LAVA TUBES

THE REMARKABLE UNDARA LAVA TUBE SYSTEM - A GEOLOGIST'S VIEW.

Anne Atkinson.

DEDICATION

To the memory of our dear son TOM
who built the first stairs into Barkers Cave
- and never lost his interest.

ABSTRACT

More than 20 arches and caves up to 13.5 m high and 1350 m long (but most less than 200 m) have been discovered in the remarkable Undara Lava Tube System. A total of over 6 km of tubes have now been surveyed and the first profile ever to depict a source volcano in addition to representative caves and arches is presented. Despite an age of 190,000 years, protection from weathering has allowed preservation of features usually seen only in younger or Recent lavas.

An estimated 23 km^3 of lava were erupted from the Undara Volcano to form a lava field 1550 km^2 in area. One of the flows extended over 160 km to become the longest flow in Australia and one of the longest flows in the world. This great length is attributed to very high effusion rate, favourable topography and lava tube efficiency. Temperature of eruption is estimated at approximately 1200°C, with no unusual viscosity.

The lava tube system, marked by caves, arches and long level ridges, extends for more than 100 km. The WALL SECTION is the first Earth feature considered analogous to sinuous ridges on the MOON. Other features are comparable with those described in lava tube systems elsewhere.

Oval to elongate depressions are adjacent to, or aligned with, the caves and arches. These are conspicuous on air photos as their "rain forest" vegetation contrasts sharply with the open forest of the surrounding country. The relationship of surface collapses to uncollapsed segments of the tube system is of particular interest.

Lava tubes are common in highly fluid volcanic eruptions but few have been recognised in older lava fields and their mode of formation has long been controversial (Atkinson, 1988, this volume).

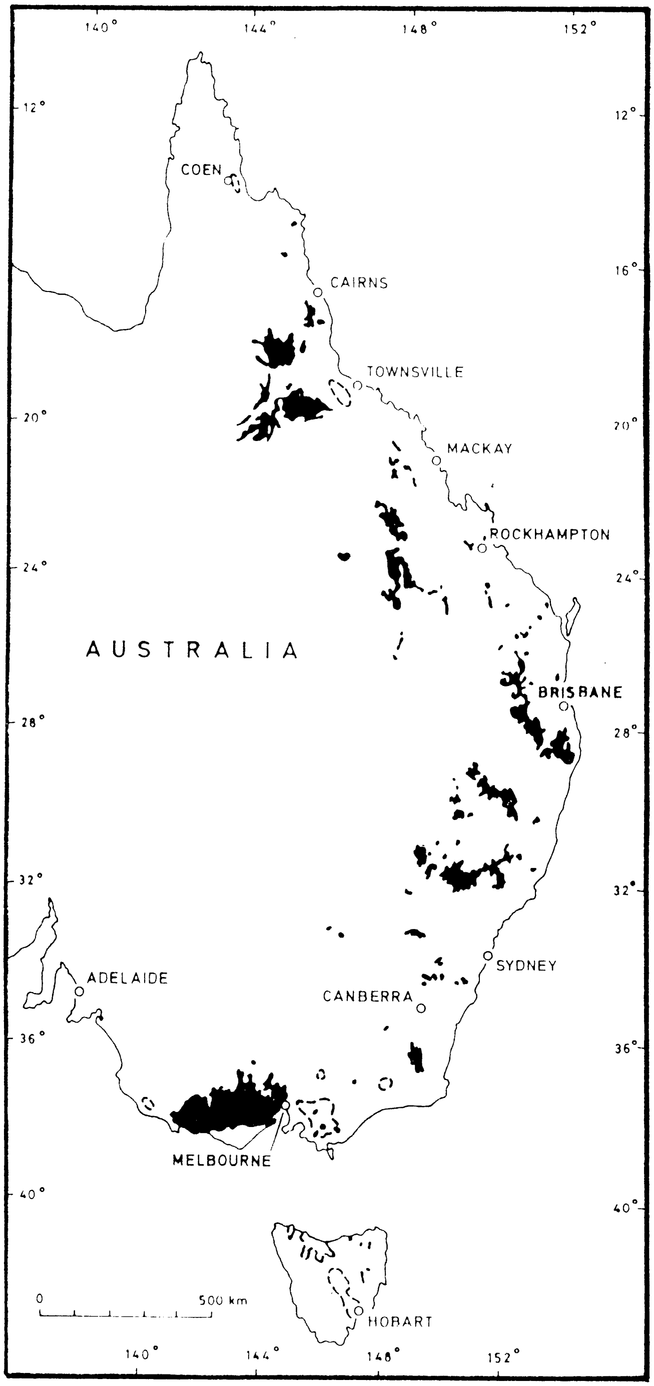


Figure 1: Cainozoic basalt outcrops of eastern and southeastern Australia, occur within 400 km of the coast and extend for over 4000 km. (Stephenson et al., 1980)

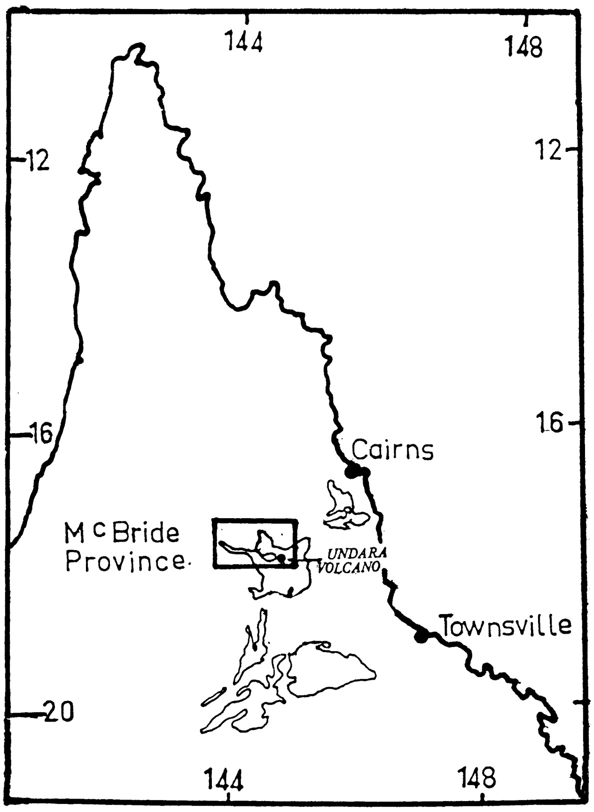


Figure 2: The main areas (provinces) of Cainozoic basalt outcropping in northeastern Australia. The boxed area is shown in Figure 6.

INTRODUCTION

Victorian lava tubes were the first described in Australia by Ollier and Brown (1965) and others. In North Queensland tubes are known in at least six localities (P.J. Stephenson, pers. comm., 1988) including Blackbraes and Spring Creek Stations and Barkers Crater area. Air photo interpretation indicates further tubes in the Toomba Flow (Nulla Province), and Kinrara Flow (McBride Province), in addition to those of Undara Volcano.

FIELD OBSERVATIONS - OVERSEAS

It has been the author's incredible good fortune on overseas visits, (1972, 1974 and 1980) to make brief observations, some in the company of noted geologists and speleologists, in the states of Washington, Hawaii, Oregon, Idaho, U.S.A., and in France, Sicily, Iceland, the Eolian Islands. As these observations are the basis for conclusions reached in this and the preceding paper they merit mention:

On the Island of Hawaii, in 1972, lava was flowing through a tube into the lava lake at Mauna Ulu and, in 1974, there was an eruption in the caldera of Kilauea Volcano. During a visit in 1980 no eruption was in progress but this and the previous visits afforded opportunity to study very recent flow features. Details of some are given in this paper.

LOCATION AND GEOLOGICAL SETTING

In eastern Australia, Cainozoic volcanism extended more than 4,000 km (Fig. 1), Stephenson, Griffin and Sutherland. In North Queensland, within 200 km of the east coast, there are five major areas, or provinces (Fig. 2) and the Undara Volcano is situated near the centre of the McBride Province (Fig. 2). The province covers approximately 5000 km^2 and topographically forms a broad dome. Of over 160 vents, the majority are in the central region and only one volcano, Kinrara, is younger than the Undara Volcano (Fig. 3).

The Yaramulla Section, in the western branch of the Undara System, contains most of the caves and arches and is in proximity to the largest granite inlier.

Figure 3: Aerial view of Undara Crater, 340 m across, looking West. The tube system commences in the line of depression running away from the crater towards the right. Photo: Tom Atkinson.

PREVIOUS INVESTIGATIONS

Unlike the American Indians whose pictographs and ancient fires give evidence of the use of lava caves from prehistoric times, local aborigines state that their people would have avoided such places. No drawings or evidence of fires have been found in the caves - only a few artifacts at one cave entrance. Two caves, Barkers (Figs. 4a and 4b) and Road Cave (Fig. 17), have been known for more than eighty years. The former was mapped by Shannon in 1969 but most of the caves were discovered, entered and mapped only in the course of the author's work, 1972-74.

TWIDALE (1956) in discussing the distribution of volcanic centres in the McBride Province noted that there were only two lineaments. Apparently through inadequate field investigation he incorrectly interpreted the aligned collapse depressions as "a clear arcuate fissure .... with a centre of eruption at its southeast end".

BEST (1960) and WHITE (1962) were the first to recognize the lava tube system. Without opportunity for detailed investigation, they interpreted the pattern of collapse features (Figure 5) as a collapsed lava tunnel, with north and west branches. SHANNON made the first lava tube survey in the system (Barkers Cave) in 1969.

Following the UQSS visit to the area in 1977, GRIMES (1977) made a very useful compilation of data from previous studies of the major known caves and these were published by MATHEWS (1988) who entered the cave names and brief descriptions in the ASF's Karst Index. IRWIN and GODWIN surveyed The Wind Tunnel and Inner Dome Cave this year.

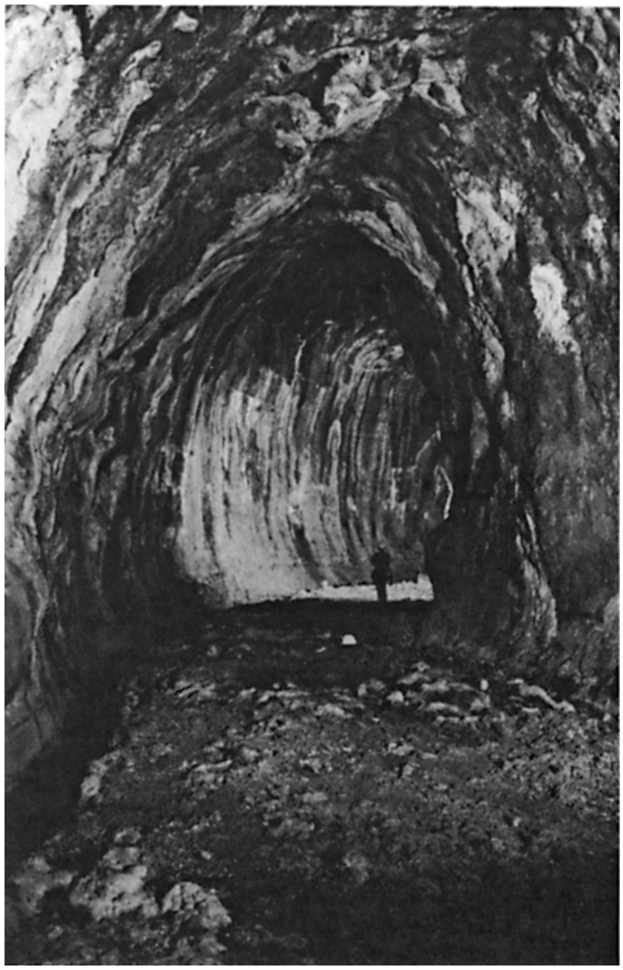


Figure 4a: Barkers Cave, 50 m from its entrance. Note gutter on left and lava level lines evident almost to the roof on distant wall. The lava tube height is 13.5 m at this point - the highest measured in the System. Granite hills are in closer proximity here than at any other location along the tube System. The relationship is interpreted between this and the height of the lava tube. Photo: H.J. Lamont, J.C.U.N.Q.

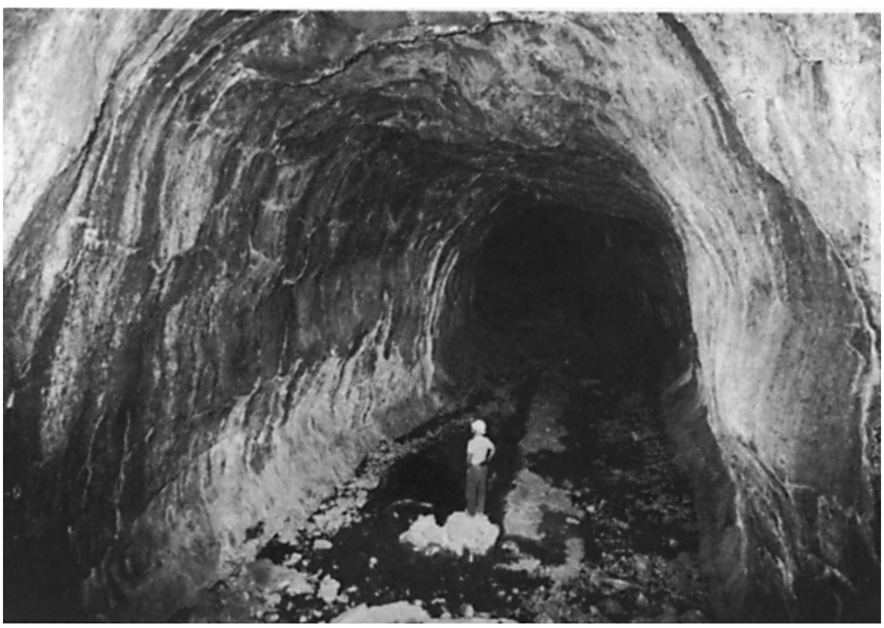


Figure 4b: Barkers Cave, viewed from the entrance collapse. Some of the original arched floor is exposed and has a distinctive "rope" structure. The distant cross section is almost circular. It is noted with interest that a distinctive pattern of vesicles on the large block in the centre foreground can be matched to one in the cave "roof" immediately above it. Photo: H.J. Lamont, J.C.U.N.Q.

Figure 5: Aerial view of aligned collapse depressions near Yaramulla, looking East. Kalkani, a pyroclastic cone not connected with Undara, is on the left. Photo: H.J. Lamont, J.C.U.N.Q.

AIMS OF 1972 - 1974 INVESTIGATION

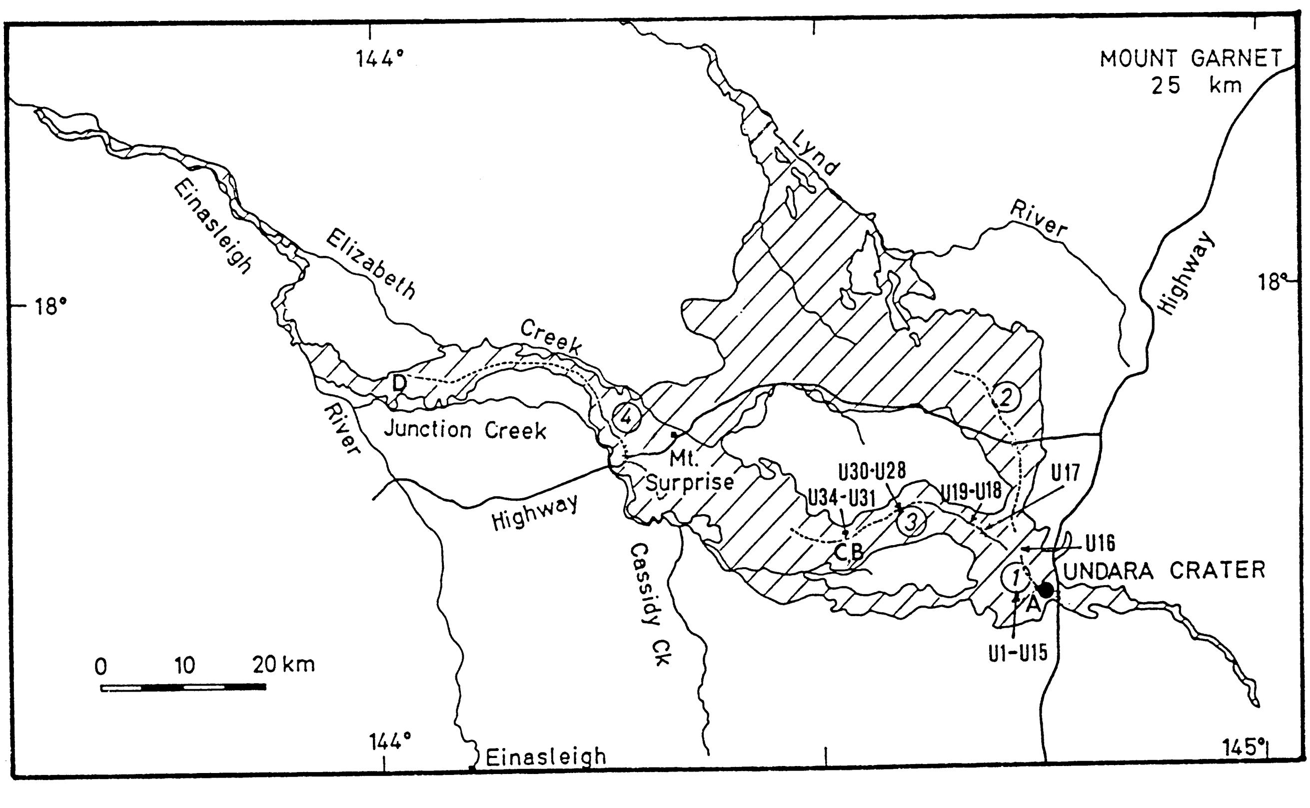
The aims of the 1972 - 1974 investigation were twofold:

1. At three locations (Figure 6), namely:
   a). close to the crater;
   b). maximum distance from it;
   c). at an intermediate location -

- to measure and map (Fig. 7) representative caves in order to establish any relationships between shape, size and distance from the source volcano. This would provide the data required to draft a longitudinal profile (Fig. 8) through a source crater as well as representative caves. No similar project had previously been attempted anywhere in the world (R. Greeley, pers. comm., 1974).

2. To discover evidence which would confirm or refute the mode of formation postulated by Ollier and Brown (1965) for lava caves in Victoria, by Hatheway (1971) for caves in New Mexico and by Greeley and Hyde (1972) for caves on Mt St Helens, U.S.A.

Figure 6: The Undara lava field. Circled numbers denote sections of the lava tube system referred to in the text: 1, Crater Section; 2, North Section; 3, Yaramulla Section; 4, Wall Section. Other numbers are locations of cave entrances as shown in Figure 8. Letters "A" to "D" denote locations of specimens chemically analysed (Table 2)



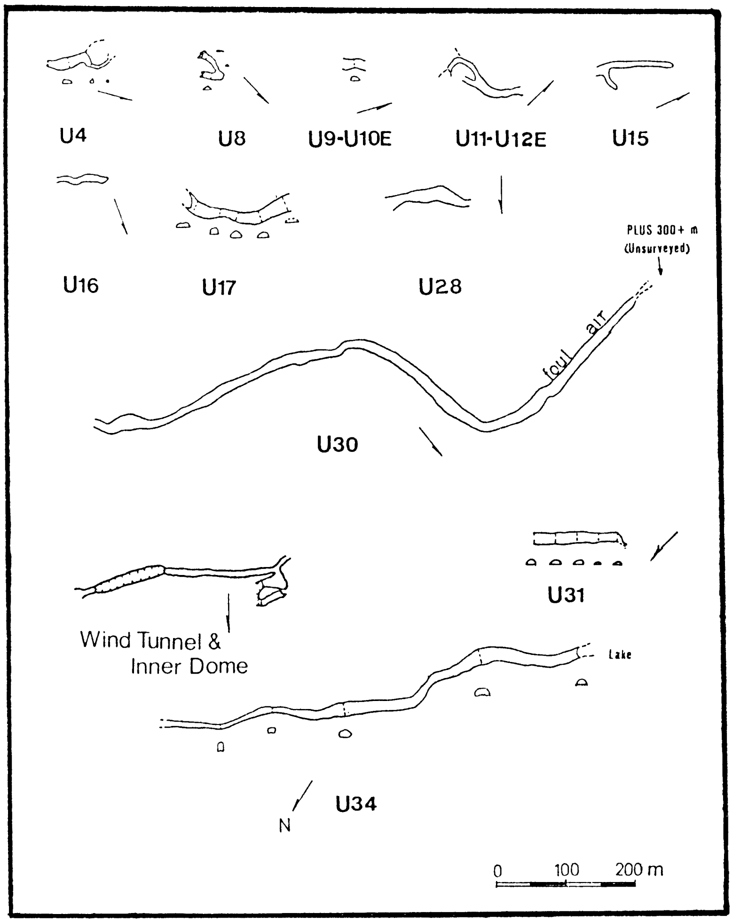
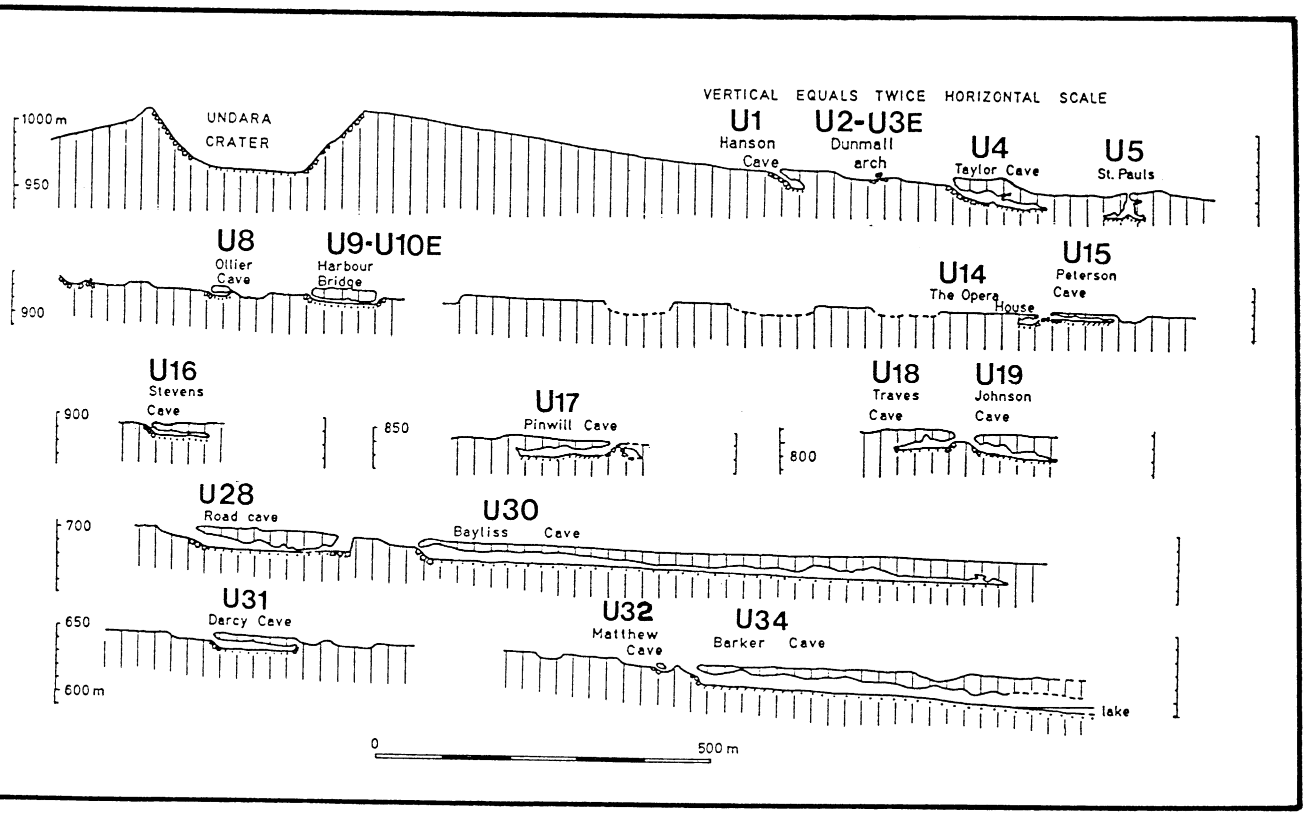


Figure 7: Maps of selected caves, with some cross sections. In all cases, lava moved from left to right. Localities - see Figure 6; cave names, Figure 8. Cave U11-12E is Greeley Cave; The Wind Tunnel and Inner Dome plans are shown. The extension (1987) of over 350 m of Bayliss Cave, now measured to over 1350 m, makes it the longest lava tube recorded in Australia. The extension is not shown as it has not yet been surveyed.

METHODS OF STUDY

Caves (locations, Fig. 6) and some collapse depressions (Fig. 5) were measured by tape, prismatic compass and Abney level from a datum approximately 10 cm square, painted on a conspicuous block at the base of each entrance collapse. At the suggestion of NASA geologist Greeley, helium balloons were used to measure cave heights. A narrow ribbon was marked and rolled on to a fishing reel and just prior to use a strong balloon was filled with helium and attached to the ribbon. Balloon gas was inadvertently supplied on one trip and found unsatisfactory. The length and inclination/s of entrance collapses were measured. Finally, a surface datum was painted to correspond as closely as possible with the cave datum. To ascertain roof thicknesses a surface traverse was then made from this point on the same bearings as the cave traverse, steel fence posts being left at most stations for easy future reference.

Figure 8: Longitudinal profiles of various caves down flow from Undara Crater. The A.S.F. Cave Register numbers are shown. Floor symbols: sediment (dotted), ropy lava (lined) and collapse blocks.



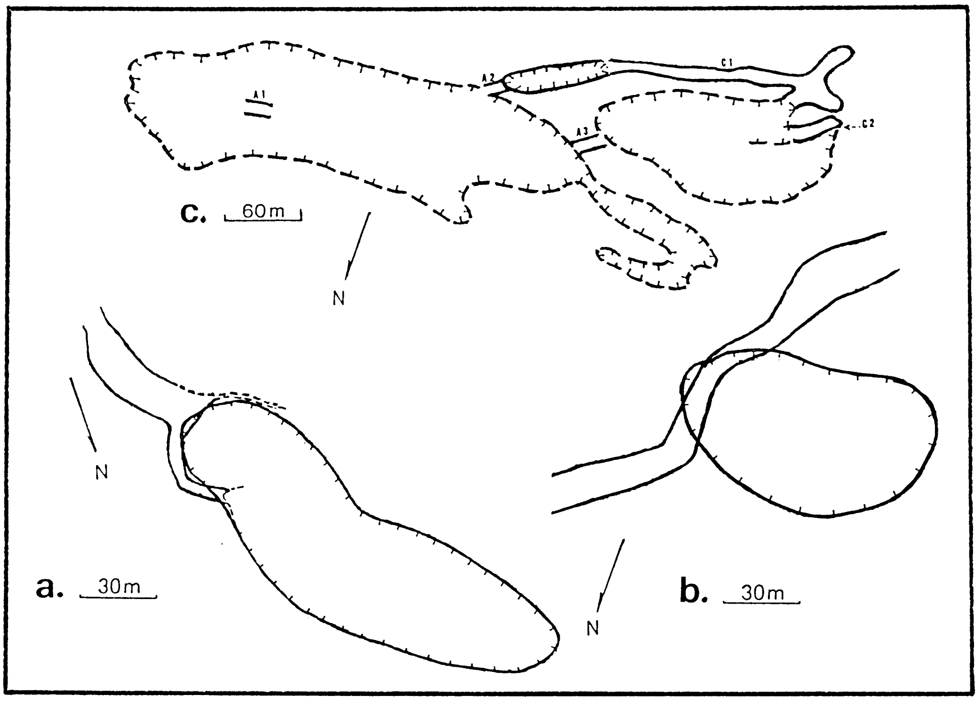


Figure 9. Relationship between surface depressions and caves: (a) Taylor Cave; (b) Barkers Cave; (c) The Wind Tunnel and Inner Dome Caves.

When no clear picture emerged re mode of formation of the tubes and because of their close proximity to some caves, two wide depressions (Figs. 9a and 9b) were investigated in 1973 by Atkinson and assistants. Similar depressions were mapped at Wind Tunnel by Irvin and Godwin in 1988 (Fig. 9c).

The method of study most significant to this investigation was, however, OBSERVATION OF FLOWING AND YOUNG LAVA. On the Island of Hawaii, in addition to traversing young lava fields (some still hot!), in the company of G.A. Macdonald and D.W. Peterson, Scientist-in-charge and staff of U.S.G.S. Volcano Observatory, the author was able to observe the following during eruption (Mauna Ulu, 1972; Kilauea Caldera, 1974):

- lava flowing in a channel;
- channel "roofing"; rafting of "roof" segments; jamming and accumulation of "roof" segments;
- lava flowing in a tube with lavicicles forming and dripping from "roof";
- temporary flow stoppage with cooling and darkening of flow front, followed by inflation and continued flow;
- degassing of flow and inflation of bubbles (less than 25 cm) of volcanic gas on the surface of channels;
- formation of spatter cone;
- formation of tree moulds;
- and other wonders.

UNDARA VOLCANO AND ITS LAVA FIELD

The Undara lava field covers 1,550 km² in the NW quadrant of the McBride Basalt Province (Fig.2). Its impressive crater (Fig. 3) is 340 m across and 49 m deep with inner slopes of up to 40°. The low rim rises only 20 m above the surrounding lava field. Outward slopes from the rim vary from 30° to 5° on the NW side. Although the major outflows occurred to the North and NW no evidence of a lava tube has been found there, despite prolonged search.

The crater walls are mainly covered by angular blocks (up to several meters across) of **highly vesicular to massive basalt.** Several indistinct terraces may mark former levels of a lava lake. Part of the crater floor is covered with fine red soil containing fragments of scoriaceous material and a small area of smooth pahoehoe basalt.

Undara Volcano, 1020 m, is the highest point in the McBride province. It erupted **190,000** years ago (Griffin and MacDougall 1975) and lavas flowed from it in all directions but mainly to the NW (Fig. 6). The major flow there reached and followed a precursor of Junction Creek and Einasleigh River for a total length of 160 km to become the longest lava flow in Australia and one of the longest flows in the world (Walker, pers. comm.,1974). Another flow, approximately 90 km long, entered the Lynd River (Fig. 6).

General thickness of the Undara lava field is estimated from 5 m near the edges up to 20 m or more in the thickest parts. Along "The Wall", West of Mt. Surprise (Figs. 10a and 10b), the flow could be up to 40 m thick but this is restricted to the width of "The Wall". Exploratory drilling on the north side of "The Wall" showed basalt depth of 25 m. Thus, if an average thickness of 15

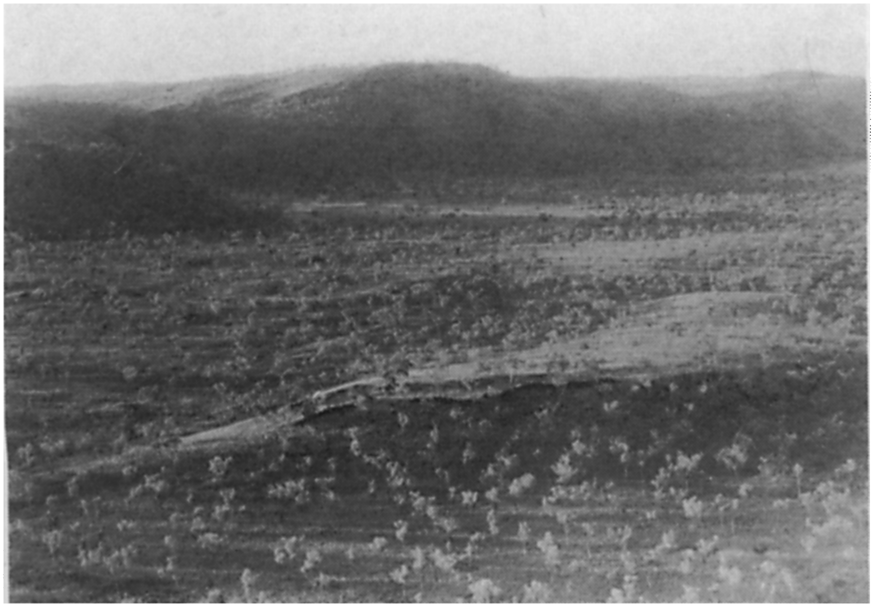


Figure 10a. Oblique aerial view of "The Wall", from the South. Note mega-columns flanking central collapsed area at the termination. Photo: Jon Edmonds

m is estimated for the whole flow, the total volume of lava erupted from the Undara Volcano is approximately **23 km^3.**

It is of interest to note that where rock is exposed near the axis of the flow, polygonal mega-**jointing** (Spry, 1962) up to 1.75 m, is evident from the crater to the termination of "The Wall". The author has not examined the flow beyond this point but the constant size of jointing over a distance of 90 km would seem to be significant.

The Undara lavas were erupted at **temperatures ranging from 1175° C to 1220° C.** They do not appear have had unusual viscosities (Atkinson et. al., 1975) which accords with the conclusions of Walker (1973) that very long lava flows reflect continued high effusion rates rather than unusually low viscosity. Stephenson and Griffin (1976a) reached a similar conclusion in a study of eight long basaltic flows in Queensland.

The main lava tube system extends North and then NW from the Volcano. For convenience four sections (Fig. 6) are named:

1. **Crater Section** - extending North from Undara crater for 4 km; average slope 1.0°.

2. **North Section** - continuing a further 16 km possibly more than 28 km; average slope 0.5°.

3. **Yaramulla Section** - extending West from the Crater Section for over 35 km; average slope 0.7°.

4. **Wall Section** - approximately 35 km in length; an almost continuous narrow ridge, known locally as "The Wall", characterizes the western end of the system; average slope 0.09°.

The caves and arches occur in the Crater and Yaramulla Sections. In the North Section no caves have yet been

Figure 10b. Termination of "The Wall" viewed from the North. Note the mega-columns on horizon. Photo: Tom Atkinson.

discovered but a line of collapse depressions suggests the presence of a lava tube.

CAVES, ARCHES AND COLLAPSE DEPRESSIONS

The lava caves and arches in the Undara system are very well preserved in spite of their age (190,000 years). Most of the known caves, with total length exceeding 6 km, were mapped in detail by Atkinson and assistants (1972-1974). Examples are given in Fig. 7 and basic measurements are listed in Table 1. (Detailed maps are available on request).

Most of the caves are elongate in the direction of the main flow. Except for short distances, the original floors of caves with up-flow entrances are covered by later silty sediment. The maps and cross-sections (Fig. 7) and longitudinal profiles (Fig. 8) indicate the variation in shape, size and "roof" thickness.

Although **most caves terminate down-flow** with collapses or a gentle downward curve of ceiling to silt floor, there are exceptions described in a later section. Barkers Cave has been explored only as far as a lake, the cave ceiling steadily declining to water level (Figs. 8 and 11). Several caves have down flow entrances and have little or no silt on their floors. Apart from collapse terminations found in some of these up-tube caves, two caves, Pinwill and The Opera House (Figure 12) have abrupt walls across the cave.

Cave floors represent the final flow in the tube. Some floors are almost flat, others are arched, as near the entrance to Barkers Cave, (Fig. 4b) and in some caves there are pronounced marginal gutters (Fig. 4a).

Where exposed some floors show interesting variations: the best examples of ropy lava being in Pinwill Cave and the almost inaccessible east Chapel of St. Paul's. In a central position near the entrance to Barkers Cave, crust fragments, approximately 8 cm thick, have been rafted at varying oblique angles (Figure 13) in a manner similar to ice slabs on a frozen river. In Peterson Cave there is a small but unique floor surface: lava drops from "roof" re-melt appear to have pitted the floor as rain drops pit a muddy surface.

TABLE 1 - UNDARA LAVA TUBE SYSTEM - CAVE DIMENSIONS

* Atkinson, Griffin and Stephenson 1975. # Estimate only.

Cave	Register Number (ASF)	Length (m)	Maximum Height (m)	Maximum Width (m)
* Hanson	U-1	40	3	12
* Dunmall Arch	U-2, U-3E	-	2	6
* Taylor	U-4	108	10.8	16.3
* Peter	U-	13.8	3.8	9.9
* St. Paul's	U-5	8	-	-
* Sarah	U-6	-	-	-
* Ollier	U-8	49.4	3	10.4
* Harbour Bridge	U-9, U-10E	35	5	14.3
* Greeley	U-11, U12E	103	3.8	12.4
* Frances	U-13	-	-	-
* Opera House	U-14	30	-	-
* Peterson	U-15	102	3.7	17.1
* Stevens	U-16	70.4	3.0	8.8
* Pinwill	U-17	150	8.9	21.0
* Traves	U-18	67	10.6	14.0
* Atkinson (formerly Johnson)	U-19	101.2	7.8	28.0
Wind Tunnel and Inner Dome	U-	467	-	20.0
Arch 1	U-21	160	5+	25.0
Arch 2	U-22	-	10	25.0
Arch 3 (SW)	U-23	50	-	-
Arch 3 (SE)	U-	100	-	-
Picnic 1	U-24	420	-	-
Picnic 2 (NE)	U-25	45	-	-
Dave 1	U-26	50	-	-
Dave 2	U-27	27	-	-
* Road	U-28	220	9.4	21.2
* Bayliss	U-30	1350+(1988)	11.5	18.9
Nasty	U-25	100 #	6.0 #	15.0 #
* Darcy	U-31	99	6.3	16.3
* Matthew	U-32	40	-	-
* Barkers	U-34	905 (1968)	13.5	19.8

Figure 11: Terminal lake, Barkers Cave. Photo: R. Dutton.

On the walls and roof of most caves there is a lava lining, typically a single layer up to 20 cm. In some places linings approach one metre in thickness. At various locations the tube lining has fallen off the wall to expose the host lava behind it. The lining is sometimes multi-layered, the best example being in Pinwill Cave, where fifteen layers, 2-4cm thick, are revealed at one location (Fig. 14b). At the entrance to the same cave a thin slab of lining, "The Table", (? showing slight plastic deformation) has become dislodged and now rests in a near-horizontal position (Fig. 14a). Most walls feature a glazed surface, with drip and dribble structures resembling cake icing (Fig. 15). In places there are lavicicles (lava stalactites), commonly 2-4 cm, rarely up to 8 cm, suspended from the roof and wall cavities (Fig. 16). Lava stalagmites are rare.

In most caves, **lava level lines and ledges** are present, representing fluctuating lava levels. The highest levels are usually evident very close to the full height of the roof, the best examples being in Taylor, Road and Barkers Caves (Figs 4a, 17 and 18). Within caves, these lines and ledges had been observed by torch light and with single flash but never with the clarity revealed in the Lamont photographs, particularly Figure 4a. The lava level lines usually slope down-tube at low angles, presumably equivalent to the original tube slope.

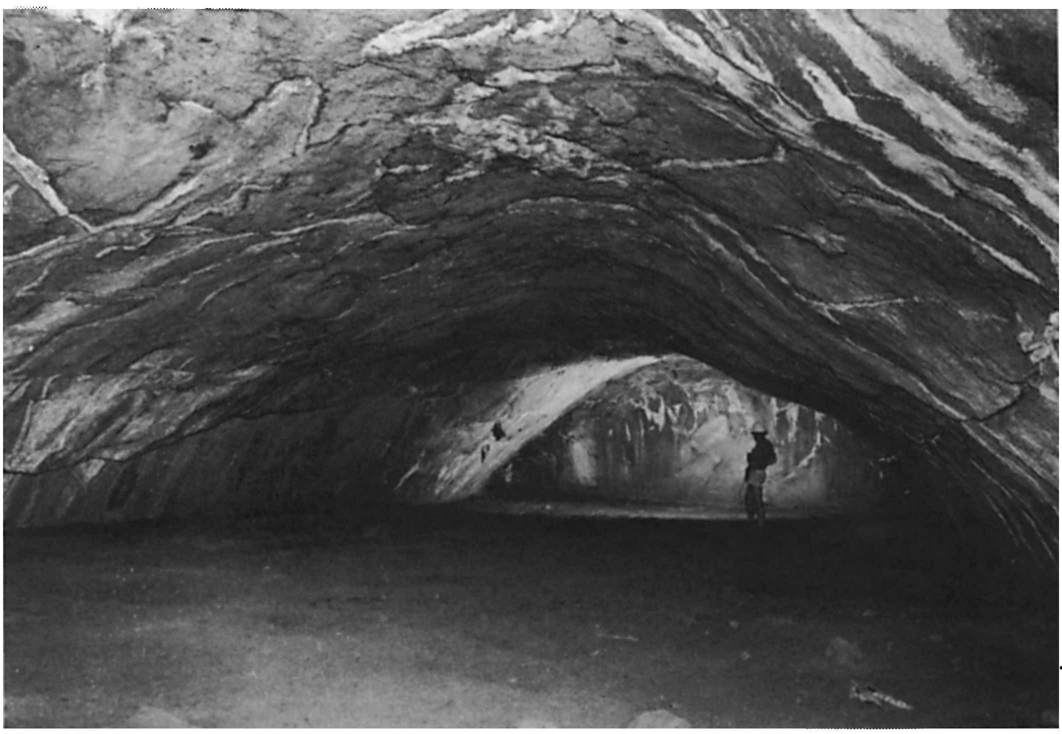


Figure 12: Termination of The Opera House, (note "wings"). Entrance is downflow. Photo: H.J. Lamont, J.C.U.N.Q.

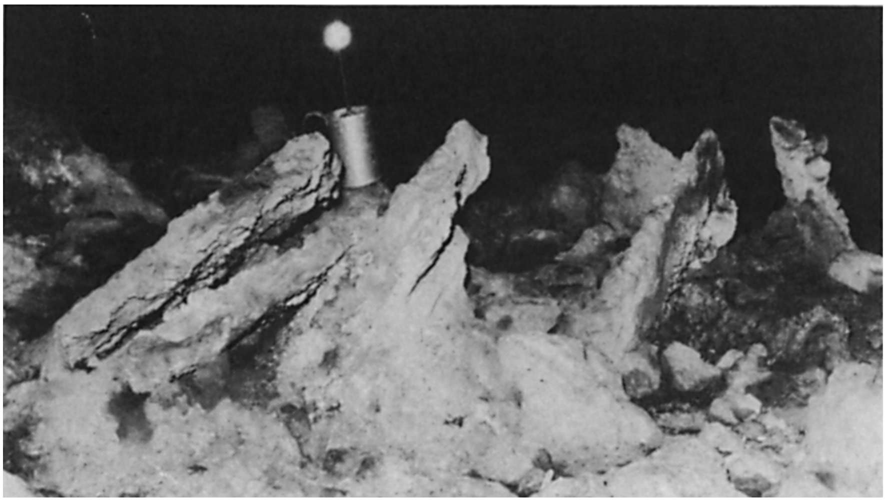


Figure 13: "Rafted" blocks of crust of the final flow have jammed at various angles. Location: Barkers Cave. Photo: V.G.Atkinson.

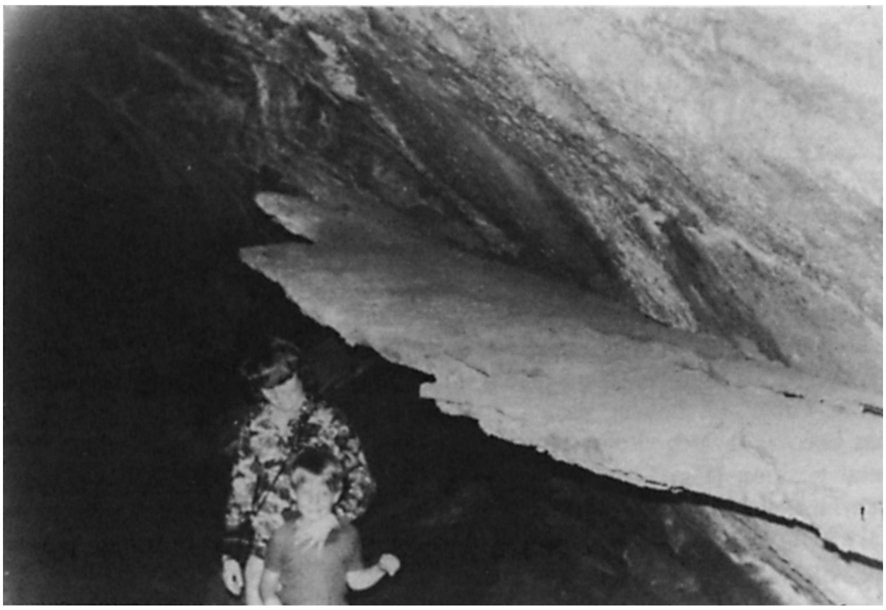


Figure 14a: Thin sheet of lining near the entrance to Pinwill-Cave. ? shows a degree of plastic deformation. Photo: V.G. Atkinson.

Figure 14b: Multi-layered lining in Pinwill Cave. Up to fifteen layers are exposed at this location. Photo: V.G. Atkinson

Figure 15: Lava dribbles in Barkers Cave. Photo: H.J. Lamont, J.C.U.N.Q.

The "**pavements**" (here-named) in Taylor Cave (Figure 18) are evidence of prolonged flow at a constant level. In the same way as deposition occurs on the convex bank of a fluvial river, lava consolidates where rate of flow is less against the convex bank. This is well illustrated in the Hawaii Volcanoes National Park film: Anthology of Hawaiian Volcanoes, where flow rates can be observed to vary laterally across the flow from the fountaining at Kiluea Iki (1969).

To date no caves have been discovered in the Wall Section of the Undara Lava Tube System but it merits mention here as the first Earth volcanic feature considered analogous to extra-terrestrial sinuous ridges (Greeley, pers. comm., 1972). This section of the system consists of a very long narrow ridge (Figs. 10a and 10b) that rises up to nearly 20 m above the general level of the flow and can be traced for 37 km. The upper surface of the ridge is relatively flat and varies in width from 70 m to 300 m. Its down-flow slope averages only 1.72 m per km, with occasional undulations. The side slopes of the ridge are up to 29°. There are several depressions, within 2 km of the termination of "The Wall". One of these may represent a collapsed lava pond which breached the wall. Another, Edmonds Lake, is a narrower, axial oval depression which is interpreted as a collapsed segment of the tube.

The significance of "The Wall" is uncertain. The tongue of lava surmounted by the ridge, certainly flowed down a precursor of Junction and Elizabeth Creeks. That the narrow ridge is localized above a former stream bed has been proved by very successful water bores in its vicinity. The nearly level course of "The Wall" and the fact that it delivered sufficient lava to flow a further 70 km beyond its termination (without further "Wall" features), suggests it had special features - it probably operated as an extensive lava tube.

COLLAPSE DEPRESSIONS AND THEIR RELATIONSHIPS TO CAVES

The following measurements emphasize a clear distinction between the collapse depressions associated with the Undara caves:

caves - up to 20 m wide;
narrower depressions - 30-60 m;
wider depressions - 50-100 m.

The **narrower depressions** commonly give entry to caves. This relationship allows the deduction that they formed by the collapse of segments of the tube. One or two "rain forest" trees almost conceal entrances to some caves but other vegetation within these depressions differs little from that of adjacent open forest. They are therefore difficult to see on air photos.

Wider depressions form a strong linear pattern, made conspicuous by dark green "rain forest" vegetation (Fig. 5). (See also Fig. 1c, Atkinson 1988, this volume). These depressions seldom give access to caves and they have

Figure 16: Lavicicles up to six cm long in Bayliss Cave. Photo: V. G. Atkinson.

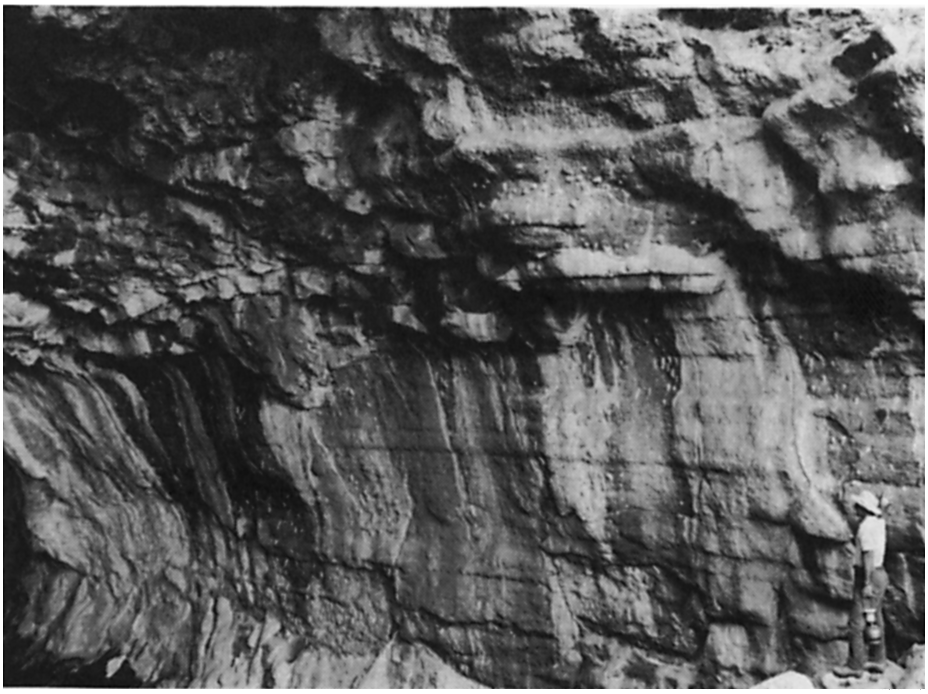


Figure 17: Road Cave. Lava level lines extend from floor to "roof" of this cave. They are the most distinctive yet discovered in the System and are more easily studied than at other locations as they are in daylight at the eastern entrance. Photo: H.J. Lamont.

have features which distinguish them from the generally narrower depressions formed by lava tube collapse. The large depressions vary in shape from circular or oval, for example Barkers Depression (Fig 19), to elongate (up to 900 m) in the direction of flow, except West of Barker's Knob, where their erratic shapes may indicate that the flow traversed marshy ground.

Rims of the wider depressions are characteristically elevated, suggesting that they represent former lava ponds. Rims and slopes of the depressions are made up of a jumble of blocks of various shapes and sizes (Fig 19b). Local areas of blocks (Fig. 19c) are interpreted as segments of lava pond crust, because they have flat upper surfaces with low vesicularity (Fig. 19d). This conclusion was drawn after discussion with R. Greeley and D. W. Peterson (1972 and 1974) from similarity to those depicted in the collapsed lava pond, Oregon, U.S.A. (Figures 21a and 21b, supplied by R. Greeley). Near the base of some depressions lower surfaces of some blocks are moulded and occasionally have fragments embedded. Rare blocks retain an original ropy lava surface.

During the 1972-1974 investigation two caves with adjacent wide depressions were mapped in detail (Figs. 9a and 9b).

In Taylor Cave, 60 m North of the entrance there is a long, deep depression directly in line with the initial cave trend. The cave might well have been expected to terminate in a collapsed closure beneath the depression, but this is not the case. Close to the edge of the depression the cave branches and the two passages roughly

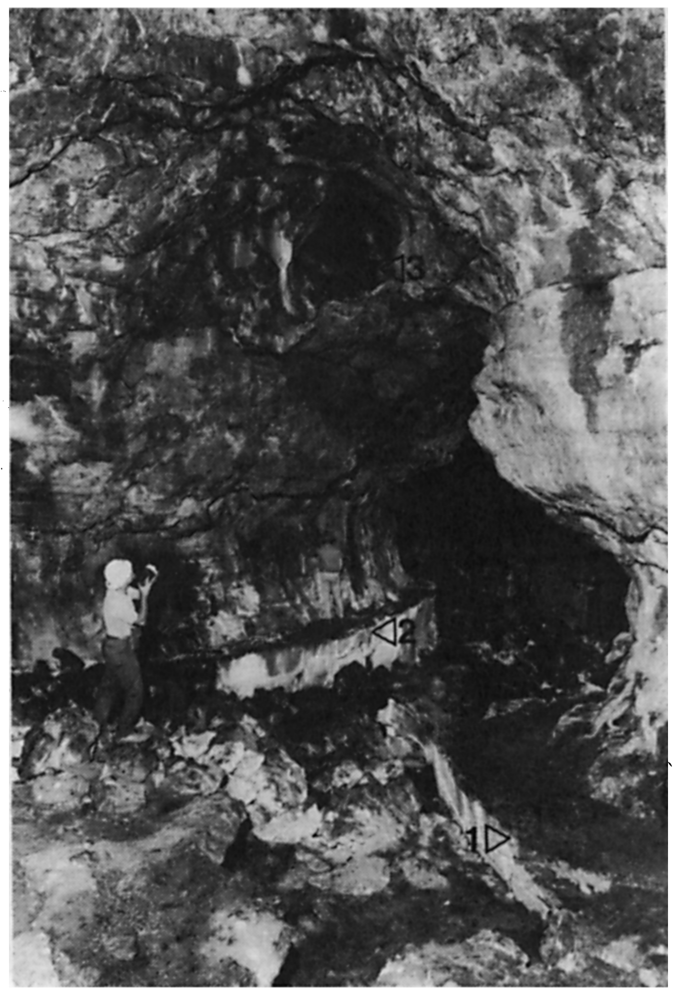


Figure 18: Taylor Cave. The prominent "pavements" (1 and 2) are evidence of an extended period of constant rate of flow. Solidification has been greatest at the apex of convexity, as in a fluvial river. There is a cylindrical opening (3) in the "roof" above the figure. The location of this opening suggests that some lava, ponded in Death Adder Depression, (in alignment to the North), may have drained back into the tube through this conduit. Photo: H.J. Lamont, J.C.U.N.Q.

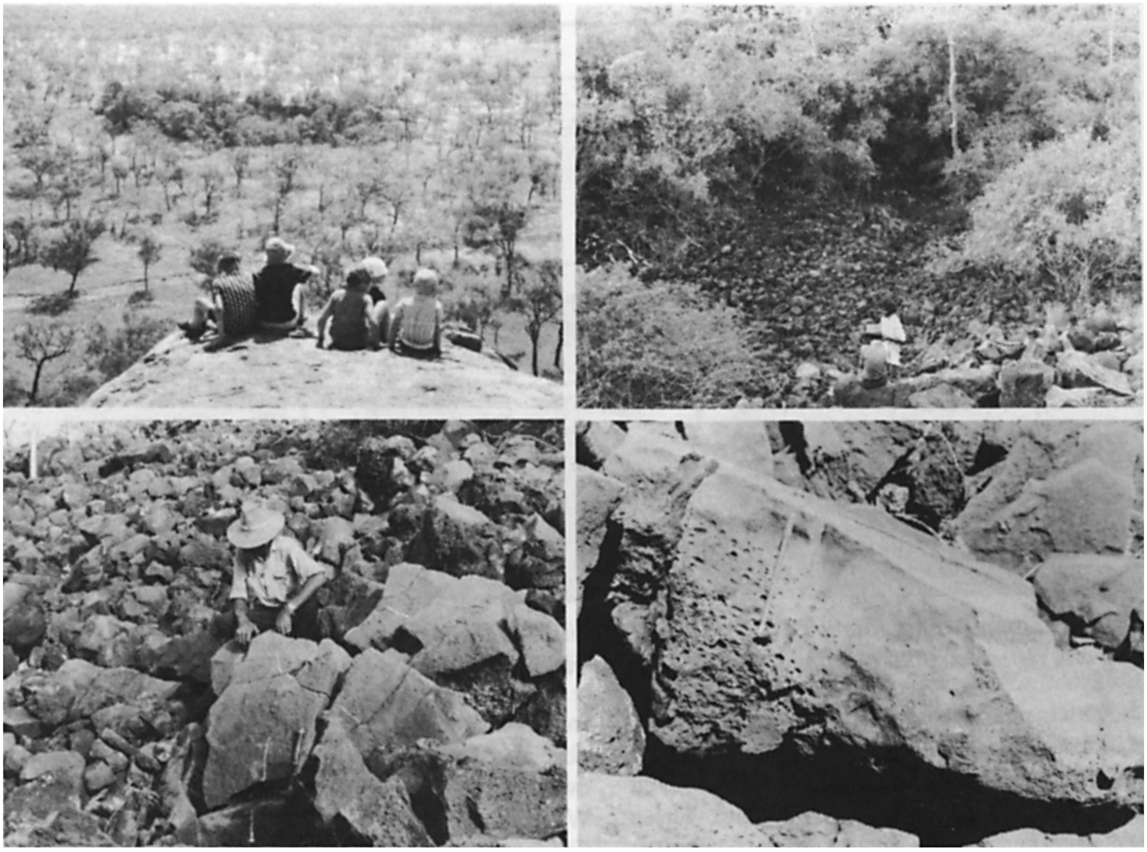


Figure 19: Barkers Depression, a drained lava pond adjacent to Barkers Cave. (a) Viewed from Barkers Knob, a granite approx 500 m to the South; (b) View from inside looking South-West; (c) "Mosaic" of crustal blocks at steep angles on inner western wall. Some corresponding cracks in adjacent blocks have been marked with chalk for clarity; (d) Crustal block showing variation in vesicularity. In the degassed upper surface vesicles are microscopic to small, contrasting sharply with those of the lower surface.

follow its outer margins. Each branch closes to an inaccessibly small tunnel, and near its termination the east branch bifurcates again. The lava level lines in the east branch are nearly horizontal and follow along both sides of the cave and across the wide pillar at the end.

The relation of the Taylor Cave passages to the depression suggests the collapse interfered with the functioning tube. The location of the cylindrical vent above the person in Figure 18 suggests that some of the ponded lava drained back into the main tube through it. It seems likely that "roof" collapse took place into a wide running tube, which bifurcated around the constriction but was constricted and finally dammed. At a late stage, the dam of lava inside the tube was drained through minor outlets.

Barkers Cave changes its course to go around the major depression 220 m West of the cave entrance (Fig. 9b). A small cavity occurs in the cave roof close under the eastern end and there are circular depressions up to 1.5 m across on the inner slope of the depression. These may be evidence that the depression drained and collapsed into a flowing tube, which adjusted its course around the collapse obstruction.

Wind Tunnel (192 m) was discovered in 1988 by Irvin and Godwin. An interesting relationship between the cave and associated collapse depressions is depicted in Fig. 9c. At the eastern side of an aligned depression, entry was gained to an arch 20 m long. At the western end the cave branched in three directions and the northern branch opened into a wide depression. No exit was found in the northwest and southwest branches of the cave.

Figure 20, from Macdonald and Abbott (1972), shows Halemaumau in Kilauea Caldera, Island of Hawaii, as an active lava lake in 1894. Similarity in appearance of its raised rim and those of wider depressions in the Undara flow, particularly Barkers depression, gave the author the first clue as to their origin.

Figure 21, supplied by NASA geologist, R. Greeley, shows a "mosaic" of blocks, which he interpreted as former crust of a drained lava lake in Recent lava in Oregon, USA.

Figures 20 and 21 and discussion with D.W. Peterson were thus of great interest and significance in aiding interpretation of the wider depressions in the Undara Flow. They are interpreted as collapsed lava ponds. D.W. Peterson et al. (op. cit.) have observed in Hawaii

Figure 20: Halemaumau, within Kilauea Caldera, Is. of Hawaii, 1894. The lava lake is held in a ring shaped levee built by spattering and repeated small overflows. (an anonymous etching reproduced by Macdonald and Abbott, 1972).

that lava becomes ponded in specific areas, particularly where the slope is small. Once formed, the ponds tend to perpetuate themselves during the life of the flow, even when the flow front has advanced far beyond. These ponds crust over, and molten lava beneath the crust is interconnected with lava tubes that had been developing in the flow both upstream and downstream from the pond.

In Hawaii, the crusted surfaces of these ponds have been observed to subside, as the rate of flow the system dwindles and ponded lava drains back into the tube. When he visited Undara in 1976, D.W. Peterson was delighted to find that all features that he observed in the wide collapses confirmed the origin he had suggested.

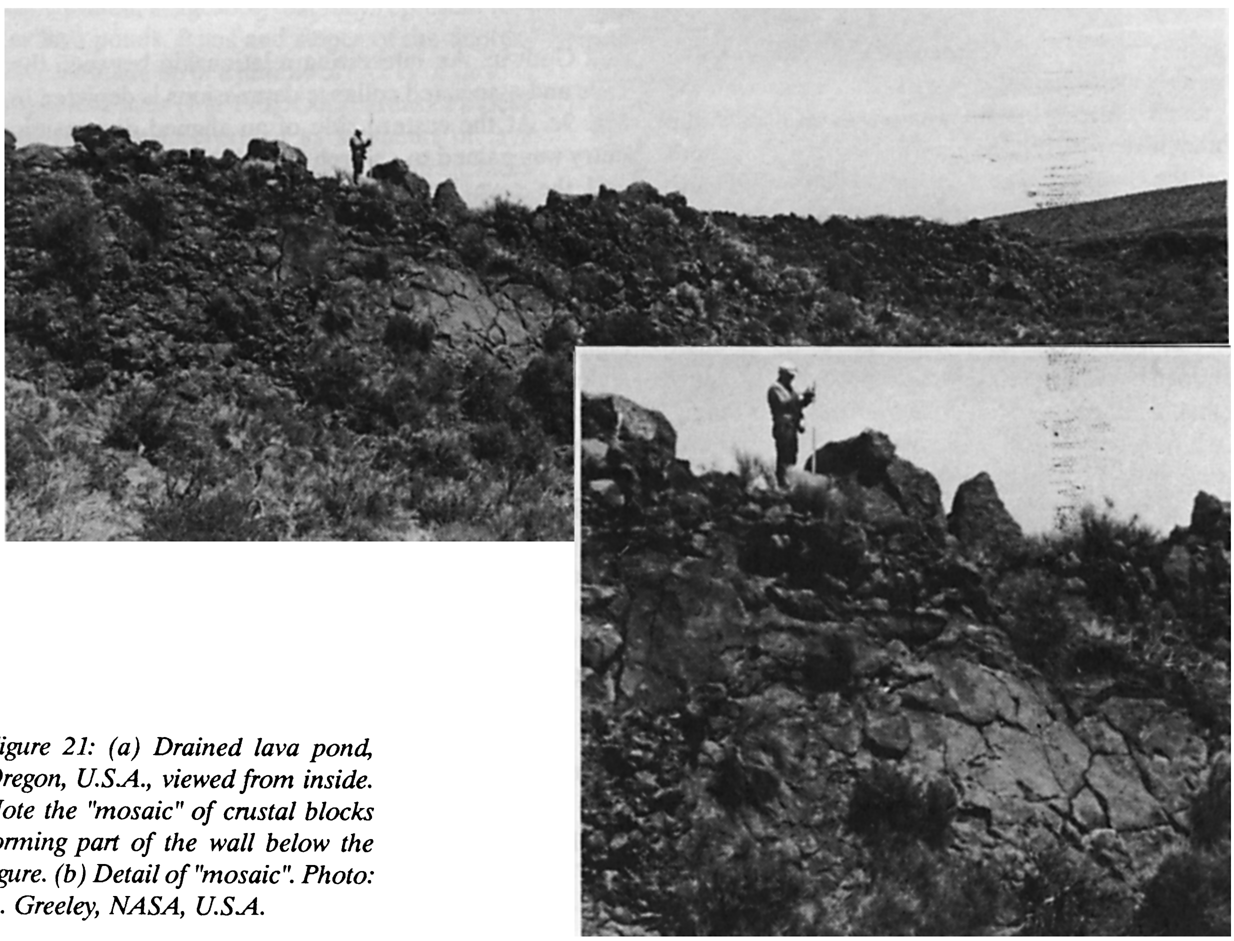


Figure 21: (a) Drained lava pond, Oregon, U.S.A., viewed from inside. Note the "mosaic" of crustal blocks forming part of the wall below the figure. (b) Detail of "mosaic". Photo: R. Greeley, NASA, U.S.A.

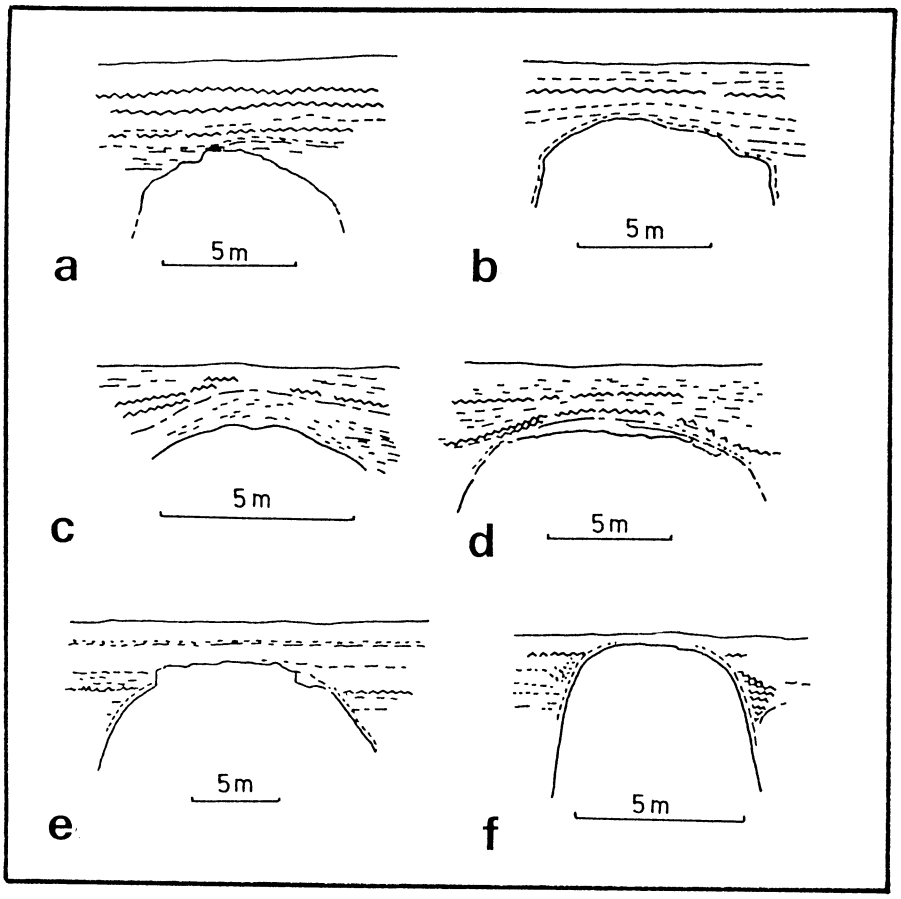


Figure 22: Cave entrance structures showing thickening of "roofs" by successive surface flow units; (a) Taylor; (b) Harbour Bridge; (c) Peterson; (d) Pinwill; (e) Road; (f) Barker. Flow units are indicated by wavy lines for recognised flow surfaces. Other near-horizontal lines are major vesicle zones. Diagram: P.J. Stephenson.

MODE OF FORMATION OF THE UNDARA LAVA TUBE SYSTEM

All observations to date confirm formation by "roofing" over a major lava channel and the thickening of "roofs" by subsequent flow units (Figs. 22 and 23), some of which flowed over ropy surfaces and bear rope imprints on their lower surfaces. That the ropy surfaces and imprints are not common is of little significance when it is remembered that Macdonald and Abbott record (1972) that ropy structure is often evident only over a small proportion of any flow.

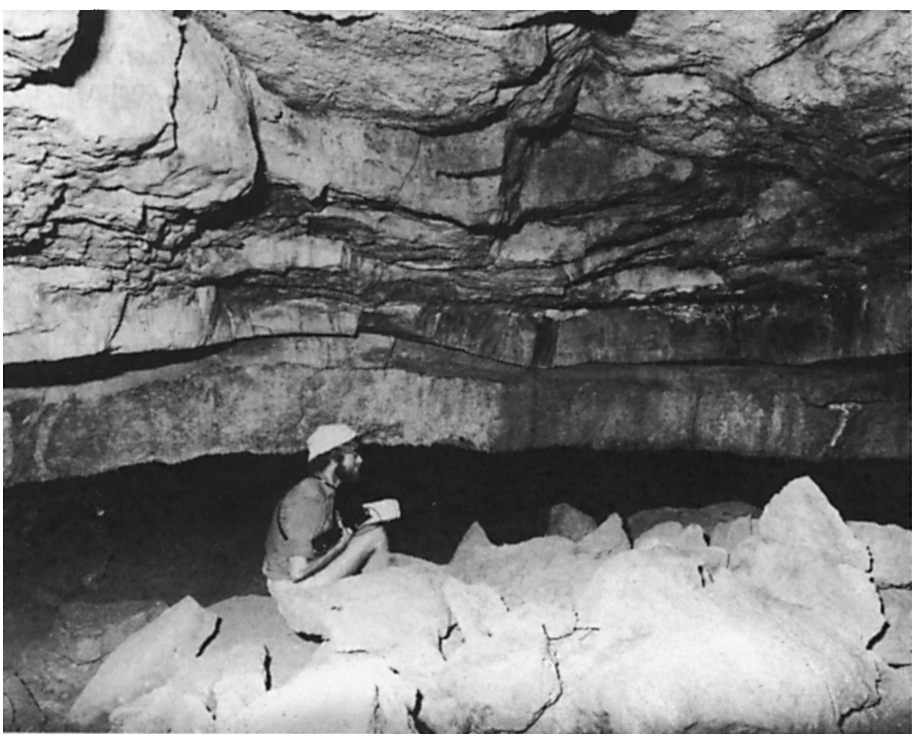


Figure 23: Roof structure inside Peterson Cave, (east branch). A ropy flow unit interface. The prominent arched flow unit just above the observers head, has a ropy interface. Higher ropy interfaces also occur. Photo: H.J. Lamont, J.C.U.N.Q..

Final drainage of much of the lava from the System provided segments that can be entered today. Further details and discussion of hypotheses concerning the formation of lava tubes in general and of the Undara Lava Tube System in particular, are given in Atkinson 1988, this volume.

SUMMARY AND CONCLUSIONS

1. 190,000 years ago the Undara Volcano erupted approximately 23 km^3 of lava. Its lava field covers 1,550 km^2.

2. The Undara lavas are thought to have had normal viscosities and no unusual properties.

3. The Undara flow extended 160 km on very low gradients (average 0.3°). This length resulted from a very high rate of effusion, coupled with channelling and an efficient lava tube system.

4. Evidence of a major lava tube system is preserved as various collapse depressions and in drained and partly drained caves. The caves are up to 1.35 km long, and a narrow ridge, "The Wall", 37 km long, is believed to have contained a lava tube.

5. The lava tubes of the Undara System developed by the "roofing" over of major lava channels.

6. Within the caves, protection from weathering has allowed preservation of ropy surfaces and other characteristics of active and recent lava flows. Other than long lavicicles (lava stalactites), cave features are comparable with those in other parts of the world.

7. Two distinct types of depression are associated with a line of narrower lava caves. The wide depressions probably represent collapsed lava ponds, whereas the narrower depressions were formed by lava tube collapse.

8. Most caves with obvious entrances have probably been discovered.

9. Many future discoveries may result from the movement of some appropriate blocks in wider collapse depressions.

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LAVA TUBES

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APPENDIX I

TABLE 2
UNDARA LAVA TUBE SYSTEM - MAJOR ELEMENT CHEMICAL ANALYSES
Specimen locations are shown on Figure 6.

* These analyses on samples dried at 110° C
n.d.: not determined

	A	B	C	D
SiO_2	48.85	49.30	49.50	48.20
TiO_2	1.82	1.70	1.67	1.75
Al_2O_3	15.23	15.40	15.90	15.80
FeO_3	2.52	11.0	10.53	4.46
FeO	7.46	trace	0.06	6.38
MnO	0.16	0.15	0.15	0.17
MgO	8.55	8.10	7.10	7.85
CaO	9.16	8.02	8.39	8.02
Na_2O	3.90	4.20	3.87	3.57
K_2O	1.75	1.77	1.53	1.71
H_2O+	0.35	n.d.	n.d.	n.d.
H_2O-	0.17	*	*	*
P_2O_5	0.64	0.50	0.34	0.72
CO_2	0.13	n.d.	n.d.	n.d.
Total	100.69	100.14	99.04	98.63
Locality (Fig. 6)	A	B & C	B & C	D

Analyses
"A": Host rock, Barkers Cave entrance,
"B": Cave lining,Barkers Cave entrance;

Analyses:
"A". T.J. Griffin, using XRF; Na, flame photometric; Fe^2, by titration.
"B"-"D". P.J. Stephenson and T.J. Griffin, using Atomic Absorption (HF-Boric Acid digestion); P, spectrophotometric; Fe^2, by titration.

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