Small Subcrustal Lava Caves: Examples from Victoria, Australia*

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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-

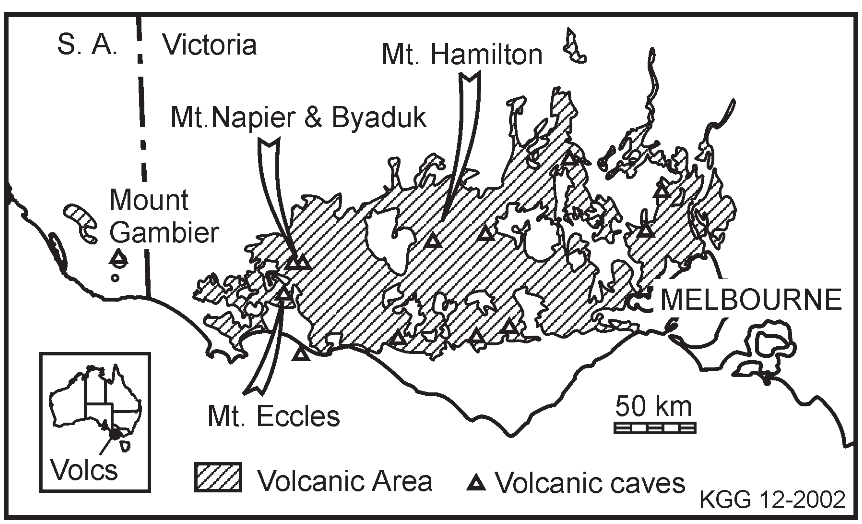

Figure 1. Location map of the Western District Volcanic Province, and its main lava cave areas.

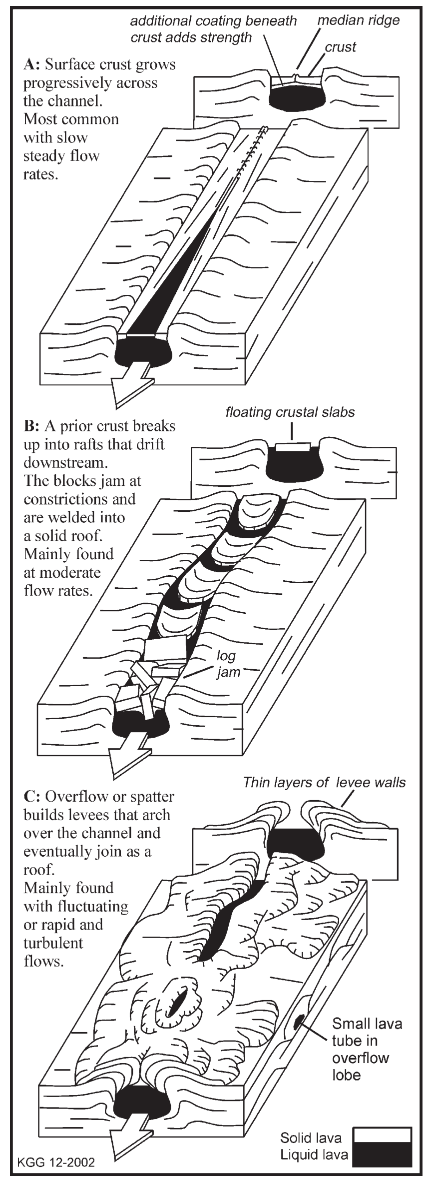

Figure 2. Three ways of forming large lava tubes by roofing a surface channel.

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".

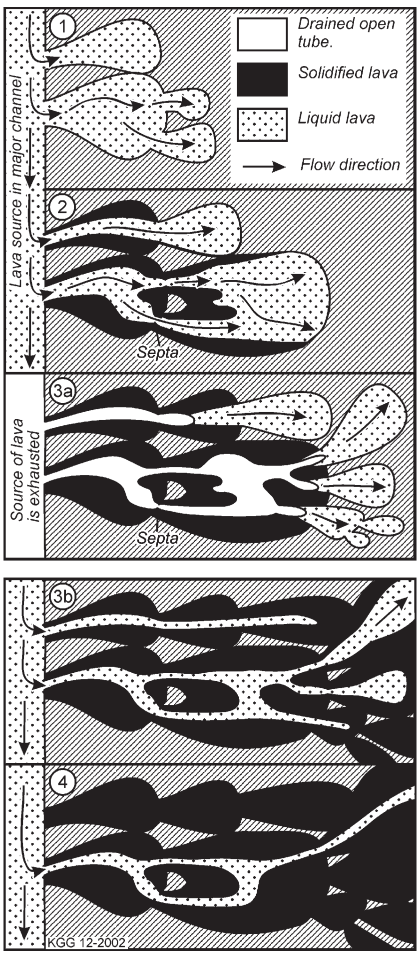

Figure 3. Formation of lava caves by subcrustal drainage of a series of advancing lava lobes. Step 3a is the situation if the source of lava ceases early in the development; irregular caves form. Steps 3b and 4 indicate the further evolution into more linear feeder tubes as lava continues to flow through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

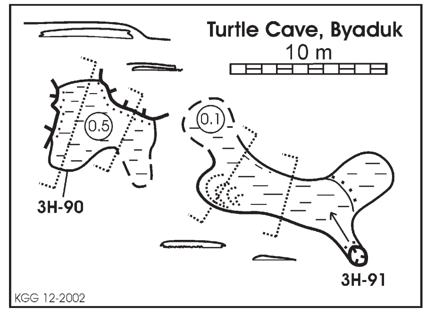

Figure 5. Turtle Cave, H-90, at Byaduk, is an example of a simple "lava blister" cave. The name derives from its resemblance to an empty turtle shell.

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).

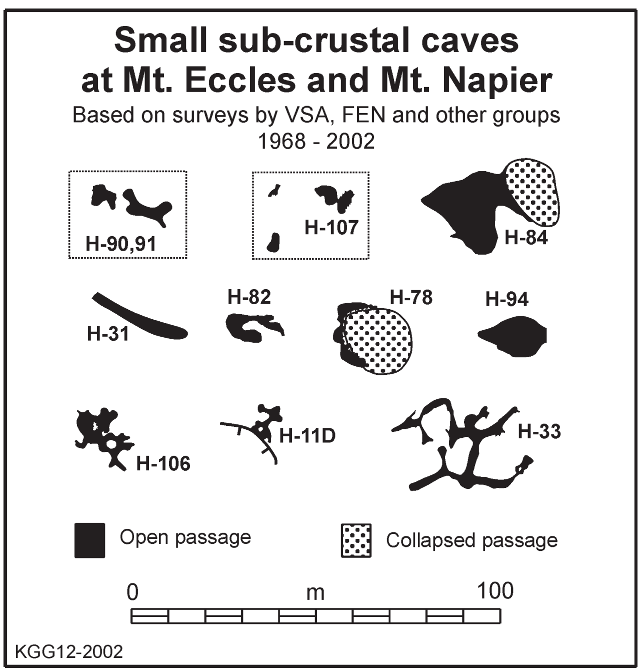

Figure 4. Examples of small, simple, subcrustal caves; mostly associated with low lava mounds. H90, 91 and 107 would be called "lava blisters"; H-78 is a "peripheral remnant" left by the collapse of the roof of shallow chamber; H-31 is approaching a linear "tube" form; H-11, 33 and 106 are grading to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

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 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

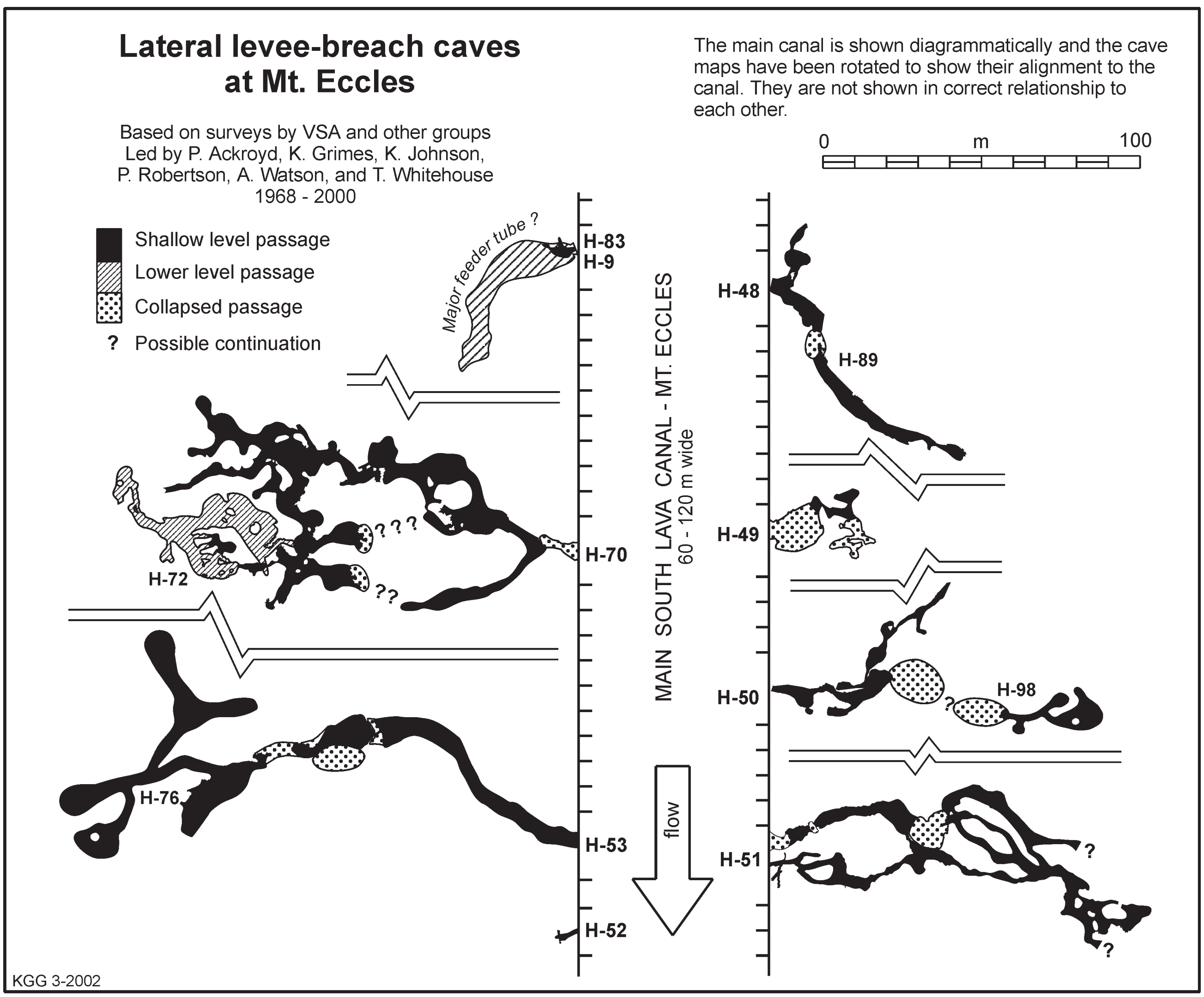

Figure 6. Examples of more complex subcrustal caves formed in thin overflows from a lava channel at Mt. Eccles. See Fig. 7 for detail of H-70/72. A detailed map of H-51 is included in the supplementary material on the CD.

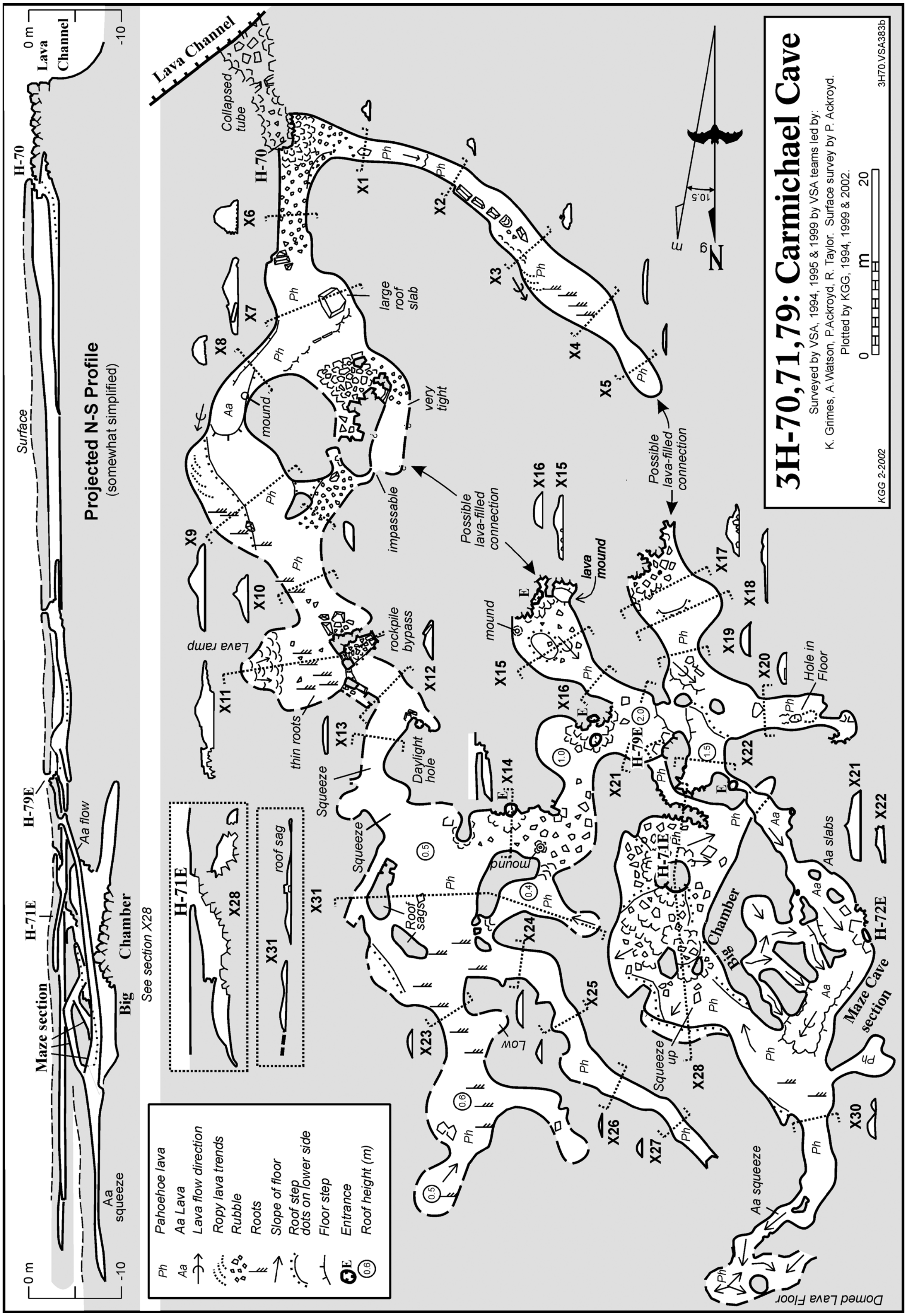

Figure 7. Detailed map of Carmichael Cave (H-70) at Mt. Eccles.

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

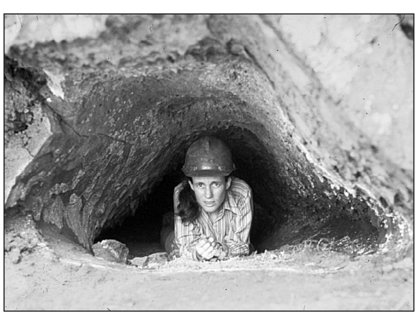

Figure 9. Small subcrustal tube, H-52 at Mt. Eccles.

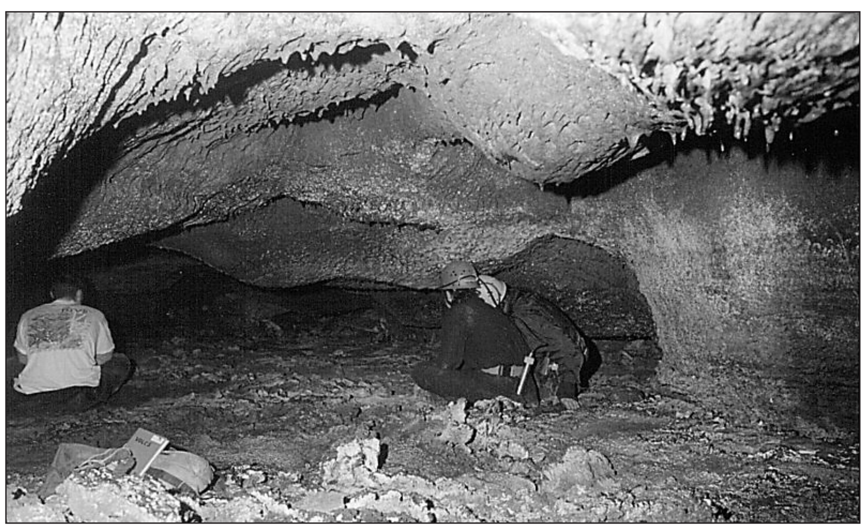

Figure 10. Chamber in H-74, showing sagged parts of roof.

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).

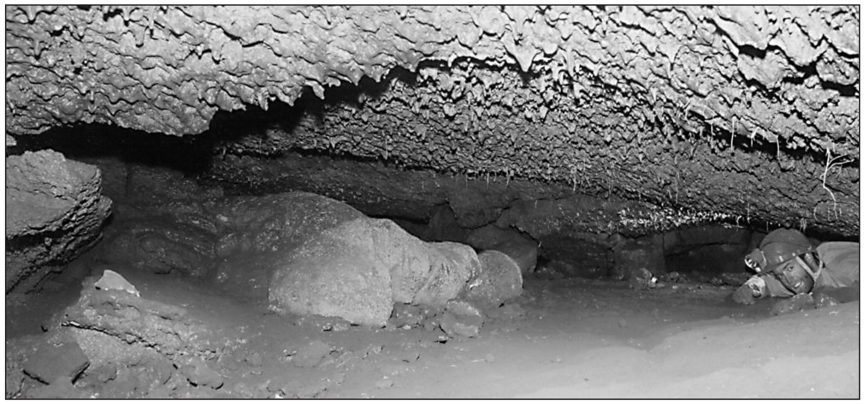

Figure 11. Low chamber in H-106, with lava drips and an intrusive lava tongue at left.

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

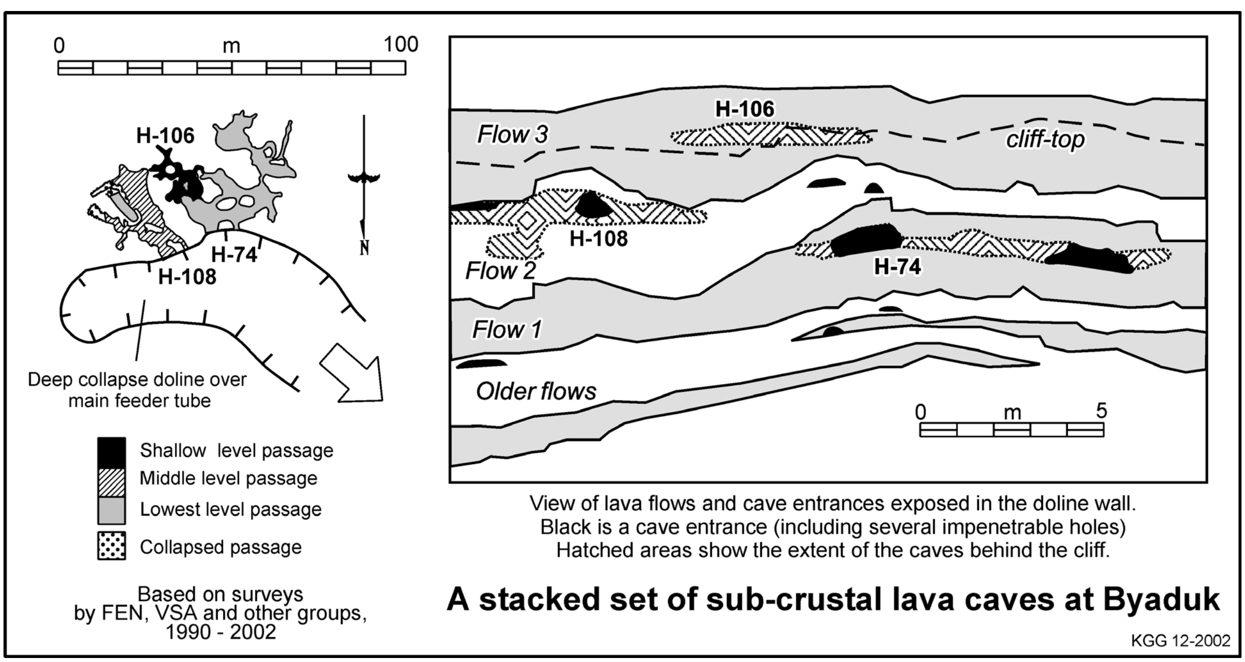

Figure 12. A set of three small subcrustal caves formed in separate stacked lava flows at Byaduk. Detailed reports and maps on H-106 and H-108 are in the supplementary material on the CD.

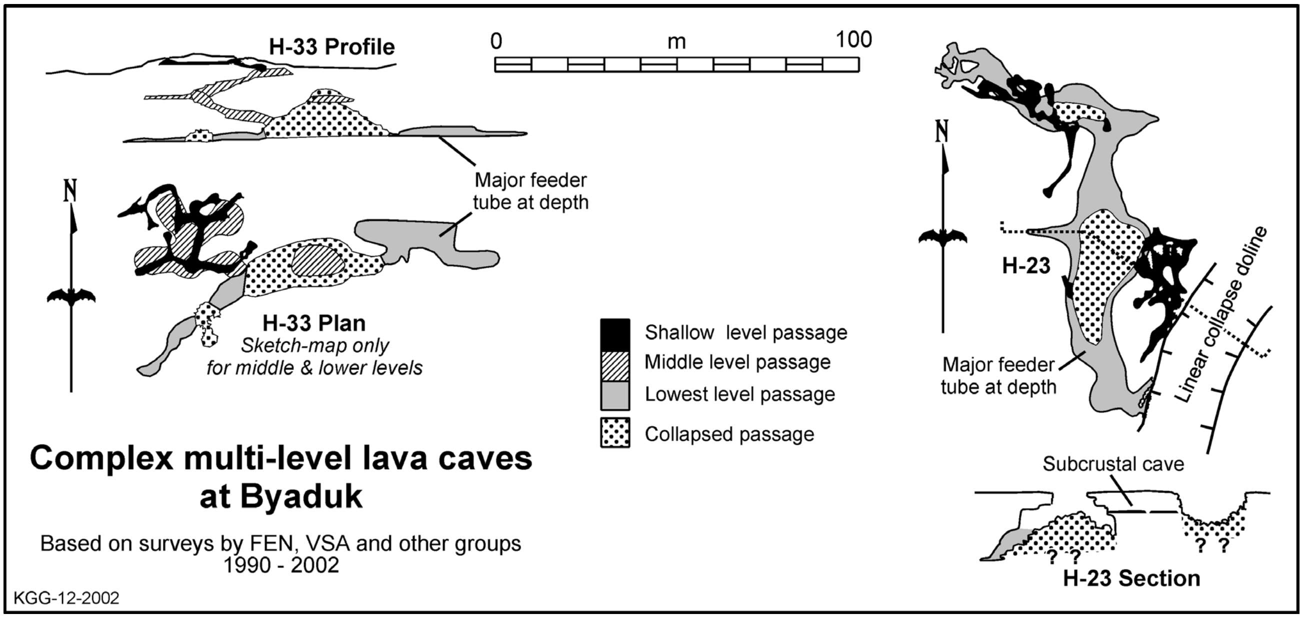

Figure 13. Complex, multi-level lava caves at Byaduk. Shallow subcrustal systems overlie large feeder tubes at depth.

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**.

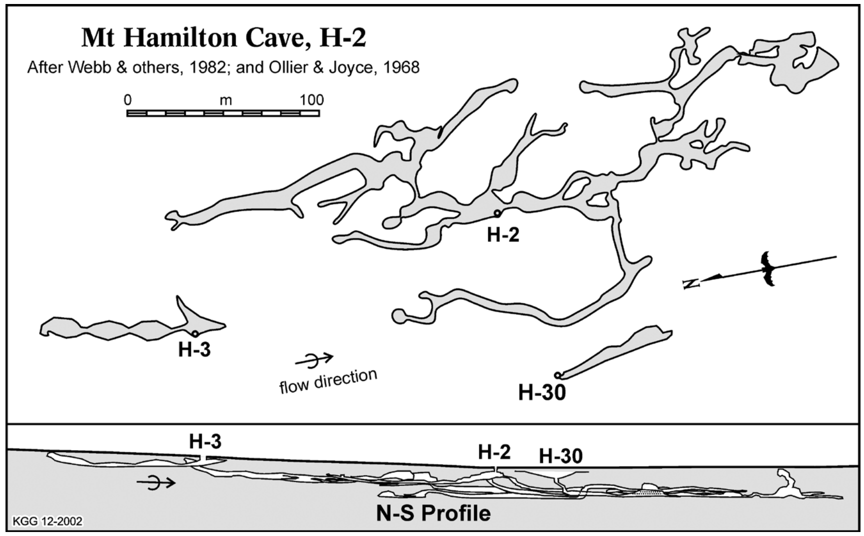

Figure 14. Mt Hamilton lava cave is an evolved system of larger, linear, bifurcating, subcrustal tubes.

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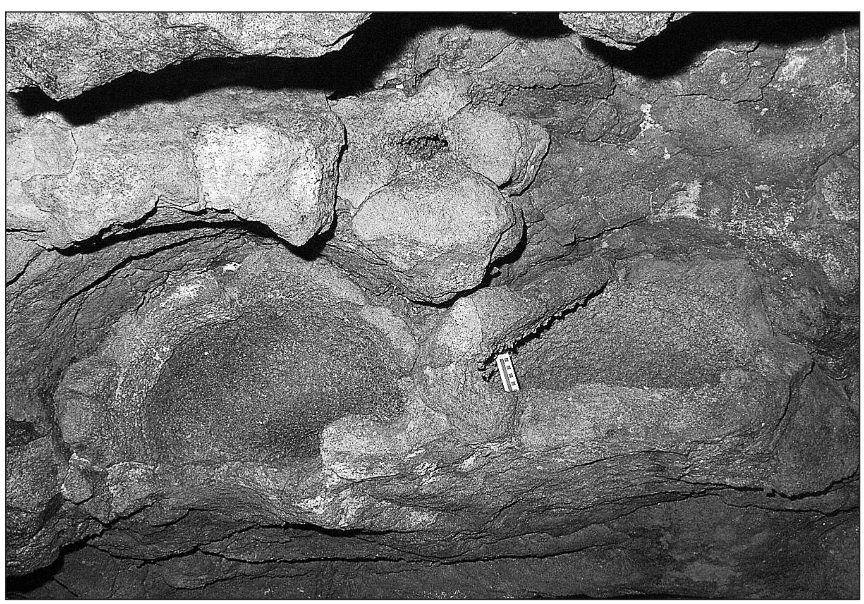

Figure 15. A pair of small 'proto-tubes', with 10 cm thick linings, exposed in the wall of a larger, more-evolved, tunnel in the Mt Hamilton lava cave. Scale bar is 10 cm.

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

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