

# Karst and Caves in the Jabal Akhdar, Oman

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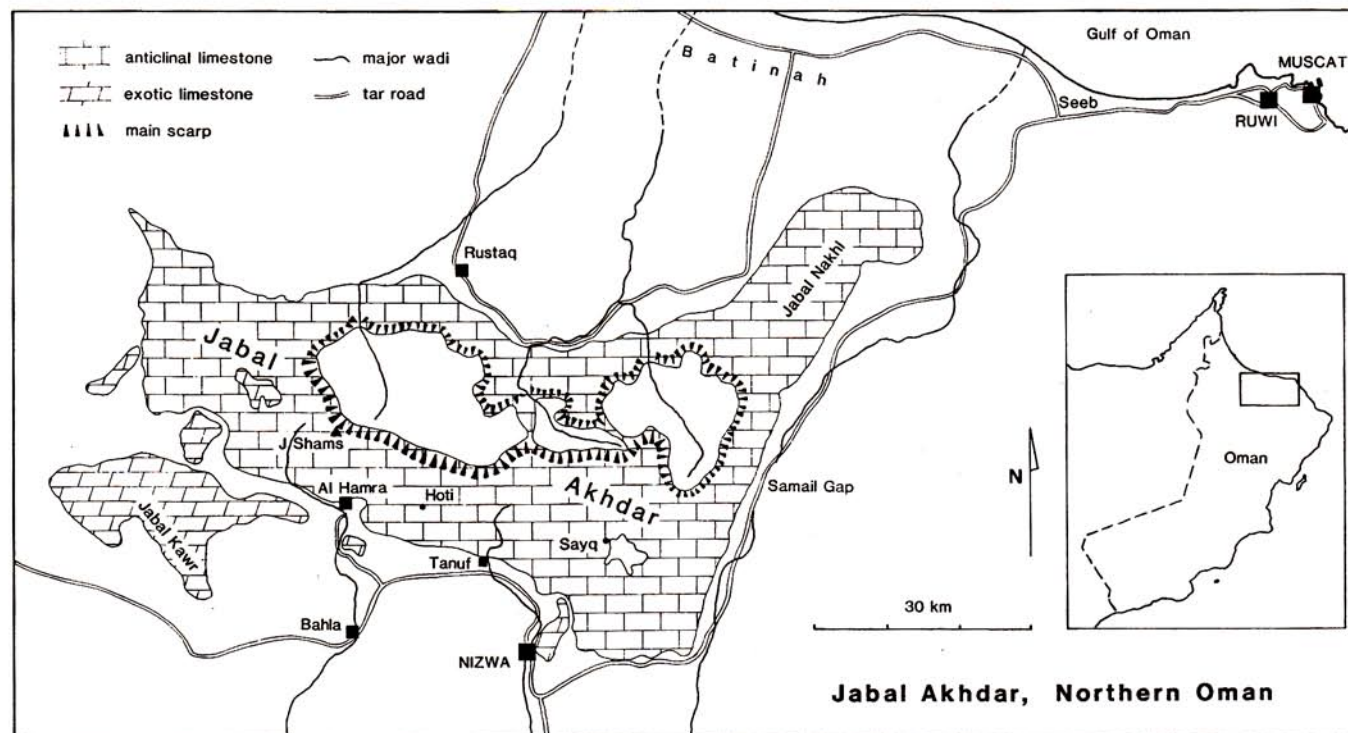
**Abstract:** The Jabal Akhdar is a spectacular anticlinal mountain range formed in a thick limestone sequence. Karst development is restricted by both the aridity of the modern climate and also the steepness of the surface slopes. The longest of the few caves known is the Hoti system, an underground flood route which provides a fine through trip nearly 5km long.

The Jabal Akhdar rises to over 3000m and forms the highest part of the mountain ranges extending across the northeast side of the Sultanate of Oman. It consists of a large breached anticline of Mesozoic limestones and dolomites. The carbonates form an area roughly 100 km by 20 km; they are surrounded by the outcrop of tectonically overlying thrust sheets of ophiolites and isolated limestone exotics. The anticlinal core is breached and inliers of pre-Permian basement, largely non-carbonate, are exposed; the main limestone outcrops therefore encircle the core inlier with outward facing dip slopes, at dips mostly between 10° and 70°, though with local structural complexities. The Mesozoic carbonate succession is over 2000m thick.

The scenery of the Jabal Akhdar is magnificent, with large rock slabs rising above narrow gorges and canyons. Jabal Akhdar translates as Green Mountain, but this is a misnomer except when compared to the rest of the desert terrain in Oman. Natural vegetation of xerophytic shrubs and trees is only conspicuous along the floors of the major wadis and in the cooler and slightly wetter environment of the upper slopes of Jabal Shams. In stark contrast are the patches of verdant foliage surrounding those villages where ancient adits, called falaj, tap groundwater supplies for the cultivation of dates, limes and other sub-tropical crops. The dominant colour is the dark grey of the bare limestone surfaces.

The Jabal is an arid and harsh environment. It receives less than 200mm of rainfall per year, and much of this falls in very localised, high intensity, summer thunderstorms. Shade temperatures regularly exceed 40°C, and the afternoon sun heats the bare rock to over 75°C, too hot to handle or climb on. Consequently it is surprising to find clusters of stone built huts clinging to the most unlikely sites wherever drinkable water is accessible. The inhabitants of these settlements appear to subsist almost entirely by the husbandry of goats. The restricted economy, rugged lifestyle and cultural isolation of these peoples is quite different from that of the inhabitants of the nearby settlements based on irrigated cultivation. Outside the cultivated areas only the most precipitous slopes are safe from the ravages of the free-ranging goats: in consequence few plants, except the most vicious thorn bushes and the poisonous euphorbias, survive the grazing pressure.

Within the thick carbonate sequence, only the Wasia limestone, at the top of the succession, appears to be significantly cavernous. It is around 300m thick, and is mainly a massive, fine grained, pure limestone, though it does contain thin-bedded and nodular horizons. The Wasia caps the main dip slopes of the Jabal Akhdar anticline, and consequently has relatively large outcrops. Karst is better developed on the southern slopes where dips and surface gradients are lower, together encouraging percolation; surface runoff





dominates processes on the steeper northern slopes. On all slope aspects, the arid climate is a further severe restriction on any approach to karst maturity.

The southern slopes contain the only known caves of any significant size on the Jabal Akhdar. These all lie in the lower dip slopes around Al Hamra and Tanuf. Immediately to the north of the cave sites, the Wasia limestone rises to the crest of the Jabal Shams escarpment, and small caves are known very close to the summit. The intervening outcrop is however broken by faulting and erosion; combined with the less karstic nature of the limestones beneath the Wasia, this places in some doubt the existence of continuous cave development over the 2300m altitude range.

#### SURFACE KARST

Due to the aridity of the climate, the modern karst of the Jabal Akhdar is immature. Rillenkarren are well developed on some outcrops but are not ubiquitous; though the karren have fine sharp crests, the level of modern activity is unknown, as the rate of destructive mechanical weathering is probably very low. Far more widespread are features which are here described as microkarren. These are grooves approximately one millimetre in width and depth which trend parallel to slope on both plane and rounded limestone surfaces. Individual grooves may show a slightly meandering habit and together they usually form crude networks. Single microkarren grooves are sometimes present in the troughs of rillenkarren. Microkarren are abundant in the Jabal and are not confined to one particular limestone lithology. They do not appear to have been recognized previously and are to be described in greater detail elsewhere (Brown et al, in prep.). Field evidence suggests that they have probably formed by solution on unvegetated limestone surfaces consequent upon rainfall or dew formation.

Dolines and discrete sinkholes are almost non-existent. Open fissures do occur in the outcrops of some of the more massive beds; though they clearly absorb any available water, most are narrow and are choked a few metres down. Hufrah Misfah (see below) is the exception. Springs and resurgences are also rare. Much of the water, which does drain through the cavernous limestone, does not resurge to daylight, but instead drains into the alluvial gravel which floor the main wadis and the plains surrounding the limestone mountains. These gravel aquifers are important



Wadi Hoti, with the rock step above the Hoti Pit entrance

water resources and the Jabal Akhdar limestones provide significant hidden recharge. Any springs in these arid mountains are of course exploited by the local people, but any caves that may lie behind them have not necessarily been investigated.

The dominant fluvial landform is the wadi. These entirely subaerial channels are normally dry, but carry spectacularly powerful, short lived, flood flows during storm events. Many smaller wadis, incised from 20 to 100m are oriented straight down the dip slopes. The larger wadis are dendritic, and some, such as Wadi Tanuf, are incised by over 1000m with dramatic and precipitous walls. Numerous cave entrances are visible in the walls of the larger wadis; these invariably fail to live up to expectations, being only rock arches, rock shelters, or passages totally choked with debris still within the daylight zone. Wadi Misfah (see below) is one of the few wadis with a perennial flow; some others had small pools of standing water at the time of survey. Bedrock fissures in the wadi floors appear to act as sinks during periods of flow, but no open cave entrances have yet been found. The blind wadi which drains into the Hoti cave system appears to be unique.

Karst is also developed on limestones other than the Wasia. The Sayq plateau, northeast of Nizwa, is formed on limestones and dolomites lower in the Mesozoic sequence. Here there are extensive tufa beds, as below the village of Al



Limestone slopes above Misfah  
(all photos by Tony Waltham and Terry Middleton)



Ayn, and also some potential cave sites, but investigation is restricted as the whole area is within a military zone. Outside the Jabal Akhdar anticline, there are mountain blocks composed of exotic limestone which has been emplaced by massive thrust displacements. Some of these west of Al Hamara are over 5km across, with impressive scarp cliffs hundreds of metres high; some small cave resurgences have been reported and also they are commonly fretted by massive karren with solution grooves up to a metre in trough width. Microkarren are seen on the pre-Permian Hajar limestone in the central Jabal inlier; however, there are no signs of caves in the wadis which incise spectacular slot gorges across the Hajar outcrop.

#### HISTORY OF CAVE EXPLORATION

Local people have explored the easily accessible entrance of any of the caves in the Jabal in their desperate pursuit of water supplies. Many of the rock shelters show signs of past habitation, perhaps mostly by transient goatherds; a family still lives in a cave in Wadi Misfah. But there has been very little serious cave exploration, for either sport or science. This is partly because tourists cannot enter Oman, so the only non-Omanis able to explore the caves have been the ex-patriates, mainly American and British, most of whom live in the capital area Muscat and Ruwi. In addition, the high temperatures make walkabout searches for cave entrances rather uncomfortable except in the months of December to March.

The entrances at the top and bottom of the Hoti cave have always been open, but it appears that the first serious explorations were by the Englishman, Doug Green. With men from the Omani army, he made the first through trip in 1977. Since then, most visitors have just gone into the Hoti Cave, with few if any making the through trip from the top. In 1981, the Americans, Don and Cheryl Davison, found the Hufrah Misfah entrance right by the path descending Jabal Shams to Misfah village; they explored down the entrance shafts, but did not push far down the miserable passage below.

In July 1985, the present authors carried out the Jabal Akhdar Project. Working with and for the Public Authority for Water Resources, they explored Hoti Pit and the inner part of Ghubrat Tanuf Cave, pursued Hufrah Misfah a little further and made the first surveys of all these caves. They completed an air photo search for entrances, and walked several wadis and ridges, but without turning up any new caves. The splendid Hoti Cave seems to be unique and the Jabal Akhdar does not hold immediate promise of any more large caves. However new entrances could await discovery by an enthusiastic walker, and some small caves, recorded by the Davisons outside the Al Hamra area, await checking.



Hoti Sink entrance



Main passage inside Hoti Sink

The potential for cave exploration in Oman appears to lie in karst blocks other than the Jabal Akhdar. Unchecked reports tell of cave resurgences in exotic Mesozoic limestones and in the Tertiary limestones, west of Al Hamra and around Ibri. South and southeast of Muscat, there are more karst blocks, with reports of isolated caves in various remote sites. These include the Selma plateau, where the Davisons are currently exploring the deepest caves in Oman. In southern Oman, the Jabal al Qara, immediately inland of Salalah is a limestone range containing some shafts and massive sinkholes over 100m deep; some of these have been descended but they have not been systematically explored.

#### THE HOTI CAVE SYSTEM

Lying 8 km ESE of Al Hamra, the Hoti Cave System is a major karst conduit within the dip slope of the Wasia limestone. Its top entrance is at the end of a deep, blind, vertical-sided wadi adjacent to the tiny village of Hoti, and its lower exit is a massive cave mouth almost at the foot of the dip slope. The cave contains 4975m of mapped passages, of which 4300m are on the single trunk route from sink to rising, which are 2600m apart in a straight line. The vertical range of the cave is 262m.

#### Morphology of the cave

The upper entrance of the system, Hoti Sink (990m a.s.l.) lies at the foot of a 60m high vertical cliff, terminating a boulder strewn wadi. The boulder floor continues unchanged beneath the low entrance arch, into a high chamber, and to the lip of 10m deep holes in bedrock. These holes enter the roof of horizontal passages floored with mud, left by periodic flooding; the gallery extends back beneath the entrance to a mud choke, and also downstream, with no sign of its bedrock floor. After a short descent over breakdown and boulders, there is another horizontal stretch at a level of 33m below the entrance; the passage is over 20m wide, only a few metres high, and has a mud floor due to frequent ponding of flood waters which fill it to the roof.

Blockfall up to 10m in diameter, and water-hammered, rounded boulders up to 5m in diameter, characterise the passage as it steepens into the Wadi Styx; this is a massive tunnel over 25m wide and more than 12m high, with huge piles of angular breakdown sloping down into boulders rounded by flood torrents. The passage is again level through First Lake and Icefloe Lake - the latter named after the spectacular wafer-thin rafts of floating calcite which cover most of its surface. A wide passage then follows down the bedding; it contains some massive gour dams up to 8m high, breached by subsequent scouring. In the wider sections of Cairn Hall and Stump Cavern, limited roof stoping has left low arches spanning breakdown piles. Beyond them, another muddy

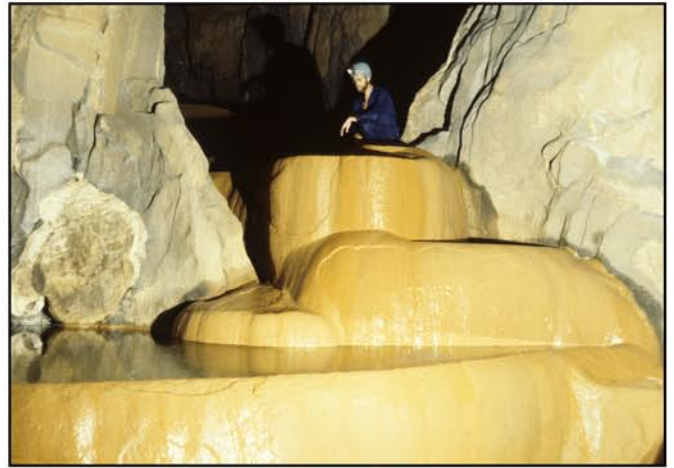


horizontal section is a site of floodwater ponding at the -122m level.

Below that level, the passage develops into a joint-guided rift, over 20m high and mostly just a few metres wide. It descends steeply through the joints, with flowstone shrouded cascades descending into deep lakes. The Warm Inlet has a small permanent stream, but it can be followed up for less than 20m to a constricted sump. Its water is actively depositing calcite, and the next section of passage is splendidly floored with deep clean gour pools separated by barriers of fresh rimstone. The tall rift passage continues in this fine style, though the amount of active flowstone deposition decreases with distance downstream.

The cave again changes character at the Main Lake. This is over 800m long, in a rounded tunnel 10m wide; roof height ranges from 1m to 4m over deep water and a soft sediment floor. The lake ends at a cobble slope over 10m high where floodwaters have banked the rounded cobbles against a zone of blockfall. The lower flood route passes through this blockfall, while a dry high level parallels it to the north until it breaks into Fossil Cavern; this is a segment of ancient conduit totally blocked upstream by massive flowstone deposits.

The downstream tunnel is floored by high boulders, breakdown and massive eroded flowstone, as far as a major boulder pile which rises to the floor at the daylight entrance chamber of Hoti Cave. Beneath the entrance boulder choke, a lower series of rifts and bedding planes reaches standing water at a number of places, and also provides an exit route to the flood rising among the boulders of the wadi floor.



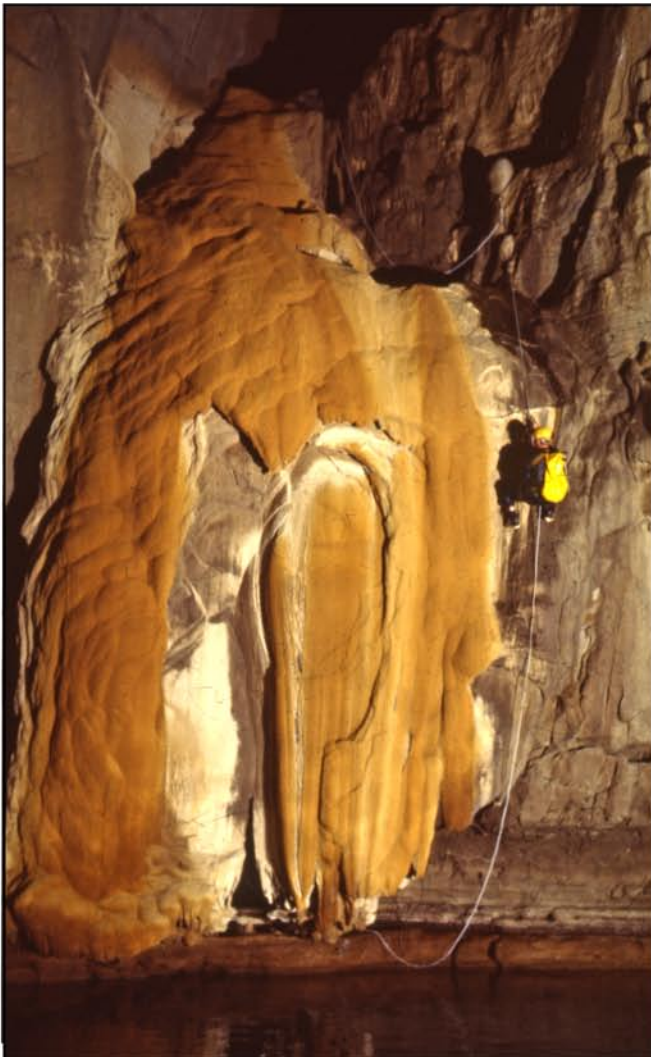
Gours midway through Kahf Hoti

Hoti Pit is an independent cave system with 380m of mapped passages descending 43m. It is entered in the wall of a deep, dry, plunge pool in the wadi floor 400m upstream of Hoti Sink. A 12m shaft drops into a zone of filthy organic mud. The exit passage has a sawtooth profile, down the bedding and up the joints, and is constricted by the sediments dumped by floodwater on the low gradient. Eventually it opens up into Breakdown Cavern, with a roof arched by bedding collapse over a massive blockpile; the far exit is closed by huge banks of laminated clay and silt which reach to the sloping roof. Down through the breakdown, the route of floodwaters is recognised by the rounding of the boulders, and a short spacious passage descends gently to standing water in a fetid sump pool.

#### Cave geomorphology

The Hoti cave is a system of considerable age, essentially fossil though still periodically invaded by floodwaters in a regime very different from that in which the cave developed. The wadi feeding Hoti Sink is incised over 50m into the limestone surface, yet the ancient dry valley continuing beyond the sink is a barely recognisable trough.

Throughout the cave, roof pockets provide abundant evidence of major early phreatic development. It would appear that the cave was a substantial conduit within the phreas, before any vadose drainage consequent on surface lowering at the foot of the adjacent dipslope. This accounts for both the level stretches within the main conduit, and also the phreatic roof morphology of even the highest rift passages. There are no major canyons, and only minimal signs of vadose erosion; any such features are buried beneath the massive cave fill.

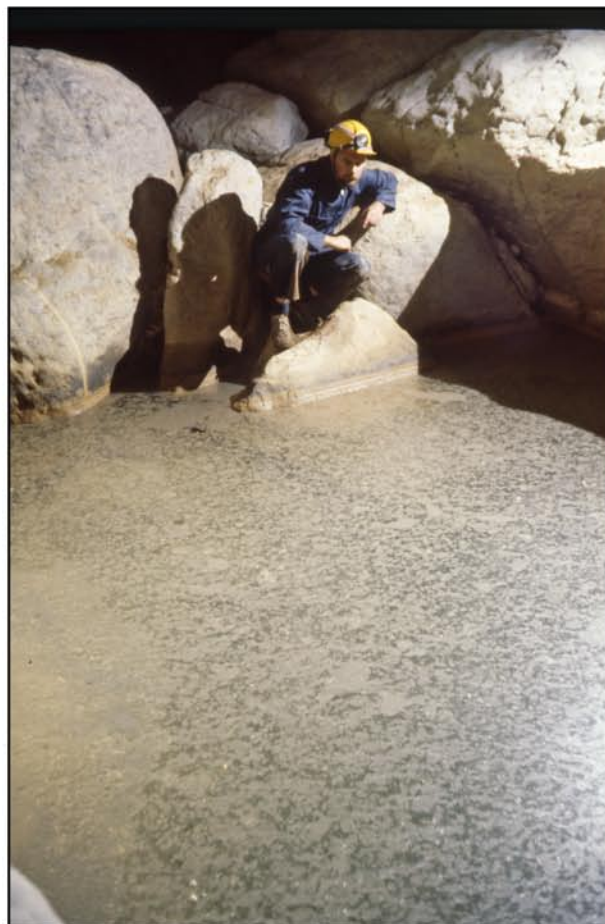
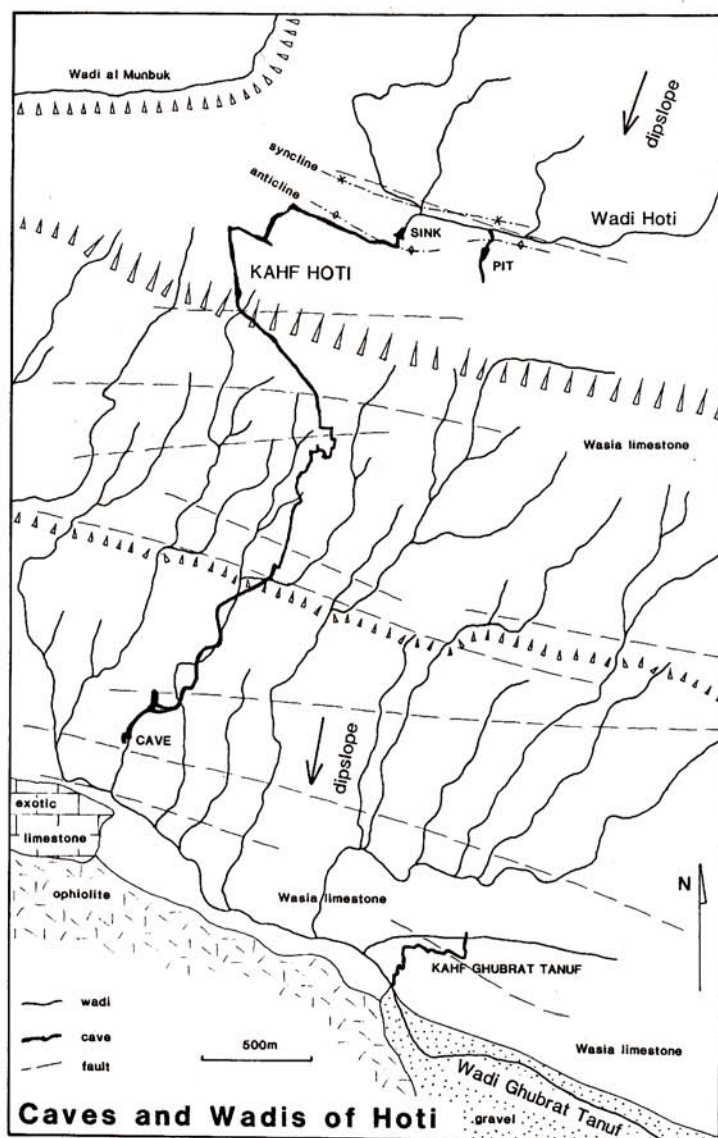


The 13m flowstone cascade in Kahf Hoti



Fossil Cavern in Kahf Hoti





Floating rafts of calcite on Icefloe Lake, Kahf Hoti

An important phase of the cave's history involved massive amounts of deposition. Huge banks of flowstone probably filled the cave to the roof in places; gour dams (rimstone) built up many metres high; thick gravels were cemented by calcite, and false floors now survive at many levels. The age of this phase (or phases) of deposition is as yet undetermined, but it almost certainly relates to climatic variations within the Pleistocene.

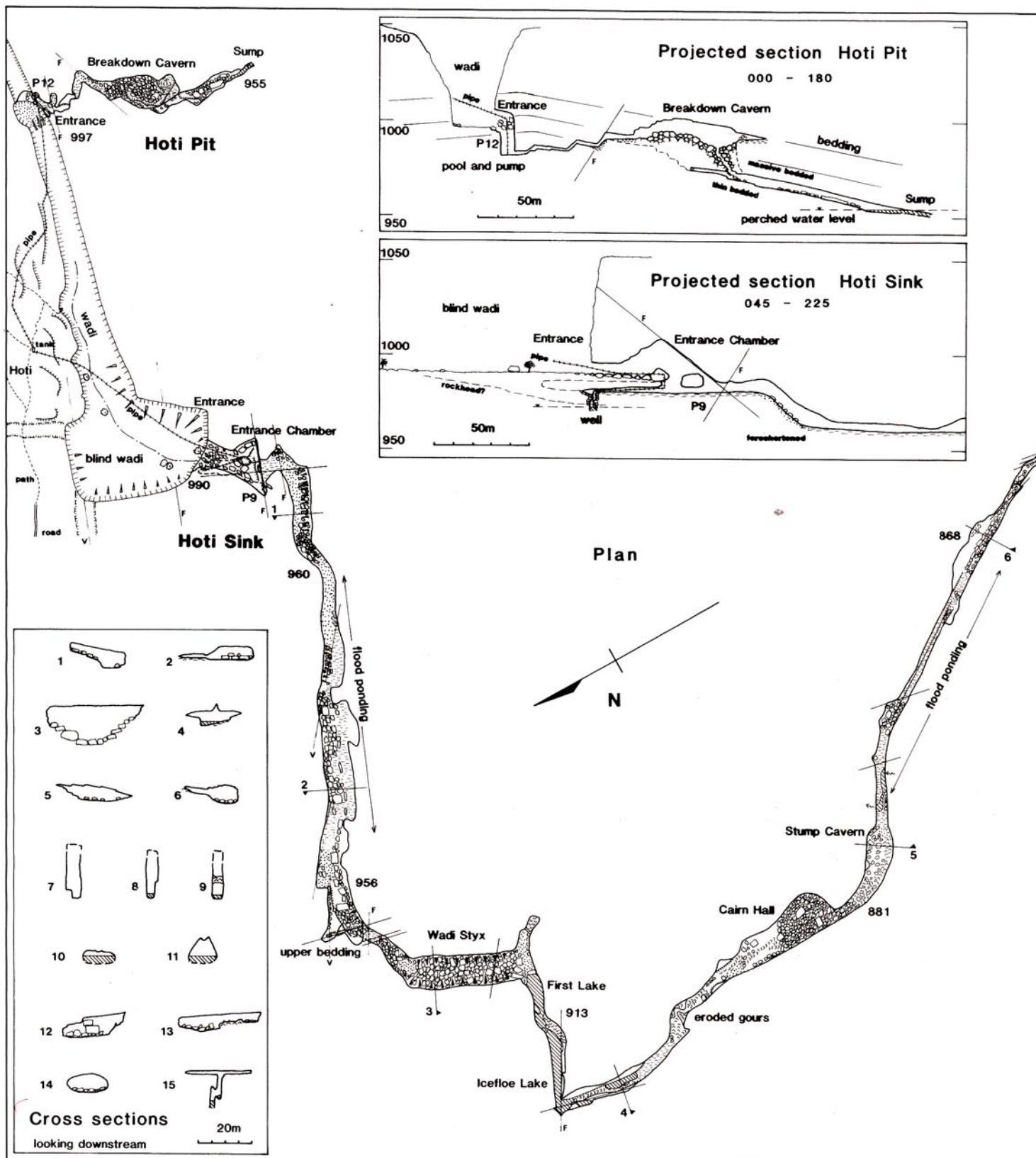
Subsequently major re-excavation has been carried out by sporadic flood flows, and this continues within the present climatic regime. In the steeper sections of the cave, boulders of 20 tonnes and more are transported and rounded; gour dams are completely breached, and moulins over a metre across are cut into flowstone. Waning floodwater leaves extensive mud deposits in the level stretches of passage. Modern solutional activity is limited; flowstone is being deposited by the percolation water from Warm Inlet, all the way down to the Main Lake; abundant calcite rafts are formed on the surface of most pools and lakes whose water is both saturated and evaporating; echinoliths occur at a few sites clear of the main areas of abrasive scour.

The 800m of passage containing the Main Lake cuts across the bedding and reveals only limited control by the major joints. It is difficult to explain its origin as anything other than a shallow phreatic conduit closely controlled by an ancient water table; it lies 40m above the main

floor of the adjacent modern wadi. At its top end, the tall, upstream, rift passages terminate abruptly. Downstream of the lake the morphology is complicated by the intersection with the older passage of Fossil Cavern; this is the upper end of a fine phreatic tunnel which probably has a phreatic lift concealed under the boulder piles leading up into the entrance chambers. Upstream of Fossil Cavern, beyond the choke, probably lies the ancient phreatic trunk route which relates to the upper part of the cave and predates the section of passage containing Main Lake; though where this departs from the upper cave is unknown.

The nature of modern phreatic cave development in the Wasia Limestone is indicated by the lowest passages in the Hoti cave. Inclined bedding plane caves are open to heights approaching a metre over wide areas, and are connected by a number of parallel, vertical fissures along the dip joints. Some of these are mapped in the epiphreatic flood zone, and they appear to continue below the base water level.

Hoti Pit is clearly of phreatic origin, with its distinctive sawtooth profiles, though there is limited vadose modification of both the entrance shaft and the lower stream passage. The massive flowstone and thick laminated clastic fill in Breakdown Cavern, together with the subsequent dissection and partial re-excavation, represent further stages in the climatically controlled evolution of the karst.

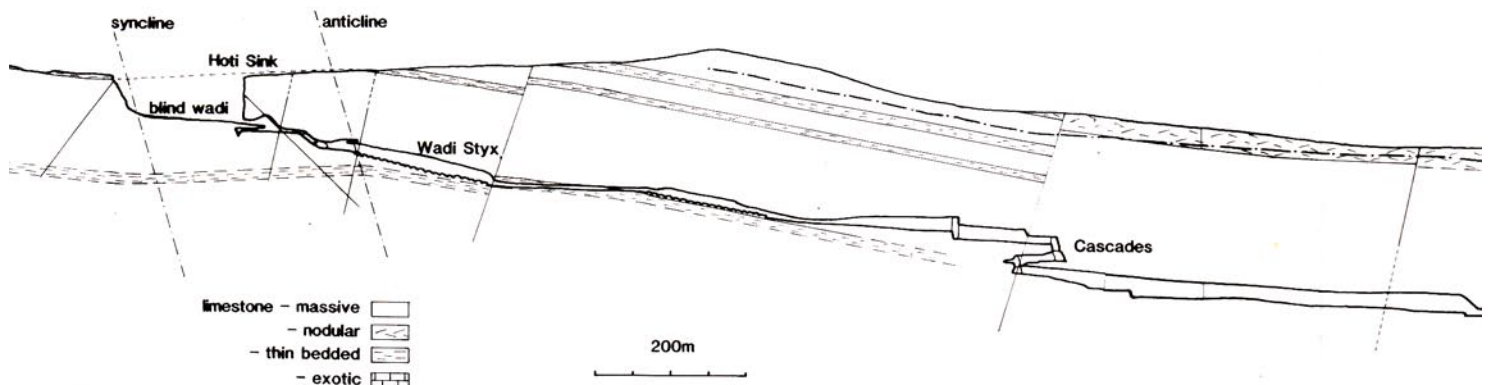
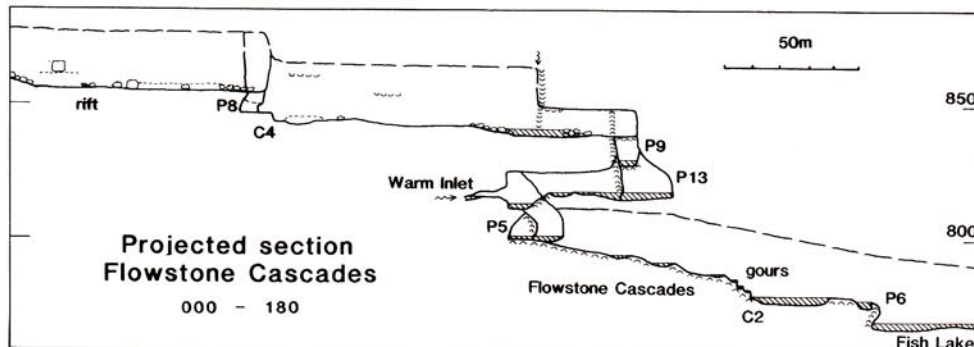
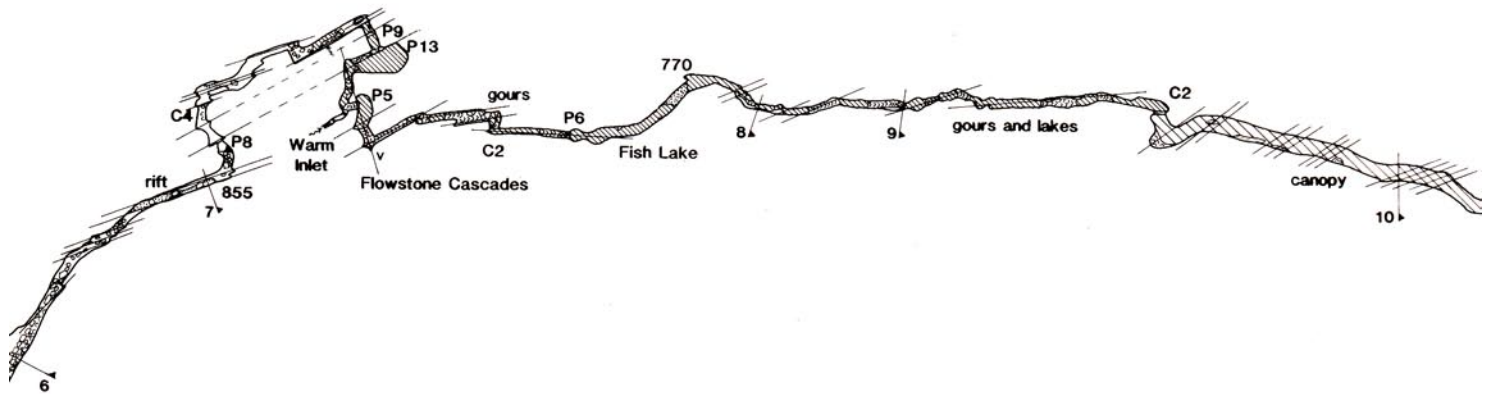




# KAHF HOTI

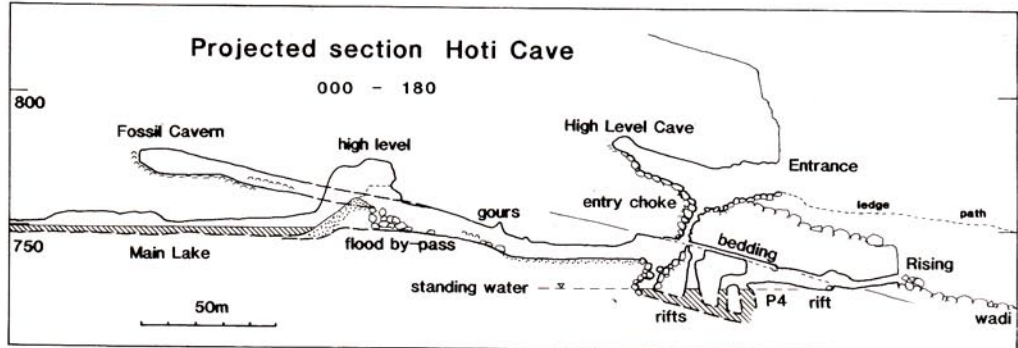
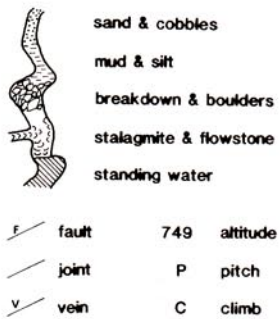
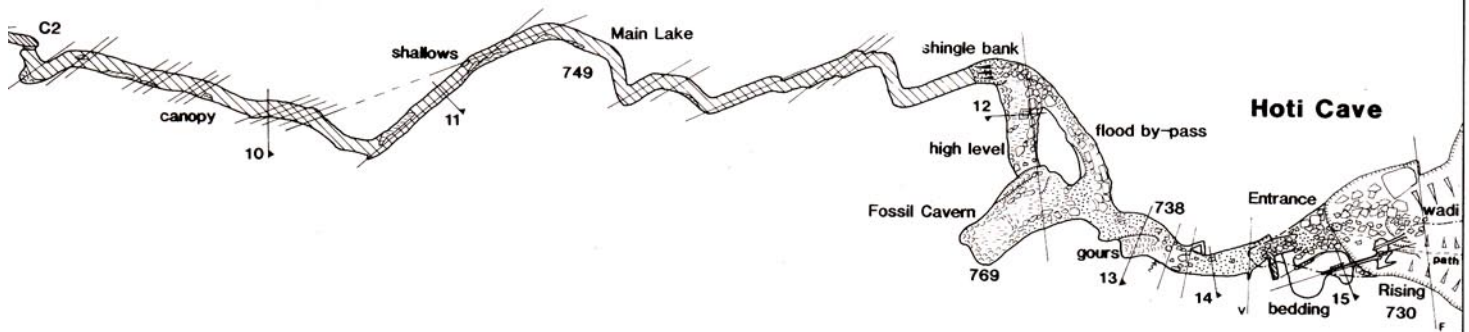
# THE HOTI CAVE SYSTEM

Jabal Akhdar Sultanate of Oman



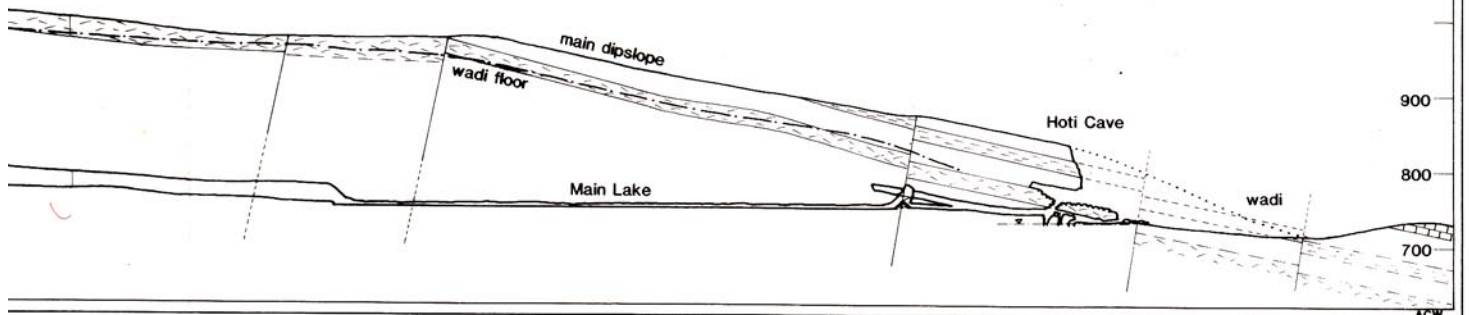
Survey 1985 © A C Waltham, R D Brown, T C Middleton

Hoti Sink is at EL377549, 8km east of Al Hamra



### Main Elevation - projected

028 - 208







Main passage inside Hoti Cave

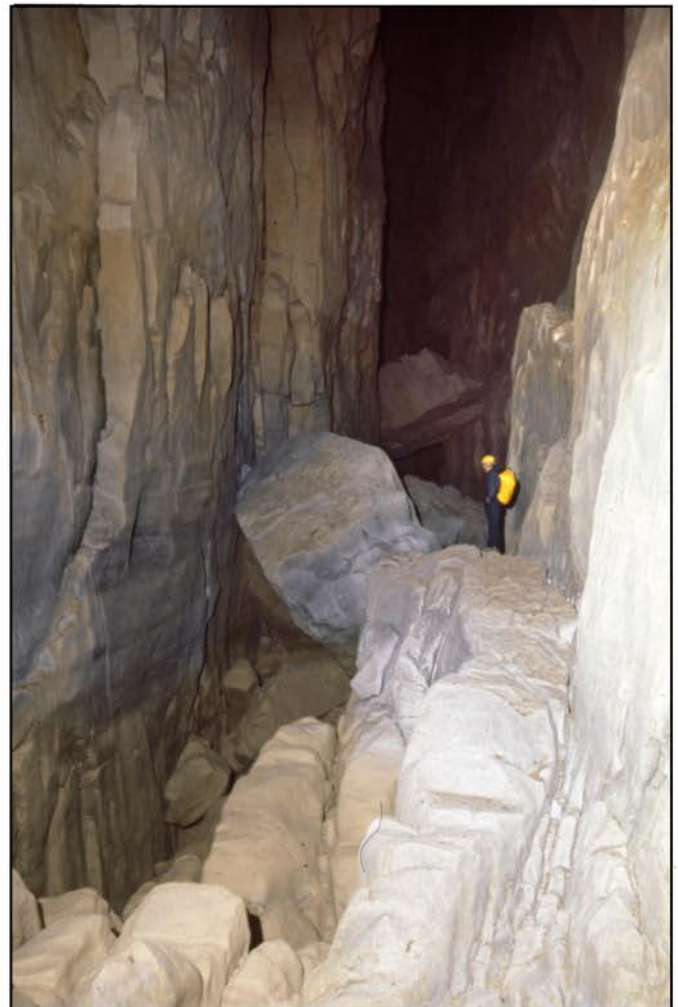
### Geology of the cave

The entire cave system is formed in the Natih member of the Wasia Group of limestones, and through most of the cave these are dipping between  $5^\circ$  and  $15^\circ$  to the south. Overall there is a crude stratigraphic control on the cave, as the main passage is essentially a downdip conduit. But in detail, the bedding has rather less control; only some sections of passages are primarily on bedding planes - these include much of the upper cave down to the -130m level, Fossil Cavern and the lower entrance passages, and also most of Hoti Pit. Favoured horizons of passage development appear to be massive beds immediately above rather thinner bedded zones; however, this impression may be partly created by any upward passage migration, by stoping and collapse, through the thinner beds until terminated by a stronger roof unit. The cave system is probably confined to a stratigraphic thickness less than 200m, but some fault displacements are unknown. The main passage descends stratigraphically by way of the dip joints, and rises through the succession via either water table levels or joint controlled phreatic lifts.

A critical feature of geological control is the gentle syncline which extends through the Hoti Sink entrance; it is a parasitic fold with an east-west axis breaking the dipping limbs of the Jabal Akhdar anticline. The fold is only about 250m across, with maximum dips on both limbs of around  $10^\circ$ . It appears to be the major feature controlling the location and development of the cave system. The depression created by it on the stratimorphic surface of the mountain dipslope would clearly be a favoured site for sinkhole drainage, with no available exit route for a developing wadi. Either alternatively or additionally, any enhanced fracture opening across the flexure would have encouraged underground



Breakdown passage inside Hoti Cave



Rift passage above the cascades in Kahf Hoti

drainage. It is perhaps significant that no other comparable synclines, or cave systems, have been recognised on the Wasia outcrops; elsewhere the downdip surface wadis are uninterrupted.

Superimposed on the overall dip trend of the cave, there is considerable control of plan detail by both joints and faults. The major control on the cave passages is by the dip joints. Conspicuous joint sets are close to the north-south orientation. The cave map shows how the passages sometimes follows these joints, step obliquely across them or else they completely ignore them, and, as normal in limestone caves, there is little predictable about the pattern. The descending zone midway along the main passage also utilises these north-south joints, but the long fissure between there and the Main Lake is conspicuous in its absence of recognisable fracture control. The main strike fractures are reverse faults with thick veins of crystalline calcite; they have little effect on the cave development except where they have displaced the cave's overall dip trend for short distances near each end of the main passage.

### Hydrology of the cave

The wadi which drains into the Hoti Sink has a catchment area of 28km<sup>2</sup>. In normal conditions there is no surface flow; even localised storms of high intensity produce no wadi flow. Clearly though, a major storm event would produce a spectacular flash flood through the cave; this probably occurs on average only once or twice a year. Based on passage size and sediment size transported, the flood flows in the cave may be estimated to exceed 100 m<sup>3</sup>/sec.

Percolation flow into the cave is minimal. Warm Inlet, and a few other smaller sources, have





Main Lake in Kahf Hoti

a total base flow of about 2 l/sec. These flows do respond to rain; on a day following a short evening storm, they were observed to have increased by 300%. This response may be rapid, but the water's saturation with calcite suggests a longer fissure residence time. There are no known surface sinks above the cave, and the surface wadis are unbroken; the input is all through narrow fissures.

The cave provides storage, of both percolation water and remnant floodwater, in various lakes, which are perched above regional water tables. The largest is the Main Lake with at least 15,000m<sup>3</sup> of water standing 22m above water levels in nearby fissures. Water flows continuously through the cave from the Warm Inlet to the Main Lake, out of which it drains through sediment and then down into bedrock fissures. Clastic sediments in the cave act like those in

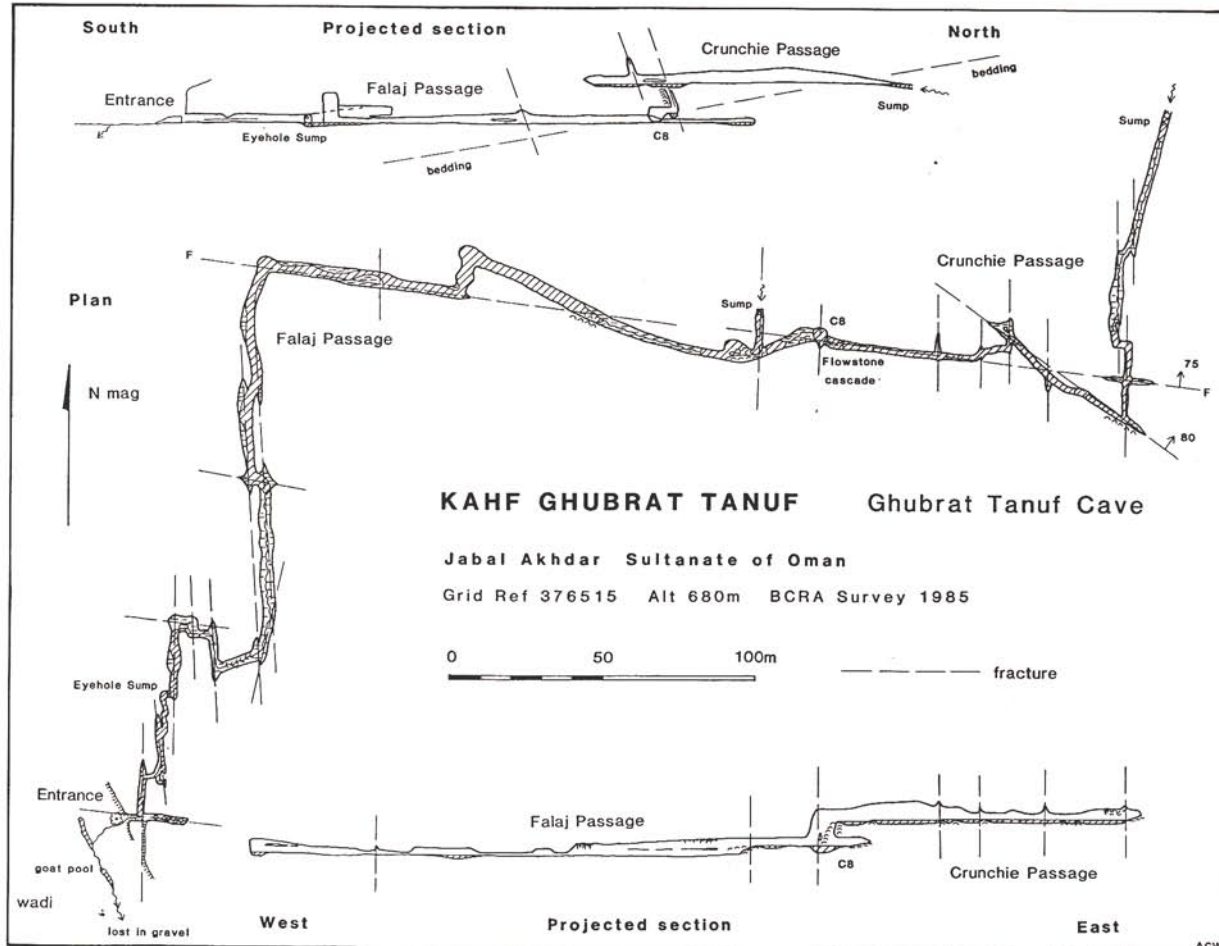
wadis; intersecting flows pass through them, and they provide transient storage. This storage has been exploited by the villagers of Hoti who have dug a well in the blind upstream passage of Hoti Sink; water is pumped from between the boulders and from fissures in the bedrock cave floor, though the yield appears to be small and variable.

Ultimately most cave water drains down to a fissured phreatic such as is seen below the lower entrance. There are two exceptions to this general case. Floodwater is lost by discharge from the normally dry resurgence into the surface wadi. Also, water is lost from the cave lakes by evaporation in the conspicuously powerful cave wind; this blows down through the cave every afternoon in response to solar warming of the external air. The extent of the evaporation may be appreciated from the consequent cooling of the cave lake waters; the temperature of the Main Lake is 21°C, while the Warm Inlet, fed from closed fissures with no air circulation, is at 32°C.

#### KAHF GHUBRAT TANUF

The Ghubrat Tanuf Cave is located on the north side of the long wadi of the same name, adjacent to the roadhead. It is a resurgence with a base flow of around one litre per second; the water flows into shallow pools used by goats and then sinks into the wadi gravel.

The cave passage can be followed for 690m, to an upstream sump 14m above the entrance level. Almost all the passage is joint controlled rift, mostly 1-3m wide and up to 8m high. The floor is completely covered by clastic and calcite sediments. There are some fossil roof levels in sections, while elsewhere the roof descends to low arches with little clearance over pools. Falaj Passage has been entered by local people at some unknown time in the past; they have dug trenches in sediment banks to connect the pools, and in the lower section have built a tiny falaj channel on



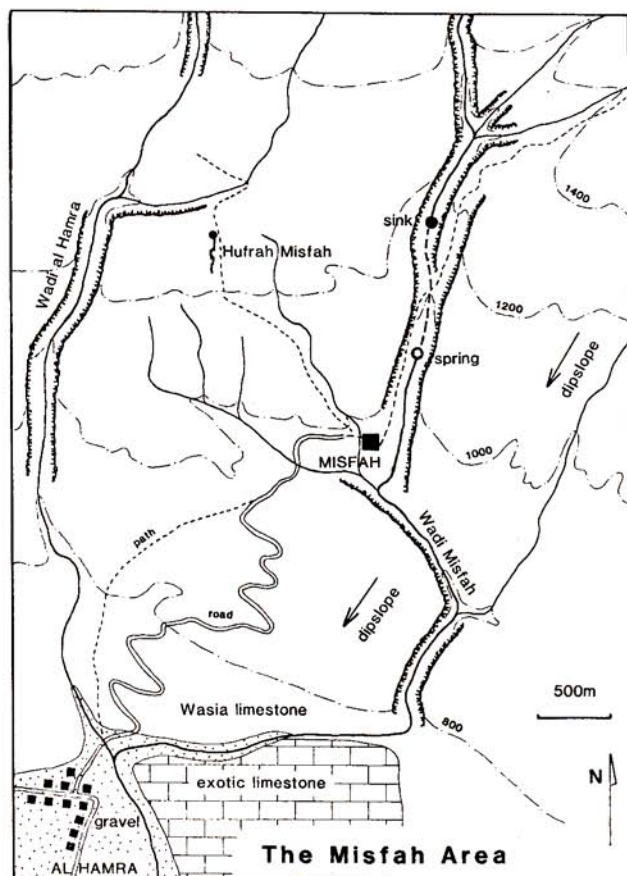


ledges and along the wall. Such effort was presumably expended in some past drought period, but the falaj is now not in use. Above an 8m climbable cascade the passage had received no early visitors; it has a sequence of gour dams (rimstone), with each pool floored by crystalline calcite which crunches underfoot.

All the known passage originated as phreatic rifts. Initially the connected route through these had a far more irregular switchable profile; later development has seen the crests of phreatic loops abandoned, while the troughs have filled with sediment and have had their roofs raised by solution. The subsequent profile is almost graded along each of the two levels. There is no geological cause for the step in the long profile of the cave. The two levels could have originated close to successive water tables; correlation with wadi terraces could substantiate this, but there is no lateral continuation of the upper level, and such an origin would beg the question of when the cave developed. The age of the cave remains unknown.

Joint control on the pattern of development is obvious from the map of the cave. It is indeed a spectacular example of a joint controlled cave, with almost every segment of passage formed along a joint, in some cases regardless of the overall drainage direction. In contrast, the bedding is ignored by the cave passage.

The relatively constant flow through the cave suggests percolation through a fissure zone in the source area upstream of the known cave. The high water temperature, of 32°C, and its saturation with respect to calcite, further indicate a long residence time in a shallow fissure zone within reach of solar heating. The flow may be partly fed by leakage in the bed of the wadi just to the north. Though there is no normal surface flow in this wadi, its sediments contain groundwater, and the cave offers a simple cutoff route inside the substantial westerly deflection of the wadi course.



Misfah village

#### WADI MISFAH

Just north of Al Hamra, Misfah is one of the larger and more accessible Jabal villages. Its survival depends on a major spring in the floor of Wadi Misfah, 700m upstream of the village. The springwater is fed into a falaj with a capacity around 20 l/sec, and this contours the lower wadi to irrigate all the palm terraces and supply the village. The spring emerges between boulders in the wadi floor, with a baseflow of about 10 l/sec of good, clear water. Though there is no adjacent bedrock, the point source suggests that this is a karstic resurgence fed by limestone fissures beneath the wadi fill.

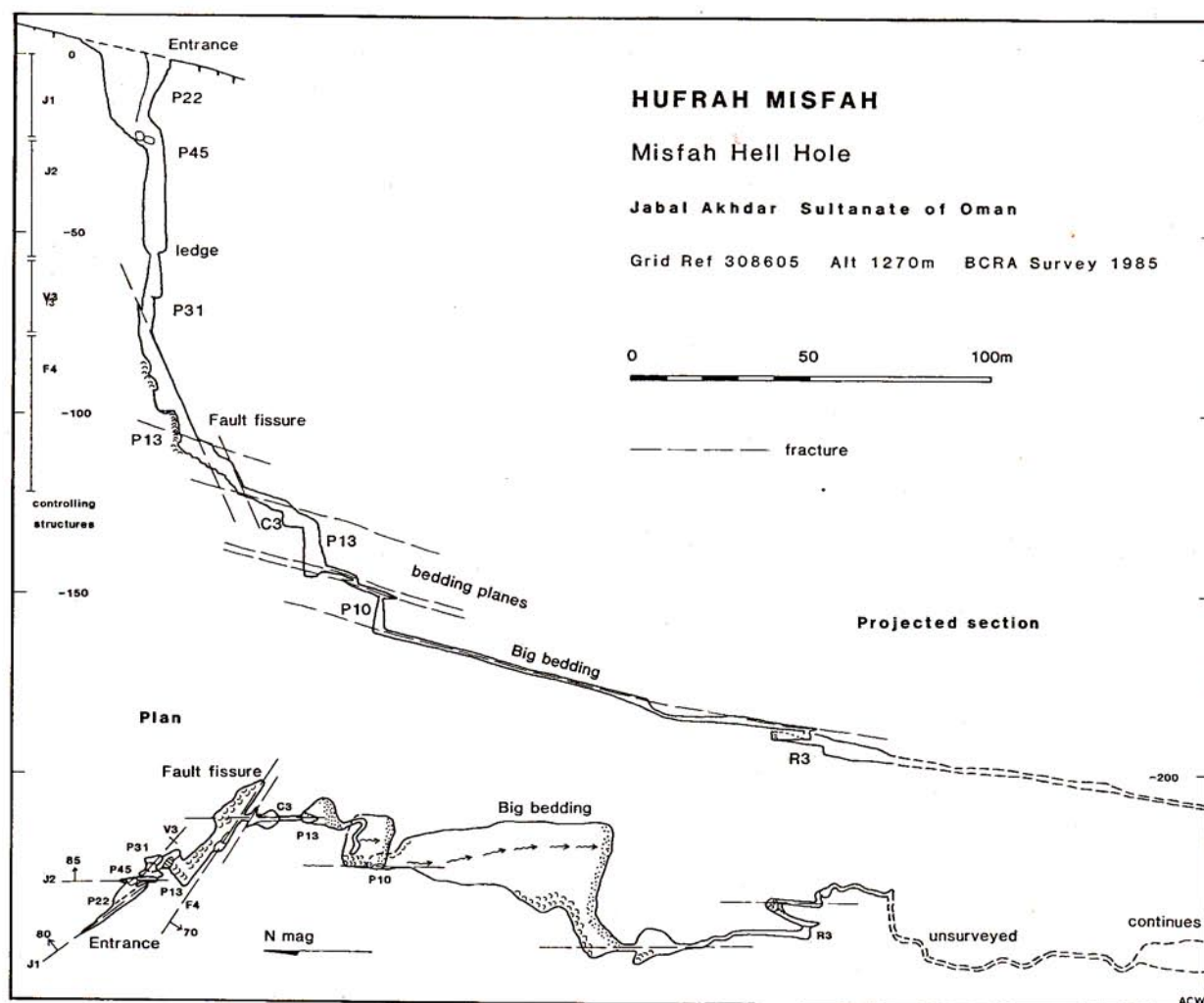
Above the spring the wadi is normally dry, and further up it is incised in the Wasia limestone, in a deep and narrow gorge section. In the higher reaches there is a permanent surface stream, and this sinks underground about 700m up-wadi from the spring. The terminal sink is in a sediment choked pool in the bedrock limestone, and there is clearly also leakage into bedrock fissures in the section of wadi immediately upstream. There is no access to the underground channel. This is almost certainly the same water which emerges at the spring, and the sinking flow is around 75% of the resurgence flow; the additional spring water must originate from leakage further up the wadi and from hillslope infiltration. The cave route for the main water therefore appears to be about 700m in direct length, with a fall of around 80m. In this distance it climbs stratigraphically and passes through a thin bedded unit above the massive bed containing the main sink; the cave is therefore likely to have a saw-tooth profile with sumps and sediment chokes in each downturn. The passage is probably restricted and immature, and floodwaters occupy the surface wadi between sink and rising.

#### HUFRAH MISFAH

On the dip slopes of the Wasia limestone, either side of Wadi Misfah, the more massive beds contain numerous solutionally opened fissures. Most are choked with debris less than 10m down, but they clearly swallow available surface water. The one fissure which has been explored to greater depths is Hufrah Misfah, also known as the Misfah Hell Hole due to its uncomfortable temperatures. It is a generally small passage system, mapped to a depth of 197m.

The cave starts with a nearly vertical descent of 120m into a large fault fissure. From there its one route continues down a series of rifts and inclined bedding planes. Though some of the bedding passage is very wide, most of it is only about a metre high. It has been mapped to a point 435m from the entrance, and continues in constricted and rather miserable style beyond the patience of both explorers and surveyors. Geomorphologically, it is a simple vadose drain taking the easiest, almost direct, route down through the limestone.





The whole cave exhibits close response to geological structure. The entrance shaft system is down an opened zone of intersecting fractures. In succession, the route follows down two inclined joints, a vertical vein and an inclined fault (all of which are labelled on the cave map), but always stays close to the mutual intersections. From the fault fissure, the drainage has opened a route down a series of bedding planes, following close to the direction of true dip, which ranges 12-18°. The cave steps down the bedding planes by utilising the major dip joints.

There are pools of standing water in the cave, but there is no permanent flow. Rock bruising, due to cobble hammering, indicates the power of flood flows which must occasionally invade the cave; it is a natural storm drain. The catchment area of the cave drainage must be small, probably around 25 ha, but it is unknown in detail; it is determined by the disposition of fissures, especially around the entrance shaft. There is a notable lack of inlets in the cave, and there is no sign of dendritic drainage convergence. The resurgence for the cave is unknown. Though it could drain to the Wadi Misfah spring, there is no apparent reason why it should not maintain its down-dip course and ultimately drain through a limestone phreatic into the wadi gravels around Al Hamra.

#### KARST DEVELOPMENT ON THE JABAL AKHDAR

Karst in the Jabal Akhdar is in general poorly developed - largely due to the limitations of climate. The main beds of the Wasia are potentially cavernous limestone, which would support a mature karst in any other environment. Other carbonates on the Jabal, notably the more massive units in the Kahmah and some of the Sayq

dolomite, could support karst and contain caves, but on a lesser scale than in the Wasia.

The modern climate is not conducive to solutional activity and karst development. Karst landforms are generally subordinate to surface wadis and stratimorphic slopes. Rainfall is erratic. Major storm events create massive, short-lived, flood flows in the numerous surface wadis; these permit rapid runoff. Only limited infiltration occurs, in both major and minor storm events, and there is then efficient groundwater flow through the fissured limestone.

A critical feature in the Jabal is the fossil karst, dating from ancient wetter climates, probably during the Pleistocene. It includes many cave conduits, which have subsequently been partly or completely filled with clastic and calcite deposits. Where still open, these fossil caves are important modern groundwater routes. They are however few and far between. In the modern environment, most caves are being further filled and not enlarged; modern percolation water is depositing calcite in them, and erosive flood flows stay on the surface as they cannot normally find access to the deeper underground zones.

Overall, wadi drainage on the steep surface slopes is much more important than cave drainage. Caves have few opportunities to develop, and the synclinal location of Hoti Sink appears to be uniquely favourable. Wadi leakage has developed on a visible scale both at Hoti Pit and in Wadi Misfah. No other comparable sites are known, and though they may exist, they are not common; the observed wadis, even in the massive limestone, are notably lacking in sinkhole sites. Less conspicuous fissure sinks may be more widespread, as for example in the potential source area for the Ghubrat Tanuf Cave. Fissure inputs away from the wadis are important sources of percolation





The 45m pitch in Hufrah Misfah

water in the limestone. They are, however, rarely large enough to develop into open caves; Hufrah Misfah demonstrates the form these may take, but its size appears to be anomolous.

#### CAVE FAUNA

The Jabal Akhdar caves are like any others in a warm climate, in that they contain an extensive fauna which even non-biologists cannot fail to appreciate. Large huntsman spiders and tailless whip-scorpions were seen at a number of sites. Small bat populations occupy all the caves, and the Ghubrat Tanuf Cave contained at least two species of snake. This cave also had wasps' nests inconveniently sited in its narrow entrance, and many rock shelters contain large numbers of hornets' nests, which could be a major hazard at certain times of the year.

The most distinctive fauna are the fish in the Hoti cave. These are eyeless, pale pink in colour, and mostly 3-5 cm in length; they have been identified as *Garra barreimiae* (Banister and Clark, 1977). Large numbers of them were seen in all the lakes in the lower half of the Hoti cave, but the most remarkable concentrations occur in Fish Lake, just below the bottom pitch. At one point in this lake, hundreds of fish were crowded into a wall notch; there was no apparent reason for this behaviour, though it is possible that a bedrock fissure is yielding a small inflow which is somehow attractive to the fish. Even to the passing geologists, it was a remarkable sight.

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Notli Sink is at EL377549, 8km east of Al Hamra

