PRELIMINARY SURVEY FOR LAVA-TUBE CAVES ON HARRAT KISHB, KINGDOM OF SAUDI ARABIA

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هيئة المساحة الجيولوجية السعودية
SAUDI GEOLOGICAL SURVEY

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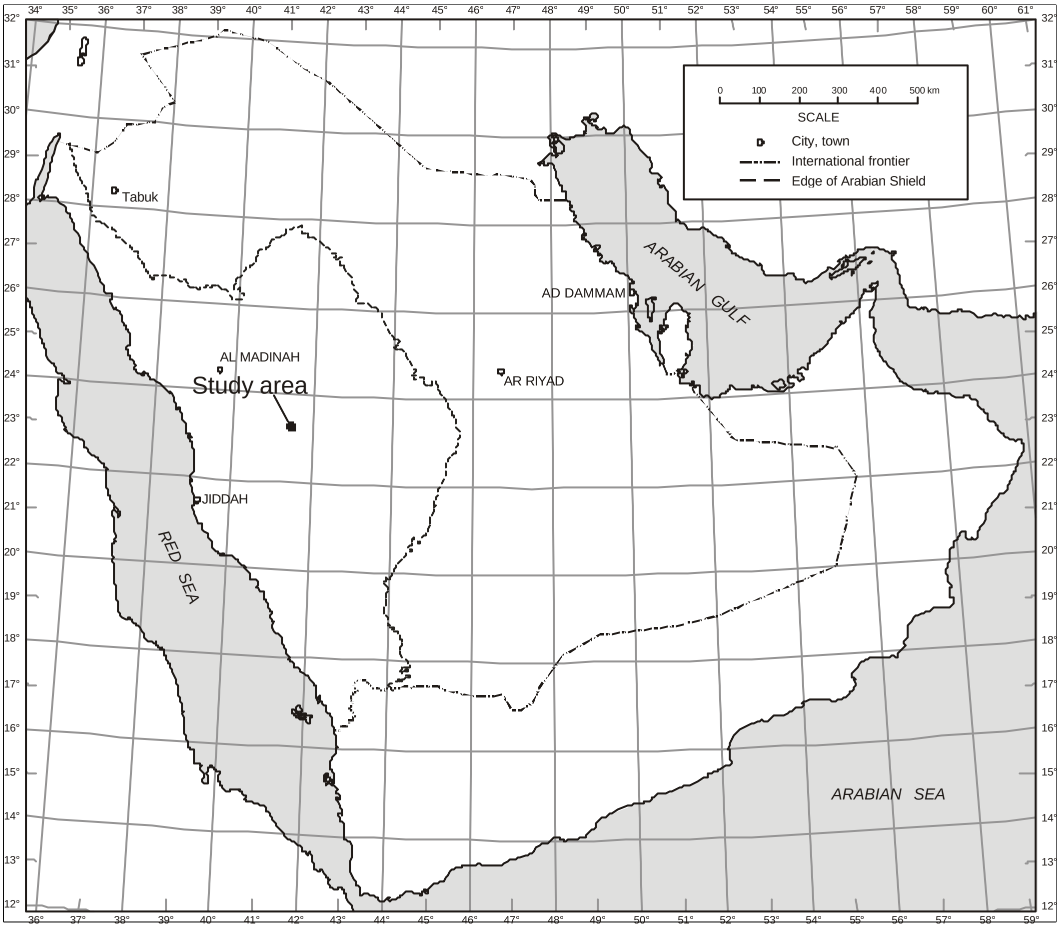

Index map of the Arabian Peninsula

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ABSTRACT

Caves are known to occur in the Phanerozoic limestones of northern and eastern Saudi Arabia. They formed in past intervals of moist climate rather than the present hyperarid one. Few caves are known in the west because the predominant rocks are metamorphosed, tectonized and crystalline, comprising the Precambrian shield. There are however two geological units younger than the crystalline basement in western Saudi Arabia, where caves might be found. These are: (1) raised Quaternary coral limestones along the Red Sea coastline; (2) the extensive Cenozoic basalt lava fields.

The present report describes the first and successful search for lava-tube caves in the Cenozoic basaltic lava fields of Harrat Kishb (area 5,892 km^2). Cenozoic lava fields, or harrats, occupy 80,000 km^2 of western Saudi Arabia, where they mainly occur as 12 large lava fields in a chain extending from Syria in the north, across easternmost Jordan, southward for the entire length of western Saudi Arabia; and into Yemen in the south.

The investigation reported here was largely confined to an area of central Harrat Kishb. Here, six lava-tube caves were located in three closely spaced areas in central Harrat Kishb in basalt lavas of four different stratigraphic units. All occur in lavas of the Cenozoic Hil basalt, which is less than one million years old. The Hil basalt is subdivided into six subunits. By far the largest and longest lava tube occurs on the western side of the scoria cone of Jabal Hil, which erupted a few thousands of years ago and belongs to the youngest subunit Qh6 of the Hil basalt. A detailed geologic map was made of the surface features of a major arterial lava tube extending for 3 km to the west of the parent cone. Basalt lava flows were extruded from five points along the arterial lava tube to build a ridge comprising a chain of low rootless shield volcanoes. Later, when the eruption ceased, the arterial lava tube drained and subsidence occurred into it. The interior of the lava tube is visible in several of these collapses. It has a height of over 20 m and the floor has a maximum below-surface depth of 42.5 km. Nearby, in stratigraphic subunit Qh4, a single lava tube cave (First Cave) is visible at the bottom of a 26.5 m deep shaft. The sides of this shaft are dangerously loose and the cave was not explored. Farther east, in subunit Qh3, three closely spaced lava-tube caves were found and are here named Ghostly Cave, Bushy Cave and Kahf al Mut'eb caves. The largest of these, Ghostly Cave has two passages extending 143 m and 140 m from the entrance. Nearby, in the same stratigraphic subunit, a small erosional cave (Window cave) only one meter deep is present in weakly lithified agglomerate. This is the only example of an erosion cave known on Harrat Kishb. A sixth lava-tube cave (Dahl Faisal), some 22 m long, was located on northern Harrat Kishb in subunit Qh1 of the Hil basalt. The lava-tube caves are elliptical in cross-section and have short lava stalactites on the roof and lava levées on the walls. They contain evidence of ancient man in the form of defensive walls, and two throwing sticks of possible Neolithic age were found. These tubes are half-filled with fluviatile sands and wind-blown dust, which may preserve a stratigraphic record in pollen and spores.

Lava tubes form in basalt lavas after eruption ceases to extrude molten lava. At this stage, basalt lava may continue to flow downslope away from the volcano by draining the main feeder tube inside the flow at its highest point. Theoretically, every lava flow can have a lavatube. There are over 2,000 basaltic volcanoes standing in western Saudi Arabia, many of which have produced multiple lava flows. This fact and the success of the first search for lava-tube caves suggests that numerous such caves may exist in the Cenozoic lava fields of western Saudi Arabia, and further searches are recommended.

مسح أولي عن كهوف أنابيب اللابة في حرة كشب
بالمملكة العربية السعودية
الخلاصة

تتواجد الكهوف في صخور الحجر الجيري التابعة لدهر الحياة الظاهرة في الجزءين الشمالي والشرقي من المملكة العربية السعودية. وقد تكونت هذه الصخور خلال فترات مناخية رطبة تختلف عن الفترة الحالية المفرطة الجفاف. والكهوف المعروفة في الغرب قليلة لأن الصخور السائدة في هذه المنطقة عبارة عن صخور متحولة وحركية بلورية يتكون منها الدرع العربي. إلا أن هناك وحدتان جيولوجيتان أصغر عمراً من صخور القاعدة البلورية في الجزء الغربي من المملكة حيث يحتمل تواجد الكهوف بهما وهما : (١) الشعاب المرجانية المرتفعة من الحقب الرابع على طول ساحل البحر الأحمر. (٢) حقول اللابة البازلتية الشاسعة من حقب الحياة الحديثة.

يتضمن التقرير الحالي وصفاً لأول عملية بحث ناجحة عن كهوف أنابيب اللابة في حقول اللابة البازلتية من حقب الحياة الحديثة في حرة كشب (على مساحة تبلغ ٥,٨٩٢ كلم٢). تحتل حقول اللابة أو الحرات من حقب الحياة الحديثة مساحة تبلغ ٨٠,٠٠٠ كلم٢ من الجزء الغربي للمملكة، حيث تتواجد أساساً على هيئة ١٢حقلاً كبيراً من اللابة في سلسلة تمتد من سوريا شمالاً عبر أقصى الجزء الشرقي من الأردن وجنوباً لتشمل كامل طول الجزء الغربي من المملكة إلى داخل اليمن في الجنوب.

تنحصر الدراسات الواردة على هذا التقرير بشكل كبير على المنطقة الوسطى من حرة كشب حيث تم العثور على ستة كهوف من أنابيب اللابة في ثلاث مناطق ذات فوصل متقاربة في حرة كشب الوسطى داخل لابات بازلتية تعود لوحدات طباقية مختلفة. وتتواجد جميعها في لابات بازلت الهيل من حقب الحياة الحديثة الذي يقل عمره عن مليون سنة. تم تقسيم بازلت الهيل إلى ست وحدات فرعية. وحتى الآن فإن أكبر وأطول أنبوب لابة يوجد في الجانب الغربي من مخروط إسكوريا جبل هيل الذي ثار قبل آلاف قلائل من السنين وهو يحتوي على أصغر الوحدات الفرعية عمراً لبازلت هيل وهي Qh6 . تم إعداد خريطة جيولوجية مفصلة للملامح السطحية لأنبوب لابة شرياني رئيسي يمتد لمسافة ٣ كيلومترات إلى الغرب من المخروط الأصلي. وقد إنبثقت تدفقات اللابة من خمس نقاط على طول أنبوب اللابة الشرياني مكونة حيداً يشكل سلسلة من براكين الدرع اللاجذرية المنخفضة. وفي فترة لاحقة وعندما توقف الثوران ثم تصريف أنبوب اللابة وحدثت به إنخسافات. ويمكن مشاهدة الجزء الداخلي لأنبوب اللابة في العديد من هذه الإنهيارات.يبلغ إرتفاع أنبوب اللابة ٢٠متراً ويبلغ أقصى عمق تحت السطح لقاعة ٤٢,٥كيلومتراً وبالقرب منه وفي الوحدة الطباقية الفرعية Qh4 يمكن مشاهدة كهف أنبوبي لابي (الكهف الأول) على قاع مهوى يبلغ عمقه ٢٦,٥متراً. وجوانب هذا المهوى غير مترابطة بشكل خطر كما أن الكهف لم يتم إستكشافه . وبعيداً نحو الشرق وفي الوحدة الطباقية الفرعية (Qh3) تم العثور على ثلاثة كهوف أنبوبية متقاربة الفواصل سميت هنا بكهف الشبح وكهف الشجيرات والكهف المتعب. ويحتوي أكبرها وهو كهف الشبح على ممرين يمتدان إلى ١٤٣متراً و ١٤٠متراً من المدخل.

وبالقرب من هذا الكهف وفي نفس الوحدة الطباقية الفرعية هناك كهف تحاتي صغير(كهف النافذة) يبلغ عمقه متراً واحداً يوجد داخل مدملك ضعيف التحجر. وهذا الكهف هو المثال الوحيد المعروف للكهوف التحاتية في حرة كشب. وتم اكتشاف كهف أنبوبي سادس (دحل فيصل) يبلغ طوله ٢٢متراً في الجزء الشمالي من حرة كشب داخل الوحدة الطباقية الفرعية (Qh1) لبازلت الهيل. تتميز كهوف أنابيب اللابة بمقاطع عرضية بيضاوية الشكل وتحتوي أسقفها على هوابط لابية قصيرة كما تحتوي جدرانها على سدود لابية. وبها أدلة تشير لآثار بشرية قديمة تتمثل في وجود جدران دفاعية كم وجدت بها عصاتان للرمي تعودان إلى العصر الحجري الحديث. وهذه الأنابيب شبه ممتلئة بالرمال النهرية والغبار المجلوب بالرياح مما قد يحافظ على سجل طباقي من غبار الطلع والأبواغ.

تتكون أنابيب اللابة في اللابات البازلتية بعدما يتوقف ثوران البركان عن قذف اللابة المنصهرة. وخلال هذه المرحلة قد تستمر اللابة البازلتية في التدفق للأسفل عبر المنحدر بعيداً عن البركان عن طريق تصريف أنبوب التغذية الأساسي داخل التدفق عند أعلى نقطة له. ومن الناحية النظرية فإن لكل تدفق لابة أنبوب لابة. وهنالك أكثر من ٢٠٠٠ بركان بازلتي في الجزء الغربي من المملكة نتج عن العديد منها تدفقات متعددة من اللابة. إن هذه الحقيقة ونجاح أول عملية بحث عن كهوف أنابيب اللابة يوحيان بأن عدة كهوف مثل هذه قد تتواجد في حقول اللابة من حقب الحياة الحديثة المنتشرة في الجزء الغربي من المملكة العربية السعودية وعلية يوصي بإجراء المزيد من عمليات البحث.

Figure 1. Map showing the Cenozoic lava fields of Saudi Arabia with Harrat Kishb indicated

INTRODUCTION

One of the first projects of the newly formed Saudi Geological Survey in the year 2001 was the recording of underground natural cavities or caves known to exist in Phanerozoic carbonate rocks (limestones) in the eastern part of Saudi Arabia. Subproject 4.1.1.3 “Mapping of underground cavities (caves) in Phanerozoic rocks” was initiated because of the formation of the Saudi Tourist Board and its interest in documenting areas of possible touristic interest.

Saudi Arabia today has an arid desert climate, and caves in limestone resulting from the passage of groundwater through soluble limestone rock would not be expected to be a common feature. However in the recent past, the climate of Saudi Arabia was different and several moist intervals occurred (Edgell, 1990a and b; McClure, 1978), during which limestone caves developed.

As expected, the occurrence of limestone caves chiefly follows the trace of the Phanerozoic limestone belts in the north, east, and south of the country, and caves are well known near the high-density population center of Ar Riyad. In contrast, in the western third of Saudi Arabia, the rocks are mostly ancient, comprising Precambrian crystalline basement, and are not favorable for the development of natural cavities. However, there are two exceptions; namely: (a) raised Quaternary limestone along the Red Sea coastline, (b) the extensive Cenozoic basaltic lava fields (Figure 1).

This report documents the results of a search for and exploitation of lava-tube caves on one of the Cenozoic lava fields of west-central Saudi Arabia (Harrat Kishb). Lava tubes are naturally roofed feeder channels of lava flows within the length of the flow. As a lava flow lengthens during the course of an eruption, the margins of the flow (with the exception of the advancing flow front) cease to flow and a central channel (often with levées) forms in the older part of the flow to feed the advancing flow front. With time, this may become roofed over to form an arterial passage or lava tube. At a late stage in the eruption, usually after the lava supply from the vent has ceased, parts of the lava tube may drain to produce an open-like passage or lava tube. Local collapses of the roof along its length provide access. Inside, lava stalactites, stalagmites, lava levées and channels may be preserved. Most lava tubes are known in basaltic lava, which is the most fluid of molten volcanic rocks.

The existing literature reports lava tube caves on two of the lava fields of Saudi Arabia. On the 2,000 km^2 coalesced lava fields of Harrat Khaybar, Ithnayn, and Kura to the north of the Al Madinah, Roobol and Camp (1991a, p.14) reported several lava-tube caves containing delicate lava stalactites present in the basaltic stratovolcano of Jabal Qidr, which may have erupted in 1800 AD. Other lava-tube caves up to 10 m high occur in older stratigraphic units (Roobol and Camp 1991a, p.11). On southern Harrat Khaybar another lava tube 100 m long was described by Roobol and others (1994) when it was entered, and a fumerole measured at its deepest point. On Harrat Kishb, a major 3-km long lava tube with several collapse craters, as well as other lava tubes in older stratigraphic units, were described by Roobol and Camp (1991b) as part of the regional mapping. However the SGS Caves Mapping Project is the first attempt to accurately document and map these underground caves.

Caves, particularly those with difficult access, can be viewed as safe havens that support a flora and fauna as well as preserve archeological remains. The literature on lava-tube caves in this part of the world is not extensive and this is the first report describing them in Saudi Arabia. Lava caves have been described from the northern Chyulu Hills of Kenya in an area very similar to Harrat Kishb comprising numerous basaltic scoria caves and associated lava flows (Simons, 1974). Other lava-tube caves have been described from Mount Suswa volcano in Kenya by Simons (1966). These caves were formerly the lairs of leopards and have rich vertebrate remains.

GEOLOGY OF HARRAT KISHB

The geology of Harrat Kishb is described by Roobol and Camp (1991b) in a colored 1:250,000 Geoscience Map with a 34-page explanatory text. The area visited on central Harrat Kishb to search for lava tube caves is covered by 1:50,000 WSA airphoto mosaic No. 475 (Aero Service Corp., Pennsylvania, 1958), and the 1:50,000 topographic sheet “Jibal al Hil” Number 4122-41 (Ministry of Petroleum and Mineral Resources, Aerial Survey Dept., Ar Riyad, 1980).

Harrat Kishb is a young basaltic lava field with an area of 5,892 km^2 centered about 270 km northeast of Jeddah. Based on eighteen K/Ar ages, the entire harrat is younger than 2 million years. The lavas have been grouped into 3 major stratigraphic units, which from oldest to youngest, are named the Diakah, Nafrat, and Hil basalts. The four areas where lava-tube caves were located are all in the Hil basalt, which is younger than about 1 million years. Roobol and Camp (1991b) divided the Hil basalt into six stratigraphic units numbered from oldest to youngest Qh1 to Qh6. The youngest of these is subunit 6, which comprises the products of 3 eruptions – the scoria cones and basalt lava flows of Jabals Hil* and Aslaj (both characterized by extremely voluminous outpourings of basalt lava), and the scoria cones and thick phonolite domes and flows of Jabal Shalman (names and types of volcanoes are shown in Figure 2).

GEOLOGY OF JABAL HIL

Jabal Hil is a single circular scoria and ash cone situated in the middle of Harrat Kishb at the south end of a distinct north-south chain of scoria cones and phonolite domes (Figure 2). South of Jabal Hil, the scoria cones and phonolite domes are considerably scattered to the southwest, probably due to channeling of rising magmas along crustal faults bounding the subsidence basin of Sahl Rakbah. The cone of Jabal Hil is extremely youthful and lacks erosion. It is built upon the rim of an older maar crater (subunit Qh3) and rises from a base at 1,340 m a.s.l. to the highest point on the eastern crater rim at 1,475 m. The base of the cone measures 1,100 m east-west by 1,100 m north-south. The cone has fed an extensive basalt lava field with flows extending to the south and particularly to the west to cover an area measuring 34 km east-west by 17 km north-south. In the west, the basaltic flow front forms an impressive area where 3-m thick pahoehoe lavas partially encircle the tuff ring of the 2 km Al Wahbah maar crater. The composition of the basalt is basanite (Roobol and Camp, 1991b).

A detailed geological map has been prepared of Jabal Hil and its lava flows in its immediate vicinity to show the details of the main arterial lava tube (Plate 1). Shortly before the eruptions ceased, the Jabal Hil crater became flooded with basalt lava, formed a crater lake and overtopped the crater rim to form a lava fall or cascade down the southwestern flanks of the cone. Later the lava drained away to form a deep crater. Around this crater, the edge of the lava lake is preserved as a flat-topped rim at an altitude of 1,400 m. Inside the crater are remnants of other lava lake margins that formed at lower levels. This must have been an impressive sight as the lava lake was accompanied by fire fountaining that entirely coated the inside of the crater, the crater rim, and southeast outer flank with a thin layer of molten spatter that congealed to a thin coating of hard lava. The bottom of the crater is at about 1,287 m a.s.l.

Both on the crater rim and below the lava cascade on the southwestern flanks of Jabal Hil, a series of structural features (numbered 1 to 12 on Plate 1) trace the path of the arterial lava tube for a distance of 3 km from the cone. At six places along its length the arterial lava tube erupted thin basalt lavas to build a chain of rootless shield volcanoes that form a distinct ridge above the lava tube as indicated by the topographic contours (Plate 1). At the end of the eruption, the lava tube emptied over most of its 3 km length, so that near the cone of Jabal Hil collapses of the roof (at collapse structures numbers 2 to 7) reveal the interior of the lava tube. It is around 20 m high with lava levels and gouge marks on its walls. When exposed, the bottom of the arterial lava tube is at a maximum depth of 42.5 m below the surface. Farther away from the cone are elliptical areas of subsidence with bottoms of rubble, which do not reveal the arterial lava tube (structures 9, 10, and 11). In the west, at the most distal point on the arterial tube, rather than subsidence, there is an area of local updoming. The lava tube clearly has a complex detailed history. Mapping of the flow directions of the pahoehoe lavas clearly shows that the subsidence areas and one area of local doming (Plate 1) correspond to the earlier sites of extrusion of pahoehoe lava flows. The arterial lava tube breached its roof at regular intervals to erupt lava and form local rootless shield volcanoes. Figure 3 shows geologists standing on the flanks of the small rootless shield volcano (structure 8), showing a part of the radial cascade of the pahoehoe and aa flows derived from local extrusion of basalt lava through a breach in the roof of the main lava tube. An interesting feature of subsidence areas 9, 10, and 11, is that they are surrounded by a rim of jumbled and overturned lava blocks (Figure 4), rather like a wall, surrounding the subsidence area. This structure indicates that before subsidence there was an episode of local updoming of the lava surface above the arterial tube. Viewed from 3 km away, the course of the lava tube appears as a low-angled ridge

** Although the topographic map refers to Jibal al Hil, this report uses the place name Jabal Hil, in concert with the name given by Robool and Camp (1991b).*

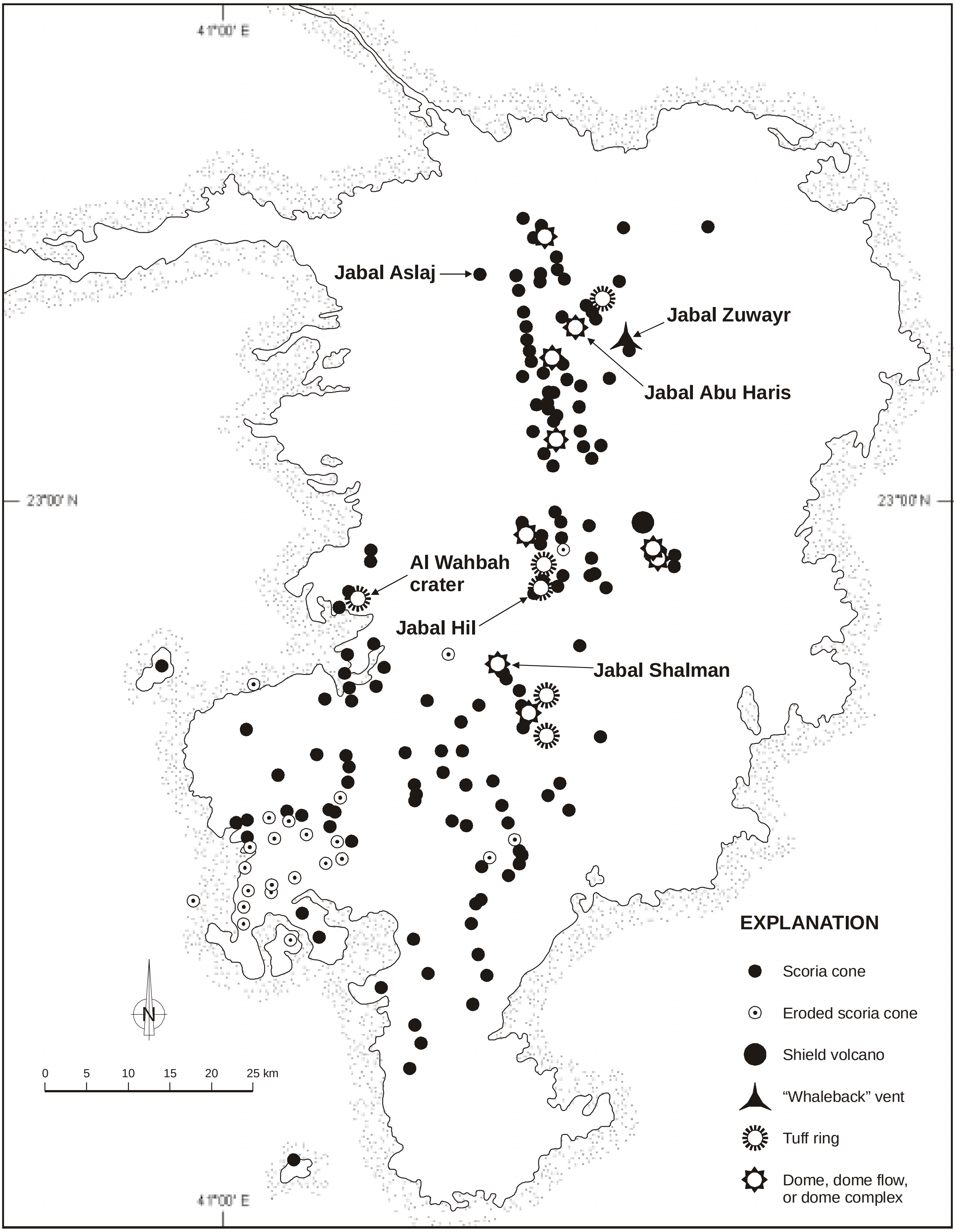


Figure 2. Positions, names and types of vents exposed on Harrat Kishb

along which there is a chain of low rootless shield volcanoes. The map (Plate 1) indicates that the lava tube not only fed the distal parts of the Jabal Hil lava field, but when full of molten basalt, broke through its roof to extrude lava flows near the main cone. Later, when lava ceased to be supplied from the vent at the cone site and the eruption had technically ended, the lava flows continued to advance so that the arterial lava tube was drained and local areas of collapse and subsidence occurred into the empty tube.

Figure 3. Geologists standing on dipping aa lava flows on the flanks of the structure 8 rootless shield volcano. Jabal Hil with its lava cascade is in the background.

Figure 4. Geologist standing by 2-m high wall of tumbled lava blocks surrounding collapse structure 10.

GEOLOGY OF SUBUNIT Qh4 OF THE HIL BASALT

Subunit Qh4 is a well-preserved essentially uneroded set of basanite lava flows occurring immediately north of Jabal Hil (Plate 2). The unit is the product of two eruptions each of which produced a scoria cone and lava flows. The flows are mainly of pahoehoe type and partially encircle and bury cones of older subunits of the Hil basalt in the central vent area of Harrat Kishb. A westerly-directed lava flow of subunit Qh3 is overlain by the extensive lava field of Jabal Hil (Qh6) - see Plate 2. The lava tube located in these flows occurs 1.2 km east of the flow vent, which is an unnamed scoria cone situated 1.5 km north-northeast of Jabal Hil.

GEOLOGY OF SUBUNIT Qh3 OF THE HIL BASALT

The volcanic deposits of subunit Qh3 of the Hil basalt are distinguished from overlying subunits because they are significantly eroded. The deposits comprise both scoria cones and lava flows as well as five maar craters and associated tuff rings (Plate 2). Maar craters and tuff rings are the products of phreatomagmatic activity where lava and water meet to produce more powerful explosions than are normally encountered in a dry-vent eruption of basalt lava. This fact, together with the erosion, suggests that subunit Qh3 formed during a moist climatic period or pluvial interval.

Two of the maar craters are shown in Plate 2. The lava tube caves located in this subunit lie on the eastern flank of the harrat adjacent to a small but distinct scoria cone assigned to subunit Qn1. This older scoria cone is encircled by pahoehoe lava flows of subunit Qn3, in which the lava tubes occur.

GEOLOGY OF SUBUNIT Qh1 OF THE HIL BASALT

This subunit was described by Roobol and Camp (1991b) as:

> "The oldest subunit (Qh1) is by far the most extensive and voluminous of the six subunits of the Hil basalt. It consists mainly of basanite and alkali olivine basalt (AOB), with small volumes of hawaiite, phonotephrite, and phonolite. The basanite, AOB, hawaiite, and phonotephrite form scoria cones and associated lava flows, and a sample from the Jabal Zuwayr "whaleback" lava flow is hawaiite. Of the four samples collected from the 12-km-long line of seven scoria cones and flows, three are AOB and one is basanite. In addition there are two phonolite domes on northern Harrat Kishb and two phonolite dome flows of subunit Qh1. One dome flow and its associated hawaiite scoria cone is Jabal Abu Haris and the other is in the south of the harrat and was also erupted from a basaltic scoria cone.
>
> All the scoria cones, domes, and dome flows of subunit Qh1 are deeply gullied. However, in order to compare degrees of erosion with other subunits, reference is made to the nearly flat-lying Qh1 basaltic lava flows. These have their surfaces smoothed by erosion and are also gullied. The aa and pahoehoe surfaces have been destroyed and the flow margins are indistinct because of the accumulation of marginal debris fans from the flow tops."

THE LAVA TUBES OF JABAL HIL

The major arterial lava tube extending westwards from Jabal Hil has surface expressions indicating that it is at least 3 km long. On the map (Plate 1) small shield volcanoes, collapse caverns, subsidence areas, and one area of local updoming are aligned along the roof of the arterial lava tube. These are numbered 1 to 12 in Plate 1. Distal to the cone, structures 12, 11, 10, and 8 are blocked by debris, but access to the main arterial tube is possible through small lava tubes at subsided vent 9 (Figure 5). The main arterial lava tube

Figure 5. View of collapse structure 9. The partially solid surface of a molten lava lake was lowered as the lava drained into the underlying arterial lava tube. This surface partly survives intact but locally drapes over underlying basalt rocks.

is well exposed in collapse structures 2 to 7, but has not yet been investigated underground. Collapse structure 1 and the small crater of small basaltic shield of structure 8 are blocked by rubble.

The arterial lava tube is well seen in collapse structure 7, through a vertical collapse pipe 5 m deep measuring 12.4 m north-south by 9.5 m east-west (Figure 6). Beneath this the westward-directed arterial lava tube can be seen to be elliptical in cross section with a height of 21.5 m (beneath the vertical pipe) with

Figure 6. The 5 m deep vertical collapse pipe leading down into the westward oriented 21.5 m deep arterial lava tube at collapse structure 7. The lava coating the collapse indicates that it occurred while the lava was still molten.

Figure 7. View into the 21.5 m arterial lava tube of Jabal Hil at collapse structure 7 showing lava levées and gouge marks along the wall.

walls inclined to the south. Lava levées, marking lava levels on the walls of tube and gouge marks, are present (Figure 7).

The arterial lava tube is again visible in collapse structure 6 (Figure 8) where the depth to bottom is 28.5 m. Again in collapse structure 5, it is particularly well seen, and again in the large collapse structure 4

Figure 8. Collapse structure 6 looking west showing the upper part of the arterial lava tube with geologists standing on the roof.

Figure 9. Collapse structure 4 measuring 90 by 72 m with the arterial lava tube having a base 22 m below the surface.

(Figure 9). The latter measures 90 m southwest by 72 m southeast-northwest and the lava tube occurs in the lower part of the collapse structure with its bottom at a depth of 22 m beneath the surface.

This relationship (of exposure of lava tube in the bottom of collapse structure) is again repeated in collapse structure 3, which measures 38 m north-south by 52 east-west. The lava tube is exposed in the bottom of this structure at both the cone and distal ends. The depth to the base of the lava tube from the surface was measured at 42.5 m.

Whereas the main arterial lava tube is up to 20 m high, and oriented east-west, secondary small lava tubes exist in the pahoehoe lava flows leading north and south away from the vents above the main lava tube. These secondary lava tubes have heights of no more than 3 m and widths of 4 m. They occur inside drained pahoehoe flows and have basalt roofs usually less than 1 m thick.

THE LAVA TUBES OF SUBUNIT Qh4 OF THE HIL BASALT

A single lava-tube cave was found in lavas of this subunit and is here named First cave (Plate 1). By tracing its host lava uphill at a right angle to the directions of the topographic contours the source can be seen to be an unnamed scoria cone 1.2 km to the west.

FIRST CAVE

The latitude and longitude of First Cave are given in Pint, J., 2002 (updated July 2002). This cave is located on a locally steep slope of pahoehoe basalt lava derived from an unnamed cone of the upper Hil basalt subunit Qh4 only 1.2 km upslope (Plate 2). The cave entrance is a shaft 7 to 8 m in diameter (Figure 10) and 26.5 m deep. From the entrance, one can look down into the cave and see the opening to a horizontal lava-tube passage heading west. A lot of broken lava blocks lie on the floor below the shaft and the edges of the cave entrance and walls of the shaft looks very fragile and ready to collapse. On the south side of the entrance pit, at surface level, there is a small passage leading to a ledge overhanging the pit. Because of the instability of the walls and edges of the shaft, it was decided that the cave was too dangerous to risk entry down the deep shaft.

Figure 10. Photograph showing the entrance of First Cave

THE LAVA TUBES OF SUBUNIT Qh3 OF THE HIL BASALT

Three closely spaced lava-tube caves (Kahf al Ashbaah, Kahf al Mut'eb, and Bushy Cave) were located on the west side of an older (subunit Qh1), low basaltic scoria cone from which all loose ash has been eroded to leave a sharp rim of agglutinated spatter. The subunit Qh3 lava containing the three caves has flowed eastwards around this cone as a series of basalt lava flows originating in the central vent zone of the harrat, 5 km to the west. The path of the lava can be deduced in Plate 2 by following the track of the lava flow uphill from the caves at right angle to the topographic contours.

The caves are situated on a local relatively steep slope of basalt of approximately 2°. In contrast the flanks of the harrat are at slopes of a half to quarter degree. The host is a lightly eroded basaltic pahoehoe lava that has piled up behind the older eroded scoria cone to form a series of sinuous pressure ridges that wrap around the obstructing cone. The lava divided to pass on either side of the older cone and flow away towards the east as two separate flows. Downslope of the older cone, the two tongues of lava are separated by a long passage or pathway of gravel.

Commonly, lava tubes would form near the vent where the lava drains away from the cone. This is not the case for these three caves, which have formed in a local high area where lava piled up (about 10 meters higher than the main lava surface) behind an obstruction in the path of the flow (the older scoria cone). At a late stage, lava drained away from inside the locally elevated area behind the obstruction, to form the three caves some 5 km from the eruptive vent.

Nearby (Plate 2) a small erosional cave was found in weakly lithified agglomerates of subunit Qh3. The deposits are part of a large tuff ring surrounding a filled maar crater. This was named Window Cave and is included in this report because such caves are common in the volcanic areas of Kenya, although this is the only example known on Harrat Kishb.

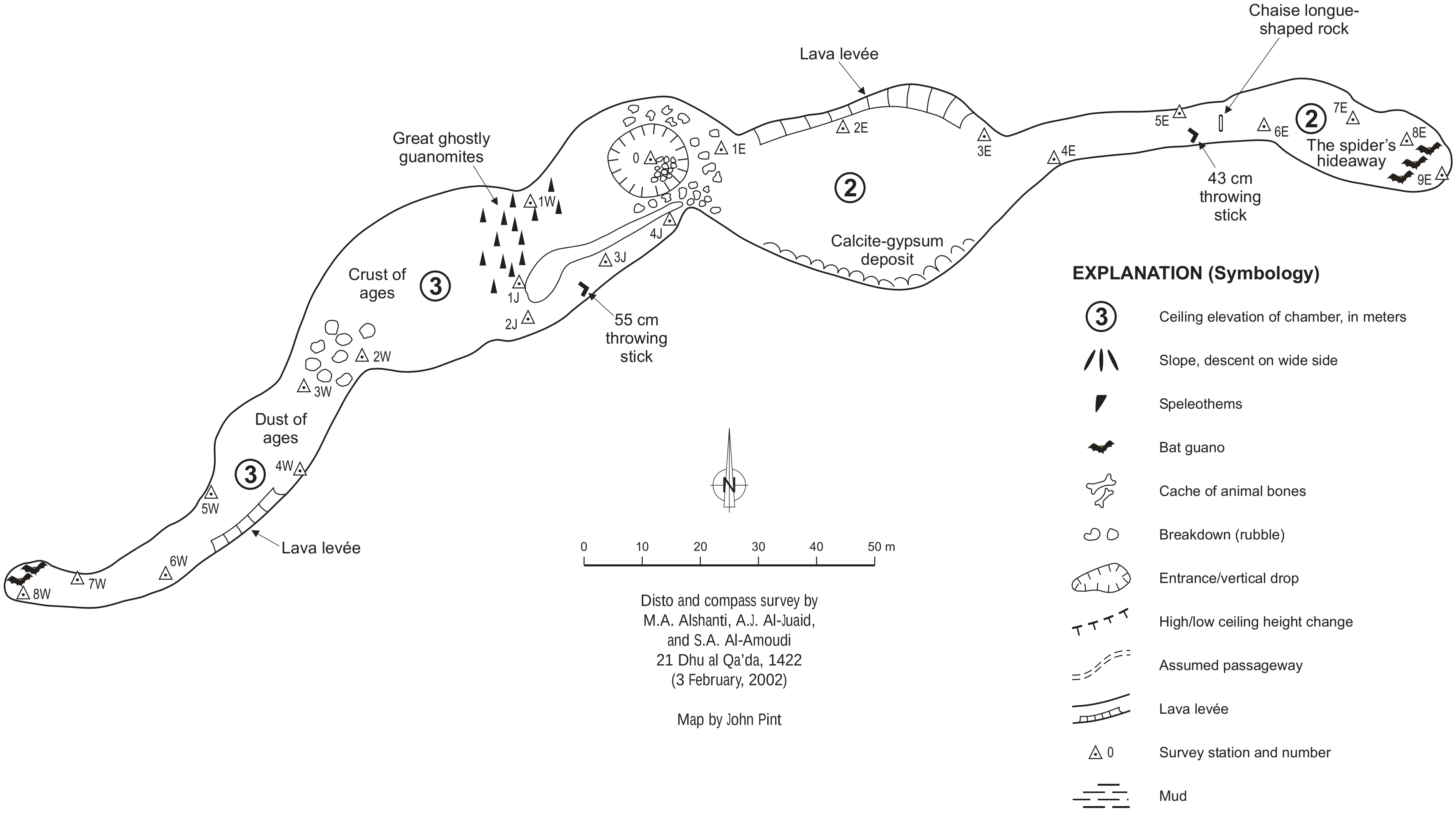


Figure 11. Map of Kahf al Ashbaah (Ghostly) Cave in Harrat Kishb.

KAHF AL ASHBAAH (GHOSTLY CAVE)

The latitude and longitude of Kahf al Ashbaah are given in Pint, J., 2002 (updated July 2002). A map of the cave is shown in Figure 11. The entrance, (station 0 on Figure 11) is a collapse structure, ten meters in diameter and seven meters deep (Figures 12 and 13), which was entered using a cable ladder connected to a vehicle on the surface and dropping down to a heap of stones piled up by people in the past to facilitate access to the cave (see Appendix 1). The lava in the area has ridges and folds due to stress of flowing lava around a nearby cone. Around Ghostly Cave, the lava is flat.

Figure 12. The 10-m wide collapse entrance to Ghostly Cave (Kahf al Ashbaah).

Figure 13. Bats exiting the entrance of Ghostly Cave (Kahf al Asbaah) shortly after sunset

Passage 1 to the west of the entrance collapse

This cave is called Ghostly because close to the entrance are stalagmites of rock-dove guano inside the western passage, which appear like statues in the semi-darkness (Figures 14 and 15). These tall, thin cones of guano are seen through the entrance hole, which is four meters high and eleven meters wide. They are located at, and extend 15 m beyond, station 1W.

Figure 14. Guanomites of rock-dove guano at the entrance to the western passage of Ghostly Cave. The guanomites beneath the entrance collapse have vegetation growing on them following recent rainfall.

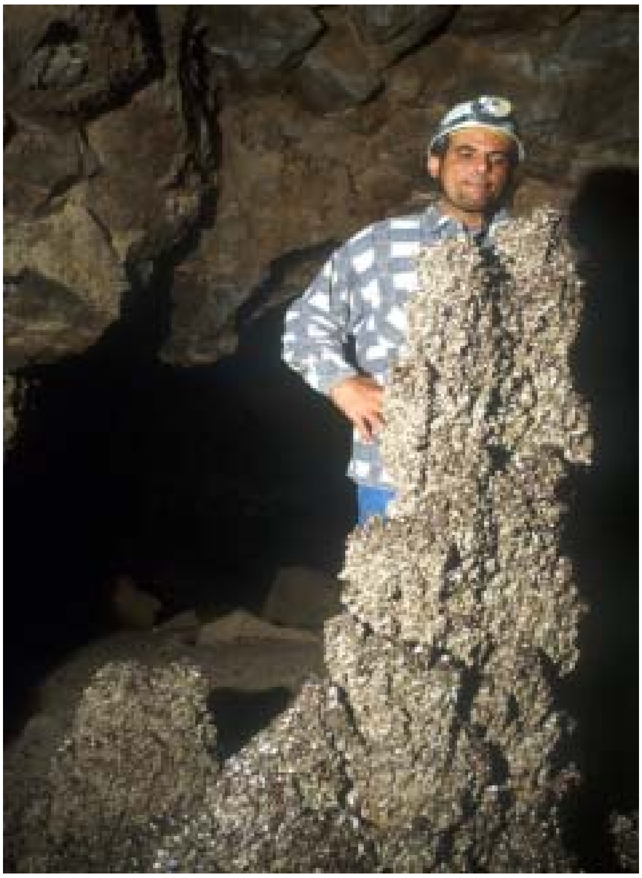


Figure 15. The tallest guanomite in Ghostly Cave.

Inside, one can see the gray to dark gray basalt flow, caused by rain seeping through the ceiling. The floor is slightly muddy due to the presence of water. Minor lava levées, with a height of 50-60 cm are visible on the northwest wall of the entrance.

Sixty meters beyond the entrance collapse, at station 2J, there is a side passage 4.5 m wide,, 21 m long, and 3.5 m high. When observed, the floor of this small tunnel was dry and dusty and the rocks looked cracked. In one crack, 1.5 m above the floor, between station 2J and 3J, an L-shaped throwing stick was found (see Appendix 2). This is flat and smoothly rounded at the edges and measures 55 cm long. Its surface is somewhat battered, suggesting that it is not a boomerang, but a throwing stick that would strike the ground if the target is missed. Some bones, less than 25 cm long, were seen on the floor. This passage ends at station 4J with a pile of breakdown rocks through which light can be seen from the entrance hole. Five meters beyond this point the passage narrows and closes.

Between stations 1W and 2W of the western passage, the floor is covered with a phosphate-rich compound (see Figure 42: SGS Laboratory Analytical Results Report Multielement LCP Analysis, Job Number GHO-003). A person's foot can sink 10-15 cm into this layer, breaking through a crust.

At station 4W, bones can be seen at the southeast side of the cave. These appear to have been carried in by water movement along with debris from outside the cave. On the ceiling, white calcareous patches are visible on the cracks and dark brown patches of bat urine are also present (Figure 16).

Across from station 5W, along the southeast wall of the passage, there is a lava levée 150 cm above the floor, 70 cm in width (Figure 17). The powder analyzed in Figure 42 is very dusty in this area and rises as one walks, making breathing very difficult. Here, small basaltic stalactites can be observed on the ceiling, somewhat stained brown by the bat urine (Figure 13).

The western passage of this lava tube ends 2.5 m beyond station 8W. Between 7W and 8W, on the north side of the passage, there is an upper level opening three meters high with a small entrance 1.5 m in diameter, which appears to lead farther on. This was not explored so that the bats in this area would not be disturbed. These bats are white, and have a wingspan of less than 25 cm. More than forty were flying about during the exploration of this end of the cave (Figure 13).

Figure 16. The roof of Ghostly Cave (Kahf al Asbaah) stained white with gypsum/anhydrite and brown bat urine.

Figure 17. The best developed lava levée which is 70 cm wide in Ghostly Cave (Kahf al Ashbaah).

Passage 2 to the east of the entrance collapse

The entrance to this passage is 6.5 m wide with a height of 3 m in the middle. On the ceiling, cracks can be seen in the basalt through which moisture has seeped, leaving the ceiling wet and muddy. Layers can be seen in this ceiling.

On the north side of the passage, there is a levée 30-40 cm above the floor, running along the wall. Ten to twelve meters inside, the floor becomes dusty. A chemical analysis of this dust (Table 1) shows it consists mainly of calcium, potassium, and phosphate, suggesting it is bone dust. There are soft, white patches of calcite-gypsum widespread over the south wall and on the ceiling, which begins to lower at station 3E. The passage then narrows to an average width of eight meters.

NAMES	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	MnO	TiO_2
UNIT	%	%	%	%	%	%	%	%
MIN.	1	1	1	1	1	0.5	0.01	0.01
MAX.	100	100	100	100	50	20	20	35
SAMPLE GHO-003	15.50	4.1	2.6	10.7	7.9	16.3	0.11	0.37
NAMES	P_2O_5	Li	Be	B	V	Cr	Co	Ni
UNIT	g/t	g/t	g/t	g/t	g/t	g/t	g/t	g/t
MIN.	100	10	2	10	10	10	5	10
MAX.	80000	40000	3500	18000	40000	13000	25000	18000
SAMPLE GHO-003	351091	4	0	54	51	60	20	63
NAMES	Cu	Zn	As	Sr	Y	Nb	Mo	Ag
UNIT	g/t	g/t	g/t	g/t	g/t	g/t	g/t	g/t
MIN.	5	5	50	5	20	20	5	1
MAX.	5000	20000	50000	10000	5000	15000	7500	300
SAMPLE GHO-003	669	3053	36	423	7	11	25	0.3
NAMES	Cd	Sn	Sb	Ba	La	Ce	W	Pb
UNIT	g/t	g/t	g/t	g/t	g/t	g/t	g/t	g/t
MIN.	5	50	10	10	20	10	10	10
MAX.	5000	20000	25000	3000	15000	5500	15000	5000
SAMPLE GHO-003	9	10	3	151	5	11	4	1
NAMES	Bi	Zr						
UNIT	g/t	g/t						
MIN.	10	250.00						
MAX.	10000	13000						
SAMPLE GHO-003	4	75						

Table 1. Chemistry of white dust from floor of Ghostly Cave (Kahf al Ashbaah) (Multielement analysis).

Between stations 3E and 4E a curtain of basalt can be found. The color of the basalt changes to brownish due to cracks through which mud and sand leach from the surface and are deposited on the ceiling.

Bats were first observed at this point in this passage. Bat guano can be found on the floor and bat urine on the ceiling. On the south side of the passage, across from station 5E, a second throwing stick was found, lying on the floor. This one is 43 cm long, smaller and of a darker wood than the first. Six meters beyond this point, there is a large rock two meters long, 120 cm high and 75 cm wide, in the shape of a chaise longue (Figure 18).

At station 6E, there is a crack in the ceiling and light enters from the surface. A spider web was observed in this area as well as several white eggs attached to the north wall (Figure 19). These are located between stations 7E and 8E and are thought to be gecko eggs. The ceiling lowers in this area.

Station 9E is at the entrance to a passage less than one meter high and extending farther on for a distance of two meters. Approximately twenty bats, some with a white coloration, and some with a brown coloration were observed flying about near station 9E.

Figure 18. The "chaise longue" rock in Ghostly Cave, on which the right-handed geologist is holding an ancient left-handed throwing stick.

Figure 19. White gecko eggshells attached to the wall of Ghostly Cave.

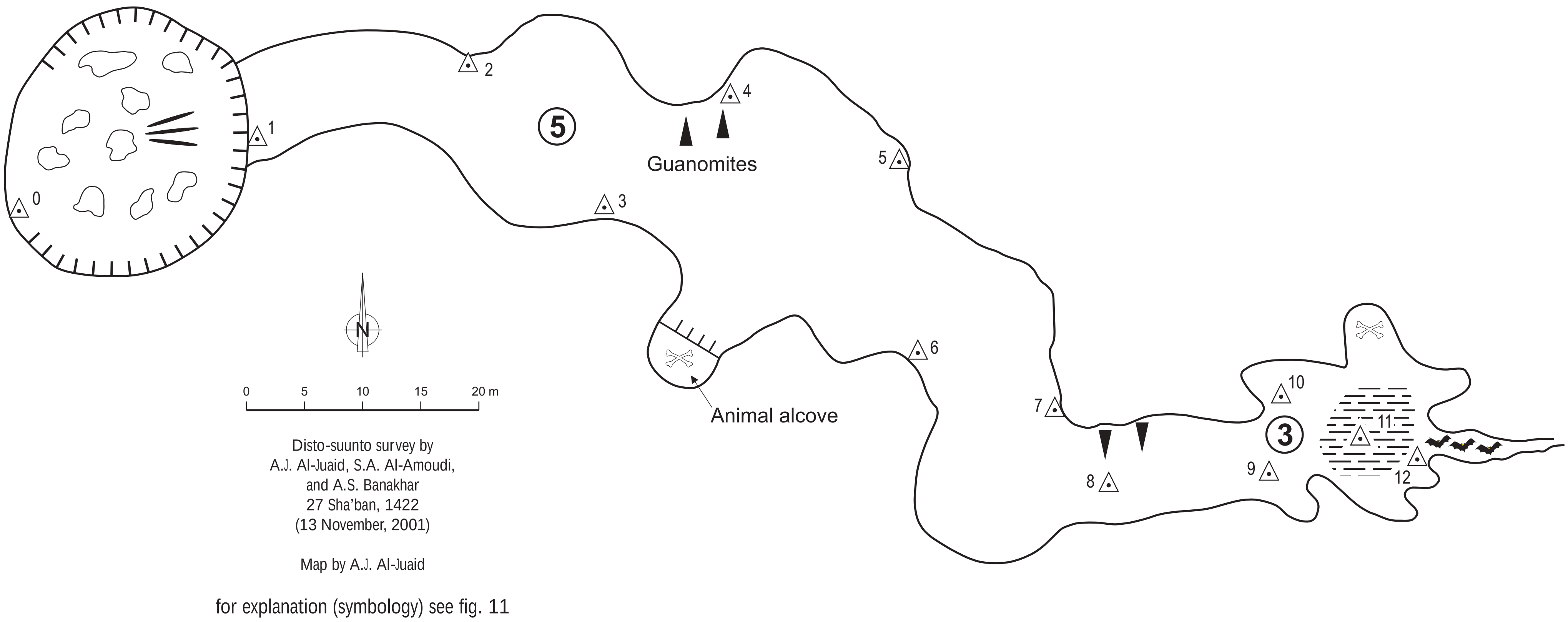


Figure 20. Map of Kahf al Mut'eb Cave in Harrat Kishb.

KAHF AL MUT'EB

The latitude and longitude of Kahf al Mut'eb are given in Pint, J., 2002 (updated July 2002). The cave map is shown in Figure 20. The relationship of Kahf al Mut'eb to Kahf al Ashbaah can be seen in Plate 2. The entrance to Kahf al Mut'eb is in smooth, hard lava containing columnar cooling joints, with a surface scatter of loose lava blocks. It is an elliptical collapse feature where part of the roof of the cave has collapsed. The cave and the tunnel exist in a sinuous ridge of lava, which partly wraps around the edge of the older cone (Figure 21). There are a series of these pressure ridges or folds in the upper part of the lava flow as indicated by the orientations of the columnar joints seen above the cave entrance. The upper two meters of the flow must have been solidified when the ridges formed and this is the thickness of the lava in the roof of the cave. The lava tube inside the pressure ridge of lava also curves around the older cone obstruction.

The entrance to the cave is a flat-lying tunnel with an elliptical cross section. Across the front of it is an ancient man-made wall of basalt blocks, 2 m in height (see Appendix 1). Man has used the cave at some time in the past, and the defensive entrance wall contains blocks of vesicular basalt up to 60 cm long. The wall has acted as a dam to sediment being carried into the cave by streams of rainwater runoff, so there is a steep drop into the cave on the inner side of the wall.

Inside, the elliptical passage shows indentions and flow marks along the sides, and the floor is covered in debris, mostly water-channeled sand and gravel of basaltic fragments, together with a number of large blocks. These blocks have not all fallen from the roof, but appear to have been pushed aside by human activity in the past. If the cave has a simple elliptical channel, then the fill of sediment near the entrance is about one quarter full, because the widest part of the lava tube is about 1 to 1.5 m above the floor of the cave (Figure 22).

Just inside the entrance to the cave, along the south wall, there are a series of well-preserved lava levées (sometimes called lava ledges). These are ridges running parallel to the roof and floor of the lava tube and are remnants of molten fills in the tube. There are three levels preserved on the walls of the cave with 30 cm between the lower and middle levels and 60 cm between the middle and upper ones. Remnants of the same lava levées are present on the north side of the lava tube, but are less well preserved there, because blocks have fallen off the wall.

At Survey Station 1 the roof of the lava tube is not smooth, but contains a series of dome-shaped cavities, about 2 m in diameter, indented into the roof about 20 cm deep, where slabs of the roof have spalled off. In the tops of these areas columnar joints are visible.

Figure 21. The entrance to Kahf al Mut'eb Cave which follows the sinuous pressure ridge visible in the top of the lava flow. The ridge arcs around the older obstructing scoria cone to the right.

Figure 22. The spacious interior of Kahf al Mut'eb cave showing the internal form of the lava tube. About one quarter of the lava tube is here filled with fluviatile sediments.

At Survey Station 2, 44.1 m inside the cave, which is about the limit of natural light, there is abundant evidence of life. The sandy floor is covered with stacks of "guanomites" or bird droppings, which are up to about 40 cm high, and the walls of the cave are covered in thousands of knobby clay wasps' nests (Figure 23). The loose blocks of basalt on the floor of the cave are no longer found east of Station 2, and from Station 2 to 6, the floor of the cave is mainly sand with occasional ripple marks and a very broad water channel occupying most of the floor. These indicate that each time it rains, water flows into the cave and floods it.

Figure 23. Clusters of abandoned wasps nests built of clay on the walls of Kahf al Mut'eb.

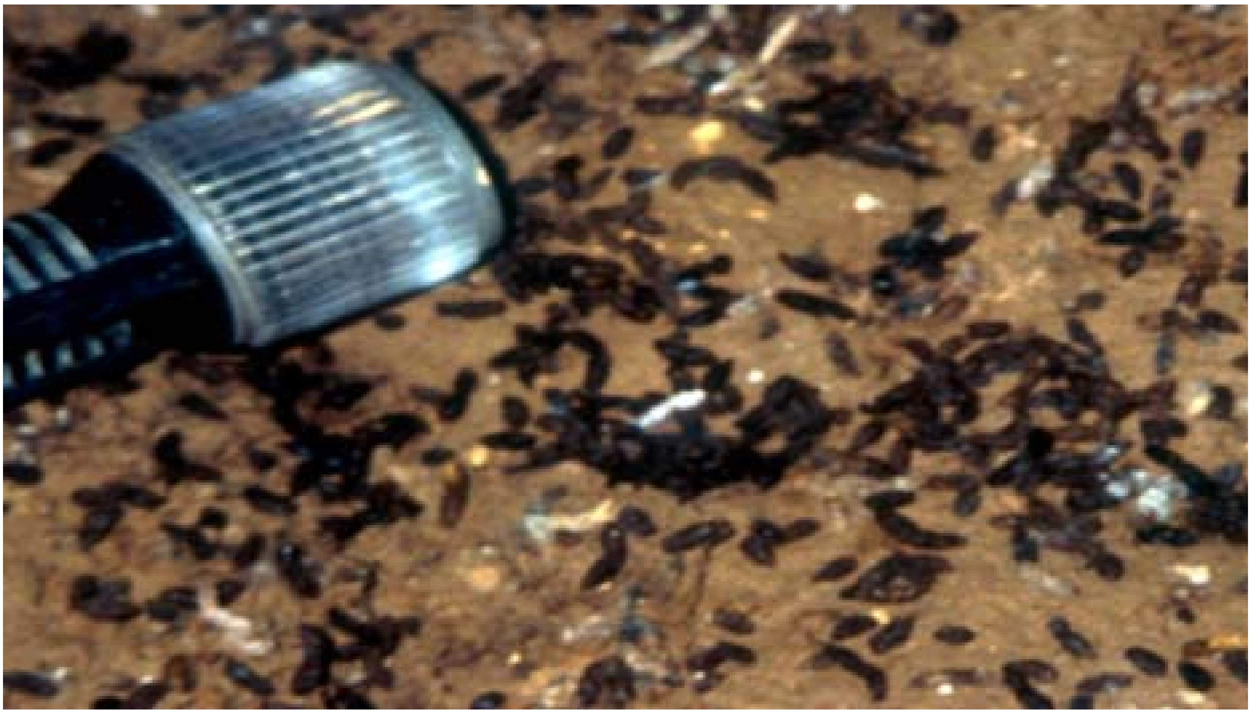


Figure 24. Fresh bat droppings on the wet floor of Kahf al Mut'eb.

The wasps nests are not found east of Survey Station 4. The bird droppings continue into the dark part of the cave until the point where the entrance is no longer visible (Station 6). Fresh bat droppings were seen on the wet sandy floor (Figure 24) between Stations 4 and 5.

Opposite Station 4 (44 m from the entrance), there is a recess that indents the south wall of the main lava tube. This is a flat shelf at a level about 3 m above the sandy floor of the cave. On the flat shelf, there are some animal droppings and an intact lower jaw of a camel, fragments of other camel jaw bones, some large bones probably from the legs of a camel, and at the east end of the shelf the roof has collapsed forming large blocks more than a meter in size, and pieces of firewood stacked and thrown around the collapse. On the roof above the bones, there is minor water seepage with two stalactites (carbonate/sulfate) less than 4 cm long. Nearby on the roof is a patch of dark sticky red-brown bat urine.

East of Station 4, the roof and walls of the lava tube are covered with a white encrustation of what is probably gypsum/anhydrite. This coating is being eroded at the present time and represents water seepage from a time in the past when rainfall was higher (Figure 25). In the same area are preserved original parts of the lava tube, distinguished by the presence of many small lava stalactites (these are lost where the spalling from the roof has occurred). They are short and stubby in form and only about 4 to 6 cm long (Figure 26).

Figure 25. The roof of Kahf al Mut'eb cave showing the eroding thin layer of gypsum/ anhydrite.

Figure 26. Short stubby basalt lava stalactites on the roof of Kahf al Mut'eb.

At Station 6 (66 m east of the entrance), the sand on the floor of the cave is wet with many ripple marks indicating flow into the depths of the cave. The white gypsum/anhydrite coating on the roof is no longer present and bird droppings were not observed. There are many patches on the roof preserving lava stalactites less than 4 cm in length.

Immediately east of Station 6, the roof shows considerable collapse, but the fallen blocks are not visible and presumed to be buried under the wet sand floor. Inside the collapse areas in the walls, the basalt contains sheets of gas bubbles about 5 cm apart, which parallel the elliptical walls of the cave. Because sheets of gas bubbles like this are usually flat, lying parallel to the flat surface, the structures observed are inferred to be the folded upper part of the flow.

Just east of Station 8 (86 m from the entrance), on the north side of the cave, a curtain of basalt lava hangs from the roof. It resembles the keel of a ship and is elongated along the passage of the cave (Figure 27). Here, the main passage is arcuate, and the 2 m curtain hanging from the roof separates a smaller arcuate cave, about 1.5 m, wide from the main lava tube. The curtain is wedge-shaped and 6 m long. One end is broken off, to reveal an internal layered structure parallel to the outer form of the curtain, suggesting that it was built up by the addition of layers of basalt lava onto an irregularity in the roof. The basalt coatings vary from 3 to 6 cm in thickness.

At Station 10 (109 m from the entrance), there is a solitary basalt stalactite on the roof from which bats hang. There are bat droppings below it, on the floor, and on the ceiling, bat urine has been sprayed, resulting in a sticky coffee-color-dark brown stain.

At the eastern end of the cave, a wet sandy floor rises to meet the gently sloping roof where the tube is filled with sand (Figure 28). Because the cave is filled with sediment and is eventually blocked, the greatest thickness of sediment (perhaps 4 m) is in this deepest part of the cave. Here, the floor is distinctly clay-rich with well-developed 5-sided columnar jointing due to shrinkage as the clay dries. At the easternmost point of the cave, immediately under the roof, are a series of circular pits about 50 cm deep with clay dust rims. These are dust volcanoes caused by air escaping the filled tunnel when rainwater floods the sediment fill of the buried tube (see Appendix 4). On the floor, pieces of bones and firewood are scattered about. There are also water-level marks of mud on the walls, indicating that the back of the cave floods to a depth of about 1 m (Figure 29).

Figure 27. The lava keel curtain of basalt built up of successive layers on the roof of Kahf al Mut'eb.

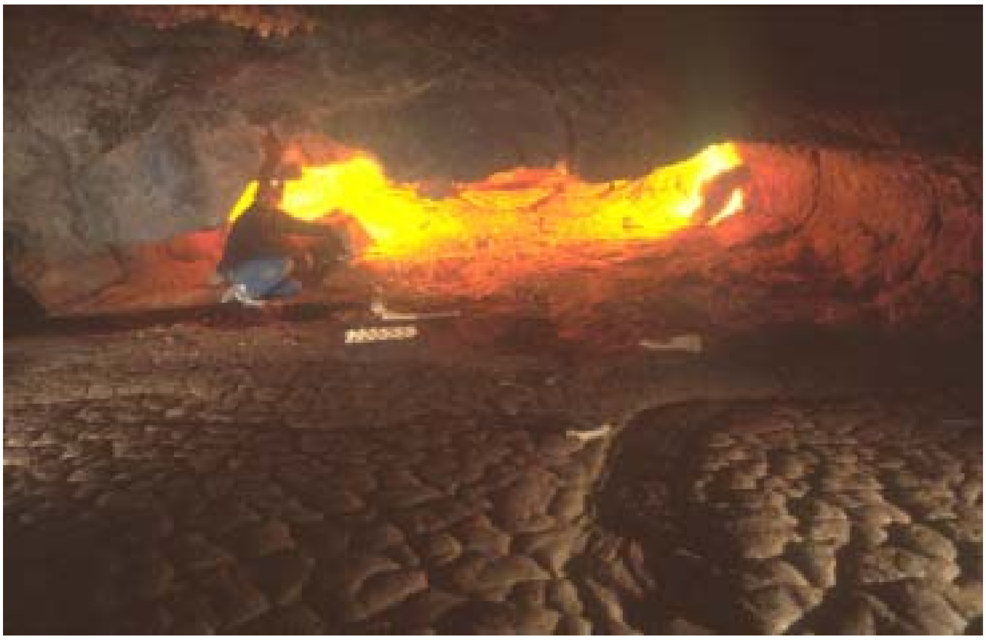


Figure 28. Artificial lighting at the back of Kahf al Mut'eb, showing where the sediment fill has almost reached the roof, the mudcracked floor of wet sediment, and scattered animal bones.

Figure 29. Cave surveyors at the back of Kahf al Mut'eb. The lower 1 m of the cave walls are stained by mud after the cave has been flooded.

BUSHY CAVE

Bushy cave is a small lava tube situated in weakly eroded pahoehoe basalt lava flows of quaternary subunit Qh3 of the lower Hil basalt (Plate 2). The latitude and longitude of Bushy Cave are given in Pint, J., 2002, (updated July 2002). The relationship of Bushy Cave to Kahf al Mut'eb and Kahf al Ashbaah can be seen in Plate 2. Topographic contours (Plate 2) can be used to indicate that the host lava flow is at least 5 km from its source vent. The cave lies on the north side of an older eroded cone of red agglutinated spatter of Quaternary subunit Qh1 of the Hil basalt.

The entrance is inside a circular collapse area in the top surface of the lava flow, 6 m in diameter and 2 m deep. Rubble inside the collapse slopes downwards towards two large bushes at the south end. Behind these bushes, there are two cave entrances leading to the same room (Figure 30). The western entrance is blocked by vegetation, but the cave can easily be entered through the eastern entrance, which is about 1 m high and 60 cm wide.

Figure 30. The circular collapse entrance to Bushy Cave.

Bushy Cave is a single room 13 m long. The height is 1.2 m at the north end, increasing to 1.8 m at its highest point near the middle. The room is 6 m wide.

There is a thin coating of calcite on the cave roof, caused by leakage from the surface through small cracks. At the entrance, less than ten mud cracks were observed, but otherwise, the floor was sandy, dusty and dry with no sign of past water flow.

The presence of large green bushes and trees growing inside collapsed lava tubes in otherwise sterile areas of basalt, was successfully used by Simons (1998) and members of the Cave Exploration Group of East Africa (CEGEA) to locate caves in the lava fields of the East African Rift Zone of Kenya. In future, this approach will be tried in the Cenozoic lava fields of western Saudi Arabia.

WINDOW CAVE

The latitude and longitude of Window Cave are given in Pint, J., 2002 (updated July 2002). Window Cave measures only 1 m in length from front to back and strictly speaking is not really a cave. It was mistaken for a cave because it throws a dark shadow that stands out on a hillside. In Figure 31, it can be seen to occur in coarse stratified lithified pyroclastic deposits on the flanks of a large tuff ring associated with a filled maar crater of subunit Qh3 of the lower Hil basalt (Plate 2). Large blocks of basalt up to 3 m in diameter ejected from the maar crater are scattered in the area. They were hot when they were ejected as indicated by polygonal jointing that formed when they cooled. Such blocks are referred to as “hot blocks” in pyroclastic literature.

The cave is oriented 270° on the bank of a dry-stream bed or gully only 2.5 m wide that is filled with boulders and rock fragments of all sizes. The gully originates at a point only 10 to 12 m above the level of the cave. The entrance is 1.7 m wide and 30 cm high. Inside, the cave is 2 m wide, 1.0 m long, and 35 cm high.

Window Cave is not a lava tube, but formed by water erosion of a less lithified layer of pyroclastic material than its surroundings. It is included in this report because caves of this type are described as commonly associated with lava-tube caves in the volcanic areas of the East African Rift Zone. They have been described by Simons (1998), who refers to them as “tuff and agglomerate caves”. He reports that such caves make up about a third of all caves in the volcanic areas, where they are associated with rivers, and may reach 300 m in length with chambers up to 100 m wide.

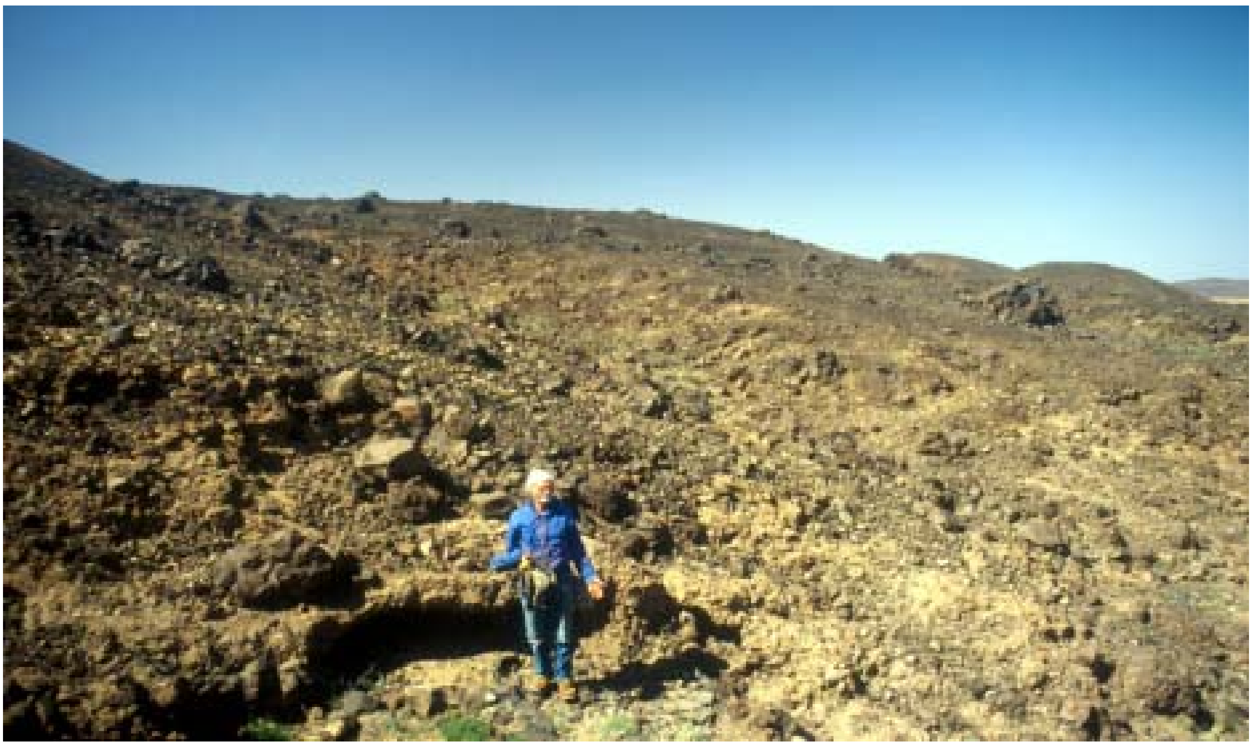


Figure 31. Photograph of Window Cave – the dark shadow behind the speleologist’s legs. The host rock is crudely stratified agglomerate with ejected “hot blocks” of basalt.

A LAVA TUBE IN SUBUNIT Qh1 OF THE HIL BASALT (DAHL FAISAL)

A single lava-tube cave was shown to the Caving Team by Mr. Faisal Allam and named Faisal's Cave (Dahl Faisal). The latitude and longitude of Dahl Faisal are given in Pint, J., 2002 (updated July 2002). It is situated on northern Harrat Kishb on the Jabal Zuwayr volcano (Figure 2) with two large lava flows (Figure 32). These flows were named "whaleback" lava flows by Roobol and Camp (1991a) who described them as follows:

> The term "whaleback" lava flow was introduced by Roobol and Camp (1991b) to describe large-volume pahoehoe flows on Harrat Khaybar that superficially appear to be chains of coalesced shield volcanoes. Unlike lavas extruded into sloping ground that could form long thin flows, those erupted onto flat ground appear to have heaped up and propagated themselves by upward rupturing of a main arterial lava tube. Thus they built up a chain of coalesced shield-like volcanoes with rootless vents that descend systematically away from the center of the harrat. The Jabal Zuwayr landform on northeastern Harrat Kishb resulted from a single eruption which produced two "whaleback" lava flows of similar age. They are the only examples exposed on Harrat Kishb.
>
> The two Jabal Zuwayr "whaleback" lava flows (Figure 32) are the only known examples on the Arabian harrats of completely exposed "whaleback" flows where the vent area can be seen (on Harrat Khaybar the vents of the 39 "whaleback" flows are all hidden beneath younger basalts). A single sample from Jabal Zuwayr is composed of hawaiite. The main vent is marked by two elliptical, flat-bottomed craters, the largest of which measures 250 by 150 m and is oriented about 340°. This crater morphology is typical of the basaltic shield volcanoes of the Arabian harrats. From the craters one lava tube extends towards the northeast and another toward the southeast. The northeastern branch divided several times and the resulting lava tubes can be traced from the lines of collapse craters along the crests of the flow tongues (Figure 32). The northeastern "whaleback" lava flow is about 16 km long and the one to the southeast is about 7 km long.
>
> The two "whaleback" lava flows form morphologic highs, or ridges, with low-angle slopes – crest slopes are about 1.5° and the flanks slope at about 0.5°. On the crests of the flows near to the vent, there are lengthy meandering channels formed by the collapse of the roof of the lava tube. In more distal parts of the flow, collapse was sporadic and chains of collapse craters occur. The surface features of the flows have been obliterated by erosion; the surfaces now consists of gravel and cobbles, and the collapse craters have been largely infilled with wind-blown dust. Helicopter reconnaissance showed that the collapsed lava tubes and lines of craters are remarkably sinuous and have a morphology similar to lunar rills.

DAHL FAISAL

The latitude and longitude of Dahl Faisal are given in Pint, J., 2002 (updated July 2002). A map of the cave is shown in Figure 33. This lava-tube cave is accessed only through a small hole, 80 cm in diameter (barely visible from a few meters away).

To enter the cave, one must slide down through a 3 m-long-tube, which is on a 60° angle. The smooth, rounded curve of this entrance tube suggests that it may have been formed by the suction of outside air as lava flowed out of the lava tunnel below (Figure 34). Part of this entrance tube is coated with white calcareous tufa up to 3 cm thick. From the entrance tube, one steps onto a pile of stones placed there long ago to serve as something like stairs for easily entering and exiting the cave (see Appendix 1).

The ceiling of the cave is 4 m above the sandy floor. At Station 1, lava levées can be seen on both sides of the cave, from 1 to 1.2 m high. These resemble shelves on the walls. Coprolites are found on these (Figure 35). In some places, liquid basalt has dripped down from the ceiling of the tube onto the edge of the levée and these stalagmites have further dripped down to form minor stalactites.

SGS Pubscenter Drafting section c:\gc\IMRM\Roobol\SGS-OF-2002-6\Fig. 32.cdr mrv: 29 July, 2002 g.c.certeza

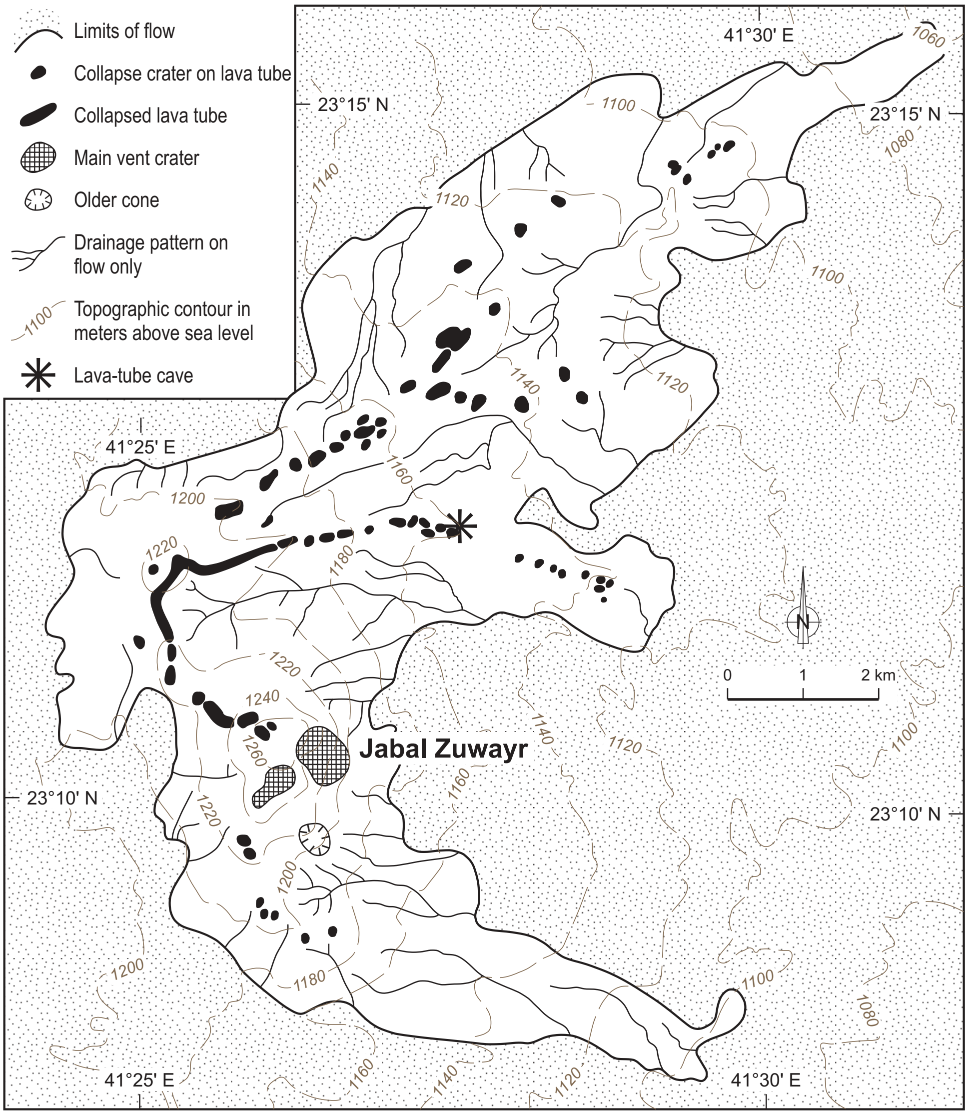


Figure 32. Jabal Zuwayr "whaleback" lava flows; branching collapsed lava tubes lead from the two vent craters and are marked by collapse craters at their distal ends. Jabal Zuwayr is part of subunit Qh_1 of the Hil basalt. The position of Dahl Faisal is indicated. (✳)

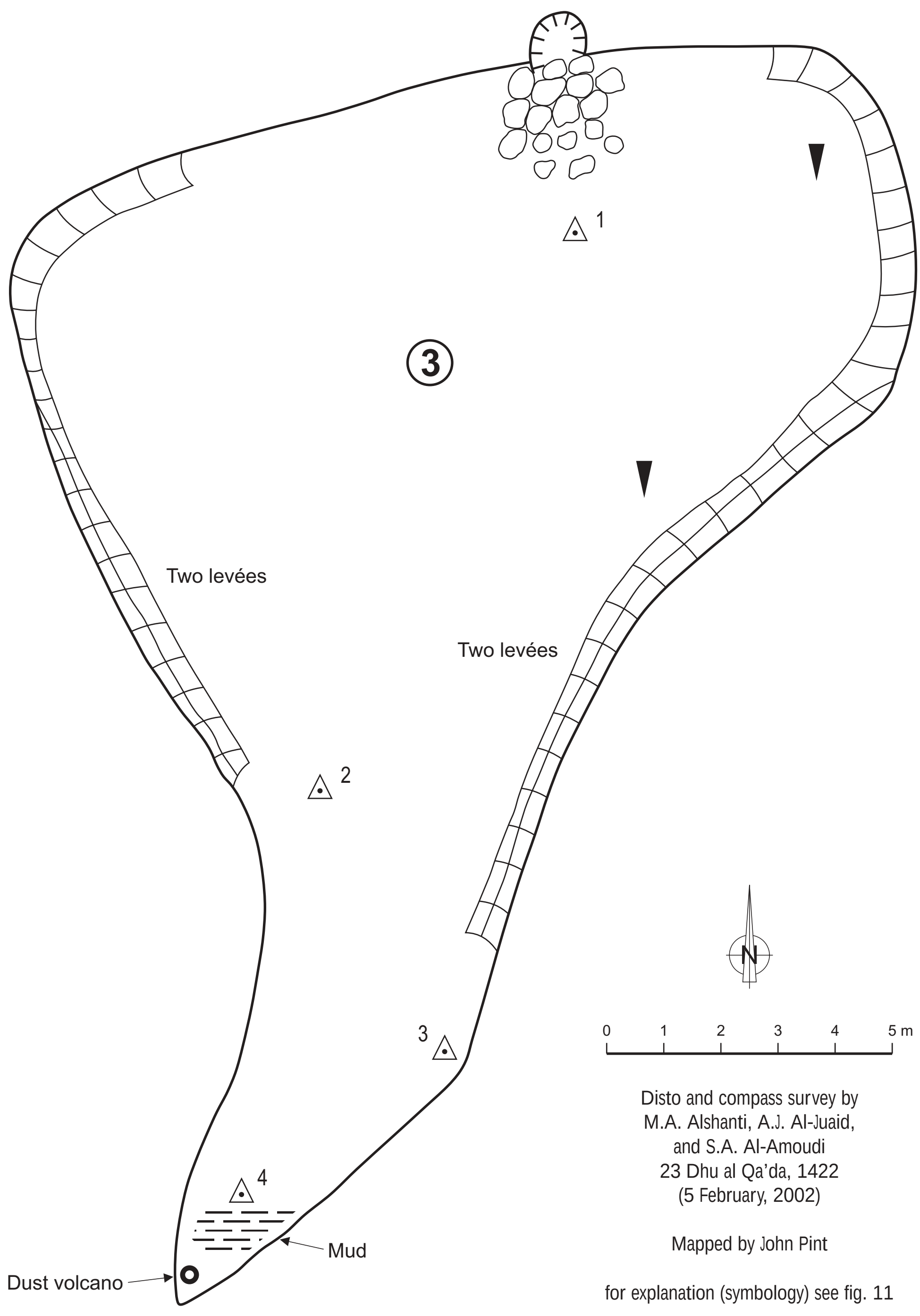


Figure 33. Map of Dahl Faisal Cave in Harrat Kishb

Figure 34. The entrance to Dahl Faisal showing the jointed lava surface dipping down into the entrance pipe.

Figure 35. Coprolites from Dahl Faisal.

Three meters south of Station 1, the lava levée on the east wall widens to 1 m (Figure 36) and is partially detached from the wall of the tube by an open fissure, again displaying the stalagmites/stalactites on its edge. Below this levée, 70 cm above the floor level, there is another lava levée, which shows that the lava level dropped twice as the lava tube was draining.

Four meters north of Station 2, the ceiling of the cave lowers to a height of 2.5 m (Figure 37). At Station 2, well-formed minor basaltic stalactites can be seen on the ceiling (Figure 38).

At the south end of the cave, near Station 4, the tube gets narrow and the ceiling gets lower, measuring 2 m wide and 1 m high. Here, wet mud covers the floor, due to recent rain and at the very back of the cave, 2 m southwest of Station 4, there is a circular crater in the mud floor, which might appear to be an animal's burrow, but is interpreted here to be a dust volcano with a central crater 40 cm in diameter and 20 cm deep (see Appendix 4).

Figure 36. The prominent, partly detached lava levée in Dahl Faisal.

Figure 37. The interior of Dahl Faisal where the roof descends towards the sediment fill of the floor.

Figure 38. Small lava stalactites on the roof of Dahl Faisal and some weakly developed lava levées on the side walls.

SOME OBSERVATIONS ON THE FORMATION OF THE KISHB LAVA TUBES

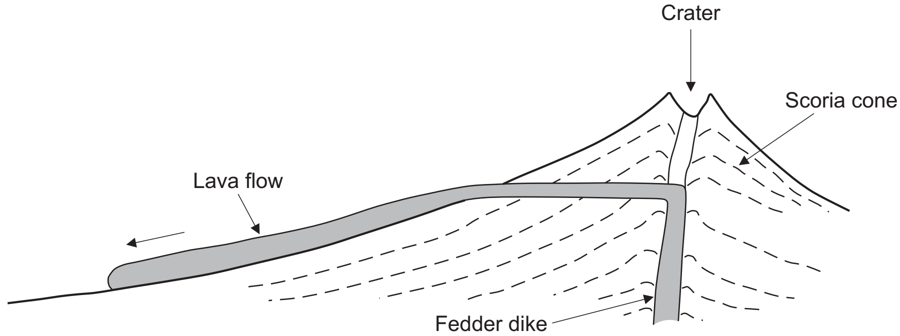
The three locations with lava tubes located to date on Harrat Kishb are in three different structural and physical positions relative to their parent volcanic cones. Although internally the lava tubes are very similar, their positions suggest three somewhat different mechanisms of formation.

Basically the formation of a lava tube can be regarded as similar to that of water entering a garden hose from a tap on the wall of a house (Figure 39A). There is a hydrostatic head equivalent to the difference in height of the distal (down-slope) lava front of the advancing lava flow and the height of the scoria cone where the lava is emitted. As a lava flow advances downslope, the margins of the flow become immobile and begin to solidify, while the newly emerging hotter lava continues to fill a central feeder channel. The main lava channel may become roofed over with solidified lava to form an arterial lava tube.

When lava ceases to be extruded at the vent or cone, the lava front may continue to advance downslope. This can only be achieved by emptying the arterial lava tube. By analogy with the garden hose example, if the tap is shut off and air enters the hose at the tap connection, the hose will empty from the tap towards the distal end as water continues to flow out from the hose (Figure 39B). This is the mechanism of formation of the 3 km long arterial lava tube of Jabal Hil, where collapses of the roof into the tube reveal it to have a height of 20 m and a similar diameter.

In the case of the Bushy, Ghostly (Kahf al Asbaah) and Kahf al Mut'eb lava tubes in subunit Qh3, the exposed lava tubes are situated about 7 km from the parent volcano. Their location is distinct because it is an area where the path of the advancing lava flow was blocked by the presence of an older cone. On the upside of the obstruction the lava flow piled up to a local height of 10 m above normal and a number of arcuate pressure ridges formed that arc around the obstruction (Figure 40A). Sometime later in the locally elevated area only, the lava drained away when the roofs of the tubes partly collapsed permitting air to enter the tubes to form the local cluster of open lava tubes (Figure 40B).

A.



B.

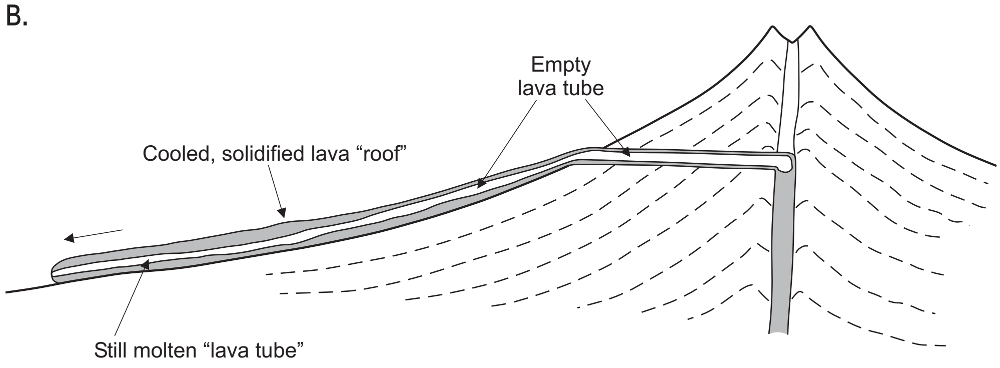
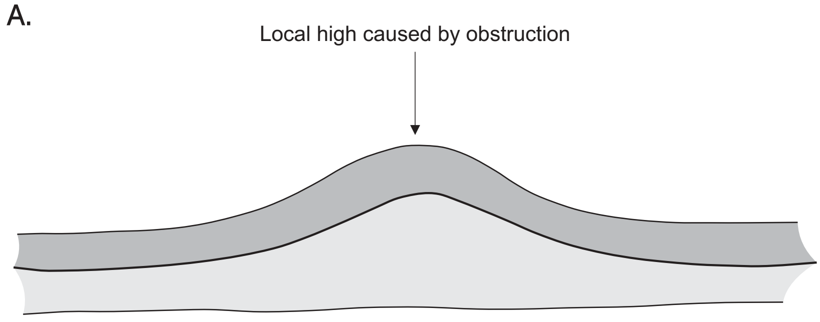


Figure 39. Diagrams to illustrate the mechanism of formation of a proximal lava tube

A.



B.

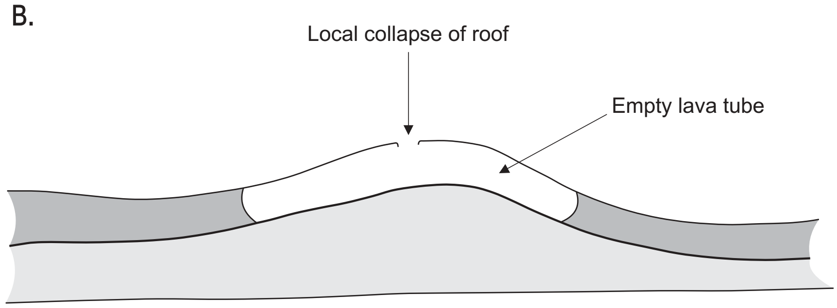


Figure 40. Diagrams to illustrate the mechanism of formation of a lava tube in an area of local highs

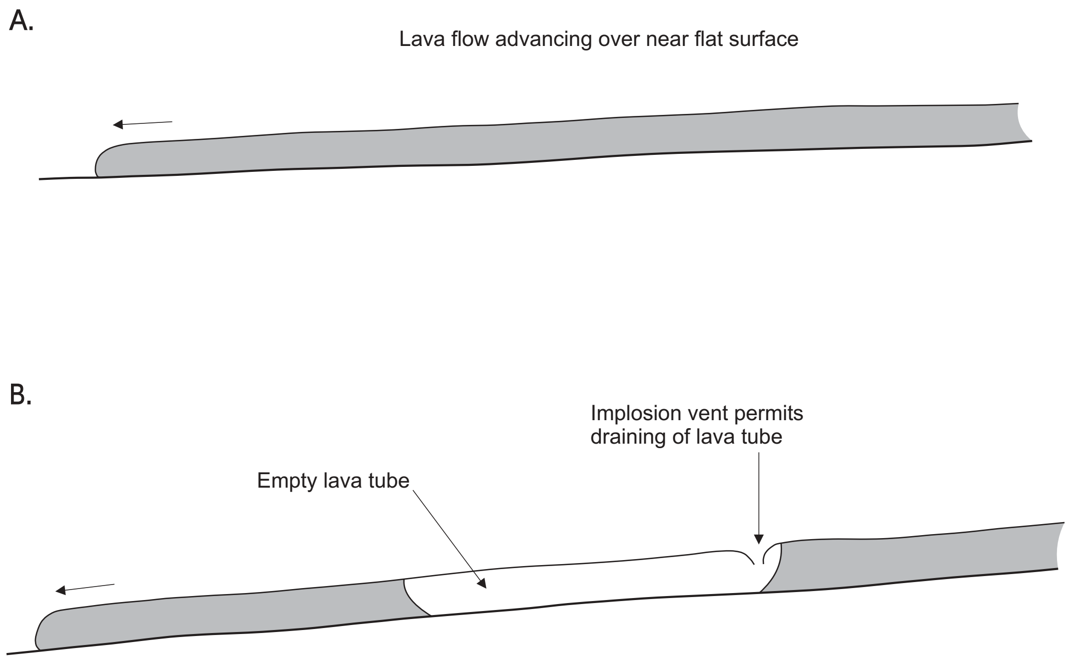


Figure 41. Diagrams to illustrate the mechanism of formation of a distal lava tube

In the case of Dahl Faisal's cave on Jabal Zuwayr the lava tube is distal to the parent vent but here, there is no obstruction, nor local topographic high. Rather the morphology of the entrance pipe with its locally depressed surface suggests a local implosion of the roof. This occurred at a thin point in the roof of the main lava tube, so that the still plastic hot rock of the roof was drawn down into a funnel-shaped entrance. From this point downslope, the lava tube drained so that there is a blind end to the tube on the upside of the entrance (unlike, for example, Figure 40B). The mechanism is suggested in Figures 41 A and B.

CONCLUSIONS AND RECOMMENDATIONS

This report confirms earlier mentions of the existence of lava tube caves on the harrats of Saudi Arabia. The report goes further in identifying more of these structures as well as providing the first underground surveys of examples in Saudi Arabia. The results suggest that lava tube caves may be far more common in Saudi Arabia than previously realized.

As seven caves were found in only a small area during this first search, it is likely that many such caves exist elsewhere in the Cenozoic lava fields of Saudi Arabia.

The initiation of the cave project was because of the planned development of tourism in Saudi Arabia, when selected caves will be opened for commercial exploitation. However, the Cave Mapping Program has pointed to the possibility of hundred of caves, both in the limestone of northern and eastern Saudi Arabia and the presence of lava tube caves in the west. A large number of caves in all parts of Saudi Arabia is an unexpected result of the Caves Survey Program. Owing to the security and strategic importance of a large number of caves, it is recommended that the search, exploration, and surveying be continued, for what is emerging as a new resource for Saudi Arabia.

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APPENDIX 1

EVIDENCE OF PREHISTORIC USE OF THE CAVES – STONE WALLS AND RAMPARTS AT ENTRANCES

Most of the caves show evidence of human use in the form of defensive stone walls at the entrances and stone piles or ramparts to gain access. Many of these are inferred to be ancient as they are largely buried beneath fluviatile sediments and rock-dove guano deposits. Figure A1-1 shows the entrance collapse feature of Ghostly Cave. Access today is by a wire-cable ladder onto a pile of basalt slabs placed there in antiquity. A wooden ladder or tree trunk would have given access from the top of these slabs in the past. Figure A1-2 shows the area of guanomites near the entrance to Ghostly Cave. An ancient stone wall can be seen which is largely buried under the guano deposit. Figure A1-3 shows the entrance to Kahf al Mut'eb Cave, which has a defensive wall across the entrance. This wall has acted as a sediment trap, so if viewed from the outside (Figure 21) the wall is barely visible because of the sediment ponded against it. Figure A1-4 shows the entrance to Dahl Faisal where a ramp of loose basalt blocks has been constructed to facilitate access.

Because of the easy access into most of the caves there is evidence in them of use by animals as well as people. Most contain the bones of large vertebrate animals (mainly camel) probably brought in by hyenas whose possible coprolites can be found. In addition there are the bones of small animals that died in the caves such as mice and bats. Artifacts by ancient humans include two wooden throwing sticks (Appendix 2), cord (Appendix 3), and firewood.

Figure A1-1. The entrance to Ghostly Cave showing the pile of basalt slabs set by ancient man who probably used a wooden ladder for access.

Figure A1-2. The guanomite area of Ghostly Cave showing an ancient stone wall largely buried in the guano.

Figure A1-3. The ancient wall across the entrance to Kahf al Mut'eb Cave. The walls have acted as a sediment trap and outside fluviatile deposits reach the top of the wall.

Figure A1-4. The man-made stone rampart below the entrance to Dahl Faisal made by ancient people.

APPENDIX 2

TWO ANCIENT THROWING STICKS FROM GHOSTLY CAVE

Two ancient throwing sticks (Figure A2-1) were found in fissures in the walls of Ghostly Cave, where they were preserved from the wet floor of the cave. The larger one measures 56 cm long by 4.5 cm wide and is 1.7 cm thick. The smaller is 45 cm long, 4.2 cm wide and 1.7 cm thick. Both are made from camel thorn wood. This is a particularly hard dense wood favored by local modern populations as the wood, used for cooking fires, burns with minimal smoke. The throwing sticks are made from the branches of the tree, where the wood is white, rather than the dark red wood of the trunk. The wood grain shows that the tree branch was naturally curved. Because the wood is from the branches, it contains many wood knots. Each stick shows where such a knot has fallen out, but the grain passes around the hole indicating that it is natural. Throwing sticks are known in Saudi Arabia from petroglyphs at Jubba and Hanakiya where they have been described and illustrated by Nayeem (2000) and attributed to Neolithic populations about 7,000 years ago. At this time the climate of Saudi Arabia was more moist (Edgell, 1990b), so that the flora and fauna would have been considerably different and much richer than today, as indicated on the petroglyphs of Saudi Arabia where lions and hunting scenes depict aurochs (wild cattle) and wild camels.

Throwing sticks rotate in the air and generate lift. Unlike a spear, which has no lift and has to be thrown above the target as it travels in a curve, the flat nature and rotation of the throwing stick ensure that it travels straight to the target. Distances of 150 m are commonly achieved. They are used for hunting small birds and rabbits and have also been called kylies and rabbit sticks. In more recent examples (but not those from Ghostly Cave) they can have an aerodynamic form like the wing of an aeroplane. The two examples from Ghostly Cave are flat on one side and symmetrically rounded on the other. Throwing sticks are rather like aircraft wings and can be made to be thrown by the left or right hand. As shown in Figure A2-1, the wing push is on the left-hand side not the right. As seen in Figure A2-1 the upper rounder surfaces are shown with the shorted end on the right side. This would indicate that both of the sticks are left-handed throwing sticks and the owner was left-handed. When thrown by the left hand, they rotate in a clockwise direction. The opposite is the case for right-handed sticks.

The problem of symmetrical cross sections in the throwing sticks has been commented on by an engineer from a local airline as follows (Dr. Martin Danks, written communication, 2002):

> "The fact that its cross sectional shape is symmetrical isn't an issue, since aerodynamic lift will still be produced when it is thrown inclined to the airflow. Note that the wings of aerobatic aircraft are usually symmetrical in order to ease inverted flight and that at zero incidence a symmetrical aerofoil produces zero lift. A non-symmetric or cambered aerofoil produces lift at zero flow incidence: its zero lift angle is negative. With this in mind, a cambered boomerang is probably easier to throw than a symmetrical boomerang as the skill of releasing the boomerang at an incidence that produces a lift force in correct direction is less critical."

Ancient throwing sticks are found in Egypt, Sub-Saharan Africa, Poland, the Netherlands, the United States, and Australia. The oldest known example is from Poland and is made of mammoth ivory and has been radiocarbon dated at 20,000 years. Studies of aboriginal peoples in Australia have shown that throwing sticks are also used for digging up plant roots, as clubs, for cooking and for rubbing and banging together to make music.

Figure A2-1. The two ancient throwing sticks found inside Ghsotly Cave.

APPENDIX 3

THE KNOTTED CORD FROM KAHF AL MUT'EB CAVE

The cord is shown in Figure A3-1. It was found beneath a rock in Kahf al Mut'eb Cave in a dry side area. The cord is 40 cm long and composed of two strands twisted together and each composed of long plant fibers, rather than animal hair as used by some local inhabitants today due to the paucity of fibrous plants in the hyperarid present climate. It was knotted when found and hidden beneath a basalt block. Knotted cords of this type have been regarded to be associated, for some people, with the placement of a curse or spell.

Figure A3-1. The knotted cord from Khaf al Mut'eb Cave after the knot was undone.

APPENDIX 4

DUST VOLCANOES

These may be a previously unrecognized geological feature characteristic of caves in hyperarid regions, where the caves are partially infilled by sand and wind-blown dust and subjected to rare flooding by streams of rainwater runoff from surrounding rocky surfaces.

During our investigation, two of these structures were seen in the farthest reaches of the back of Kahf al Mut'eb cave. They were difficult to reach, as they are close beneath the basalt roof of the lava tube, which plunges beneath the cave floor of younger sediment fill. They are ring structures about 70 cm in diameter, with a rim about 20 cm high and a central conical hole that is deeper than the floor of the cave. Although most of the cave floor was wet after recent rain with ripple marks and stream channels in a sand-dust mixture, the floor at the very back of Kahf al Mut'eb is elevated about 10 cm higher than the wet floor and remains dry, so that the dust volcanoes were dry. At the time of our visit, they were quickly passed over as probable animal nests, but attention was drawn to the very dusty state of the cave walls in the vicinity as they are too far inside the cave to be affected by blowing wind. Later, when the single example shown in Figure A4-2 was found at the back of Dahl Faisal cave, the whole area had been flooded by stream water leaving mud levels on the cave walls at the very back of the cave. Although this third example has been immersed in water (Figure A4-1) its form is still perfectly preserved.

Both Kahf al Mut'eb and Dahl Faisal caves have entrances situated on flat basalt lava, so that rainwater runoff enters the caves and largely floods the floor. The recent rain at the time of our visit on Harrat Kishb is the first for about five years and the desert had become very dry. It seems that over such a time period in a hyperarid climate, cave sediments can dry out. The sudden flooding of the floor of the cave produces stream channels and ripple marks. The water has no outlet other than to sink down into the sediment filling the lava tube at lower levels. In order for the rare floods of rainwater to sink into the cave-fill sediments, air from within the pore spaces of the dry sediment must be expelled. This is commonly seen in desert streams when it rains, or on a sandy seashore as an incoming tide advances with waves over dry sand driving streams of air bubbles from the sediment. Such a process cannot occur where the lava tube is filled with sediment to the roof. Thus, air trapped in a filled lava tube will rise to the roof area. Those will be channeled beneath the lava roof to emerge through the cave floor at the deepest recesses at the back of the cave. The proposed mechanism is illustrated in Figure A4-2. Because this process operates in dry dust, the walls at the back of the cave become coated with dust. The term "dust volcano" was devised here to describe them. The mechanism and structure are wholly sedimentary, but the process is not unlike that of the formation of "sand volcanoes" in submarine sediments caused by dewatering of compacting unlithified sediment.

Figure A4-1. The dust volcano at the very back of Dahl Faisal.

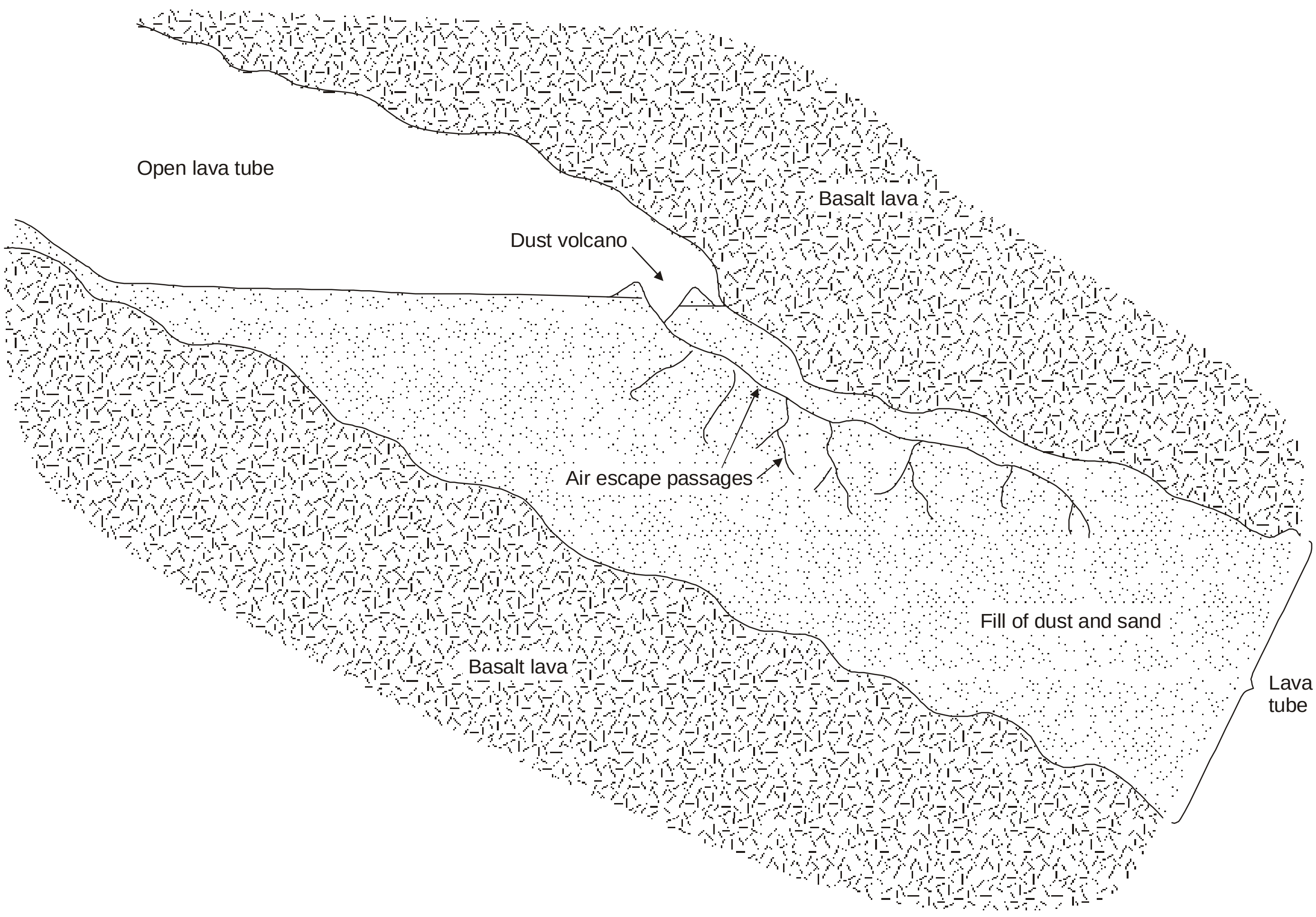

Figure A4-2. Diagram illustrating proposed mechanism of formation of a dust volcano at the back of a lava-tube cave. Flooding of the floor in rare wet periods of rainfall causes saturation of the sediment fill. Trapped air is forced out along the buried roof to vent as a dust volcano.