BCRA TRANSACTIONS

BRITISH CAVE RESEARCH ASSOCIATION

Volume 8 Number 3 September 1981

BRITISH CAVE RESEARCH ASSOCIATION

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Speleological expeditions have a moral obligation to produce reports (contractural in the cases of recipients of awards from the Ghar Parau Foundation). These should be concise and cover the results of the expedition as soon as possible after the return from overseas, so that later expeditions are informed for their planning. Personal anecdotes should be kept to a minimum, but useful advice such as location of food supplies, medical services etc., should be included.

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Cover photo: Smooth, sub-circular passage forms with conical stalactites may indicate that this part of Kazumura Cave, Hawaii, carried full-bore flow.
Photo by A.C. Waltham.

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EXPLORATION AND GEOLOGY OF SOME LAVA TUBE CAVES ON THE HAWAIIAN VOLCANOES.

(Report of the U.K. Speleological Expedition to Hawai'i Island, 1979)

by C. Wood.

Abstract

Many of the surface lava flows of the great Hawaiian shield volcanoes were probably fed internally via lava tubes, and this tube-fed effusive volcanic process may be responsible for the low-angled forms of these volcanoes. The recent U.K. expedition to Hawai'i Island investigated this hypothesis by seeking out, exploring and mapping caves which were the drained parts of former lava tube systems on the active volcanoes Mauna Loa and Kilauea. The expedition mapped 24km of cave passage and found lava tube caves of world significance in terms of their dimensions (lengths extending up to 11.713km in Kazumura Cave), their morphologies, and their internal lava formations. Cave surveys illustrate the forms of lava tube systems, and provide data upon which studies of the mechanics of tube-fed flow may be made. Geological observations within the caves contribute toward a better understanding of tube construction and operation.

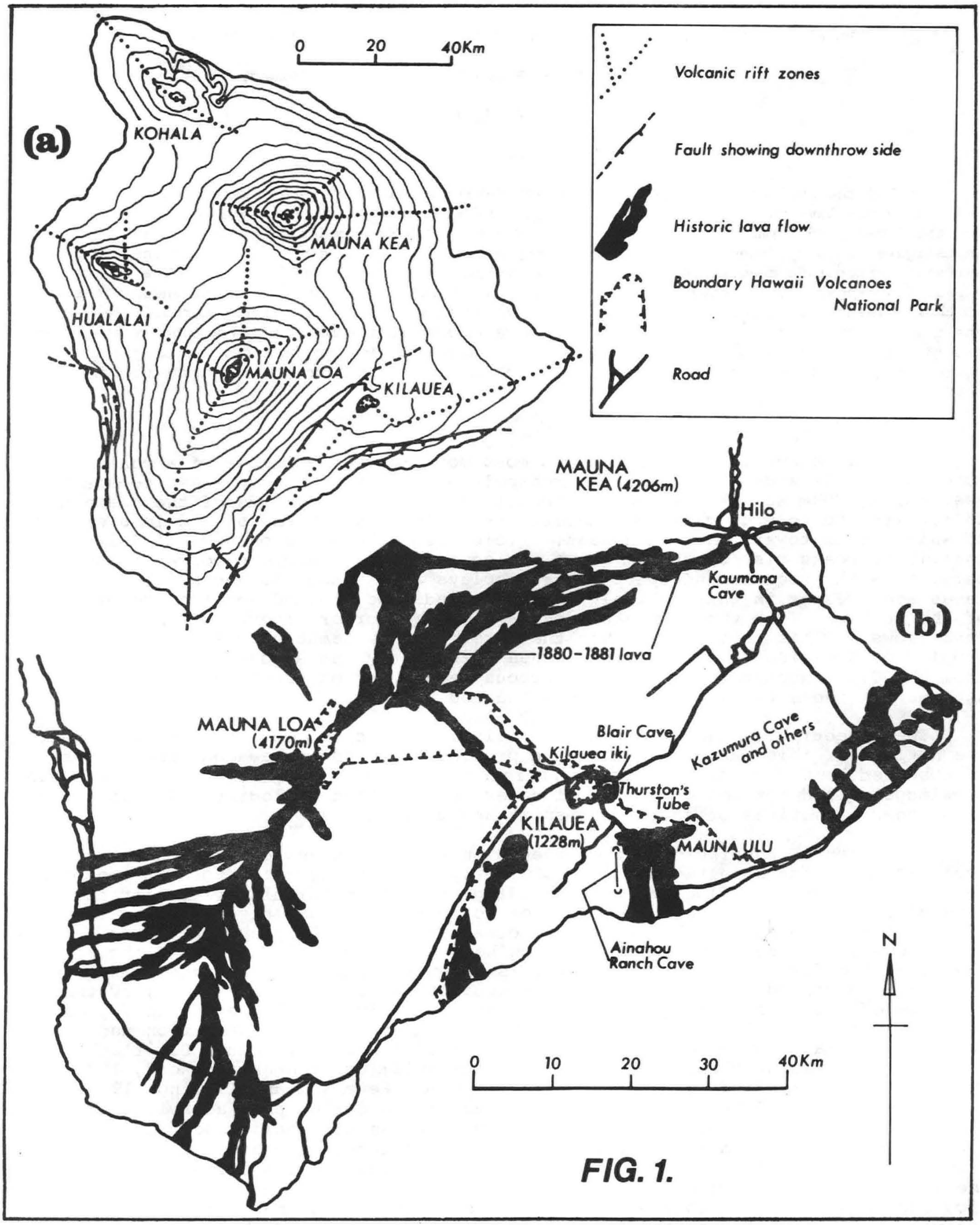
Hawai'i Island is the largest and most south-easterly member of a chain of more than 50 islands (the Hawaiian Archipelago), stretching north-west to south-east for 3,500km across the central Pacific Ocean. The islands of the chain are in reality the tops of many huge undersea volcanoes, the youngest and less eroded of which occur toward the south-east. Volcanism culminates on Hawai'i Island, where individual peaks rise over 9 km above the ocean floor, and where volcanic activity persists with frequent and spectacular displays from Mauna Loa and Kilauea. Caves are present in this entirely volcanic landscape, formed not from solution of the rock but from the segmental drainage of the former arteries of basaltic lava flows. This report describes the first ever systematic exploration and mapping of Hawaiian lava tube caves, when during July and August, 1979, a team from the U.K. encountered caves of enormous length and of great scientific interest on the active volcanoes Mauna Loa and Kilauea.

RATIONALE

The objective of the expedition was simply to locate, explore and map caves. The motive for this was scientific - to provide some knowledge about the process of tube-fed lava flow on the Hawaiian shield volcanoes - though the pursuit of this knowledge called for the expertise of cavers rather than geologists, who were also encouraged by motives of adventure, sport and competition.

The scientific purpose of the expedition relates to new concepts about the evolution of major basaltic landforms. Newly erupted lava will possess one of a number of distinctive flow styles, depending upon its particular viscosity and its rate of effusion. Common to the flow of low viscosity basalt, and to the flow of some other lavas, is the development of an internal artery system, or lava tube system, that conveys the liquid flow between the erupting vent and the advancing flow front. This flow style is known as 'tube-fed pahoehoe' (Swanson, 1973) and in cooled flows it may be distinguished (amongst other things) by the presence of lava tube caves, which represent the drained portions of the former artery system. Geologists were much enlightened about the construction and operation of lava tubes following observations of the 1969-74 Mauna Ulu flank eruption of Kilauea Volcano (Greeley, 1971 and 1972; Cruikshank and Wood, 1972; Swanson, 1973; Peterson and Swanson,1974; Holcomb, Peterson and Tilling, 1974). These observations revealed that the tubes developed during this activity were highly efficient transporters of liquid flow, for the original temperature and mobility of the erupted fluid were only slightly reduced even after flowing through some 12km of lava tube. A later study of lava tube systems, based upon the morphologies of lava tube caves (Wood,1978), emphasised this efficiency of flow and drew attention to the similarities between the channel forms and activities of water rivers and lava rivers. It was proposed that, like a water river, a lava river may possess the capacity to 'adjust' its channel, through erosion and deposition, in a manner that minimises thermal and mechanical energy losses.

The proposal implicit in these studies - equilibrium flow through a lava tube system - is far reaching, for it infers that the tube-fed volcanic process may be a reason for the apparent anomaly of very long lava flows emplaced down



Maps of Hawai'i Island: (a) showing the five volcanoes, their rift zones and fault systems; (b) showing cave locations and features mentioned in the text.

negligible slopes. In theory, accumulations of these flows would form a low-angled lava shield if they were erupted from a single vent, or form an expansive lava plain if erupted from multiple vents. Such landforms occupy large areas of the earth's surface, and an even greater proportion of the surfaces of others of the inner planets of the solar system. It is therefore important to have more information about the morphology and operation of lava tube systems but, because good observations of active lava tubes are extremely infrequent, research must be based upon the explorable parts of ancient systems.

Cavers pursuing their sport in the volcanic provinces of the world have provided most of the current knowledge about the abundance and forms of lava tube caves. They have shown that these caves may be as extensive, as deep, as complex in form, and as beautiful in internal decoration as limestone caves (Wood,1976). Indeed, the ever continuing search for new caves, the detailed mapping of these, and the healthy competition to hold title to the world's longest known cave of this type, are considerably advancing geological knowledge about lava tube systems.

It was both these scientific and sporting incentives that drew this team to the Hawaiian volcanoes. By reasoning, lava tube caves should be abundant and of record length and depth on these great mountains, and to enter and map such caves would provide new information about the morphology of lava tube systems, as well as providing data upon which studies of the durations and volumes of liquid movements through them can be made.

BACKGROUND GEOLOGY

The Hawaiian volcanoes are immense lava cones, each composed of thousands upon thousands of thin basaltic lava flows, erupted from a central crater or from radiating rift zones. Hawai'i Island may have been constructed from seven or eight of these volcanoes, though only five are apparent today (Fig.1). The younger volcanoes Mauna Loa and Kilauea each possess a form typically resembling an inverted saucer, and they are composed mainly of tholeiitic lava flows bearing either aa (spiny surfaced) or pahoehoe (smooth-surfaced) characteristics. On the older volcanoes Kohala, Mauna Kea and Hualalai, however, the original shield form has been modified by a capping of more alkaline and silica rich lavas, ashes and cinder cones. Pahoehoe flows fed by lava tubes appear to have been important in the building of all these volcanoes, for their surfaces possess conspicuous lines of pits that have resulted from cave collapse, and entrances to lava tube caves abound in the high sea cliffs that surround Hawai'i Island. Indeed, a photogeological study of the summit area of Mauna Loa (Greeley,Wilbur and Storm, 1976) showed that 82% of its surface flows were either channel-fed or tube-fed (the two being genetically related), while recent mapping of Kilauea (Holcomb, 1980) has similarly revealed a surface dominated by tube-fed lava flows. Such flows may be very long (up to 50 or 60km), and although some may have been emplaced across a vertical range of over 3000m, their average gradient may be as little as 1-2^{o}.

PREVIOUS CAVE EXPLORATION

Previous explorations of the Hawaiian caves have been surprisingly few. Those that have been recorded in the literature have been listed by Mills (1979). Thurston's Tube is undoubtedly the best known cave on Hawai'i Island, and it has the earliest recorded exploration. The cave is today a tourist attraction situated within the Hawai'i Volcanoes National Park, at Kilauea's summit. It was first explored in detail by a team led by L.A.Thurston in August, 1913 (Anon., 1913), and was later mapped by Powers (1920 and 1922). Kaumana Cave, underlying the Saddle Road on the outskirts of Hilo, has similarly long been on the tourists' routes, but a good description of its exploration was not forthcoming until Carroll (1954) recorded an expedition through the downflow part of the cave in 1952. The explorers were all members of the Hilo Lions Club, and they published a crude map upon which was based a blow-by-blow account of their traverse through the cave. The downflow part of Kaumana Cave was again mapped in 1967 (Von Seggern and Adams, 1969) during an electromagnetic mapping exercise at the cave. No recorded complete exploration of the upflow part of Kaumana Cave is known to exist.

Continuing explorations of long caves on Kilauea have been described by Howarth (1972 and 1976), to whom credit must be given for information about the 10km+ long Kazumura Cave and other long caves on that volcano, though maps and good descriptions of these are lacking. The best recorded work in caves on Hawai'i Island was undertaken in 1978. Kempe and Ketz-Kempe (1979) recorded explorations, and provided maps of, the 1.4km long Keana Momoku Ahi-Calabash system on the south flank of Kilauea, the Mauna Loa Ice Cave at 3,500m altitude, and the 600m long Skylight Cave also on Mauna Loa. That same year Nieland and Nieland (1978) explored Thurston's Tube and Kaumana Cave, small caves in the Mauna Ulu lava, a cave near the island's South Point, and part of the long Ainahou Ranch Cave, which they mapped.

Undoubtedly the literature does not include all the explorations of caves that have been undertaken on Hawai'i Island, and it was clear from meetings with scientists and residents on the volcanoes during the expedition that there is an enormous store of untapped information about previous explorations and cave locations. Howarth, for example, has for long been the principal in Hawaiian cave exploration, and he attempts to keep abreast with new cave finds, while also actively researching into the unique ecology of these caves. Many geologists at the Hawaiian Volcano Observatory also have knowledge about cave locations, though few have found time to explore any caves. Most exciting has been the mapping of the surface flows of Kilauea by Holcomb (1980), for he has located the routes of many tubes from the lines of skylights and collapses revealed on aerial photographs. His published map is destined to become the cave hunters' guide for the future on this volcano.

CAVE DESCRIPTIONS

During the five weeks of the expedition 24km of cave passage were mapped and many more kilometres of cave were explored which were not mapped. Some statistics on these caves are listed in Table 1., while cave locations are shown on Fig.1.

There were two parts to the work of the expedition. In the first two weeks special attention was paid to cave prospecting on the 1969-74 lava erupted from Kilauea's upper east rift zone. This work was intended to supplement the knowledge about lava tubes observed in operation during this period of Kilauea's activity. In the following three weeks the net was cast wider and long caves elsewhere on Kilauea and Mauna Loa were sought out. This was particularly exciting caving, with discoveries proving beyond doubt the great potential for internationally important caves on the Hawaiian volcanoes.

Due to problems with the transportation of surveying equipment and the limited stay on Hawai'i Island, it was thought best to map caves magnetically and to employ the more rapid 'leap-frogging' technique. Generally, two survey parties were fielded, each using a 30m fibron tape read to the nearest 0.1m, a hand-held Suunto compass (type K8-14/360) read to the nearest degree, and a hand-held Suunto clinometer (type PM-5/360 PC) read to 0.5°. On return to the UK the survey figures were reduced to rectangular co-ordinates and plotted at a scale of 1:2000, except Kazumura Cave which was plotted at a scale of 1:4000. The cave maps that appear in this paper were prepared from these larger maps. It will be appreciated that due to the variable magnetic attraction of the basalt rock of a lava tube cave (Bowler, 1971), the true line of the cave will vary slightly from that ascertained by a magnetic survey. However, in a traverse through the middle part of Kazumura Cave and back to the starting point across the surface - a total traverse length of 8,035.8m - a closure error of only 1.29% was discovered, and so it is thought that after correction of the survey figures, the cave maps in this paper show a relatively accurate representation of each cave form.

CAVES IN THE MAUNA ULU LAVA

Kilauea Volcano has been very active in the last twenty years, with much activity emanating from its upper east rift zone. The most spectacular eruption during this period was a sustained outpouring of lava between 1969 and 1974, causing the construction of a new parasitic lava shield astride the rift, that was eventually called Mauna Ulu ('Growing Mountain'). A complex system of lava tubes fed long flow units that tumbled down great fault scarps (the palis), before they entered the ocean 15km beyond the vent. The lava eventually covered 4050 hectares of forest and bush within the Hawai'i Volcanoes National Park, and added 80 hectares of new land at the coast. It was the first long-duration flank eruption of a Hawaiian volcano ever to be witnessed in detail, and scientists from the Hawaiian Volcano Observatory were able to establish during the activity the routes of the principal tubes from the lines of fume clouds emitted from skylights (roof collapses over active lava tubes). This information enabled Holcomb (1976) to plot the positions of the main tubes with some accuracy when constructing his map of the cooled flows. Thus, the rough plan form of the Mauna Ulu tube system was known before the arrival of this team, though no systematic search for caves had ever been undertaken in these very young lava flows. Holcomb's map and the published observations of tube activity provided a useful basis for such a search.

Caves in the 1971 lava (Cave Group 'A".

This cave group is located beneath a most impressive line of skylights and post-activity collapses, that trends NNW-SSE, for 2 km, between altitudes 701m and 610m, in the 1971 tube-fed pahoehoe. The downflow termination of the group lies only 100m north of the Chain of Craters Road. There are three respectable caves, explored upflow to downflow to lengths of 70m,120m and 230m respectively, though none of these caves were mapped. All of the caves are remnants of a single, unbranched tube, and they exhibit multi-level development, with false floors, lateral benches and deep trenches, and many false roofs beneath skylights. The long line of skylights and collapses representing this cave group on the surface is of classical form: elevated slightly above the surrounding flow, each skylight displays structures and forms indicative of channel and tube construction, as well as internal features greatly illustrative of the processes observed at skylights by the Hawaiian Volcano Observatory staff (see, for example, Peterson and Swanson, 1974).

Caves in the 1973 lava—Apua Cave.

The only large unburied expanse of the 1973 tube-fed pahoehoe occurs between the Poliokeawe Pali and the coast, where it forms the western arm of the Mauna Ulu lava. Between the Pali and the vent this lava is buried by later flow units. Nevertheless, the 1973 lava contains one obvious line of skylights and post-activity collapses, trending N-S down the axis of the flow, with the two ultimate (seaward) collapses giving access to a large cave that must rank as one of the most richly decorated lava tube caves in the world. This cave has been given the name Apua Cave because of its close proximity to Apua Point. It has a mapped length of 1.34km and a vertical range of 32m. Apua Cave is most voluminous in its middle section, where its two great entrance collapses are located only some 340m apart, with the more accessible upflow entrance being located at 49m altitude. The cave is sinuous and braided in plan form. Upflow from the top entrance it is relatively featureless, though parts are greatly broken down, and it eventually becomes too tight in a stalactite-filled crawl. Downflow from the top entrance an enormous passage quite soon diminishes in stature and branches, with the eastern loop displaying a smooth, sub-circular profile, while the western loop possesses a rich display of lava straws and some globular stalagmites. These passages rejoin after 100m at a large chamber full of rockfall, and then 130m farther on the lower entrance is encountered at the top of a huge mountain of collapsed roof rock. Great piles of collapse debris infill the cave beyond the entrance, though branch passages at the base of the western slope of the debris pile contain abundant stalactites. The debris piles finish 100m downflow from the lower entrance and a small chamber is encountered, its fallen roof slabs being covered with small globular stalactites, and tiny beads of lava glaze that give the appearance of having been sweated from the rock. Beyond this the roof becomes lower and the cave from now on is spectacularly decorated. Immediately on entering the uncollapsed portion of the cave the explorer is confronted with a fabulous group of 30-40 globular stalagmites, each one at least 1m tall, and in total representing perhaps the finest display of lava stalagmites yet known. Once the route past these has been carefully negotiated, the roof of the cave lifts, and display after display of lava straws, globular stalagmites and other formations in the chocolate brown glaze of the cave are discovered. Eventually the roof lowers again, and the terminal choke is preceded by a flat out crawl.

Caves in the 1974 lava (Cave Groups 'B' and 'C'.

The 1974 tube-fed pahoehoe contains two significant, but quite independent lines of skylights and post-activity collapses. The flow units fed by these tubes terminate just below the Poliokeawe Pali (a longer flow unit fed by an open channel terminates on the lower Holei Pali), but above the Pali they form the upper western part of the Mauna Ulu lava. The line containing Cave Group 'B' lies on the east and its orientation is N-S. It extends from the vent, though only between altitude 793m and the top of Poliokeawe Pali at 640m altitude are there any important caves. North of the Chain of Craters Road there are two short caves, one of which is quite complex in form, with a maze of small passages located about a single larger passage. Downflow of the Chain of Craters Road the first three caves are apparently remnants of a single,unbranched tube. Sometimes well decorated, the unifying feature of these is their canyon-like passage profile, at least 6m high in places,that is spanned in the middle cave by one or more complete or partly collapsed false floors. Continuing down the tube line there are two small caves before the pali is reached, and one other cave actually survives in the loose lava on the pali face (a gradient of about 60°). This cave group comprises 780m of cave passage.

The line of skylights and post-activity collapses containing Cave Group'C' is located at the very western edge of the Mauna Ulu lava, though caves are only present north of the Chain of Craters Road between 847m and 820m altitude. This cave group consists of four caves, totalling 468m in length, that together appear to have evolved from a complicated parent lave tube system. After Apua Cave, these are the most interesting caves in the Mauna Ulu lava, with a form comprising a common axial passage 3-4m in diameter, from which numerous smaller tubes egress. The lower caves of the group are richly decorated with lava stalactites and stalagmites, though because they lie only a few hundred metres from a view point on the Chain of Craters Road they will need some protection if they are to survive in their present form. The upflow cave of the group is a passage complex developed around a braided part of the common axial passage. Here the main passage is 8-10m wide, but it soon terminates upflow in a choke.

OTHER LAVA CAVES

Ainahou Ranch Cave.

It seems probable that the Ainahou Ranch Cave is located in the Kamapua'a Flow, the eruption of which figures in Hawaiian legend (pers. comm. R.T.Holcomb). When the English missionary, William Ellis, walked over the flow in 1923 he was told that it dated from the time of a lovers'quarrel between Pele, the goddess of the volcano, and Kamapua'a, the pig man (a very ugly renegade who apparently resembled a pig - embellishment of the legend eventually elevating this character to the status of a god who was half pig and half man). Pele was then a young woman from a wandering family that had settled in the Ainahou area. When she spurned Kamapua'a's advances, he called down a volcanic eruption that covered her family's land. She and her family took refuge in a cave, but when this was also covered by the new lava she reappeared as a goddess in the volcano, and carried on a sustained battle with Kamapua'a,the battle raging back and forth between the vent and the coast. Recent mapping in the Ainahou area by Holcomb suggests that a sustained eruption did infact take place some time between 350 and 500 years ago, possibly from the vent of Puu Huluhulu, and that this eruption produced an assemblage of lava flows resembling the Mauna Ulu assemblage. The Ainahou Ranch tube was probably a principal feeder in this activity.

The cave is a magnificent wild cave, full of interesting features. It is principally one enormously long, sinuous passage, in total 7.11km long, with a vertical range of 352m. The upflow entrance of the cave is a small roof collapse located at 945 altitude, some 250m south-west of the junction between the Ainahou Ranch jeep track and the Chain of Craters Road. From there it trends SSE beneath the Ainahou track, to terminate eventually at a window or balcony high up the face of the Poliokeawe Pali. Daylight enters the cave at 23 locations along its length, and at one collapse site the roof completely blocks the passage, breaking the cave in two. The cave in all probability continues downflow from the Poliokeawe Pali, for a line of obvious collapse pits may be seen from the window on the Pali to extend to the top of the lower Holei Pali. The cave may also continue beyond its present upflow termination, for uninvestigated caves marked on the USGS topographic map of the area are aligned with the Ainahou Ranch Cave.

Fig 1. This collapse in the 1974 Mauna Ulu lava allowed access into a roomy, but short cave; the lava tube from which it formed had its source on the 500m high Mauna Ulu lava shield seen on the skyline. (Photo: C. Wood)

Fig. 2. The cave group in the 1971 Mauna Ulu lava was shown by the tube line elevated slightly above the surrounding flow; overflow sheets surrounding the skylights explain the horizontal stratification of the wall rock inside the caves.(Photo: C.Wood)

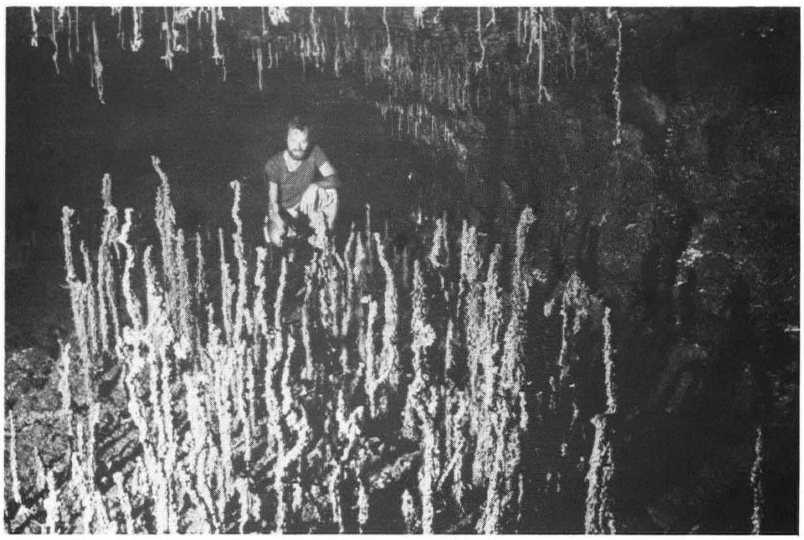


Fig.3. These magnificent lava stalagmites in Apua Cave were constructed from globules of glassy lava dripping from the cave roof. (Photo: A.C.Waltham).

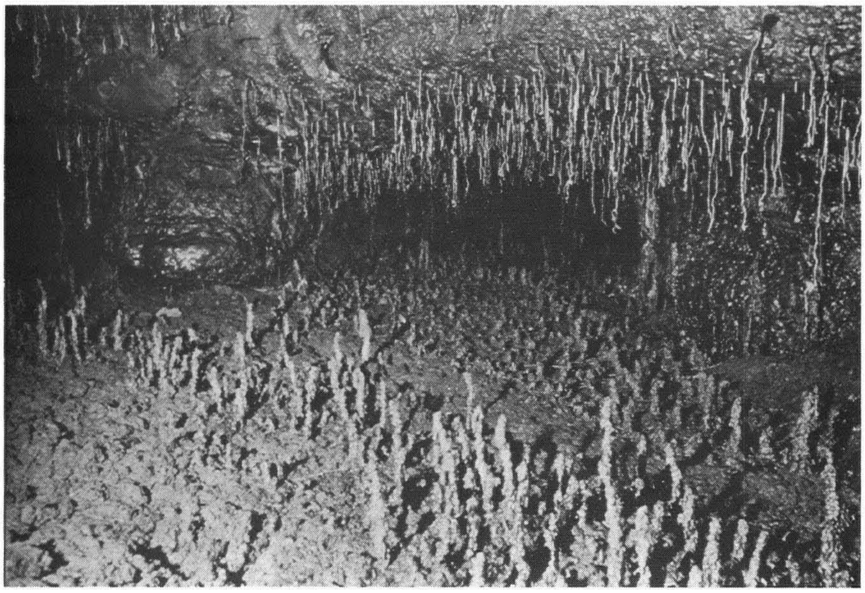


Fig.1. In Apua Cave recesses abound with delicate straw stalactites and globular stalagmites both composed of lava. (Photo: A.C.WAltham)

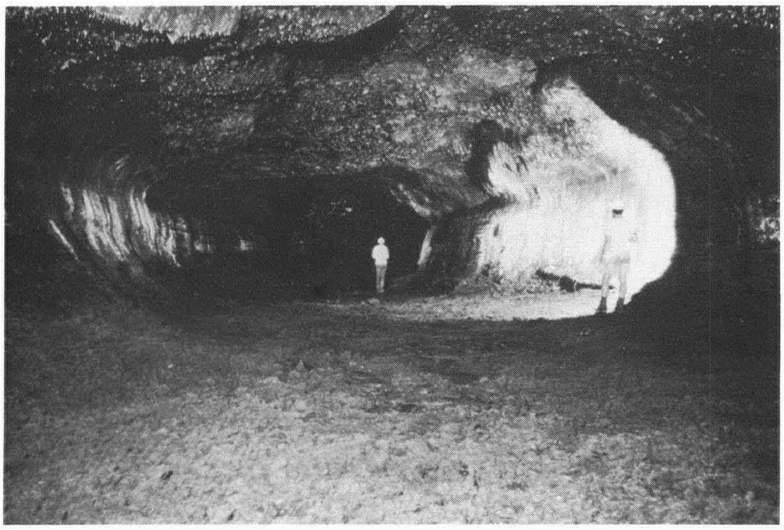


Fig. 2. Kazumura Cave is only a part of an extensive cave system on the north-east flank of Kilauea Volcano that may be 20km or more in length. (Photo: A.C.Waltham)

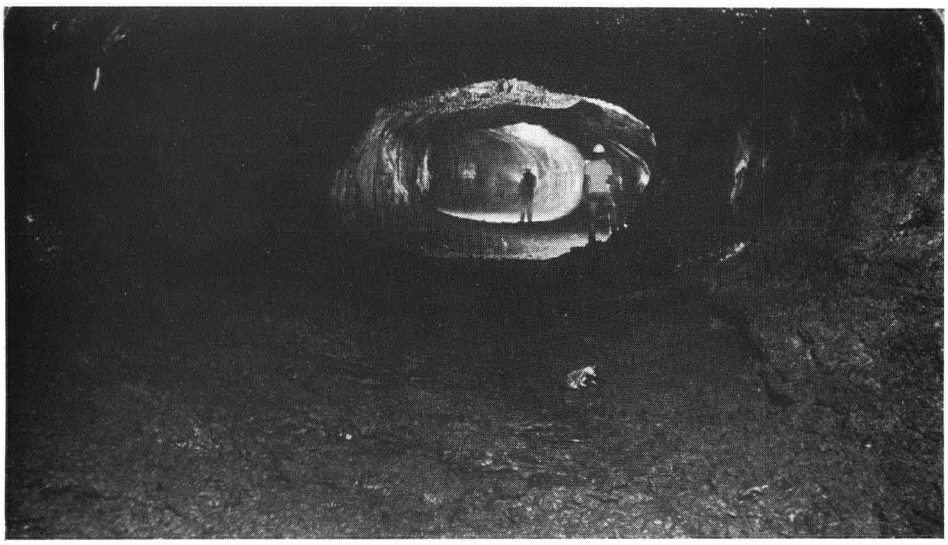


Fig. 3. In places, the Hawaiian caves are truly tube-like. (Photo: A.C.Waltham)

Ainahou Ranch Cave possesses the most pronounced sinuosity of any cave investigated on Hawai'i Island, and it displays for long stretches an awesome smooth, circular or elliptical passage profile, giving to the caver more accustomed to limestone caves the impression of walking through a phreatic tube. Variations in the gradient of the floor are apparent at frozen lavafalls and rapids, while a floor tube extends for a considerable length through the upflow part of the cave. A distinctive feature in Ainahou Ranch Cave is its double or triple-tiered main passage, in which windows connect each tier. Invariably it is the upper tier that is the largest passage, though a continuous route through the cave is only possible via the lowest tier. At places where the cave is not tiered, there are wide lateral benches, from which loop passages diverge and re-enter the main passage. The downflow part of the cave connects with a maze of smaller passages overlying the main route. Ainahou Ranch Cave is not well decorated with lava formations, but it does highlight outstanding petroglyphs (Hawaiian rock carvings) in one of its downflow entrances and a solitary human skeleton in the upflow part of the cave.

Thurston's Tube.

Thurston's Tube comprises a single passage, 593m long, with a vertical range of 22m. Its entrance is located at 1200m altitude in the wall of one of two small pit craters that indent the low shield on the east side of Kilauea Iki pit crater. The cave is well known as a tourist attraction within the Hawai'i Volcanoes National Park, and the first 120m is lit by electric light. Apart from the pit crater entrance, there is one other entrance situated part way along the cave, from which the tourist trail exits . In general, the cave is some 3-4m in diameter, though at times it widens into significant chambers, and at two places there are large steps in the floor. Thurston's Tube is today featureless, but it is believed that in the past it was well decorated with lava stalactites and stalagmites.

Blair Cave.

The low shield in which Thurston's Tube is situated was apparently the source of enormously long tube-fed lava flows which today extend some 40-50km from Kilauea summit to the coast south of Hilo (Holcomb,1980). These flows are potentially rich in very long caves, but because they are located in forest and scrub, their entrances are difficult to find. Blair Cave is a member of this group and is certainly the most accessible. It possesses four roof collapse entrances in its downflow part, the highest of which lies only 50m off the south side of Highway 11 (Hilo-Kona), at 874m altitude, a short distance below the village of Volcano. The cave was not mapped by this group, though a cursory exploration assigned to it a length of 2.5km. It is a most interesting cave, that is in the main unspoilt. It comprises of one large, sinuous passage, some 5m diameter, that is greatly collapsed in its downflow half. Upflow, the cave is a large meandering tube, displaying ponds and lavafalls, and at one place a particularly fine canyon sandwiched between high lateral benches. There are also in this part of the cave two small loop passages, one on the north side and one on the south. The cave possesses few stalactites and stalagmites, though its glaze lining is well developed and well ornamented. Blair Cave downflow from the topmost entrance was mapped by Halliday (1980) in November, 1979, and he assigned to this part of the cave a length of 1.11km.

Kazumura Cave.

Knowledge of the existence of Kazumura Cave and its reputed great length of over 10km was one of the factors that drew this expedition to Hawai'i Island. This cave was thoroughly explored and mapped by the expedition with the help of Frank Howarth, its original explorer, and a full traverse length of 11.713km with a vertical range of 261m, was established. Thus, Kazumura Cave is longer than the 11.1km long Leviathan Cave, Kenya, and is now the longest known lava tube cave in the world. Of greater significance, thanks to Holcomb's mapping of Kilauea,it is now known that Kazumura Cave is just one of a number of giant caves that lie on the volcano's north-east flank, some of which may even range up to 15 or 20km in length. Kazumura itself can probably be extended to 15km if its lower terminal choke is passed.

Kazumura Cave is one huge, sinuous passage, the downflow one third of which is greatly broken down. Rarely does the explorer have to stoop on a traverse through the cave, and in the main movement is easy through a smooth, elliptical passage profile, ranging up to 15m in diameter. There are seventeen skylight or collapse entrances along the length of the cave, though many are difficult to locate on the surface. As one would expect in a cave of this size and length, points of interest are many, ranging from spectacular incised meander loops, deep canyons, wide benches, lava decorations, lavafalls (one 4m high), enormous breakdown chambers and multi-level passages. The cave also has great archaeological interest, for it houses two Hawaiian burial chambers, complete with skeletons, and a great stone structure interpreted to be an altar or 'heiau'. There are a few branch passages, but these are mostly unimportant. One side passage reputed to exist in the downflow part of the cave, however, is said to be 600m long. This passage was not found during this expedition, and it is believed that its entrance is now buried beneath recent rockfall. The cave terminates upflow at a lava seal and downflow at a choke.

Dr. Bellou Cave.

This cave overlies part of Kazumura Cave and may have been part of the same parent lava tube. From its single entrance the cave may be explored upflow for 140m. Here there is one small side passage and the cave ends at a lava seal. Downflow, the passage is initially wide, with much breakdown, leading to a ponded area and a final choke about 170m in. The cave was not mapped.

John Martin's Cave.

John Martin's Cave lies parallel with and 1 km south of Kazumura Cave. It was cursorily examined by this group, though John Martin, the owner of some of the land overlying the cave, has reputedly explored his cave for a great distance. A group of U.S. cavers explored part of the cave in November, 1979, and reported (Allred,1980) that they traversed a large single passage, 13m wide and 3-5m high, for 2.5km, before they had to turn back because they ran out of time.

Kaumana Cave.

Kaumana Cave County Park is a well known tourist spot located beside the Saddle Road, 8km from the centre of Hilo. The cave is located in the 1880-81 lava flow from Mauna Loa, and the part downflow from the picnic ground had been mapped prior to this expedition by Carroll (1954) and by Von Seggern and Adams (1969), the latter proving a length of 1.62 km for this part of the cave. The earlier crude map produced by Carroll and associates shows that the cave then continued beyond its present lower terminal choke. Although this expedition walked through the lower half of the cave, only the part upflow from the picnic ground entrance was mapped, and this was established to be 1.02km long. Thus, Kaumana Cave is approximately 2.64 km long.

The cave is particularly interesting because the flow in which its parent lava tube developed was actually observed in activity in 1881 (Baldwin, reprinted 1953). The eruption started on November 5,1880, when a lava flow 1.5km wide was observed to flow down the mountain at about 800m per month. By July, 1881 it was moving through Kaumana Wood, after having flowed 50km from the vent, across a vertical range of nearly 3000m. Here the flow narrowed to a few hundred metres, and its velocity increased eight-fold. For some time the 1880-81 lava flow seriously threatened the city of Hilo.

Today, the cave is large and impressive. It is mainly a single, unbranched passage, though upflow of the picnic ground entrance this passage braids and is greatly collapsed. The cave is most voluminous in its middle section, where it reaches 10m in diameter. The part downflow of the picnic ground contains many thick curtains of tree roots and occasional debris piles. There are no collapse entrances here, except at the terminal collapse. Upflow there are a further four collapses entrances and the cave terminates at a lava seal.

Bird Park Cave or Kipuka Puaula Cave.

This cave appears to be very old and is located in the Bird Park, 1.5km along the Mauna Loa Strip Road, within the Hawai'i Volcanoes National Park. It is Stop No.7 on the Bird Park's trail guide. The cave trends downhill at walking size for 150m, before it ends at an earth fill.

GEOLOGY OF THE HAWAIIAN LAVAS AND LAVA TUBES

Exploration and mapping of Hawaiian lava tube caves by this expedition enabled some contributions to be made toward a number of problems relating to tube-fed lava flow.

(1) Discovery of a great abundance of long lava tube caves on Kilauea and Mauna Loa adds weight to the view that the tube-fed volcanic process has contributed significantly toward the construction of the Hawaiian shield volcanoes.

(2) The forms of the Hawaiian caves, as revealed in the maps, fill some gaps in our visualization of the forms of lava tube systems. The long, unbranched forms of the Hawaiian caves complement the complex forms of lava tube caves mapped elsewhere (for example, the Cueva del Viento, Tenerife - Wood and Mills, 1977)

(3) The cave maps enable the dimensions and volumes of lava conduits to be worked out, aiding future studies on the mechanics of tube-fed flow generally, and studies of the volumes and durations of liquid movements through specific tubes during past volcanic episodes.

(4) Entering the drained parts of the Mauna Ulu lava tube system 7-12 years after it ceased functioning enabled for the first time cave wall structures and internal forms to be related to known tube-forming processes. This knowledge will benefit interpretations of lava tube caves elsewhere in the world.

Cave Occurrences, morphologies and internal features.

Occurrences. The locations of the caves investigated are shown on Fig.1. Significant caves develop from lava tube systems only if their locations are favourable for the drainage of most of their liquid fill after the vent effusion has stopped. This means that the residual fluid within the tube must retain mobility on the existing slope and that there must be space available downslope for the reception of the draining fluid (Wood, 1975).

In practice, it is the larger feeder tube lying along the axis of the flow that most readily drains to form an extensive cave. This is reasonable, for in activity these tubes are rarely filled to brimming, and so there is room in the downflow tube to accommodate additional fluid draining under gravity from higher up the flow. If the head is great enough, the downflow tube may rid itself of excess fluid by overflowing through skylights, or it may feed a continuing advance of the flow front. Smaller tubes branching from the main tube tend to be blind alleys, which soon choke for lack of heat, unless they re-enter the main tube downflow and throughflow of hot liquid is maintained. Obviously, due to variations in the angle of the slope, some parts of a lava tube system may drain more readily than others, causing the system to become segmented, with a number of aligned caves sealed top and bottom by solidified lava sumps.

Occurrences of caves in the Mauna Ulu lava could be related to the stepped long profile of the lava flow. As expected, the best caves formed on the flat immediately upflow from the Poliokeawe Pali (though no caves were encountered upflow from the lower Holei Pali). Apua Cave too evolved in response to a variable gradient, though the gradient change at this cave is much less than that at the palis. The reason for the drainage of the long caves elsewhere on Kilauea and Mauna Loa is not so obvious. Drainage of Ainahou Ranch Cave may have been influenced by the downflow position of the Poliokeawe Pali, the steep slope of which ensured the rapid movement of liquid away from the end of the tube at the pali top. Nevertheless, the residual fluid in Ainahou Ranch Cave and in the other long caves must have remained very mobile after the cessation of vent activity, for drainage occurred on very low and constant gradients (in the case of Kazumura Cave $1\frac{1}{2}^{o}$). Where did this liquid go? One can only suppose that it fed an advancing front for a period after the vent effusion had ceased.

Morphologies. The forms of the caves in plan, long profile and cross profile are shown in the accompanying cave maps.

Common to the plan of all the caves is a major passage aligned parallel to the axis of the parent lava flow. In Kazumura Cave, Blair Cave, Ainahou Ranch

Cave and Thurston's Tube, this single, unbranched passage is highly sinuous and constitutes almost the entire cave. In Apua Cave and Kaumana Cave the passage is braided. Elsewhere, particularly in the Mauna Ulu caves, side passages diverge off a large axial passage at varying heights in either wall, though these are only minor routes (frequently they are flat-out crawls).

In long profile the caves have formed across a variety of average slopes, as listed in Table 1. Prominent in many caves are steps in the floor of the main passage; these ranging from steep ramps to distinct steps with lavafalls.

TABLE 1: CAVE STATISTICS

Name of Cave	Parent Flow or Source	Mapped Length	Vertical Range	Average Gradient
Cave Group 'A'	1971 Mauna Ulu lava	0.420km	?	?
Apua Cave	1973 Mauna Ulu lava	1.34km	32m	1¼°
Cave Group 'B'	1974 Mauna Ulu lava	0.780km	?	?
Cave Group 'C'	1974 Mauna Ulu lava	0.468km	?	?
Ainahou Ranch Cave	Kamapua'a's Flow	7.110km	352m	4°
Thurston's Tube	Thurston's Tube Shield?	0.593km	22m	2¼°
Kazumura Cave	Thurston's Tube Shield?	11.713km	261m	1½°
Dr. Bellou Cave	Thurston's Tube Shield?	0.310km	?	?
John Martin's Cave	Thurston's Tube Shield?	2.500km	?	?
Blair Cave	Thurston's Tube Shield?	2.500km	?	?
Kaumana Cave	1880-81 Mauna Loa Flow	2.639km	?	?
Bird Park Cave	?	0.150km	?	?

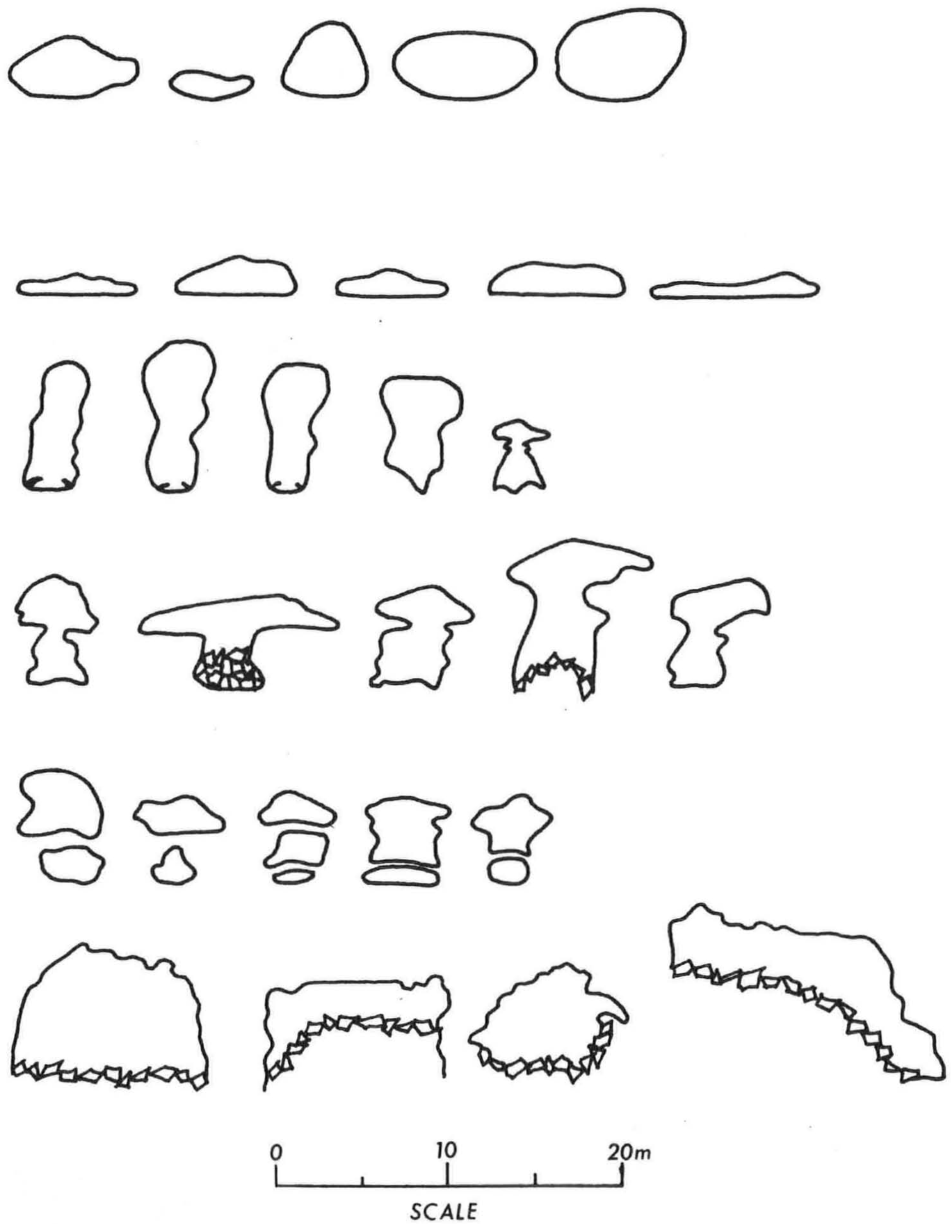
One lavafall in the main passage of Kazumura Cave is 4m high. These steps may reflect an uneven underlying topography, or places where crustal slabs have become jammed across the passage, or they may have resulted from the capture of a lava stream in an overlying tube by a lower one. A further distinct feature in many of the caves is a tiered main passage, with as many as three levels separated by false floors. Observers of the active Mauna Ulu tube system described how subsidiary roofs developed across the lava river beneath skylights (Cruikshank and Wood, 1972; Peterson and Swanson, 1974), presumably because of the greater heat loss at these points. In all of the caves explored during this expedition a double passage was invariably encountered beneath an entrance that was a former skylight (for example, entrances 12 and 15 in Kazumura Cave), but the tiered tube soon gave way to a single passage a short distance upflow and downflow of the entrance. In Ainahou Ranch Cave, however, the main passage is tiered for considerable lengths between former skylights, and each level is connected to another by internal skylights. Sometimes a double tube degrades into a single tube bordered by wide lateral benches, offering the explanation that the stacked passages are separated by a true false floor. Such a development would reflect an adjustment by the internal lava river in response to a diminution of flow, causing a narrowing of the channel by lateral accretion to the walls to produce lateral benches, and crusting on the surface of the river. Once a crust had been suspended between lateral benches, overflows would strengthen it, while collapse in parts would form internal skylights.

As in solutional caves, passage across profiles of lava tube caves are an important source of evidence for interpreting the genetic history of a cave. Following a scheme put forward previously by this author (Wood, 1977), it has been possible to recognise in the passage profiles of the Hawaiian caves a number of genetic groups, as shown in Fig.2.

<u>Internal decorations</u>. Only in the Mauna Ulu caves and in parts of Kazumura Cave are there any important lava formations, though the decorations of one of these caves - Apua Cave - are outstanding.

Crawlways in Kazumura Cave possess small globular stalagmites and straw stactites, while some other parts of the cave carry great roof clusters of conical (cow-teat shaped) stalactites. In the Mauna Ulu lava, Cave Group 'C' is particularly well decorated with straw stalactites and globular stalagmites, while the downflow half of Apua Cave abounds in great clusters of straight and erratic rod and straw stalactites, tall globular stalagmites (up to 1m high), intricate decorations formed by the dripping and sagging of the wall glaze, and a variety

Passage profiles from the Hawaiian lava tube caves.



1 Smooth, sub-circular, elliptical or triangular forms, with conical stalactites and wall striations, may indicate full-bore flow.

2 Wide, low passages are the explorable parts of lava tubes which have never extensively drained.

3 It has been suggested that canyon or gorge like forms may be indicative of bed erosion by the lava river.

4 Lowering or diminution of flow within a tube will cause channel narrowing and surface crusting, leading to the development of lateral benches.

5 Frequently lateral benches merge to form false floors and stacked passages (tube-in-tube).

6 Structural weaknesses in lava enable much spalling in caves and great modification to the original passage form.

FIG. 2.

of more unusual decorations, including glaze beads and stalagmites with an appearance of mini spatter cones.

The lava decorations encountered in the Hawaiian lava tube caves are believed to be the products of two different processes. The conical stalactites in Kazumura Cave appear to have developed when a sticky roof sagged and dripped as the lava tube emptied, apparently from a full bore state. The formation of the other lava decorations (wall glaze, straws, globular stalagmites, etc.) is more problematical, though it is generally held that such lava formations evolve when hot gases remelt the lining of the tube, forming a fine glaze that flows down the walls and drips on to the floor.

The formation of the group of tall globular stalagmites in Apua Cave exemplifies this problem of stalactite and stalagmite production in lava tube caves. These stalagmites are very tall and are not bent. They were therefore apparently built upon a floor that was stable enough to bear their weight and to remain in place for a considerable time beneath a continuing source of dripping glaze. Yet, if the subterranean lava river was covered by a thick crust, how were the very high temperatures generated enabling the inside of the tube to flow and drip? Jagger (1931) suggested that in tubes spawning stalactites a blast furnace effect is set up by the gas flow between skylights. Peterson and Swanson (1974) similarly noted stalactites around skylights in the Mauna Ulu lava, the lower end of many being bent toward the nearest skylight and probably reflecting the draft created as heat and gas left the tube. However, the problem remains.

One other unusual feature in Apua Cave is a stalagmitic form resembling a small spatter cone. Each stalagmite is less than 30cm high, with a basal diameter of 15cm, while in structure it is composed of large,flattened globules. Strangely, each dumpy cone is surmounted by a small pit, indicating either eruption of liquid from below, or more likely, spattering of the fluid drips from above. Similar features have been described from Government Cave,Arizona (Harter, 1971), where they are called 'lava roses'.

Some contributions towards an understanding of the Morphology and Operation of Lava Tube Systems

Knowledge of the morphology and operation of lava tube systems is an essential prerequisite to any future study on the mechanics of tube-fed lava flow. Such a study may have great rewards, for not only will it confirm or deny the role of the tube-fed volcanic process in the building of major basaltic landforms, but it may also enable more accurate quantifications and predictions of future active flow development (Wood,1978). However, data are hard to come by, because (1) active flow through a tube system is internal and neither the shape of a system nor its operation can be adequately observed (glimpses may be caught only at skylights). (2) in cooled lava flows a lava tube system will never have drained completely, and in most flows the explorable segments represent only minor portions of the initial system. Nevertheless, some observations were made in the Hawaiian lava tube caves that enable some further insight into the morphology and operation of lava tube systems.

Morphology. From the evidence of cave maps and observations of active tube-fed lava flows, this author has previously proposed (Wood,1978) that the ideal lava tube system feeding a simple tongue-shaped lava flow would be composed of a combination of the following morphological elements: (1) a long, sinuous, partly braided, main feeder tube lying along the axis of the flow; (2) lateral complexes of smaller tubes which transport liquid flow only when surges from the vent cause the main feeder to overflow; (3) higher tube complexes left vacant because their flow has been captured by the underlying tube; (4) a delta-like region of small distributary tubes at the flow front. Elements 1 and 4 would be common to all systems, while elements 2 and 3 may or may not be present.

The longer Hawaiian lava tube caves revealed much about the morphologies of the lava tube systems from which they evolved, principally because they had drained so extensively. Glimpses of the Mauna Ulu system as seen in the maps of the short caves located during the expedition also enabled some infilling of detail upon the crude plan established from observations of the active tubes.

The plan form of Kazumura Cave, Ainahou Ranch Cave, and to a lesser extent Kaumana Cave, Thurston's Tube and Blair Cave, add credence to the idea that long flows are fed by a large axial feeder tube. Kazumura Cave and Ainahou Ranch Cave illustrate the form of this tube admirably; Kaxumura Cave occupying approximately 20% of the length of its parent flow, while Ainahou Ranch Cave occupies approximately 40% of its flow length. It must also be remembered that it is known that both of these caves continue either upflow or downflow beyond the present limits of exploration. The forms of these axial tubes is as this author has predicted - single, large volume passages, continuous over great distances, and possessing great sinuosity and some braiding.

The Mauna Ulu lava flow contrasts with the more or less tongue-shaped flows within which the long caves described above are located. This flow is an assemblage of sheet and tongue-shaped flow units of varying dimensions, though a number of tongues extended the full 15km between the vent and the coast, each of these apparently possessing its own feeder tube. The map of the Mauna Ulu tube system as depicted by Holcomb (1976) is therefore one describing a pattern of diverging axial tubes, but cave exploration suggests that in truth this system was even more complex. Captures of flow in superimposed tubes about the vent abound (see also Peterson and Swanson, 1974), while established axial tubes, although perhaps originally evolving in distinct flow units, were utilized time and time again by later effusions, were apparently incised into underlying flow units, and even had their own flow captured by tubes underlying the Mauna Ulu lava.

Cave Groups 'A' and 'B' are unbranched in form and probably represent parts of principal feeder tubes. Similarly, Cave Group 'C' may have evolved from a feeder, though its form is more complex than that of 'A' and 'B' in that its main passage is braided and it possesses lateral passage complexes. Inevitably, the cave evidence that can add detail to our conception of the morphology of the Mauna Ulu tube system is patchy, particularly when it is understood that highly voluminous feeder tubes were observed in activity (up to 30m wide and 13m high - Peterson and Swanson, 1974, p.2201), but could not be located during this expedition. Perhaps Apua Cave is the best representation of an axial feeder tube in the Mauna Ulu lava, for this cave is very voluminous, and its position suggests that it was the main source of lava for the growing littoral delta west of Apua Point.

Operation. One problem that is highly pertinent in a study of lava tube systems is whether or not lava rivers are able to modify their channel form in response to varying flow conditions. The concept is enticing, but to date the evidence for it is slim, while the idea that lava streams 'erode' is highly controversial. Yet, some adjustments to lava channels are known to take place, as exemplified by tube construction through channel roofing. Some support also comes from observations of the Mauna Ulu activity. Cruikshank and Wood (1972), for example, recognised the processes of bank cutting and bed erosion in the Mauna Ulu lava channels, while Peterson and Swanson (1974) have gone to some length to describe their reasons for believing bed erosion and channel deepening occurred in the Mauna Ulu tubes.

A wary eye was kept open for evidence of channel adjustment in lava tube caves during this expedition, though credible evidence was limited:
(1) Cruikshank and Wood (1972) suspected that passage profiles with a vertically elongated form (canyon or gorge like) indicated channel deepening. Many such profiles were evident in the Hawaiian lava tube caves.

(2) Many of the caves mapped were highly sinuous (best example is Ainahou Ranch Cave), and it is difficult to conceive of the regular windings of these caves as chance flow around pre-flow obstructions. Some of the cross profiles of these passages beg an analogy with the asymmetrical profiles at bends in water rivers (i.e., comprising a cut bank and slip-off slope).

(3) It would have been useful if incision of a lava river into an underlying flow could have been confirmed from the wall structures of the caves. In general, such evidence was illusive, although careful study of wall structures was made, and a special exercise was undertaken with D.W.Peterson to establish whether the 1971 tube had been incised across the now buried pre-Mauna Ulu eruption Chain of Craters Road.

More interesting evidence for bed erosion by a lava stream was discovered in Ainahou Ranch Cave. There are points throughout the length of this cave where a very thin wall has collapsed, enabling bright red aa clinker to spill into the cave (Fig.3). This was immediately recognised to be anomalous, for the walls of lava tube caves are invariably composed of horizontally bedded sheet flow units, which quite often represent sections of the layered overflows of the walls of the channel from which the tube evolved. There are two possible reasons for the occurrence of the clinker backfill: (a) the tube had been guided by the route of a former water channel cut in an old aa lava flow; (b) bed erosion by the lava stream in the tube had caused its incision into an underlying aa lava flow.

There is on the south side of Kilauea Caldera a remarkable lava channel that follows the route of a short water-worn channel or gulley. The channel is only 0.5km long, and is shallow, but it does illustrate the fact that underlying topography may influence the routes of lava flows. Similarly, in their study of the caves of the Cave Basalt, Mr. St. Helens, Greeley and Hyde (1971) were able to determine that part of the route of Ape Cave was influenced by the course of an old stream channel.

There are three arguments against supporting that the route of Ainahou Ranch Cave was guided by a water-worn channel. Firstly, the cave is located on the dry, leeward side of Kilauea Volcano, close to the Kau Desert area, and while one does not advocate that this area receives no rain, the very few dry water channels do reflect a very low rainfall. The chance of the Kamapua's Flow having been emplaced across a stream channel, while not impossible is slim. Secondly, Ainahou Ranch Cave is strikingly sinuous, and such sinuosity is out of character with the few relatively straight ephemeral water channels present in the area.

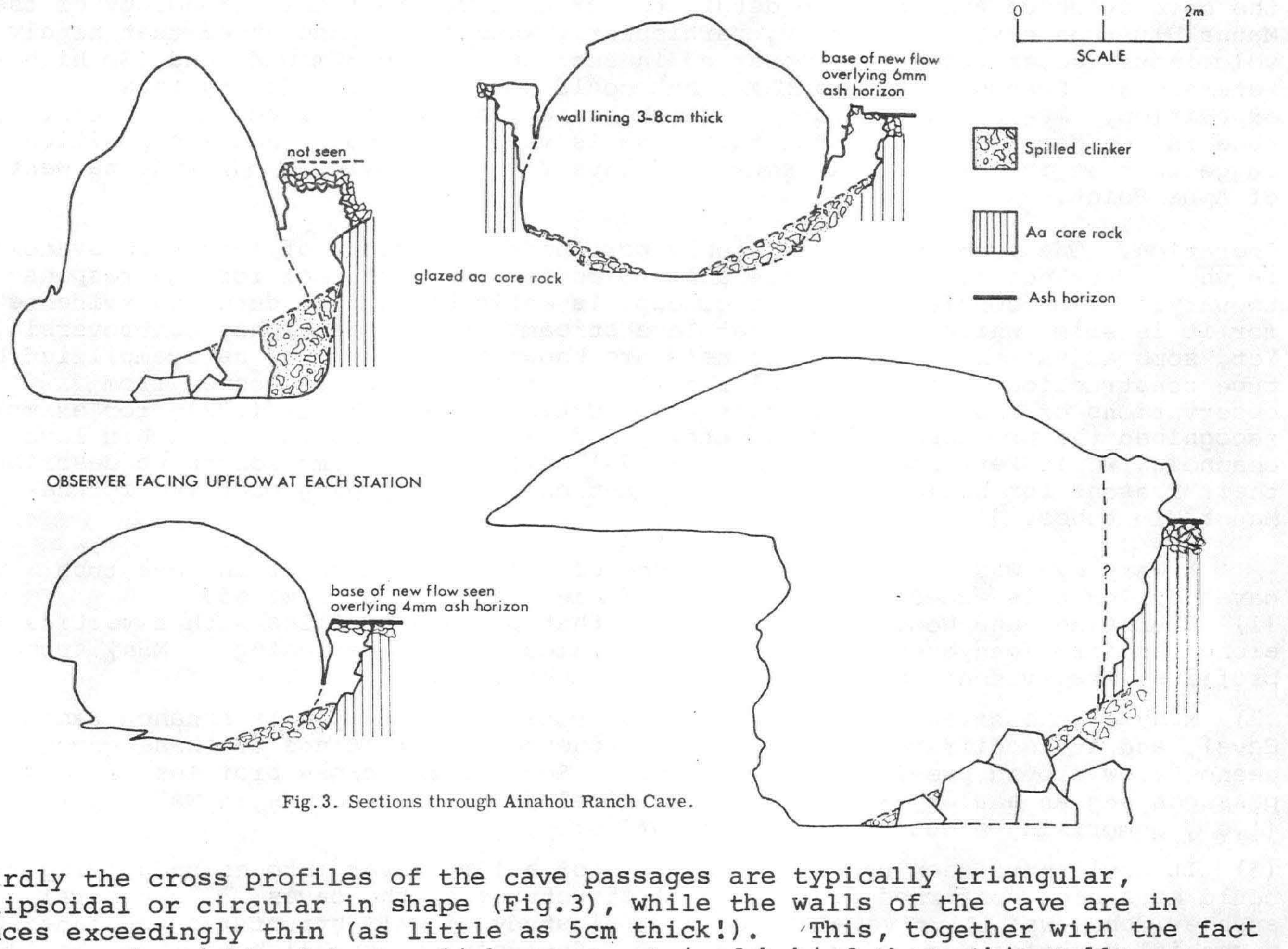


Fig.3. Sections through Ainahou Ranch Cave.

Thirdly the cross profiles of the cave passages are typically triangular, ellipsoidal or circular in shape (Fig.3), while the walls of the cave are in places exceedingly thin (as little as 5cm thick!). This, together with the fact that a great weight of loose clinker was retained behind these thin walls, suggests that the passage form was erosional: the retaining walls did not collapse as long as the tube carried full bore flow. Such passage forms are unlikely to have been adopted from a water channel, which would tend to have banks leaning outward rather than inward. (In passing, one would suspect that the clinker backfill had very high insulation value, thus explaining the extremely thin wall of the cave).

It is possible to argue that, of course, a lava stream would quite naturally 'erode' (i.e., pick up and transport) loose clinker. This problem was considered when inspecting the wall structures behind the cave wall, and in many cases it could be confirmed that part of the passage cross profile was apparently incised into the massive core rock of the aa flow.

Methods of tube construction.

It was particularly illuminating to explore caves which had developed some 7-12 years earlier during the Mauna Ulu eruption, and to relate their structures and forms to the cave forming processes observed during this activity. As expected, these structures and forms were no different from those encountered in other caves on Hawai'i Island, or for that matter in other lava tube caves throughout the world. The following points summarize the observations on tube construction made during this expedition.

(1) No evidence was found to contradict the now generally accepted modes of tube construction of channel closure and lobe extension first described by Wentworth and Macdonald (1953) and later confirmed from observations of the Mauna Ulu activity by Greeley (1971 and 1972), Cruikshank and Wood (1972), Swanson (1973) and Peterson and Swanson (1974).

(2) Many of the axial tubes in the Mauna Ulu lava possess wall structures composed of many thin sheet flow units, which represent the layered overflows of the walls of the channel from which the tube evolved. In fact, sheets and lobes produced by overflow are easy to identify on the fresh surface of the lava flow, bordering open lava channels and surrounding skylights. Nearer the Mauna Ulu vent, however, sheet wall units are to a greater extent replaced by welded spatter.

(3) It is almost impossible to establish the process by which individual lava channels became roofed to form tubes, and we must suppose that it was by a combination of the numerous processes observed during the Mauna Ulu activity; various methods of surface crusting of the lava river, and the growth of inward leaning levees by channel overflow and/or spatter accretion.

(4) Where the Chain of Craters Road has sliced through the Mauna Ulu lava ellipsoidal cross sectionsof many small lava tongues are easily identified, some holding a small cave at their core. Such internally developed tubes may also be found in overflow units on the surface of the flow.

(5) One very big problem concerning tube construction remains that is not adequately explained by the Mauna Ulu observations. Caves a considerable distance downflow from the vent (not only Apua Cave, but also such caves as Kazumura Cave and Kaumana Cave) have a wall structure composed of horizontal units ranging up to 2 or 3m thick. Such a structure does not reflect tube construction from channel closure, and this author suspects that these caves evolved by means of a process of tube enlargement and extension behind a steadily advancing flow front.

CONCLUSION

The 1979 U.K. Speleological Expedition to Hawai'i Island has been a great success. It has revealed a vast potential for enormously long caves on the volcanoes Mauna Loa and Kilauea, and has explored caves of world record length and of great internal beauty. The 24km of cave mapped during the expedition add significantly to a growing store of data relating to the forms of lava tube caves, as well as providing a basis for quantitative studies of flow development. Hopefully this expedition has provided a stimulus for more projects designed to seek out and map caves on the Hawaiian volcanoes, for the rewards to caving and to science are large.

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OXYGEN REBREATHER EQUIPMENT FOR USE IN THE EXPLORATION OF FOUL-AIR CAVES

by Donald A. McFarlane

ABSTRACT

The design of a lightweight oxygen rebreather set suitable for short duration explorations in foul-air caves is described, together with a discussion of its performance, limitations, and possible improvement.

Excessive concentrations of carbon dioxide (CO_2) are not a common feature of British caves, and their occurrence is usually limited to a few unusual situations such as sump airbells and constricted passages beneath sewage inputs as at North Hill Swallet, Mendip (Barrington and Stanton, 1972). However, with the recent increase in explorations of tropical caves, British cavers are likely to encounter many more potentially dangerous accumulations of CO_2.

The nature of these caves and their atmospheres has recently been described by James (1977) and need not be reiterated here. It will be sufficient to emphasise that the needs of the speleologist differ markedly from those of the high altitude mountaineer. The latter requires breathing apparatus purely to compensate for the small volume of oxygen inhaled at high altitude - the foul-air speleologist however, is concerned with removing or diluting an essentially toxic addition to his breathing mixture. Indeed, James (1977) has demonstrated that due to the different diffusion rates of the two gases even dangerously high CO_2 atmospheres may contain sufficient oxygen concentrations to sustain life.

The speleologist has, in theory at least, a choice of three alternative life support systems: a non self-contained system based on the dilution of the toxic element to a safe level, or one of two self-contained systems. An examination of the data however, reveals that the former system is impracticable for the speleologist. If we accept a CO_2 concentration of 10% as normal for a foul-air cave of the type that would necessitate breathing apparatus, then allowing a 50% safety factor for upwards fluctuations leads us to consider the problem of diluting an atmosphere of 15% CO_2 to an acceptable level of perhaps 1.0% in the inspired mixture. Since the only advantage of a dilution system is to reduce the volume of oxygen carried by supplementing it with a proportion of the surrounding atmosphere, the 15:1 dilution factor makes such a system redundant.

In the past, foul-air cave exploration has relied on an 'open circuit' system employing standard SCUBA diving equipment (Fincham, 1977). The system has the advantage that the equipment is readily available, well tried, and by and large very safe, but suffers from the not inconsiderable disadvantage of the weight and bulk of the compressed air cylinders. It therefore seems reasonable to suggest that the best solution is to employ a completely closed system - in other words, an oxygen rebreather - in which the expired air is passed via a CO_2 absorbant and then returned to the lungs.

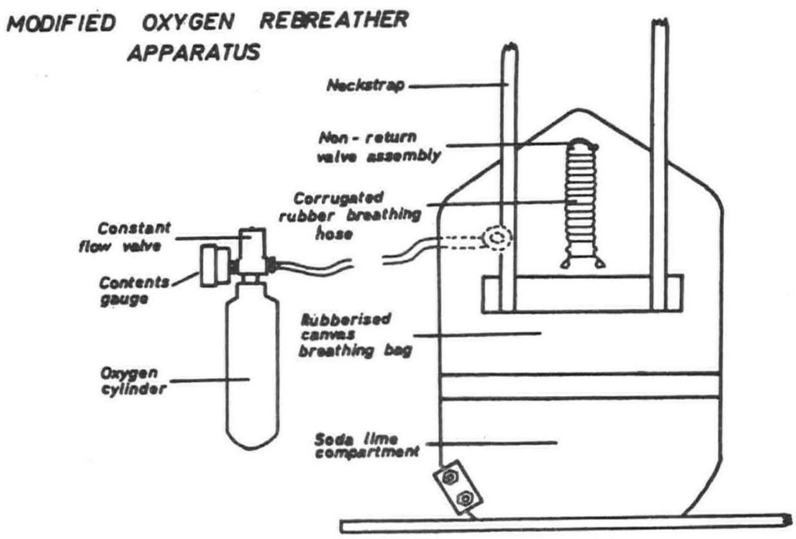
The principle relies on the fact that the human body only uses a small proportion of the oxygen it inhales with some 95-97% of the inhaled air being exhaled again so that in the SCUBA system the biggest proportion of the available oxygen (20.9% in normal air) is exhaled to the atmosphere and lost. Because the oxygen rebreather is so much more efficient, the volume of gas (and hence the size and weight of the cylinders) required for a given length of time is relatively very small.

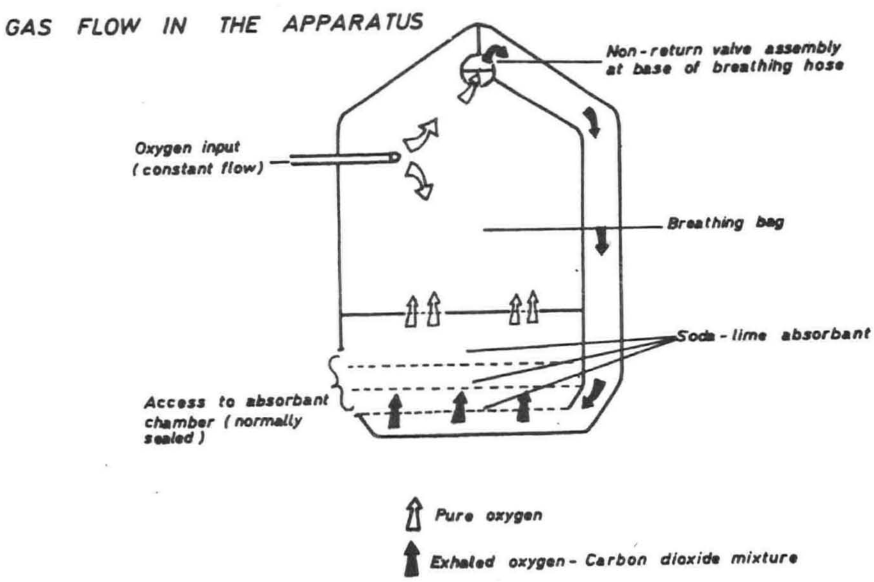
EQUIPMENT AND TRIALS

Recently, Life Support Engineering Ltd., a firm specialising in providing military underwater oxygen rebreathers, have designed and produced a small set intended primarily for emergency mine rescue work. The apparatus was loaned to members of the British Speleological Expedition to Jamaica in 1977 with the intention of testing its speleological potential in the further exploration of Riverhead Cave, where progress has been hindered by serious concentrations of CO_2 in the further reaches. Although high water conditions prevented its use in Riverhead Cave, the apparatus was experimented with by the author and others both above and below ground.

The design of the Life Support Engineering prototype is as follows (Fig. 1). A rubberised canvas "counterlung" of 6.0 dm^3 capacity is fed from a diminutive 63.0 dm^3 (0.3 dm^3/210 Bar) oxygen cylinder. The cylinder, which weighs 1.7 kgs, is fitted with a contents gauge and a fool-proof constant flow valve pre-set, in our case, at 1.5 dm^3/minute. Pure oxygen is breathed directly from the counterlung and separated from the exhaled oxygen/CO_2 mixture by a simple non-return valve arrangement behind the mouthpiece. The exhaled mixture travels down an integral sleeve at the side of the counterlung and feeds into the base of the lower compartment. This compartment contains 0.5 kg of soda lime granules in two layers which 'scrub' the exhaled gas clean of CO_2. The purified oxygen then passes back into the counterlung to begin the cycle again, with a small loss due to metabolism. The equipment is provided with a safety valve to relieve excess pressure in the counterlung, but to all intents and purposes this is superfluous since excess oxygen can be easily and comfortably vented from the mouth. The equipment, as described, provides a self-contained life support system of approximately 30 minutes duration.

Fig. 1.





Prototype oxygen re-breather apparatus in use in Bridge Cave, South Wales.

As a result of practical trials underground, several disadvantages of this prototype equipment were revealed. The first of these is particularly apparent in crawls. The construction of the sets is such that the oxygen cylinder is attached directly onto the counterlung (strapped to the caver's chest) so that the effect is reminiscent of a horse's bridle in that it prevents the wearer from seeing where he is going.

The other problem, common to all simple oxygen rebreathers, is that of the warming of the breathing mixture. Ordinarily, heat loss from the body via expired air is a significant physiological phenomenon, but in an oxygen rebreather this is obviously to some extent circumvented. The result, which may be entirely desirable in cold-water diving, is an uncomfortable overheating for the caver. Whilst this is not really dangerous, and really little more than an unpleasant hinderance, it is a factor that does need to be borne in mind if hard work is contemplated.

MODIFICATIONS TO THE PROTOTYPE

The equipment proposed by the author for speleological use is based on the described LSE prototype, with the following modifications. In order to allow for a reasonable duration in terms of speleological exploration, the 30 minute limitation of the existing apparatus needs to be extended. This is readily achieved by increasing the size of the CO_2 scrubbing compartment to allow the addition of a third layer of soda-lime, raising the absorbant charge to 0.75 kg, and adding a second cylinder to the input. This allows for one hour duration at a breathing rate of 1.5 dm^3/min, although the author has found that a fit caver undertaking moderate exertion (eg. crawling and scrambling underground) can function comfortably on an input of 1.0 dm^3/min. In the latter case a single cylinder of the size described will suffice.

The cylinder or cylinders can be conveniently side-mounted on the caver's belt, requiring only a short extension of the plastic feed hose running into the counterlung, and thereby removing the problem of the weight of the apparatus being borne on the mouthpiece.

The other proposed modification involves the insertion of a short length of corrugated rubber hose, of the type used on twin hose SCUBA demand valves, between the mouthpiece and the non-return valve of the counterlung. This allows for a much increased freedom of head movement, which is rather important in the context being discussed.

CONCLUSIONS

As a result of practical trials with prototype apparatus, a modified version has been proposed which it is felt fills some of the needs of the foul-air speleologist. The equipment represents a compromise between duration, bulk and weight, and cost. The inherent simplicity of the system is one of its great advantages, not only from a constructional point of view but also from considerations of safety. There is only a single mechanical component, the constant flow valve, which is itself the epitomy of simplicity. It can be stripped down and reassembled with a nail file in less than a minute.

The disadvantages of the equipment can be summarised as follows:

1. After 20 minutes or so of use the breathing mixture becomes sufficiently warm to be mildly uncomfortable, unless of course the apparatus is being used in a very cold environment.
2. Some individuals using pure oxygen may experience light-headedness, which is overcome only by experience.
3. The equipment is not designed for immersion in water. In an emergency the set could be submerged provided that the vent on the constant-flow falve was covered and no water was admitted to the mouthpiece, but such a situation is to be avoided except perhaps for short swims in river passages and pools.
4. Care must be taken to flush all the atmospheric air out of the equipment before use, since nitrogen being neither absorbed on soda lime nor metabolised will dilute the oxygen intake into the lungs. (A more detailed description of the use of rebreathers, relevant to this equipment, is to be found in Cullingford,(1962)).

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GEOCHEMICAL CONTROLS ON THE COMPOSITION OF LIMESTONE GROUND WATERS WITH SPECIAL REFERENCE TO DERBYSHIRE

By: N.S.J. Christopher and J.D.Wilcock

ABSTRACT

The technique of cluster analysis has been applied to 154 representative chemical analyses of both ground water and surface water originating from the Derbyshire limestone and surrounding areas to identify the major geochemical controls on the ground water composition.

The similarity coefficient was based on the concentration of the principal cations and anions, together with four derived variables which were: saturation index to calcite, partial pressure of CO_2, relative entropy and the ionic ratio (Ca + Mg)/(Na + K).

The dominant control was found to be biogenic carbon dioxide in conjunction with calcium carbonate giving a ground water of high and relatively stable calcium bicarbonate concentration. Also, the effect of shale contact was a strong influence on composition, principally in surface and thermal waters. Less dominant but recognisable controls were contact with lava or dolomite, whether the water had evolved in the aquifer under open (vadose) or closed (phreatic) system conditions and whether the area of resurgence had been subjected to a prolonged period of weathering.

Surface waters were dominantly undersaturated, low calcium bicarbonate, high P_{CO_2}, high potassium, high sulphate waters that are well mixed (low relative entropy) with a low ionic ratio. The majority of the ground waters are more homogeneous principally calcium bicarbonate waters. Open system mixed ground and surface waters are principally high potassium and high sulphate water with variable SIc and P_{CO_2} that tend to increase with flow.

Lava and dolomite effects are characterized by increased magnesium and some increase in sodium concentration. The thermal waters are usually high in sodium, magnesium, sulphate and chloride, and are supersaturated but low in nitrate due to reduction processes in the aquifer.

INTRODUCTION

A limestone area is frequently devoid of surface rivers, but has an abundance of often large springs or resurgences at lithologically or structurally controlled points in the limestone massif.

The past ten years or so have been a productive period for the literature of British karst water geochemistry and various authors have used their results to infer the nature of strata traversed prior to the sampling point (Richardson 1968), the length of time the water has spent underground (Pitty 1968), or the type of hydrological regime present behind the resurgence (Chambers 1973).

The majority of the analyses upon which previous work has been based have generally involved a limited number of determinants, usually total hardness, calcium hardness and bicarbonate; chloride and sulphate have occasionally been recorded. It is possible that some significant indicators have been omitted, so an examination of all the dominant ionic species for significant trends was thought desirable.

Previous work on the ground waters of the Carboniferous Limestone of Derbyshire has been limited until recently. Stephens (1929) devoted much of his work to the detailed stratigraphy of the various bore holes and his simple chemical analyses were largely concerned with their suitability as potable supplies. Downing (1967) studied the ground water of the limestone in the area of the Eakring oilfield down dip of the area studied in this work. He found that as the water proceeds down dip, deeper into the aquifer, there is a change in both ionic strength and dominant ionic species, with a gradual change from calcium bicarbonate waters to dominantly sodium chloride type waters and a fifty-fold increase in dissolved solids content. He has proposed that these changes are the result of calcite precipitation, sulphate reduction and ion exchange.

Back (1960, 1966) developed the concept of hydrochemical facies when studying the ground waters of the Atlantic coastal plain of North America, where the waters were classified according to the dominant ionic species, e.g. calcium bicarbonate, calcium sulphate or sodium chloride type. This broad classification is not applicable to this work as all waters described herein would be classified as calcium bicarbonate type. This work has been undertaken in an attempt to refine this classification.

The only previous work to consider adequately the calcium bicarbonate waters of the Derbyshire limestone is that of Edmunds (1971). He subdivided the waters into five general groups: grit/shale, general limestone, mineralised areas, perched watertable waters and thermal. The first and last of these groups are sensible and readily distinguishable by chemical analysis, but the remaining three groups are shown by the present study to be of dubious validity and some of his site assignments are a little surprising: for instance, Russett Well, Peak Cavern and Lathkill Head Cave are classified under mineralised areas, together with major soughs (drainage levels).

Edmunds did attempt, in his Figure 2, to quantify the origin of the various waters he studied according to four dominant influences, namely: limestone, mineral veins, igneous rocks and grit/shale, presumably on the basis of field relationships. However, the text contains no discussion of this subject or amplification of the information given in his Figure 2. The trilinear diagrams (Edmunds, Figure 6) do show significant variations in general composition, but there is no detailed discussion of them and the bulk of the text was devoted to a detailed consideration of the waters' trace element compositions and their application to mineral prospecting in particular. However, being a very comprehensive published set of data for many sites in Derbyshire, the major component analyses, not fully discussed by Edmunds, have been used as a basis for this study augmented by many additional analyses carried out by the authors.

THE GEOLOGICAL AND GEOGRAPHIC SETTING

Located in north central England, the limestone area of Derbyshire has a predominantly moist climate with a moderate to high annual rainfall of between 800-1200 mm/year (Anon 1977)

The Carboniferous Limestone area consists of an elevated block of 325 sq km of exposed limestone, principally of Holkerian (S_2), Asbian (D_1) and Brigantian (D_2) ages with reef complexes of B and P ages at the limestone margin. It is sporadically covered with a thin layer of superficial deposits of Tertiary and Pleistocene age which consist essentially of sand, gravel, wind blown loess and some boulder clay, together with extensive deposits of scree.

The limestone is surrounded by shales and grits of Upper Carboniferous (Namurian) age; to the north and west they are of greater elevation than the limestone plateau, whilst to the south the general elevation of the limestone is similar to that of the surrounding grits. To the east the limestone is separated from escarpments of shale and grit by the broad deep valley of the River Derwent, and this river either directly or indirectly eventually collects almost all the drainage of the limestone area. The predominant direction of flow is therefore southwards and eastwards.

The generalised structure is broadly an anticlinal dome, superimposed upon which are several local anticlines and synclines. The elevated limestone block has been extensively dissected by Tertiary and Pleistocene erosion to give a complex pattern of dry valleys.

Interbedded with the main limestone are intrusive and extrusive basic igneous rocks, which are broadly of olivine basalt composition. Many of the lavas have also been altered to clay minerals. These features, together with the mineralised vein fault system of Permo-Triassic age, control the local hydrology.

The natural hydrology of much of the limestone outcrop has been significantly altered by the driving of extensive drainage levels (soughs) since 1630, but principally between 1680 and 1880, in connection with lead mining. The effect of these on the hydrology of the central and southern part of Derbyshire has recently been studied by Oakman (1979 a & b, 1980).

The principal effects have been a general lowering of water tables, breaching of enclosed or perched catchments (frequently contained by impervious lavas) and in some cases, e.g. the Lathkill, transfer of water from one catchment to an adjacent one. As a result of Oakman's work (1978) we now know sufficient about most of the major soughs to understand the lithological origin of the water emerging at the sough tail (= outfall) and it has been possible to select and sample many sough tails to provide known water types for comparative purposes.

DATA SOURCES AND VARIABLES STUDIED

The numerical data for this study are from two principal sources; firstly, original analyses by one author collected over the period 1973-79 and secondly, the already published data of Edmunds (1971). Most of the authors' data are numerical averages of several analyses from each site taken at different times and flow stages. This procedure largely overcomes problems with short term temporal variations known to occur in the chemistry of karst resurgences (Chambers 1973; Bertenshaw 1979). Edmunds' data are from single samples taken at various dates during the period 1967-69; together these gave a total of 154 analyses. The standard of all analyses was assessed from the cation-anion balance. Some of Edmunds' analyses were discarded because of unacceptable balances; some were possibly contaminated with road salt (a total of 13). Also where results were available from both sources the work of the authors was preferred to that of Edmunds for the reasons stated above. This gave 62 analyses of the authors' work and 92 from Edmunds. All analyses were therefore of similar accuracy and therefore directly comparable.

The authors' samples were taken and analysed by standard methods (Anon 1975) and a full list of results is given in Appendix 1. The chemical variables were the dominant ionic species, viz. calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulphate and nitrate. Not all of Edmunds' data includes a nitrate value, so one was estimated on the basis of the cation excess if one existed; this was thought to be usually justified as nitrate concentration forms a small part (usually less than 10%) of the total ionic strength, and as the nitrate concentration was only one of 12 variables studied. However, the nitrate values so derived are subject to error.

Four derived variables were also incorporated into the data analysis: these were saturation index (SIc), partial pressure of carbon dioxide (P_{CO_2}), relative entropy and the ionic ratio (Ca + Mg)/(Na + K) where the ionic concentrations were expressed in milliequivalents per litre. The first two of these have already been shown to be useful indicators of ground water regimes (Harmon et al. 1972), and the calculation method of Christopher (1978) was used for all the data available.

Relative entropy is a term used in the geochemistry of mixed systems to describe the degree of mixing of a multicomponent system and is defined by the expression

$$RE = \frac{\sum_{i=1}^{n} P_i \text{Log } P_i}{\text{Log } n}$$

where n is the number of components

and P_i is the proportion of the component i in the whole.

It provides a standardised scale of 0-1 where zero represents no mixing, i.e. 100% of one component and 1 represents complete randomness, i.e. equal proportions of each component. The values used in this study are based on the eight ionic species stated above and the proportion Pi of each ionic species is calculated from the sum of the total; all calculated in milliequivalents per litre.

The final variable is the ionic ratio (Ca + Mg)/(Na + K) where the symbols represent concentration of the ionic species converted to milliequivalents per litre. This variable has been found by the authors to be a reasonable indicator of ground water type, having a range 0.4 to 37 for the waters studied. Several factors affect the size of the ratio: increased solution increases the numerator and increased sodium concentration from road salt, pollution, shale contact or ion exchange increases the denominator, thus reducing the size of the ratio.

THE GEOCHEMISTRY OF KARST WATER

The dominant influences on the composition of karst water have already been outlined by Edmunds (1971), while Christopher et al. (Chapter 12 in Ford 1977) have reviewed the hydrogeochemistry of the major ionic species in more detail.

Briefly, the influences on composition can be listed as follows:

1. Atmospheric;
2. Climatic;
3. Composition of the impervious catchment and soil;
4. Limestone geochemistry;
5. Geochemistry of the lavas and their degradation products;
6. Mineral vein geochemistry.

The atmospheric influence would be expected to be slight, but Edmunds (1971) has suggested that up to 50% of sulphate and chloride present in ground waters may be contributed by the atmosphere. This is supported by analyses given by Bertenshaw (1979).

By taking an arithmetic average of many analyses at different flow stages the effect of climatic variables has been eliminated. The majority of the remaining data, of Edmunds, that are single analyses, are analyses of water of more deep-seated origin that show less temporal variability.

The composition of soil is intimately linked to the rock from which it is derived and recent studies (Burek 1979) have shown that the soils of Derbyshire are either residuals from limestone, or derived from the surrounding shales. Burek (1979) has also shown that the clay fraction of these soils contains illite, chlorite and felspar fragments. It would, therefore, be expected that attack by carbonated waters would result in a water enriched with magnesium, sodium and silica. Furthermore as shales are known to be high in potassium, due to ion exchange processes during sedimentation, one would expect shale-derived water to be enriched with potassium as well.

The most significant effect on ground water composition from the soil is probably the excess carbon dioxide generated by biological action which results in a significant increase in calcium bicarbonate concentration once the water comes into contact with limestone. Therefore, as available information on the composition of the limestones of central Derbyshire (Cox & Bridges 1976) suggests that they are relatively pure, one would not expect high concentrations of ions from solution of limestone other than calcium bicarbonate, unless one is in contact with dolomitic beds when an increase in magnesium concentration will be observed.

The available petrographic evidence for the lavas of Derbyshire shows that they are essentially olivine basalt or dolerite. This implies that they consist principally of a mixture of pyroxenes (usually augite); plagioclase felspar (whole composition approximates to labradorite); olivine and a little magnetite (Stevenson & Gaunt 1972). Olivine is very readily weathered by contact with highly carbonated waters but plagioclase and augite are more slowly attacked (Wedepohl 1978; Garrels 1967); however, they all release magnesium, sodium, calcium and silica to solution.

However, a competitive reaction, especially where circulation is poor, removes magnesium from solution to form the intermediate clay mineral chlorite by the weathering of ferromagnesian minerals, e.g. olivine and weathered basalt samples are frequently found to be heavily altered to chlorite. Consequently, one would expect ground water draining from limestones containing lavas to be enriched with magnesium and sodium, but if the period of weathering has been prolonged and the lava surface is heavily altered, it may only be sodium-enriched.

Many of the lavas have been extensively altered to clay minerals by hydrothermal waters during mineralisation of the limestone and as a result the clay effectively blocks up the joints in the lava making them very effective aquicludes, giving rise to local perched water tables. Also the resulting clay minerals, principally bentonite, chlorite and illite, have significant ion exchange properties that are capable of removing divalent cations (Ca & Mg) and replacing them with monovalent cations (principally Na). Briars Well, near Matlock, was found to be discharging sodium-rich bicarbonate soft water because of this effect.

The dominant vein gangue mineral is variable throughout Derbyshire and there appears to be zoning with calcite dominant in the west, an intermediate baryte zone, and fluorite dominant in the north and east. There is, however, much intermixing due to the complex sequence of hydrothermal emplacement over several periods of geological time.

Obviously the effect of calcite will be indistinguishable from that of the surrounding limestone, and that of baryte will be minimal due to its very low solubility in water. However, fluorite, (CaF_2), has a significant solubility, sufficient for 1-2 ppm F' to be detected by Edmunds (1971) in many ground waters. Because this aspect has already been adequately covered by Edmunds (1971) and Bertenshaw (1979), it has been omitted from this analysis.

The dominant heavy metal minerals are the sulphides of lead and zinc and so one would expect mineral vein waters to be enriched with sulphate, but this effect may be masked by soil sulphate derived from the oxidation of pyrite fragments, derived from the surrounding shales.

COMPUTER AND MATHEMATICAL METHODS

Multi-variable regional surveys of the type undertaken by the authors inevitably involve the accumulation of a large bulk of analytical data, and consequently problems arise in data-handling and interpretation.

Cluster analysis is a multivariate technique which has been used extensively by numerical taxonomists and in many other fields. The sample or item must be described in terms of a number of numerical attributes or variables. In our application the items are synthesised from a number of samples taken from each site under different weather conditions, each parameter being the arithmetic mean of a number of observations on the same water source. It is normal practice to standardise the parameters by scaling them down by some mean, median or maximum value for each parameter, so that each parameter then potentially makes the same numerical contribution; this procedure also circumvents the potential problem of the dominance of the analysis by one or more variables which happen to have the largest numerical values. In the intermediate study (Christopher & Wilcock 1981) the mean of the parameters of the General Limestone Group were used for standardization. In the final analysis the medians of the General Limestone Group were used for scaling. Medians were preferred to means to prevent undue weight being given to extremes in the distribution. Saturation index was the only exception to this rule; in this case since both positive and negative values occurred the parameter was normalised on -1.

The similarity algorithm used in this study is a form of inverse Euclidean distance

$$SC = 100 \left(1 - \frac{\sqrt{\sum_{m=1}^{p} w_m \; (x_{im} - x_{jm})^2}}{\mathrm{MAX}\left(\sqrt{\sum_{m=1}^{p} w_m \; x_{im}^2} \, , \sqrt{\sum_{m=1}^{p} w_m \; x_{jm}^2} \right)} \right)$$

where sites i and j are being compared in terms of p parameters. The x values are values of the parameters and the w values are weights assigned to parameters. This yields a coefficient with maximum 100% similarity, minimum 0% similarity.

The Q mode weighted pair group average linkage method of clustering was adopted. This was preferred since it has been found that average linkage gives the best results for general purpose classification (Sokal and Sneath 1963; Sneath and Sokal 1973), whilst single linkage suffers from chaining (Gower 1967).

The anion concentrations are not completely independent of the cation concentrations, so to avoid double weighting of these features the anions were arbitrarily assigned weights of 0.5, while the remaining variables were given weights of 1.0. This procedure is admittedly subjective, but was preferred to the derivation of uncorrelated orthogonal variables by Principal Components Analysis, since it was desired to retain the original recognisable variables for use as a "fingerprint". The procedure is justified by the sensible results obtained.

The results of the clustering may be illustrated by several methods. The two methods used in this paper are the dendogram (a tree-like structure which starts with all items separate and gradually links them by branches into clusters at various similarity ("phenon") levels, terminating by all items linked into the "trunk" of the tree, see Figures 1 & 4), and the minimum spanning tree (an octopus like structure which links all items to their most similar neighbours, and elucidates the inherent structure of the data, see Figure 2).

The authors have used ALGOL 60 and FORTRAN on many different computers for similar clustering analysis projects to this study. For convenience on this occasion, however, Extended BASIC was used on a RML 380Z microcomputer with 48K of memory. The increasing availability and relatively low cost of microcomputers makes the use of them attractive for research use.

DISCUSSION

The preliminary analysis has already been reported and need not be discussed further (Christopher and Wilcock, 1981).

The data base for the final analysis was increased via intermediate stages to 154 sites and all the chemical variables and derived values, notably SI_c, Pco_2, RE and the ionic ratio were considered, with the anion values rated at only 0.5 of the significance of the remaining variables, as notes above.

The results of the final analysis are presented in Figures 1 & 2 and Appendix 3 as a dendrogram and minimum spanning tree, while Figure 3 and Appendix 4 relate to the largest single group, the "General Limestone Group". Figure 4 gives the chemical fingerprints of the various groups superimposed on the dendrogram, so that it can be seen how the groups relate geochemically. Figure 5 shows the spatial distribution of the clusters identified in Figures 1 & 2.

Figures 1 & 2 show the generalised relationship and if one takes the 60% similarity level as the limit of the relationships then we have four strong hierarchical groups (the 60% phenons), the general limestone group and associated clusters, the dolomitic cluster, the mineral/thermal cluster, and the grit/shale cluster plus a number of small clusters or individual sites (see Figure 2). Each will be discussed separately below. It is very encouraging that there are only seven individual sites not clustered at the 81% level and only one at the 60% level.

1. <u>The General Limestone Group and its associated clusters</u>

The general limestone group will be discussed separately, and this links with a single site at 79%. At 76% this cluster links to Resurgence Group B.

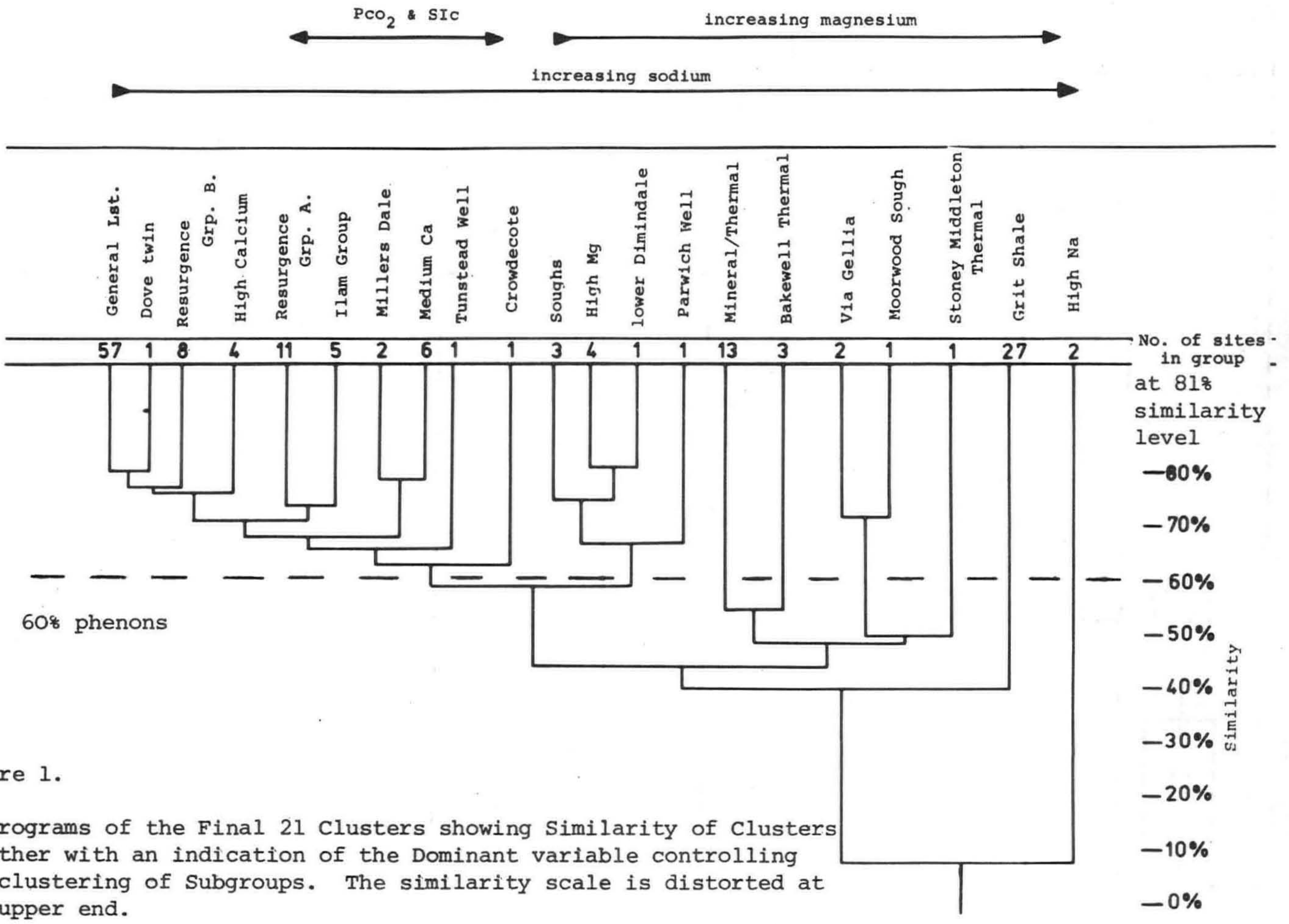


Figure 1.

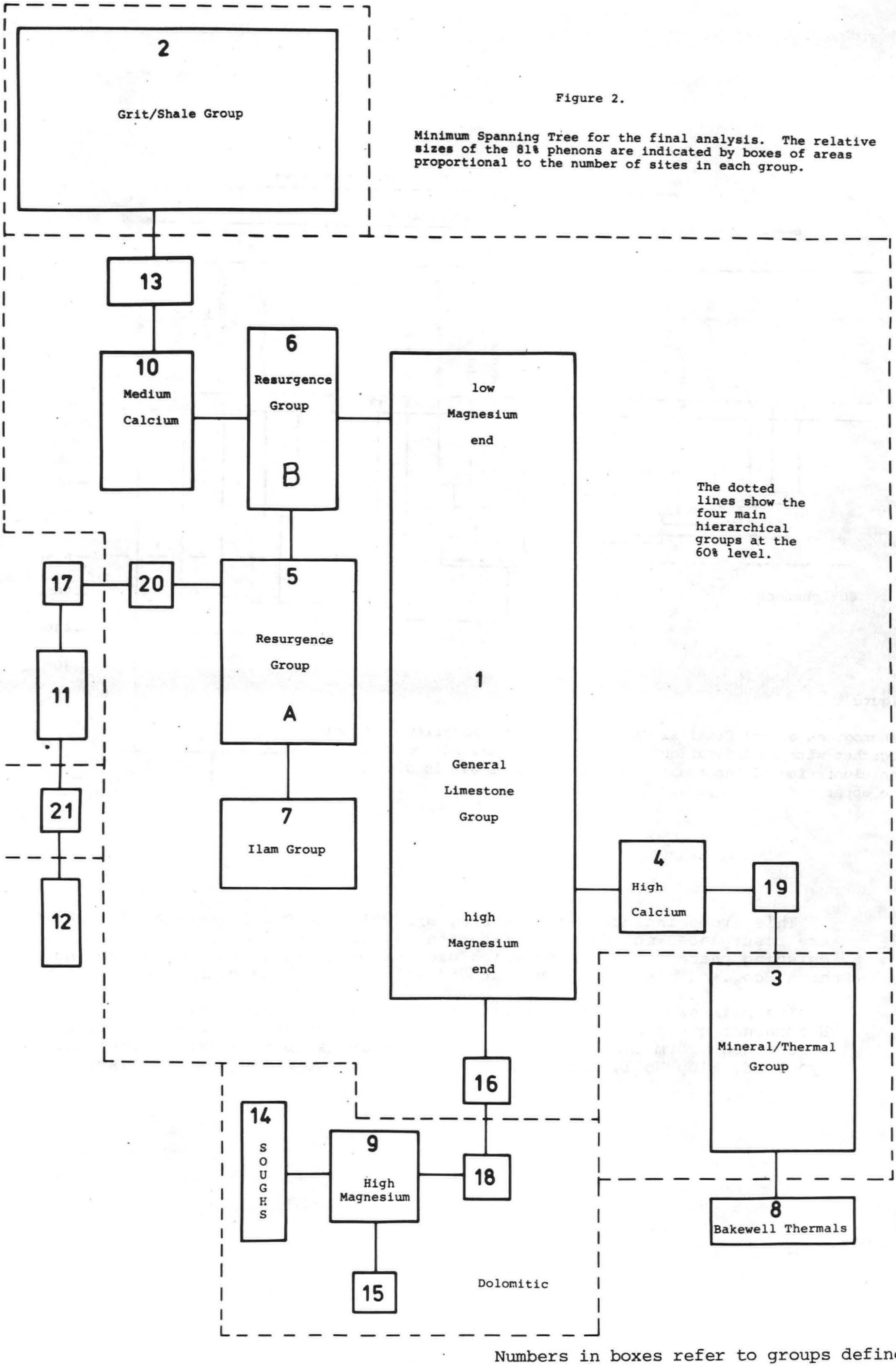
Dendrograms of the Final 21 Clusters showing Similarity of Clusters together with an indication of the Dominant variable controlling the clustering of Subgroups. The similarity scale is distorted at the upper end.

This group includes Peak Cavern, Bradwell and Dowel resurgences, which are resurgences not directly fed with allogenic swallet water, the distinguishing characteristics of which are low magnesium, high potassium and high Pco_2. This group links at 75% with the high calcium group.

The main swallet fed resurgences of Derbyshire all cluster in Resurgence group A, and the chemically and hydrologically related Ilam resurgences form the Ilam group. The former group includes Russett Well, Wye Head, Slop Moll, and Deepdale Resurgence, together with Hillcarr,

Figure 2.

Minimum Spanning Tree for the final analysis. The relative sizes of the 81% phenons are indicated by boxes of areas proportional to the number of sites in each group.



Numbers in boxes refer to groups defined in Appendix 3.

Brightside, Orchard, Oxclose and Cromford Soughs. This group has high sodium, potassium, chloride and sulphate. The main Ilam resurgences, with the exception of Ilam Weir, Ilam Well and Hinckley Wood resurgences, cluster in the Ilam Group, the characteristics of which are similar to resurgence Group A, except that they are also undersaturated. Waterhouses Sink is also incorporated in this cluster; this site is a surface stream, but as it flows for many metres over limestone and collects the percolation from calcareous soil, this has acquired the characteristics of a mixed water type typical of allogenic resurgences. These clusters incorporate all the major swallet fed systems of Derbyshire, together with shale-affected limestone sough waters, e.g. Hillcarr Sough, which are genetically identical.

The next cluster at 79% similarity links two Millers Dale resurgences (low calcium values) with the Medium Calcium Group, which is essentially a group of small resurgences in the Castleton area. Finally, there are two individual sites, Tunstead Well and Crowdecote. The total number of sites clustered here are 96 and they represent the dominance of the limestone geochemistry, together with the influence of swallet water and open passage development (high potassium, high Pco_2, undersaturated) in the major sink to resurgence systems. The lava influence evident in the initial study is now mostly incorporated in the General Limestone Group and will be discussed below.

2. The Dolomitic Cluster

The next separate cluster includes only eight sites but these incorporate the remaining high magnesium group from the dolomite-affected SE of Derbyshire, together with three soughs of the Matlock area. These merge with a single site, Parwich Well, at 66% to form the Dolomitic Cluster.

3. The Mineral/Thermal Cluster

The next major group is the mineral/thermal cluster. This includes Allenhill, Millclose, Clatterway, Bullestree and Yatestoop soughs, with the Matlock and Buxton thermals. The main characteristics of these are high magnesium and sodium and sulphate concentration derived principally from shale. The thermals are at the shale-limestone boundary and the soughs are all driven in part or whole in shale, with the exception of Clatterway sough. This sough is driven along the top of Matlock Lower Lava, and the water analysis indicates that its upper surface is not altered extensively to clay minerals because of its high magnesium concentration. This group neatly illustrates the dual effect of two geochemical influences producing similar analyses which can only be separated with field knowledge.

The genetically similar but separate high sodium waters (group 12 at the extreme left of Fig. 2) form a group of relatively high ionic strength waters with abnormally high sodium concentration. The cluster consists of two sites - Briars Well and Bradwell Thermal - the former has already been mentioned, and the latter also at the limestone margin is thought by Edmunds (1971) to be the only site in Derbyshire where some connate water is resurging.

These two sites do not form part of the mineral/thermal cluster and only join all the remaining clusters at the extremely low similarity level of 7%.

The thermals form several separate groups as suggested by Edmunds (1971). This study identifies the Matlock/Buxton Group, the Bakewell Group, with the Bradwell and Stoney Middleton thermals being of separate sites of distinct composition. This is similar to Edmunds' arrangement, but three of his "thermal" sites (Meerbrook Sough, Lower Dimindale and Beresford) are not classified as thermal by this study.

4. The Grit/Shale Cluster

The final cluster is the grit/shale group of 27 surface streams derived from the surrounding area and includes all the Rushup Edge, Hucklow Edge, Axe Edge and Hamps/Manifold swallets: the characteristics of which are low calcium, bicarbonate, relative entropy, and ionic ratio, high potassium, sulphate and Pco_2. They are also undersaturated to calcite.

One site, Ilam Weir resurgence, included in this group is not a surface stream, but this study identifies it as having many of the chemical characteristics of a surface stream, and is therefore distinct from the other Ilam resurgences.

5. The General Limestone Group in Detail

Figure 3 shows the minimum spanning tree for the 57 samples in this group; Appendix 4 contains details of the composition of the separate clusters shown in Figure 3, together with site names and fingerprints.

Examination of Figure 3 reveals that virtually all the sites in this group come from the centre of the Derbyshire Dome.

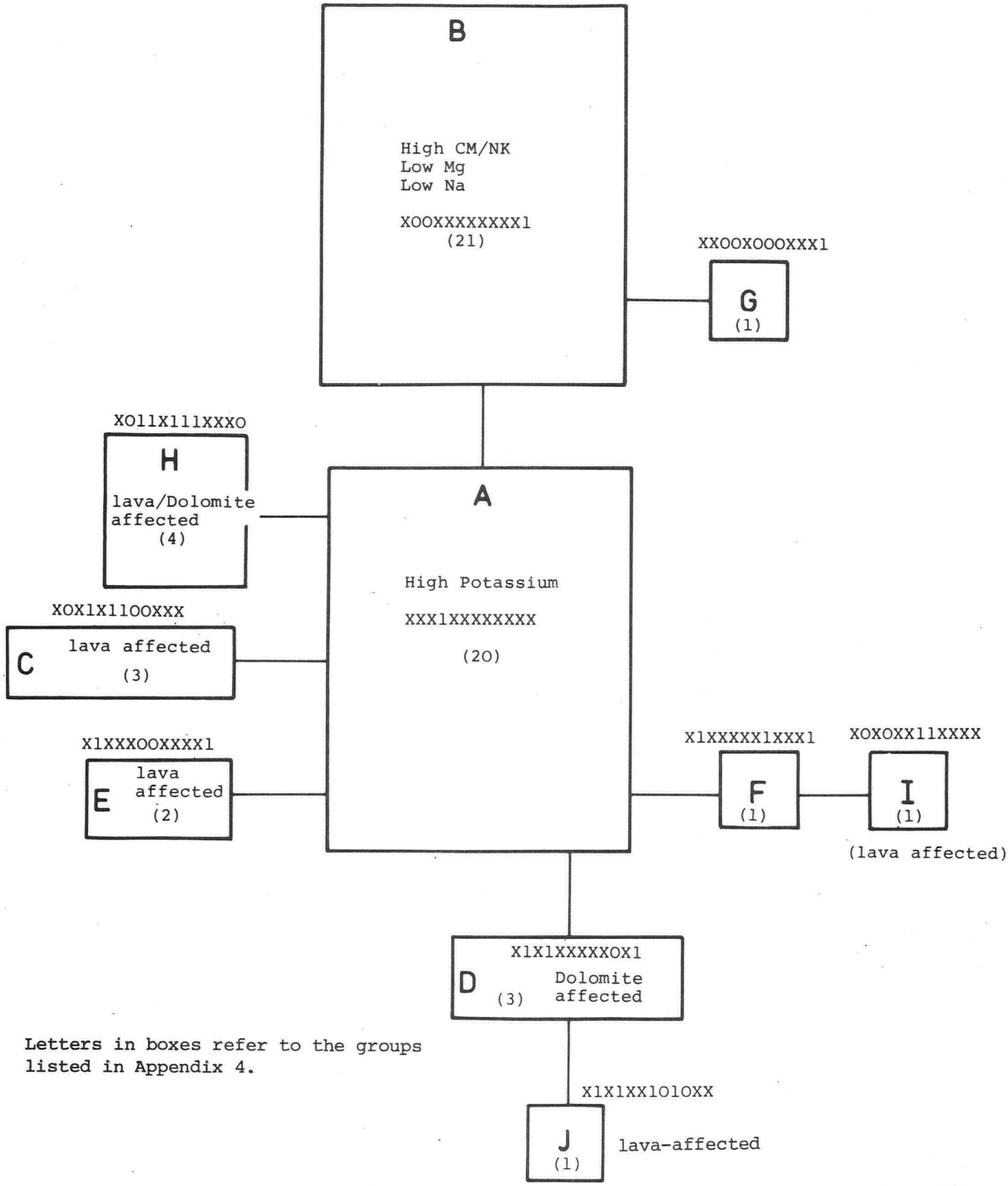
At the 82% similarity level there are six clusters, two dominant ones of 20 & 21 sites, and four individual sites not clustered. (For details see Appendix 4). These have been referred to as Groups A-J, whilst at the 85% similarity level, there are 20 groups, 7 single sites and two large clusters of 13 sites each. As can be seen from this, the waters in the general limestone group are generally of very similar composition as all the groups form one cluster at 81% similarity (the General Limestone Group). Therefore, the remaining discussion is about relatively small distinctions in composition between samples and groups of samples.

To understand the geochemical implications of Figure 3 we have to look at the composition of the "Standard Derbyshire Water" used to produce the standardized data for the whole analysis, details of which are given in Appendix 2. As no comprehensive silica data was available this factor could not be considered, so the distinguishing feature of lava-affected water would be magnesium and sodium concentration. Examination of Appendix 2 shows that of the 48 sites, 20 were definitely lava-affected and 3 were dolomite-affected.

The net result is that the median concentrations of magnesium and sodium at 5.0 and 6.5 mg/l were influenced by these two factors. Consequently, "normal waters" in Figure 3 are richer in these two ions than would reasonably be expected.

Therefore, the low magnesium and sodium waters of Group B, more fully represent "pure limestone ground water" than the "normal" waters of Group A.

Inspection of the site and field relationships given in Appendix 4 reveals, however, a further complication, because both Group A and Group B contain a significant number of resurgences (10 and 8 respectively) that occur at points above a lava bed and should therefore be lava-affected. However, as can be seen from Table 1, the average and individual values of magnesium and sodium are lower in the case of Group B sites than the Group A sites with the exception of Basrobin Sough, which, on this analysis, is more typical of Group A than Group B; but other factors in the similarity coefficient have placed it in Group B. Table 1 shows also that the higher sodium and magnesium concentrations, of Group A, are found in resurgences that occur at a much lower altitude than those of Group B; the average altitude of the Group A resurgences being 530 ft (162m) lower than the Group B resurgences. This suggests that the higher resurgences of Group B have been exposed to weathering for a much longer period: that the lava consequently has become altered on its upper surface much more extensively, sufficient to remove almost completely the most reactive components of the lava, and that secondary reactions are now dominant or the clay surface is almost non-reactive towards percolating "pure" limestone water. All the resurgences in Group A occur in the floor of the valleys of the Rivers Wye, Lathkill or Bradford. These rivers were probably down cut to their present level in the Devensian glacial episode (Burek & Ford, in Ford et al. 1977, ch. 9) and the local water tables that the lavas and the resurgences control have only been active in post-glacial times, say the past 10,000 years.



Letters in boxes refer to the groups listed in Appendix 4.

Figure 3. Minimum Spanning Tree for the General Limestone Group. The relative sizes of the 82% phenons are indicated by boxes of areas proportional to the number of sites in each group.

Table 1

Altitude, Magnesium and Sodium Concentrations for Lava-Affected Sites in Groups A & B of Figure 3

Group A		Altitude (ft)	Mg mg/l	Na mg/l
16	Magpie Sough	460	6.8	7.1
33	Well Head	500	8.9	5.4
34	Bubble Springs	510	6.4	8.0
41	Bonsall Sough	500	8.3	6.9
701	Monks Dale	650	8.5	5.2
802	Gt. Shacklow	460	5	7
903	Mandale Sough	530	5.5	6.5
18	Cressbrook Dale	625	5.4	10.9
20	Cheedale Bridge	650	5.7	10.4
810	Millers Dale 2	650	6	10.0
	Average	560	6.7	7.7
Group B				
22	Brindleys Well	1030	1.5	6.5
711	Priest Cliff	1050	4	5
803	Wormhill Moor	1250	2	5
804	Chelmorton	1200	2	4
805	Waterloo Sough	1300	2	4
807	Shothouse West	925	2.1	4.2
1104	Shothouse East	900	1.7	3.6
811	Tithe Farm	1100	4	4
	Average	1090	2.4	4.5
1017	Basrobin Sough	580	6.8	3.9

However, the higher level, Group B resurgences, will have been activated by valley cutting at the latest in the Ipswichian interglacial and possibly in the earlier Hoxnian interglacial, which allows a time period of at least 125,000 years and possibly as much as 250,000 years, i.e. between 13 and 25 times as long. It is not surprising, therefore, that the chemistry is different. This argument is strengthened by the results from Basrobin Sough, cut in the 18th century, draining a local water table above the Lower Matlock Lava near to Wensley (Oakman 1979), having a magnesium concentration within the range of Group A resurgences.

Group A resurgences therefore represent lava and mildly dolomite-affected ground waters, whilst Group B represent "pure limestone waters".

Most of the remaining groups are distinguished by magnesium concentration and other variables indicated on Figure 3. Frequently they occur at lava-affected horizons (Aldwark and Watergrove Sough) or are in close proximity to the Woodale Dolomites (e.g. Stanley Moor Borehole, Wormhill Springs and Woodale Borehole).

Group I (Ible Spring) is another lava-affected site (the Ible Dolerite Sill), but impoverished in magnesium, probably for reasons already stated, having an altitude of 925 ft.

Thus it can be seen that because of the normalising process to which the data was subjected, the majority of the lava effect has emerged as a negative (non-discriminated) influence rather than a positive influence on a group of relatively similar composition waters. This effect has been further complicated by the presence of several low magnesium, normal sodium waters that emerge above lava flows.

6. General Conclusions

It is therefore possible now to see that the Derbyshire ground waters fall essentially into four groups: surface waters, general limestone waters, dolomite-affected waters and thermal waters. These represent three dominating geochemical controls: shale, limestone and dolomite. The general limestone and associated waters show three distinct influences; the dominant one of limestone: open passage evolution and mixed composition in the major allogenic fed resurgences of resurgence groups A, B and Ilam (Figures 1 & 2) and a less strong but recognisable lava influence (Figure 3). Therefore there are three strong and two weaker geochemical controls on composition.

A surprising fact is the apparent lack of influence from mineral veins, but, as has already been explained, with the exception of sulphate there are no strong indicators of this effect, and as we have seen sulphate is dominantly shale/soil derived. If fluoride had been studied then possibly the influence of fluorite mineralisation would have emerged.

The main features that discriminate the clusters are broadly sodium and magnesium concentrations for the main limestone waters, and calcium, Pco_2 and SI_c for surface and mixed limestone types; these are indicated in Figure 4.

This sequence of genetic development progressing towards high calcium, sulphate and bicarbonate composition is similar to that described by Downing (1967) for the more deep-seated waters found downdip to the east of the limestone outcrop. However, the calcium reduction processes have not yet begun to make serious inroads into the calcium concentration at this early stage of aqueous evolution. It is also similar in many requests to the proposals and findings of Back (1961 & 1967), but, again, he worked on a much larger scale.

This also shows the confused nature of Edmunds' (1971) classification. All the Edmunds' sites used in this study are coded in Appendix 3 & 4 as follows: Grit/Shale 500's; Thermals 600's; General Limestone 700's; Perched Water Tables 800's; Soughs and Mineralised Areas 900 and 1000's respectively. Even a relatively superficial inspection of Appendices 3 and 4 shows that waters of similar general composition have been put into different groups in Edmunds' classification.

Figure 5 shows the geographical (spatial) distribution of the clusters identified in Figures 1 & 2. It is apparent from Figure 5 that such spatial control as is apparently exhibited by geographic groups, e.g. Via Gellia, Bakewell thermals, Ilam etc., is only a result of these resurgences draining localised areas of similar lithology and therefore it is lithological or geochemical control that is dominant in deciding water characteristics. This is strikingly apparent from the wide distribution over the dome of the general limestone type waters and also resurgence groups A & B, all of which are clusters of highly similar water.

THE CHEMICAL CHARACTERISTICS OF THE FINAL CLUSTERS

This final section will amplify the discussion above and attempt to put a 'fingerprint' on the various water classes.

The median analyses for the 13 clusters and 7 individual sites identified are given in Table 2.

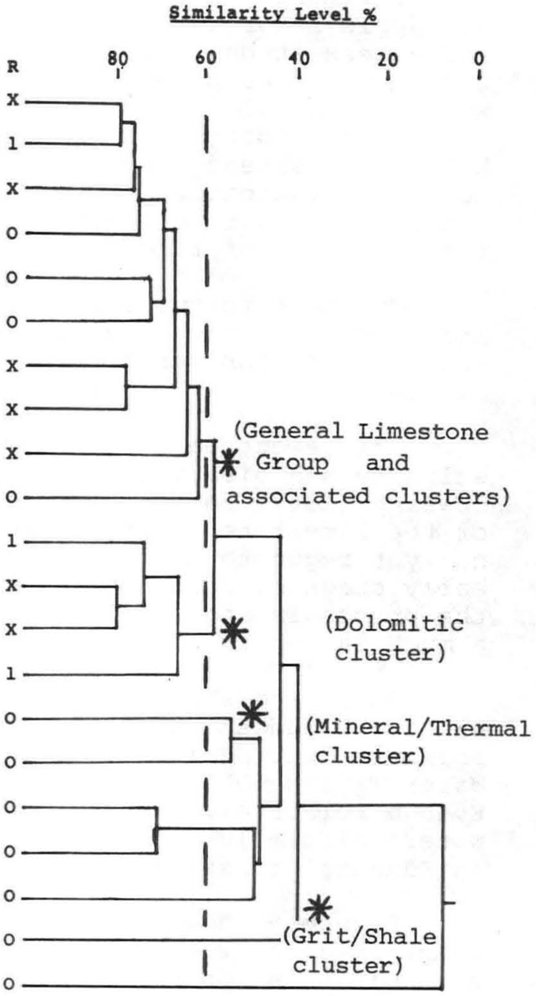
Figure 4 is derived from Table 2 by standardizing all the data, by dividing each median value by the corresponding value for the general limestone group and attaching arbitrary limits to three symbols that represent a high, normal or low state (1, X and O). The only exception is the saturation index, which is assigned the value O for supersaturated, X for saturated and 1 for unsaturated.

All the ionic concentrations are assumed to be 'normal' if their value lies within 30% of the corresponding general limestone value. The same criterion is also applied to the ionic ratio. Because of their small variability $\pm$ 10%

Figure 4

Fingerprint Code

Group No.		Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3	SI	Pco_2	RE	R
1.	General Limestone	X	X	X	X	X	X	X	X	X	X	X	X
16.	Dove Twin R4	X	1	O	X	X	X	X	X	X	X	X	1
6.	Resurgence Group B	X	O	X	1	X	X	X	X	X	1	X	X
4.	High Calcium	X	O	1	1	X	X	1	X	X	O	X	O
5.	Resurgence Group A	X	X	1	1	X	1	1	X	X	X	X	O
7.	Ilam Group	O	X	1	1	X	X	1	O	1	X	X	O
13.	Millers Dale	O	X	X	O	O	X	1	O	X	1	X	X
10.	Medium Calcium	X	O	O	X	O	O	1	X	O	1	X	X
19.	Tunstead Well	X	X	X	1	X	1	1	X	X	X	X	X
20.	Crowdecote	X	X	1	1	X	1	X	O	O	X	X	O
14.	Soughs	X	1	X	X	X	X	1	1	O	1	X	1
9.	High Magnesium	X	1	X	1	X	X	X	X	O	X	X	X
15.	Lower Dimindale	X	1	1	X	X	X	X	O	X	X	X	X
18.	Parwich Well	X	1	O	X	1	O	1	O	X	O	X	1
3.	Mineral/Thermal	X	1	1	1	X	1	1	O	X	X	1	O
8.	Bakewell Thermals	1	1	1	1	X	1	1	O	O	X	X	O
11.	Via Gellia	X	O	1	1	X	1	1	1	O	1	1	O
17.	Moorwood Sough	X	X	1	1	X	1	1	1	O	1	1	O
21.	Stoney Middleton Th.	X	1	1	1	X	1	1	X	O	1	1	O
2.	Grit/Shale	O	X	X	1	O	X	1	O	1	1	1	O
12.	High Sodium	X	1	1	1	X	1	1	X	X	X	1	O



Fingerprint Codes and Dendrogram for the Final Analysis.

Major groups are indicated by asterisks.

The numbered groups are the 81% phenons, and the major groups 60% phenons.

The similarity scale is distorted at the upper end.

Fig. 5. The spatial distribution of clusters.

Table 2. **Median values of the final groups (Figures 1 & 2)**

(For membership of each group see Appendix 3; all units of concentration are mg/l of the ion, except * which is mg/l as $CaCO_3$)

Group No.	Group Name	Ca	Mg	Na	K	HCO_3^*	Cl mg/l	SO_4	NO_3	SIc	Pco_2	RE	$\frac{Ca + Mg}{Na + K}$	No. in Group
1	General Limestone	103	4.5	5.4	0.7	218	16	38	11.9	0.11	2.00	0.629	21.7	57
2	Grit/Shale	29	4.8	8.3	1.8	55	17	46	4.3	-0.98	2.66	0.829	4.2	27
3	Mineral/Thermal	97	23.4	19	2.1	210	39	125	1.8	0.28	2.15	0.801	7.3	13
4	High Calcium	118	1.95	9.4	3.35	216	17.5	48.5	14.6	0.11	1.83	0.645	12.5	4
5	Resurgence Gp A	92	6.5	13.1	1.2	174	29	48	13.7	0.12	2.23	0.731	8.5	11
6	Resurgence Gp B	83	2.3	6.5	1.25	166	16	41	11.3	0.12	2.37	0.655	13.5	8
7	Ilam Group	70	5.6	11	3.6	159	21	47	4.0	-0.45	1.92	0.725	8.0	5
8	Bakewell Thermals	161	17	19	1.5	178	23	267	1.8	0.36	2.07	0.713	10.9	3
9	High Mg Group	95	20	5.4	1.55	266	14	43	13.7	0.53	2.16	0.685	23.8	4
10	Medium Ca Group	72.5	3.0	4.0	0.55	125	10	48	10.9	0.39	2.71	0.67	20.7	6
11	Via Gellia Gp.	111	2.05	32.8	6.7	186	66.5	60	25.2	0.36	2.35	0.778	3.6	2
12	High Sodium Gp.	113	29.7	239	4.0	273	267	266	9.45	0.29	2.15	0.812	0.8	2
13	Millers Dale	60	6.0	5.0	0.2	107	13	56	6.2	0.29	2.91	0.721	15.5	2
14	Soughs	84	29.8	4.8	0.7	262	19	49	21.2	0.47	2.35	0.718	34.5	3
Individual Sites														
15	Lower Dimindale	90	16	9.5	0.6	224	18	38	5.3	0.19	1.91	0.694	13.6	1
16	Dove Twin	100	7	3.2	0.5	223	14	37	11.5	0.00	1.96	0.627	36.6	1
17	Moorwood Sough	101	6	28	1.8	171	45	73	25.4	0.34	2.36	0.794	4.4	1
18	Parwich Well	127	10	4.0	0.8	296	10	53	6.2	0.18	1.65	0.604	36.8	1
19	Tunstead Well	127	5	8	3.6	200	24	90	15	0.12	1.92	0.688	15.3	1
20	Crowdecote	97	4	19	1.0	225	37	31	6.2	0.33	2.12	0.687	6.1	1
21	Stoney Middleton Thermal	92	29	61	1.5	210	110	100	14.2	0.60	2.33	0.868	2.6	1

and ± 20% were applied to Pco_2 and relative entropy values respectively, whilst the $\bar{S}$Ic values were normalised by dividing by -1.0 and then large positive values are unsaturated (1, high) and large negative values supersaturated (0, low). The dendogram is also included in Figure 4 for comparative purposes.

The significance of the various chemical and physochemical indicators can be deduced from Figure 4 and they are set out below:

Calcium and Bicarbonate — Low calcium: in surface waters.

Magnesium: — High magnesium: in shale, dolomite and lava-affected waters; also high in thermal waters (from shale contact). Low magnesium: "Pure limestone" water.

Sodium: — High sodium: contaminated allogenic resurgence waters, surface waters and mineral/thermal waters from shale contact. Low sodium: "Pure limestone" water.

Potassium:	High K: surface and allogenic resurgence systems and surface shale-contact waters. Low potassium: deep circulation ground water.
Chloride:	High chloride: contamination of allogenic resurgences, also in mineral, sough and thermal waters, i.e. shale contact.
Sulphate:	High sulphate: soughs, mineral and thermal waters.
Nitrate:	Low nitrate: thermal and surface waters. High nitrate: contamination by fertilizer (mostly soughs).
SIc :	Unsaturated(1): surface and allogenic mixed waters. Supersaturated(O): soughs, mineral and thermal waters.
Pco_2:	High: open passages, soughs etc.
Relative Entropy:	High: thermals and surface waters.
$\frac{Ca + Mg}{Na + K}$	Low: due to high Na or low Ca, e.g. surface waters and thermals. High: pure calcium bicarbonate waters due to high Ca or low Na.

THE EFFECT OF RAINFALL ON CLASSIFICATIONS

As has been explained, the majority of the data has been selected to eliminate temporal variations. However, if this factor had been allowed in the analysis then one would expect that it would manifest itself principally in those sites that are fed by allogenic sinks and the net result would be that these clusters, Resurgence Group A,B and the Ilam Group of Figure 2, would become more similar to the grit/shale group, as all that is happening is that these resurgences are discharging a greater proportion of grit/shale type water.

CONCLUSIONS

Based on the major component analyses and derived variables of 154 waters from a variety of sources in the Derbyshire limestone and surrounding grit-shale areas, it has been possible to identify four chemically distinct water types using the technique of cluster analysis. These groups are grit/shale surface waters, general limestone waters (incorporated in which are limestone waters with evidence of contact with lava), dolomitic waters and mineral/thermal waters.

The chemical differences are principally a much higher concentration of calcium bicarbonate in all ground waters as opposed to surface waters. This represents the dominance of calcium carbonate and carbon dioxide on composition, and subsequently an increased contribution to the total ionic strength by the ions sodium, chloride, sulphate, and to a much lesser extent, magnesium. No evidence was found that these variations in ionic type were due to reduction in calcium bicarbonate concentration, by precipitation or reduction processes acting in the unsaturated zone. Increases in ionic strength come from the addition of the ions specified to the system studied.

The only ion studied that reduces in absolute concentration with increased penetration into the aquifer is nitrate which is presumably associated with reduction to nitrite and ultimately nitrogen gas linked to dissolved oxygen concentration and redox potential (Hem 1970).

The principal controls on water composition are therefore soil and surface rock composition; biotic carbon dioxide and limestone; shale composition; open or closed system evolution; lava composition and the presence of dolomite.

The fingerprinting technique was found to be a major aid in the quick identification of low and high parameters for a water and identifying major influences on composition. Whilst it is also possible to identify catchments with chemically similar water this is only broadly acceptable in so far as rock types occur in limited areas and it is the rock type that controls the geochemistry of the ground water.

ACKNOWLEDGEMENTS

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APPENDIX 1

Computer listing of the 154 sites analysed and the results are tabulated on pages
The parameters listed are, left to right:

- Site No.
- Site name
- Catchment
- Grid reference
- pH
- Calcium
- Magnesium
- Sodium
- Potassium
- Total hardness
- Bicarbonate
- Chloride
- Sulphate
- Nitrate
- Saturation Index
- Partial pressure of carbon dioxide
- Relative entropy
- (Ca + Mg)/(Na + K) ratio.

The catchments used are as follows:

DN	Dean
DV	Dove
DW	Derwent
GT	Goyt
LK	Lathkill
MF	Manifold
NB	Norbury Brook
VG	Via Gellia
WY	Wye

APPENDIX 2

Sites in the General Limestone Group of the intermediate study, with their median parameters

Site No.	Site Name	Site No.	Site Name	Site No.	Site Name
16	Magpie Sough*				
18	Cressbrook Dale Resurgence*	722	Friden Brickworks Bore Hole+	1005	Black Sallet Mine
19	Workhill Springs*			1014	Middleton*
20	Cheedale Bridge Resurgence*;	723	Ramshorn Quarry	1016	Ludwell 2
23	Ashwood Dale Resurgence	728	Dale End Farm Bore Hole	1017	Basrobin Sough*
24	Cowdale			1102	Carters Mill
33	Well Head*	802	Great Shacklow*	1103	Stanley Moor Bore Hole*
34	Bubble Springs*	803	Wormhill Moor*	1104	Shothouse Spring E*
41	Bonsall Sough*	806	Ible Spring*	3201	Dove R1
606	Beresford	810	Millers Dale 2*	3202	Dove Footbridge R2
701	Monks Dale*	811	Tithe Farm*	3205	Dove R5
703	Crowdwell	812	Aldwark 1*	3206	Brickpit Resurgence R6
706	Pictor Spring	813	Aldwark 2*	3207	West Bank Resurgence R7
709	Litton Mill 1	903	Mandale Sough*	3209	Nabs Spring
710	Litton Mill 2	904	Watergrove Sough*	3505	Ilam Well Resurgence
713	Glutton Grange	1001	Ludwell 1	3701	Deep Dale Side Resurgence
717	Crowhill Lane	1002	Calesdale		
718	Hindlow Quarry Bore Hole	1004	Lathkill Head Cave		

(Sites marked * are lava affected; + are dolomite affected)

Median Parameters

Ca	101	HCO_3	216	SI	-1
Mg	5	Cl	17	pCO_2	2.03
Na	6.5	SO_4	35	RE	0.637
K	0.7	NO_3	11.9	CM/NK	18.4

No.	Site Name	Catchment	GR	pH	Ca	Mg	Na	K	TH	HCO3	Cl	SO4	NO3	SI	pCO2	RE	CM/NK
1	Pott Shrigley	DN	SJ944793	6.84	20	5.4	8.6	2.2	72	22	20	37	4.3	-2.3	2.77	.885	3.35
2	Pott Shrigley(Flood)	DN	SJ944793	6.84	24	7.4	10.4	12.3	92	33	30	43	4.3	-2.02	2.66	.922	2.35
3	West Park Gate	NB	SJ964842	6.59	13	4.8	6.9	1.5	53	11	15	33	2.2	-2.86	2.61	.872	3.08
4	Todd Brook	GT	SJ982793	7.04	15	4.3	8.7	1.8	55	24	17	24	2.7	-2.03	2.68	.895	2.59
12	Russett Well	DW	SK148827	7.4	76	2.1	12.1	1.1	202	144	28	34	12.5	-.23	2.23	.712	7.15
13	Slop Moll	DW	SK147828	7.56	74	2.2	12.6	1.2	191	133	30	35	13.7	-.1	2.44	.729	6.69
14	Peak Cavern	DW	SK149825	7.85	86	1.4	4.5	1.3	221	168	15	37	10.7	.38	2.64	.624	19.2
15	Bradwell Brook	DW	SK174810	7.43	92	2.2	8.6	1.2	239	172	23	42	14.2	-.02	2.21	.673	11.7
16	Magpie Sough	WY	SK180696	7.47	99	6.8	7.1	.8	277	217	21	35	13.8	.21	2.18	.665	16.7
17	Moss Well	WY	SK178723	7.82	89	2.4	8.2	.3	233	175	22	40	7	.37	2.59	.652	12.7
18	Cressbrook Dale Res.	WY	SK173733	7.34	106	5.4	10.9	1.3	288	216	30	41	17.8	.05	2.01	.692	11.3
19	Wormhill Springs	WY	SK123735	7.25	102	5.6	15.7	3.2	279	196	37	50	20	-.1	1.99	.743	7.25
20	Cheedale Bridge Res.	WY	SK128735	7.17	112	5.7	10.4	1.9	304	230	28	44	19.3	-.1	1.79	.687	12.0
21	Lower Cheedale	WY	SK130734	7.35	119	2.3	11.1	.8	307	203	30	54	38.1	.08	2.07	.692	12.1
22	Brindley's Well	WY	SK124742	7.26	120	1.5	6.5	.7	306	229	20	48	18.7	.05	1.9	.618	20.3
23	Ashwood Dale Res.	WY	SK089722	7.29	110	4.1	8.2	.6	289	230	27	31	12.9	.03	1.92	.639	15.6
24	Cowdale	WY	SK084722	7.29	98	6.2	6.8	.5	271	224	21	26	9.5	.01	1.94	.637	17.5
25	Wye Head Resurgence	WY	SK050731	7.24	89	3	16.7	1.2	235	161	37	48	11.4	-.2	2.05	.731	6.19
27	Deep Dale Res.	WY	SK097714	7.4	97	2.1	10.8	1.1	253	193	28	42	15.1	.12	2.23	.677	10.0
29	Delph Stream	DW	SK217759	0	47	9.1	16.4	2.3	0	89	37	47	3	0	2.5	.840	4.00
30	River Manifold	MF	SK088647	0	35	4.7	8.2	3.2	0	86	14	26	2	.41	3.42	.784	4.86
31	Waterhouses Sink	MF	SK087503	0	64	5	11.1	4.6	0	134	18	48	2	1.06	3.44	.743	6.00
33	Well Head	LK	SK200634	0	99	8.9	5.4	1	0	227	18	30	15	-.02	1.94	.656	21.7
34	Bubble Springs	LK	SK210659	0	97	6.4	8	.9	0	218	24	21	6.8	.29	2.26	.640	14.4
38	Thirst House Cave	WY	SK097713	0	103	1.3	3.7	.3	0	207	10	40	10	.14	2.13	.572	31.1
39	Allenhill Sough	DW	SK296604	6.79	110	19.3	14.2	3.2	354	167	59	137	.7	-.58	1.57	.787	10.1
40	Millclose Sough	DW	SK265618	7.75	124	17	10.4	3.2	381	208	24	163	2.8	.51	2.43	.733	14.1
41	Bonsall Sough	VG	SK275572	7.49	98	8.3	6.9	.8	279	219	24	27	17.6	.21	2.15	.673	17.3
42	Briars Well	VG	SK280575	8	63	17.4	237	2.8	229	367	114	205	18.7	.61	2.45	.802	.440
43	Slaley Spring	VG	SK273574	7.9	112	3.1	34.5	4.5	293	176	73	61	30.4	.57	2.66	.792	3.61
44	Gratton Dale Sough	LK	SK208608	7.77	84	29.8	3.8	.6	332	262	16	33	21.7	.47	2.35	.702	36.7
47	Cromford Court Level	DW	SK293574	8.12	91	40.1	4.8	.7	393	291	19	49	21.2	.93	2.67	.718	34.5
48	Clatterway Sough	VG	SK282577	7.56	93	23.7	11.5	3.8	330	260	29	44	20.3	.32	2.15	.758	11.0
50	Bullestree Sough	DW	SK302573	7.48	87	15	17.6	22.8	280	179	39	61	64.3	.05	2.23	.881	4.13
51	Matlock Pet. Well	DW	SK294580	7.53	116	26.5	27.5	.9	399	224	61	140	1.8	.43	2.08	.804	6.53
52	Cromford Drain	VG	SK295568	7.76	47	5.5	10.1	4	141	62	21	61	12.7	-.34	2.97	.839	5.16
501	Great Hucklow	DW	SK179778	6.8	20	6	9	1	74	44.2	16	46	14.9	-1.79	2.07	.897	3.57
502	Waterfall Swallet	DW	SK198770	7.83	49	3.2	7	2.3	148	85.3	15	54	3.1	-.06	2.81	.752	7.45
503	Bradwell	DW	SK174816	7.41	84	2	7	.9	240	163	17	51	7.4	.01	1.84	.658	13.3
504	Bull Pit Stream	DW	SK104817	7.35	27	8	4	1.1	98	59.0	11	41	8.1	-.96	2.48	.829	9.92
505	Greensides	DV	SK068685	5.8	6	5	6	1.2	32	14.7	10	20	.6	-1.9	1.53	.888	2.43
506	Hulme End	MF	SK108594	7.01	44	5	11	3.4	130	85.3	28	40	5	-.97	1.99	.820	4.61
507	Bottom House	MF	SK048526	7.24	30	2	5	4.6	82	55.7	13	59	6.2	-1.02	2.41	.805	4.95
508	Elton	LK	SK218614	7.68	14	7	7	1.5	62	48.4	22	56	6.2	-.98	2.9	.874	3.71
509	Holt Road	DW	SK286623	7.45	18	7	10	2.8	72	36.9	19	57	6.2	-1.22	2.79	.891	2.90
510	Sharder Well	DW	SK286626	7.25	19	10	9	4.1	86	36.9	17	51	6.2	-1.38	2.59	.899	3.56
601	Meerbrook Sough	DW	SK327552	7.32	75	29	9.8	.9	307	229	22	54	9.7	.08	1.85	.753	13.6
602	Matlock(Fount.Bath)	DW	SK294584	7.77	103	38	29	.8	511	229	52	192	3.1	.7	2.28	.817	6.44
603	Buxton (Thermal)	WY	SK057735	7.5	58	20	24	1.2	285	206	39	12	.1	.29	1.99	.748	4.22
604	Stoney Middleton(Th)	DW	SK232756	7.77	92	29	61	1.5	533	210	110	100	14.2	.6	2.33	.867	2.59
606	Beresford	DV	SK128586	7.22	99	8	8	1.6	281	244	12	37	2.1	.1	1.72	.627	14.3
607	Bradwell (Thermal)	DW	SK174820	7.2	162	42	240	5.2	580	178	420	326	.2	-.03	1.84	.822	1.09
608	Matlock (E Bank)	DW	SK294582	7.35	100	40	24	.9	417	232	46	125	.8	.23	1.88	.801	7.75
609	Stoke Sough	DW	SK240764	7.72	46	19	24	2.3	201	132	38	74	.9	.01	2.51	.848	3.49
610	Matlock (New Bath)	DW	SK293579	7.35	105	32	30	.9	396	222	57	150	.4	.28	1.87	.813	5.92
611	Bakewell(Rec.Ground)	WY	SK220681	7.44	186	24	19	.9	563	163	23	384	.1	.36	2.15	.688	13.2
612	Ridgeway Sough	DW	SK332549	7.43	155	14	25	1.8	446	192	47	230	1.8	.37	2.07	.746	7.83
613	Bakewell(Brit.Leg.)	WY	SK218686	7.37	161	17	19	1.5	473	178	23	262	3.1	.34	2.03	.713	10.9
614	Ball Eye Quarry BH	VG	SK289573	7.55	97	26	19	2	351	210	39	101	1.8	.02	2.16	.790	7.95
701	Monks Dale	WY	SK137740	7.4	106	8.5	5.2	.46	302	240	17	38.5	16.3	.11	1.99	.650	25.1
703	Crowdwell	DV	SK100653	7.4	98	2.5	6.5	.6	302	209	14	26	11.5	.19	1.99	.600	17.0
704	Grindlow	WY	SK180772	7.77	80	1	5	.2	204	141	13	42	4.4	.25	2.53	.613	18.3
705	Staden Farm BH	WY	SK074723	7.3	115	1.5	7	5.3	294	180	15	49	10.6	.22	1.8	.628	13.3
706	Pictor Spring	WY	SK088722	7.41	106	12	7	.6	314	240	19	31	13.1	.28	1.95	.663	19.6
707	Woo Dale	WY	SK094725	7.39	117	15	5	1.3	354	269	16	43	12.4	.34	1.88	.657	28.2
709	Litton Mill 1	WY	SK165732	7.52	107	2	7	.5	276	207	22	47	4.4	.31	2.13	.617	17.3
710	Litton Mill 2	WY	SK161729	7.52	89	3	4	.3	236	173	10	43	6.2	.17	2.19	.610	25.8
711	Priestcliffe	WY	SK151731	7.41	114	4	5	.6	302	222	13	51	11.2	.24	1.99	.615	25.8
712	Crowdecote	DV	SK101651	7.55	97	4	19	1	260	225	37	31	6.2	.33	2.12	.686	6.06
713	Glutton Grange	DV	SK084668	7.52	89	3	4	.4	234	178	10	28	15.5	.19	2.18	.609	25.4
714	Barmoor	GT	SK085797	7.29	117	4	9	4.9	308	229	18	47	18.6	.14	1.85	.662	11.9
715	Rowter Farm	DW	SK132821	8.05	78	3	3	.9	208	148	10	37	12.4	.52	2.79	.637	26.9
717	Crowrill Lane	WY	SK204692	7.85	114	5	8	.9	304	232	20	48	12.4	.69	2.41	.647	16.4
718	Hindlow Quarry BH	WY	SK087691	8	109	3	13	.4	282	200	40	39	15.5	.78	2.62	.685	9.87
719	Underhill Farm	DV	SK088664	6.8	78	4	6	1.9	210	138	14	49	12.4	-.71	1.57	.697	13.6
720	Underhill Well	DV	SK093661	7.1	66	4	5	1.1	178	132	10	34	9.3	-.5	1.89	.675	14.7
721	Dowel Resurgence	DV	SK075675	7.35	82	4	5	1.4	222	170	10	31	11.8	-.05	2.03	.640	17.4
722	Friden Brickworks BH	LK	SK169608	7.2	106	15	5	1.5	326	259	13	41	15.5	.09	1.71	.666	25.4
723	Ramshorn Quarry	DV	SK092461	7.2	105	2	5	.7	270	203	14	36	15.5	.01	1.81	.605	22.9
724	Thorswood House	DV	SK117471	7.21	116	10	5	1.7	328	284	12	38	12.4	.13	1.68	.623	25.3

No.	Site Name	Catchment	GR	pH	Ca	Mg	Na	K	TH	HCO3	Cl	SO4	NO3	SI	pCO2	RE	CM/NK
726	Tissington Hall Well	DV	SK176523	7.3	114	20	7	2.9	364	307	15	42	15.5	.27	1.74	.675	19.3
727	Parwich Well	DV	SK186543	7.2	127	10	4	.8	358	296	10	53	6.2	.18	1.65	.603	36.8
728	Dale End Farm BH	DV	SK180550	7.35	94	2	3	.8	242	203	10	33	6.2	.1	1.96	.570	32.1
801	Lower Dimindale	WY	SK172704	7.36	90	16	9.5	.6	330	229	18	38	5.3	.19	1.91	.693	13.5
802	Great Shacklow	WY	SK177698	7.7	107	5	7	1	333	228	17	34	10.6	.58	2.25	.627	17.4
803	Wormhill Moor	WY	SK107759	7.1	104	2	5	.4	329	182	12	48	10.2	-.16	1.75	.606	23.5
804	Chelmorton	WY	SK115703	7	116	2	4	.3	330	242	11	32	8.9	-.18	1.53	.552	32.7
805	Waterloo Inn Sough	WY	SK129712	7.1	114	2	4	.4	336	237	9	41	8	-.02	1.64	.560	31.7
806	Ible Spring	VG	SK250570	7.33	105	3.4	5.7	.42	277	179	19	50	40.1	.14	1.99	.682	21.3
807	Shothouse Spring W	VG	SK240588	7.3	110	2.1	4.2	.9	284	208	12	43	16.7	-.04	1.97	.602	27.5
808	Brook Head	WY	SK141775	7.22	92	4	19	.9	246	173	36	47	6.2	-.13	1.89	.723	5.79
809	Millers Dale 1	WY	SK137731	8.1	61	9	5	.3	188	118	13	60	6.2	.4	2.94	.737	16.8
810	Millers Dale 2	WY	SK146734	7.61	114	6	10	.5	308	225	22	51	14.9	.45	2.18	.671	13.8
811	Tithe Farm	VG	SK222572	7.5	89	4	4	.6	236	173	12	41	6.8	.21	2.17	.626	25.1
812	Aldwark 1	VG	SK228574	7.7	101	2	7	2.6	258	192	16	53	10.5	.43	2.34	.644	14.0
813	Aldwark 2	VG	SK228576	7.55	106	2	8	2.1	274	196	30	60	3.1	.27	2.18	.654	13.5
901	Hillcarr Sough	DW	SK259637	7.7	90	13	10	1.8	321	221	17	35	9.7	.48	2.27	.699	11.5
903	Mandale Sough	LK	SK197661	7.7	103	5.5	6.5	.8	301	228	14	31	9.3	.56	2.25	.618	18.4
904	Watergrove Sough	DW	SK210758	7.23	106	2.5	17	1.2	276	182	39	47	21.1	-.04	1.89	.716	7.13
905	Moorwood Sough	DW	SK232754	7.67	101	6	28	1.8	276	171	45	73	25.4	.34	2.36	.794	4.37
906	Brightside Sough	DW	SK242745	7.54	98	7	14	1.2	272	174	29	61	20.5	.23	2.22	.748	8.54
907	Orchard Sough	DW	SK282608	7.31	95	12.2	13.1	2.5	288	190	36	55	23.3	-.09	1.86	.777	9.06
908	Oxclose Sough	DW	SK289606	7.75	73	6.5	13.5	1.6	209	143	24	50	12.3	.18	2.56	.765	6.65
1001	Ludwell 1	DV	SK124624	7.54	102	4	4.5	.7	306	232	11	23	8	.39	2.09	.574	25.3
1002	Calesdale	LK	SK173654	7.5	109	2.9	10.6	1.2	336	228	30	26	7	.32	2.26	.629	11.5
1004	Lathkill Head Cave	LK	SK171659	7.5	107	1.5	7.3	1.28	336	207	20	31	17.5	-.17	2.2	.620	15.5
1005	Black Sallet Mine	DW	SK219740	7.68	94	1.5	6	.3	240	163	12	44	7.6	.32	2.39	.611	17.9
1006	Treak Cliff Cavern	DW	SK136832	8.05	74	4	4	.8	202	114	11	55	18.6	.4	2.19	.701	20.6
1007	Treak Cliff Spring	DW	SK136832	8	71	3	4	.3	190	118	10	49	9.3	.37	2.84	.665	20.8
1010	Hay Dale	WY	SK178721	8.13	92	7	11	.4	256	178	25	48	24.8	.79	2.79	.734	10.5
1011	Ravenstone Cottages	WY	SK172737	7.95	58	3	5	.1	156	95.9	13	52	6.2	.18	2.88	.704	14.2
1012	Dirtlow Farm 1	WY	SK188686	9	38	3	4	.5	106	55.7	12	41	6.2	.84	4.16	.758	11.4
1013	Dirtlow Farm 2	WY	SK193685	8.25	67	2	5	.2	176	95.9	14	51	15.5	.53	3.18	.699	15.7
1014	Middleton	LK	SK199633	7.3	86	17	5	.5	282	237	10	23	14.9	.07	1.84	.659	24.7
1015	Winster	DW	SK258608	7.8	77	20	4	.3	262	210	10	43	12.4	.47	2.39	.697	30.2
1016	Ludwell 2	DV	SK124625	7.3	94	5	4	.6	256	210	10	22	11.2	.05	1.89	.594	26.9
1017	Basrobin Sough	DW	SK262610	7.98	89	6.8	3.9	1.2	249	182	12	54	9.7	.51	2.89	.666	24.9
1018	Matlock Bank	DW	SK296605	6.9	95	20	15	3.1	316	125	44	147	6.2	-.53	1.71	.807	8.72
1101	Ecton Clayton Adit	MF	SK096581	8.2	76	19	4.7	.8	285	224	15	43	5.8	.95	2.76	.695	23.8
1102	Carters Mill	LK	SK182656	7.6	88	12	4.5	.5	289	232	12	20	8	-.05	2.03	.628	25.7
1103	Stanley Moor BH	WY	SK050715	7.2	82	4.5	4	.4	246	191	9	14	4.9	-.07	1.83	.571	24.2
1104	Shothouse Spring E	VG	SK242589	7.38	95.4	1.7	3.6	.35	256	202	13	26	11.9	.03	2.09	.577	29.6
1105	Cromford Sough	VG	SK296569	8.25	99	9	14	1.8	286	200	29	56	22	1.01	2.87	.750	8.67
1106	Tunstead Well	WY	SK109748	7.3	127	5	8	3.6	336	200	24	90	15	.12	1.92	.688	15.3
1107	Nether Low	WY	SK111692	7.85	74	1	3	.3	190	136	10	47	5	.32	2.63	.608	27.3
1108	Tissington Spring	DV	SK176522	7.55	113	24	6	2.3	378	355	13	44	15	.58	1.92	.661	23.8
1109	Lidgate Farm	VG	SK229575	7.4	110	1	31	8.8	278	196	60	59	20	.14	2.03	.763	3.54
1110	Yatestoop Sough	DW	SK264626	7.67	88	23.4	18.7	2.1	315	238	31	65	9.3	.53	2.42	.780	7.28
2801	Perryfoot Cave P1	DW	SK099813	7.4	35	3.8	7.5	2.6	104	55	10	40	2.3	-.92	2.65	.791	5.24
2802	Sheepwash Cave P2	DW	SK100813	7.2	29	4.7	15.9	1.8	91	43	23	41	5.2	-1.32	2.56	.869	2.48
2803	Gautries Hole P3	DW	SK102814	7.9	32	2.4	4.7	1.4	91	63	10	42	6.5	-.4	3.09	.775	7.46
2805	Perryfoot P5	DW	SK103815	7.5	43	4.4	4.8	1.3	125	75	11	52	2.6	-.61	2.61	.748	10.3
2806	Perryfoot P6	DW	SK104816	7.3	22	6.5	11.9	4	81	33	22	53	7.8	-1.43	2.77	.904	2.63
2807	Perryfoot P7	DW	SK105817	7.3	27	1.2	4.8	1.5	72	21	12	50	1.8	-1.53	2.97	.751	5.85
2808	Jackpot P8	DW	SK108818	7	24	2.9	7	1.5	71	20	17	47	1.6	-1.91	2.69	.814	4.18
2810	Snelslow Swallet P10	DW	SK114823	7.7	44	3.1	11.3	1.5	124	61	22	51	9.5	0	2.9	.814	4.62
2812	Giants Hole P12	DW	SK119826	7.3	41	3.1	17.3	1.7	120	57	33	45	2.4	-.81	2.41	.821	2.89
3201	Dove R1	DV	SK130580	0	85	4.4	4	.4	0	186	17	23	14.1	0	2.13	.633	24.9
3202	Dove Footbridge R2	DV	SK130580	0	104	5.3	4.8	.8	0	232	12	30	9.9	.19	2.03	.602	24.5
3204	Dove Twin Res.R4	DV	SK130540	0	100	7	3.2	.5	0	223	14	37	11.5	0	1.96	.626	36.6
3205	Dove R5	DV	SK140550	0	95	9.8	4.8	.7	0	205	17	33	26	.04	2.13	.685	24.4
3206	Brickpit Res.R6	DV	SK140550	0	101	5.2	4.9	.8	0	227	15	23	20	-.17	1.75	.620	23.4
3207	West Bank Res.R7	DV	SK140530	0	99	4.5	4.7	.7	0	250	12	57	10	.17	2	.624	23.8
3208	Dove (Milldale)	DV	SK138547	0	77	2.5	7.9	1.8	0	156	17	26	15	.23	2.79	.672	10.3
3209	Nabs Spring	DV	SK142537	7.45	88	9	4.8	.6	292	199	13	42	12	.19	2.06	.670	22.8
3501	Manifold Springs	MF	SK127508	0	88	5.6	10.7	2.5	0	194	23	30	5.1	.06	2.1	.679	9.16
3502	Ilam Main Res.	MF	SK132506	0	62	6.6	8.2	3	0	144	16	35	4	-.45	1.91	.725	8.39
3503	Ilam Weir Res.	MF	SK138508	0	49	7.2	8.3	2.9	0	151	17	49	2.8	-.52	2.03	.752	6.97
3504	Ilam Upper Res.	MF	SK131506	0	82	5.9	11.1	3.6	0	177	24	47	2	-.51	1.59	.711	7.96
3505	Ilam Well Res.	MF	SK133506	0	103	15.1	8.3	1.2	0	233	19	81	7.3	-.49	1.39	.714	16.2
3506	Hinkley Wood Res.	MF	SK128503	0	101	6.9	6.6	2.7	0	224	17	29	6.2	-.46	1.45	.637	15.7
3507	Hamps Spring	MF	SK127508	7.4	70	4.7	11	4.6	216	159	21	51	6.2	-.47	1.92	.740	6.50
3701	Deep Dale Side Res.	WY	SK098718	0	107	2.5	13	1.3	0	194	39	52	15.4	-.23	2.06	.699	9.26
3702	Deep Dale Lower	WY	SK104721	0	120	1.6	9.8	1.8	0	238	17	48	10	-.11	1.62	.614	12.9

APPENDIX 3

Membership of the groups derived in the final analysis using twelve parameters

For the meanings of the site numbers refer to Appendix 1.

Group No.	Group name	Site Nos. for members
1. (57 sites)	General Limestone Group	16,18,19,20,22,23,24,33,34,38,41,606,701 703,706,707,709,710,711,713,717,718,722, 723,724,728,802,803,804,805,806,807,810, 811,812,813,903,904,1001,1002,1004,1005, 1014,1016,1017,1102,1103,1104,3201,3202, 3205,3206,3207,3209,3505,3506,3701.
2. (27)	Grit/Shale Group	1,2,3,4,29,30,52,501,502,504,505,506,507, 508,509,510,1012,2801,2802,2803,2805,2806, 2807,2808,2810,2812,3503.
3.(13)	Mineral/Thermal Group (mostly Matlock area)	39,40,48,50,51,602,603,608,609,610,614, 1018,1110.
4.(4)	High Calcium Group	21,705,714,3702.
5.(11)	Resurgence Group A (including some soughs)	12,13,25,27,808,901,906,907,908,1010,1105
6. (8)	Resurgence Group B	14,15,17,503,704,719,721,3208
7.(5)	Ilam Group	31,3501,3502,3504,3507.
8. (3)	Bakewell Thermals	611,612,613.
9.(4)	High Magnesium Group	726,1015,1101,1108.
10.(6)	Medium Calcium Group (including Treak Cliff)	715,720,1006,1007,1013,1107.
11.(2)	Via Gellia Group	43,1109.
12. (2)	High Sodium Group	42,607.
13. (2)	Millers Dale Group	809,1011.
14. (3)	Sough Group	44,47,601.

The above groups are the 81% phenons (i.e. groups which exist at the 81% similarity level)

In addition the following sites are still distinct at the 81% level:

15. Lower Dimindale 801
Merges with the High Magnesium Group at 80% similarity.

16. Dove Twin Resurgence R4 3204
Merges with the General Limestone Group at 79% similarity.

17. Moorwood Sough 905
Merges with the Via Gellia Group at 71% similarity.

18. Parwich Well 727
Merges with Groups 9,14 and 15 at 66% similarity.

19. Tunstead Well 1106
Merges with Groups 1,4,5,6,7,10,13 and 16 at 65% similarity.

20. Crowdecote 712
Merges with Groups 1,4,5,6,7,10,13,16 and 19 at 62% similarity.

21. Stoney Middleton thermal 604
Merges with Groups 11 and 17 at 49% similarity.

The General Limestone Group is dominant, while the Grit/shale, Mineral/Thermal, Resurgence A & B, Medium Calcium, High Calcium, High Magnesium, Sough and High Sodium groups are all significant, in descending order of size. There are also a number of groups showing geographical grouping, notably in the Matlock, Ilam, Bakewell, Via Gellia and Millers Dale areas.

APPENDIX 4

The General Limestone Group in detail

Group No.	Characteristics	Sites included (Site No. in brackets)
1. (13 sites)	No anomalies	Magpie Sough*(16), Ashwood Dale(23), Cowdale+(24), Well Head*(33), Bubble Springs*(34), Bonsall Sough+(41), Monks Dale*(701), Crowdwell (703), Pictor Spring (706), Gt. Shacklow*(802), Mandale Sough*(903), Lathkill Head Cave(1004), Dove R6(3206).
2. (4 sites)	high Na,K,Cl, SO_4,NO_3.	Cresbrookdale*(18), Cheedale Bridge*(20), Crowrill Lane(717), Millers Dale 2*(810).
3. (2 sites)	high Mg,K,low NO_3, Pco_2.	Beresford(606), Hinckley Wood(3506)
4. (1 site)		Calesdale (1002).
5. (13 sites)	low Mg,low Na. high ionic ratio.	Brindleys Well*(22), Thirsk House (38), Priestcliffe+*(711), Ramshorn Quarry(723), Dale End Farm BH+(728), Wormhill Moor*(803), Chelmorton*(804), Waterloo Inn Sough*(805), Shothouse Spring West*(807), Ludwell 1 (1001), Ludwell 2 (1016), Shothouse Spring East* (1104), Dovefoot Bridge R2(3202).
6. (3 sites)	low Mg,K,Cl,NO_3. high Pco_2.	Litton Mill 2(710), Tithe Farm*(811), Black Sallet Mine(1005).
7. (2 sites)	low Na,K, high ionic ratio.	Glutton Grange(713), Dove R 1(3201).
8. (2 sites)	high Mg,SO_4,Pco_2, low Na, Supersaturated	Basrobin Sough*(1017), Nabbs Spring(3209).
9. (1 site)		Dove West Bank R.7(3207).
10.(1 site)		Litton Mill 1(709).
11.(1 site)		Aldwark 2*(813).
12.(1 site)		Aldwark 1*(812)
13.(3 sites)	high Mg,K, ionic ratio	Woodale BH+(707), Friden Brickworks BH+(722), Thorswood House(724).
14.(2 sites)	high Mg,ionic ratio. low Cl,SO_4.	Middleton*(1014), Carters Mill(1102).
15.(1 site)	high Mg,NO_3, ionic ratio	Dove R5(3205).
16.(1 site)	low Na,K,Cl,SO_4, NO_3 high ionic ratio	Stanley Moor BH(1103)
17.(1 site)		Wormhill Springs (19).
18.(3 sites)	low Mg,ionic ratio. high Na,K,Cl,SO_4, NO_3.	Hindlow Quarry BH(718), Watergrove Sough*(904), Deepdale Side(3701).
19.(1 site)	low Mg,K,high SO_4, NO_3	Ible Spring(806)
20.(1 site)	high Mg,K,SO_4 unsaturated. low NO_3,Pco_2.	Ilam Well(3505).

The above groups are the 85%phenons. In addition at 82% the following groups are still distinct:

Group No.	Characteristics	Groups included
A. (20 sites)	High Potassium Group	1,2,3,4.
B. (21 sites)	Low Mg,Low Na High ionic ration Group	5,6,7,8,9.
C. (3)	Low Mg,NO_3 High K, Cl, SO_4 Supersaturated	10,11,12
D. (3)	Low pCO_2 High Mg, K, ionic ratio	13
E. (2)	High Mg, ionic ratio. Low Cl, SO_4	14
F. (1)	Dove R5 (High Mg,NO_3, ionic ratio)	15
G. (1)	Stanley Moor BH (Low Na,K,Cl,SO_4,NO_3. High ionic ratio)	16
H. (4)	Low Mg, ionic ratio. High Na,K,Cl,SO_4,NO_3	17,18
I. (1)	Ible Spring+ (Low Mg.K. High SO_4, NO_3)	19
J. (1)	Ilam Well Resurgence* (Low NO_3,Pco_2, High Mg,K. SO_4. Unsaturated).	20

Group A. (High potassium) and Group B (Low Mg,Na,High ionic ratio)are dominant.

The General Limestone Group (57 sites) is formed at 81% similarity.
* = lava affected sites
\+ = dolomite affected sites.

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TUNNEL CAVES IN SWEDISH ARCHEAN ROCKS

by Rabbe Sjöberg

ABSTRACT

Two theories have been used to explain the origin of round eroded caves in Archaean rocks in Sweden: 1. They are the result of glacial activity; 2. they are formed by abrasion on present shores. No evidences of glacial or glaciofluvial formation of the caves can be found. A model of development by cobble abrasion on present shores is presented and a formula has been derived for the length of time required to form the caves.

The special type of cave described in this paper is, firstly, a cave formed along a fissure of tectonic origin in noncalcareous rocks, preferentially in coarse-grained rocks such as granites, anorthosites, metagreywackes and metasediments. Secondly, this type of cave has a pear-shaped cross-section which is often repeated in the cliff outside the cave-mouth (Fig. 1). The length of these caves varies from 5 to 30 m. Their height varies from 5 m to more than 10 m, and their width varies from 0.5 m to about 5 m.

Caves of this type seem to be rare in Sweden, and only about 50 examples are known at present. Most of these caves have been found along the Northern Baltic Coast of Sweden, situated from sea level up to about 200 m a.s.l. (Fig. 2). Others are found on the Swedish West Coast, and inland in the middle of Sweden, around the former shores of the Ancylus Lake and the Litorina Sea, both of these being former post-glacial stages of the Baltic Sea. This type of cave is not known by the author to exist in any other part of the world, except on parts of the Norwegian Atlantic Coast (Reusch 1877, p.195).

DESCRIPTION OF THE CAVES, EXEMPLIFIED BY STORA LIDBERGSGROTTAN

As a typical example of this type of cave, Stora Lidbergsgrottan (roughly translated as "the big cave at Lidberget Mountain") at Nordmaling in Northern Sweden will be described (Fig.1) (Plate 1). It is formed in an escarpment of metasedimentary rocks facing east. The cave is one out of ten such caves found along this escarpment (Plate 2) and it is situated at an altitude of 85 m a.s.l. The mountain is situated 10 km northwest of the nearest present coastline, and no other mountain is found between Lidberget and the coastline. Just below the cave, at the foot of the cliff, there is a big field of cobble-stones.

The cave is formed along a fissure of tectonic origin, striking N 86°E. In the upper, outer part of the cave the fissure is 1-2 m wide, and it narrows inside to an average of 0.5 m, closing in completely in the innermost part of the cave. The dip of the fissure, 60° to the N, creates a kind of roof for the entire cave. Between 16-18 m from the mouth of the cave, a dyke of dolerite intersects the cave, in a direction of N 50° W. These dykes of dolerite are found in many of the caves, but not in all of them.

The concave basal part of the cave is polished, up to a height of 5 m above the almost horizontal cave floor. The concavity varies from the mouth towards the interior of the cave, as can be seen by comparison of the cross-sections in Fig. 1. In this respect the walls, which show a texture of ridges, resemble those in spirally-formed potholes. Above this concave part of the cave, the walls are polished almost flat, except for places at 8 and 12 m from the mouth, where frost-splitting has made parts of the uppermost walls of the cave collapse. This is clearly seen in the cross-sections in Fig. 1. Lesser frost-splitting is found along the entire open crevice from which weathered fragments have fallen down on to the cave floor. In the innermost part of the cave, 18 m from the mouth, a sort of half-pothole is found in the northern wall. The round rim of the pothole reaches up to 2 m above the floor.

As in most such caves, there is little infill (Tell, 1969, p.14). The outermost part of the cave floor is covered by a 30 cm deep pool, on the bottom of which is a 30 cm-deep layer of organic origin. Between 4 and 10 m from the cave mouth, the floor is covered by a bank of relatively big weathered fragments, and some round, smoothly-eroded boulders are also present. In the above-mentioned pothole, the depth of the sediments is 60 cm. The sediments include gravel, with mixed-in round eroded and weathered finer sediments and finer materials such as clay.

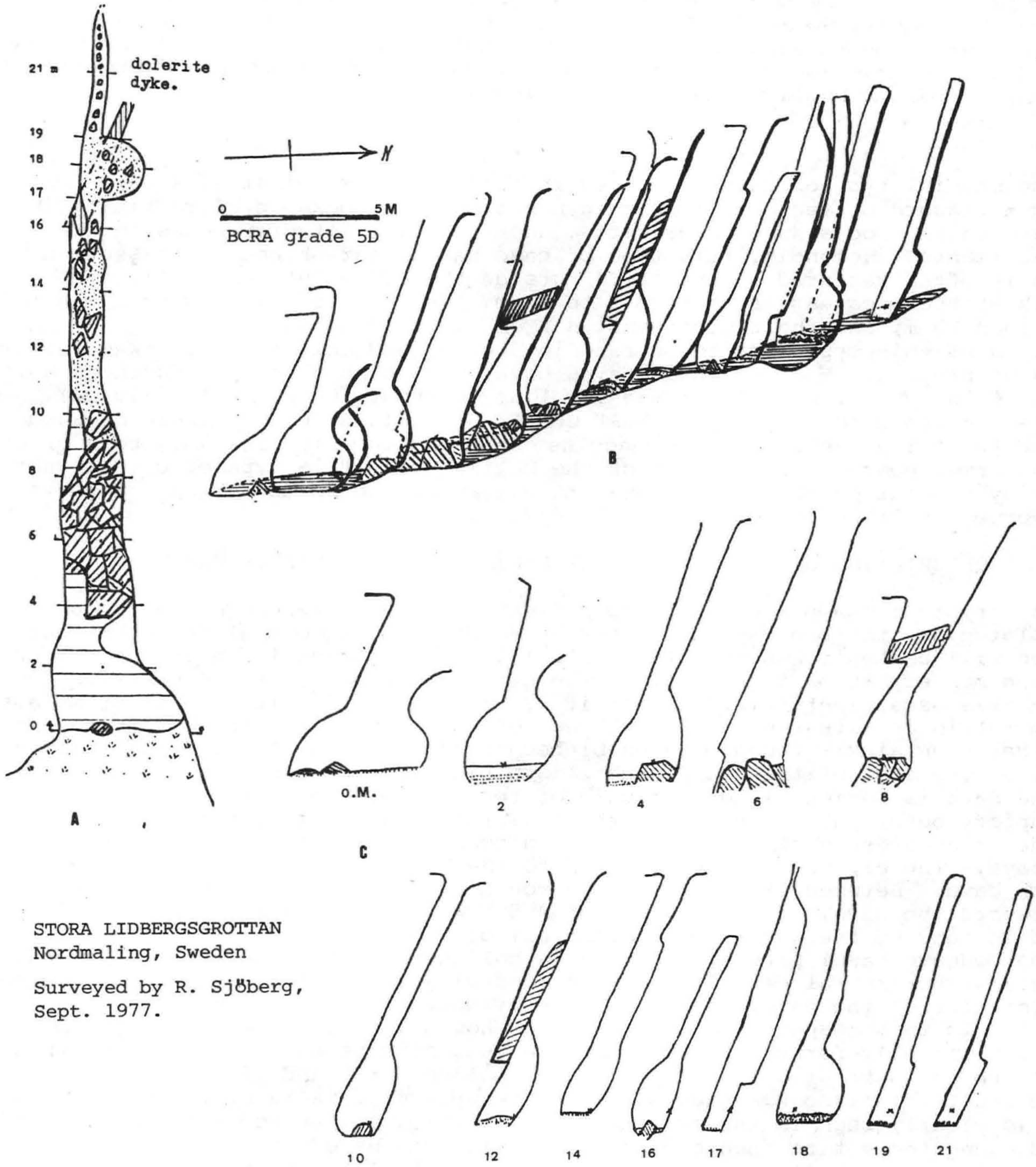


Fig. 1. Survey of Stora Lidbergsgrottan.
A = plan. B = 3 D projection of the cave. C = Cross sections for every 2 metres.

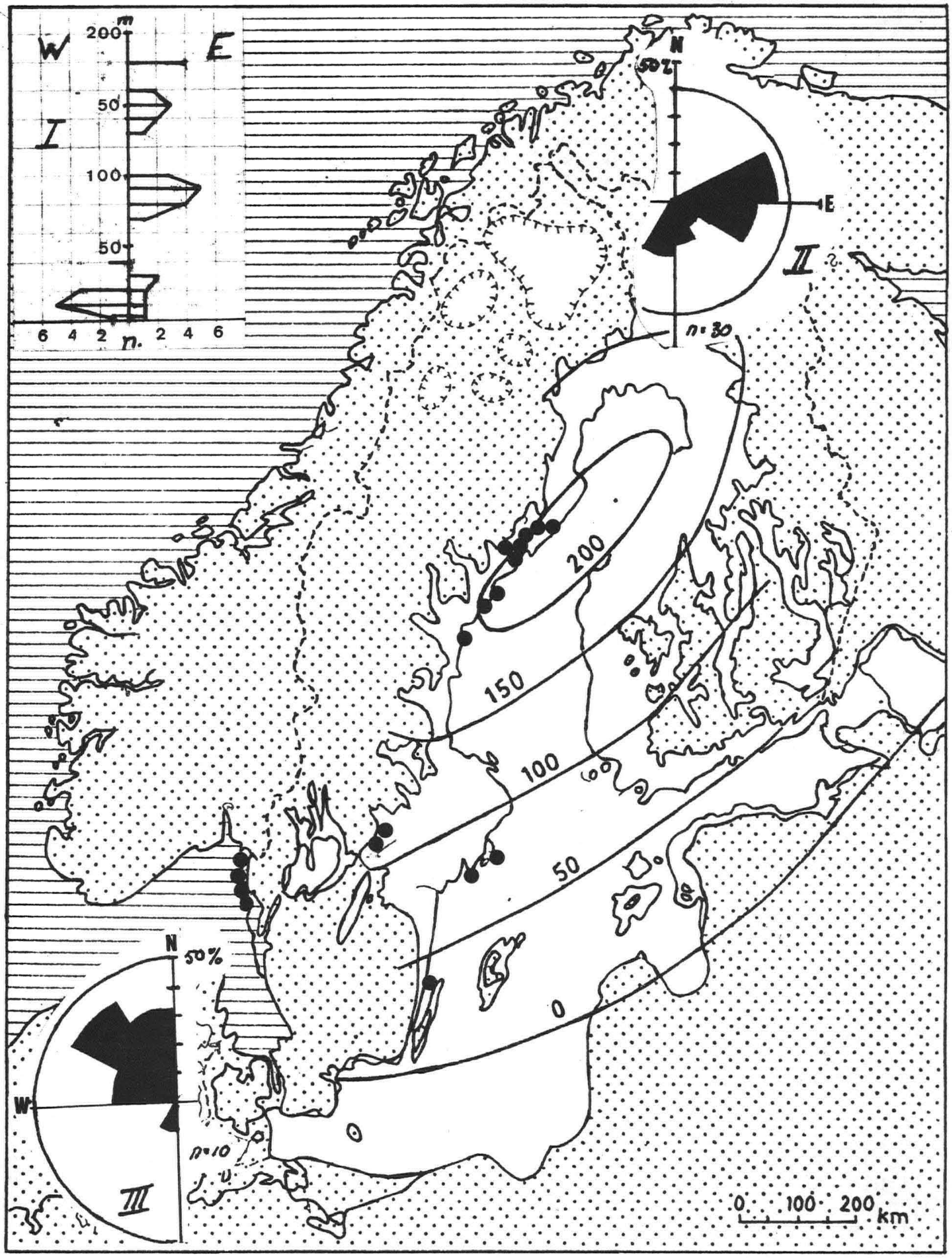


Fig. 2. The Ancylus lake about 8.700 years B.P., with approximate isobases for every 50 meters (after G. LundQvist 1963). The black dots show areas with tunnel caves.

i. The distribution of altitudes of the caves on the west and northeast coast of Sweden.

ii. The orientation of the cave mouths in per cent of the number of measurements made on the northeast coast. The material is divided into 30°-classes. n = 30.

iii. The orientation of the cave mouths on the west coast. n = 10.

PREVIOUS RESEARCH TO EXPLAIN THE ORIGIN OF THE CAVES

Generally two theories have been used to explain the origin of the caves. One theory claims that the caves were the result of glacial activity, especially the erosive activity of the sub- and postglacial rivers. The other theory suggests that the caves are shore-phenomena, and that such caves are also formed by abrasion in present shores.

The glacial theory.

This theory rests on the idea that these caves can be considered horizontal potholes. Hence, explanations of the origin of vertical potholes could also be used to explain the origin of these caves. The vertical potholes can be divided into two groups according to the time at which they were formed:
1. Potholes of recent origin; 2. Fossil potholes.

The formation of recent potholes has been researched in Sweden by Ängeby (1951) who describes them as "fluviatile phenomena of erosion", which means that they were created by eddies and grinding stones swirling in running water. The fossil potholes, according to Ängeby, developed in the same way as those of recent origin, in sub-glacial and latero-glacial times. Since Angeby's publication, potholes have been described by Markgren (1962-63), Johnson, (1956) and Dahl (1965). These later publications suggest that the potholes were formed in glacial times.

According to this description, the caves could be horizontal potholes, formed in glacial and sub-glacial rivers. The Swedish speleologist Leander Tell returned to this theory several times. In 1977 he wrote in the NSS Bulletin: Most cauldrons are vertical, but horizontal ones also exist. The largest horizontal pothole, of Räckeberga Kyrka at Torsböle in Northern Sweden, is 25 m long, 8 m high and 6 m wide; two adjacent ones are also quite large" (Tell, 1977 p.112). In a paper for the 6th International Congress of Speleology he wrote: "This cave has been hollowed out in granite by ice, and shows erosional marks from glacial streams", (Tell, 1973, p.403). Räckeberga Kyrka is situated within the area researched by the author, and the cave is similar in type to the one described above (Plate 4).

The Abrasion theory.

In 1917-19 Henrik Munthe, one of the pioneers in Swedish speleology, made an inventory of all Swedish caves known at that time (Munthe, 1920). He wrote: "Another type of cave - and to them most of our caves belong - have been formed by the work of waves on exposed cliffs, especially when these consist of limestone or other hard rocks which are broken through by crevasses and diaclases ... these caves often have a more or less marked, rounded form, depending on several factors such as the petrographic character of the rock, the longer or shorter time whereby the waves have had occasion to work, and the quality of abrading tools in the form of cobble-stones, sand, etc. that the waves have had at their disposal" (Munthe, 1920, p.10).

Erik Ljungner (1924) described what he calls "tunnel caves" from the Swedish West Coast, and he pointed out that these caves are typical examples of marine abrasion. This theory was developed in his doctoral thesis (Ljungner 1927-30, pp. 432-476). Here he defined two types of "tunnel caves". Firstly, there are those formed near a cobble-field, where the boulders from the field were tools for the abrasion which formed the cave. Secondly, there are those caves formed where no field of cobble-stones is present, but where materials quarried away from within the cave by the waves became tools which further enlarged the cave.

The next Swedish scientist to deal with cave formation by shore abrasion was Sven E. Behrens. He too noted the proximity of cobble-fields to these caves. He discussed the possible factors affecting shore abrasion (Behrens, 1953, p.181). These are:

1. The dimensions of the waves.
2. The angle between the waves and the shore line.
3. The quality of the rock.

The dimensions of the waves depend in turn on:

a. The strength and durability of the wind.
b. The depth of the sea.
c. The fetch of the sea.

The ways in which these different factors could affect the caves are discussed below.

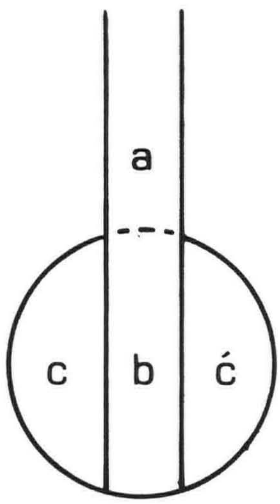


Fig. 3. Morphogenetic division of a tunnel cave, according to Ljungner. a + b = the cave-crevice. c + ć = the concave polished part of the cave.

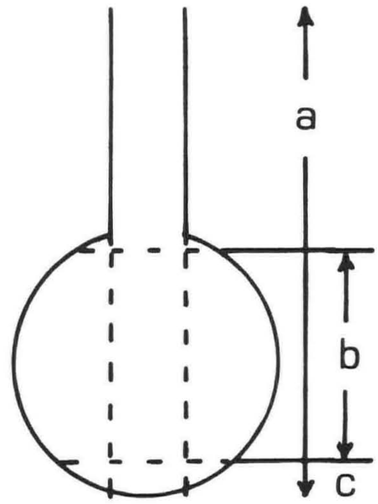


Fig. 4. Morphological stages in the formation of a tunnel cave. a = the initial stage., b = the optimal stage., c = the recessive stage.

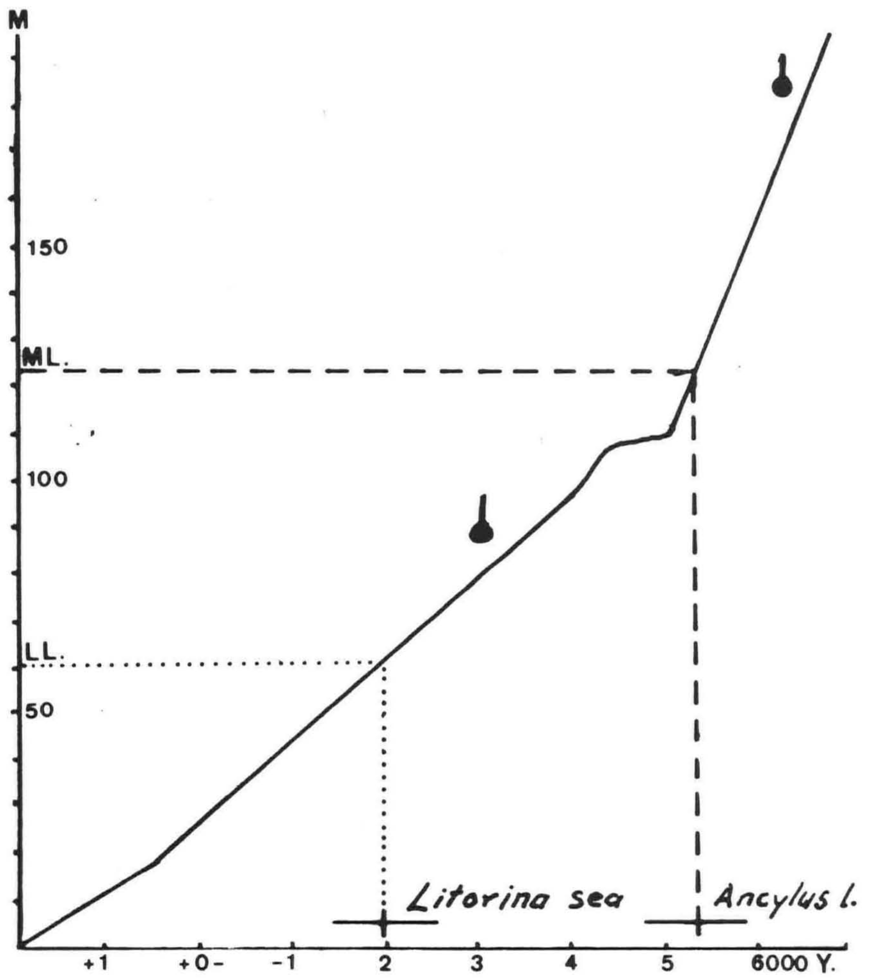
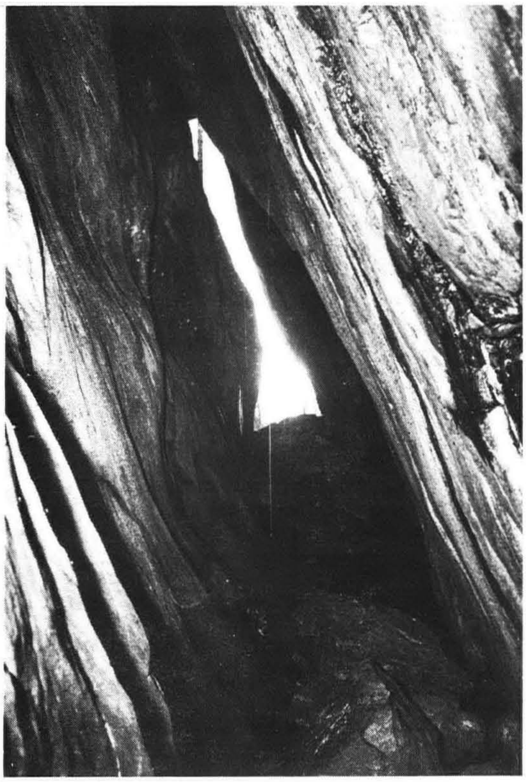
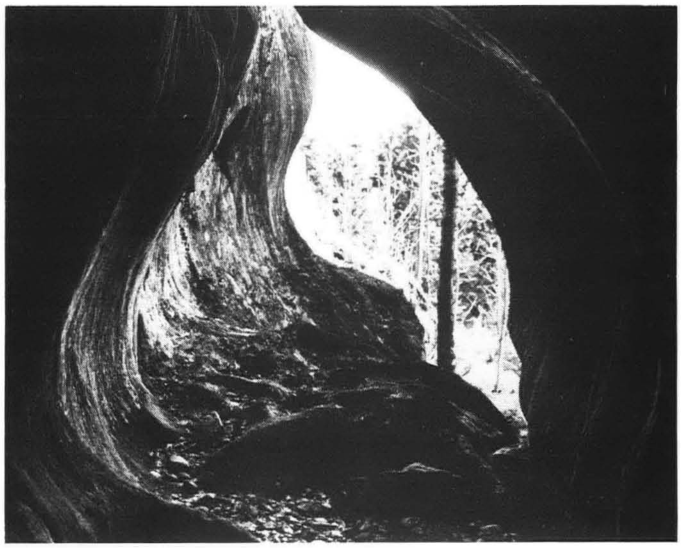


Fig. 5. Diagram showing the isostatic uplift in North-Eastern Sweden. By plotting the altitudes of the caves on the diagram one can calculate their age.

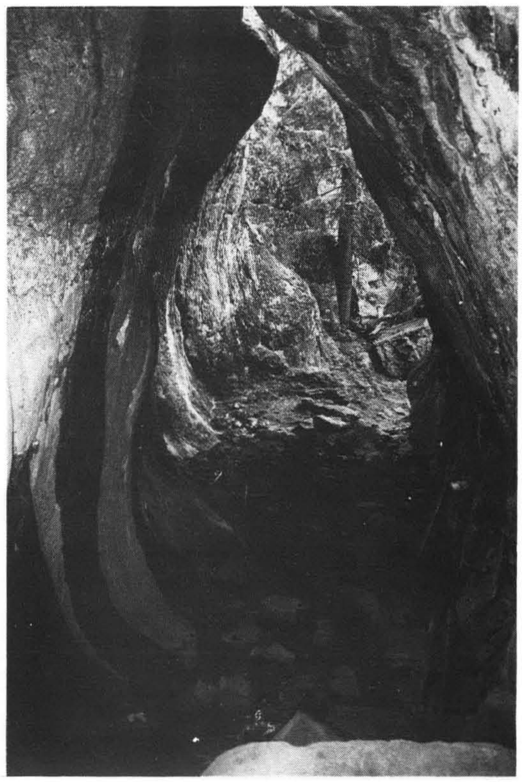


Pl. 1. Stora Lidbergrsgrottan. The cave passage seen from cross-section 17 m on fig. 2. The ridges mentioned in the text are clearly seen.



Pl. 2. Marmitegrottan at the Lidberget escarpment. Ridges and initially formed shore abrasion potholes in the entrance of the cave.

Pl. 3. Klingkyrkan on the island of Stora Kornö is the most perfectly formed tunnel cave on the Swedish west coast.



Pl. 4. Räckebergskyrkan. The cave passage from the inside.

DISCUSSION

The Glacial Alternative of Cave Formation

The direction of movement of the last glaciation, in the area investigated along the Baltic Coast of Sweden (Fig. 1) was towards the south. The erosional forms created by a moving ice-sheet strike mostly in the direction of the moving ice. This is not the case with the caves. In the vicinity of the caves, no striae or p-forms (plastic sculptured forms) have been discovered. The cliff surfaces are mostly just as much polished as those of the caves.

As regards the possibility of post-glacial and latero-glacial streams, there are no other indications of stream erosion except for a few semi-circular pot-holes near the cobble-fields, and near some of the caves. Post-glacial streams might have formed waterfalls down the escarpments which contain the caves. The erosion due to such a waterfall would surely have polished the upper parts of the fissures in and outside the caves, but these are mostly weathered. Rounded boulders stuck between the walls of the caves and in the fissures are also brought in from below, which would not have been the case if they were brought in by a waterfall.

The Shore Abrasion Alternative of Cave Formation.

As pointed out above, there is no evidence of glacial or glaciofluvial formation of the caves. Most of the facts point toward an abrasive origin. It is therefore necessary to investigate the altitude and exposure of the caves, in relation to past levels and post-glacial stages of the Baltic Sea.

The caves investigated are mostly situated along the coasts of the Litorina Sea, which reached a level of 124 m above present sea level. Some others are found along the shores of the Ancylus Lake between 124 m a.s.l. and 180 m a.s.l. The highest shoreline of the area varies between 272 m in the north and 285 m in the southern part of the area investigated (Fig. 2/I). It shows the distribution of the caves at different altitudes, and these can be compared with the distribution of the altitudes of caves on the Swedish West Coast, on the same map.

The exposure of the caves toward the past shorelines can be seen in Fig. 2/II. The few caves exposed towards the southeast can be explained by the distribution of protecting, high islands in the southern parts of the area investigated. The greatest fetch would be attained by winds from south to southeast, where fetches of about 600 km were possible (Hornsten, 1964, p.184). From the east, fetches of about 300 km were possible. The exposure of the eastern caves can be contrasted with that on the Swedish West Coast (Fig. 2/III) investigated by Ljungner (1927-30) and Sjöberg (1978), (Plate 3).

THE DEVELOPMENT OF TUNNEL CAVES

Morphological Development.

Ljungner (1927-30, p.469) described two types of tunnel caves, as seen above. The second type, where no cobble-field is found in the neighbourhood of the cave, will be discussed here in more detail. Ljungner constructed a mathematical formula for the morphological development of this type.

Fig. 3 shows how the cave can be divided into the cave-fissure (a+b) and the concave polished part of the cave (c, c′). In the ideal case, $a + b = c + c'$. That is to say, the quarried block material corresponds to the concave polished parts of the cave. Supply and demand are equal. Usually, however, $a + b \neq c + c'$. Different possibilities exist here. One is $a \simeq b = c + c'$. The total height of the crevice is dominant in this case. Another is $a + b > c + c'$. Only a part of the quarried material has been used in this case. Another possibility is $a + b < c + c'$. In this case it is necessary to count on provision of material from outside the cave. Davies (1977, p.83) wrote: "Greater quarrying means more tools for abrading waves".

Ljungner's formulas are independent of the post-glacial isostatic land uplift, which in Northern Sweden in early post-glacial times was about 15 cm/year, and which now has slowed down to 0.8 cm/year. If we include this factor in trying to explain the origin of these caves, we can start the discussion at the moment when the foot of the cliff is about 10 m below the surface of the sea. "Below that depth erosive capacity is negligible", according to Rice (1977, p.359).

Weathering, quarrying and cavitation produce the boulders which collect at the foot of the cliff. Cavitation excavates crevices and zones of natural weakness in the cliff. The upper and outer part of the cave crevice is opened up, as in a in Fig. 4. Here the creation of the cave is in an initial stage.

Meanwhile, the land is rising. The boulders at the foot of the cliff can now be moved by the waves and the breakers. The walls of the crevices are beginning to be hollowed out. The conditions for this work become more and more favourable, as the cobble-field is transported closer and closer to the surface. The basal parts of the crevice become more and more polished and rounded, and the bottom of the cave fills up with rounded boulders. The conditions for creation of the cave are then optimal. The uplift of the land continues, until the basal parts of the cave are less and less often reached by the breakers. The cave then passes into a recessive stage of evolution. Evacuation by breaking waves now begins to draw the rounded boulders out of the cave, and under favourable conditions, the cave can be totally cleared of boulders.

Time required for the Formation of the Caves.

From this model of cave formation a formula has been derived for the length of time required to form the caves.

$$\text{time required} = \frac{\text{the cave passage's height in mm.}}{\text{isostatic uplift in mm/year}} + n \text{ years}$$

where n varies with the rate of uplift, but is not more than several hundred years. This formula measures the mean time for the formations of the cave to within about 1,000 years.

Subjectively, this seems to yield a very short time of formation, but if we compare these caves with vertical potholes, then we can find interesting measurements for the latter. Ångeby (1951, p.67) described an example from a water-power plant in Northern Sweden, where a pothole with a diameter of 1-1.5 m and a depth of 1-1.5 m was formed in 10 days in concrete, with a flow of 5 m^3/sec. of water. In another example (p.58) he mentioned an average deepening of potholes in granites, of 3 cm per year. Ångeby added that it was possible for the rate of erosion to increase with further deepening of the pothole.

If the postulations discussed above are correct, then one can calculate the ages of the caves by plotting the altitudes of the caves on a diagram of the isostatic uplift in the area. This indicates (Fig. 5) that a cave at an altitude of 180 m a.s.l. has an age of about 8,000 years, and that Lidbergsgrottan at an altitude of 85 m a.s.l. is about 5,000 years old.

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SMALL-SCALE SPATIAL VARIATIONS IN THE CHEMISTRY OF DIFFUSE-FLOW SEEPAGES IN GUA ANAK TAKUN, WEST MALAYSIA

by J.Crowther

ABSTRACT

A survey and description are presented of Gua Anak Takun, West Malaysia. Detailed observations of 63 closely spaced, diffuse-flow seepages in the cave reveal marked local variations in groundwater chemistry. Striking increases in total hardness, non-alkaline hardness and potassium occur where groundwaters come in contact with bat guano within the aquifer. The effects of shales, interbedded with the limestone, are to increase non-alkaline hardness. but differences in discharge and in the thickness of stalactitic deposits have little effect upon water chemistry. These findings have wider research implications. In particular, they suggest that: (1) significant amounts of solutional lowering may occur beneath guano-rich, cave earth deposits, and (2) marked inter-site variations in the chemical properties of diffuse-flow seepages may be anticipated where flow within the aquifer is confined to vertical or subvertical joints, and where the thickness of limestone overlying a cave is comparatively small.

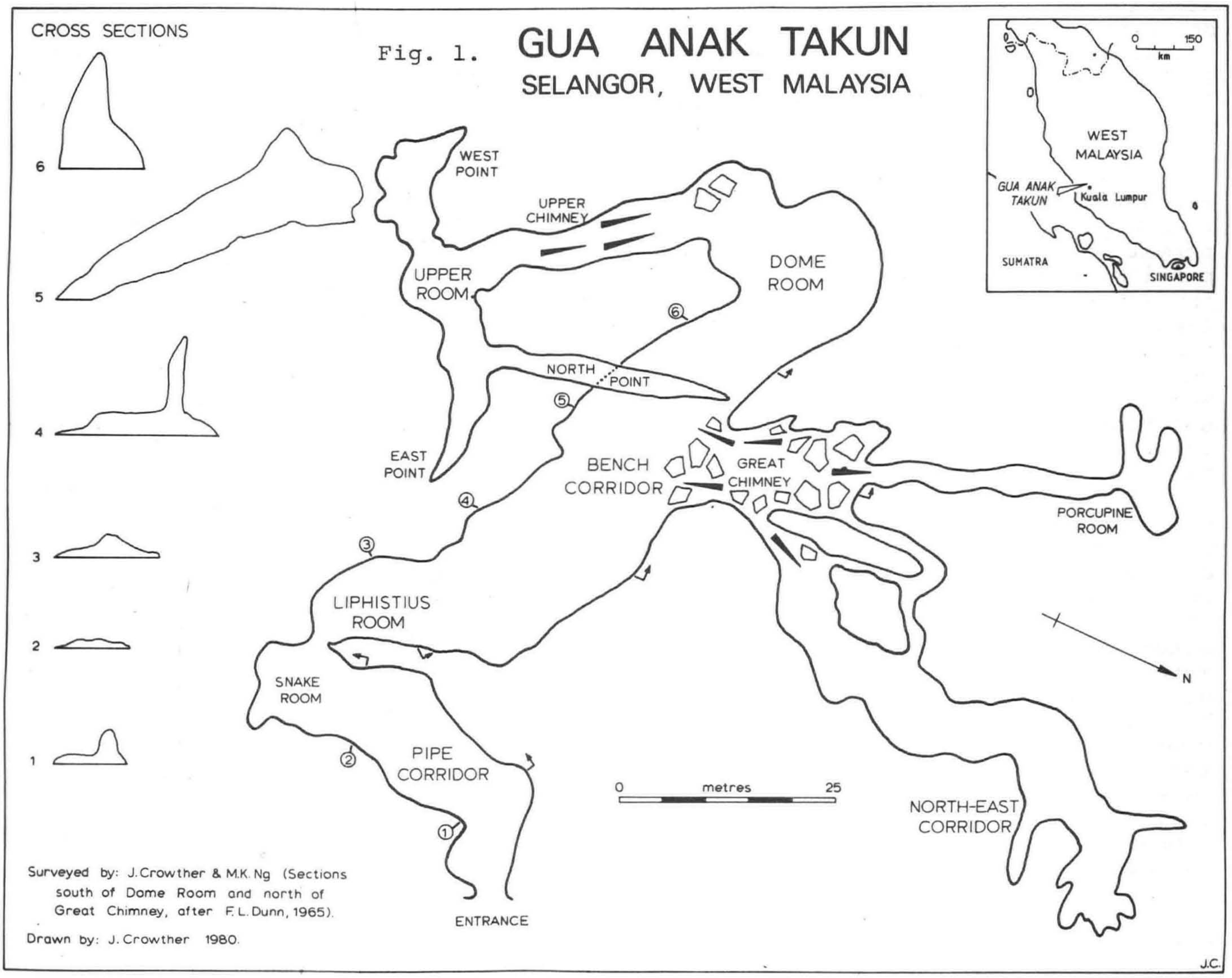
The average chemical composition of a given autogenic seepage is dependent essentially upon three factors: first, the capacity of percolating waters to dissolve rock and sediment within the aquifer; secondly, the rate at which solution occurs; and, thirdly, the rate and nature of secondary deposition. Since each of the above factors is governed, in turn, by a complexity of natural controls (see, for example, review by Smith and Atkinson, 1976), the solute contents of underground, diffuse-flow seepages often differ markedly from site to site, even over short distances. Also, the influence of any one specific variable on the chemistry of diffuse-flow seepages is difficult to isolate. However, by sampling a large number of seepages in a cave system, or part of a system, the total spatial variability in karst water properties is encompassed, and the effects of certain more important variables may be established, either from the distribution patterns which emerge or from the relationships found between water chemistry and measured environmental characteristics, such as discharge. Furthermore, with increased sample size, greater confidence may be placed in the representativeness of the overall results. Thus, the data reported in the present study are for all the seepages which have sufficiently high flow rates to permit adequate sample collection in selected parts of a single cave system. A total of 63 seepage points was investigated, from which more than 500 water samples were collected.

The site selected for detailed examination is Gua Anak Takun (3°18'N, 101°38'E), 18 km NNW of Kuala Lumpur, West Malaysia (Fig. 1). This cave was chosen because it is readily accessible and has a low roof, both of which facilitate sample collection. In its origin, form, and hydrological characteristics, Gua Anak Takun is closely similar to other caves in the tower karst hills of the Malay peninsula (Crowther, 1978).

The results reported below are, therefore, thought to be typical of a broad area of tropical karst terrain. Moreover, they may be indicative of the spatial variability of diffuse-flow seepages which might be encountered in caves in other parts of the humid tropics, where, hitherto, exhaustive sampling of the type illustrated here has not been undertaken.

DESCRIPTION OF GUA ANAK TAKUN

The cave is located in Anak Bukit Takun, a small residual tower of Kuala Lumpur Limestone. The bedrock, of Silurian age, is a very pure, crystalline marble, of low primary porosity and high mechanical strength. It comprises mostly calcium carbonate, the average molar ratio of Mg:Ca, being 0·024. Concentrations of potassium and sodium are both low. The former is barely detectable, whilst the latter averages 0.03 per cent by weight. Only traces of the original bedding are preserved. Thus, whilst the strata dip almost



vertically, vertical and subvertical joints, rather than bedding planes, form the main lines of structural weakness. Locally, the limestone is interbedded with bands of metamorphosed shale, 2m or so in thickness.

Pipe Corridor, Snake Room, Liphistius Room, Bench Corridor and the Dome Room (Fig. 1) were surveyed during the present investigation in order to locate precisely the position of the cave drips. Those parts of the survey to the north of Great Chimney and beyond the Upper Chimney, and the names of the various sections of the cave, are based on an earlier map by Dunn (1965). The entrance, which lies at the base of a cliff at the eastern side of the hill, is level with the adjacent plain at an altitude of 95 m a.s.l. The passages occur essentially at two heights. The lower sections, which extend as far as the Dome Room, and include those passages beyond the Great Chimney, are virtually level with the entrance. In fact, the floor of the cave between the entrance and the Dome Room is almost perfectly flat and comprises a thick deposit of compacted mud. This material may well be quite recent, possibly being deposited at the bed of a former mine pool. There are numerous tin-mine workings in the vicinity of Anak Bukit Takun, and the mine pools are frequently sited so that they abut against the hill. It is conceivable, therefore, that the lower parts of the cave may have been flooded periodically. The particle-size distribution, of 49.1% clay, 20.3% fine silt, 22.8% medium silt, 7.2% coarse silt and 0.6% sand, is consistent with this interpretation. In view of the great depth of alluvium which is exposed in nearby mines it seems likely that the finer sediments of the lower parts of the cave are underlain by considerable thicknesses of alluvium. A steep, cliffed section of the Upper Chimney, to the south of the Dome Room, connects with the upper part of the cave. This comprises the Upper Room and three short passages. Of the latter, that which terminates in North Point cuts transversely across Bench Corridor of the lower cave, the two being separated by 12 m or more of bedrock (Wycherley, 1975, p.41).

Since the bedrock floor and basal parts of the walls of the main passage which link the entrance and the Dome Room are concealed by an undetermined thickness of mud (and alluvium?), the 'true' form of the cave and its mode of formation are somewhat conjectural. However, as the roof of the cave, particularly in Pipe Corridor, is indented by large, rounded scallops, and as the exposed walls show little evidence of concentrated stream action, it seems likely that Gua Anak Takun is largely phreatic. Also, it is reasonable to suppose that the 'true' cross-section of the main passage, in common with most phreatic systems in the tower karst hills, is high in relation to its width, and that only the uppermost parts are presently exposed. In addition to solutional processes, rockfall has been an important mechanism, at least in the later stages of cavern enlargement. This is demonstrated most clearly by the large rock pile at the base of the Great Chimney.

Inputs of water are mostly from stalactites in the cave roof. The frequency of seepage points per unit area is higher than in many of the other caves investigated in the peninsula, and the bedrock joints are generally tightly closed. In consequence, the flow rates of individual seepages tend to be low. For example, 86% of the sites sampled in the present study have a mean discharge of less than 10 ml/min, the highest being 33 ml/min. The discharge at individual sites is quite variable. At 27 sites, the seepage rate was measured on six or more occasions during the course of one year. The coefficient of variation of discharge, calculated for each of these sites, has an average value of 106.4%. This is higher than figures obtained from other caves in the peninsula and probably reflects the relatively small size of the outcrop. The maximum thickness of limestone through which water percolates before entering the cave is about 70 m. However, because of the overall morphology and deeply dissected form of the hilltop (Crowther, 1979), the usual length of groundwater flow is probably no more than 30 to 40 m. Under these circumstances, some response to seasonal variations in rainfall and, possibly, to single storms may be anticipated.

A final noteworthy feature of Gua Anak Takun is that it is inhabited by a small colony of bats, chiefly of insectivorous species. In 1974/75, when the present study was undertaken, the population was considerably smaller than the mean figure of 400+ reported by Dunn (1965), with most tending to congregate in the upper sections of the cave, where small openings in the roof allow ready access. The floor of the cave has an irregular covering of guano.

EXPERIMENTAL DESIGN AND ANALYTICAL METHODS

The investigation was confined to Pipe Corridor, Snake Room, Liphistius Room, Bench Corridor and the Dome Room, with the principal objective being to determine the average chemical composition of every seepage. Ideally, each site would have been sampled regularly throughout the year. However, the sheer number of man-hours required to undertake such a scheme rendered it impractical. The following two-tiered sampling strategy was therefore adopted. First, 27 sites were sampled at approximately three-week intervals over a period of one year to establish the temporal variability of karst water quality and discharge. These were primarily the seepages with faster flow rates, but a range of slower sites was also included. A second sampling phase was undertaken towards the end of the year, when results from the first phase revealed only small fluctuations in water chemistry, particularly at the slower seepages. This involved the collection of a single sample from the remaining seepage points. Although some were necessarily excluded because they yielded an inadequate volume for chemical analysis in a day's field-work, 36 sites were sampled, giving a total of 63.

Standard methods of water analysis were used throughout the study. The magnesium concentration (referred to as 'magnesium hardness') is expressed in terms of the equivalent concentration of calcium carbonate. This ensures compatibility with results reported in other studies where total hardness and calcium hardness have more usually been determined by titration with E.D.T.A. and magnesium hardness has been calculated as the difference between these values. In the present study total hardness has been calculated as the sum of magnesium and calcium hardness, the latter being measured by titration with 0.02N E.D.T.A. Alkaline hardness was determined by titration with 0.02N sulphuric acid using the British Drug Houses (B.D.H.) 4.5 mixed indicator, with non-alkaline hardness being calculated as the difference between total and alkaline hardness. Potassium and sodium were assessed by flame emission. pH and alkaline hardness, the properties most susceptible to change during storage (Brown et al, 1970), were determined within 4 hours of collection, and all the analyses were carried out within 24 hours. Saturation extracts for samples of guano were prepared by the method used for soils (Bascomb, 1974, pp. 39-40), and their aggressiveness was determined by measuring the total hardness of samples before and after saturation with AnalaR grade calcium carbonate (Stenner, 1969).

RESULTS

Table 1 summarises the results obtained from the 63 sites. Undoubtedly, the most striking feature of the data is the high degree of inter-site variability. For example, specific conductance ranges from 135 to 1399 μmho/cm at 25°C, with a standard deviation of 333.5 μmho, whereas concentrations of potassium vary between 0.10 and 26.01 ppm, with a standard deviation of 6.49 ppm. When the spatial variations in water chemistry are examined (Fig. 2), certain broad trends become apparent. Most conspicuous is the grouping of sites in Bench Corridor to the south-east of North Port (upper cave). These seepages are thought to be affected by guano. Of the remaining sites, those with a comparatively high concentration of non-alkaline hardness and a high Mg:Ca ratio tend to be confined to those seepages which lie close to, or in contact with, the shale beds in the south-eastern corner of the cave. The specific effects of the guano, the shale beds, and other possible environmental controls are considered below.

TABLE 1 Chemical properties of diffuse-flow seepages in Gua Anak Takun

	MEAN*	MINIMUM	MAXIMUM	STANDARD DEVIATION
pH	7.81	7.46	8.15	0.140
Specific conductance (μmho)	370.8	135.0	1399.0	333.5
Total hardness (ppm)	175.9	65.3	660.6	142.4
Alkaline hardness (ppm)	96.7	32.1	180.1	31.0
Non-alkaline hardness (ppm)	79.2	0.0	628.5	154.1
Non-alk:Total hardness	0.231	0.0	0.951	0.315
Calcium hardness (ppm)	166.3	63.7	631.0	136.7
Magnesium hardness (ppm)	9.6	1.2	32.7	7.50
Mg:Ca (equivalents)	0.068	0.010	0.230	0.051
K (ppm)	3.11	0.10	26.01	6.49
Na (ppm)	1.28	0.20	4.74	0.977
K:Na (equivalents)	0.834	0.06	3.89	1.082

* _n_ = 63, except pH where _n_ = 37.

Guano-affected seepages

Initially, the discovery of seepage waters in Bench Corridor with exceptionally high levels of potassium and total and non-alkaline hardness posed an intriguing problem, particularly as six limestone samples from various parts of the cave revealed no marked variations in chemical composition. However, sites with similar solute characteristics were also found in Gua Batu, a large cave 10 km south-east of Gua Anak Takun, and it was these which first established the connection with bat guano. In Gua Batu, waters of this type either issue from high-level, air-filled conduits in the roof, where bats congregate in large colonies, or were sampled at points where they flow over large stalagmites, located beneath bat roosts. In both cases the waters come in contact with bat

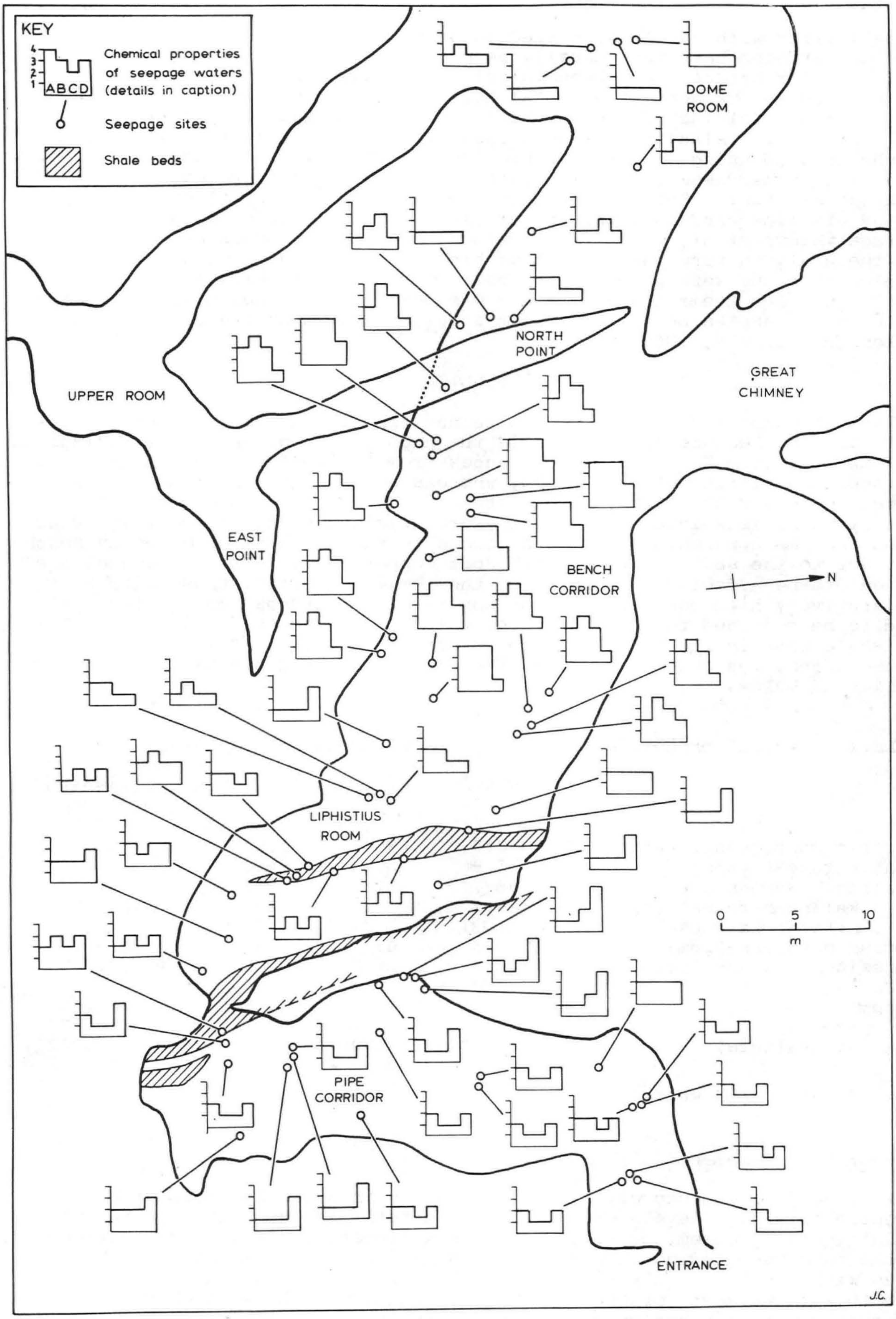


Fig.2. Variations in chemical properties of diffuse-flow seepages:

A. Total hardness (ppm) - 1. < 100, 2. 100-199.9, 3. 200-399.9, 4. > 399.9

B. Non-alkaline hardness (ppm) - 1. < 5, 2. 5-19.9, 3. 20-39.9, 4. > 39.9.

C. Potassium (ppm) - 1. < 0.4, 2. 0.4-0.99, 3. 1.0-9.99, 4. > 9.99.

D. Mg:Ca (equivalents) - 1.< 0.05, 2. 0.05-0.099, 3. 0.10-0.199, 4 > 0.199.

excreta. Two samples from this cave had nitrate concentrations of 84 and 120 ppm. These figures confirm the above interpretation, since Hem (1970, p.118) found high nitrate concentrations are characteristic of pools in caves frequented by bats. Those groundwaters in Gua Batu which are known to be guano-affected have annon-alkaline hardness content of more than 65.0 ppm and a potassium concentration in excess of 2.0 ppm. For Gua Anak Takun, corresponding figures of 40.0 and 1.0 ppm distinguish the 'contaminated' waters. Sites which exceed these levels occur in a fairly clearly defined zone of Bench Corridor (Fig. 2), the boundary of which indicates a relationship with the upper passages. Thus, one site is located directly beneath North Point, and all lie within an area which could receive seepage waters from the corridors of East and North Points. It is suggested, therefore, that the solutes in these waters are partly derived from the floor of the upper cave. The generally lower concentrations of non-alkaline hardness and potassium in guano-affected waters of Gua Anak Takun as compared with those of Gua Batu are probably attributable to the seepage of water through 12 m or so of limestone bedrock after contact with the guano.

A comparison of the chemical characteristics of the two broad groups of waters in Gua Anak Takun is presented in Table 2. The guano-affected seepages

TABLE 2 Effect of contamination with guano upon the average chemical composition of diffuse-flow seepages in Gua Anak Takun.

	UNCONTAMINATED SEEPAGES (_n_ = 46)	GUANO-AFFECTED SEEPAGES (_n_ = 17)	SIGNIFICANCE LEVEL OF DIFFERENCE
pH	7.85	7.69	0.05
Specific conductance (µmho)	214.1	794.7	0.001
Total hardness (ppm)	111.0	351.6	0.001
Alkaline hardness (ppm)	105.1	74.1	0.001
Non-alkaline hardness (ppm)	5.9	277.5	0.001
Non-alk:Total hardness	0.053	0.715	0.001
Calcium hardness (ppm)	103.4	336.5	0.001
Magnesium hardness (ppm)	7.6	15.1	0.05
Mg:Ca (equivalents)	0.077	0.044	0.001
K (ppm)	0.32	10.68	0.001
Na (ppm)	0.92	2.24	0.001
K:Na (equivalents)	0.245	2.43	0.001

are clearly distinguished from the remaining sites by their higher cation concentrations, non-alkaline hardness and K:Na ratio, and by their lower pH, alkaline hardness and Mg:Ca ratio. These results contrast with data reported from Finim Tel, New Guinea (Brook, 1976, p.188). Here, one drip which is thought to be affected by guano has an exceptionally low pH of 6.5 (cf. 7.69 in the present study), but otherwise differs little from other seepages. The consistently low alkaline hardness content of the guano-affected waters in Gua Anak Takun (maximum, 124.0 ppm) explains why stalactites are often absent or, at most, poorly developed at these sites.

Saturation extracts from three samples of fresh and older, partially decomposed, guano were analysed to examine more closely the influence of guano upon groundwater chmistry. The results are summarized in Table 3. Extracts from fresh guano are neutral in reaction, with a high specific conductance (mean, 1906 µmho/cm) and a particularly high potassium content (mean, 286.0 ppm). As the guano decomposes, the electrolyte content of the saturation extract decreases, with a notable fall in specific conductance, magnesium and potassium. However, more importantly from the point of view of karst groundwaters, the solution becomes more acidic (mean pH 5.68), and its aggressiveness towards calcium carbonate increases from an average of 12.0 to 156.3 ppm. Clearly, waters seeping through guano accumulations on the floor of a cave will mostly tend to have greatest contact with old rather than fresh deposits, simply because the former are generally deeper. It would appear, therefore, that the high calcium hardness levels of the guano-affected seepages are largely attributable to solution of limestone, with only a small proportion of the

TABLE 3 Chemical properties of saturation extracts from samples of guano

	FRESH GUANO	PARTIALLY DECOMPOSED GUANO
pH	7.03	5.68
Specific conductance (μmho)	1906	1640
Ca (ppm)	23.6	25.3
Aggressiveness (ppm, $CaCO_3$)	12.0	156.3
Mg (ppm)	32.5	19.0
Mg:Ca (equivalents)	2.27	1.24
K (ppm)	286.0	194.0
Na (ppm)	10.3	11.2
K:Na (equivalents)	16.3	10.2

calcium being derived directly from the guano. Inevitably, some waters may not reach chemical equilibrium with the guano, either because the seepage rate is high, as may occur following heavy rainfall, or because the deposits are shallow. As a result, the saturation extracts may not be completely representative of groundwater at the guano/rock interface. Nevertheless, they provide some indication of the solute concentration and levels of chemical aggressiveness which may be derived from this source, and confirm the link between the seepage characteristics in Bench Corridor and the bats in the upper part of the cave.

Uncontaminated seepages.

The 46 diffuse-flow seepages which appear to be unaffected by guano display considerable variations in water chemistry. Total hardness, for example, varies between 65.3 and 181.3 ppm, whilst the corresponding ranges for non-alkaline hardness and the Mg:Ca ratio are from 0 to 35.8 ppm and from 0.01 to 0.23, respectively. The Mg:Ca ratio of the pure diffuse-flow seepages (0.077) is considerably higher than that of the bedrock (0.023). In part, this may possibly be attributed to magnesium carbonate being less likely to be precipitated from karst waters than calcium carbonate (Douglas, 1965). Further possible explanations are considered below.

(a) Effects of interbedded shales.

From Fig. 2 it may be seen that seepages in the vicinity of the shale beds differ in certain respects from the other pure seepages. For example, the seven seepages which issue from the shale/limestone junction have a consistently higher non-alkaline hardness. The range is from 7.7 to 34.9 ppm, with a mean of 14.7 ppm. The latter figure compares with a mean value of 4.3 ppm for the remaining pure seepages, the difference being significant at the 99.9% confidence level. It seems likely, therefore, that the shales are a source of inorganic anions. A further feature which may be identified from Fig. 2 is that those pure seepages with a Mg:Ca ratio of more than 0.10 and with potassium concentrations in excess of 0.4 ppm are almost entirely confined to that part of the cave between, and immediately adjacent to, the shale outcrops. Since samples of the shale were found to contain relatively high proportions of magnesium and potassium, 1.86 and 4.13 % by weight, respectively, the higher concentrations of these elements in the groundwaters may be derived, in part,from the weathering of the shale. Another possibility is that the limestone adjacent to the shale beds contains comparatively high percentages of magnesium and potassium. Thus, whilst a single limestone sample taken from between the shale beds did not differ markedly in chemical composition from other samples from the cave, it is quite conceivable that the bedrock may contain bodies of limestone which are fundamentally different in character from the bulk of limestone matrix. Indeed, the Kuala Lumpur Limestone is locally dolomitic (Gobbett, 1964). Clearly, more detailed sampling of bedrock would be required to pin-point the exact cause of the observed differences in karst water quality adjacent to the interbedded shales.

(b) Effects of flow rate and thickness of stalactitic deposits.

It might be anticipated that the total hardness of the pure seepages will be affected by the flow rate, and by the thickness of stalactitic deposits through or over which waters pass before dripping into the cave. Cooke (1971), for example, has shown that redeposition of calcium carbonate from groundwaters influences considerably the hardness of cave seepages in Tanzania, with total hardness varying directly with discharge, and inversely with the length of flow over secondary deposits. Since the 46 sites sampled in Gua Anak Takun display wide variations in flow rate (0.08 to 33 ml/min) and stalactite length (2 cm to 4.5 m), they provide an ideal opportunity for assessing the relationship between water hardness and these suggested environmental controls.

Total hardness was found to vary inversely with stalactite length (r = -0.270). This result lends some support to the hypothesis that more deposition occurs where stalactites are longer, and hence there is greater opportunity for gaseous exchange between groundwater and the cave atmosphere. However, since the correlation coefficient is not statistically significant at the 95% confidence level, the relationship is far from clear-cut. No relationship was found between total hardness and discharge. These results suggest, therefore, that inter-site variations in total hardness in Gua Anak Takun are not strongly controlled by differences in the rate of deposition.

BROADER IMPLICATIONS OF THE RESULTS

Significance of bat guano in cave development.

In tower karst regions the catchment areas afforded by the individual limestone outcrops are often insufficient to support permanent vadose streams, and the water-table often lies at, or below, the level of the adjacent plains. Consequently, apart from small inputs of water from diffuse-flow seepages, caves in the residual towers are mostly dry. Under such circumstances, solutional enlargement of the underground passages is thought to be minimal, and the dominant process is characteristically regarded as being one of progressive infilling with speleothems and other cave deposits. Hitherto, the possibility of limestone solution beneath cave floor deposits has been largely overlooked. Results from the present investigation demonstrate that groundwaters may gain renewed chemical aggressiveness where they percolate through accumulations of guano. Thus, whilst cave drips are responsible for infilling otherwise dry underground passages, the additional aggressiveness which such waters gain in seeping through guano deposits may cause significant solution of the bedrock floor. In humid tropical regions, where caves are frequently inhabited by bats, such a process may be important in cavern development.

Hydrological characteristics of Anak Bukit Takun.

The absence of a strong relationship between the total hardness of uncontaminated seepage waters and either flow rate or stalactite length suggests that variables other than the rate of secondary deposition exert an important control over the chemistry of these groundwaters. Small-scale, spatial variations in the chemical characteristics of recharge waters probably account for much of the observed variability. Studies undertaken on the summit of Anak Bukit Takun, for example, provide direct evidence of the wide variations in solute characteristics which may be encountered in runoff from bare and partially covered rock surfaces (Crowther, 1979). However, in order for variations in the quality of surface inflows to be detectable in the spatial pattern of water hardness in the cave, bodies of water must necessarily follow discrete flow paths through the aquifer, with little intermixing. Two lines of evidence suggest that these hydrological conditions obtain in Anak Bukit Takun. First, since groundwater movement is confined almost entirely to tight, vertical and subvertical joints, there will be little lateral movement of groundwater. Secondly, because of the small size of the outcrop, groundwater flow lengths are typically less than 40 m, and this further limits intermixing of waters within the aquifer.

An important corollary of the above findings is that the chemical properties of diffuse-flow seepages in a cave will tend to exhibit greater spatial variability where either (1) the bedrock is very massive and water flow is confined principally to vertical fractures, or (2) the thickness of limestone above the cave is comparatively small. Investigations undertaken to establish the average chemical composition of diffuse-flow seepages in a cave should, therefore, take these factors into consideration in the experimental design. Where, as in Gua Anak Takun, both conditions obtain, wide variations in groundwater quality may be anticipated.

Groundwater chemistry and cave exploration.

The results from Gua Anak Takun show that where an outcrop is frequented by bats, patterns of groundwater chemistry in a cave system may provide a reliable indication of the presence, and approximate location, of open, high-level passages. Initially, some intimation as to which ground-waters might be contaminated by guano may be gained without recourse to chemical analysis. Thus, on the one hand, guano-affected seepages have a high electrolyte content, which may be readily detected by means of a portable conductivity bridge. On the other, stalactitic deposits are often poorly developed, or even absent, at the point at which such waters emerge into the cave. These findings have clear practical applications in the field of speleological exploration in that guano-affected seepages in a known part of a cave system may indicate those areas in which further extensions are most likely to be made.

CONCLUSIONS

The present study demonstrates the value of exhaustively sampling diffuse-flow seepages in part of a cave system. In such an investigation, not only is the spatial variability encompassed, thereby ensuring the representativeness of the overall results, but also the distribution patterns which emerge and the relationships observed between water quality and systematic variations in environmental characteristics, allow the effects of certain more important variables to be established with some confidence. Three main conclusions may be drawn from the results from Gua Anak Takun.

(1) Where groundwaters come in contact with bat guano within an aquifer, their electrolyte content increases, as is reflected in their higher concentrations of potassium, sodium, magnesium and non-alkaline hardness. More importantly, however, such waters also gain renewed aggressiveness towards the limestone. Thus, in caves which are inhabited by bats, active solutional lowering of the bedrock floor may well be occurring beneath cave earth deposits. Infilling with speleothems may not therefore be the only karst process operative in the abandoned, high-level cave passages which are characteristic of many tower karst hills.

(2) Waters issuing from the shale/limestone junction have a significantly higher non-alkaline hardness content than the other uncontaminated seepages, and levels of magnesium and potassium are generally higher in those waters which emerge between, or immediately adjacent to, the shale beds. Whilst the exact reason for these variations has not been determined, it is clear that the presence of interbedded shales and local variations in the mineralogy of the limestone may cause marked differences in the chemical properties of diffuse-flow seepages.

(3) The total hardness of the uncontaminated seepages appears to be affected only slightly by differences in the amount of secondary deposition. It is postulated, therefore, that the wide, inter-site variations of total hardness observed in Gua Anak Takun are largely attributable to small-scale, spatial variations in the chemical properties of surface recharge waters. The small size of the outcrop, combined with the dominant flow of groundwater along tight vertical fractures, produces hydrological conditions which favour the discrete movement of water bodies from the surface to the cave, with little intermixing. Clearly, marked spatial variations in the properties of diffuse-flow seepages may be anticipated in other karst regions where similar conditions obtain.

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FURTHER PALAEOMAGNETIC STUDIES OF SEDIMENTS FROM AGEN ALLWEDD

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ABSTRACT

Thirty 5 x 5cm oriented samples of cap mud were collected from four sites in Main Passage and Keyhole Chamber, Agen Allwedd and their palaeomagnetism and magnetic fabric measured using spinner magnetometers. The remanent magnetisation was found to be very stable and due to the depositional alignment of magnetite particles by the earth's magnetic field. A correlation of remanence directions from the four sites and one previously studied suggests that cap mud deposition was synchronous throughout the cave while the magnetic fabric of the sediments demonstrates that weak currents were flowing during this phase. It is still uncertain from our results whether the sediment cones which are found against the walls of the cave were formed by water flow into or out of fissures.

Measurements of the remanent magnetisation of slowly deposited sediments can provide information concerning changes in the direction of the earth's magnetic field in the past and this technique has become well established through studies of lake and deep sea sediments. Additional information concerning ancient environments of deposition can be obtained from an examination of the magnetic fabric of a sediment which is usually closely related to the strength and direction of any water currents which flowed during the time of sedimentation. In marked contrast to lake or deep sea sediments, cave sediments are often exceptionally well preserved due to the absence of appreciable desiccation or biological disturbance and they are therefore ideally suited to a palaeomagnetic investigation. This has been shown by the results of a preliminary palaeomagnetic study of cap mud from a site in Main Passage, Agen Allwedd (Noël et al, 1979). Ten specimens from this site (now designated AG1, Fig. 1) were found to have a very stable remanent magnetisation with a mean direction of Declination = 5·9°, Inclination = 40·7°. It was concluded that the magnetisation had been acquired depositionally by the systematic alignment of magnetised detrital grains in the earth's magnetic field. The magnetic fabric contained a lineation suggesting a current that flowed from N.E. to S.W. during this phase. By measuring the changes in declination through the 5cm thick cap mud it was proposed that the fine laminations may represent annual varves and thus reflect seasonal pulses of water into the cave.

To extend this study and examine some of these conclusions in greater detail it was decided to investigate the palaeomagnetism of a more comprehensive collection of samples of cap mud from Agen Allwedd. This report describes the remanence and magnetic fabric of 30 samples of silt from four new sites whose locations are shown in Fig. 1. These data suggest that cap mud was deposited synchronously throughout the flooded cave while at the same time weak currents continued to flow.

SAMPLING

The sedimentary stratigraphy of the deposits within Agen Allwedd and corresponding palaeo-environmental reconstructions have been given by Bull (1976, 1980). The final phase of sedimentation occurred about 11,000 y.B.P. when the cave was flooded and a fine-grained cap mud was deposited over an extensive area. This finely-laminated unit varies in thickness from about 5 to 15cm and is thought to have entered the cave by downward percolation from the surface via numerous fissures (Bull, 1981). Samples were only taken from those exposures which remained untouched by cavers and which were also well away from desiccation cracks. The specimens were obtained by pressing 5 x 5cm plastic cylinders vertically into the sediment and then scribing the cylinders with marks corresponding to the direction of magnetic north. The cylinders were then lifted together with the sediment and the ends sealed with plastic discs.

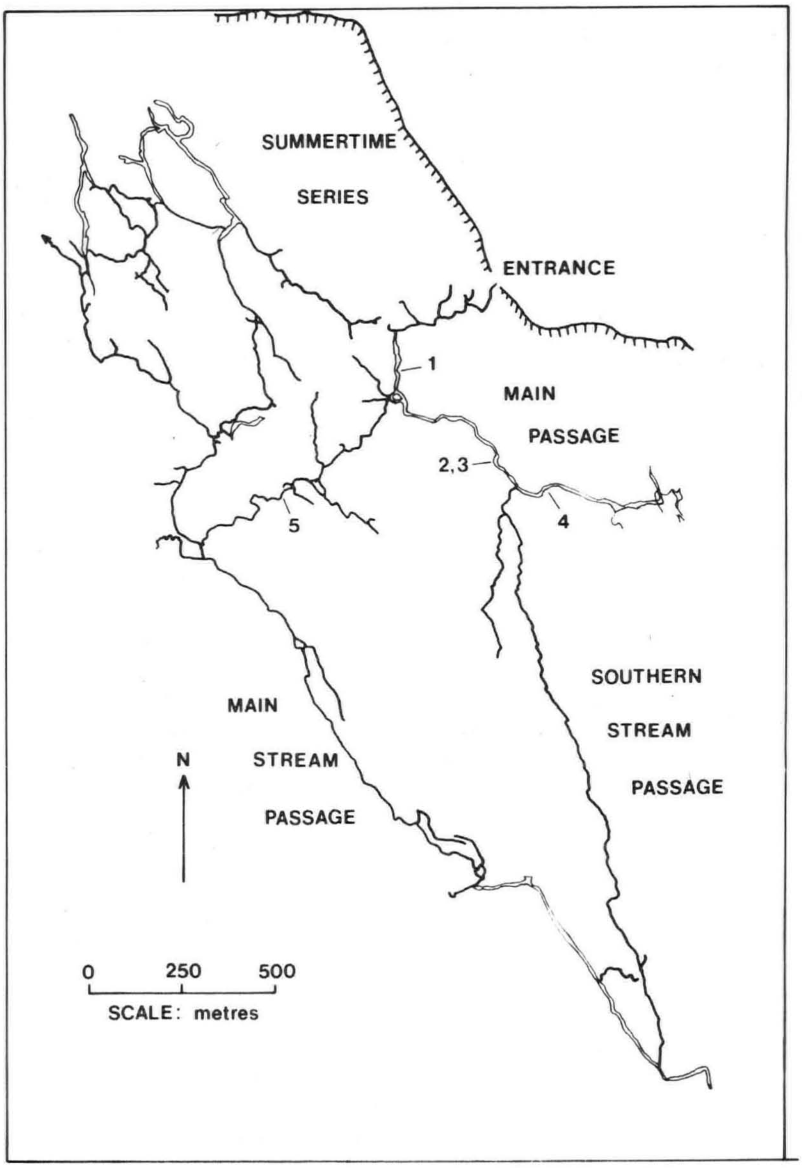

Fig. 1 Map of Agen Allwedd showing the four new locations where cap mud was sampled. Site 1 refers to the position of an earlier collection, AG1 the palaeomagnetic results from which have been described in a previous report (Noël et al, 1979).

Sites AG2 and AG3

The position of these two sites, about halfway along Main Passage, is shown in Fig. 1. A notable feature at this point was a large sediment cone which appeared to originate from two fissures in the western wall (Fig. 2). It was decided to sample material from the cone (site AG3) and also from the less steeply-inclined sediment adjacent to it (AG2). This would allow a comparison of results from sediments which had been deposited on a steep slope (29^{o}) with those from nearly horizontal bedding (8^{o}) in the near vicinity.

Site AG4

This site was in Main Passage about 100m past the entrance to Southern Stream Passage (Fig. 1). The samples were taken from an approximately horizontal surface about 1m from the eastern wall.

Site AG5

These samples were obtained from an alcove in the eastern wall of Keyhole

Chamber. This was one of the few remaining pockets of relatively undisturbed cap mud and unfortunately the material was less well preserved than in the preceding samples.

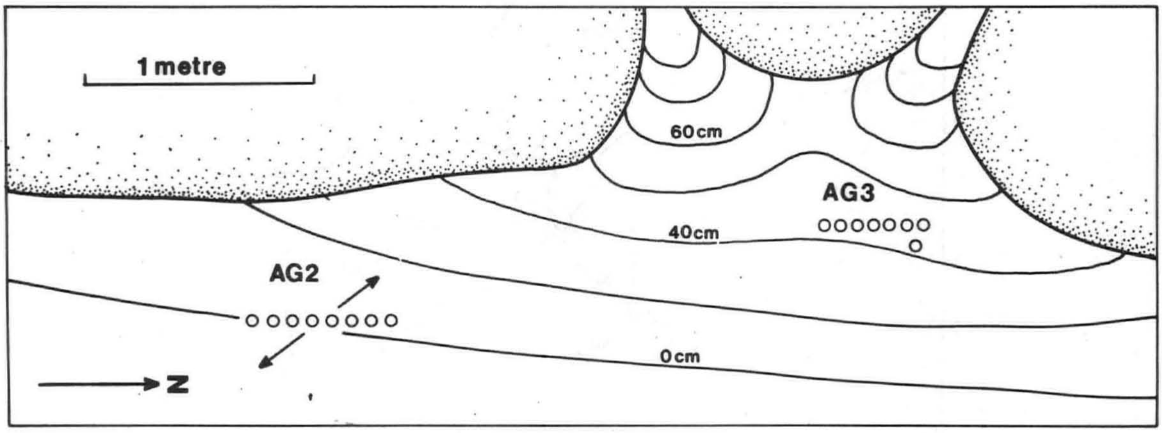

Fig. 2 Plan showing the locations of the AG2 and AG3 samples with respect to a steep sediment cone against the wall of Main Passage. The direction of the mean magnetic susceptibility lineation in the AG2 sediments is shown by the arrowed line.

Measurement

The direction and intensity of the natural remanent magnetisation of the specimens were measured as soon as possible after sampling using a Digico spinner magnetometer (Molyneux, 1971). A pilot specimen was then selected from each site and the stability of the remanence examined by remeasuring the magnetisation after successive exposures to steadily increasing alternating magnetic fields. The behaviour of a typical sample, AG2/8, is shown in Fig. 3. On the basis of the results from the pilot specimens it was decided to partially demagnetize the remaining samples in an alternating magnetic field of 200 Oe. This then isolated in each sample a primary component of remanence whose direction and magnitude were then remeasured in the magnetometer. (Fig. 4 and Table 1).

Variations with depth in the cores of the horizontal component of remanence (declination) were then measured at 1cm intervals using a Digico long core spinner magnetometer (Molyneux et al, 1972). The results are shown in Fig. 5.

2.3 x 1.9cm oriented sub-samples were next removed from each specimen and the direction and magnitude of their magnetic susceptibility anisotropy measured using a modified spinner magnetometer (Singh et al, 1975). The magnetic susceptibility of a sediment is proportional to the quantity of magnetic material present while the anisotropy of this parameter reflects any tendency for the magnetic grains to hold a preferred orientation. In Fig. 6 the results have been presented in terms of the directions of the three principal axes of an ellipsoid whose shape represents the anisotropy or "magnetic fabric" within a given sediment sample.

Finally, in order to identify the mineral responsible for the remanence a magnetic extract was subjected to a Curie temperature determination using a translation balance. In this technique the magnetisation which is induced by a strong field is monitored as the sample is slowly heated to about 700^{o}C. The critical temperature at which the magnetisation falls to zero, the Curie temperature, is diagnostic of the magnetic mineral. The results are shown in Fig. 7.

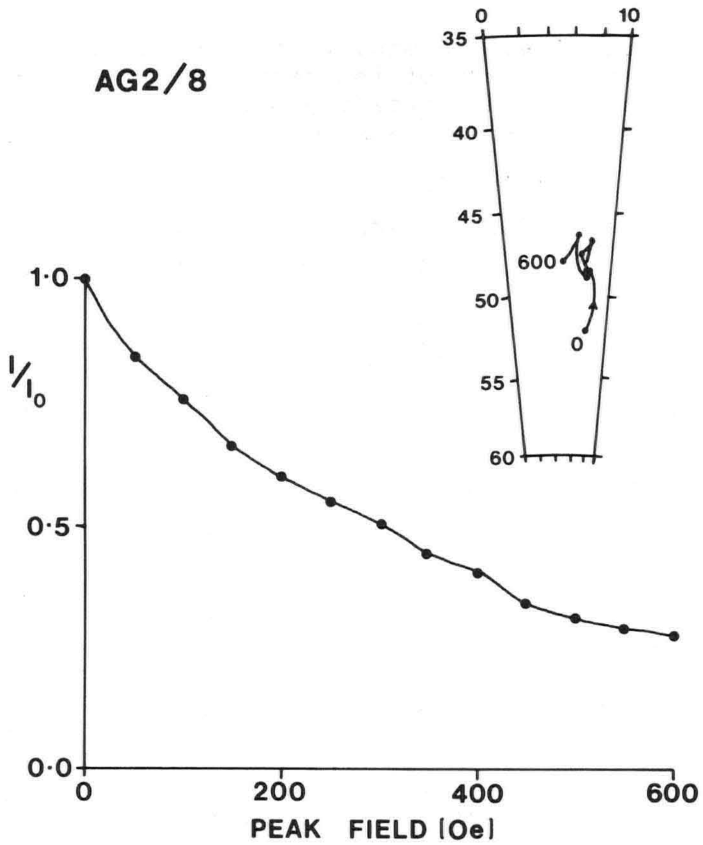

Fig. 3 Changes in the relative intensity (lower) and direction (upper) of the remanent magnetisation in a typical pilot specimen during alternating field demagnetisation.

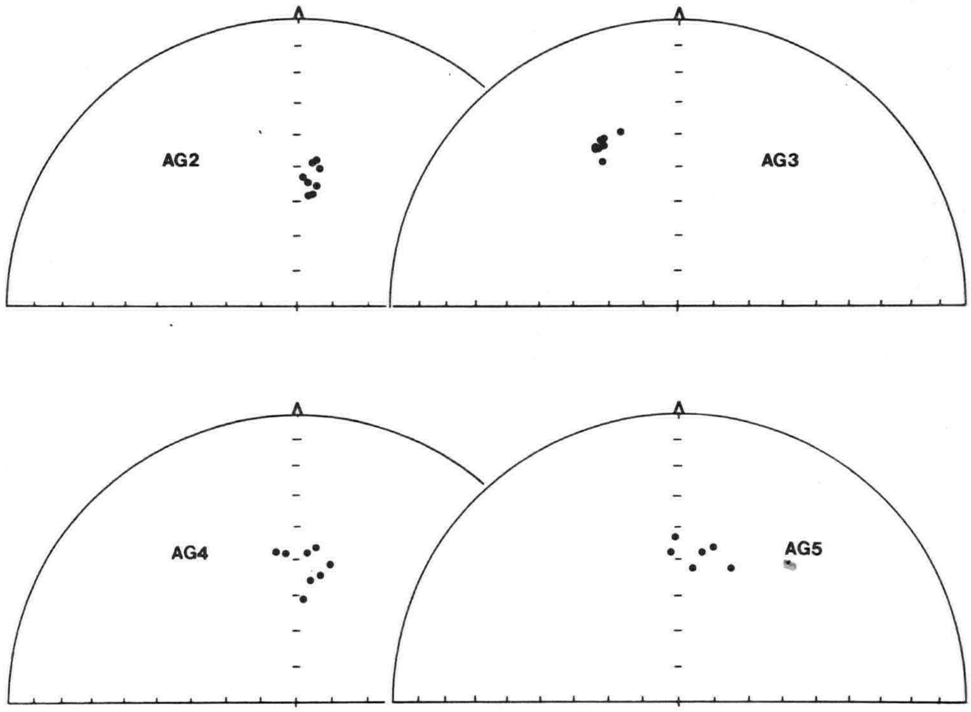

Fig. 4 Stereograms showing the directions of the remanent magnetisation in the cap mud samples after partial demagnetisation by an alternating magnetic field of 200 Oe.

TABLE 1 - Palaeomagnetic results. Intensity of magnetisation is in units of Gauss x10^{-6}. The accuracy of the mean direction at each site is expressed in terms of the precision parameter, K and the semi-angle of the 95% cone of confidence, α_{95} (Fisher, 1953)

	Natural Remanent Magnetisation			Remanence at 200 Oersteds		
Sample	Intensity	Declination	Inclination	Intensity	Declination	Inclination
AG2/1	10.246	5.7	61.3	8.846	5.4	58.0
2	8.809	4.7	59.5	7.321	7.6	57.7
3	8.935	11.0	56.9	7.304	9.1	54.8
4	8.364	2.3	53.2	6.557	4.8	53.9
5	9.145	2.5	53.9	7.419	2.5	52.8
6	8.822	7.5	1.0	6.799	5.6	48.2
7	8.729	7.9	51.1	6.860	9.1	50.1
8	9.708	6.1	51.0	7.343	7.1	47.6
MEAN	9.09	5.9	54.7	7.31	6.4	52.9
K	342.9			368.6		
α_{95}	2.9°			2.8°		
AG3/1	8.632	335.6	40.2	6.877	335.1	38.5
2	8.197	338.0	38.1	6.381	334.8	36.5
3	9.232	333.4	40.7	6.931	333.0	38.3
4	8.996	340.3	39.6	5.667	341.6	36.2
5	7.886	338.0	35.9	6.352	336.1	36.2
6	8.094	334.2	39.0	6.584	332.3	37.8
7	8.612	335.5	46.8	6.863	332.1	42.2
8	8.438	332.3	41.6	6.722	332.0	38.2
MEAN	8.51	335.9	40.2	6.55	334.6	38.0
K	495.5			636.5		
α_{95}	2.5°			2.1°		
AG4/1	7.933	8.8	55.5	6.524	9.9	53.3
2	4.795	358.8	57.9	4.529	6.5	55.3
3	7.733	9.3	52.7	6.545	13.6	50.1
4	7.659	358.1	52.4	6.453	355.7	47.9
5	8.368	7.6	50.0	7.187	7.1	46.0
6	7.469	4.8	51.4	6.489	3.9	48.1
7	6.943	2.3	62.1	6.049	4.0	61.1
8	7.763	353.8	50.7	6.775	352.4	47.2
MEAN	7.33	2.9	54.2	6.31	3.9	51.3
K	229.0			140.9		
α_{95}	3.6°			4.6°		
AG5/1	5.638	4.1	49.5	5.019	9.3	46.9
2	5.622	4.8	52.0	3.411	6.3	51.9
3	5.648	17.5	53.1	4.687	12.8	44.8
4	5.592	25.4	54.6	4.590	22.0	49.6
5	6.225	354.9	54.0	5.013	357.3	47.7
6	5.999	352.5	50.3	4.296	358.9	42.8
MEAN	5.79	6.2	52.8	4.9	7.6	47.5
K	103.7			134.3		
α_{95}	6.6°			5.8°		

DISCUSSION

The pilot sample behaviour, e.g. Fig. 3, suggests a very stable primary magnetisation in combination with a weak secondary component. The shallowing of the remanence by alternating magnetic fields of up to 150 Oe corresponds to the removal of a soft viscous magnetisation in the present day field direction and for this reason the 200 Oe 'cleaning' field was chosen. The demagnetisation curves for all the pilot specimens were smooth with mean coercivities in the range 200-320 Oe which contrasts with the value of 500 Oe found in the AG1 sediments. Since, for a given mineral, coercivity increases with decreasing grain size this suggests a smaller mean size for the magnetic grains at the northern end of Main Passage. A scanning electron micrograph of the magnetic extract revealed a grain size varying from about 3 to 40 microns while the Curie temperature of 540^{o}C identifies this mineral as being magnetite (Fig. 7).

Partial demagnetisation at 200 Oe produced an improvement in the grouping of the remanence vectors of sites AG2, 3 and 5 and a small increase in the scatter of directions of AG4 as shown by changes in the precision parameter K and α_{95} (Fisher, 1953). The mean directions for each site are listed in Table 1 and it is seen that with the exception of the result from the cone they are all indistinguishable within the angular uncertainty expressed by the error α_{95}. This is, therefore, good evidence to suggest that deposition of cap silt was simultaneous at these three sites and this conclusion may be extended to include site AG1 on the basis of its declination, 5.9^{o} if one interprets the low inclination of 40.7^{o} in terms of an 'inclination error'. The latter effect is caused by the tendency for elongated magnetic grains to settle with their long axes horizontal (King, 1955) and this effect would also account for the unusually shallow inclinations for this latitude of the remanence in the new sites AG2, 4 and 5.

The anomalous directions of magnetisation in the material from the cone can be explained by considering the influence of the steep slope on the depositing particles when they settled from suspension. The slope will have caused the majority of grains to roll downhill slightly before coming to rest with the result that the final remanence appears to have been rotated through an angle β about the strike axis of the bed. This phenomenon of 'bedding error' has been observed in laboratory redeposition experiments (e.g. King, 1955; Griffiths et al, 1960) and it has been found that to a good approximation β is related to the slope angle α by the expression $\beta = (1.42 \pm 0.15)\alpha$, (Hamilton & King, 1964). The slope of the cone was 29^{o} and thus from above $\beta = 41^{o}$. This figure has been used to correct the mean remanence direction as shown in Fig. 8. A similar correction has been made for bedding error on the 8^{o} slope at site AG2. When further corrections are applied for the inclination error according to methods described by Rees (1961) the mean directions for sites AG2 and 3 closely converge (Fig. 8). The success of this technique confirms that the magnetisation is depositional in origin. The residual discrepancy between the corrected directions reflects a combination of orientation errors and additional rotations caused by water currents flowing over and around the cone.

The remanence directions given in Table 1 represent the averages of any directional changes that might occur with depth and these are illustrated by the downcore results shown in Fig. 5. Within the AG2 samples there is no significant change in declination through the cap mud, the absolute differences being accountable by orientation errors. In contrast, the cap muds from the cone record a consistent decrease in declination down to a depth of about 2cm. This effect cannot be explained in terms of a changing bedding error since the slope of the laminations is constant and instead it is thought that the observed rotation has been caused by a changing water current flowing either into or out of the fissures. The results are consistent with either a diminishing current flow out of the fissures and down the cone or an increasing current in the reverse direction, into the fissure. The former conjecture may correspond to a model in which the cap silt was deposited during the initial flooding of the cave, via fissures, followed by ponding up, while the latter implies that the cap silt was deposited during an accelerating drainage of the cave via such fissures in the walls.

The systematic declination swing seen in the cap muds of AG4 may similarly have been caused by the effects of water currents during a flooding or draining episode. However, no regular variation at all is seen in the Keyhole Chamber samples, Fig. 5. The lack of a consistent declination vs. depth signature which correlates between every site casts doubt on our earlier suggestion

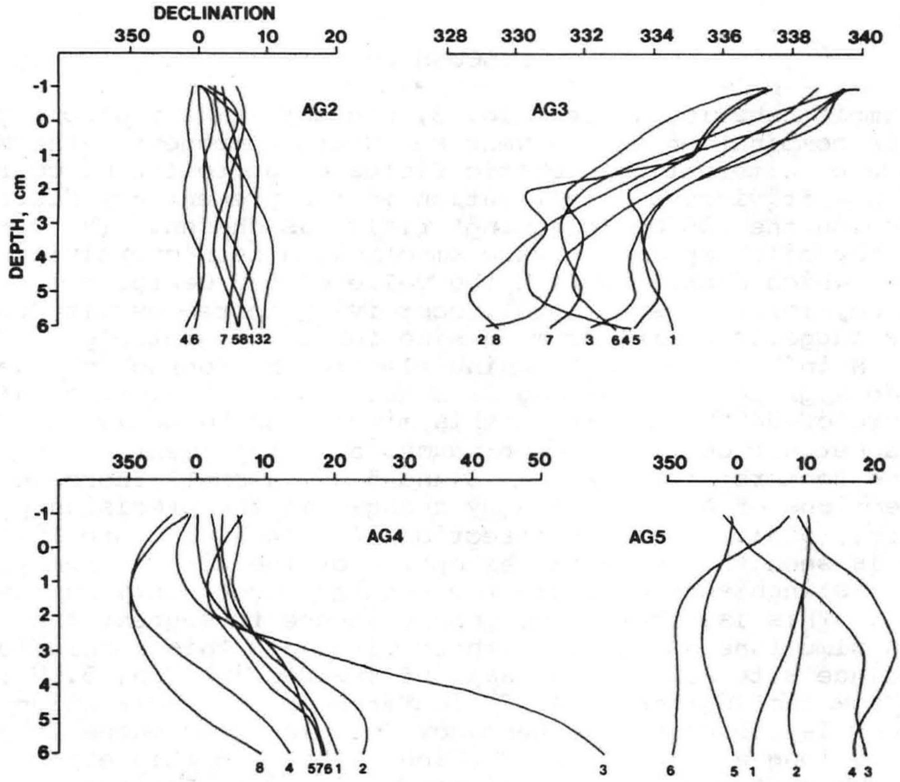

Fig.5 Changes in the horizontal direction of remanent magnetisation (declination) with depth in the cap mud samples. The measurements extend 1cm beyond the ends of each 5cm long sample.

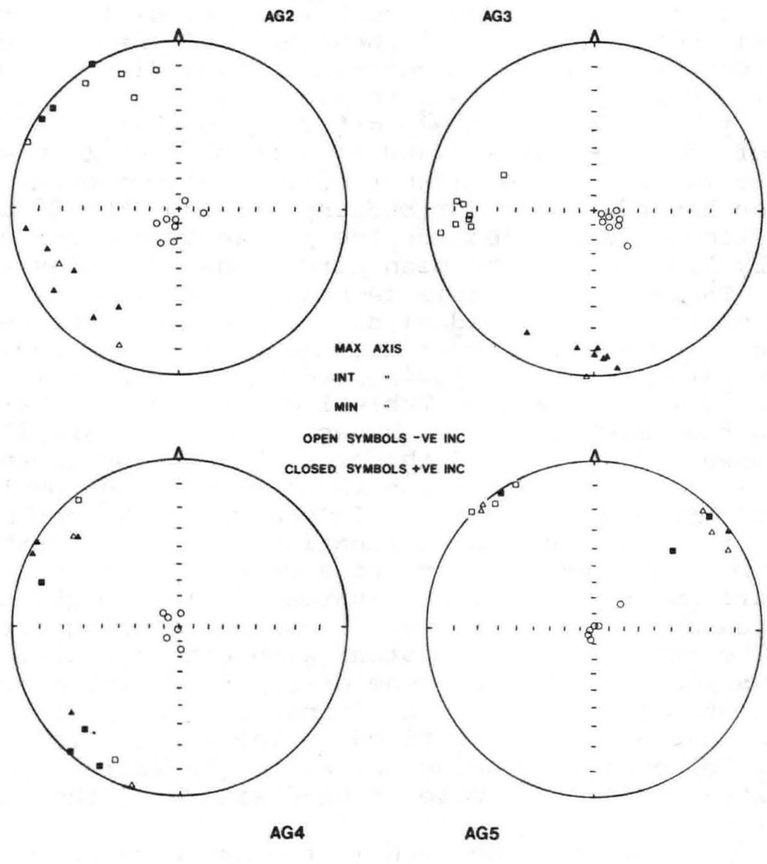

Fig.6 The results of the magnetic susceptibility anisotropy measurements The anisotropy is represented in terms of the three principal axes of an ellipsoid whose positions are shown on the stereograms.

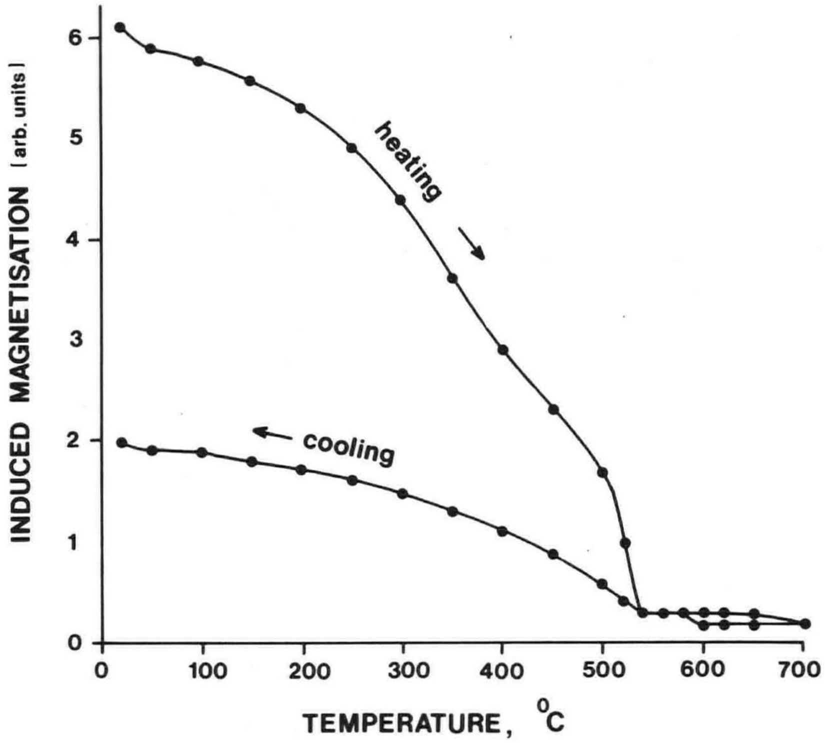

Fig.7 The thermomagnetic identification of the magnetic mineral in the cap mud. The graph shows the decay of the induced magnetisation with rising temperature and the Curie temperature of 540°C indicates the presence of magnetite. The imperfect recovery upon cooling is due to oxidation of the extract.

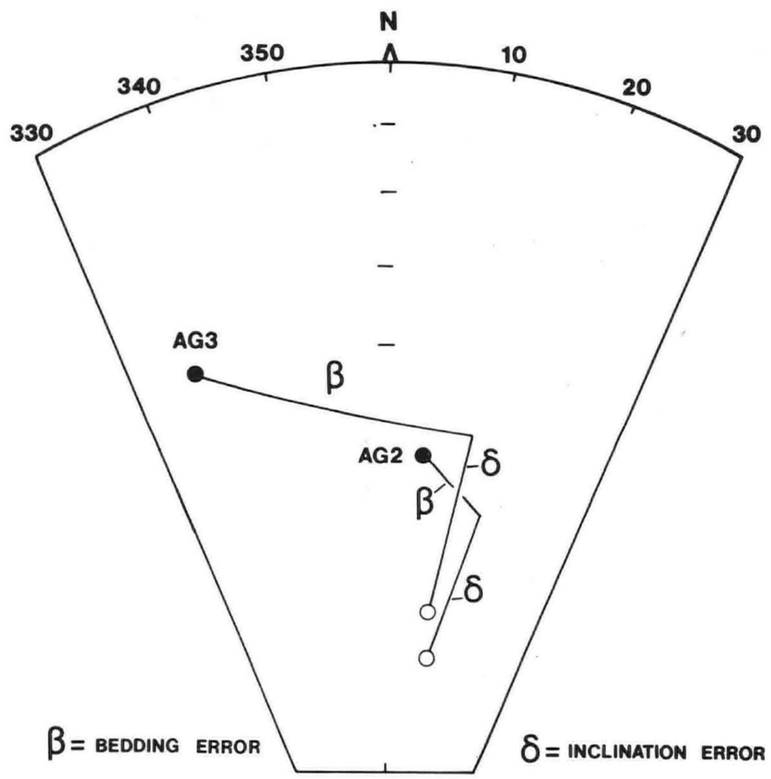

Fig.8 A stereogram showing how after applying angular corrections for the bedding error and inclination error it is possible to bring the two remanence directions for the cone samples AG2,3 into acquiescence.

that the cap muds contain a reliable record of geomagnetic secular variation (Noël et al, 1979). To establish this conclusively will require examining a more extensive collection of palaeomagnetic samples in order that the effects of water currents and changes in the earth's magnetic field can be separated.

The degree of susceptibility anisotropy in all samples was found to be low, with site averages varying between 5.4% (AG2) to 9.1% (AG3). A similar anisotropy was found in the AG1 samples (5%). Within the AG2 specimens the tilt of the minimum susceptibility axes defines a foliation plane which dips in the same direction as the bedding, as expected for a depositional fabric (Rees, 1966). The lineation direction defined by the maximum axes suggests a current direction of 142^{o} and this has been shown as a trend line in Fig. 2. The deviation of this direction of lineation away from the axis of the passage suggests that the fabric has been produced by a combination of water flow both along the passage and into or out of the fissures.

A well-defined fabric is present within the cap muds deposited on the cone with a clear lineation in the direction of the slope. The magnetic imbrication is similar to that produced in the laboratory for deposition onto slopes of 30^{o} in still water (Rees, 1966) and it is,therefore, impossible to suggest from this data alone whether flow occurred into or out of the fissures.

Sites AG4 and 5 have an unusual magnetic fabric in which two lineation directions co-exist at right angles (Fig. 6). This implies that elongated grains are present in the sediment with a mixture of parallel and transverse orientations to the water flow. Although transverse magnetic lineation has been detected in sand grade sediments (Rees, 1965) the mixture of orientations seen here have not previously been reported.

The results of this study have shown that cap mud was deposited simultaneously at five locations in Agen Allwedd and it seems likely that this unit is synchronous throughout the cave. Magnetic fabric measurements and records of changes in remanence direction through the silt show that currents were present during deposition. Although it seems probable that silt entered the ponded-up cave from the surface it is still uncertain whether the sediment cones which formed on the floor of the cave arose from water entering or leaving via lateral fissures.

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