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GEOMORPHOLOGY OF DENNY'S HOLE AND ASSOCIATED CAVES, CROOK PEAK, WEST MENDIP: A NEWLY RECOGNISED HYPOGENE CAVE COMPLEX

by

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ABSTRACT

Denny's Hole is a short multi-chambered cave, the largest of several on the lower slopes of Crook Peak. It is developed in the Clifton Down Limestone, which is here splintery, partially dolomitised and cut by a number of calcite/haematite and iron ochre mineral veins with some silicification. The base level for cave development is determined by the position of the marl facies in the Triassic Mercia Mudstone as indicated by the current outlet at Dunnet's Springs at the south-east end of the ridge. The cave is predominantly controlled by the bedding, with anastomosing tube networks floored by platy breccia ('terrace breccias') extending out from the First Chamber. The chambers are dome shaped, have blank up-dip terminations, walls with facets, phreatic pocketing, rock steps and unusual secondary carbonate accumulations, and appear to be incised into the bedding tube network. The links between the chambers are breached partitions with very small tubular passages and bridges. With the exception of material entering from the present entrance, there are no allogenic sediments in any of the caves, and there is an absence of typical vadose stream forms. The chambers are floored by a breccia also found in Unit 6 Picken's Hole and Sandy Hole, which is characterised by a significant degree of calcite cementation and by the presence of iron-oxyhydroxides, terminated by banded flowstone (some of which is aragonite) and popcorn. The main phase of calcite cementation comprises pond deposits and includes unusual festoon panels of rhombohedral calcite growing from a central iron-oxyhydroxide layer, which is very similar to present deposits in Thornton's Cave, an estavelle in west-central Florida (Florea, *et al,* 2011). The breccia has been formed by breakdown of secondary carbonates deposited on the wall and roof, and indicates a fluctuating environment with both vadose and sub-aqueous deposition, but the earlier parts of the sequence are not present in the cements of the terrace breccias.

The features of the cave indicate a hypogene origin most probably by thermal waters rising from depth beneath the Triassic cover and mixing with more oxygenated local meteoric water. Cooling caused undersaturation and dissolution in an initial bedding tube network, with contemporaneous deposition of subaqueous calcite in the near surface zone of active degassing in Unit 6 of Picken's Hole. The cave chambers were then incised into the bedding network as a result of near- surface condensation corrosion above a thermal pool in a closed cave environment with elevated PCO_2 as base level fell. Reflooding and pond calcite deposition occurred when base level rose during interglacial conditions. Correlation with uranium series dated base level changes for the Cheddar Caves suggests that the higher parts of the system (Foxes Hole and Picken's Hole) were active during Marine Isotope Stage (MIS) 9, with re-flooding during MIS 7, and abandonment prior to MIS 5 the last interglacial.

INTRODUCTION

Denny's Hole is a short (c. 114 m long and 35 m deep) cave comprising the First Chamber accessed from the surface at 51.9 m AOD and several smaller chambers and short passages. Immediately to the northwest is Foxes Hole a low dug chamber accessed by a constricted vertical shaft (surface 54.5 m, base 51.2 m AOD), and Picken's Hole a short cave at c 50.0 m AOD which has partially collapsed accumulating surficial sediments. This was exposed following archaeological investigations which are reported by ApSimon *et al* (2018) and ApSimon and Smart (2018). It is likely from their proximity and alignment that these 3 caves are part of the same system. To the south west of Denny's Hole is a small alcove (Supra-Scragg's Hole, 59.5 m AOD) and Scragg's Hole (40.08 m AOD). The latter is again short and was opened in a series of archaeological excavations by Sidcot School and others as described by Russ and Summerfield (2018). To the south east down the ridge, Sandy Hole (main level 35.2 m AOD) is a short segment of passage intersected by quarrying, and above it just east of the ridge top is Supra-Sandy Hole (38.8 m AOD), an alcove well used by sheep and goats. There is also an unnamed alcove on the quarried slope northwest of Denny's Hole (44.2 m AOD). All the caves are located on the lower slopes of Crook Peak, and lie within a limited elevation range of c 51 – 34 m AOD. In addition to descriptions in Barrington and Stanton (1977), the caves have also been described and surveyed by Legg (1992).

At the base of the Crook Peak ridge at an altitude of about 20 m AOD there is a series of springs which are known collectively as Dunnet's or Dunyeat Springs (ST 4009 5471). Barrington and Stanton report that these were previously used by Bristol Water for supply and had a mean daily flow of about 0.2 million gallons per day. They report that the water was very hard. Further to the east midway between Cross and Bisphops Sutton and at a similar elevation to Denny's Hole, lies the entrance to Coral Cave. Knight (1915: 359-360) reports that: 'This was discovered about 1904 by a man, who while quarrying stone, broke through the rock into the side of a sort of natural shaft leading down into a spacious chamber some 60-70 feet high, with galleries extending out from it.' Tucker (1962) reports that: 'The entrance shaft is fifty feet deep and because of its smooth appearance with solutional evidence it seems to be phreatic in origin, as does the rest of the cave. … The domed chamber rises to a height of about forty feet. …… From here the gallery extends for 100 feet rising about twenty five feet over its length and is approximately ten feet wide and six feet high. At the end of this gallery there are some fine examples of three-dimensional phreatic solution.' We have not however visited this cave as part of this study.

In this report we present a new survey of the Crook Peak caves and suggest from their pattern, morphology and deposits that they are hypogene in origin. Since the pioneering work of Klimchouk in gypsum caves of the Ukraine, there has been an increasing recognition of the hypogene origin of many cave systems (see recent global review in Klimchouk *et al* 2017). There is, however, some discussion on the meaning of the term hypogene. Klimchouk (2007) based on his studies of gypsum caves adopts an essentially hydrological definition:

> *"The formation of caves by water that recharges the soluble formation from below, driven by hydrostatic pressure or other sources of energy independent of recharge from the overlying or immediately adjacent surface."*

Whereas Palmer (2000) from his work in carbonate caves of the western United States emphasises the source of the geochemical drive for bedrock dissolution as being the critical defining factor:

> *"Hypogenetic caves are formed by water in which the aggressiveness has been produced at depth beneath the surface, independent of surface or soil CO2 or other near surface acid sources."*

Klimchouk (2007) writes:

> *"Although we prefer to associate our conceptual use of the term hypogenic with the source of the water being per ascensum (Ford, 1995) rather than with the source of solutional aggressivity being deep-seated (Palmer, 1991; 2011), we do not find the two interpretations of the term mutually exclusive......"*

Whilst Veni (2016) also combines both approaches:

> *"The origin of caves through the predominantly upward flow of chemically aggressive groundwater, relative to a soluble rock, that leaks to the surface through a confining unit, with its groundwater originating beyond the limits of the confining unit."*

Unfortunately this further confounds the problem by introduction of the presence of a confining unit. Many conventional epigenetic caves are formed on the rising limbs of deep circulation systems, the deep terminal conduit in Wookey Hole for example, but dissolution in this situation is driven by undersaturation of the swallet derived waters which at times of flood penetrate the system. The emphasis in this report is therefore on the Palmer (2000) definition of hypogene which emphasises a deep-seated source of aggressivity, rather than that derived from epigenic surface carbonic acid and associated organic inputs.

METHODS

The Crooks Peak caves including Sandy, Scragg's, Denny's, Picken's and Foxes Holes were surveyed in 1983 to BCRA Grade 4 (note this pre-dates use of laser distometers for wall position, but some were measured and others have subsequently been checked (Figures 1, 2, 3 and 4). An inter-entrance survey was also conducted using a level with directions taken from the bezel ring. There were 2 short loop closures in Denny's Hole with errors of 0 and 1.4%. For the 417 m surface survey the Survex closure error was 0.42%. The elevation and position of the caves were fixed on the National Grid by a prior survey by ApSimon and co-workers.

In the caves, observations were made of the geological structures present, the morphology of the walls and ceilings and the nature and distribution of the floor deposits and other sediments. Samples for petrological investigation were initially collected from Denny's Hole, but subsequently additional samples have been collected from the other caves. Cut slabs were used in some cases in combination with carbonate staining to identify mineral phases and paragenetic sequences (note the term is used here in a mineralogical sense as the sequence of events recorded in samples, rather than in the cavern genesis use of the term). Some thin sections were also prepared and examined under plane and crossed polar light. Sediment samples were also collected from some of the sites, as reported in Smart and Springall (in prep.).

TOPOGRAPHY AND GEOLOGY

The study area is on the southern flank of the Blackdown Pericline (Figure 5). Unlike in the classic area to the east and adjacent to Blackdown itself, the Old Red Sandstone (now Portishead Formation) does not form an upstanding core to the pericline. Rather, in this area, it was subject to erosion during the Triassic, and now forms a low lying area where the sandstone is overlain by the Triassic Dolomitic Conglomerate the marginal facies of the Mercia Mudstone Green and Welch, 1977 and see their Plate 11). This area is known as the Vale of Winscombe

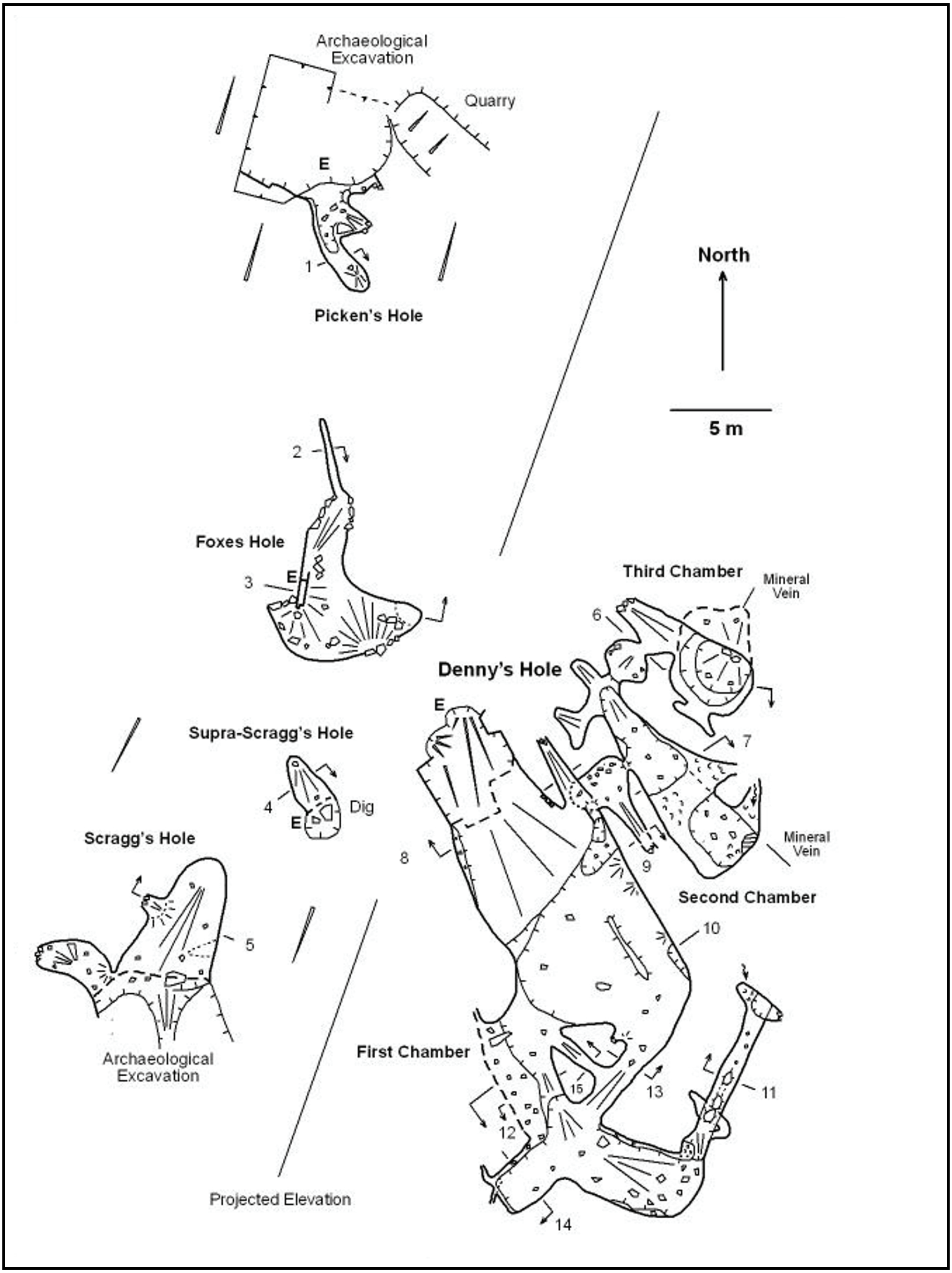

Figure 1. *Plan of the main Crook Peak caves with numbered cross-sections and line of projected elevation.*

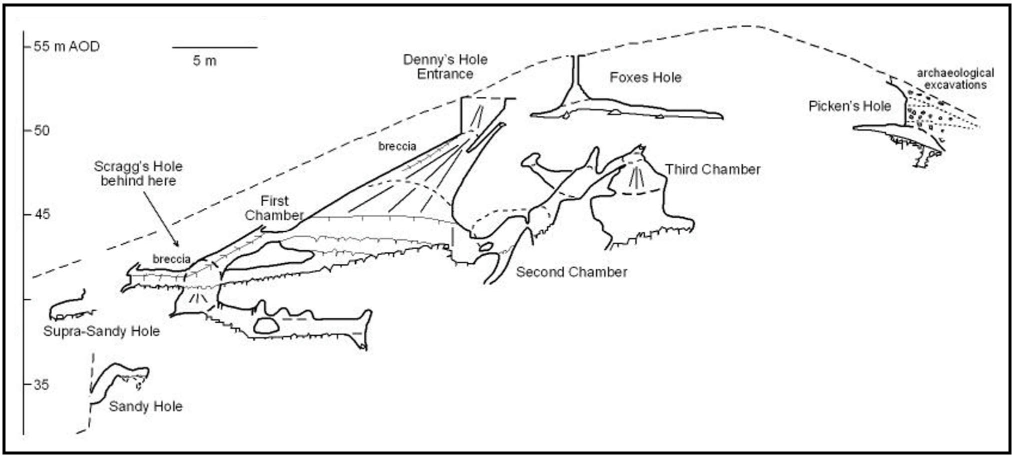

Figure 2. *Projected elevation facing 290º. Scragg' Hole lies behind the lower part of First Chamber and is omitted for clarity. Details of the sediment sequence at Picken's Hole are representative only. Unit 6 lies below the current floor level of the cave, but was penetrated by 2 soundings, one of which is shown schematically.*

with elevations falling from 50 m in the east near Winscombe to 10 m at the Lox Yeo gap west of Crook Peak, where the Lox Yeo river discharges to the south. The Carboniferous Limestone then forms hills both to the north and south of the low lying Old Red Sandstone core. Wavering Down to the south forms an upstanding area between 165 and 211 m AOD, with steep slopes both to north and south. Those to the north are underlain by the Lower Limestone Shales (now Avon group) which form the base of the Carboniferous Limestone Formation and then the Old Red Sandstone, while to the south the Black Rock Limestone is succeeded up dip by the Burrington Oolite, before passing unconformably under the Triassic Mercia Mudstone which underlie Compton Bishop (<30 m AOD). The dip of the Carboniferous Limestone is to the south or south southwest at 30º. Some 10 km to the south of the outcrop the Carboniferous Limestone is confined by the Triassic mudstones at a depth of over 1000 m in the Central Somerset Basin (Green and Welch 1977 plate 11) where it forms an extensive but little known confined aquifer.

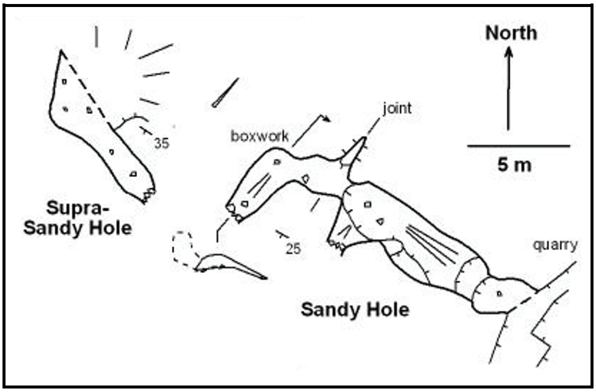

Figure 3. *Plan of Sandy Hole and Supra Sandy Hole.*

In this area, the Mercia Mudstone formation which comprises a basal marginal facies with clasts of Carboniferous Limestone varying from angular to well rounded up to a metre

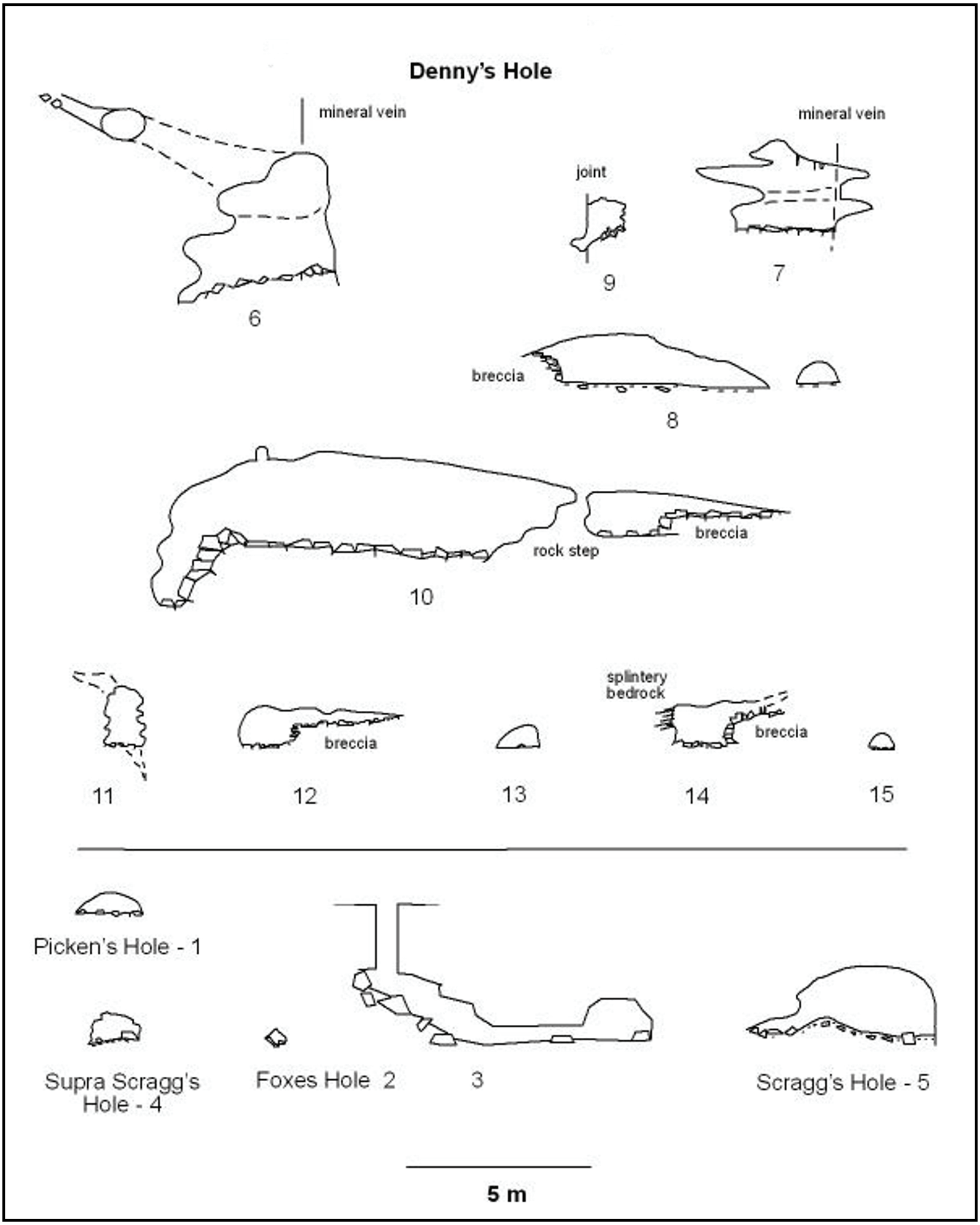

Figure 4. *Passage cross-sections for Denny's Hole and the smaller caves. For locations see Figures 1 and 3.*

in diameter, and set in a matrix of red marl or sandstone. These rocks are known locally as the Dolomitic Conglomerate and are generally considered as scree and wadi deposits formed in a desert environment after folding, uplift and exposure of the Palaeozoic rocks (Tucker 1977).

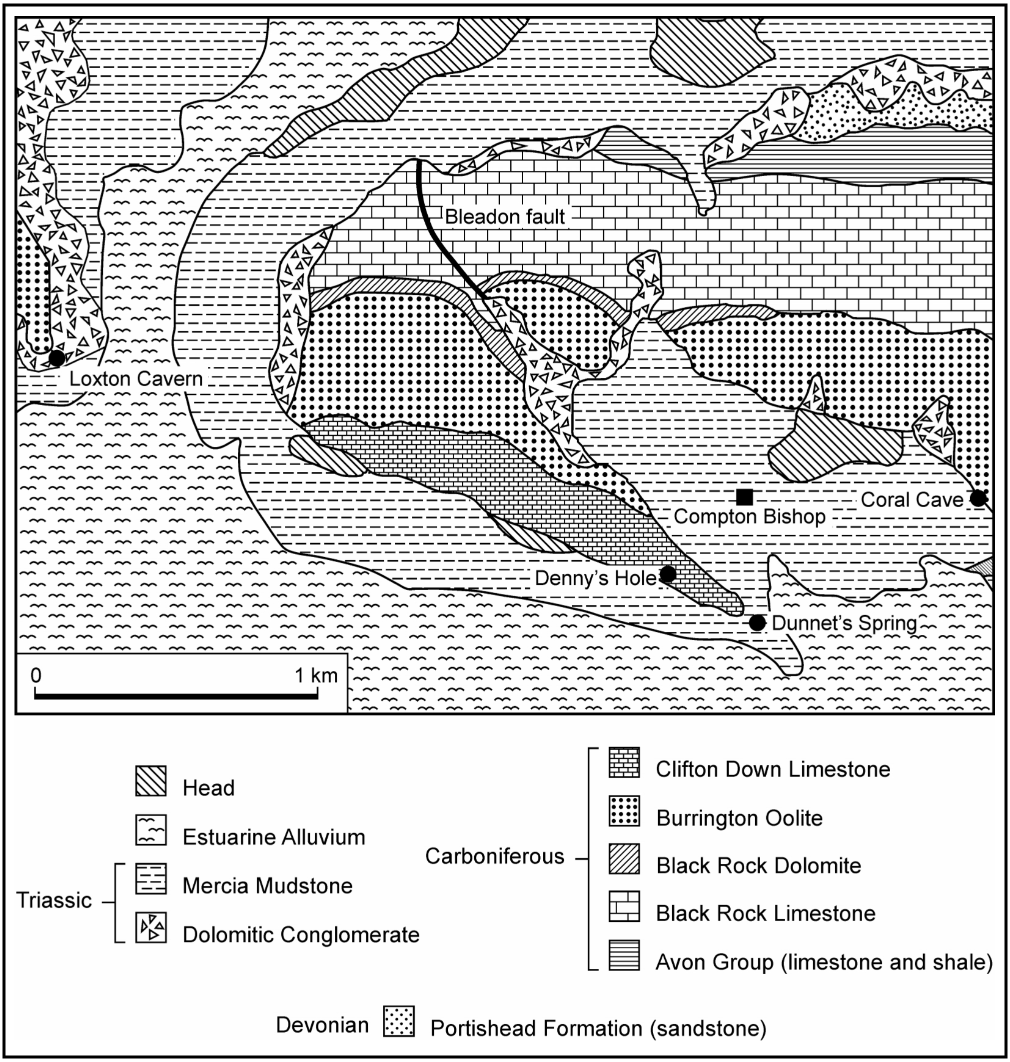

Figure 5. *Geology of the Crook Peak area from the British Geological Survey Bristol Special Sheet. The Cheddar resurgence lies some 6.5 km to the east and also on the southern flank of the Mendip Hills.*

They are commonly found in paleo-valleys that dissect the flanks of the Palaeozoic folds. Two such paleo-valleys are present on the southern flank of Wavering Down north and northwest of Compton Bishop, and define the head of the Compton Bishop vale. The Dolomitic conglomerate is absent on the south flank of Crook Peak carbonates are directly overlain by marls of the distal facies. This comprises red and sometimes green mudstones which may contain carbonates and evaporites, and are the considered to be outwash and ephemeral lakes sediments in the lowlands surrounding the Palaeozoic hills. Wright and Sandler (1994) propose a continental geochemical model for the evolution of the brines and the carbonates and clay minerals that they deposit. This involves progressive increase in the Mg/Ca and Si/Al ratios of the groundwaters passing through the sediments, with precipitation of calcite, dolomite and silica with high Mg silicates such as sepiolite. Density reflux of such waters may have affected the underlying Carboniferous Limestone resulting in dolomitisation, as suggested for the marine high-stand Triassic Clevedon Oolite (Milroy and Wright, 2002). Whilst the marls of the Mercia Mudstone are considered hydrologically to be confining beds, the Dolomitic Conglomerate is in hydraulic continuity with the Carboniferous Limestone and is karstified as at Wookey Hole.

No specific features indicating faulting were identified in the caves, but Crook Peak is separated geologically from Wavering Down by the Bleadon Thrust (Green and Welch, 1977). This is a major structural feature comprising a north-west / south-east strike slip fault, which is interpreted by Williams and Chapman (1986) as a thrust fault (T2). They suggest that the T2 structure is a large-scale oblique ramp which is frontal to the west with a low angle (c. 6° to south), but steeper to the east where it is progressively known as the Southern (or South-western) Overthrust, and the Emborough Thrust. The displacement associated with the thrust fault causes the outcrop of the underlying Clifton Down Limestone unit which hosts the Crook Peak cave complex, which is not exposed elsewhere on the western part of Wavering Down. Green and Welch (1977) describe the Clifton Down Limestone as comprising 'bands of splintery fine-grained limestone containing Lithostrotion alternating with finer-grained oolite'. There is a significant degree of patchy dolomitisation, which also affects the underlying Burrington Oolite. The dolomites are pinkish to creamy yellow when weathered, and have a sugary texture with dolomite grains 0.05-0.25 mm in size. Weathering can result in formation of dolomite sand, as seen at the old quarry near Loxton church. The splintery nature of the limestone does not appear to be depositional (Figure 6) and may arise from the proximity to the T2 thrust and the more brittle nature of dolomite compared to calcite.

In the following text the terms carbonate and limestone are used generally for the bedrock unless there is specific information as to the composition.

The limestones are also locally mineralised, but detailed studies have not been made either of the mineralisation or of the dolomitisation in this area, which was not important for metalliferous mining. Our observations in Denny's Hole indicate that post-dolomitisation there were 2 phases of local mineralisation. The main phase of mineralisation comprised veins of calcite and haematite. The calcite contains inclusions of iron oxides and black euhedral haematite, but more generally the 2 phases form separate but adjacent phases in the vein, or in other cases separate veins. Some of the veins are quite large with widths of up to 50 cm, and in places such as the Third Chamber they project from the cave walls by several metres. Here they are encased within hard black amorphous haematite but have weathered centres with voids filled by red and yellow ochre often intergrown with rhombohedral calcite crystals. At Sandford Quarry, Axbridge and west of Canada Coombe, Burr (2015) reports that pseudomorphs after pyrite are present in such ochreas fills, but they were not recorded in our samples. In the northern part of First Chamber there is a high density of these veins (c. 8 per 10 m), with a strike 045° which can be followed through into the Second and Third Chambers. In the southern part of First Chamber a subsidiary set which are much less wide and with a rather lower density strike 010°. No galena was specifically observed in the veins inspected. Finally in the southern part of Second Chamber the northeast wall is determined by a thick weathered iron vein striking c.135°.

The second phase of mineralisation comprises small white to red coloured euhedral quartz crystals which line many joint surfaces and vugs, and are prominent in the roof of Sandy Hole. Microscopic inspection shows inclusions of haematite. Some bedrock samples have been partially silicified, and can be differentiated from the pink orange and red dolomitised bedrock by a grey colouration and raised fine sugary crystal texture. In the figured sample (Figure 7), the silicification post-dates both dolomitisation and calcite/haematite veins, and appears to extend in from the base of the sample. It is likely that at the time of silicification, this was the outer surface of the sample, and that after deposition of a thin veneer of iron oxides and rhombohedral calcite, the sample fell from its position on the cave wall, with late stage banded calcite flowstone forming on the rotated upper surface of the block (see below in relation to paragenetic sequence). In Sandy Cave Burr (2015: p 88) reports yellow ochre and orbicular chalcedony (silica). Morphologically the latter looks rather similar to carbonate popcorn, but we have not recorded siliceous popcorn deposits from Denny's or Picken's Holes.

Figure 6. *Splintery carbonates formed beneath a more massive unit exposed in the quarry face to the east of Picken's Hole. Note the irregular non-depositional? surface between the splintery and massive carbonates and the termination of the splintery unit at the second joint to the right of the person suggesting some degree of structural stress is involved.*

By analogy with similar deposits locally, in South Wales and Cumbria, it is likely that the mineralisation is associated with Late Triassic rifting and represents relatively high temperatures 180-200^{o} C, although some authors suggest lower temperatures for the calcite/haematite mineralisation (80-120^{o} C). Such difference may result from differential mixing between deep water sources and more shallow brines (Ault, *et al* 2016; Burr, 2015; Crowley, *et al* 2014, Fletcher, *et al* 1993; Hagerty, *et al* 1996; Rankin and Criddle, 1985; Wogelius, *et al* 1997).

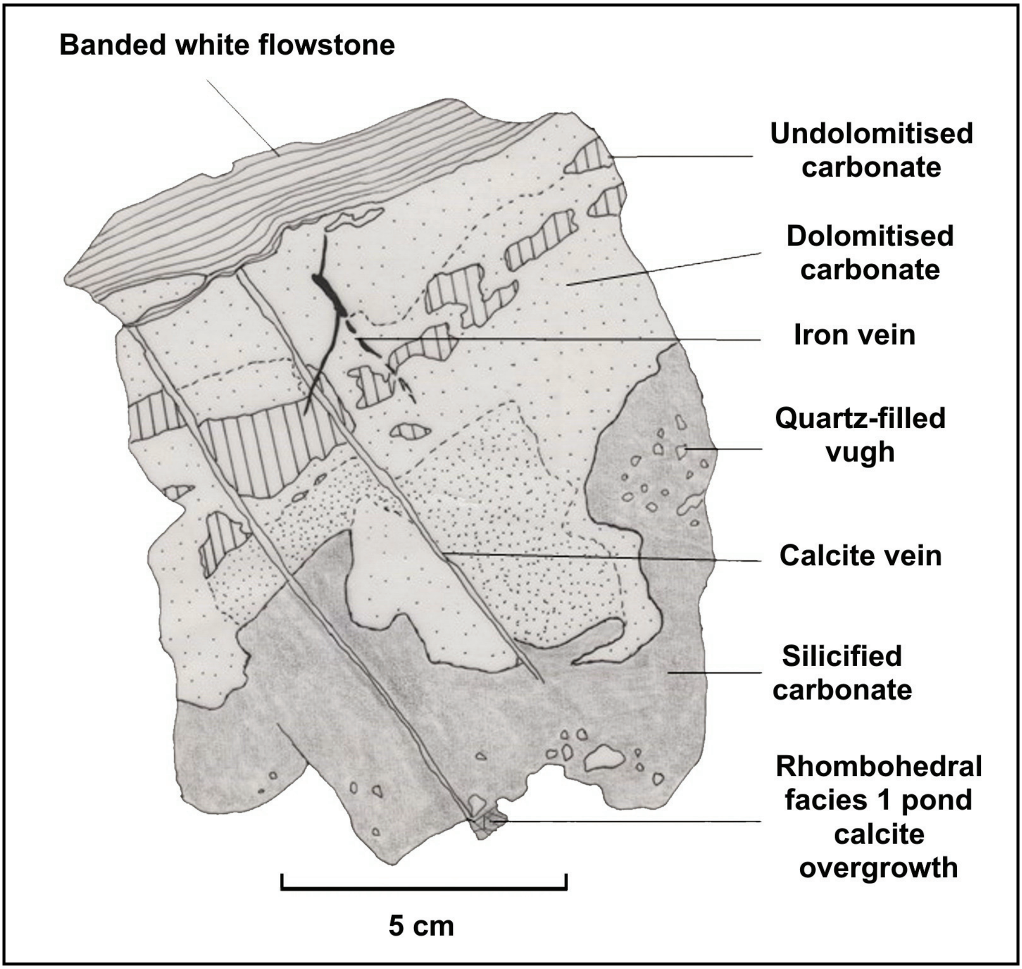

Figure 7. *Cut and stained section of clast from floor breccia in First Chamber, Denny's Hole. The clast is predominantly of the carbonate bedrock and shows details of the dolomitisation and silicification of the carbonates in relation to the iron/calcite mineralisation. The stipple differentiates coarse and fine textures within the dolomitised carbonate, the finer texture being preferentially silicified. Calcite veins postdate the dolomitisation, and the silicification and iron mineralisation postdate the calcite veins. Thin rhombohedral pond calcites are locally present, and in some parts of the sample overlie a thin iron-oxyhydroxide layer above the silicified carbonate (not shown). The sample was capped by a layer of white densely banded calcite speleothem before it was broken.*

Unlike calcite and dolomite which have retrograde dependence of solubility on water temperature, silica solubility increases with temperature (Wood and Hewett, 1992). Thus whilst deep thermal waters rising and cooling may cause dissolution of carbonates, they may also precipitate silica. Modelling in fracture systems suggest that deposition rates are low at temperatures below 100°C because of slow kinetics, and in wide fractures and systems with large flows which may eliminate the driving temperature gradients (Lowell, *et al* 1993). The diffuse silicification must therefore be an early hydrothermal phase prior to the opening of the karstic fissures. As an additional complication, if the rising waters contain high concentrations of magnesium, dissolution of calcite by cooling waters may drive the solution to supersaturation with respect to dolomite, replacing the carbonate matrix. This may explain both the rather patchy distribution of the dolomites and their clear association with the caves.

PASSAGE PATTERNS AND MORPHOLOGY

In a cave as short as Denny's Hole it is difficult to adequately define a cave pattern, yet this is often crucial in identifying hypogene caves (Audra, *et al* 2009a). Nevertheless, the high density of passages within a limited area and their nonlinear nature is immediately very different from the typical branchwork pattern of Mendip swallet to rising cave system, exemplified by systems such as the Charterhouse caves and the associated Goughs Cave resurgence system (pattern terminology after Palmer, 2007). Many hypogene caves show a strong structural control forming a rectilinear pattern controlled by the joints, but this is not the case at Denny's Hole. Despite the high density of mineral veins and the possibility that at some time they may have contained pyrite a potential source of acidity, these largely cross-cut the Second and Third Chambers with minor impact on their gross dissolutional form. Rather they are expressed as large fins or blades protruding from the cave walls, such as those in Second Chamber which is cored by ochre cased in unweathered iron oxides and veneered in later speleothem (Figure 8). Somewhat surprisingly, there does not seem an obvious joint line controlling the linear passage at the lowest point in the cave, and it does not lie along the 2 prominent vein directions identified (23° versus veins on 045° and 010°). There does however appear to be a downdip continuation in the floor at the eastern end of the passage, now choked by floor breccia, and roof domes and cupolas are developed up dip in the roof of the passage (Figure 4 and cross-section 11). Possibly the veins have remained tight and did not provide initial routes for water circulation.

The roof of the First Chamber is formed on the bedding, but towards the south the form is less planar and more arched in cross-section (cross-section 10). All three chambers share a common elongation northwest to southeast, somewhat oblique to the measured dip, and rather more parallel to the strike of the Bleadon Thrust just to the north. Inspection also indicates that to the northwest they all head in smaller 'up-dip' passages sloping down into the cave (Figures 1, 2 and 3 cross-section 5). These either terminate in blank dissolution walls (as in the Second Chamber), or become constricted over platy angular weathered limestone fragments, as for example in the separate tubular passage which enters the cave to the east of the entrance slope (cross-section 8). A similar but somewhat thicker (0.5 – 0.7 m) cemented breccia terrace forms the west wall of the First Chamber and can be followed down dip into the short rectangular chamber which extends to the west. As elsewhere the up-dip end of the terrace leads into restricted tubular passages with breccia floors. Above the breccia there is a restricted slot from 0.5 to 1.5 m wide with phreatic roof features in a splintery weathered carbonate (cross-sections 10 and 12). In the up-dip corner of the rectangular chamber a small (c. 0.25 cm wide) phreatic tube enters above the surface of the breccia arrayed along the southwest wall. The breccia can be followed from here onto the southeast wall of the chamber, where it passes into intact splintery limestones with dense jointing (cross-section 12). Here there is no void over the limestones which form the wall of the cave. There is no doubt of the continuity of

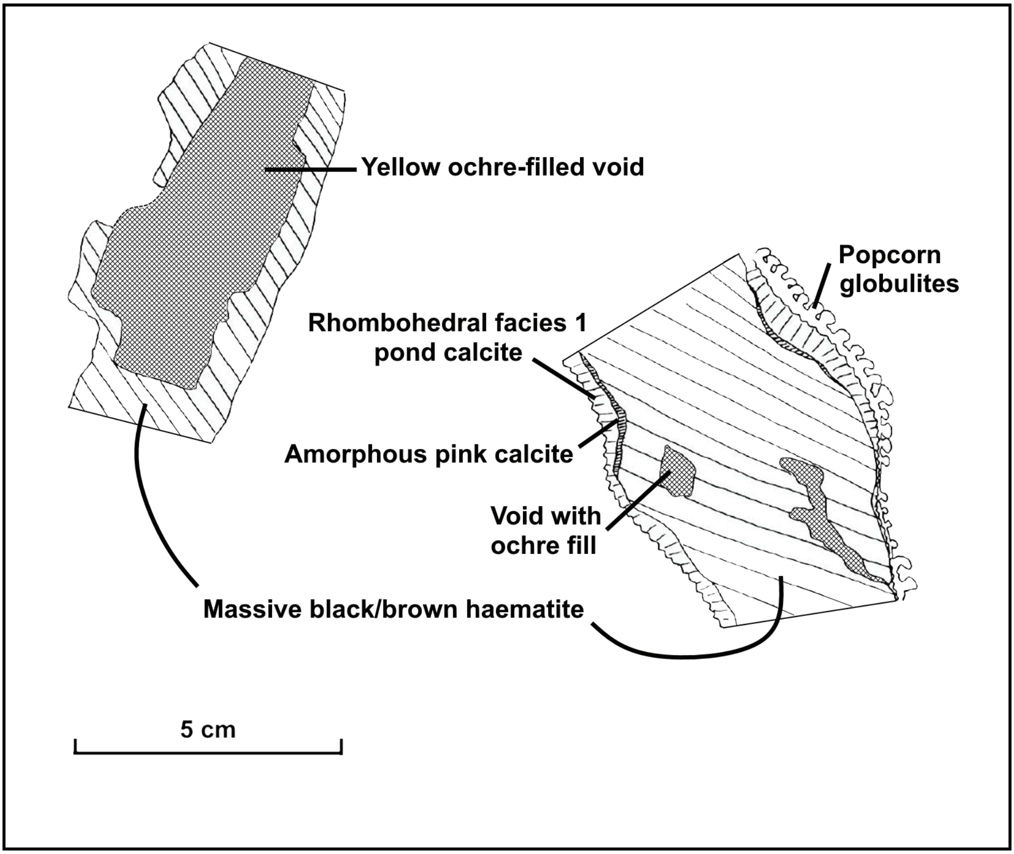

Figure 8. *Sections of ochreous iron veins from Second Chamber. Massive black haematite some of which have ochreous fill, with various secondary phases including pink homogeneous calcite, followed by palisade main calcite (which may fill a central void) and popcorn botryoids.*

the breccia and the splintery limestone, the former is simply an expanded version of the latter with more dissolution and variable displacement of the clasts.

Vadose features such as incised meandering trenches, fretting and high flow scallops are absent in the cave. Rather the walls and roofs of the chambers and the lower passage have either irregular surfaces representative of failure in the splintery limestones, or smooth domes and large-scale convective type wall scallops and irregular phreatic pocketing. Phreatic pockets and faceted surfaces extend to floor level in all the chambers, and form a number of rock steps, some of which are undercut as in Third Chamber (Figure 4 cross-section 6), and below the entrance slope in First Chamber (Figures 1 and 2). The latter is about 1.5 m high and can be followed laterally to a somewhat smaller feature (c. 0.5 m) along the west wall of the chamber which links to cupola forms on the walls of the rock pillars separating the individual tubular passages leading out of the chamber to the south. Unfortunately, the lateral extent and form of the rock cut floor of First Chamber cannot be adequately defined because it is overlain by up to 1.5 m of breakdown from the roof and entrance collapse, but in the most westerly of the small tubes there is a further and lower rock step. These features may be similar to the corrosion tables and wall convection notches described by Audra, *et al* (2009b) from the Grotte du Chat, France. The connections between the 3 chambers are all tight squeezes in quite thin (<0.3 m) pierced rock barriers with rounded phreatic form, and bridges between vertically separated openings. Such forms are favoured in convective systems where expansion of the void occurs from the point of local input, leading to narrowing and eventual elimination of the intervening walls, as described by Osborne (2007) in Cathedral Cave, New South Wales, Australia, and noted also in Grotte du Chat by Audra (2009b). This process is termed integration by Osborne (2007) and can occur both vertically and laterally resulting in a cave with larger chambers (he used the term cathedrals) connected by much smaller and low level passages (termed lows), such as those leading south from First Chamber. Finally in the roof of First Chamber there is a shallow (15-25 cm deep) sloping fissure 30 cm wide and c. 3.5 m long (plan and section 10). This lacks the generally smooth morphological features which are characteristic of convective roof channels (Klimchouk, 2007) or the somewhat smaller bubble trails seen in many phreatic hypogene caves (Audra, *et al* 2009b), but may have been modified by later cold conditions, or be a later epigenetic vadose feature.

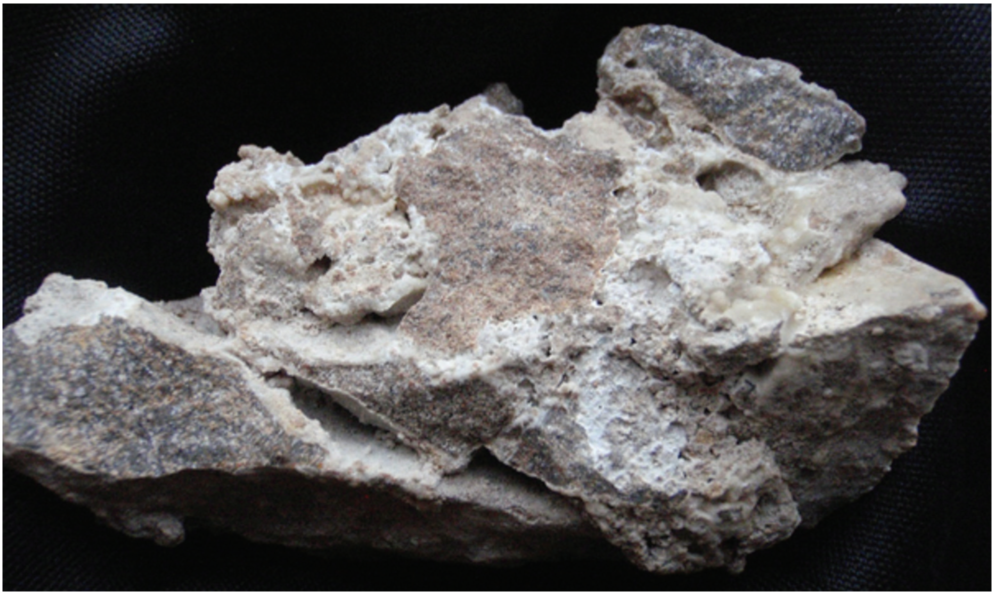

Figure 9. *Sample of 'terrace breccia' from west side of First Chamber (width of image sample 6.5 cm). Fresh to somewhat weathered small angular carbonate clasts are cemented by white gravitational cement forming bridges and infilling inter-clast pores. Note presence of dolomite grains within the cement (top left of centre) and botryoidal habit (top left).*

The other small caves in the area confirm some of the key features described above, they lack vadose forms, and they have accumulations of weathered platy breccia beneath domed phreatic or breakdown passage roofs (Scragg's and Picken's Holes cross-sections 1 and 5). Sandy Hole has a tubular passage largely free of sediments and the passage floor can be seen to comprise cemented limestone clasts and small irregular phreatic pockets (Figure 4). The roof is domed with constricted links to the ongoing passage. One of these is bypassed down the bedding to the south west, and the cave terminates in a wide (1-1.5 m) but irregular clast-filled down-dip slot c. 0.25 m high and with phreatic pockets. There is little speleothem, but a small fretted vadose shaft developed on a joint leads up to roots just below the present surface.

PASSAGE PATTERNS AND MORPHOLOGY: INTERPRETATION

There appear to be two rather different phases of cave void generation in Denny's Hole. The first phase comprises an anastomosing network on bedding planes of limited height (10—25 cm) and with a floor of platy weathered breccia fragments, and the second the sponge-work pattern of the main cave chambers. The chambers appear to be incised into the bedding tubes as a series of stepped smooth pocketed bedrock surfaces. These may also truncate the breccias associated with the tube network to form terraces well seen on the west side of First Chamber (see discussion of 'terrace breccias' below).

A possible and somewhat speculative hydrological model is that mineralised veins were essentially tight, but dilational movements associated with the T2 thrust immediately to the north permitted the opening of preferred inception horizons. These may be associated with the splintery nature of the limestone under near surface conditions, or have focused on dolomitised zones, as indicated by the close association between the Crook Peak caves and dolomitisation of the host carbonates. The aperture of the planar anastomosing network developed above the breccia was not large (10-25 cm) but it appears to have extended laterally over the full width of the cave c. 30 m in a series of sub-parallel planar voids. In many hypogene systems, the size of the feeders may be quite small as it is the contact with oxidising or air-filled conditions that is often responsible for the aggressivity which forms the major voids (Audra, 2009b, Palmer, 2007). The fact that there are a series of more or less horizontal bevels in the walls of the different chambers and that the walls are incised down vertically into the sloping bedding suggests that the chamber phase occurred with an open water surface, the level of which fell progressively with time. The cave morphology strongly suggests formation by condensation corrosion above a standing cave pool. If the rising waters were thermal, evaporation would condense on the cave walls adsorbing CO_2 from the cave atmosphere, which may have had an elevated PCO_2 due to degassing at the water surface (Palmer, 2007 and Dublyansky and Dublyansky, 2000). This suggestion is strongly supported by the chamber morphology, specifically the large scale scallops, domed chamber roofs, breached partitions between chambers and rock-cut wall and floor steps (Audra *et al* 2009b).

CAVE SEDIMENTS

With the exception of Sandy Hole (intersected by quarrying), all the Crook Peak caves have been intersected by surface erosion. In some cases such as Scragg's and Picken's Holes, they have then been partially filled with surface derived sediments. At Scragg's Hole these are known to be Romano-British (Russ and Summerfield, 2018), whilst at Picken's Hole they probably derive from the end of Marine Isotope Stage 5 (the last interglacial), through to the Late Glacial or Holocene (Smart and Springall, in prep.). As the latter note, sediments from the Crook Peak caves do not contain any swallet derived material such as fragments of Old Red Sandstone in the 2-10 mm fraction. There is also a general paucity of clastic fills, even accounting for the recent ingress of surficial materials. Thus at Denny's Hole there is some allochthonous clastic material on the entrance slope and in the floor of the First Chamber, but the remainder of the cave is largely free of such material. In fact Sandy Hole lacks any allochthonous clastic sediments, the bedrock floor being very sparsely covered with a few clasts (some possibly excavated by diggers from the downdip passage continuation) and a yellowish dolomite derived sand. The latter is also a significant component of Unit 6 in Picken's Hole (Smart and Springall, in prep.), also floors Foxes Hole and provides the matrix component of the sub-Romano British material present at Scragg's Hole.

The majority of the floor in the Denny's Hole chambers and passages is floored by breccia. There has been substantial disturbance because of digging to gain access to further cave passage from the First Chamber, but much of this material remains *in situ* if somewhat disturbed. There are two breccia facies: 'Terrace breccias' (which are associated with the bedding tube network described above) comprise small (cm to dm) sized irregular weathered splintery fragments of the bedrock carbonates and form upstanding sloping terraces with flat upper surfaces and a cut sub-vertical face overlying the bedrock floor and walls on west side of the First Chamber, where they are specifically associated with the anastomosing tube network which they floor (Figures 2 and 4 cross-sections 8, 10, 12 and 14). The terrace form indicates that the breccias have been eroded subsequent to deposition and that the previous distribution was more extensive. For example there is a marked terrace on the west of the entrance slope, whilst on the east side remnants can be seen adhering to the walls suggesting a laterally continuous cover (Figure 2). The terrace breccias are cemented by an irregular micritic white to buff coloured cement which includes frequent grains of dolomite sand, and coats the carbonate breccia fragments forming bridges and eventually void filling cements (Figure 9). The surfaces of the cement sometimes comprise mm scale cave coral botryoids, and in places they are capped by normal layered dripstone or flowstone. These breccias are rather similar to those seen below the Roman-British deposits in Scragg's hole where they were initially interpreted as 'thermoclastic scree'. The latter are however not cemented.

The second breccia facies here termed the 'crystalline breccia' comprises irregular loose (and elsewhere cemented) blocks typically 25 - >50 cm in diameter which mantle the floors of the chambers and passages. In First Chamber some of this material has been derived by the collapse of the present surface entrance, and forms a surficial scatter of angular somewhat weathered carbonate clasts. In the lower parts of the chamber and elsewhere in the cave the composition includes a high proportion of secondary carbonates, often based on weathered bedrock fragments but subsequently broken to form the clast. This material is unusual and is further described below (Secondary Mineralisation).

Some insight into the association of detrital sediments and the crystalline breccia is provided by the excavations at Picken's Hole, where attempts were made to penetrate the cemented breccia which comprises the bulk of Unit 6 at the base of the deposits. In square E, Unit 6 was c3 m deep, the top being variably cemented and with open voids and the lowest 1.5 m comprising 'shattered bedrock' (Apsimon and Smart, 2018). This sequence from breccia to splintery limestone is identical to that seen in Denny's Hole in the rectangular chamber south of First Chamber (Figure 4 cross section 14). In square F a sounding developed through the breccia using explosives again established a transition between breccia and shattered bedrock established (Apsimon and Smart, 2018, Figure 7). In this area a local sequence of granular clastic sediments floored by hard red-brown sand with streaks of calcium carbonate and fine gritty limestone fragments (context F17) was present above weathered limestone bed-rock. Above clean yellow sand with small weathered limestone clasts up to 1 cm (context F15) passed up into stone free sands (context F14). Examination of a later sample from this area indicates that the coarser material is predominantly fragments of haematite, the sands being a mixture of carbonate and also quartz, presumably from the silicification of the carbonates. It appears from the sloping bedding surfaces between contexts in this pit that the sediments may have been discharged from the area via downdip openings in the bedrock. In this area the upper surface of the cemented breccia was variably covered by a thin skin of calcite. Elsewhere, limestone clasts on the upper surface of the Unit 6 breccia were rounded and weathered, and the pockets and hollows in its upper surface were filled with reddish sandy loam and clay loam of Unit 5 which formed the cave floor when first opened to the surface.

CAVE SEDIMENTS: INTERPRETATION

It is highly probably that Denny's Hole and Picken's Hole are part of the same cave system. As described further below (Secondary Mineralisation) it appears that the cemented breccias of Unit 6 in Picken's Hole and the crystalline breccia in Denny's hole have similar if not identical paragenetic mineral sequences. However, unlike the latter the Picken's Hole cemented breccias contain local accumulations of dolomite derived sandy sediments. One possible explanation is that dolomite sand grains released by dissolution in the restricted bedding conduits initially active in Denny's Hole may have been transported up to stiller waters in a flooded Picken's Hole chamber where they were deposited. This phase of upward sediment transport must however postdate an earlier phase of chamber enlargement and cemented breccia deposition in Picken's hole implying a repeated sequence of cave forming events with falling base level prior to the eventual abandonment of the outlet before 200 ka (based on a mass spectrometric uranium series age of subaerial flowstone on the breccia surface, (Hodge *et al.* 2016)). An alternative interpretation is that following abandonment of the Picken's Hole outlet, aggressive condensates derived from thermal waters lower in the system may have affected the cave walls and breccia clasts, causing disaggregation of the partially dolomitised rock. Subsequently, later vadose infiltration may have redistributed some of this unconsolidated sediment within the voids of the crystalline breccia. In particular it is likely that in the near surface environment which affected Picken's Hole, epigenic vadose inlets may have developed, forming voids in the crystalline breccia into which the sediments were re-deposited. This would explain their down dip configuration, the percolation water running down the existing passages towards Denny's Hole (Smart and Springall, in prep.).

The terrace breccia appears to have developed by failing of small sections of the phreatic tube roof, perhaps associated with the reduction of confining stress or as a response to the 'splintery' nature of the limestones when exposed to weathering. The detached clasts tended to block the small sized tubes and flow diversion into adjacent more open areas occurred. The bedding anastomoses thus developed both laterally and vertically by a stoping process, eventually giving rise to a substantial accumulation of platy weathered limestone breccia with a residual tube network above. The flow in this network may have been sufficiently active to evacuate dolomite sands formed by partial dissolution of the bedrock as suggested above, but normally flow in hypogene systems is slow and transport of sand-sized sediment does not occur.

SECONDARY MINERALISATION

The primary mineralisation (that which precedes development of the cave void) was discussed above, here we focus on secondary mineralisation which postdates all or part of the cave void and is a particular feature of the crystalline breccia.

Knight (1915) in describing Denny's Hole notes that:

> *"Its steeply sloping entrance leads down to a lofty and very picturesque archway of a large chamber, whose roof and walls were, when the cave was first discovered, -apparently towards the close of the 18C, - beautifully decorated with stalactites, all of which, however have been carried away."*

This together with the use of the cave by the Home Guard in World War 2, and its ease of access strongly indicates that many of the speleothems in the cave are broken, removed or otherwise disturbed. Some normal stalactite and stalagmite dripstone and flowstone formations are present, but are relatively minor, although they frequently adorn the protruding iron veins, where they may encase the softer ochre.

Of rather more interest is a complex sequence of secondary deposits predominantly of calcite which both adhere to the cave wall and comprise the clasts of the 'crystalline breccia' which mantles the cave floor. Some 24 samples of the crystalline breccia predominantly derived from broken material were examined from the Crook Peak caves. The deposits observed in Denny's Hole appear to be identical to those which form the main structure of the cemented limestone breccia of Unit 6, the lowest and oldest unit of the Picken's Hole sequence (ApSimon and Smart, 2018). However the latter were when excavated in situ and cemented whereas the sampled material at Denny's Hole is from loose clasts. Possibly cemented material lies beneath the loose surface material. The Picken's Hole samples also show surface dissolution and some remobilisation and redeposition of iron and manganese oxy-hydroxides, probably as a result of their burial beneath later cave and surficial sediments. Similar crystalline breccia is also present on the floor and in the rising dip beddings of Sandy Hole, but is not observed at other sites in the area. About half of the samples collected are predominantly secondary material, often with a broken base or margins.

Commencing with the carbonate host-rock clasts, there appears to be a general paragenetic sequence, some phases of which may be absent from individual samples, but which overall occur in the same stratigraphic order. The sample in Figure 10 displays most of these growth phases, and they are summarised in Table 1. The bedrock clasts are generally irregular somewhat platy sub-angular weathered dolomitised carbonate typically 20-30 cm in size with a somewhat porous texture and reddish-brown to grey-brown colouration. In a few samples the clasts are more intensely weathered with brown to orange-brown colouration of decalcified material with small spots of black manganese oxides. There are also samples in which partial silicification of the bedrock has occurred (Figure 7). In about half of the samples collected, clasts are only a minor component of the breccia.

In a significant number of samples, the surface of the clasts are covered by a **black (manganese oxyhydroxide?)** layer. This is generally thin (<1 mm) and dense, but in places is thicker (2-3 mm) and includes layers of iron oxides. The black phase precedes a distinctive dense microcrystalline cream to **pink coloured calcite**, which reaches a maximum of 1.5 - 2.0 cm in one sample but is generally thinner or entirely absent. Deposition appears to be only on upper and side surfaces suggesting vadose conditions. In the sample (Figure 10), the pink calcite is succeeded in one void by dense pure non-banded cream calcite with a similar texture,

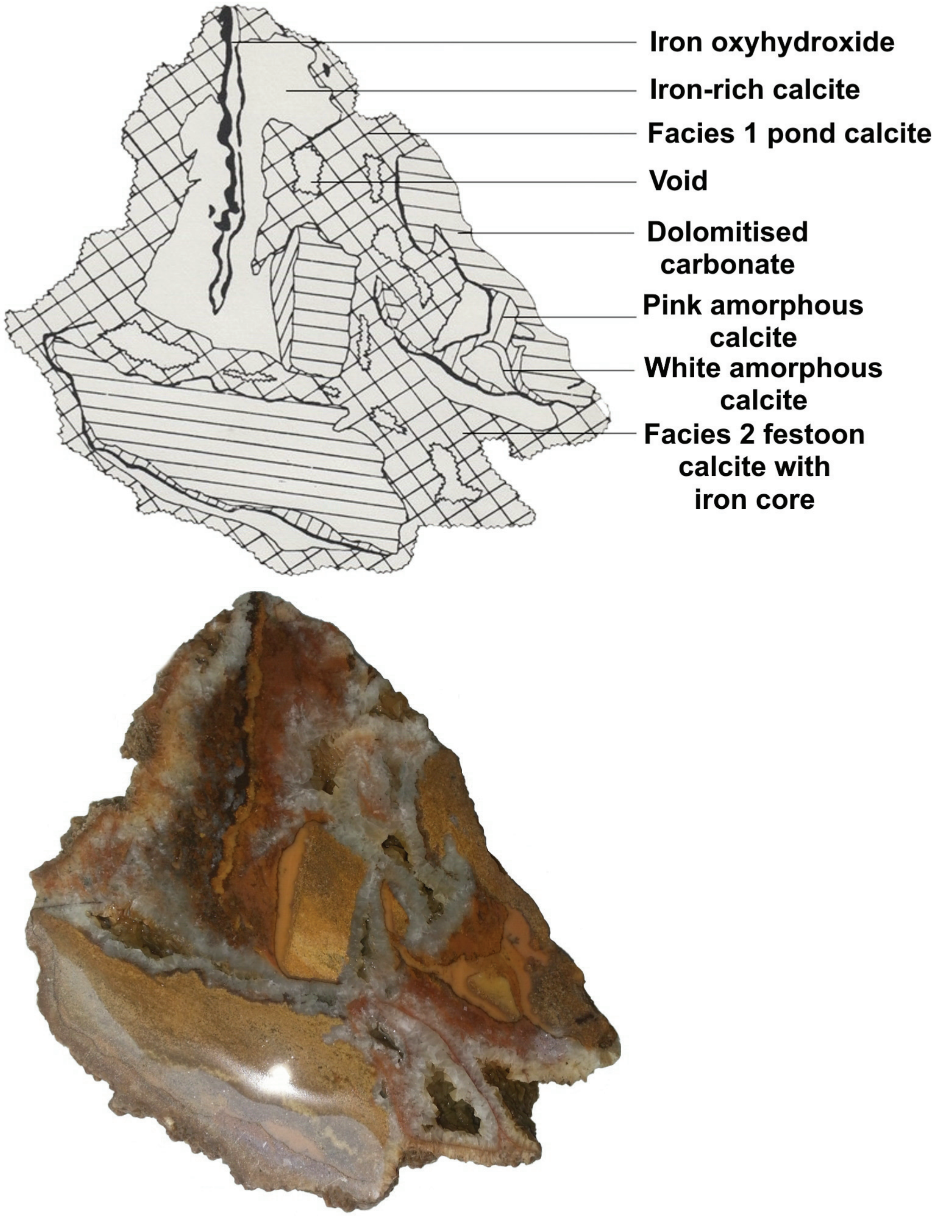
Iron oxyhydroxide
Iron-rich calcite
Facies 1 pond calcite
Void
Dolomitised carbonate
Pink amorphous calcite
White amorphous calcite
Facies 2 festoon calcite with iron core

Figure 10 (opposite). *Sectioned sample from a loose clast crystalline breccia, First Chamber Denny's Hole. The weathered and somewhat porous dolomite fragments are overgrown by a thin coating of pinkish finely crystalline calcite which lacks the layering generally found in subaerial speleothem. This does not however overgrow all surfaces equally but appears to be either pendent or more likely encrusting of the upper surfaces of the clasts suggesting deposition in vadose conditions. The following texturally similar phase of cream calcite is only present in a void (bottom right). Both phases are terminated by a thin dark brown to black iron oxyhydroxide boundary only seen to directly overlie the pinkish calcite (centre, centre right and centre to top left where it is much thicker) which also encrusts parts of the dolomite clasts (centre beneath clast). The next phase is a clear red to orange calcite, which in thin section comprises equant crystals with extensive iron inclusions. This phase is terminated in thin section by a somewhat iron rich boundary over which the elongated calcite crystals with a rhombohedral termination of facies 2 developed. Note also that some of the growth centres are freestanding marked by a central iron rich layer (bottom centre). This non-ferroan low magnesium prismatic calcite forms the main bulk of the deposit, forming iron oxide cored festoons, sheets and panels, which in this sample terminate secondary carbonate deposition (bottom and left side of sample). Sample width 10 cm.*

probably from the same general growth phase. The termination of both phases is always sharp and in some samples is marked by a second very thin black manganese coating, or by a thicker amorphous iron rich layer transitional to the overlying calcite. Interestingly, where first encountered in Picken's Hole, the cemented breccia was noted to include 'considerable amounts of a dark brown mineral with radiate structure… shown to be mainly limonite/haematite ($Fe_2O_3.3H_2O$), plus a little psilomelane (MnO_2 $.H_2O$)' (ApSimon and Smart, 2018). Examination of samples from the excavation waste tip confirms this and suggests that as in samples from Denny's Hole, the manganese is early within the paragenetic sequence and certainly prior to the main calcite. Manganese dendrites are also observed in the partially weathered dolomite wall rock in Denny's Hole, suggesting that there may have been contemporaneous deposition of manganese at the time of dolomite dissolution, and in one sample from the lower chamber at Denny's Hole also extend down from the layer at the top of the pink calcite (Figure 12). The latter appear to be very similar to manganese shrubs sampled from pool crust in Lechuguilla Cave but are inverted (see Palmer, 2007: 204, one possibility is that way up is incorrectly identified in the loose clast that formed the sample).

In most samples the main depositional phase comprises translucent coarsely crystalline calcite with some red colouration caused by the presence of particulate iron oxides within the calcite (Figure 10 and Figure 11), deposition of which may be either above the cream calcite or directly on clast surfaces. There are however two very different end member 'facies' which are probably coeval as both are suggestive of a predominantly sub-aqueous depositional environment (Figure 12). **Facies 1** comprises a sugary vuggy equant to palisade calcite with varying amounts of iron rich inclusions which may define growth banding (Figure 12). In one sample the banding appears to suggest a pro-grading outgrowth from a previous broken surface suggesting enhanced growth. The base is frequently iron rich due to the presence of iron-oxy-hydroxide inclusions. Where not overgrown the surface shows a variety of nail-head (rhombohedral) crystal terminations. **Facies 2** comprises festoons and platy panels of coarse (1-2 mm diameter) translucent to white rhombohedral calcite crystals arrayed between the weathered dolomitised clasts and other prior phases. The festoons appear to form thin (2-3 mm) irregular undulose panels several cm laterally in size and with similar crystal orientation which interlock with adjacent panels which may have sub-parallel or rather different orientation (Figure 13).

Each panel or festoon is cored with a very thin (<1 mm) iron rich carbonate layer. Progressive growth and infilling of the voids between these panels can produce a dense cement, with an irregular rhombohedral terminated or interlocking bladed surface. We have not been able to find an illustration of this type of deposit in the general speleothem literature. Neither of the facies shows evidence of significant hiatuses in deposition.

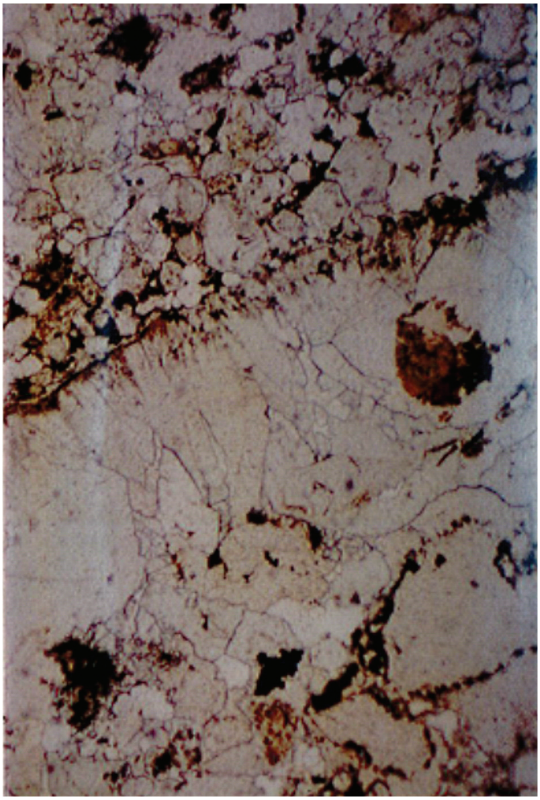

Figure 11. *Thin section showing boundary between pink subaerial speleothem (acicular crystals lower part of image), and iron rich equant spary calcite (top). Note that iron inclusions are present in both parts of the sample but are more frequent and more disseminated in the subaqueous upper layer. In this section the black iron oxyhydroxide boundary (running to top right corner) is thin and impersistent.*

At some points in the cave such as the passage leading to Third Chamber from Second Chamber and the lowest passage in the cave, small scale single 'boxwork' fins are observed on the cave walls. These generally have similar orientations to the calcite/geothite veins and associated later silicification. However, close inspection of these and of some of the hand samples suggests that some of the boxwork morphology is due to the platy form of facies 2 of the main subaqueous calcite phase.

The final two paragenetic phases comprise a thin (1-2 mm) **white opaque densely banded calcite flowstone** which translates vertically into dense **white to grey calcite popcorn** overgrowths. The latter may be on both upper, side and lower free surfaces. Both are widely present on the walls of the cave. In one or two samples the flowstone is much thicker, presumably due to higher flows in the local drip points. Popcorn is now generally recognised to be an evaporitic deposit formed when thin films of water become focused at positive protuberances and are subject to evaporation which precipitates the dissolved carbonate (Palmer, 2007, Caddeo, *et al* 2015). In one sample which has a relatively thick accumulation of the flowstone phase (Figure 14) a mineralogically more complex history is indicated. Staining indicates that both the more acicular parts of the sequence, and also both some parts of the banded succession and apparently some of the popcorn botryoids are metastable aragonite not calcite. The implication is that some, or less likely, all of the last two phases were deposited as aragonite and may subsequently recrystalise to calcite. The sample also indicates that in some samples popcorn botryoids were deposited without a prior phase of densely banded flowstone deposition (base centre of sample), and conversely that some botryoids were succeeded by the

Figure 12. *Crystalline breccia clast from First Chamber Denny's Hole. Pink homogeneous calcite at base with manganese dendrites extending down from the thin capping iron oxyhydroxide layer. Iron rich porous calcite passes up into facies 1 main calcite. Note the presence of thin iron festoons and stringers typical of facies 2 calcite suggesting that the 2 phases are intimately associated. Upper part of sample is more irregular equant facies 1 calcite with voids and iron rich inclusions. This culminates in a porous iron rich poorly crystalline calcite capped by bedded pure white speleothem with popcorm botryoids. Sample width 9 cm at base.*

flowstone (top right of the sample) indicating local scale environmental control on secondary carbonate deposition. Note also the presence of a fragment of mammal limb bone in the base of the sample, indicating some degree of connection with the surface.

No cave clouds, folia, calcite rafts or raft cones (all speleothems typical of hypogene caves) have been identified in Denny's Hole or the other Crook Peak Caves. We have also found no sulphate minerals. The latter are frequently encountered in copious quantities in caves where the geochemical driver to dissolution is oxidation of hydrogen sulphide (Hill and Forti, 1986; Palmer, 2007; and papers in Klimchouk, *et al* 2017). However, sulphate minerals are highly soluble, and may have been removed by subsequent dissolution. There is however, no evidence of this either in the presence of moulds or pseudomorphs after sulphate minerals.

Table 1. *Products, hydrological environment and active processes during cave development phases at Denny's Hole. Note: there is uncertainty on the timing of the terrace breccia formation and its cementation, and other higher and lower caves may have different contemporaneous products and processes dependent on their position relative to the spring outlet.*

Phase	Products	Hydro-environment	Processes
1 1	Anastomosing bedding tube network Terrace breccia clasts?	Sub-aqueous-flowing Sub-aqueous-flowing	Thermal (& mixing?) driven dissolution
2 2	Chamber dissolution Terrace breccia cement and popcorn	Vadose Vadose	Condensation corrosion high PCO2 Corrosion, degassing & evaporation
3	Manganese oxyhydroxide layer 1	Sub-aqueous-slow flow	Thermal dissolution? Redox interface
4	Pink (& white)	Vadose	Slow degassing constant conditions
5 5/6	Manganese oxyhydroxide layer 2 Iron-rich calcite	Sub-aqueous-slow flow Sub-aqueous-slow flow	Redox interface Rapid degassing redox interface
6 6	Main calcite facies 1 – pond deposits Main calcite facies 1 – bacterial deposits	Sub-aqueous-static Sub-aqueous-slow flow	Rapid degassing near surface (minor redox)
7?	Terrace breccia clasts	Vadose	Frost action
8 8 8	Banded calcite/aragonite flowstone Popcorn Terrace Breccia cement and popcorn	Vadose Vadose Vadose	Degassing & evaporation Dissolution? Degassing & evaporation

SECONDARY MINERALISATION: INTERPRETATION

The crystalline breccia in Denny's Hole appears to be derived from failure of fins and irregular protrusions associated with the partial dolomitisation, iron mineralisation and silicification of the wall rock which causes differential dissolution of the cave wall. This is well seen in the downdip passage leading out of the connection between First and Second Chambers (Figure 4 cross-section 9), and the lowest level in Denny's Hole. Here a series of sub-parallel sloping ledges are present essentially perpendicular to the dip (Figure 4 cross-section 11), and there are also remnants of main calcite facies 2 on the walls which have been subsequently covered with sub-aerial flowstone. This failure process is termed renovation by Osborne (2009). The growth of secondary carbonates occurred in situ on the weathered bedrock, but subsequently in some cases the point of attachment has failed, the block falling to the floor to form a clast in the crystalline breccia. Failure may result either from the mass of secondary carbonates accumulated or more generally a lowering of the water surface which reduced buoyant support. There may then have been continued or later secondary carbonate deposition on the fallen clasts dependent on the local environment which resulted in the complex and incomplete sequence of phases observed in individual samples. This is demonstrated by the sample (Figure 7) which appears to show rotation between the original silicified outer surface which has patchy calcite overgrowths, and the final phase of banded flowstone. Silicification along fractures is also recognised in Pal-Volgy Cave in the Buda thermal karst area, where it forms much thicker zones (dm to m) than those at Denny's Hole (Bolner, 1989). These silicified zones resist dissolution, subsequent cave voids developing in the carbonates adjacent to the fractures (although Klimchouk, *pers comm,* suggests that the silicified zones not the fractures are the focus for cave development). Subsequently, mechanical failure of the somewhat loose porous tuff-like silicified zones in the cave roof has occurred, with residual sediments and blocks accumulating on the cave floor. Elsewhere in the area in Jozsef-hegy Cave there are areas of cemented breccias which block the cave passages for over 25 m (Leel-Ossy, 2017), and appear to be similar to the crystalline breccia of unit 6 in Picken's Hole, where cementation appears to have been in situ.

Figure 13. *Festoons and panels of the main calcite facies 2 formed by paired chains of prismatic rhombohedrally terminated calcite crystals between dolomite clasts (bottom right and top centre) in clast from First Chamber. Occlusion of the inter-clast porosity is incomplete in this sample.*

Both iron and manganese are only very sparingly soluble in oxidised waters of near neutral pH, but are soluble under reducing conditions. Similar manganese (and iron) coatings are reported from within the calcite pond crusts in the Buda thermal karst by Leel-Ossy (2017), where they have been identified as the minerals romanechite and hollandite. They also form distinctive layers within the sediment deposits in Cave of the Winds, Colorado (Luiszer 1987). Here there is a sequence comprising solution debris, iron oxide, manganese oxide, clay, silty sand, and gravel. In both cases the iron and manganese are thought to be deposited following mixing of deep-seated reducing waters which supply the iron and manganese and near surface oxygenated meteoric waters. Sampling of the present Manitou Hot Springs shows that the despite lower concentrations than those of the manganese, iron is deposited at depth (>24 m) explaining its position in the stratigraphy. Deposition at depth is also the case in the central spring area of the Buda karst where the manganese laminations are in the sub-aqueous calcite crusts, but in the south deposition of the Fe/Mn-oxyhydroxides was concurrent with near water surface raft deposits. Other explanations have been advanced for manganese coatings in caves which include bacterially mediated scavenging of manganese in percolating waters under reducing conditions, with reprecipitation in the oxidising cave environment (Gasquez, *et al* 2011 and 2012, and Spilde, *et al* 2006) but the lack of evidence for surface acidification and development of ‘punk rock’ suggests these processes are unlikely at Denny’s Hole.

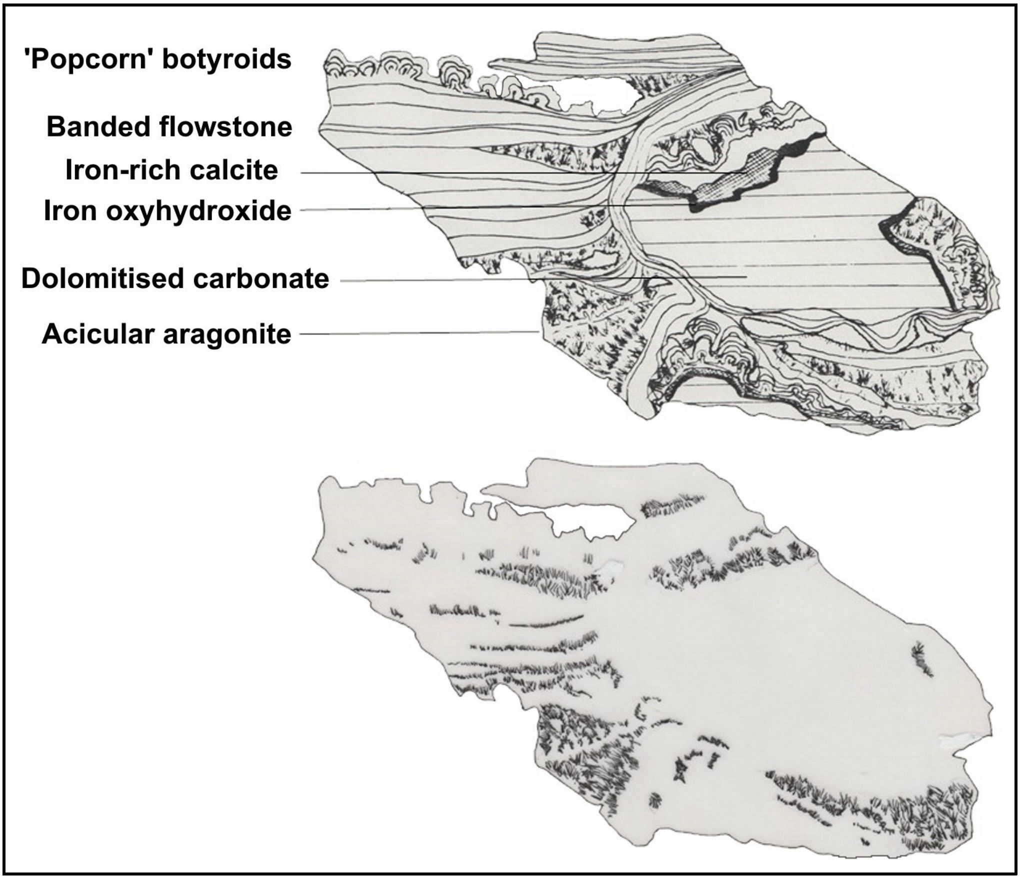

Figure 14. *Cut sample of thick flowstone from the crystalline breccia, First Chamber Denny's Hole (broken clast). Top shows growth habit and lower is stained using Leitmeir and Fiegl's stain for aragonite (black this image). Note complex internal structure with iron hydroxy-oxide and subsequent iron-rich speleothem over bedrock clasts (right top and centre). The main sub-aqueous calcite phase is absent, but a complex sequence of gravitational banded white flowstone drapes and popcorn botryoids are present with aragonite predominantly present in the acicular carbonates, but also in banded and botryoidal facies. A fragment of bone was present at the base of the sample beneath the botryoid overgrowths indicating the cave was at this time open to the surface.*

The pink calcite is very similar in colour and texture to that figured by Palmer (2017, Figure 8) in the base of a sample from Jewel Cave. As for the pink calcite at Denny's Hole this also appears to be preferentially deposited on one surface indicating vadose conditions, but was subsequently followed by a fully sub-aqueous pond calcite phase. Palmer suggested the darker coloured layers in the sample contained microscopic filaments of iron and manganese oxidising microbes, and that these represented intermittent anoxic inputs which were oxidised within the cave, but it is unclear whether this also referred to the basal pink calcite.

Facies I of the main calcite is a typical sub-aqueous pond deposit formed under relatively low temperature from low salinity waters (Palmer, 2007). These deposits are often associated with hypogene caves because the latter have relatively static water allowing continuous crystal growth. Near-surface growth rates are relatively high due to rapid degassing and can give rise to pro-grading shelf-stone type features and more equant crystals. Larger crystals are frequently found at depth where they form wall deposits up to 15 cm thick. Classic hypogene sites with calcite crusts include Jewel and Wind Caves, South Dakota, USA (Bakalowicz, *et al* 1987) and the Buda thermal karst, Hungary (Dublyansky, 2000a). In Wind Cave deposition occurs currently in the water-filled parts of the system (Palmer, 2000).

Facies 2 differs morphologically from accumulations of calcite rafts as the plates are not flat and do not have a smooth upper termination, a general characteristic of raft deposits formed at the water surface (Hill and Forti, 1986). They also do not stack in a surface parallel manner as is normal when rafts sink to the floor of a pool. Whilst they share some features in common with the crystal shrubs described by Chafetz and Guidry (1999) from travertine deposits, the structures developed at Denny's Hole are more planar than the typical radial shrub morphology. It is possible that the regular, repeating orientation of the branches which can be observed at a microscopic scale is not displayed in hand specimen as commonly the elongate straight branches are encased in a single crystal of calcite, but we do not see shrub structures in thin section. The planar precursor appears to be an iron-oxyhydroxide filament or layer. A possible present-day analogue is suggested by Florea, *et al* (2011) from Thornton's Cave, an estavelle in west-central Florida. They describe biofilms that are predominantly comprised of FeOOH-encrusted hollow sheaths that are overgrown and intercalated with calcite. These form both as rafts at the water surface and as fibrous membranes which hang from the ceiling. They suggest that the primary organism in the biofilm is *Leptothrix* sp., a common Fe-oxidizing bacteria, and explain that:

> *"To prevent hydrolysis and mineralization within the cell,* Leptothrix *sp. oxidizes Fe(II) in solution by secreting heteropolysaccharides that catalyze the precipitation of FeOOH nanoparticles (Banfield,* et al.*, 2000). These nanoparticles then bind to proteins and encrust the bacterial sheath (Frankel & Bazylinski, 2003)."*

Small (<0.5 μm) platy and polygonal calcite crystals accumulate between the tubes, and likely form nucleation sites for the thicker symmetric overgrowth of calcite that comprises the second layer of the biofilm. The calcites display both rhombohedral and scalenohedral crystals. The high degree of intercalation between the 2 layers strongly suggest that the calcite layer was precipitated directly on the biofilm in the water. Unlike the Florida case, where the cave was periodically air-filled, generating cave raft types platelets, it appears that in Denny's Hole similar geochemical conditions may have occurred in a wholly water-filled environment.

Geochemical sampling of cave waters indicates that the dominant control on **aragonite** deposition is the Mg/Ca ratio. Early work by Fishbeck and Muller (1971) showed that

Mg/Ca >2.9 allowed co-deposition of aragonite with calcite, but above 4.4 aragonite was the only form of calcium carbonate precipitated from solution. Subsequent studies have found somewhat lower ratios (minimum Mg/Ca for aragonite deposition in range 0.5-1.5) and also a secondary dependence on saturation or CO_3^{2-} (Gonzalez and Lohmann, 1988). Because of a high degree of local dolomitisation, relatively high concentrations of Mg may be present in drip waters at Denny's Hole, but ratios greater than the molar ratio present in dolomite (ie >1) are generated by prior precipitation of calcite, either by progressive degassing and precipitation along the flow path, or by evaporation which may lead to deposition both of calcite and, where sulphate concentrations are elevated, gypsum. There is very limited simultaneous precipitation of Mg (usually by partition into calcite) raising the Mg/Ca ratio into the field for aragonite deposition.

The alternation of calcite and aragonite, and of flowstone and popcorn botryoids during the last paragenetic phases suggests variable rates of cave ventilation and or water supply during the deposition of the top part of the sequence. Variable hydrological conditions are also suggested by the alternation of vadose and sub-aqueous deposits (Table 1). As suggested above the main dissolution phases occur under sub-aqueous (anastomosing bedding tubes) and the subsequent chambers under vadose conditions. Although some vadose processes have been suggested to precipitate manganese oxyhydroxides, it seems likely that at Denny's Hole these were sub-aqueous phases, but they are separated by a clearly vadose phase of pink calcite deposition. The flooding represented by the second manganese oxyhydroxide layer continues into the main calcite phase, although the reasons for the facies differentiation presented in the samples is not clear. This is the last subaqueous phase, thereafter conditions remained vadose.

A specific issue in this paragenetic scheme is the origin and cementation of the terrace breccias. The morphology of these breccias and their intimate association with the bedding tube network implies that they are contemporaneous with the development of the tube network. They are subsequently corroded as indicated by the weathering of clasts and the terrace form which could well be a product of the chamber dissolution phase, the more porous breccias retreating at a rather faster rate than the associated bedrock steps which characterise this phase. However, it appears (based on a small number of samples only) that despite their position low in Chamber 1, the breccia cements do not contain the sequential sub-aqueous secondary deposits. Rather they have the appearance of the phase 8 calcite flowstone and popcorn phases, the only apparent difference being the incorporation of some detrital carbonate grains. An alternative chronology would have an essentially bedrock floored tube network, the roof of which when subject to cold conditions following the opening of the cave entrance was affected by freeze thaw activity which was particularly effective in the splintery limestones. This suggestion is somewhat confirmed by the sequence of deposits at Scragg's Hole, and it could be argued that this cold phase also resulted in the re-shaping of the First Chamber roof and the generation of many of the clasts in the crystalline breccia as exposed in loose form on the chamber floor. Subsequently as conditions warmed the terrace breccias would be cemented as part of the phase 8 speleothem deposition, which has similar form.

DISCUSSION

There are a number of diagnostic features which identify Denny's Hole and the other Crook Peak caves as hypogene:

1. They do not have a branchwork pattern typical of epigenic caves. The dominant pattern is spongework, typical of hypogene caves, but this obscures an earlier planar network of small-scale anastomosing tubes. This tube network does not comprise either progressively enlarged tubes or paragentic (*sensu* cave development) passages typically found in epigenic caves, rather it is underlain by a somewhat unusual platy weathered limestone breccia which may be contemporaneous with its dissolution.
2. There are no clear hydrological feeders to the system, flow appearing to originate down dip possibly from fissures or bedding in the lowest passage which are partially obscured by breakdown.
3. Cave walls exhibit morphologies including semi-isolated chambers separated by lows, blind terminations, domed roofs, large wall scallops, wall pockets, pierced partitions, bridges and stepped wall facets and ledges typical of slow convective circulation of air or water. Many of these features are typical of initially isolated voids which have become integrated with growth over time (Osborne, 2007).
4. With the exception of the present collapse entrance, there are no clear vadose features within the caves such as incised meandering trenches or small scallops.
5. There is a lack of any swallet derived sediments in the Crook Peak caves, and other than those associated with recent surface entrances, clastic sediments are rare or absent. Those that are present are autogenic derived from partial dissolution of the dolomitised limestone. Only in Picken's Hole do these comprise a significant component of the sediments of Unit 6, the original cave fill.
6. Whilst no sulphate minerals are present, there are a range of unusual encrusting iron manganese and calcite secondary deposits which coat the lower cave walls and floor breccias. Precipitation of these may be bacterially mediated at a redox front.
7. Cave popcorn is a late phase secondary calcite precipitation which is often but by no means uniquely associated with hypogene caves systems (Caddeo, *et al* 2015). Unusually metastable aragonite also appears to be included within the complex popcorn and calcite flowstone floor deposits, another possible indicator of exotic geochemical conditions.

Note that several types of secondary carbonate precipitates which are often found in hypogene systems are not seen in the Crook Peak caves. These include cave clouds, calcite rafts and calcite cones (subaqueous) and folia (water table) secondary calcite deposits. Perhaps these lie at depth within the system and are not currently accessible, or some specific geochemical factors prevented their deposition.

As described above and summarised in Table 1, for Denny's Hole there appear to be eight phases of cave development and secondary deposition which require explanation. It is necessary both to provide a hydrological and geochemical explanation for these cave development phases, and it would be parsimonious to identify a general model which embraces both. A critical starting point is that the Crook Peak caves do not have any evidence for deposition of extensive sulphates. Such deposits are characteristic of spongiform systems such as Carlsbad

Caverns in which deep seated hydrogen sulphide produce local acidic conditions where the waters and gases are oxidised in near surface conditions (Hill, 1990; Palmer, 2007). In such systems there is often a big change in passage dimensions from the narrow ‘feeder’ slots which transmit the source water into much larger ‘reaction chambers’ where oxidation generates the sulphuric acid and dissolution occurs (Audra, *et al* 2009b). Conceptually this model is useful, but whilst it is possible that metastable sulphates have been totally leached in later phases of development at Denny’s Hole, this seems unlikely. A possible test would be to sample for exotic clay minerals such as alunite which form under very acidic conditions.

Undersaturation in hypogene waters can also result from the mixing of waters of different composition and cooling as waters rise towards the surface as the solubility of calcite is retrograde (increases with decreased temperature) (Dublyansky, 2000b; Palmer, 2007). There is likely to be much less size differentiation of feeder and reaction chambers for such systems. There are 2 reasons for this, first rising waters may cool progressively, leading to incremental undersaturation and dissolution of the feeder, and secondly mixing is also likely to be a diffuse process, and is not specifically localised as in oxidative systems resulting in chamber formation. Differentiation between these two incremental processes is thus difficult if not impossible on morphological grounds. Rising (and cooling) groundwaters occur within discharge zones which may have both shallow local and deep long travelled feeders remote from the recharge area. Mixing may be the dominant process at depth, whilst cooling is important as the waters rise to the discharge zone. A rather useful model is provided by the very well-studied Buda karst of Hungary (Madl-Szonyi, *et al* 2016 and references therein). At Buda, waters derive from local circulation through ‘normal’ karst in the hills to the west, but east of the Danube, the carbonate units are downfaulted and are confined beneath siliciclastic sediments. Numerical modelling of groundwater flow and heat transport (Madl-Szonyi and Toth, 2015) indicate that some slow recharge occurs into the confined carbonates through the siliclastics which form an area of low hills. This recharge flushes some marine pore waters high in chloride, sulphate and sodium into the confined carbonates. However, there is also deep eastward recharge to the confined carbonates from the unconfined part of the aquifer, the water being predominantly calcium bicarbonate in composition. This water is heated during lateral flow at depth, but must recurve at a shallower depth to the west to discharge into the Danube, the lowest hydrological outlet from the system. There is then a mixing zone between the sodium chloride waters recharged through the siliclastics, and the evolved and heated deep carbonate circulation which is focussed on the basin boundary faults underlying the Danube valley. It is in this zone of rising thermal and mixing waters that the Buda caves have been developed (although they are now exposed by base level lowering). The analogy with Crook Peak is clear. Here the Carboniferous Limestone is confined to the south under the Mercia Mudstone so deep thermal circulation may occur in the underlying carbonates with mixing of limited recharge from the Triassic marls which may contain high sulphates from evaporites. These waters must discharge at the lowest point in the area which is the western part of the Blackdown anticline. At Crook Peak the Bleadon thrust fault rises through the carbonate succession and potentially provides an enhanced permeability route. However because of the Triassic paleo valley underlying Compton Martin, the confining unit lies at a higher elevation at the thrust outcrop at the back of the vale than the topographically lower part of the Crook Peak ridge. The Denny’s Hole cave complex is the karstic discharge for this deep geothermal circulation.

Palmer (2007) provides a useful conceptual model for the development of water-filled thermal caves. Cooling of carbonate waters as they rise to the surface causes undersaturation and progressive dissolution of the initial fissure. In the near surface zone (c. 15 m below water surface) the pressure decrease results in degassing of CO_2 from the rising groundwater with formation of gas bubbles and a rapid change to oversaturation with respect to calcite. Calcite pond deposits are then formed on the wall of the initial dissolutional fissure. With decline in outlet level, the zone of calcite deposition extends deeper into the cave void. This model provides a good explanation for the dissolutional anastomosing bedding tubes of phase 1, and also the main calcite deposits of phase 6. Rising waters are also subject to redox gradients as they mix and near the surface, so phases 3 and 5 are also readily explained using this rising and mixing thermal waters model.

Degassing of high PCO_2 rising thermal waters can result in the formation of bubbles of CO_2, as for instance occurs at Jacklands Bridge Springs at the base of the Carboniferous Limestone Clevedon ridge, a similar hydrological setting to that at Denny's Hole. Bubbles may rise through the water column against the cave wall along topographically defined pathways, generating distinctive bubble trail morphologies (Audra, *et al* 2009c). We have not specifically been able to identify such features within Crook Peak caves. When degassing occurs, the expulsion of high PCO_2 bubbles at the water surface may if ventilation is limited (the cave void is not directly open to the atmosphere) generate a local atmosphere with elevated PCO_2. Any percolating waters entering such an environment will adsorb CO_2 and may become aggressive to calcite dependent on their prior saturation state. Such waters may cut drip holes or incised karren type features below the entry points (eg Audra, 2002). We have not specifically been able to identify such features within Crook Peak caves. Where the rising waters are also of elevated temperature, there may be condensation of water vapour evolved from the warm water surface on the cooler cave walls and especially ceiling. Condensation is common in cave which have few or no entrances, little running water and a thermal water source, and is most effective in near surface cavities where the heat generated by condensation can be lost to the surface (Dreybrodt, *et al* 2005). The condensed water contains no dissolved carbonate, but will adsorb the local elevated atmospheric CO_2 thus becoming aggressive. The aggressive condensation waters generate significant small-scale relief where there are textural or compositional difference in the carbonate wall rocks, generating features such as box work (Audra, 2002b). Typically this effect is concentrated in the upper part of ceiling domes and passages, with less differential dissolution where flow approaches saturation lower down the walls, and possibly a zone of precipitation where the water film is re-evaporated and popcorn and frostwork are deposited (Palmer, 2007; Audra, *et al* 2002). We have not specifically been able to identify such sequential patterns at Denny's Hole. However, condensation corrosion may be responsible for the chamber phase (phase 2) of cave development, as suggested above by the evidence for progressive void integration with elimination of intervening walls, large scale convective forms and walls steps and notches which infer some water table control. In fact there is some lack of clarity as to which phreatic scalloped rising cupola networks are formed under water-filled phreatic conditions ('thermal convection per ascensum') and which by condensation corrosion in the vadose zone, as both involve slow convective fluid flow (see references in Dublyansky, 2000b). In the case of Denny's Hole the presence of features which appear to be corrosion tables or wall convective niches suggests that condensation corrosion was the predominant process (Audra, 2009b). Note however that the former are more normally associated with sulphuric acid systems and may be pool water level phenomena (Klimchouk *pers comm*). Condensation corrosion may specifically cause differential dissolution of the less silicified and dolomitised parts of the bedrock, generating friable irregular protrusions and fins which may be subject to later failure forming the crystalline breccia clasts with more or less subsequent secondary depositional phases. Leel-Ossy (2016) reports similar cementation of collapse deposits in the classic hydrothermal Buda caves, Hungary.

CHRONOLOGY

As part of the Bristol work, Farrant (1995 and others summarised in Waltham, *et al* 1997) have reported alpha spectrometric uranium series and electron spin resonance (ESR) ages for dripstone speleothems developed after progressive abandonment of successive cave levels in the Goughs Cave and Charterhouse swallet to resurgence caves systems, resurging on the south flank of the Mendip Hills some 6.5 km to the west. The subaerial speleothems are deposited in the abandoned phreatic cave passages when base level falls as a result of isostatic uplift in response to regional erosion. This is most probably dominated by stripping of the erodible Mercia Mudstone (and other Mesozoic mudstones) from the lowlands surrounding the Mendip Hills, the primary cause of the present local relief. The oldest ages at each level are typically at the times of interglacials when speleothem deposition is at an optimum, with incision of the fine-grained clastic lowlands occurring predominantly during the intervening cold periods when sea level was lowered. The main Goughs Show Cave level (c45 m AOD) was abandoned prior to 120 ka (the last interglacial), and the Boulder Chamber route (c60 m AOD) prior to 230 ka. Correlation of these levels with those of the Crook Peak caves and correcting for the 7 m difference in the current resurgence levels would suggest that the lowest parts of Denny's Hole and Sandy Hole (c35 m AOD) were abandoned prior to 120 ka, whilst Foxes Hole and Picken's Hole (c52 m AOD) were abandoned by 230 ka. This chronology is supported by the mass spectrometric uranium series age of 200 ka on the flowstone capping the calcite breccia at Picken's Hole. The chronology allows the intermediate levels and lower levels in Denny's Hole and Sandy Hole to be active during MIS 7. At least 2 sea level highs to just below present day levels are known for this time (c240 ka and 200-210 ka, evidence for a late MIS 7 high at c170 ka is equivocal), there is also a late MIS 9 high at 290 ka (the main MIS 9 high being at c320-330 ka; Spratt and Lisiecki, 2016). The Bristol Channel near Weston Super Mare was incised to a maximum of -27 m AOD during low sea levels, whilst this increased down-stream to c -37 m AOD south of Port Talbot (Gibbard, *et al* 2017). It is likely that full channel incision did not occur until at or after the main MIS 8, MIS 6 and MIS 2 low sea levels, particularly in the 'headwater' streams draining from the Mendips. Thus changes from phreatic to vadose conditions at the termination of warm phases are quite likely to have occurred within Denny's Hole and the other Crook Peak caves, with reflooding during the subsequent MIS 7 interglacial in Denny's Hole and the other lower caves. Interestingly dating of pond deposits in Boxwork Pit, Wind Cave, shows similar reversal in water-level although they are much smaller than at Denny's Hole (Bakalowicz, *et al* 1987). Palmer (2017) also noted that the pond calcite crust contained weathered and evaporite zones and suggested these were caused by water level variations related to glacial advances and retreats to the east.

Thus sea level changes superimposed on conditions of falling base level may well explain both the sudden change from earlier thermal water-filled anastomosing bedding to vadose condensation chamber development, and the presence of the clearly sub-aerial phase 4 pink calcites which postdate sub-aqueous manganese oxyhydroxide crusts (phase 3) and are followed by the main sub-aqueous calcite pond deposits of phase 6.

Based on the faunal remains of Unit 5 which overlies the crystalline breccia in Picken's Hole, this cave was first opened to the surface by MIS 5a (c70-90 ka), when it was used as a wolf den (Scott, 2018; Currant and Jacobi, 2011). Given the relatively small thickness of limestone at the Denny's Hole entrance and its present limited size, and specifically the comparative lack of archaeological deposits in First Chamber, the opening of the cave must have been late in MIS 3 or possibly MIS 2. The local climate during MIS 3 was highly variable but included periglacial conditions with cold winters and relatively warm summers (Van Andel, 2003). Conditions deteriorated to cold dry polar desert at the maximum of the MIS 2 glacial, before returning to periglacial and eventually present-day conditions c 11.6 ka at the start of the Holocene (Atkinson, *et al* 1987). Gelifraction would most certainly affect the cave roof once opened, and may be responsible for its arched rather than cupola form, and for the delivery of material to the breccia on the chamber floor. Similarly it may be responsible for generation of the terrace breccias, the subsequent phase of cementation being Holocene in age. The latter suggestion is supported by the lack of earlier phases in the terrace breccia cements, and the limited volume of cement. However, it is difficult to envisage within cave processes that could form the very clear truncated terrace morphology of these features. Possibly snow may have accumulated in the cave and its thawing allowed some dissolution along the breccia/snow contact, as occurs in post-glacial 'schactdolines' which generally have steep sides and a flat rock-cut? bottom where percolating snowmelt drives dissolution (Versess, 2017). Rates of dissolution by snowmelt are however low as the water has often not even equilibrated with atmospheric PCO_2 and lacks aggressivity (Ford, 1979; Küfmann, 2014). In the case of the terrace remains on the entrance slope, there may have been some mobilisation by snowmelt and runoff down the steep entrance slope (Bertran, *et al* 2009 and 2015).

Rates of fracture widening by thermal dissolution are given by Palmer (2007) and Andre and Rajaram (2005) and are of the order 1 mm/ka. These are slow but the anastomosing beddings are of limited aperture (max 25 cm), and the time scale for cave development is potentially very long (C 1.2 Ma based on rates of incision of Cheddar Gorge beneath the Mendip plateau surface). Palmer (2007) also gives rates of surface dissolution by condensation corrosion ranging from 0.3-1.0 mm/ka for a well-ventilated temperate karst to 1.0-1.4 mm/ka for Movile Cave, Romania where H_2S may be involved. Somewhat higher rates are given by Dublyansky and Dublyansky (2000) from the Russian literature, 0.5-4 mm/ka and 90-121 mm/ka for CO_2 and H_2S situations respectively, with somewhat higher rates calculated theoretically. These rates are far too low to generate chambers of 1 to 10 m width observed at Denny's Hole in the maximum 100 ka timeframe indicated by the chronology above. Dreybrodt, *et al* (2005) have numerically modelled the condensation corrosion process. The rate of dissolution is directly proportional to the temperature difference between the thermal water pool and the cave roof temperature, with shallow caves having a lower roof temperature for a given surface temperature than deep ones. The rate is also directly proportional to the calcium carbonate concentration of the condensed waters, which is determined via rapid equilibrium with the PCO_2 of the cave atmosphere. Figures presented in Dreybrodt, *et al* (2005) are somewhat confusing as the exact conditions are not always explicitly stated, but expansion of a 1 m sphere to 3 m at a depth of 25 m would take c5000 ka for a 1ºC temperature difference, or c500 ka for 10ºC difference at atmospheric PCO_2 (60 mg/L $CaCO_3$ for dissolution to equilibrium). Major Mendip resurgences such as Cheddar have average concentrations of c 250 mg/L, whilst Dunnet's Spring is described by Barrington and Stanton as 'very hard'. Assuming a conservative value of 'very hard' as 300 mg/L $CaCO_3$, carbonate dissolution wholly due to carbonic acid and complete enclosure of the cave atmosphere, the timescale reduces to 100 ka, and to 50 ka at a likely maximum value of 600 mg/L. The highest rates could explain the development of the smaller chambers, but for First Chamber appear too short, although the volumetric extent of the cave void prior to the vadose condensation corrosion phase is not clear, nor is the extent of subsequent modification by gelifraction. Comparison of the chronology and process rate estimates thus requires that the latter operate at very high but possibly attainable rates, or that some other process is responsible for incision of the facets and steps in the chamber floors. One issue is that so far is has been difficult to directly discriminate between sub-aqueous and vadose convective dissolutional forms, rather this relies on the presence of subsidiary features such as sub-aqueous bubble trails, or vadose karren and drip pits (Audra, 2009b). Although the temperature gradients required to produce sub-aqueous cupola forms would need to be large (Palmer, 2007 *cf* Rudnicki, 1989), there are other convective forms in caves such as linear wall facets which are clearly convective in origin and may result from quite small density differences (Kempe *et al* 2016). Thus some of the chambers may have evolved during a sub-aqueous phase where dissolution rates may have been higher than those of condensation corrosion. However, it is difficult to identify other processes which would produce the bedrock steps that are present within the cave.

CONCLUSIONS

In reviewing hypogene caves in the UK, Farrant and Harrison (2017) reports that:

> *"No definitive hypogene caves are known from the Mendip Hills, although some of the lead and zinc mineralisation was undoubtedly accompanied by karstic development. However, some isolated phreatic chambers and caves in the western Mendips may have a hypogenic origin. These include Axbridge Hill Cavern, Loxton Cavern and other nearby caves. These are associated with ochre (iron) workings, and may be associated with hypogene karstic development at or just below the Triassic unconformity."*

We have demonstrated that many of the features in Denny's Hole and the Crook Peak caves are indeed best explained by a hypogene speleo-genetic model. Specifically, many of the cave features are characteristic of thermal hypogene caves in which dissolution results from mixing and cooling of the resurging waters and from condensation corrosion. Eight detailed phases for cave development can be identified in Denny's Hole, but can be simplified to 4 different system states: 1) thermal and mixing? driven dissolution in water-filled anastomosing bedding plane system, 2) vadose condensation corrosion above a thermal pool generating cave chambers, 3) fluctuating sub-aqueous to vadose conditions with deposition of iron and manganese oxyhydroxides and secondary carbonates, and 4) a late stage with gelifraction and subsequent speleothem deposition. This scheme can be set into a chronology constrained by the uranium series dated rate of base level lowering at the nearby Cheddar Caves resurgence, and from a consistent mass spectrometric uranium series age of 200 ka from Picken's Hole. This chronology would suggest that the bedding anastomoses developed prior to MIS 9 when Picken's Hole was still functional and was likely subject to precipitation of the carbonate cements of Unit 6, whilst the condensation corrosion and secondary precipitates in Denny's Hole were associated with MIS 7, the lowest known part of the system at Sandy Hole being drained by MIS 5. The higher caves were then exposed to cold conditions during MIS 4, 3 and 2, when both Picken's and later Denny's Hole were opened to the surface. Compared with known process rates, the assignment of system states 2 and 3 to MIS 7 presents some problems, but alternative chronologies and processes are difficult to envisage. Detailed isotopic and petrological characterisation of the depositional phases, and their dating would help in this respect.

The thermal hydrological system which gave rise to the caves probably compares closely to the well-studied example from the Buda karst, Hungary (Madl-Szonyi, *et al* 2016). The thermal waters derive from deep circulation in the Carboniferous Limestone where it is confined below the Mercia Mudstone beneath the adjacent lowlands, and rise up to the lowest available outlet along fractures associated with the Bleadon fault just to the north of the caves.

Mixing of these more mineralised and probably reducing waters with shallow oxygenated meteoric recharge from the elevated limestone massif may also occur generating carbonate undersaturation, and in the case of precipitation of iron and manganese oxyhydroxides, could provide an additional source of acidity. The geochemistry and behaviour of Dunnet's Well the probably current outlet from the system may be instructive

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