speleological Society (ISS) in 1989 it has been the society's goal to enhance and further collaboration and cooperation with governmental bodies in the field of cave conservation and general preservation

of volcanic phenomena.

A bold and brave step was taken in 1974 by the Nature Conservation authorities, when all protruding and hanging lava formations (stalactites and stalagmites) were subject to an "automatic" and undisputable conservation as a Natural Monument, in accordance to the Nature Conservation legislation valid at that time. The speleothems were protected regardless of their position in the cave and if the cave itself had any direct or indirect conservations status and if it was known or unknown. The speleotheme conservation is formation oriented and bears resemblance to protection of bird species – i.e. the protection is broadly aimed at the form and occurrence but not at an in-situ individual formation.

After removing an ice-plug in Víðgelmir in 1993 the ISS proposed the idea of gating the cave but it had been blocked since 1972 by the before mentioned perennial ice. The landowners were very positive towards the idea and participated in the project of building the gate. Since the installation of the gate all traffic has been controlled and the landowner now rents caving equipment and takes visitors on guided tours to the cave. The involvement of government authorities was not needed in the gating process of Viðgelmir, but proper authorities were notified of the action.

Following the discovery of the enormously decorated cave Jörundur in 1979 there was an ongoing debate about necessary efforts to protect the cave. In 1985 the cave Jörundur was legally declared a natural monument and subsequently the cave was closed by a steel-gate on the surface, leaving it only open for scientific purpose, and managed by the Nature Conservation Agency. The lock on the gate was broken several times, but no serious damage was done to the cave, except a few specks of candle wax were left on some of the stalagmites. The gate was removed by ISS in September 1999 and a new chain-gate installed in a narrow passage.

The cave Árnahellir is another specific cave-conservation issue the be mentioned. The cave was discovered in 1985 and an escalating number of visitors was experienced in due time from the day of the discovery. In 1995 the ISS took a radical step in cave conservation when after some negotiation time a treaty was signed with the land-owner giving the ISS the sole right to take necessary steps to protect the cave, including the installation of a gate. The treaty was notarized at the sheriff's office in Þorlákshöfn. Immediately, or when the action was legally binding, the ISS prepared for gating the cave. The cave has been closed since and access controlled by the ISS. This privatized conservation has been a little disturbing and irritating for the authorities but the latest development is very satisfying and encouraging for the ISS. In 2001 the ISS board signed a contract with the Nature Conservation Agency granting the ISS the right to maintain and manage all protected caves and caves enclosed on areas where specific conservation effort or actions have been taken, i.e. natural parks, recreations areas, protected lava – or volcanic fields and other reserves. This action of forwarding the authority to the ISS is a milestone for the ISS´s efforts toward cave conservation in Iceland and the Minister of Environmental Affairs authenticated the arrangement in July 2002. The ISS/land-owner treaty wassubsequently abandoned and Árnahellir legally declared a Natural Monument.

In the future the ISS will propose new specific cave conservation projects to the Nature Conservation Agency or if the matter allows, take the necessary steps unaided in power of the treaty made with the Nature Conservation Agency and Ministry of Environmental Affairs.

Vulcanospeleology as Tourism: Case Study of Samoa

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The Independent State of Samoa is located in the South Pacific region immediately east of the International Date Line. Located to the north of the Tonga Trench, the country of Samoa comprises several small volcanic islands as part of a 1200 linear volcanic chain extending 550 km from Rose Atoll in the east to the Samoan island of Savaii in the west. The Samoan islands are composed almost wholly of basic volcanic rocks such as olivine basalt, picric basalt and olivine dolerite of the alkaline basalt suite. Although the age of the rocks is poorly known, it is thought that the oldest Fagaloa Volcanics erupted in the Pliocene period. The islands are still volcanically active, with the last eruptions in Savaii of Mauga Afi in 1760, Mauga Mu in 1902 and Matavanu in 1905.

There are an unknown number of caves located within the volcanic landscape of Samoa. Most caves appear to be of subcrustal forms that have been modified by subsurface river systems. The Samoan Visitors Center advertise tours through several caves including the Peapea Cave in the Le Pupu-Pue National Park, and the Paia Dwarf's Cave below the summit of Mt Matavanu. Other caves, such as the Piula Cave Pool between the Piula Theological College and the coast, are available for visitor exploration.

This study aimed to identify as many vulcanospeleological features in Samoa as possible and to relate the location of the caves to geology and land tenure. A short inventory of the caves was undertaken by identifying physical and cultural features of significance. The use of the popular and lesser known caves for tourism was examined, and the relationship between cave tourism and local village ownership was explored. The challenges and impediments to the expansion of vulcanospeleology as part of tourism in Western Samoa was also examined.

Patterns of Lava Tube Development on the North Flank of Mauna Loa, Hawaii

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Mauna Loa is a shield volcano on the island of Hawaii with a surface area of about 5,500 sq. km and rising to an elevation of 4,170 meters above sea level. The U. S. Geological Survey estimates that about 40 percent of its surface area is covered by lava flows that are less than 1,000 years old. In the time period 1992-2001, members of the Hawaii Speleological Survey have surveyed 55 km of passage in 107 lava tubes within a 60 square km area on the north side of Mauna Loa's northeast rift zone. The tubes are found in flows ranging in age from 5,000 years BP to as recent as the historic 1935 flow. These tubes exhibit several distinct configurations. The most commonly observed tube pattern consists of a single sinuous conduit containing occasional loops and short branches. Other, more complex tube patterns are also observed in the Mauna Loa lava flows and include:

(a) *Unitary, multi-level tubes*. Some of the thicker flows are up to 20 meters deep and contain multilevel tubes in canyon like passages. These tubes appear to result from stable lava levels that partially filled the tubes. Crusting took place on the top of the lava in the tubes with molten lava flowing below. Subsequent lowering of the level of flow in the tube and crusting of the tops of the lower lava flow levels resulted in evacuated multi-level tubes with the crusted upper surfaces of the partially filled tubes remaining as intermediate ceilings when flow through the tubes ceased.

(b) *Shallow complex tubes*. The 1935 flow is only 7-8 meters thick but contains a grid-like tube complex having 4,500 meters of surveyed passages in an area that is 700 meters long and 250 meters wide. This tube appears to have been developed by multiple flow lobes advancing along the distal end of a sheet flow with the lobes diverging and converging as inflation occurred, resulting in a tubes having a maze-like pattern.

(c) *Single level tube complexes in broad flows*. Over 8 km of parallel tubes have been surveyed in the historic 1855 flow. The tubes extend across the flow in at least three parallel lines. The tubes are at about the same depth beneath the surface, appear to be in the same flow unit, and are not branches of large loops.

(d) *Giant tubes*. Emesine Cave in the historic 1881 flow is the largest surveyed tube on Mauna Loa. With a linear extent of over 8 km, a vertical extent of 436 meters, and having a surveyed length of 20.72 km, this single tube contains almost 40 percent of the total surveyed passage found in the northeast rift zone tubes. Although much of Emesine Cave consists of a unitary tube, some parts of the cave are a complex braided network of passages on more than one level.

Carvão Cave (S. Miguel Island, Azores, Portugal: An Educational Experience

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"Gruta do Carvão" (meaning "Coal Cave") is the biggest lava cave in S. Miguel Island, and one of the most impressive underground structures in the archipelago. It is a well-known cave, reported in old manuscripts since the sixteenth century, and visited by many national and international explorers.

Carvão Cave has nowadays a total acknowledged length of about 1650 m, with a general NNW-SSE trend and along three different sections, most of it more than five meters wide. However, the original path of the main channel can be traced for about 2400 m from the coastline, and it might be able to have reached more than 5 km long. This cave develops in a basaltic *s.s.* lava flow (SiO_2=45.6%; Na_2O=2.53%, K_2O=1.19%) probably extruded from the Serra Gorda scoria cone area. This strombolian cone is one of the about 200 volcanic cones pertaining to the "Picos Volcanic Complex", an area of basaltic nature that extends in the western sector of S. Miguel Island as a shallow platform, built by lava flows of *aa* and *pahoehoe* type. The lava flow of Carvão Cave is covering a pumice layer and a paleosoil, in witch some charcoal remains were found and dated by ^{14}C conventional gas counting technique, at Geochron Laboratory (USA). The ages determined were 11,880 years BP (±80y) and 12,100 years BP (±140y), pointing a Holocene age to Carvão Cave.

Owing to its size, a great variety of microstructures can be found inside the cave, which are undoubtedly an eloquent sample of the creative force of the Azorean volcanism. Among those are flow marks, lava tree molds, *pahoehoe* slabs, ropy and spongy lavas, burst bubbles of lava, branching galleries, superimposed channels and long extensions with benches at several steps. On the roof there are many fusion lava stalactites and other irregular deposition-type stalactites, sometimes over the former. Some sectors of the cave, mostly the flatter ones, were affected by sand and clay deposition, which silt them up and block the cave in some places. Thus, it was needed some removing work in recent times to allow a permanent and easy walk inside the lava tube. Carvão Cave has been used for many years as warehouse of the local tobacco factory.

Given its size and location, right in the urban area of Ponta Delgada city, close to the downtown, airport, schools and tourist facilities, the cave is the perfect spot for visitors interested in the speleological thematic, or in a wider sense, to all who want to know the natural volcanic underground landscape of the S. Miguel Island. Therefore, a project to open Carvão Cave to the general public is in progress, taking profit of the many potentialities of that cave, namely in terms of its scientific, educational and touristy value.

That project is based on well-sustained museum programme and the dynamics of several activities associated, including an exhibition area nearby the main entrance. In fact, it is believed that Carvão Cave is the perfect place to enhance the importance of the volcanic phenomena (specially of the basaltic volcanism) to the genesis and evolution of the Azores archipelago, and its influence in the Azorean way of life. This cave is also an excellent scenario for educational approaches, namely in terms of Environment Education, owing for a better knowledge of Man and Nature, calling attention to Environmental problems and creating a new behaviour. With these ideas in mind, a special attention is given to schools (with the appropriate connection with their teachers and school programmes) allowing that many students visited Carvão Cave, in what it's expected to be a fruitfully educational experience.

The Grotta dei Rotoli (Mount Etna, Italy)

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Only few years ago discovered, the Grotta dei Rotoli (*cave of rolls*) develops in the flow field who was generated during the eruption of 1865. This basaltic effusion shows both pahoehoe and 'a'a flows but it is in the former morphology that the studied lava tube develops. Plan view, longitudinal and transverse sections of the cave are presented in this work.

This lava tube has a length of only 260 meters but its importance is given by big rolling-over structures drapping the walls of the cave. In his short lenght the cave bifurcates twice, in general agreement with the observation that many lava tubes show an increase in size with increasing distance from the vent (Calvari and Pinkerton, 1999).

Is supposed that the enlargement of the lava tube, join to a fast draining of lava (probably due to the opening of an ephemeral vent), promotes a slow longitudinal collapse of the still not self-supporting roof. This kind of collapse generates a downward directed bulge: because this bulge touches the floor it create the splitting of the lava tube. This partition of the transverse section works as a stoppage for the new following flow. Is in fact assumed that only a new re-filling of the tube with fresh lava can lock the collapse of the roof, giving to it more time to cool and solidificate. The successive rapid draining gives eventually rise to rolling-over structures that embrace the bifurcation.

Thanks to thin sections studying, substantial differences in porphyritic indexes are detected between rolls and roof samples, giving force to the theory of the second flow injection.

Key words: lava flow; lava tube; rolling-over structures; Etna volcano.

Growth of a Submarine Lava Tube at Ustica Island (South Tyrrhenian Sea)

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The island of Ustica is a small (8 km^2) volcanic island, located in the Tyrrhenian Sea, 60 km north of Sicily. The island rises from the bottom of the sea of 2.000 m and reaches the elevation of 248 m a.s.l..

Several authors have recognised in the island an articulated volcanic succession, with different eruptive centers, the last of wich has been active 147 ky b.p. (Cinque et al., 1988; De Vita et al., 1998; Romano & Sturiale, 1971). The morphologies of lavas cropping in the island vary from pahoehoe to pillow. Explosive activity produced large amounts of tephra, going from hydromagmatic breccias to pumice. All existing geochemical data comes from subaerial outcrops, they indicate for the volcanics of Ustica a mostly alkaline and subordinately subalkaline character.

Due to the reduced dimension of the island all subaerial lava flows reached the sea. This produced a great amount of morphologies of the transition from subaerial to submarine lava flows. The tectonic uplift wich has affected the island after its last period of activity allows us to see the submarine lavas, and the transition from pahoehoe flows to pillow breccias.

In this work we want to point out the existence of a little lava tube (14x2 m) found in one of these submarine pillow-breccia levels. Such lava tubes are considered to be very rare occurrences in submarine lavas.

The origin of this lava tube can be explained considering the formation of a mega-pillow in an advancing submarine lava flow. Its outer layer solidified protecting the inner part of the tube from the water. Inside the tube the gas expanded, probably part of this gas was provided by the vaporization of small volumes of sea water that entered the tube. The expansion of the gas caused an inflation of the walls of the tube wich were still in a plastic state. Such an inflation left a space in the tube so that liquid lava inside could develop tipically pahoehoe ropy morphologies.

Key words: lava flow; lava tube; pillow-lava; Ustica; Tyrrhenian Sea.

Lava Tubes of Harrat Kishb, Saudi Arabia

John J. Pint
Cave Unit Consultant, Saudi Geological Survey

This presentation features a Powerpoint slide show on the discovery and exploration of several lava tubes located in Harrat Kishb, a lava field located 300 kilometers Northeast of Jeddah, Saudi Arabia.

The first visit to Harrat Kishb had two goals. One was to investigate a series of collapse holes, visible in air photos, extending from an extinct volcano named Jebel Hil and suggesting the presence of a lava tube at least three kilometers long. The second goal was to try locating several shorter lava tubes seen in this area by a hunter.

A hair-raising, nearly impossible climb up Jebel Hil revealed an opening in the side of the crater, presumed to be the upper end of the long lava tube. A ground reconnaissance then gave the coordinates of most of the collapses and indicated the floor of the tube was from 26 to 42 meters below the surface.

Two days of searching the stark landscape of Harrat Kishb failed to reveal the location of the smaller lava tubes, but these were finally found with the help of Bedouins living at the edge of the lava field. One of the tubes, Kahf Al Mut'eb, was surveyed to a length of 165.8 meters and was found to contain lava levees, stalactites and animal bones. A brief look at a nearby lava tube revealed that it was "populated" by tall, shadowy figures which turned out to be stalagmites of rock-dove guano, giving this hole the name Ghostly Cave.

During a second visit to Harrat Kishb, a survey of Ghostly Cave was undertaken. Samples were taken of the basalt and mineral coatings found on the walls and of the thick layer of choking, potassium-rich dust on the floor. The "guanomites" were photographed and sampled. During the survey, two L-shaped throwing sticks were found inside the cave. These are similar to sticks seen in the hands of figures in Arabian Neolithic rock art and may be five to eight thousand years old.

A photography session held in Kahf Al Mut'eb resulted in the discovery of a plant-fiber rope which may also be of Neolithic age.

Finally, a visit was made to a lava tube located much farther north in Harrat Kishb. Its entrance is unusual in that it is not a collapse, but apparently the result of surface air being sucked into the tube as the lava was draining from it. This cave, named Dahl Faisal, also features a "dust volcano" produced by the release of air trapped in mud during flooding.

Topographical Map of Lower Hallmundarhraun

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Hallmundarhraun is morphologically and speleogenetically one of the most interesting lavas in Iceland. Hallmundarhraun is in the authors opinion at least two different lavas. An older one, probably coming from southern main crater in Jökulkrókur and a younger one around 1200 years old, coming from the northen crater. It totally covers the older lava, except where the lavas meet east of Þrístapafell and in Laski south and south east of Þorvaldsháls. There are other separate lavas in Jökulkrókur south of the southern crater coming from craters covered by Langjökull.

A geomorhological map of the lower two quarters of the lava showing surface features and the underlying caves is presented and discussed.

The History of Lava Cave Preservation in Iceland

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The author spent several summers as a child helping out at Kalmanstunga in the vicinity og the great caves in Hallmundarhraun in the fifties and sixties. Peoples interest in the caves and that new caves were found was very stimulating. But there was an other side, a black side that was only wispered about. The damage. The dwindling bone heap in Vígishellir in Surtshellir, deliberate breaking and taking of formations from all the caves. This had a deep effect on the author. The relationship became clearer as the years went by. Every find of a new cave had been presented in the newspapers and or the radio. This stimulated interest, interest traffic, traffic damage, intentional as well as unintentional, the well known evil cicle. All caves were easily accessible. By 1982 sensitive formations in all known Icelandic caves had been either severly or totally damaged. The papes describes the steps taken after 1982 in the preservation of lava cave features as seen by the author.

Five Vertical Conduits in Iceland

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The paper describes five interesting vertical conduits in Iceland. First four are in the Gjábakka / Þjófahraun fissure system. The first three, Tintron, Pyttlur, Vambi are seen by the author as either as pure chimneys or chimneys with some overflow, on an otherwise closed vent / tube cave system. The fourth is a 24m deep very well preserved mineature volcano. A chamber with an inflow tube from below, chimney and a small outflow tube. At last the great pit crater Þríhnúkagígur is presented and discussed.

Complex Tree Mold Labyrinth found in Ken-Marubi Lava Flow in Mt. Fuji

Hiroshi Tachihara, Yumi Kuroishikawa, Tadato Makita,
Nobuyoshi Watanabe, Haruko Hinata, Kisara Nakaue,
Takanori Ogawa, and Tsutomu Honda
Mt.Fuji Volcano-Speleological Society

At the north-east flank of Mt.Fiji, the tree molds are often found in the lava flow erupted about 1000 years ago. During the field survey for tree mold in this lava flow, a very complex tree mold is found and observed (H. Tachihara,T. Makita,1998).

This tree mold is not a single tree mold, but combined labyrinth like tree molds which consist of 39 tree molds attached one after another and total lenght of the cavity (the maximum diameter is about 1.5m) penetrable by personnel is 204 m by excepting unpenetrable cavity of less than 50cm diameter. The longest tree mold cavity reported in US hitherto was 40.84m (D.G.Davis et al,1983).

The following table 1 shows length/depth and cross section of penetrables in the combined tree molds.

Combined 39 tree molds are, one vertical standing tree mold, fourteen horizontally inclined tree molds, and other unpenetrable twenty four samall tree molds of branches or creepers.

The inner surafece of some tree molds have a remelted layer of lava and lava stalactite are often observed. The remelting of the inner surface of the tree mold seems to be produced by gas burnig with oxygene by chemical reaction of carbon after carbonization of living tree or cellulose with water in the tree(T.Honda,1998). The tree molds located at the bottom area are laid down on a scoria layer and have no remelting surface.

As for details on the origin of the structure of tree mold and vegetation succession stage at the eruption time, extensive studies are still under going together with the historical dating investigation of this lava flow.

At the symposium poster session, the photos and drawings of this combined tree molds will be presented.

References:

H. Tachihara: The press interview document, Mt. Fuji Volcano-Speleological Society, 1998, p.1~3.

T. Makita: "Report on the lava tree mold of important memorial object no.102", The annual meeting of the Speleological

Table 1 (Tachihara et al. "Complex Tree Mold Labyrinth). Depth/length and cross section of combined tree molds.

Tree mold	Depth or Length	Cross section
Tree mold A	675 cm	160x120~140x110cm
Tree mold B	2420cm	360x140~90x90cm
Tree mold D	400cm	70x70cm
Tree mold E	940cm	45x50cm
Tree mold F	886cm	70x70cm
Tree mold G	2835cm	500x120~70x70cm
Tree mold H	160cm	420x120~100x65cm
Tree mold K	2760cm	110x80cm
Tree mold L	1800cm	100x120~90x40cm
Tree mold M	1800cm	70x60cm
Tree mold O	1770cm	150x110cm
Tree mold Q	300cm	70x70cm
Tree mold S	320cm	200x90~74x60cm
Tree mold T	900cm	50x35cm
Tree mold V	500cm	50x50cm

Society of Japan, 1998, July, p.21.
D.G. Davis, R.B. Scoville: "Lost long Lava Labyrinth" NSS news,1983 July, p.196.
T. Honda: "Interpretantion of remelting layer of inner surface of tree mold.", The annual meeting of the Speleological Society of Japan, 1998, July, p.17.
T. Honda: "Physico-chemical explanation for remelting process of inner surface wall of Tainai-tree molds located on the flank of Mt. Fuji". Journal of the Speleological Society of Japan, vol.23, December,1998, p.29-38.

Recent Discoveries on the Laki Flow Field, S. Iceland

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Speculative expeditions to the 1783/4 Laki flow field (Skaftáreldahraun) in 2000 and 2001 discovered significant caves in the upper part of the eastern arm of the flow field, known as the upper Eldhraun. In an area of approx. 12 km^2, northeast of Miklafell, approx. 12 km of cave passage were located, explored and mapped. Many of the caves were short, but 4 were over 500 m long, and the longest had a survey traverse length of 1.982 km. The caves had impressive volumes, varying forms and a diversity of internal features. Some had isolated locations in remote parts of the flow field, but others were members of complex cave groups. One group located on the eastern side of the flow field appeared to have an origin related to the formation of a large collapse trench. Another, larger and more complex, group of caves, lay on the western side of the flow field adjacent to the seasonal lake, Laufbalavatn. Here approx. 5.0 km of cave passage underlay and had a close association with a range of surface landforms, including short collapse trenches, lava rises and closed depressions. Accurate mapping of the caves and their relationship with the surface landforms in the study area has provided evidence on which to base an interpretation of the morphogenesis and nature of emplacement of the upper Eldhraun.

A Mega-Tube System in the Hallmundarhraun, W. Iceland

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Experimental work to track and map lava tube caves remotely from the surface of a lava flow with geophysical methods was undertaken with great success on the Hallmundarhraun flow field in 2001. Using a caesium magnetometer and a survey method known as area survey, it was possible to accurately map the dimensions and route of an entranceless cave passage lying upflow from the terminal lava seal of Stefánshellir. The work proved the presence of 300m of open cave that trends upflow in an easterly direction. The length of cave discovered simply reflects the dimensions of survey block and it is probable that a future survey will be able to map a further length of this passage.

Farther east and extending over a distance of about 18 km upflow from Stefánshellir is a series of crater-like features, each made of a ring of large blocks of lava crust and sitting like a crown at the summit of a low lava shield. Similar features recently observed on Kilauea have been termed 'shatter rings'. The rings extend across the flow field in the manner of a sinuous necklace. Magnetic survey between three revealed that cavities exist beneath and between them. Interestingly, another shatter ring occurs in the lower part of the flow field, overlying the upflow end of Víðgelmir and demonstrating that shatter rings and lava tubes may be genetically related. A working proposal is that the long necklace of rings formed over the master lava tube that fed lava into the Norðlingafljót valley. It is believed that the newly discovered entranceless cave is also a part of this mega-system.

The Volcanic Landforms and Lava Tube Caves of Jeju Island, S. Korea: Candidates for World Heritage Site Status?

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Bournemouth University, UK

This paper will be a report-back on a visit to Jeju Island made by the author in mid-August, 2002. The purpose of the visit was to provide some advice to the S. Koreans on technical aspects of a bid to UNESCO seeking nomination of the lava tube caves and other volcanic landforms as a World Heritage Site. The island has over 100 caves, the three longest ranking 8, 10 and 18 on Bob Gulden's list of the world's longest lava tube caves.

2002 SYMPOSIUM PAPERS

Lava Tubes of Harrat Kishb, Saudi Arabia

John J. Pint

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Introduction

Prior to the year 2001, very few reports were made regarding lava caves in Saudi Arabia and no surveys are known to have been carried out. This situation changed in November of 2001 when Dr. John Roobol led an expedition to the vicinity of Jebel Hil Volcano in Harrat Kishb, a lava field located 300 km northeast of Jeddah. The explicit purpose of the expedition was to locate and survey lava caves, as well as to describe them accurately. The location of Harrat Kishb is shown in Figure 1.

The first expedition to Harrat Kishb took place November 10-14, 2001, led by Dr. J. Roobol, J. Pint and M. Al-Shanti. The project took place at the urging of Dr. William Halliday, member and founder of the Commission on Volcanic Caves of the International Union of Speleology (UIS). By coincidence, Dr. Roobol had received, from geologist Faisal Allam, several photographs of cave entrances found some 6 km east of Jebel Hil in Harrat Kishb. Accordingly, the goals of the expedition were to locate the caves shown in the photographs as well as to precisely locate the collapse holes west of Jebel Hil which were observed by Roobol and Camp (1991) and thought to be entrances to a lava tube.

After much searching, the photographed caves were located and one of them, Mut'eb Cave, was surveyed. In addition, the GPS locations of twelve collapse entrances of the Jebel Hil Lava Tube were taken, a difficult undertaking since 12 km of mostly a'a lava had to be traversed on foot.

A second visit to Harrat Kishb was made from February 2-5, 2002, again led by J. Roobol, J. Pint and M. Al-Shanti. Ghostly Cave was surveyed and a new cave, Dahl Faisal, was located and surveyed. The results of the Kishb Surveys were published in Roobol et al., 2002.

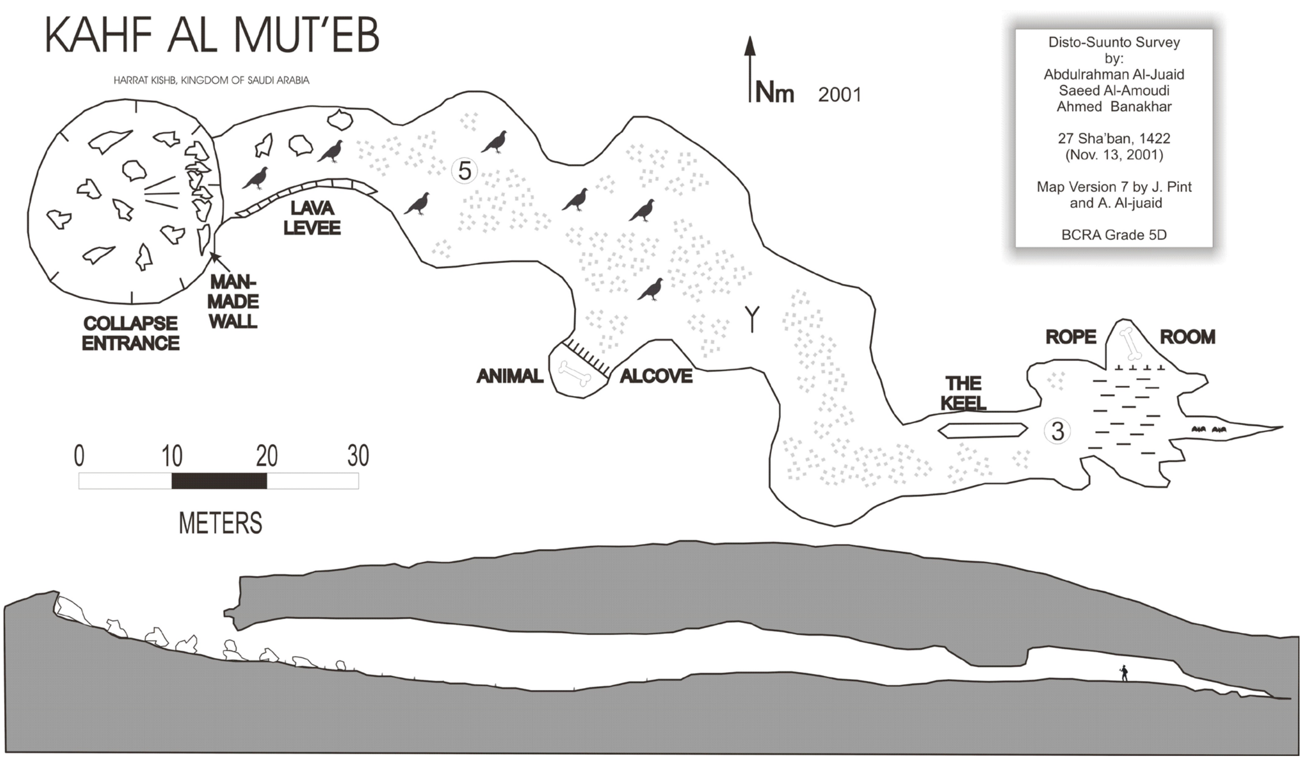

Figure 2. Map of Mut'eb Cave.

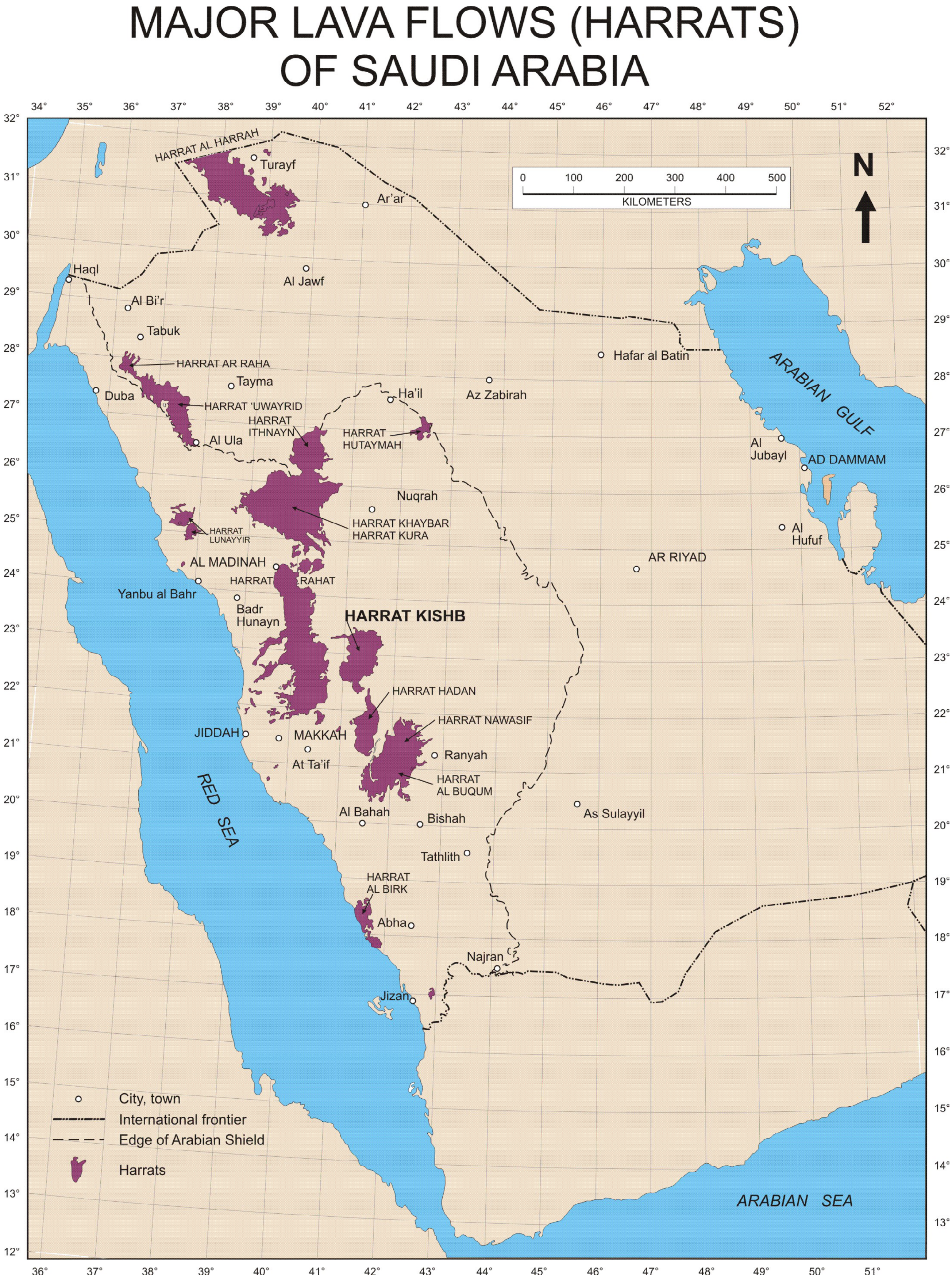

Figure 1. Map showing the location of Harrat Kishb lava field in Saudi Arabia

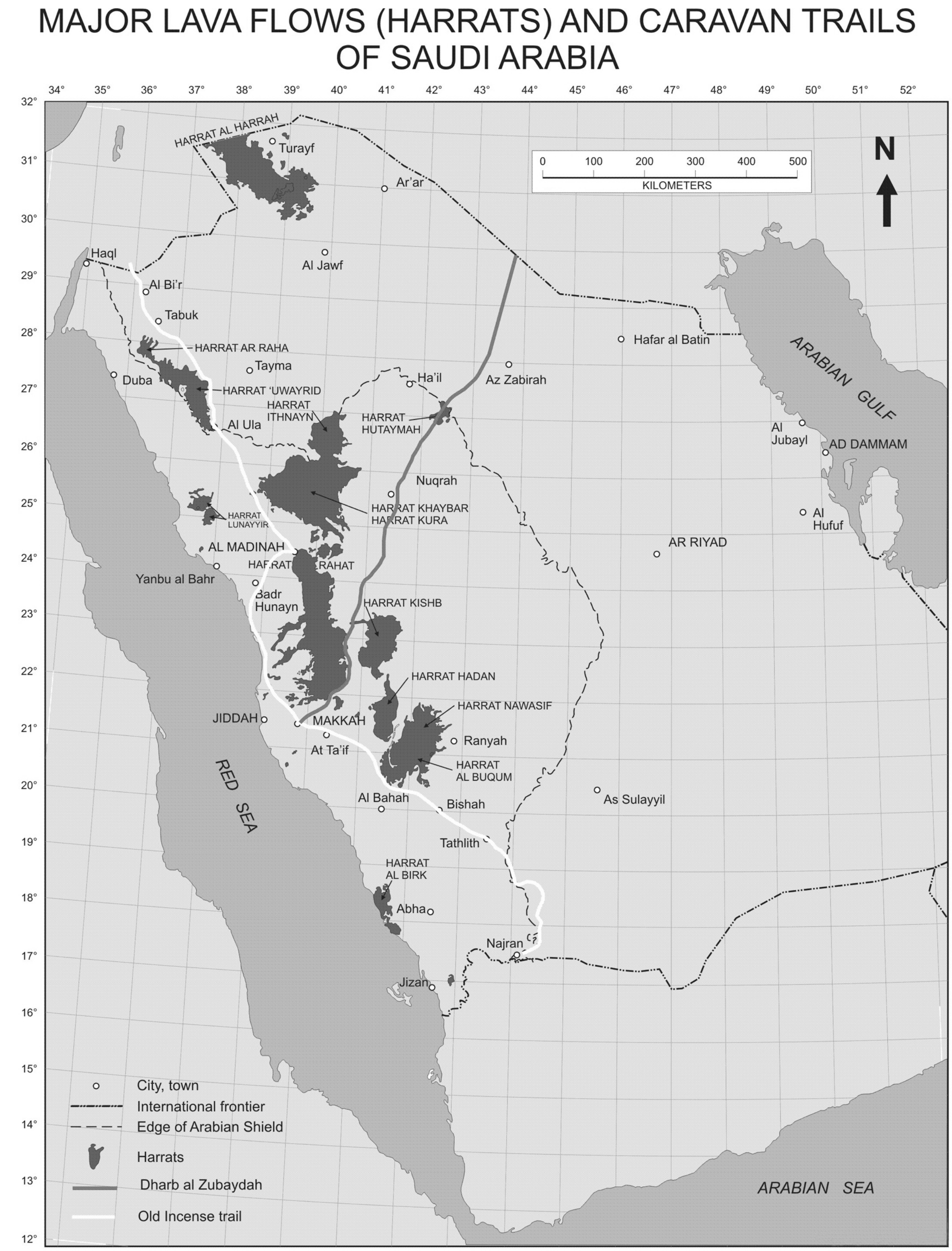

Figure 3. Map of two ancient caravan trails in Saudi Arabia, showing lava fields. After Hussein Sabir, 1991.

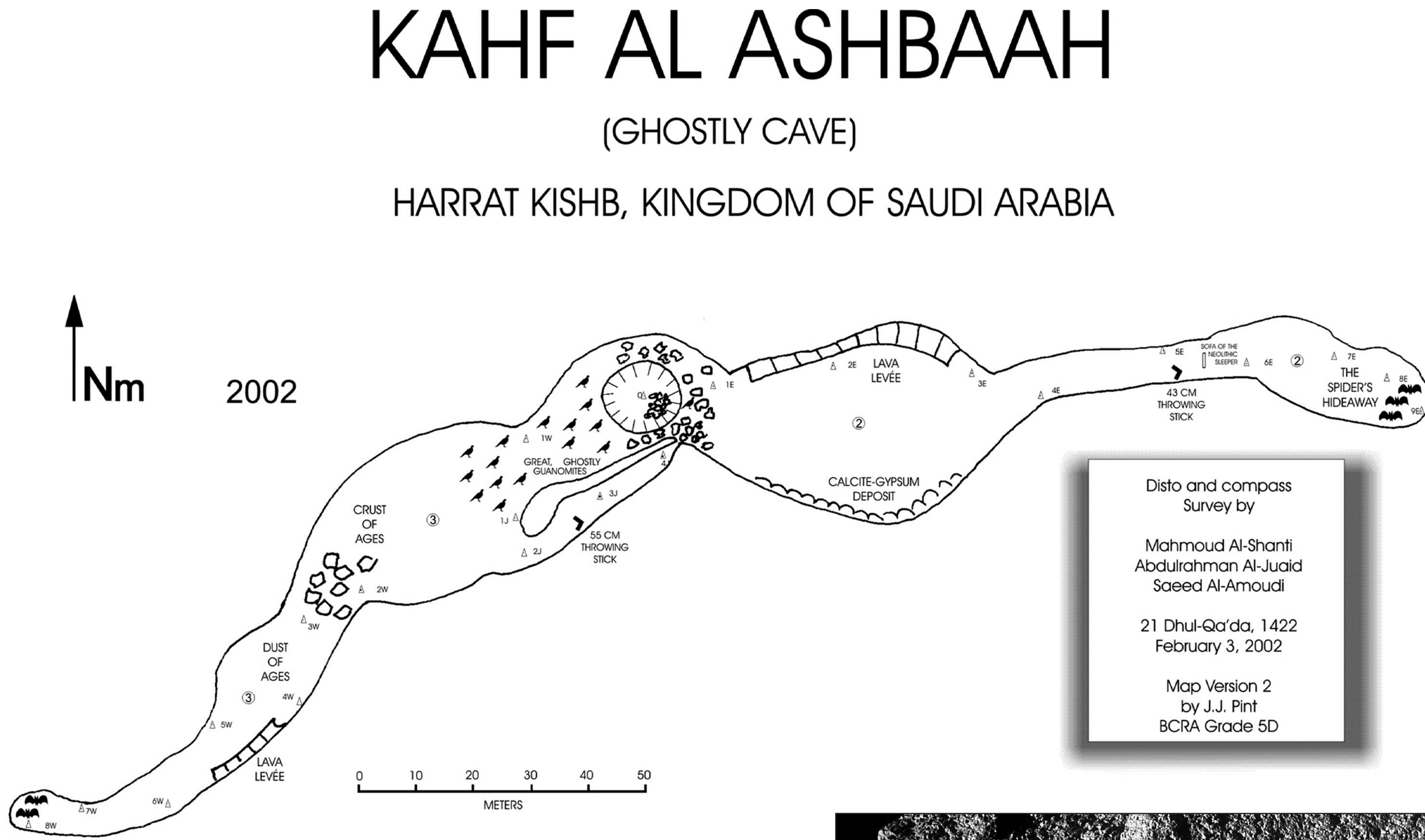

Figure 4. Map of Ghostly Cave.

Figure 5. Throwing sticks found in Ghostly Cave are flat on the bottom and curved on top to provide aerodynamic lift.

Geology of the Hil Basalt

All the surveyed caves found in Harrat Kishb are located in the Hil Basalt, which is a basaltic lava field younger than one million years, with an area of 5,892 km^2, centered about 270 km northeast of Jeddah. These deposits comprise both scoria cones and lava flows which were probably formed during a moist climatic period or pluvial interval and which are distinguished from overlying subunits because they are significantly eroded (Roobol et al., 2002).

Mut'eb Cave

Mut'eb Cave, or Kahf Al Mut'eb is registered as number 124 in Pint, 2002 and is located at 22°55′N,41°24′E. Note: seconds of latitude and longitude have been omitted in this paper in order to help protect these caves from vandalism. The precise location of each cave is given in Pint, 2002.

Geological setting. The cave is found in a sinuous ridge of smooth, hard pahoehoe lava curving around an older, obstructing scoria cone in the volcanic deposits of the Hil Basalt.

Description. A map of this cave is shown in Figure 2. Mut'eb Cave is 150 m long. The entrance to the cave measures 3 x 7 m and is found on the eastern side of a collapse 20 m in diameter. There are remains of an ancient, man-made wall across the front of the cave. A single passage trends east, sometimes reaching a width of 20 m. The passage height varies from 3 to 5 m. Sand or clay-rich sediment cover the floor to an undetermined depth. The cave contains abandoned wasps' nests, mounds of rock-dove guano, animal bones, and bat urine stains on the walls and ceiling. A 40-cm-long cord composed of long plant fibers, with one knot in it, was hidden beneath a flat rock at the eastern end of the cave (Roobol et al., 2002).

Comments. Because a man-made structure is found at the entrance to this cave and because an apparently ancient artifact was found deep inside, it is suggested that the cave be investigated by archeologists. Note that Mut'eb Cave, in Harrat Kishb, is located approximately 55 km east of the celebrated Darb Zubaydah, a well-marked trail complete with shelters, water wells and reservoirs one day's march apart (See Fig. 3). The trail led from Baghdad to

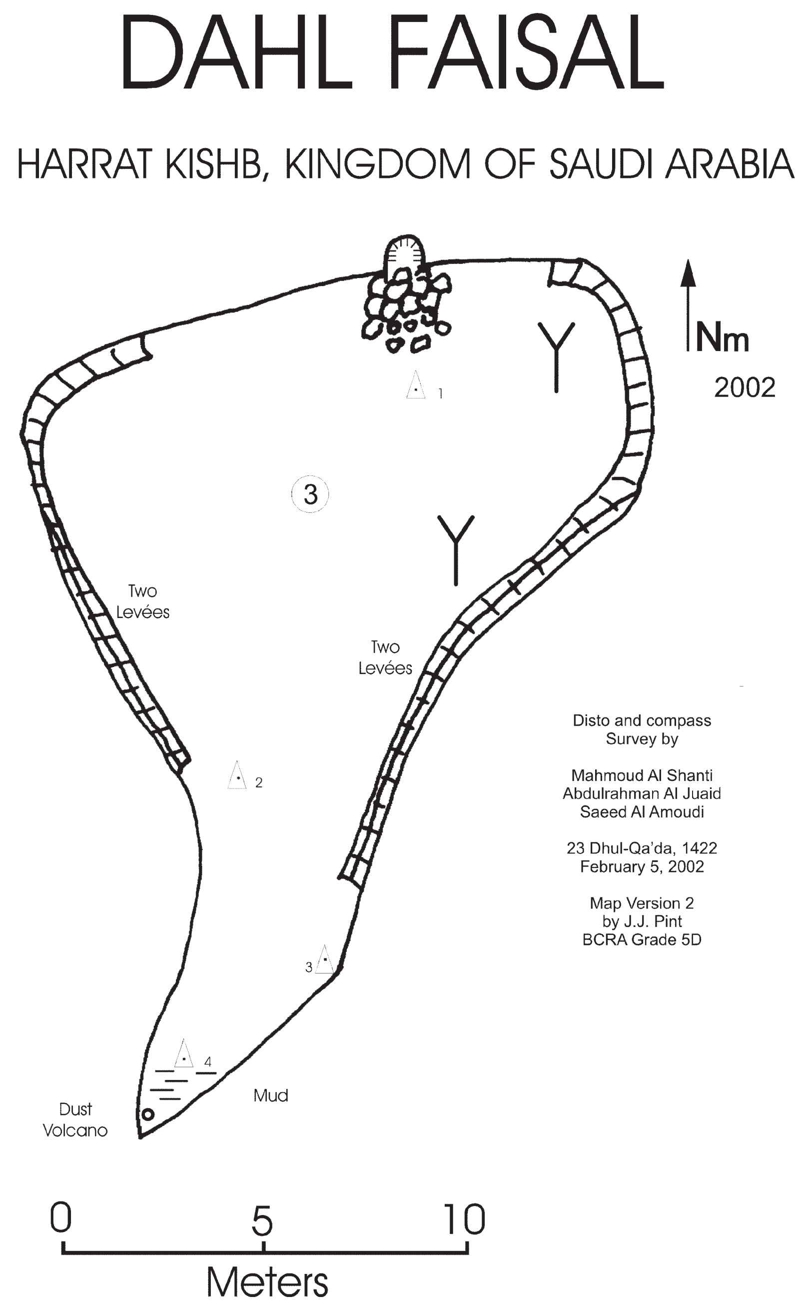

Figure 6. Map of Dahl Faisal.

Mecca and was built by Queen Zubaydah, the enterprising wife of Caliph Harun al-Rashid around the beginning of the ninth century A.D.

Ghostly Cave

Ghostly Cave or Kahf Al Ashbaah is registered as number 123 in Pint, 2002 and is located at 22°55′N,41°25′E.

Geological setting. The cave is found in a flat area of basaltic pahoehoe lava in the volcanic deposits of the Hil Basalt .

Description. The cave is 320 m long. The entrance is a collapse 10 m in diameter with a 7 m drop to a flat floor below. The passage leads off east and west. Up to 50 stalagmite-like mounds of rock-dove guano are found just inside the entrance to the western passage along with the remains of a stone wall partly buried beneath bird guano. The cave passages have a maximum width of 30 m and vary in height from 1 to 3 m. Both passages have white, calcareous patches on the ceiling and a thick layer of powdery dust on the floor. This consists mainly of calcium, potassium and phosphate. Bats are found at both extremes of the cave. Two flat, L-shaped wooden throwing sticks were found in dark areas of the two passages, resembling similar instruments depicted in Neolithic rock art found in Saudi Arabia. See Fig. 3 and 4. (Roobol et al., 2002)

Comments. Man-made constructions and two ancient throwing sticks were found in this isolated and difficult-to-enter cave. Digging in the sediment which completely covers the cave floor may produce historically or archeologically important finds. As noted in the comments on Mut'eb Cave, Ghostly Cave is Cave is located approximately 55 km east of the celebrated Darb Zubaydah (see Fig. 3).

Dahl Faisal

Dahl Faisal is registered as number 162 in Pint, 2002 and is located at 23°11′N,41°27′E.

Geological setting. The cave is found in a nearly flat-lying "whale-back" lava flow of the Jabal Zuwayr volcano. This volcano and its flows consist mainly of basanite and alkali olivine basalt with small volumes of hawaiite, phonotephrite and phonolite and are located in the northern portion of the Hil Basalt.

Description. Dahl Faisal is 22 m long. The cave is entered through a smooth, 3-m-long pipe, 80cm diameter at its narrowest point, oriented at a 60° angle. This appears to have formed when the cave was created. Below the entrance tube lies a heap of rocks apparently piled up by people using the cave in the past. Dahl Faisal consists of one room, 17 x 22 m, with a maximum ceiling height of 3 m. Sediment of unknown depth covers the original floor. The cave contains basaltic stalactites, stalagmites and lava levées. Desiccated animal scat apparently from wolves, hyenas and foxes was also found. See Fig. 5. (Roobol et al., 2002)

Comments. Dahl Faisal is located 60 km east of Darb Zubaydah and about 70 km southeast of Mahad adh Dhahab, an operating gold mine and reputedly the site of one of King Solomon's Mines. See Fig. 3. Carbon-14 dating of wood from fires used for smelting suggests that the mines are 3,000 years old. This information, together with historical studies, indicate that gold, silver and copper were indeed recovered from this region during the period considered by some to be the reign of King Solomon: 961-922 B.C. Evidence of human use and the proximity of the cave to known historical sites, suggest that it could contain artifacts.

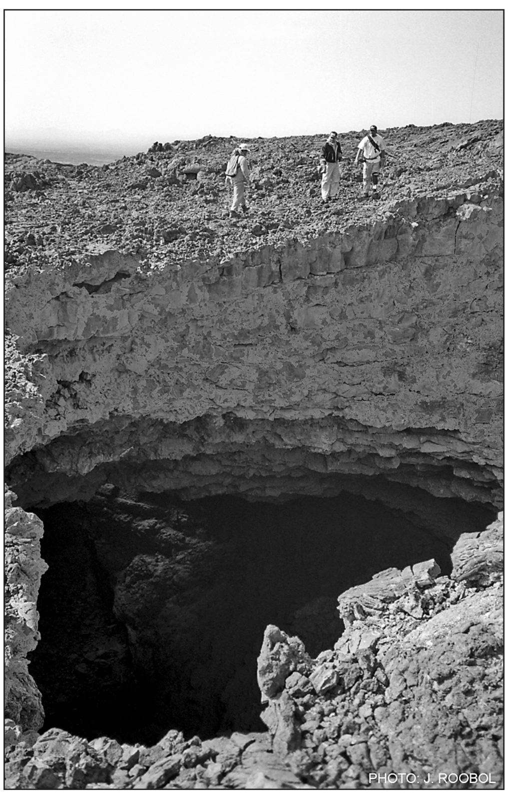

Figure 7. Collapse Structure 6 of the Jebel Hil lava tube, looking west, showing the upper part of the lava tube with geologists standing on the roof. Photo courtesy J. Roobol.

Jebel Hil lava tube

This lava tube extends westwards from Jebel Hil. Along its length are aligned small rootless shields, collapse holes, subsided areas and one area of local updoming. Twelve such features were located, one of which is shown in Fig. 6. The lava tube is up to 20 m high and the depth of its floor beneath the surface varies from 28.5 to 42.5 m, measured by Disto Laser Measuring Device at each hole. The surface features of this lava tube were mapped and described, and they suggest that the tube is at least 3 km long. However, the cave itself was not entered. A detailed map and description of these features are given in Roobol et al., 2002.

Other caves located on Harrat Kishb

Two other lava caves, First Cave and Bushy Cave were also located during the Kishb surveys. The entrance to First Cave is a collapse 20 m deep in what appeared to be a lava tube. It was not entered due to apparent instability of the entrance walls. Bushy Cave is a nearly round room 12X13 m, possibly formed by a gas bubble. It was sketched, but not surveyed.

Conclusions

The fact that six caves were located on the first attempt to find and study lava caves in Saudi Arabia should encourage more attempts to carry out vulcanospeleological projects in this country, which has over 80,000 square km of lava fields. The fact that three apparently Neolithic artifacts were found in two of the caves studied suggests that an archeological study of Saudi lava caves may produce interesting results.

The SGS open-file report on the Caves of Harrat Kishb can be downloaded at http://www.saudicaves.com/spspubs. The trip report and photos are at http://www.saudicaves.com/kishb/kishb.htm .

References

Pint, J. 2002: Master list of GPS coordinates for Saudi Arabia caves: Saudi Geological Survey Confidential Data File SGS-CDF-2001-1.

Roobol, M.J. and Camp, V.E., 1991: Geologic map of the Cenozoic lava field of Harrat Kishb, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geoscience Map GM-132, with explanatory text 34 p.

Roobol, M.J., Pint, J.J., Al-Shanti, M.A., Al-Juaid, A.J., Al-Amoudi, S.A. & Pint, S., with the collaboration of Al-Eisa, A.M., Allam, F., Al-Sulaimani, G.S., & Banakhar, A.S., 2002: Preliminary survey for lava-tube caves on Harrat Kishb, Kingdom of Saudi Arabia: Saudi Geological Survey Open-File report SGS-OF-2002-3, 35 p., 41 figs., 1 table, 4 apps., 2 plates.

Small Subcrustal Lava Caves: Examples from Victoria, Australia*

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* Presented in 2002, revised in 2006.

Introduction

This paper discusses the formation of a type of small lava cave that forms by "Subcrustal drainage" of lava flows. Examples will be drawn from the Western District Volcanic Province of western Victoria, Australia (Figure 1). Caves from that province are numbered in the Australian Karst Index with a "3H" prefix, abbreviated here to just "H" e.g. H-70 (Matthews, 1985).

In a review/study of active volcanoes in Hawaii, Peterson & others (1994) proposed two distinct models for the formation of lava tubes: either by the roofing over of linear surface lava channels (Figure 2); or by the draining of still molten material from beneath the solidified crust of pahoehoe flow lobes (Figure 3). The former process produces relatively large and simple lava tubes. However, this paper will concentrate on the smaller, but commonly complex, caves formed by localisation of flow beneath the crust of thin flow lobes or sheet-flows, and subsequent partial draining - a process that has been progressively recognised and described by Peterson & Swanson (1974), Wood (1977), Greeley (1987), Peterson & others (1994), Hon & others (1994) and Kauahikaua & others (1998) and which is illustrated in Figure 3. Recently, Halliday (1998a & b) has described two types of small lava cave: His "sheet flow caves' and 'hollow volcanic tumulus caves' which he regards as being distinct. I will argue that these are probably just two of several possible members of a continuum of forms which have been referred to as "**Subcrustal lava caves**" (e.g. Stevenson, 1999).

The terminology of surface lava flow features and their caves has become rather complex and confusing in recent years, so I will list here some terms - and my intended usage.

Surface lava features — what is a tumulus? The changing usage of "tumulus" affects the definition of a "tumulus" cave ! Walker (1991) gave the term "tumulus" a genetic definition which both expanded the term to incorporate all lava rises, including elongated ridges, and narrowed its usage to those rises that show evidence of inflation, given by opened axial clefts on the crest, but which have no evidence of lateral compression (if there was, Walker would call them pressure ridges). Unfortunately, on the relatively old (20-40,000 year) flows in Victoria weathering and vegetation growth has reduced much of the surface to a cracked and jumbled rubble. Thus, definitive axial clefts are difficult to identify and the new (genetically-

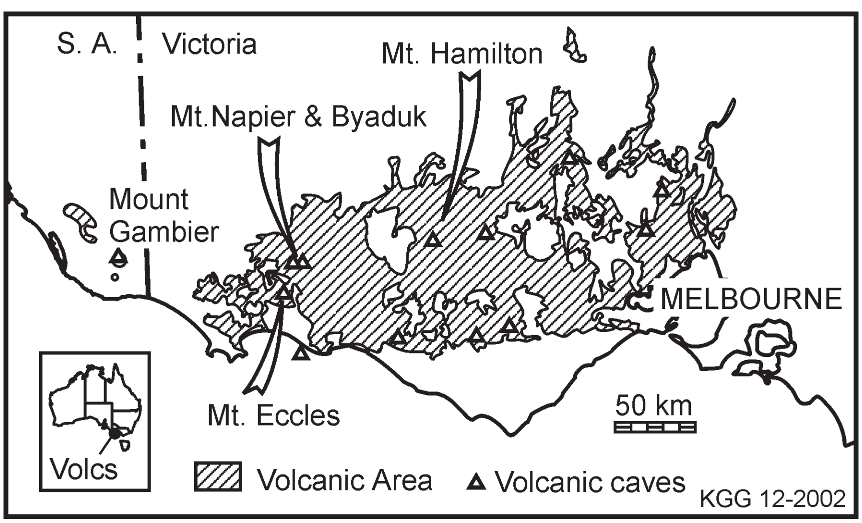

Figure 1. Location map of the Western District Volcanic Province, and its main lava cave areas.

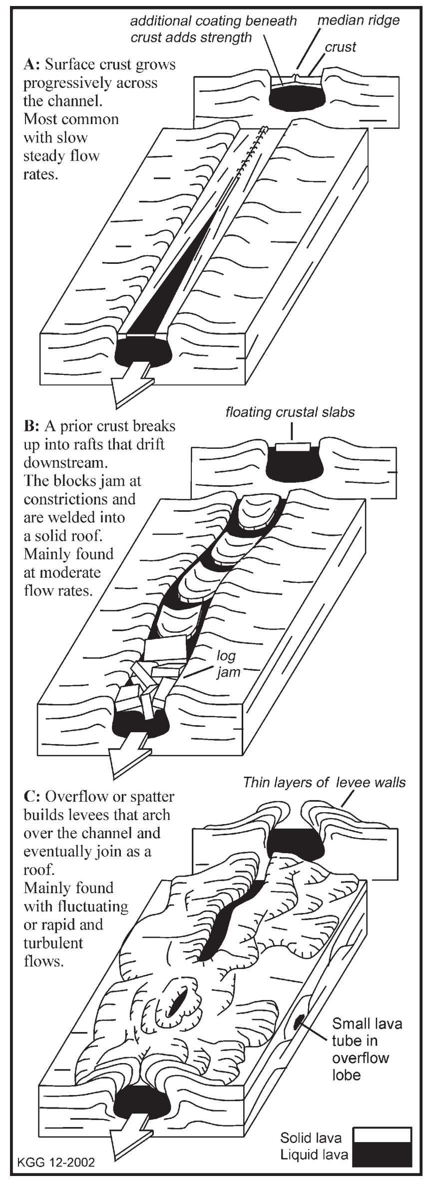

Figure 2. Three ways of forming large lava tubes by roofing a surface channel.

based) usage of the term "tumulus" has limited use. In Victoria the usage of "**tumulus**" has always been restricted to the distinctive, steep-sided, roughly-circular mounds described by Ollier (1964) in the Harman valley (many of which do have obvious large summit clefts) and the more general term "**stony rises**" is used for the chaotic complex of broader hummocks and hollows that occur on many of Victoria's younger lava surfaces. This local usage of "stony rises" would seem to correspond to the "hummocky pahoehoe" of Hon et al (1994) but some have relatively flat surfaces that correspond to their "sheet flows" and there are also transitional forms. In Walker's (1991) terminology the Victorian "stony rises" represent a mix of his "tumuli", "pressure ridges", "lava rises" and "lava rise pits".

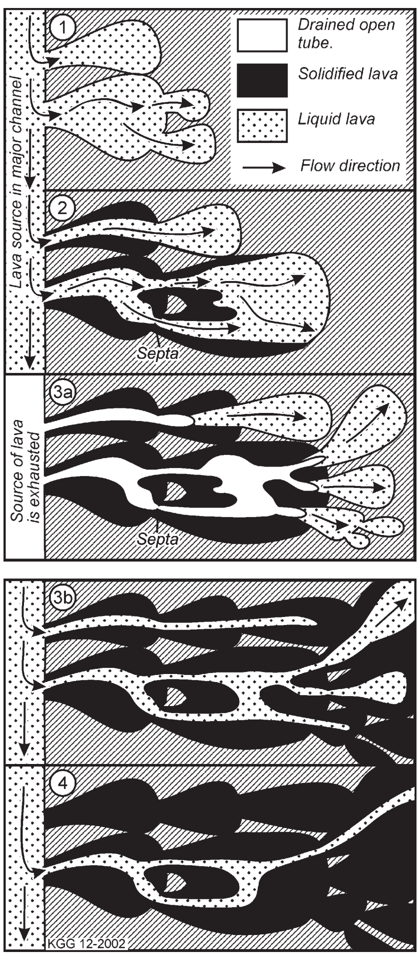

Figure 3. Formation of lava caves by subcrustal drainage of a series of advancing lava lobes. Step 3a is the situation if the source of lava ceases early in the development; irregular caves form. Steps 3b and 4 indicate the further evolution into more linear feeder tubes as lava continues to flow through the system.

For this paper I will use the descriptive, non-genetic, term "lava mound" to describe all high areas within a lava field. Lava mounds are likely places for the formation of small drained subcrustal lava caves, whatever the process of mound formation.

Cave types: In any discussion of lava caves and their genesis it is important to distinguish between active (lava-filled) proto-caves and the drained tubes and chambers (i.e. caves) which appear at the end of the eruption – as discussed by Halliday (2004).

In an earlier paper (Grimes, 1995) I described complex, lateral, levee-breach systems associated with lava channels at Mount Eccles, and distinguished them from smaller, isolated, drained chambers in the surrounding "stony rises" but did not suggest a formal nomenclature. The terminology of Halliday (1998a,b), which is based on the surface lava flow character (after Walker, 1991), is difficult to apply to the Victorian subcrustal caves because of the problem in distinguishing "tumuli" (sensu Walker, 1991) from other lava mounds. I also suspect that rather than two discrete genetic types of small subcrustal cave as proposed by Halliday ("sheet flow caves' and 'hollow volcanic tumulus caves'), we have a broad continuum of forms with a number of distinctive end-members.

I suggest that the cave classification should not be tied to the surface terminology until the processes of cave development are better known. Also, basing the cave nomenclature on the surface lava forms may be confusing cause and effect—rather we should be explaining some surface mounds and tumuli as a result of localised subcrustal flow in tubes, not the cause (see conclusion). The unifying factor in all these caves is that they form by drainage from beneath a broadly-crusted lava flow; hence I will refer to them here collectively as **subcrustal lava caves**.

In this paper my discussion will concentrate on the smaller subcrustal lava caves, those that form originally, rather than the larger more evolved forms which can develop from them over time and which tend to become closer in shape to the tunnels formed by roofing of surface channels. In Victoria, the Mt. Hamilton lava cave (Figure 14) may be an example of the latter type.

In Victoria, speleologists have used the term "**blister cave**" for the small, simple, isolated chambers found under the stony rises (Figure 4). However, care is needed to avoid confusion with another usage of that term for small chambers formed by gas pressure (Gibson, 1974, and Larson, 1993). I suggest usage of **lava blister** for those inflated by liquid lava (and later drained), and **gas blister** for those generated by gas pressure. "Blister" should only be used on its own where the genesis is uncertain.

The basaltic **Western District Volcanic Province** (previously known as the Newer Volcanic Province) of western Victoria has over 400 identified eruptive points and it ranges in age mainly from Pliocene (about 5 Million years) up to very recent times (5ka), though there are some volcanoes as old as 7 Ma (Joyce, 1988, Joyce & Webb, 2003, Price & others, 2003). Lava caves are known across the whole province (Figure 1), but are most common in the younger flows associated with Mount Eccles (20-33 ka, Head, & others, 1991, and P. Kershaw, per comm, 2005) and Mount Napier (about 32 ka, Stone & others, 1997). Recent summaries of both the surface landforms and the volcanic caves of the province appear in Grimes (1995, 1999); and Grimes & Watson (1995). The earlier literature on lava caves of the region by Ollier, Joyce and others is reviewed in Webb & others (1982) and Grimes & Watson (1995) and only some of those papers are referenced here. The younger lava flows have surfaces ranging from strongly undulating ("stony rises") to flat.

At **Mount Eccles** the main volcano is a deep steep-walled elongated crater which contains Lake Surprise. At the north-western end the crater wall has been breached by a lava channel that flows west and then branches into two main channels (referred to locally as 'lava canals') running to the west-northwest and to the south-southwest (Grimes, 1995, 1999). Extending to the southeast from the main crater there is a line of smaller spatter and scoria cones and craters. Several smaller lava channels run out from these. Lava caves occur in a variety of settings.

Beyond this central area of explosive activity, basalt flows form a lava field about 16 km long and 8 km across. From the western end of this lava field a long flow, the Tyrendarra Flow, runs 30 km southwards to the present coast and continues offshore for a further 15 km (sea level was lower at the time of the eruption). This long flow must have had a major feeder tube, but no drained sections have been discovered to date.

Mt Napier and the Harman Valley flow: Mt Napier, about 20 km northeast of Mt. Eccles, is a steep cinder cone capping a broad lava shield 10 km in diameter. Some lava caves occur on the lower slopes of the cone, and on the lava shield, but the main cluster is at the **Byaduk Caves**, at the start of a long lava flow that follows the Harman Valley for at least 20 km to the west. Other lava caves occur further down the valley, as do an excellent set of sharply-defined tumuli (Ollier, 1964). It was at the Byaduk Caves that Ollier & Brown (1965) derived their 'layered lava' model of tube formation - which is still invoked by some authors (e.g. Stephenson, 1999).

Mount Hamilton is a broad lava cone surrounded by "stony rise" lava flows. There is a large lava crater at the summit. The cone contains one group of complex lava tubes (Ollier, 1963).

In the late Quaternary lava flows of Mount Eccles and Mount Napier, in the Western District Volcanic Province, we find both cave types described by of Peterson & others (1994) and also isolated "lava blister" caves - I will draw my examples from those areas. The complex lava cave system at Mount Hamilton appears to be a further-evolved "feeder" system.

Most of the longer caves known at **Mount Eccles** are in or adjacent to the lava channels, but there are a number of small caves scattered throughout the area, and the known distribution may simply reflect the more intensive exploration along the main canals. There are several types of lava cave in the area. Roofed channels include Natural Bridge (H-10; Grimes; 2002b), which has the distinctive "gothic" ceiling of tubes formed by overgrowth of a levee bank (Figure 2c), and also possibly Tunnel Cave (H-9; Grimes, 1998). The remainder are shallow, low-roofed caves that fall into two types: complex, levee-overflow systems on the sides of the major lava channels, e.g. H-51 & H-70 (Figure 6); and small, isolated, drained chambers ("lava blisters") within the stony rises (e.g. H-78; Figure 4).

At **Mount Napier**, and in its long flow down the Harman Valley we find both very large tubes (which might be roofed channels, though the evidence is ambiguous) and many small subcrustal caves. Some of the small subcrustal caves are exposed, along with their containing lava flows, at various levels in the walls of collapse dolines formed above the large tubes; for example, the upper of level of Fern cave (H-23, Figure 13) and H-74 and H-108 (Figure 12). Others are shallow isolated caves on the flow surface (H-31, 90, 91 and 106; Figures 4 & 12). One shallow cave has an open feeder from below that connects to a larger 'feeder' tube at depth (H-33, Figure 13).

The shallow lava caves involve a broad array of styles ranging from simple single chambers to multi-level, complexly-interconnecting systems of tubes and chambers. All gradations occur between these extremes, but the group has in common the dominance of shallow, low-roofed, irregular chambers and small-diameter tubes. They also grade (and possibly evolve over time) into larger and more-linear "feeder" tubes. Thus, while we can identify several distinctive types, there are many transitional forms that are hard to classify. Their genesis is discussed in more detail later in this paper.

Simple drained lava mounds and "lava blister" caves: Scattered through the stony rises there are small, shallow, low-roofed chambers; typically only 1m high with a roof 1m or less thick. These can be circular, elongate or irregular in

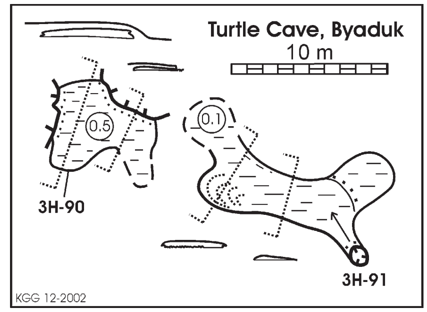

Figure 5. Turtle Cave, H-90, at Byaduk, is an example of a simple "lava blister" cave. The name derives from its resemblance to an empty turtle shell.

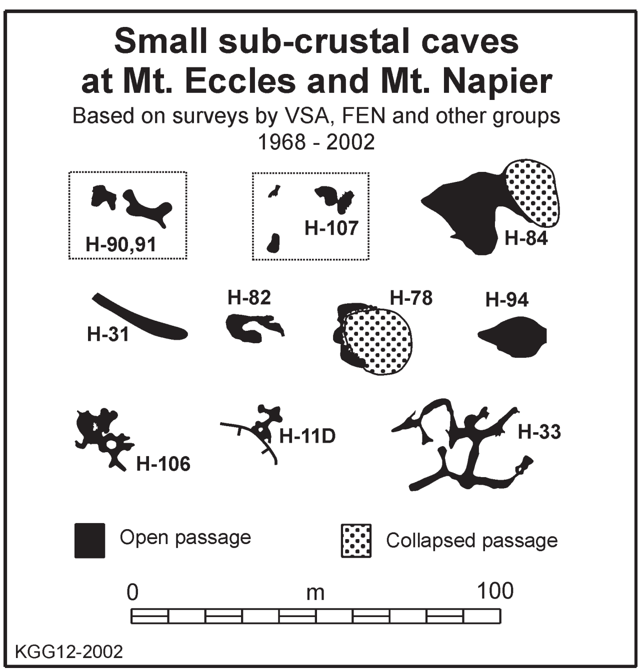

Figure 4. Examples of small, simple, subcrustal caves; mostly associated with low lava mounds. H90, 91 and 107 would be called "lava blisters"; H-78 is a "peripheral remnant" left by the collapse of the roof of shallow chamber; H-31 is approaching a linear "tube" form; H-11, 33 and 106 are grading to the more complex forms.

plan; up to 10m or more across but grading down to small cavities only suitable for rabbits. Some Victorian examples are shown in Figure 4, and include Turtle Cave (which looks like an empty turtle shell) illustrated in Figure 5. In section, the outer edges of the chambers may be smoothly rounded or form a sharp angle with a flat lava floor. The ceiling may be arched or nearly flat, with lava drips, and sometimes has a central "soft" sag that would have formed while the crust was still plastic. Commonly, the thin central part of the roof has collapsed and we find only a peripheral remnant hidden behind rubble at the edge of a shallow collapse doline (e.g. H-78, Figure 4). The more elongate versions grade into small "tube caves"; for example, Shallow Cave (H-31, Figure 4) described by Ollier & Joyce, 1968, p70.

These caves generally are found beneath low lava mounds (with or without the central clefts required to class them as "tumuli"!), though in some cases the surface relief may only rise half a metre! These small simple chambers have been locally called "blister caves" (see discussion in the Terminology section).

A large cluster of well-defined tumuli (*sensu* Walker, 1991) occur in the Harman Valley (Ollier, 1964). One of these is reported to be hollow by G. Christie (pers comm) who entered it as a child, but has not been able to relocate it. There is a 'donut' shaped tumulus which presumably has resulted from collapse of a central hollow. Within its annulus, one can squeeze through the rubble into a small 'peripheral remnant' cave.

More complex **overflow caves** associated with the lava channels at Mt. Eccles are generally shallow systems formed in the levee banks on each side of the channels and would have fed small lateral lava lobes or sheets when the channel overflowed or breached through the levee (Grimes, 1995). Figure 6 shows the lateral caves associated with the South Canal at Mt. Eccles, and Figure 12 shows a group of shallow caves adjacent to a large collapsed feeder tube at Byaduk.

Some of these lateral caves are simple linear tubes (e.g. H-48, 89, and the proximal part of H-53), but mostly they are branching systems with complexes of

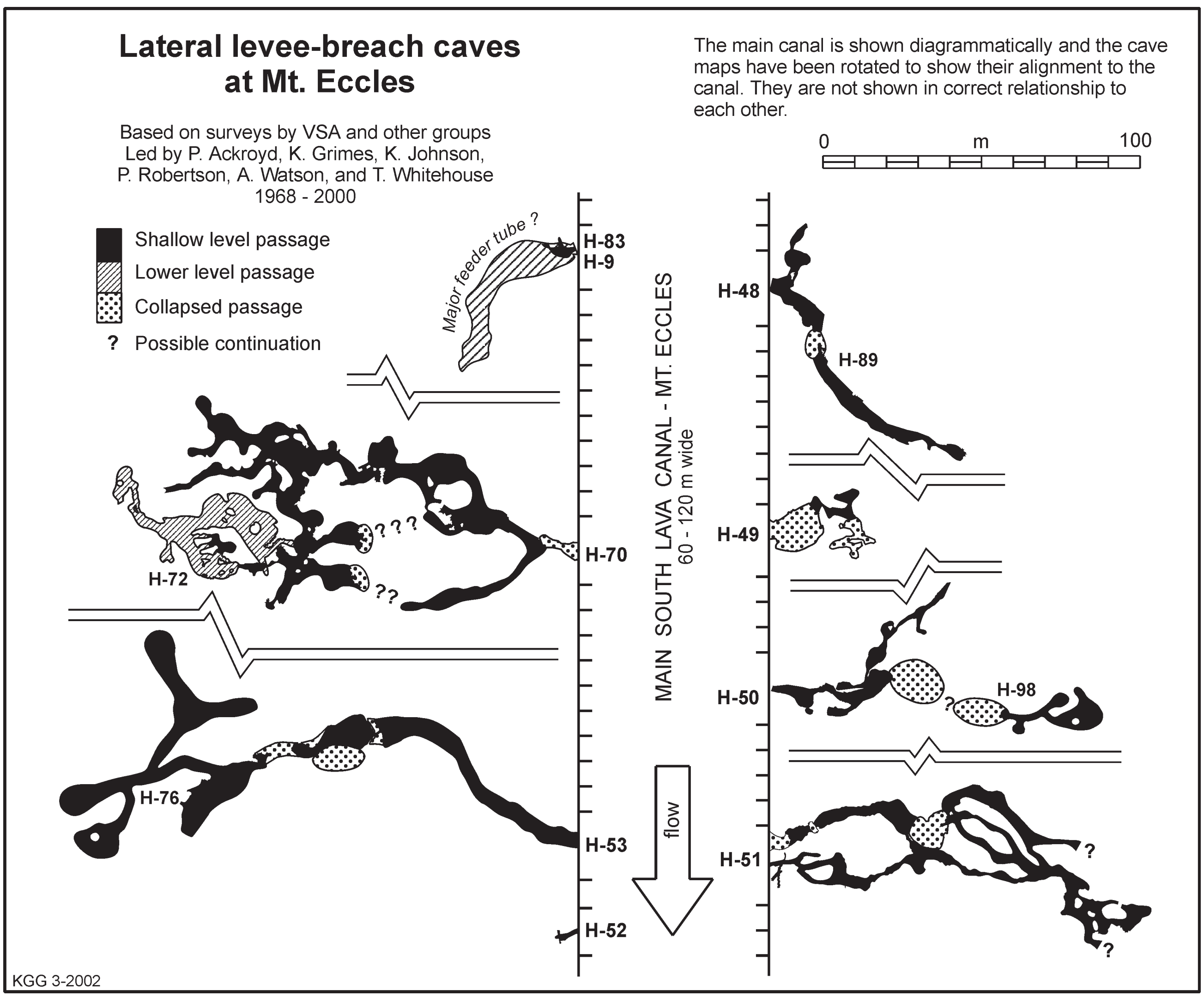

Figure 6. Examples of more complex subcrustal caves formed in thin overflows from a lava channel at Mt. Eccles. See Fig. 7 for detail of H-70/72. A detailed map of H-51 is included in the supplementary material on the CD.

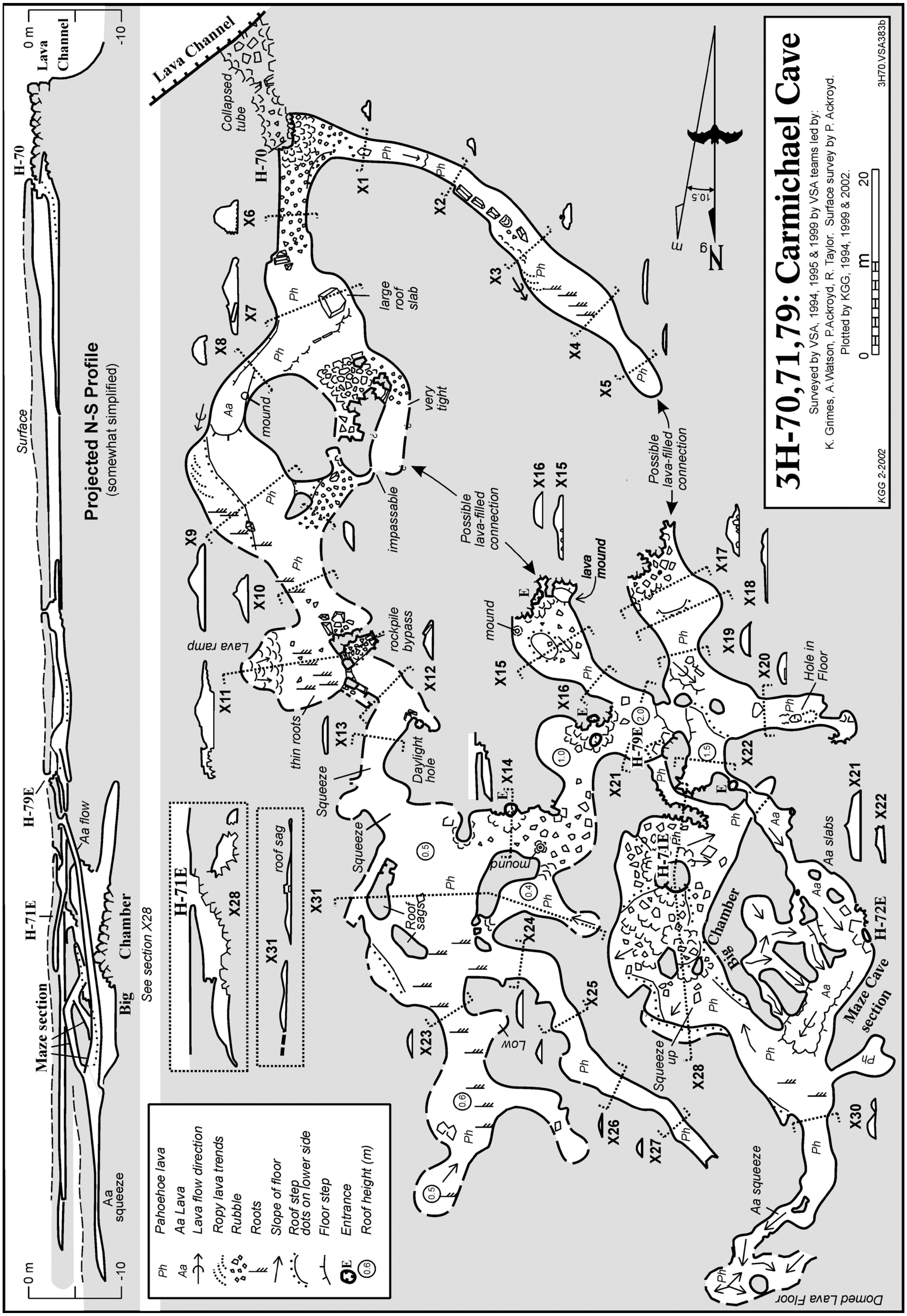

Figure 7. Detailed map of Carmichael Cave (H-70) at Mt. Eccles.

Figure 8. Two-level passage in H-70, looking south from section X22 (Fig. 7). Note the "window" on left which might be the remains of a partition between two lava lobes.

low passages that bifurcate and rejoin, or open out into broad low chambers. The shape suggests draining from beneath the thin solidified roof of a series of coalesced flow lobes. Only a few of the passages are large enough to stand in, typically (but not always) those nearest the proximal end - the channel entrance (e.g. H-48, H-53, H-70). Most passages are crawl-ways about a metre high with low arched roofs and flat lava floors (Figure 8). Some of the smallest passages have smoothly-rounded cross-sections (Figure 9). The ceiling is generally only a metre or so below the present surface, and in places breakdown has exposed the base of overlying pahoehoe flows, indicating that the original roof was less than a metre thick. In some chambers the roof has sagged down in a smooth curve to reach the floor (Figure 10). Where not covered with introduced soil, the floors are generally pahoehoe, with smooth, platy or ropy surfaces; but sharp aa lava floors occur in several places (e.g. H-51 and H-70). Some of these are late-stage additions; running over an earlier pahoehoe floor.

Where not disrupted by breakdown, the walls and roof typically have thin (2 - 20 cm) linings. These conceal the original wall, but in a few places fallen linings have exposed "layered lava" comprising thin sheets with ropy or hackly surfaces (eg the proximal end of H-70). Most caves are at a single level, but some show evidence of several levels (only a metre or so apart vertically) that either have coalesced vertically into a single passage or chamber or are joined by short lava falls (e.g. H-48, H-70 (Figure 7) and H-108).

At Byaduk, three caves occur in a stacked set of thin, 1-3m, lava flows exposed in the wall of a large collapse doline (H-74, 106 & 108; Figure 12). The elongated doline formed over a deeper large feeder tube (up to 25 m wide and 15 m high) and the thin flows may have been fed by overflows from the feeder tube, through roof windows. The three shallow caves comprise low-roofed branching passages and chambers very similar to those found beside the channel at Mount Eccles (Figure 11). In the lowest cave (H-74) there are intrusive lava lobes that may have entered through roof holes from the overlying lava flow. Likewise, in the next highest cave (H-108) a lava fall drops a metre to a short section of lower-level passage that might be in the same flow as H-74.

More complex stacked systems also occur. These can be fed from below, through a skylight in a major feeder tube, or laterally from a remote source. The upper level of **The Theatre** (H-33) is a small subcrustal cave system obviously fed from below as the shallow branching tubes occupy an isolated raised mound and a drain-back tube allows access to lower levels of low-roofed chambers and eventually to a large feeder tube at depth (Figure 13). Lava would have welled up from this lower level and formed the surface rise in several stages (the different "levels"), then drained back to leave the small tubes and chambers. **Fern Cave** (H-23) comprises a large 'feeder' tube at depth, but there is a higher level of low-ceilinged irregular

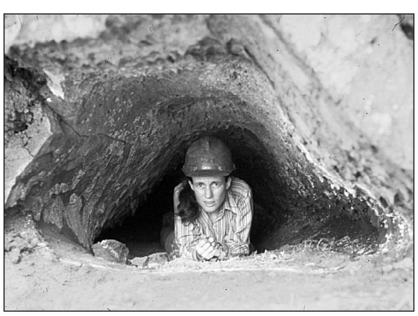

Figure 9. Small subcrustal tube, H-52 at Mt. Eccles.

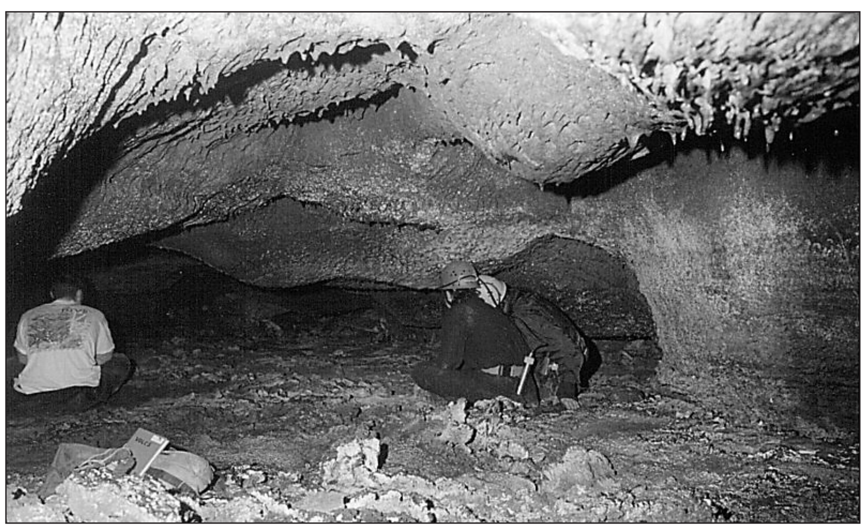

Figure 10. Chamber in H-74, showing sagged parts of roof.

chambers and passages which appears to be in a younger flow that ran over the prior roofed tube (Figure 13). This flow would seem to have been fed from the large collapsed tube to the south, which might have been an open channel at that time. The present connections between the upper and lower levels of Fern cave are later accidents of collapse of the lower tube roof.

The **Mount Hamilton Cave** (H-2) is a complex system of moderately large bifurcating tubes at several levels (Figure 14; Ollier 1963, Webb et al, 1982). It is dominated by linear tubes rather than the broad low chambers typical of most other caves considered in this paper and may indicate a more evolved style of larger subcrustal lava cave (see below).

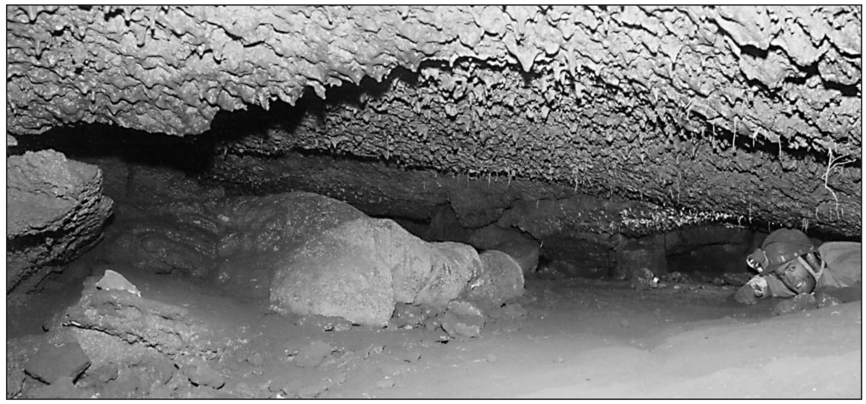

Figure 11. Low chamber in H-106, with lava drips and an intrusive lava tongue at left.

Genesis

When discussing genesis one must keep in mind the distinction between active tubes (lava-filled) and drained tubes (caves) – as discussed by Halliday (2004). Only some active tubes will be drained and become accessible at the end of an eruption, most will remain filled and solidify. As long as a tube or cavity remains active, its form can evolve by, firstly, mechanical and thermal erosion of its edges; secondly, solidification of its stagnant parts including linings, and thirdly, partial drainage to form an open cave. Collapse of the roof can occur while the tube is active, as well as after it is drained.

Ollier & Brown (1965) used the Victorian lava caves, in particular those at Byaduk, to propose a "layered lava" model of tube development. This is similar to the more recent subcrustal models of Hon & others (1994) but their concept of "layered lava" is confusing as they seem to apply that term to two distinct types of "layer". The lavas exposed in the collapse dolines at Byaduk have flow units from 0.5 to 5m thick that are distinguished by lobate ropy surfaces at top and bottom, with small gaps and partings between them and local areas of rubble. These flow units host small subcrustal lava tubes (e.g. Figure 12) but those had not been mapped at the time of Ollier & Brown's report. However, Ollier & Brown also referred to a still-finer layering within what are now recognised as flow units - marked by sub-horizontal cracks, trains of vesicles, and small flattened cavities which may have stretch structures or small lava drips. They rejected the suggestion that separate flow units were present, and believed that all the layers were "formed by differential movement within one thick lava flow" (not within thinner flow units) and that they were "possibly shearing planes formed during flow just before solidification". They recognised that the flow somehow become differentiated

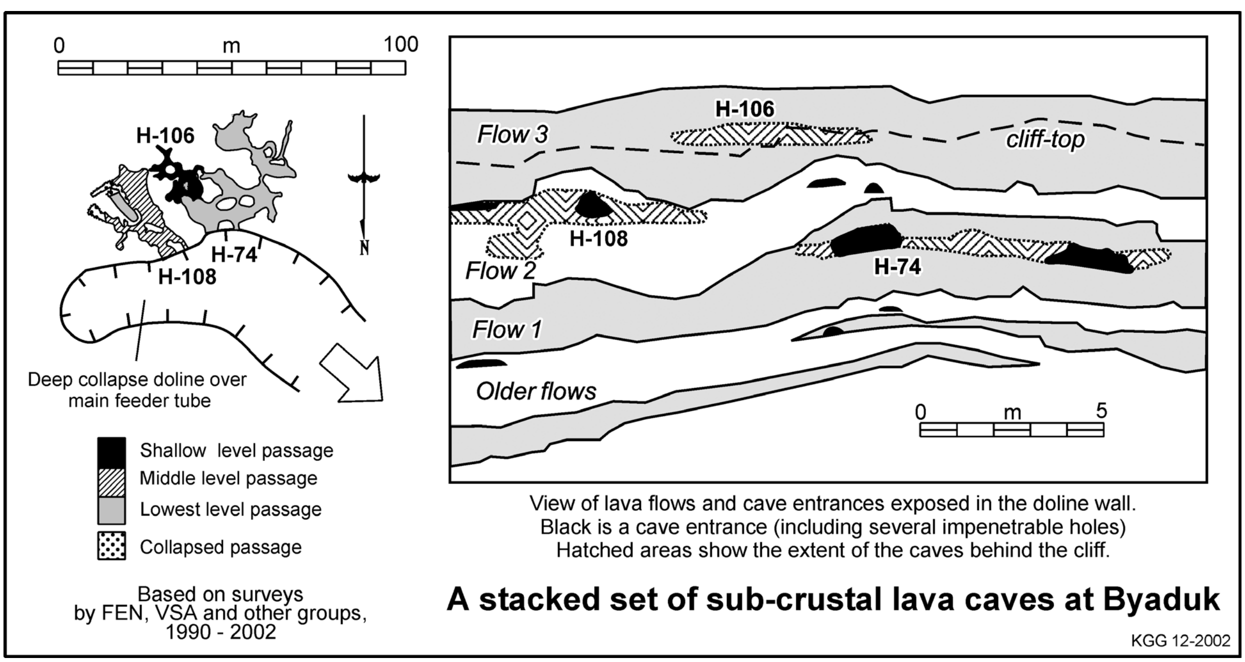

Figure 12. A set of three small subcrustal caves formed in separate stacked lava flows at Byaduk. Detailed reports and maps on H-106 and H-108 are in the supplementary material on the CD.

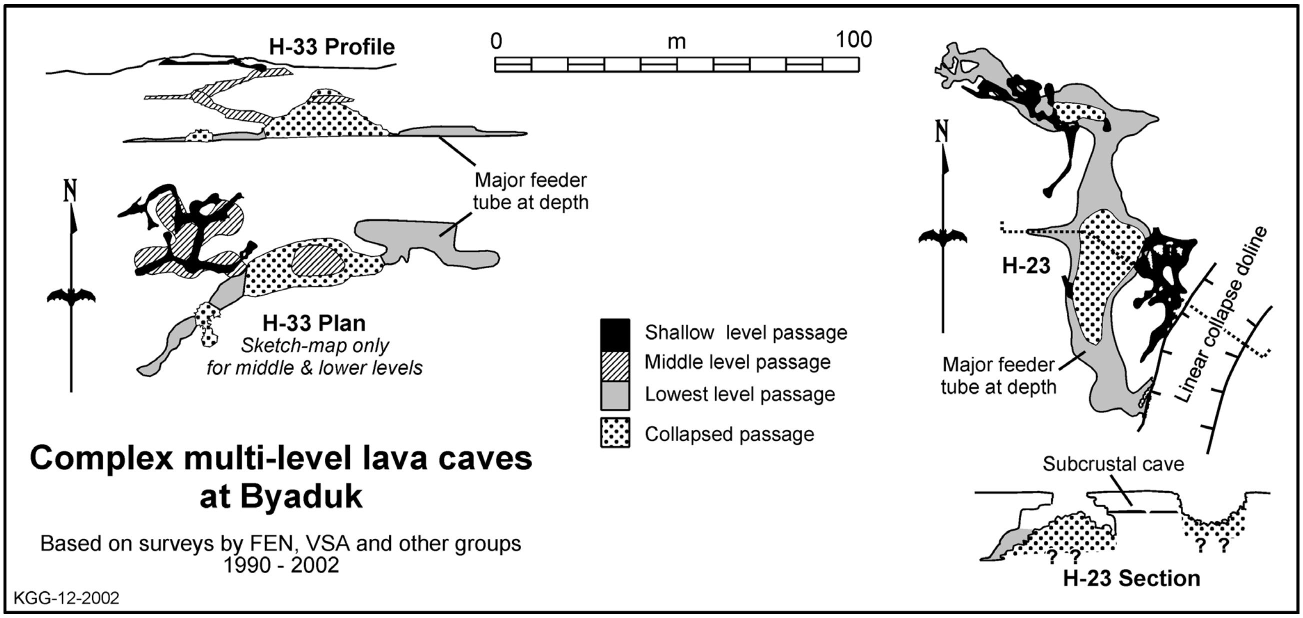

Figure 13. Complex, multi-level lava caves at Byaduk. Shallow subcrustal systems overlie large feeder tubes at depth.

into solid parts and liquid-filled tubes, but a detailed understanding of how this happened had to wait on the observations of active tube-fed lavas by later worker (e.g. Peterson & others,1994 and Hon & others,1994). Ollier & Brown did, however, recognise that the tubes, once formed, could enlarge by eroding the surrounding (layered) lava rock.

For a more detailed description of the observed processes seen in active lava flows, and models deduced from these, see Peterson & Swanson (1974), Wood (1977), Greeley (1987), Peterson & others (1994), Hon & others (1994) and Kauahikaua & others (1998). The model used here is essentially that described in the last three of those papers (Figures 2 & 3).

Isolated small "lava blister" caves found beneath low mounds in the "stony rises" would form by the irregular draining of cavities beneath the thin solidified crust of a broad lava flow. The process is similar to that which forms other subcrustal drainage tubes (see below), but less organised so that only isolated low-roofed chambers appear to result beneath the high points of the undulating surface. Commonly the chamber roof sags (while hot) or later collapses so that only a crescentic 'peripheral remnant' survives, as at H-78 (Figure 4).

Figure 3 illustrates the formation of more complex tubes and cavities by *subcrustal draining* from beneath a crusted flow. The figure shows the case where a channel has overflowed, as along the Southern Canal at Mount Eccles, but similar effects occur at the front of an advancing pahoehoe lava flow where the lava is delivered by a channel or major feeder tube, but then spreads out into a series of lobes. These lobes grow by a process of 'budding' in which a small lobe develops a skin, and is inflated by the lava pressure until the skin ruptures in one or more places. Lava escaping through the rupture develops new lobes and so on (Figure C-1, 2, 3). If the supply of fresh lava is cut off, the still-liquid parts of a lobe may be drained to form a broad but low-roofed chamber (Figure C-3a). However, if fresh hot lava continues to be delivered from the volcano it may become progressively concentrated into linear tubes that feed the advancing lobes, while the remaining stagnant areas solidify (Figure C-3b, 4, 5).

Tubes formed by draining of lava lobes and flows are generally smaller than those formed by the roofing of a channel – although inflation of the flow can provide a thickness of ten metres or more in which larger subcrustal drainage tubes can form. However, if flow continues after they are formed, several small tubes within a lobe complex may coalesce by breakdown of their thin walls or floors (the "partitions" or "septa" of Hon et al, 1994, and Halliday, 1998b) to form a larger feeder tube. Also, a continuing flow of hot lava through a small feeder tube can enlarge it by erosion of the walls or floor (Peterson & Swanson, 1974; Greeley, 1987). Destruction of the crust above the active tube can form skylights or local surface channels, and overflow from these can form secondary flow lobes. Thus, pahoehoe lobes can be stacked vertically as well as advance forwards so that a complex three-dimensional pattern of branching tubes and chambers can form.

H-53 could be regarded as showing a transition from the low branching and chambered systems at the (younger) distal end, to the more linear unbranching tube systems at the proximal end that would develop in time as flow becomes more localised and organised to feed an extensive overflow sheet. The proximal end of this cave approaches the character of a 'roofed channel' tube and determining the origin of simple large lava tubes can be difficult as much of the evidence may have been removed by erosional enlargement of the original tube, or be hidden behind wall linings.

The Mount Hamilton Cave (H-2, Figure 14) may be a further-evolved system in which the original irregular chambers and small passages of subcrustal drainage caves in several stacked flows have combined and evolved into a more linear system of larger "feeder" tubes as lava flow continued through the conduit system on its way to the lava field below. This suggestion is supported by the presence of small 'proto-tubes', 20-60 cm in diameter, that are exposed by breakdown in the walls and ceiling of the larger tubes in several parts of the cave (Figure 15).

Conclusion

Small subcrustal lava caves form by drainage of lava from beneath a thin crust developed on a lava surface. In its simplest form, drainage of lava from beneath high areas on the crusted surface will form simple isolated chambers - "lava blisters". Complex nests of advancing lava lobes create equally complex patterns of active tubes and chambers which can later drain to form open caves. As lava continues to flow through these complex systems they will evolve by erosion and solidification to form larger, more streamlined, linear tube systems that act as "feeder tubes" to carry hot lava to the advancing lava front. If sufficiently evolved, these linear tubes can converge on the form of the, generally larger, linear tubes formed by roofing of surface lava channels. Thus the genesis of many large lava caves remains difficult to deduce.

The "drained tumulus caves" described by Halliday (1998a) & Walker (1991) would be a special case of the small subcrustal type in which the crust was pushed up into a tumulus (sensu lato) before it drained. Halliday's (1998b) "sheet flow caves" are also a special case tied to a particular surface form. I would expect all gradations between these features and the more extensive systems which can form under both flat-topped "sheet-flows" and undulating "stony rises".

I suggest that the cave classification should not be tied to the surface terminology until the processes of cave development are better known. Also, basing the cave nomenclature on the surface lava forms may be confusing cause and effect—rather than argue that some types of caves form beneath/in tumuli and others beneath "sheet flows", it might be better to say that tumuli tend to form above active localised flows within a sheet (i.e. above lava tubes). The hot flowing lava would inhibit thickening of the crust above the tube or chamber so that it would be weaker and more likely to be uplifted by hydraulic pressure in these local areas. A linear lava tube could thus produce a linear 'tumulus' or a chain of rounded ones. Wider chambers along the line of the tube would have weaker roofs and hence explain the localised nature of the *sensu stricto* tumuli.

The unifying factor in all these caves is that they form by shallow drainage from beneath a crusted lava flow - hence they can be referred to collectively as **subcrustal lava caves**.

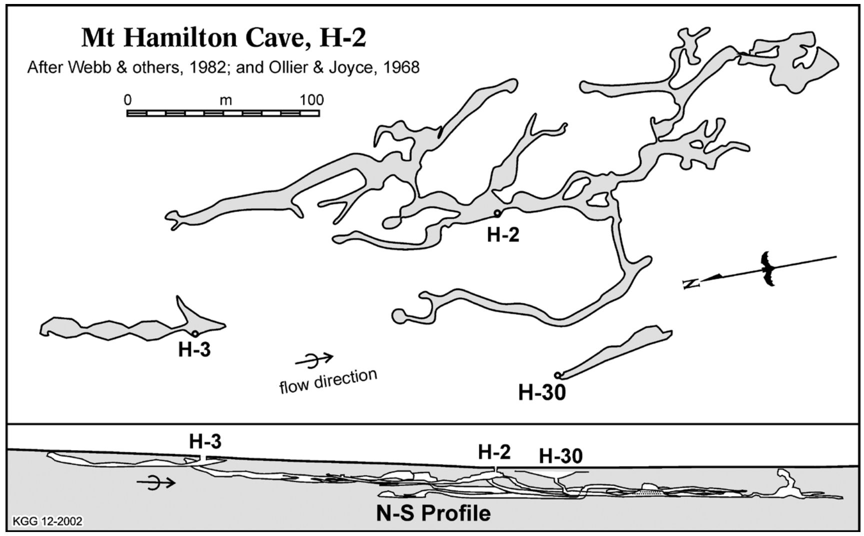

Figure 14. Mt Hamilton lava cave is an evolved system of larger, linear, bifurcating, subcrustal tubes.

Acknowledgements

With acknowledgements to my predecessors who conceived most of the ideas expressed here: In particular Don Peterson, Ken Hon, Bill Halliday, and many other speleo-geologists. This report draws on the exploration and mapping efforts of numerous speleologists from the Victorian Speleological Association and other groups over the last 50 years.

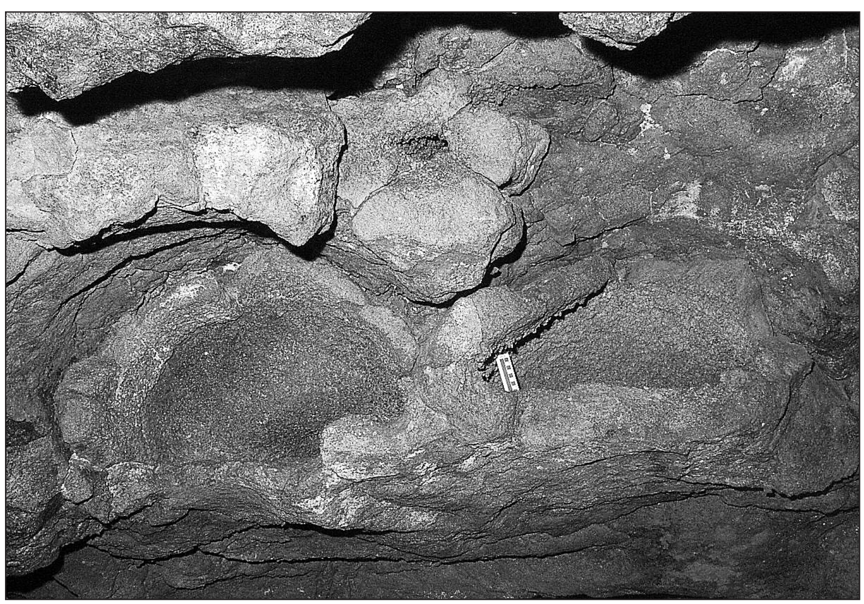

Figure 15. A pair of small 'proto-tubes', with 10 cm thick linings, exposed in the wall of a larger, more-evolved, tunnel in the Mt Hamilton lava cave. Scale bar is 10 cm.

References

(Note: *Nargun* is the journal of the Victorian Speleological Association)

GIBSON, L.L., 1974: Blister caves associated with an Ethiopian Volcanic ash-flow tuff. *Studies in Speleology*, **2(6)**: 225-232.

GREELEY, R., 1987: The Role of lava tubes in Hawaiian volcanoes. *US Geological Survey, Professional Paper* **1350**, 1589-1602.

*GRIMES, K.G., 1995: Lava caves and channels at Mount Eccles, Victoria. *in* BADDELEY, G., [Ed] *Vulcon Preceedings* 1995. Australian Speleological Federation, Melbourne. pp 15-22.

GRIMES, K.G., 1998a: Tunnel Cave, Mount Eccles. *Nargun*, **30(10)**: 172-173.

GRIMES, K.G., 1999: Volcanic caves and related features in western Victoria. *in* HENDERSON, K., [ed] *Cave Management in Australasia 13*. Proceedings of the thirteenth Australasian Conference on cave and Karst Management, Mt Gambier, South Australia. Australasian Cave and Karst Management Association. Carlton South. pp 148-151.

*GRIMES, K.G., 2002a: Carmichael Cave (3H–70): A complex, shallow, "sub-crustal" lava cave at Mount Eccles, Victoria. *Nargun*, **35(2)**: 13-17.

*GRIMES, K.G., 2002b: Natural Bridge (3H–10), Mount Eccles: a special type of lava tube. *Nargun*, **35(2)**: 18-21.

GRIMES, K.G., & WATSON, A., 1995: Volcanic caves of western Victoria. *in* BADDELEY, G., [Ed] *Vulcon Guidebook 1995*. Australian Speleological Federation. Melbourne, pp 39-68.

HALLIDAY, W.R., 1998a: Hollow volcanic tumulus caves of Kilauea Caldera, Hawaii County, Hawaii. *International Journal of Speleology*., **27B (1/4)**, 95-105.

HALLIDAY, W.R., 1998b: Sheet flow caves of Kilauea Caldera, Hawaii County, Hawaii. *International Journal of Speleology*, **27B (1/4)**, 107-112.

HALLIDAY, W.R., 2004: Volcanic Caves, in Gunn, J. (Editor) *Encyclopaedia of Caves and Karst Science*. Fitzroy Dearborn, NY., 760-764.

HEAD, L., D'COSTA, D., & EDNEY, P., 1991: Pleistocene dates for volcanic activity in Western Victoria and implications for Aboriginal occupation. *in* WILLIAMS, M.A., DE DEKKER, P., & KERSHAW, A.P. *[eds] The Cainozoic in Australia, a re-appraisal of the Evidence*. Geological Society of Australia, Special Publication, **18**: 302-308.

HON, K., KAUAHIKAUA, J., DENLINGER, R., & MACKAY K., 1994: Emplacement and inflation of pahoehoe sheet flows: Observations and measurements of active lava flows on Kilauea Volcano, Hawaii. *Geological Society of America Bulletin*. **106** 351-370.

JOYCE, E.B., 1988: Newer volcanic landforms. in DOUGLAS, J.G., & FERGUSON, J.A., [eds] *Geology of Victoria*, Geological Society of Australia, Victorian division. Melbourne. pp. 419-426.

JOYCE, E.B. & WEBB, J.A. (co-ordinators), 2003: Geomorphology, the evolution of Victorian landscapes (section 18.10.1, Volcanic Plains). in BIRCH, W.D., (editor) *Geology of Victoria*. Geological Society of Australia, Special Publication **23**: 553-554.

KAUAHIKAUA, J., CASHMAN, K.V., MATTOX, T.N., HELIKER, C.C., HON, K.A., MANGAN, M.T., & THORNBER, C.R., 1998: Observations on basaltic lava streams in tubes from Kilauea Volcano, island of Hawai'i. *Journal of Geophysical Research*, **103**: 27303-27323.

LARSON, C.V., 1993: An illustrated glossary of lava tube features. *Western Speleological Survey Bulletin*, **87**. 56 pp.

MATTHEWS, P.J., 1985: *Australian Karst Index, 1985*. Australian Speleological Federation, Melbourne. 481 pp.

OLLIER, C.D. 1963: The Mount Hamilton lava caves. *Victorian Naturalist*. **79**, 331-336.

OLLIER, C.D. 1964: Tumuli and lava blisters of Victoria. *Nature*. **202**, 1284-1286.

OLLIER, C.D., & BROWN, M.C., 1965: Lava caves of Victoria. *Bulletin Volcanologique*. **28**: 215-30.

OLLIER, C.D. & JOYCE, E.B., 1968: Further descriptions of Victorian lava caves. *Victorian Naturalist*. **85**: 70-75.

PETERSON, D.W., & SWANSON, D.A., 1974: Observed formation of lava tubes during 1970-71 at Kilauea Volcano, Hawaii. *Studies in Speleology,* **2(6)**: 209-222.

PETERSON, D.W., HOLCOMB, R.T., TILLING, R.I., & CHRISTIANSEN, R.L., 1994: Development of lava tubes in the light of observations at Mauna Ulu, Kilauea Volcano, Hawaii. *Bulletin of Volcanology* **56** 343-360.

PRICE, R.C., NICHOLLS, I.A., & GREY, C.M., 2003: Cainozoic Igneous Activity (section 12.4.6, Western District province), *in* BIRCH, W.D., (editor) *Geology of Victoria*. Geological Society of Australia, Special Publication **23**: 366-370.

STONE, J., PETERSON, J.A., FIFIELD, L.K., & CRESSWELL, R.G., 1997: Cosmogenic chlorine-36 exposure ages for two basalt flows in the Newer Volcanics Province, western Victoria. *Proceedings of the Royal Society of Victoria*. **109(2)**: 121-131.

STEPHENSEN, J., 1999: Emplacement and tube development in long tube-fed lavas in N. Queensland, Australia. *Proceedings of the 9th International Symposium of Vulcanospeleology of the UIS*. Centro Speleologico Etneo, Catania. pp. 134-145.

WALKER, G.P.L., 1991: Structure and origin by injection of lava under surface crust, of tumuli, "lava rises", "lava-rise pits", and "lava-inflation clefts" in Hawaii. *Bulletin of Volcanology*, **53**, 546-558.

WEBB, J.A., JOYCE, E.B., & STEVENS, N.C., 1982: Lava caves of Australia. *Proceedings, Third International Symposium on Vulcanospeleology,* Oregon, USA. pp 74-85.

WOOD, C., 1977: The origin and morphological diversity of lava tube caves. *Proceedings, 7th International Speleological Congress*, Sheffield, England. 440-444.

*Papers Grimes 1995, Grimes 2002a, and Grimes 2002b are included in the supplementary material on the CD.

A Small Cave in a Basalt Dyke, Mt. Fyans, Victoria, Australia

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Abstract

A small but unusual cave has formed within a large dyke that intrudes a scoria cone at the summit of Mt. Fyans, western Victoria. Draining of a still-liquid area, after most of the dyke had solidified, left an open cavity. Features within the cave mimic those of conventional lava caves, and suggest that the lava levels oscillated within the cave several times.

The volcano

Mount Fyans is a volcano within the Newer Volcanic Province of western Victoria, Australia. The age of the province dates back at least 5 million years, but Mt. Fyans is a relatively youthful eruption, undated, but possibly less than 100,000 years old – judging by the well developed "stony rises" (remnants of the original hummocky lava surface) and minimum soil development. The volcano is a broad shield of basaltic lava with a low scoria cone at the summit and possibly a crater - though an extensive quarry in the scoria makes the original form difficult to deduce!

The scoria at the summit has a thin cap of basaltic lava, and ropy patterns on the underside of this are well-exposed on the southern margin of the quarry. The loose scoria has been intruded by two large basalt dykes up to 12 m across (which would have fed the lava cap) and a number of smaller pipe or finger-like basalt bodies, some of which have been partly drained to leave small cavities. Figure 1 shows the quarry and the main dyke. An inset map in Figure 2 shows the location of the various feaatures described here. The quarry operations have worked around the large dykes, but damaged the smaller intrusive features (which is how we know they are hollow!).

Mt. Fyans Cave

A small horizontal cave occurs within the largest dyke. It lies close to the west edge of the dyke and runs parallel to it (Figure 2). Entry is via a small hole broken into the roof by the quarry operation. The cave is about 17 m long and generally less than one metre high. The roof and walls have numerous lava drips (Figure 3). The floor is a horizontal ropy pahoehoe surface which rises gently towards the northern end – but the ropy structures suggest a final flow direction from south to north. The drainage points for the lava are not obvious; but there is a very small hole in the floor at the southern end. Both roof and floor have common patches of pale-cream coatings over the basalt – possibly fumerolic alteration? There are well-developed rolled benches (10 cm diameter) along the edges of the floor (Figure 4). These suggest that the lava rose and fell several times within the cavity. One small hole in the roof, near the entrance, opened into broken scoriaceous material.

Related features

As well as the cave, the main dyke also has a drained vertical pipe at its southern end – this has been broken into by the quarry operation and we found the upper part lying on its side 20 m to the NE (see inset map, Figure 2). This pipe had spatter and dribble patterns on its inside walls. Elsewhere in the quarry there are intrusive pipes and smaller fingers of basalt that have pushed up through the loose scoria. Several of these have drained back after the outside had solidified so as to leave a hollow core, some with lava drips. Probably the most distinctive are conical "Witch's hat" structures (Figure 5).

The area has other features of both geological and historic interest and warrants preservation. For example, the underside of the lava flow capping the scoria is exposed in several places and shows a wrinkled "belly" with fragments of the loose scoria stuck to it. The surrounding "stony rises" have some particularly elegant and distinctive drystone walls that were constructed by early European settlers.

No other volcanic caves formed in dykes have been reported in Australia, but a larger one has been reported from the Canary Islands (Socorro & Martin, 1992).

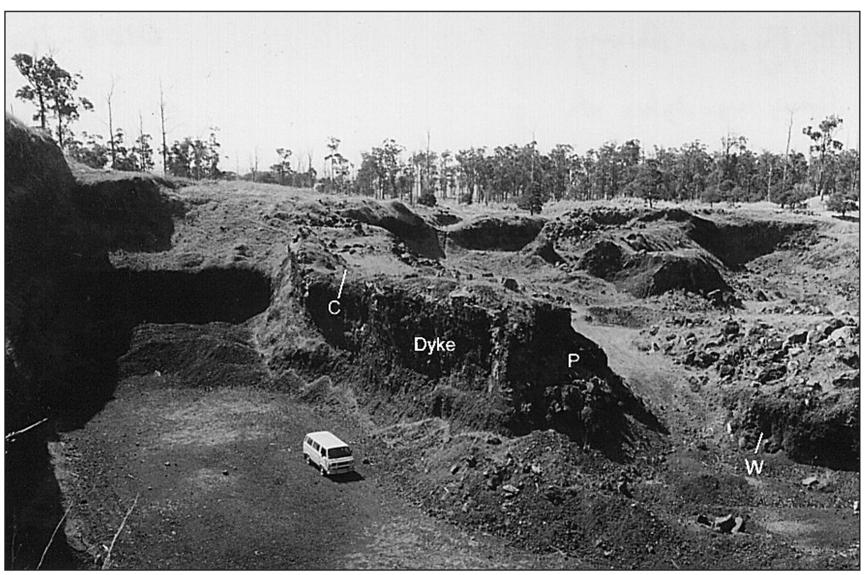

Figure 1. View of Mt. Fyans Quarry, looking north towards the large dyke. C = cave, P = Pipe, W = Witch's hats.

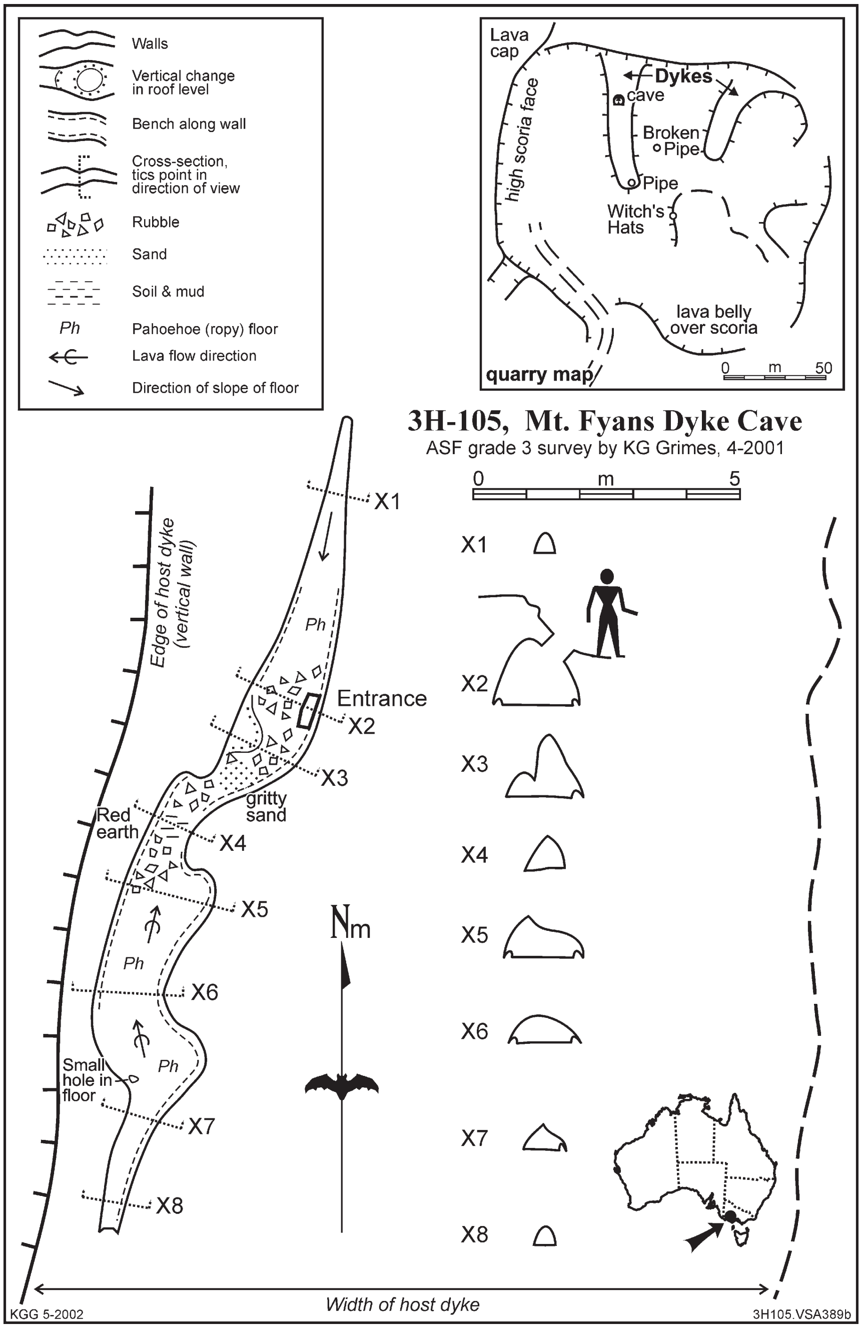

Figure 2 (left). Map of Mt Fyans Cave, 3H-105. The inset map shows the volcanic structures within the quarry.

Figure 3 (below left). View looking north from the cave entrance.

Figure 4 (below right). Looking south from section X5. Note the small rolled bench against the foot of the wall and the pale patches on the wall.

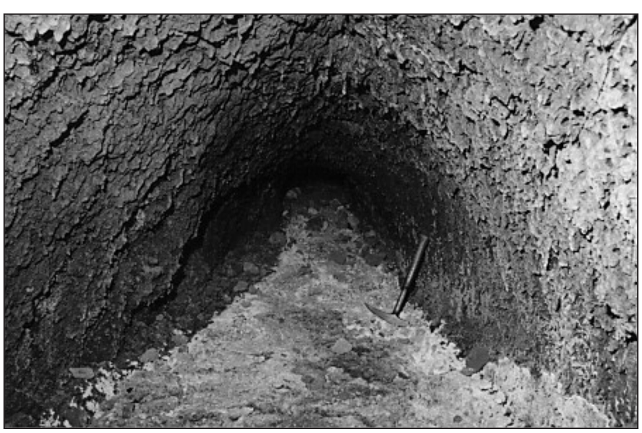

Figure 5. A conical "witch's Hat" formed by a finger of lava that intruded the loose scoria, then drained back to leave a hollow core. Stereopair.

Genesis

The dykes and other bodies would have been intruded into the loose scoria towards the end of the eruption, would have cooled and partly solidified, and then as pressure was lost those liquid parts that were still connected to the main feeder channels would have drained a little way back to leave the cavities. There may have been some oscillation to form the rolled benches in the dyke cave.

Reference

Socorro, JS., & Martin, JL., 1992: The Fajanita Cave (La Palma, Canary Islands): A volcanic cavity originated by partial draining of a dyke, *in* Rea, GT., [ed] *6th International Symposium on Volcanospeleology*. National Speleological Society, Huntsville. pp 177-184 [in spanish].

This paper as published in *Helictite* in 2006 is included in the supplementary material on the CD. That version includes one additional photograph.

What Is a Lava Tube?

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Abstract

Variances and imprecision in defining the term LAVA TUBE have led to its application to a wide range of features, some of them far removed from the ordinary meaning of the word TUBE: "a hollow body, usually cylindrical, and long in proportion to its diameter..." The current American Geological Institute definition helpfully limits the term to roofed conduits and requires that they be formed in one of four accepted mechanisms. However it provides little guidance on whether a variety of injection structures traditionally termed LAVA TUBES actually are undrained or refilled examples or are entirely dfferent phenomena.

Ideally, lava tubes and lava tube caves should be defined as discrete structures with definable parameters which differentiate them from all other volcanic features, e.g., aa cores, lava tongues, tumuli, sills and related injection masses. The defining characteristics should be compatible with:

1) the common meanings of TUBE and CAVE;
2) the presence of solid, liquid, and/or gaseous matter within them;
3) observations of all phases of their complex speleogenesis, e.g., crustal and subcrustal accretion and erosion;
4) their tendency to form braided and distributory complexes, and multlevel structures of at least two types;
5) their propensity to combine with or produce other volcanic structures, e.g., lava trenches, rift crevices, tumuli, drained flow lobes, lava rises, dikes, etc.

The ideal may not be achievable at the present state of knowledge and technology. However, new concepts of flow field emplacement and drainage offer a notable opportunity to shape a clearer definition of this elusive term. I propose that the Commission on Volcanic Caves of the IUS develop such a definition, in collaboration with the AGI and other concerned agencies and organizations, for consideration at the 2005 International Congress of Speleology.

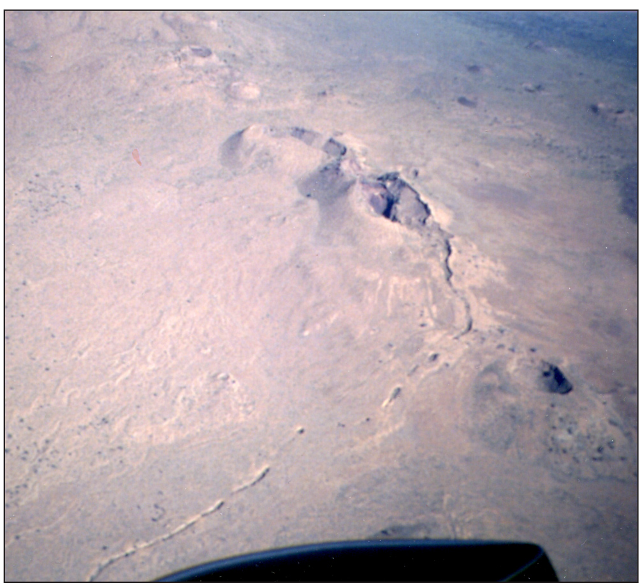

Figure 1. Aerial view of Poikahe Crater and partially collapsed braided lava tube system, Hualalai Volcano, Hawaii Island. Similar patterns have been photographed in several extraterrestrial sites. Photo by the author.

Introduction

Some geologists recently have used the presence or absence of lava tubes or tube-fed lava for important inferences and conclusions. Thus it has become important to have a common understanding of the term. But the term "lava tube" currently is applied to a variety of features which are inconsistent with standard geological and speleological definitions of the term (Jackson, editor, 1997; Larson, 1993), and different observers specify widely different parameters as characteristic of lava tubes.

These inconsistencies are the result of several factors. Uninformed persons commonly confuse tree casts with lava tubes, and vice versa. Indeed, small scale examples lacking bark molds and arborescent branching may be difficult to differentiate; glaze, lava stalactites and accreted linings are sometimes found in tree molds and associated gas cavities (Honda, 2002).

At least in Hawaii, the problem is even more complex. Here and elsewhere, many persons have come to believe that any cave or rockshelter in lava necessarily is a lava tube cave, often simply mistermed a lava tube. Especially misidentified as lava tubes are well-known littoral caves, e.g., Waianapanapa Caves, Maui Island and Kaneana (Makua Cave), Oahu Island (Figure 2). Boatmen on the Na Pali Coast of the island of Kauai commonly refer to spectacular Queen's Bath (Figure 3) as a "vertical lava tube". Actually it is a large littoral cave which has lost most of its roof. Nonlittoral erosional features like Kauai's Fern Grotto are not exempt from this misconception. Such misunderstandings commonly appear in the popular

Figure 2 (top). Entrance of Kaneana (Makua Cave), a littoral cave formed along a dike complex on the northwest tip of the island of Oahu, Hawaii. In the popular literature, it commonly is termed a lava tube. Photo by the author.

Figure 3 (middle). Interior of Queen's Bath, Na Pali Coast of Kauai Island, Hawaii, a large littoral cave which has lost most of its roof. Boatmen commonly refer to it as a vertical lava tube. Photo by the author.

Figure 4 (bottom). Solid invasive structure on the northwest face of Makapuu Point, Oahu, Hawaii. This structure has been termed a solid lava tube. Photo by the author.

press and in a few compilations which unwisely have relied on the supposed accuracy of press accounts.

In the geological literature, various solid features in volcanic terranes have been identified as lava tubes. Palmer (1929) and Wentworth (1925) described caste of lava tubes exposed by erosion on the islands of Oahu and Lanai. Palmer analyzed and depicted features characteristic of these "fossil lava tubes": near-concentric bands of vesicles and "a very slight tendency toward radial jointing" which is not impressive on the accompanying photographs. The example he reported may be considered the prototype of cores of solid lava tubes.

In contrast, Waters (1960) proposed that the elliptical "war bonnet" structures of Columbia River flood basalts are undrained lava tubes 15 to 35 m in diameter. This was not widely accepted. Greeley (1998) pointed that these features lacked linings typical of lava tubes, nor had they the concentric vesicle patterns which he considered "characteristic of lava tubes". Harper (1915) previously had cited and depicted a rosette pattern of smaller radiating features in at least one of several finger-like littoral ridges of dense Permian basalt in Australia, but did not refer to lava tubes as did two recent reports on this locality (Campbell et al, 2001; Carr and Jones, 2001). Others have applied the term to the entire width of cores of flow lobes and lava rises, to intermittent volcanic ridges, to at least one laccolith and a partially hollow dike, and to a variety of inferred structures.

Solid and inferred structures cited as lava tubes

"Radiating columnar jointing" in digitate littoral ridges of Permian basalt were said to be "indicative of filled lava tubes" (Campbell et al, 2001). Imprecise wording has hindered understanding of features at these and other sites. Carr and Jones (2001) asserted that "the larger, more laterally continuous lava masses (at this Australian site) are interpreted as lava tubes while the smaller, less laterally continuous masses are interpreted as lava lobes". The lava fingers at this site "may contain radially arranged columnar joints and less pronounced concentric joints" 5 to 20 m in diameter. An example which they depict appears somewhat similar to an undescribed light-colored

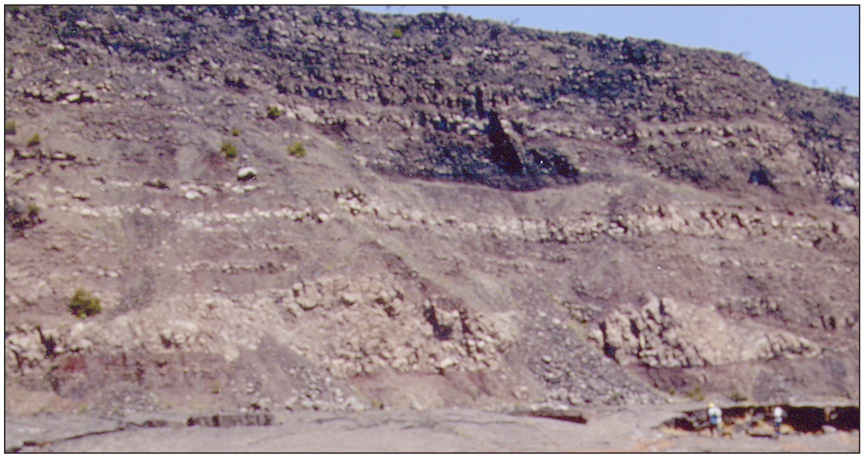

Figure 5 (right). Laccolith exposed in the west wall of Kilauea Caldera. At one time, this was termed a lava tube. Photo by the author.

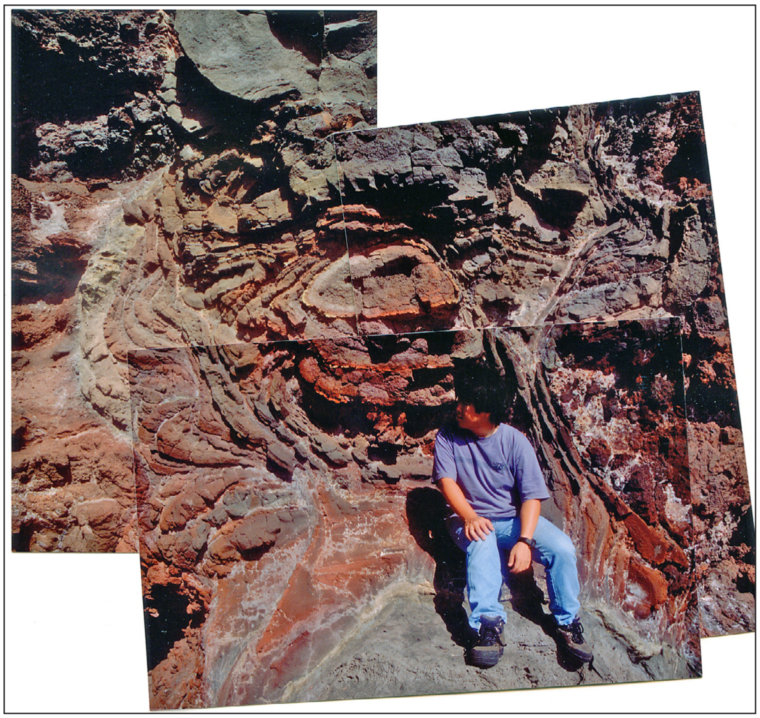

Figure 6 (below). Detail of central part of structure shown in Figure 7. Note complex of filled tubes and laterally displaced lava filling irregular width of buried crevice. Photos by the author.

Figure 7 (below right). Complex structure on the east fact of Makapuu Point, Oahu, Hawaii. This structure has been termed a solid lava tube. Photo by the author.

feature exposed in the northwest side of Makapuu Point, Hawaii which rests on a narrow outcrop of pyroclastic material (Figure 4) and has "baked" adjacent lava. In local geological circles it is said to be a filled lava tube (C. Okubo, written communication, 1999). A light-colored laccolith exposed prominently in the west wall of Kilauea Caldera, Hawaii (Figure 5) also was proposed as a solid lava tube until its actual structure was determined conclusively (Anonymous, cited by Don Swanson, oral communication 1999).

An especially complex feature termed a filled lava tube by Coombs et al (1990) and by Kesthelyi and Self (1998) is located on the northeast side of Oahu's Makapuu Point It is much lower in the stratigraphic column than the feature discussed above and is not aligned with it The two features have little in common. Contrary to the cited reports, the jaggedness of its lateral margins (Figure 6) indicates that it was a tectonic crevice along which lava flowed turbulently and by discrete injections, much as in the case of the Great Crack of Kilauea Volcano (Halliday, this volume). Present are two cores of dense lava (Figure 7) similar to those reported by Palmer (1926) and several solid tubes of less dense lava (Figure 6) which meet criteria published by the American Geological Institute (Jackson, editor, 1998). A few somewhat similar groups of more or less filled tubes (Figure 9) are exposed in roadcuts on Hawaii Island.

Extraterrestrial and sea floor features identified as lava tubes

Several extraterrestrial and sea floor features have been identified as lava tubes. Fornari (1986) considered that segmentation of a sea floor ridge proved that it is a lava tube. Some lunar rills have been termed collapsed lava tubes, but are many orders of magnitude larger than any terrestrial feature which fits the cited standard definitions of this term. On Kalaupapa Peninsula, Molokai Island,

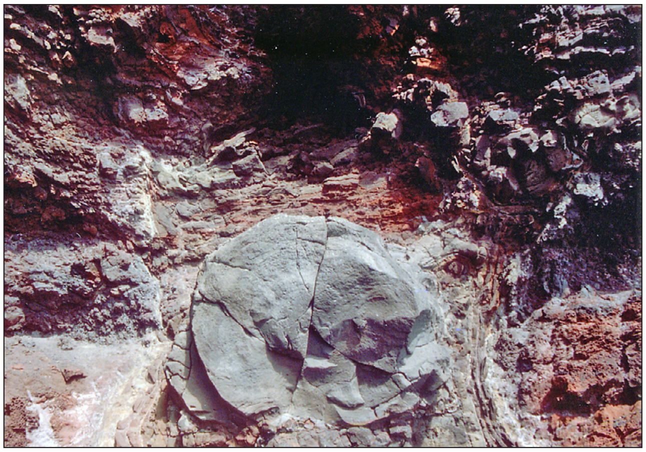

Figure 8. Detail of top of structure shown in Figure 7. Dense solid cylinder with offset concentric vesicle rings is like that reported by Stearns. Above it is horizontally layered lava filling top of buried crevice. Photo by the author.

Figure 9. Cross sections of small lava tubes in aa exposed in road cut along highway between Kailua and Captain Cook, Hawaii County, Hawaii, USA. Maximum height of open tubes is about 10 cm. Photo by the author.

Figure 10. Lava trench on Kalaupapa Peninsula, Molokai Island, Hawaii said to be a collapsed lava tube extending to small volcanic shield beneath lighthouse in background. Photo by the author.

Hawaii (Figure 10), Kauhako Channel is of similar size and also has been termed a collapsed lava tube (e.g., Coombs et al, 1990). Close field examination of this structure, however, revealed that it is a lava channel complex containing eruptive foci (Halliday, 2001) as reflected on a recent geological map of the peninsula (Okubo, 2001). Coombs et al (1990) considered "three land bridges" (channel-wide accumulations of talus) to be proof of collapse of a lava tube, but such "land bridges" also are present in grabens along the Great Crack of the Southwest Rift Zone of Kilauea Volcano (Okubo and Martel, 1998). Four aligned vents are present downslope from the channel (Okubo, 2001). Coombs et al (1990) asserted that the collapsed tube was the feeder for these vents but no evidence is known that these are tube-fed rather than crevice-fed.

Evidence of a huge, deep-lying tube also was said to be evident in Ka Lua o Kahoalii, a pit crater complex opening downward on a level bench within Kauhako Crater (Figure 11). Coombs et al (1990) interpreted it as a collapse skylight of the tube. The vertical shaft of this pit complex opens downward from the surface of a partially destroyed lava pond within Kauhako Crater and is 8 m from the rim of its funnel-shaped inner pit All of its cavernous extension is beneath the talus-covered slope of the inner pit (Figure 11), and slants downward toward it (Halliday, 2001). The total volume of some thinly glazed cavities in the complex (Figure 11, 12) is >> 1% of the volume of Kauhako Channel. Ka Lua o Kahoalii appears to be part of the vertical conduit system of Kauhako Crater and its pond rather than the beginning of some enormous collapsed lava tube.

Extraterrestrial and ocean floor phenomena which are fully congruent with surface expressions of subaerial lava tube caves (e.g., Figure 13) may be considered to indicate the presence of lava tubes with a high degree of certainty (Halliday, 1966). Others are much less conclusive.

Flow lobes and lava rises as lava tubes

Whitehead and Stephenson (1998) conjectured the existence of even larger undiscovered lava tubes in northeastern Australia. Others have written of cores of lava rises, flow lobes and other seemingly amorphous inflation conduits of lava as being lava tubes. Whitehead and Stephenson emphasized "how much larger these wide, flat lava tubes were... in relation to most known lava tubes... the widths of the Toomba inflation conduits were as great as 500 m. . . ." They explained this seeming dichotomy as the product of a new concept which developed in the decade prior to 1998: "any feeder beneath a lava surface" now may be considered a lava tube. Others (e.g., Fornari, 1986) appear to believe that any subcrustal conduit of lava is a lava tube. While nowhere specifically stated, this presumably extends the concept to include crevices, dikes and sills as well as the cores of lava rises and similar structures. No article specifically proposing this concept has been located, however. It may be that it has moved from theory to partial acceptance without adequate scientific testing.

Conduit tubes and drain tubes

Redefinitions of the term lava tube should consider still other tubular structures in lava. Numerous investigators (e.g., Fornari, 1986; Calvari and Pinkerton, 1998) have written as if lava tubes by definition were conduits of flowing lava. On the other hand, some tubular structures in pahoehoe flow fields have features consistent with subcrustal drainage caves (Grimes, 1999, 2002; Grimes and Watson, 1995; Halliday, 1998 a and b). Lack of downcutting, rheogenic abrasion and accretion all show that such caves have carried little or no flowing lava (other than the small volumes drained from the structures themselves). Most of the shallow, thin-roofed "surface tubes" which formed in profusion on some pahoehoe flows (e.g., the Huehue telephone repeater section of the Kaupulehu flows of Hualalai Volcano, Hawaii), also are drain structures rather than conduits.

In the 1919 flow of Kilauea Caldera, Hawaii, numerous elongate flat-floored depressions are present where still-plastic cave roofs slumped when their feeder halted abruptly. A variety of more or less tubular voids are associated with these closed depressions. Some are shallow, relatively featureless corridors locally split by as many as three subparallel slumps. Others are boundary ridge passages on one or both sides of a wide linear or sinuous depresssion. Nearby, caves

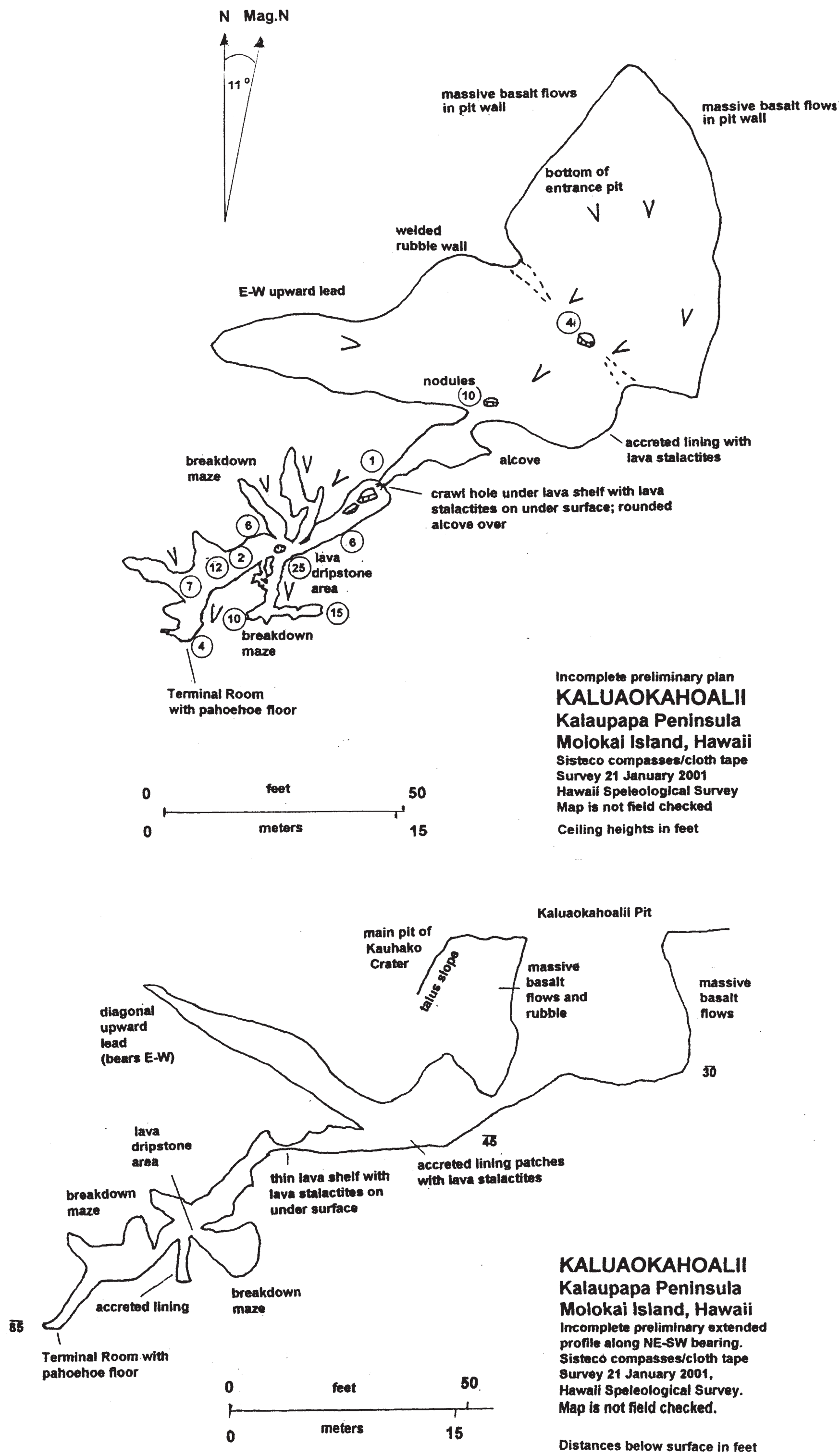

Figure 11. Plan and extended profile of Ka Lua o Kahoalii, Kalaupapa Peninsula, Molokai Island, Hawaii, commonly said to be the start of a lava tube extending from Kauhako Crater to the lighthouse at the tip of the peninsula.

Figure 12. Small lava upwelling at start of break-down area, Ka Lua o Kahoalii, Kalaupapa Peninsula, Molokai, Island, Hawaii. Photo by the author.

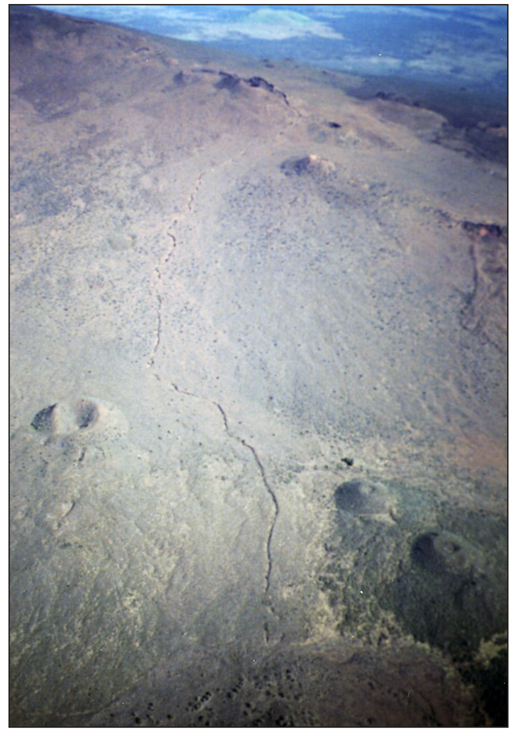

Figure 13. Full length of Poikahe Crater lava tube system, Hualalai Volcano, Hawaii. Poikahe Crater is just below top center. Extraterrestrial and submarine phenomena which are fully congruent with such surface features indicate the presence of lava tubes with a high degree of certainty. Photo by the author.

in sinuous hollow tumuli are essentially featureless but otherwise are much like those of conduit tubes. Cross-sections of donut-shaped boundary ridge caves of lava rises with depressed centers (Figure 14) are similar to those of conduit tubes, and complexes exist combining two or three of these forms. In areas with patent drained flow lobes, some individual cavities are interconnected by essentially featureless drain tubes. Individually, these short tubular segments can easily be accepted as lava tubes, but as a whole, the resulting cave complexes resemble giant ant nests rather than lava tube conduit caves (Figure 16).

At least one basaltic dike (Figure 17) drained and assumed the form of a lava tube cave (Figure 18) where it approached the face of a sea cliff (Socorro and Martin, 1981).

Redefinition of the term "lava tube"

From the above, it is easy to conclude that the term "lava tube" should be redefined in unmistakably specific terms. Ideally, both hollow and solid forms should be included, in terms of specific parameters which differentiate them

Figure 14. Tube-like circumferential boundary ridge passage, Lava Rise C-3 Cave, Kilauea Caldera, Hawaii. Photo by the author.

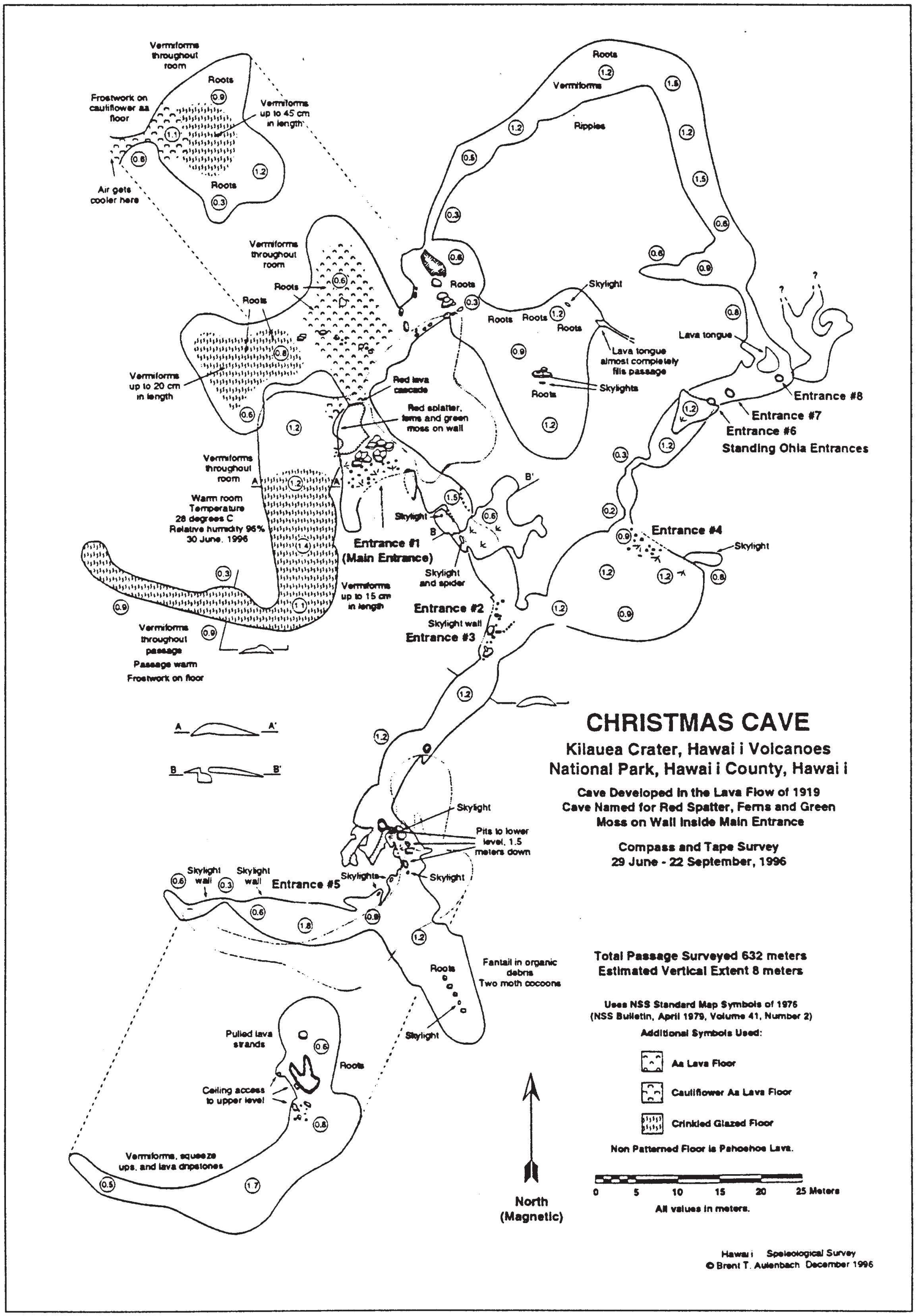

Figure 16. Plan of Christmas Cave, Kilauea Caldera, Hawaii: a nested complex of flow lobe cavities and short tubular connecting passages.

from all other volcanic features (e.g., aa cores, lava tongues, tumuli, sills, self-propagating crevices and related injection masses. But the ideal may not be achievable at the present state of knowledge and technology. However, recent discoveries and new concepts of flow field emplacement and drainage (e.g., Hon et al, 1994) offer a notable opportunity to shape a clearer definition of this elusive term.

In my opinion, the defining characteristics should be compatible with:

1) the common meanings of "tube" and "cave".
2) the presence of solid, gaseous, or liquid matter within them.
3) observations of all phases of their complex speleogenesis, e.g., crustal and subcrustal accretion and erosion.
4) their tendency to form braided and distributory complexes, and multilevel structures of at least two types.
5) their propensity to form within, combine with or produce other volcanic structures, e.g., lava trenches, rift crevices, tumuli, drained flow lobes, lava rises, dikes, etc.

I propose that the Commission on Volcanic Caves of the IUS take the lead in developing such a redefinition, in collaboration with the American Geological Institute and other concerned agencies and organizations, for consideration at the 2005 International Congress of Speleology.

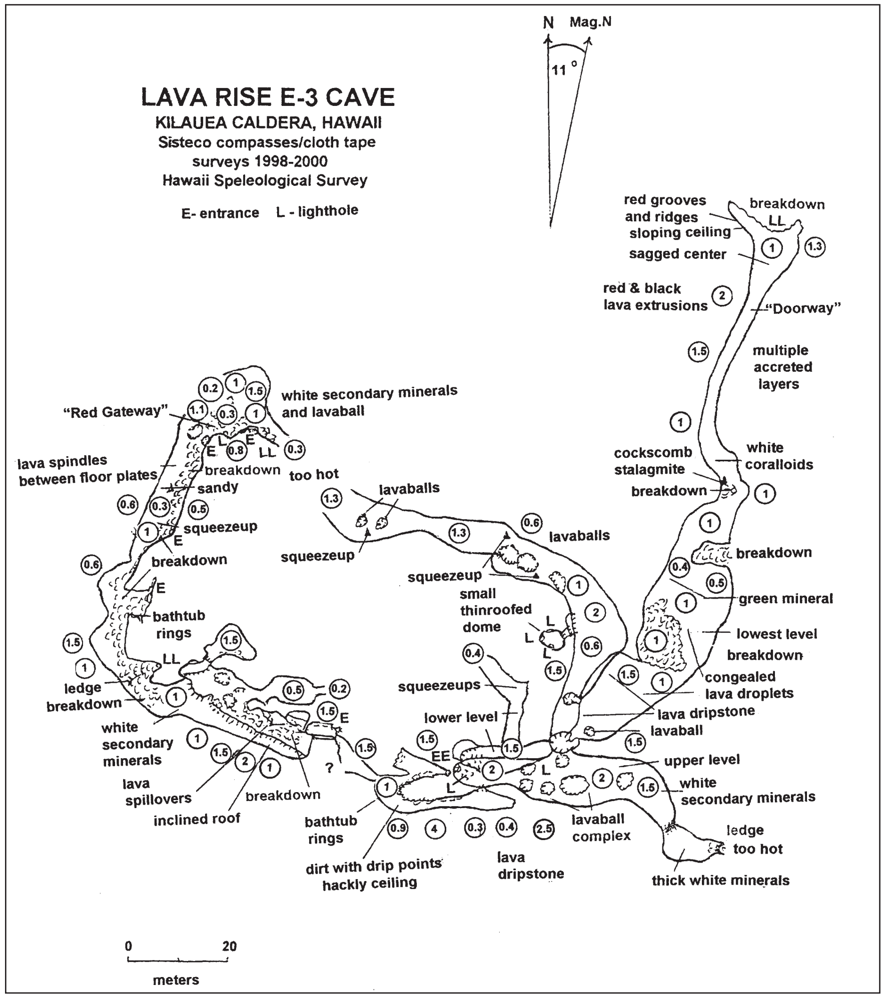

Figure 15. Plan of Lava Rise C-3 Cave, Kilauea Caldera, Hawaii. A typical cross section of the tubular circumferential passsge is depicted in Figure 14.

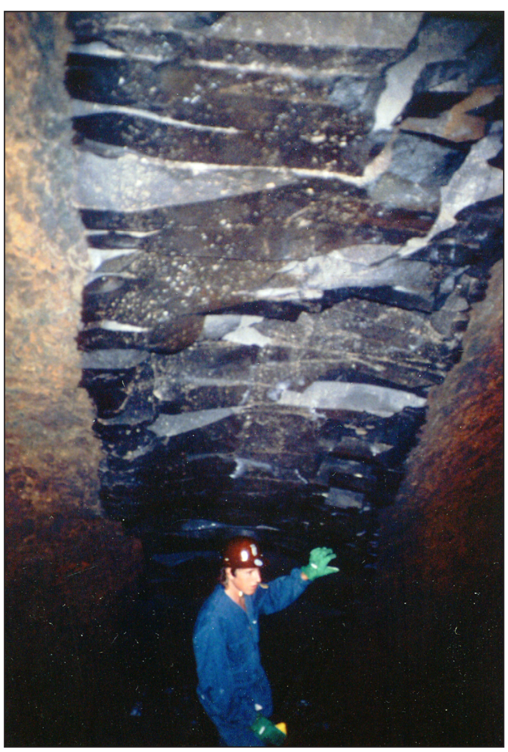

Figure 17. Dike exposed in ceiling of inner chamber formed in pyroclastics, Cueva de la Fajanita, La Palma Island, Canary Islands. This dike is hollow from a point a few meters behind the photographer to the sea cliff. Photo by the author.

References

Calvari, Sonia and Harry Pinkerton. 1999. Lava tube morphology on Etna and evidence for lava flow emplacement mechanisms. Journal of Volcanology and Geothermal Research. Vol. 90, p. 163-280.

Campbell, L. H., P. J. Conaghan and R. H. Flood. 2001. Flow-field and palaeogeographic reconstruction of volcanic activity in the Permian Gerringong Volcanic Complex, southern Sydney Basin, Australia. Australian Journal of Earth Sciences, Vol. 48, p. 357-375.

Carr, Paul F. and Brian G. Jones. 2001. The influence of palaeoenvironment

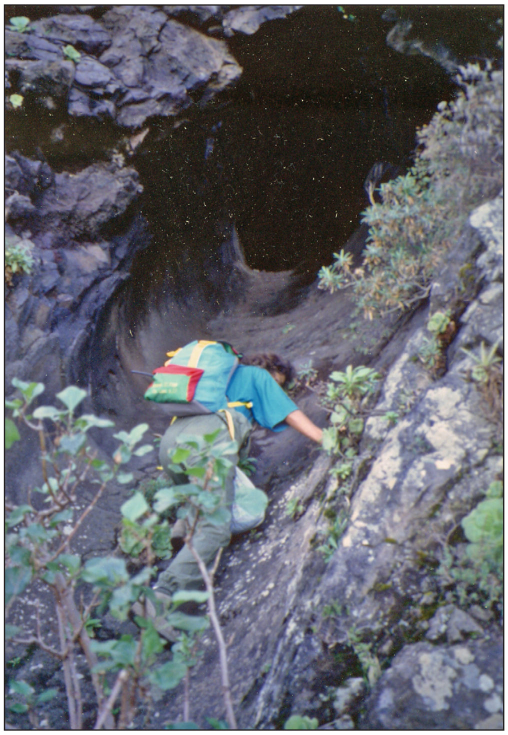

Figure 18. Ascending into the sea cliff entrance of the tubular hollow section of the dike of Cueva de la Fajanita, La Palma Island, Canary Islands. Photo by the author.

and lava flux on the emplacement of submarine, near-shore Late Permian basalt lavas, Sydney Basin (Australia). Journal of Volcanology and Geothermal Research. Vol. 112, p. 247-266.

Coombs, C. R., B. R. Hawke, and L. Wilson. 1990. Terrestrial analogs to Lunar sinuous rilles: Kauhako Crater and Channel, Kalaupapa, Molokai and other Hawaiian lava tube conduit systems. Proceedings of the 20th Lunar and Planetary Science Conference, Lunar and Planetary Institute, Houston, p. 195-206.

Fornari, Daniel J. 1986. Submarine lava tubes and channels. Bulletin of Volcanology. Vol. 48, p. 291-298.

Greeley, Ronald et al. 1998. Erosion by flowing lava: field evidence. Journal of Geophysical Research. Vol. 103, no. B11, p. 27,325-27,345.

Grimes, Ken G. 1999. Volcanic caves and related features in western Victoria, Proceedings of the 13th Australian Conference on cave and karst management, Mt Gambler, Australia, p. 148-151.

Grimes, Ken G. 2002. Subcrustal drainage lava caves; examples from Victoria, Australia (abstract). Abstract volume, Xth International Symposium on Vulcanospeleology, Reykjavik, Iceland. September 9-15,2002. p. 12-13.

Grimes, Ken G. and Tony Watson. 1995. Volcanic caves of western Victoria. In:

Baddeley, G., editor. Vulcon Guidebook (20th Australian Speleological Federation Conference), Victoria Speleological Association Inc, Melbourne, p. 39-68.

Halliday, William R. 1966. Terrestrial pseudokarst and the lunar topography. National Speleological Society Bulletin. Vol. 28, no. 4, p. 167-170.

Halliday, William R. 1998a. Hollow volcanic tumulus caves of Kilauea Caldera, Hawaii County, Hawaii. International Journal of Speleology. Vol. 27B, no. 1/4, p. 95-105.

Halliday, William R. 1998b. Sheet flow caves of Kilauea Caldera, Hawaii County, Hawaii. International Journal of Speleology. Vol. 27B, no. 1/4, p. 107-112.

Halliday, William R. 2001. Caves and cavernous features of Kalaupapa Peninsula, Molokai, Hawaii. Report no. 01-1, Hawaii Speleological Survey of the National Speleological Society, July 2001. 48 p.

Halliday, William R. 2002. Caves of the Great Crack of Kilauea Volcano, Hawaii (abstract). Abstract volume, Xth International Symposium on Vulcanospeleology, Reykjavik, Iceland, September 9-15, 2002. P. 19.

Harper, L. F. 1915. Geology and mineral resources of the Southern Coal Field: Part I: the south coastal portion. Memoirs of the Geological Survey of New South Wales. Department of Mines, William Appleton Gullick, Government Printer, Sydney.

Honda, Tsutomu. 2002. On lava stalactite formation in the hollow of tree molds at ML Fuji (abstract). Abstract volume, Xth International Symposium on Vulcanospeleology, Reykjavik, Iceland. September 9-15, 2002. P. 22.

Jackson, Julia A. 1997. Glossary of Geology: 4th Edition, Alexandria (Virginia), American Geological Institute.

Kesthelyi, L. and S. Self. 1998, Some physical requirements for the emplacement of long basaltic lava flows. Journal of Geophysical Research. Vol. 103, no. B11, p. 27-447-27,464.

Larson, Charles V. 1993. An illustrated glossary of lava tube features. Western Speleological Survey Bulletin no. 87. Vancouver, WA. (ABC Printing), 56 p.

Okubo, Chris. 2001. Preliminary geologic map of Kalaupapa Peninsula, Molokai, Hawaii. Figure 1 in Halliday, 2001, op. cit

Okubo, Chris and Steve Martel. 1998, Pit crater formation on Kilauea volcano, Hawaii. Journal of Volcanology and Geothermal Research. Vol. 86, p. 1-18.

Palmer, Harold S. 1929. A fossil lava tube. Journal of Geology. Vol. 37, no. 3, April-May, 1929. P. 272-274.

Socorro, J. and J, Martin. 1984. The Fajanita Cave (La Palma, Canary Islands): a volcanic cavity originated by partial drainage of a dike. Proceedings, 8th International Symposium on Vulcanospeleology, Santa Cruz de La Palma, Canary Islands, November 1984, p. 177-184.

Waters, A. C. 1960. Determining the direction of flow in basalts. American Journal of Science, vol. 258A, p. 350-366.

Wentworth, Chester K. 1925. The geology of Lanai. Bernice P. Bishop Bulletin no. 24, p. 50.

Whitehead, P. W. and P. J. Stephenson, 1998. Lava rise ridges of the Toomba basalt flow, north Queensland. Journal of Geophysical Research. Vol. 103, no. B11. p. 27,371-27,382.

Caves of the Great Crack, Kilauea Volcano, Hawaii

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Abstract

The Great Crack ("17 Mile Crack") is the most prominent feature of Kilauea volcano's Southwest Rift Zone. Rather than consisting of a single crevice, much of the "crack" consists of en echelon crevices of various widths in a strip locally more than 1 km wide. Numerous grabens and collapse pits are present.

Detailed studies of this complex have been begun only in the past decade. Some of the participating geologists have requested support and some leadership by speleologists in investigating cavernous pits at the bottom of steep talus slopes. The Hawaii Speleological Survey of the National Speleological Society subsequently has cooperated with University of Hawaii and U.S. Geological Survey researchers in investigating cavernous pits in the principal axis of the crevice complex. Two pits yielded minimal spelean findings, but the third—labelled Pit H by University of Hawaii geologists—was found to require SRT expertise. In 2001 it was explored and mapped to a depth of 183 m. Despite extensive breakdown, accretion by laterally flowing lava was identified on several levels. A total of 600 m of passage was mapped.

In a similar crevice at the bottom of Wood Valley Pit Crater (which is nearby but off the principal axis of the rift zone), accreted linings and tube segments have been found along the crevice at a depth of almost 90 m. No such tube segments are present in Pit H Cave. These findings indicate that tube formation is not essential to lateral flow of lava in rift crevices, but occurs in some locations. Numerous other pits remain to be investigated along the Great Crack and elsewhere.

Introduction

The Great Crack ("17 Mile Crack") is the most conspicuous feature of the Southwest Rift Zone of Hawaii's Kilauea Volcano (Figure 1,2). The section of this feature discussed in this report is about 2 km long and is located about 2 km north (up-rift) of the historic 1823 Keaiwa lava flow which emerged from its lower end. Okubo and Martel (1998) identified and described 14 collapse pits here, located along two dominant crevices (or paired crevices). The present study reports initial investigations of crevice caves associated with some of these collapse pits, as conducted by members of the Hawaii Speleological

Figure 3. Main (lower) entrance. Cathedral Cave, Pit B of the Great Crack. Photo by the Author.

Figure 4. Looking upward along talus slope to upper entrance of Cathedral Cave located at edge of Pit A. Photo by the Author.

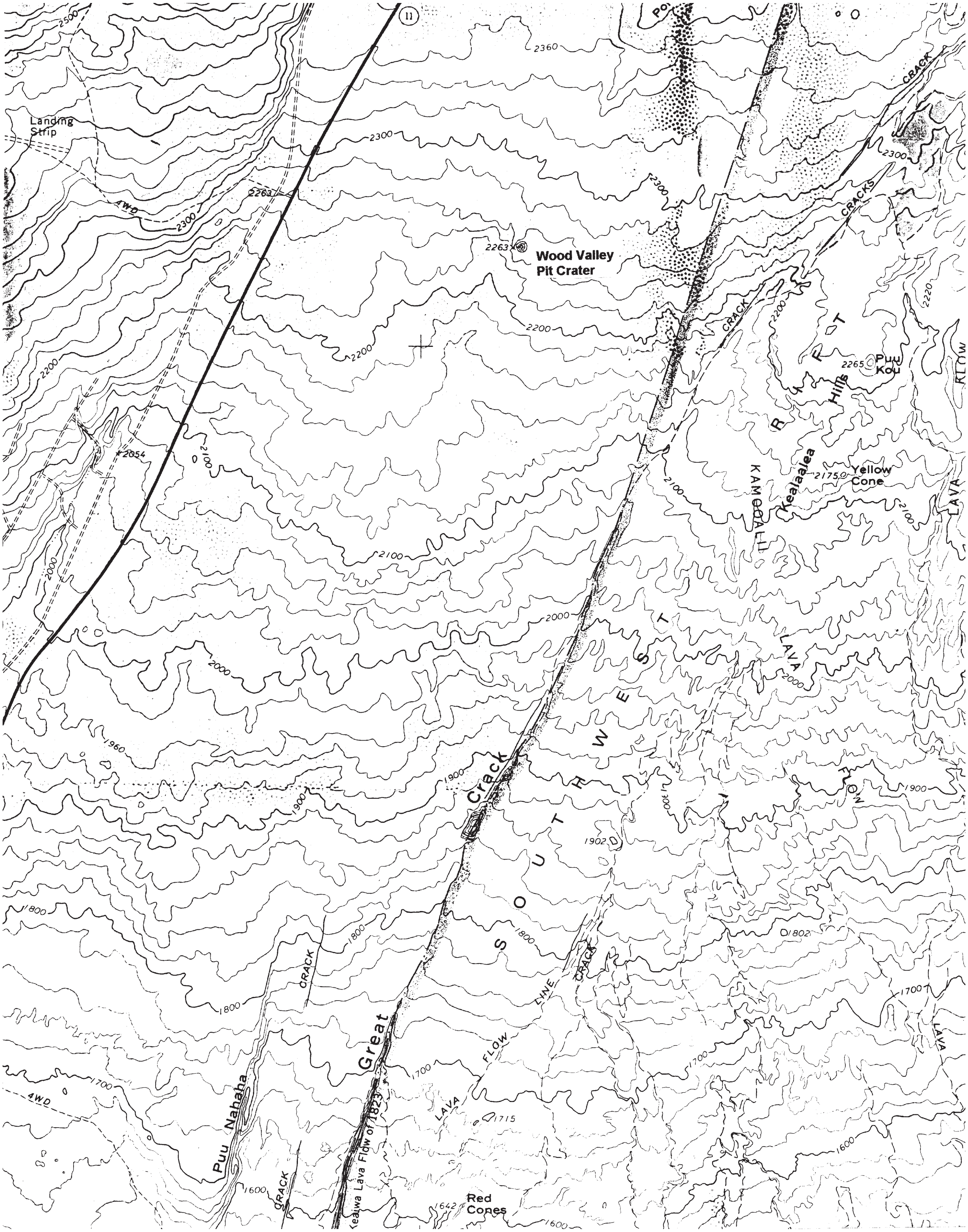


Figure 1. Section of 1981 US Geological Survey 1:24,000 Wood Valley Quadrangle showing the Great Crack and Wood Valley Pit Crater.

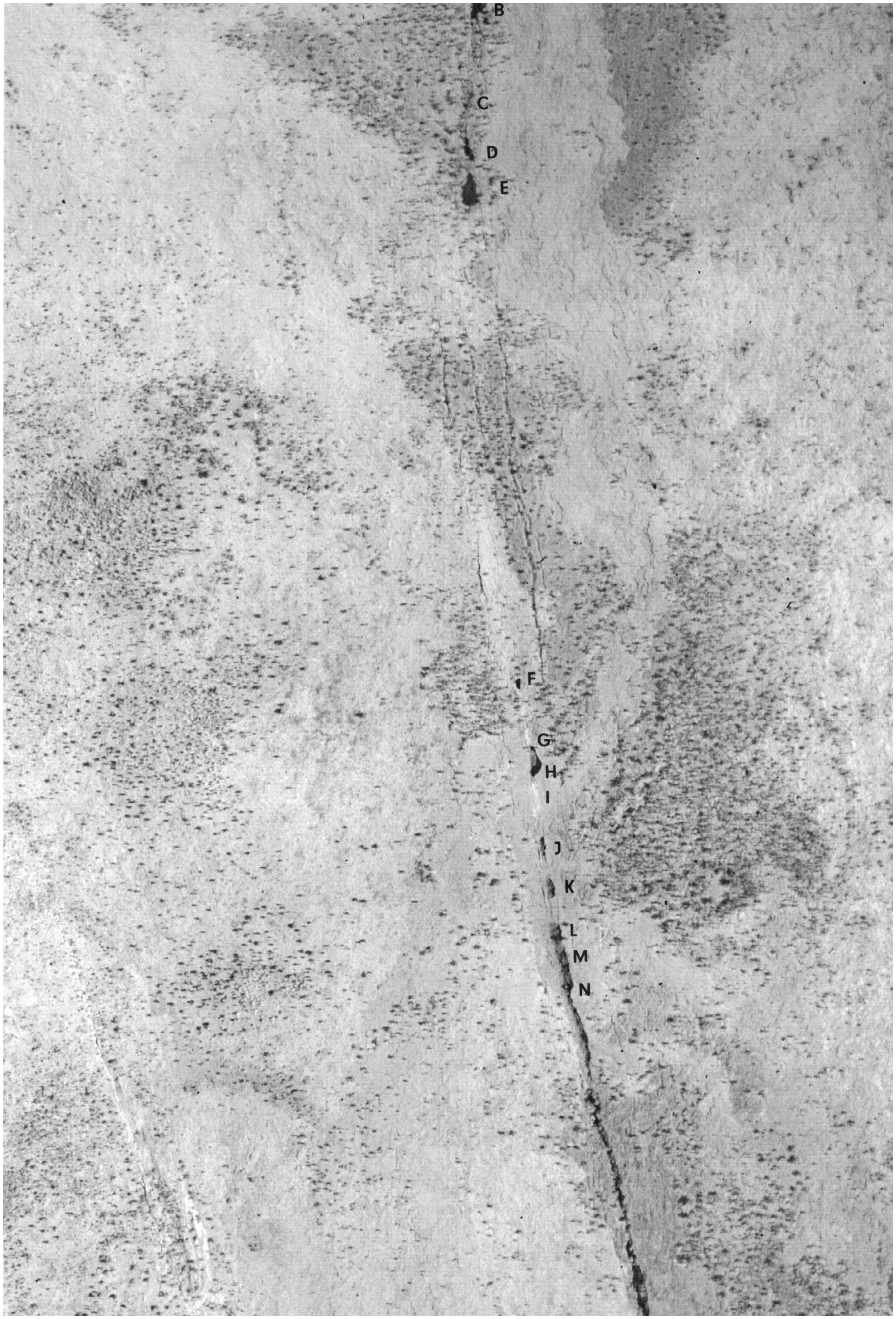
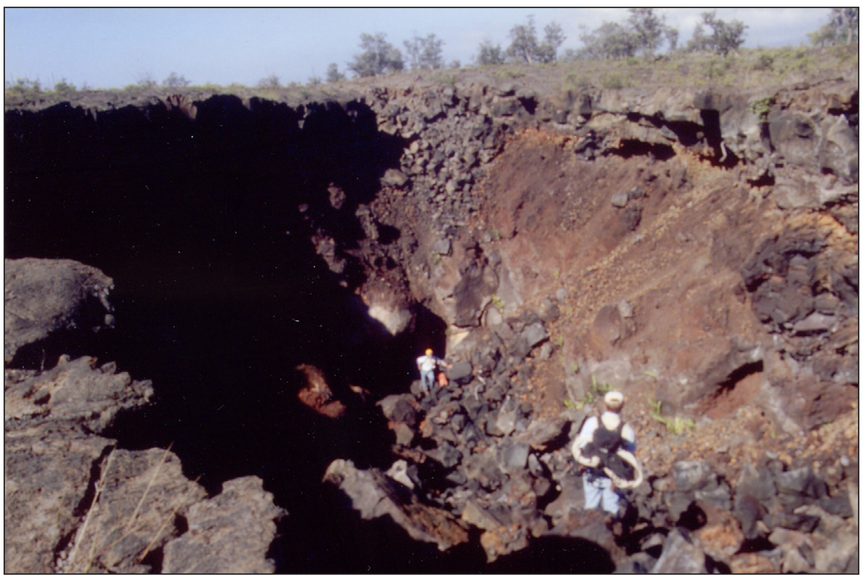


Figure 2. October 1988 NASA aerial photo of study area showing collapse pits B to N. Courtesy Chris Okubo.



Survey of the National Speleological Society in cooperation with Okubo and Martel and with Don Swanson of the U.S. Geological Survey. It compares findings during these explorations with those by Favre et al (Favre, 1993) during exploration of the nearby Wood Valley Pit Crater Complex.

Overview of the study area

The term "Great Crack" implies that the principal rift structure here consists of a single dominant crevice, but this is not the case. Instead, the feature consists of a complex of en echelon crevices of various widths. These are encompassed in a strip locally more than 1 km wide. The area is geologically active, and at least one important collapse pit has developed in the last few years (Okubo and Martel, 1998). As Okubo and Martel have shown, the pits are from 8 to 45 m in diameter and 6 to 28.5 m in depth. They occur in two groups along shallow linear depressions which are not quite aligned with each other. Pairs of deep, near-vertical cracks with apertures of several cm are characteristic of the collapse pits,

Pits A through E (Figure 2) are located along a narrow graben 5 to 7 m wide and 2 to 15 m deep. Locally it is nearly filled with talus and volcanic ash. Individual pits are separated by septae of talus extending almost to ground level. Pits F through N are in a slightly wider depression which is generally shallower but locally contains steep-walled troughs 5 to 7 m wide and 2 to 3 m deep. No tephra is present south of Pit F. Lava exposed in their walls largely consists of pahoehoe and a basaltic lava flows 0.5 to several m thick. Rubble and blocks of talus of similar dimensions mantle pit and cave floors and lower walls. Overhanging pit walls are common; some overhangs initially were mistaken

Figure 5 (top). Hollow dike, Cathedral Cave. Photo by the Author.

Figure 6 (middle). Entrance sink, Pit H Cave of the Great Crack. Photo by the Author.

Figure 7 (bottom). Entrance of Pit H Cave, located beneath dense lava core. Photo by the Author.

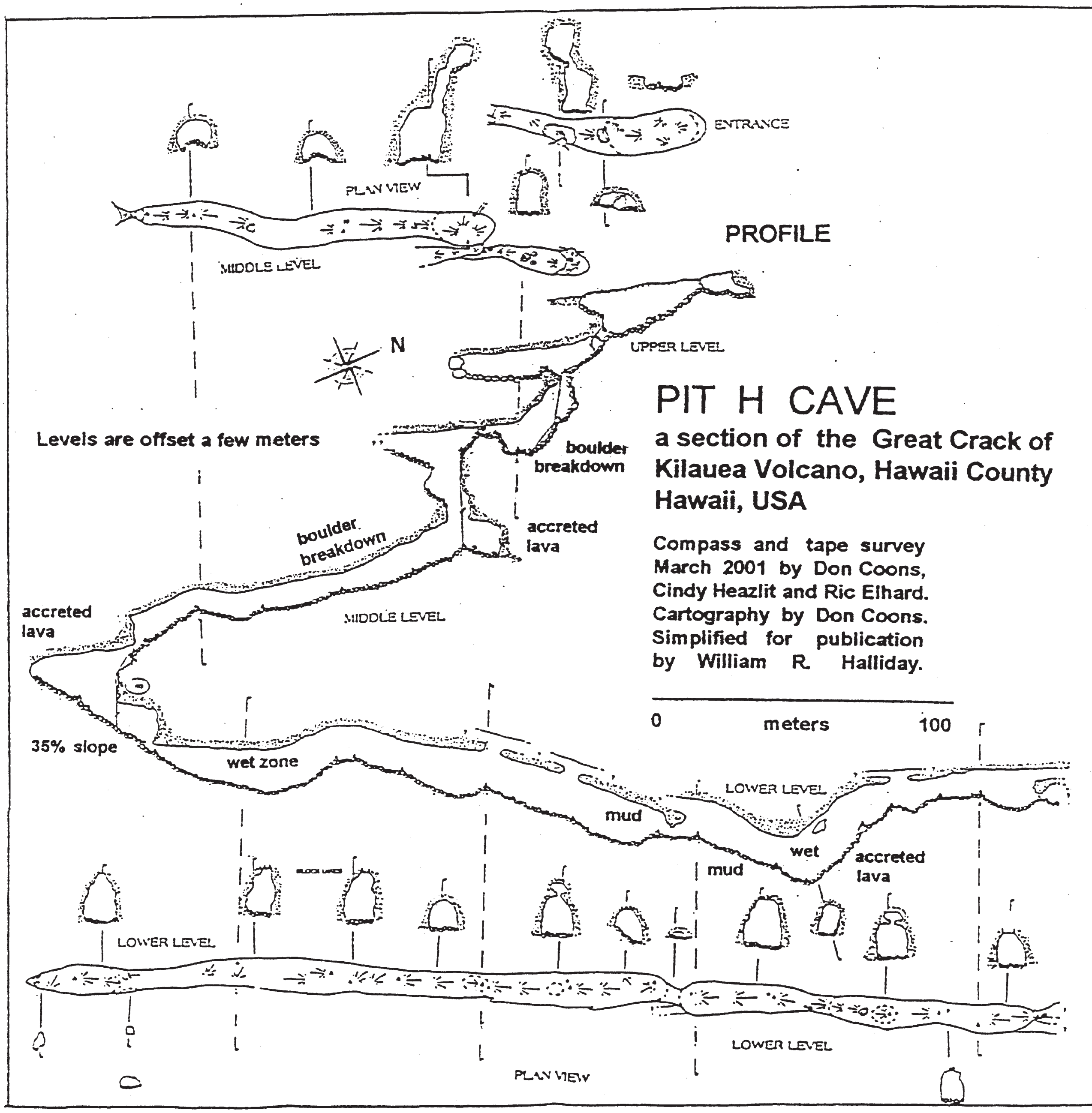


Figure 8, Map of Pit H Cave, redrawn by the author from map courtesy Don Coons.

for cave entrances. Some unusual lava injection features also are seen locally (Figures 5, 10) these are discussed below. Farther downrift are additional collapse pits, then a continuous steep-walled depression from which emerged the historic 1823 flow.

Initial investigations

Based primarily on views from the ground surface, Okubo and Martel (1998) listed all pits from Pit A to Pit I as having known caves. In July 1998 and August 1999, this writer and Chris Okubo investigated cave entrances in the northern group (Pits A - Pit E) which were accessible without special climbing gear. At the north (up-rift) end of Pit B we clambered down into a spacious crevice cavern. Locally almost 10 m wide, its lower portion was both impressive and scientifically significant; its walls contain unusual lava structures which show flow of molten lava into the cavity from within the wall (Figurers 5, 10). The upper portion of this cave extends steeply upward through large talus fragments to a narrow upper entrance which is just within the down-rift margin of Pit A - a vertical extent of nearly 20 m. Because of the spaciousness of its main chamber, we called it Cathedral Cave.

Investigations of Pit H Cave

We planned to return and map Cathedral Cave. On 18 February 2000, however, Okubo and I investigated Pit H Cave in the lower group, Descending a steep entrance slope with large talus blocks at

Figure 9. Mapping the entrance slope of Pit H Cave. Photo by the Author.

Figure 10. Hollow dike in twilight zone of Pit H Cave. Photo by the author.

Figure 11. Composite photograph of upper level of Pit H Cave, looking across pit at end of twilight. Photos by the Author.

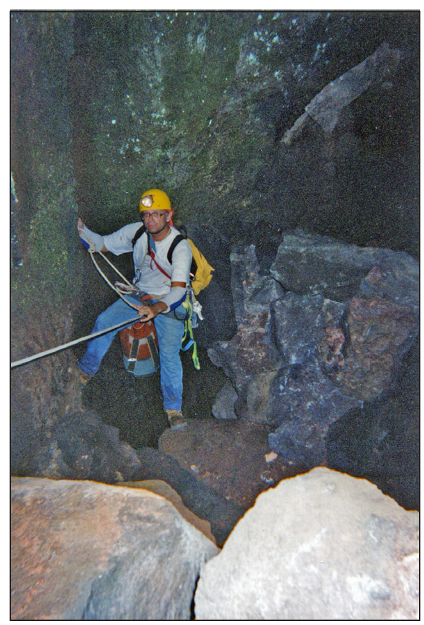


Figure 12. Don Coons at narrows of pit leading to lower levels. Photo by the Author.

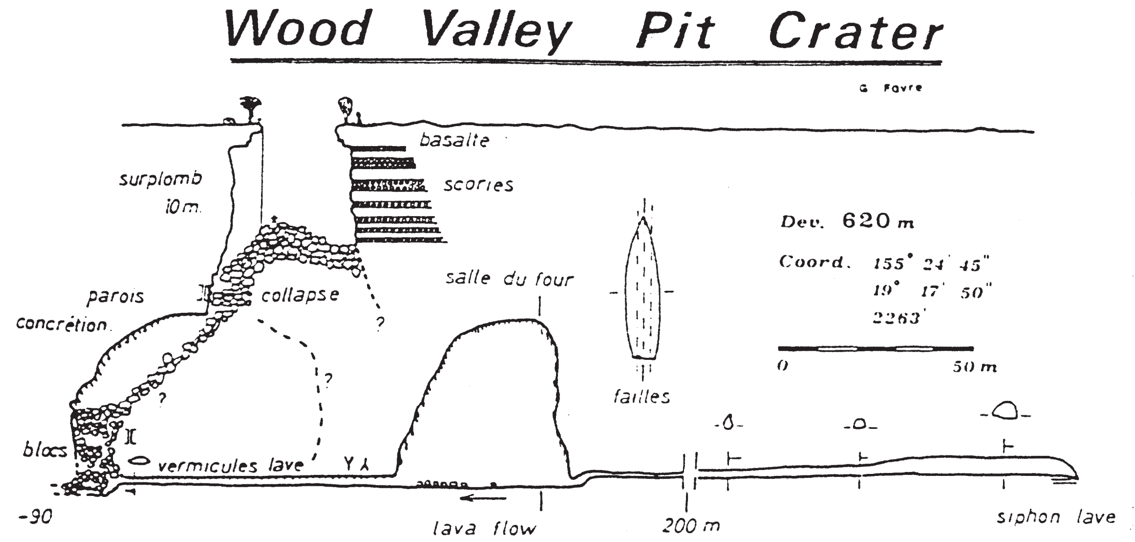


Figure 13. Plan and longitudinal section of Wood Valley Pit Crater Complex. Courtesy Gerald Favre.

the angle of repose, we mapped as far as a funnel-shaped pit in wedged talus, located at the inner margin of twilight This pit extended completely across a near-horizontal passage 5 to 6 m wide, floored by wedged talus. Its depth could not be determined but eventually was found to be 26 m. We photodocumented the accessible area (including a hollow dike exposed in section - Figure 10) but could do no more without specialized climbing gear.

On August 7, 2000 Don Coons accompanied Don Swanson and myself to Pit H Cave. Coons traversed the pit where Okubo and I had stopped, finding about 25 m of additional passage on this level. Then he descended the pit to the next level, 26 m below. After a minor initial ascent here, he encountered an additional pit for which he needed additional rope and a support team (Coons, 2001).

Coons was designated chairman of a formal project of the Hawaii Speleological Survey. On 23 February 2001 he returned to Pit H Cave, accompanied by Rick Elhard and Cindy Heazlitt. In one vigorous day, 30 survey stations yielded 600 m of passages which reached a depth of 183 m. The second vertical pitch was found to be 37 m, with a third pitch of 22 m farther downslope (Figure 8).

Remnants of accreted linings were found at several levels in Pit H Cave. Near the lowest point in the cave, the lining was found to be 25 cm thick and composed of two units: a porous brownish inner layer and a dense black outer layer. Closer to the surface, the accreted lava is increasingly thin and none was found above the second pitch. Nothing suggesting the presence of a lava tube was observed (Coons, 2001).

Comparison with previous observations

Okubo and Martel (1998, page 10) summarized Jaggar's 1947 observations of lava entering the principal Southwest Rift Zone conduit in the wall of Halemaumau. They concluded that Jaggar described "stoping into a previously widened subsurface fracture", rather than a rift tube. This is consistent with findings in Pit H Cave.

On the other hand, Favre (1993) reported dissimilar findings in a crevice passage in the nearby Wood Valley Pit Crater Complex. Wood Valley Pit Crater also is within Kilauea volcano's Southwest Rift Zone, but is off its principal axis (Figure 1). Here, "totally glazed" lava tube segments were found along the crevice, forming most of a cave more than 460 m long at a depth of almost 90 m. Average height of the tube segments is 8 m, average width, 12m. Two large linear chambers also are present. One is directly beneath the shaft of Wood Valley Pit Crater and is nearly filled with talus. The other is 80 m farther along the crevice and is 40 m high, 10m wide and 40 m long. It is intact and is lined with accreted lava ("congealed basalt"). Comparison of these findings with those in Pit H Cave indicates that lava tubes can form in active rift crevices but some lateral flow exists without tube formation.

To confirm and amplify these findings, much more exploration and investigation of volcanic crevice caves and pit craters is needed, along the Great Crack and elsewhere.

References

Coons, D. 2001. The Great Crack, an update on recent exploration. Hawaii Speleological Survey Newsletter no. 9, June, p. 27-28.

Favre, G. 1993. Some observations on Hawaiian pit craters and relations with lava tubes. Proceedings, 3rd International Symposium on Vulcanospeleology, William Halliday, Chairman. Bend, Oregon, July 30-August 1, 1982. International Speleological Foundation, Seattle, p. 37- 41.

Jaggar, T. 1947. Origin and development of craters. Geological Society of America Memoir 21.

Okubo, C. and S. Martel. 1998. Pit crater formation on Kilauea volcano, Hawaii. Journal of Volcanology and Geothermal Research. Vol. 86, p. 1-18.