

COASTAL TUFAS AND SPELEOTHEMS OF PRUSSIA AND STACKHOUSE COVES, SOUTH-WEST CORNWALL

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Within Mount's Bay on the South-West coast of Cornwall, Late Quaternary marine transgressions have substantially incised faulted Late Palaeozoic sedimentary and intrusive rocks to produce a series of coves, *zawns* (geos) and littoral caves. Prussia and Stackhouse coves exhibit particularly good evidence for at least two former sea-level stands. Fault-controlled caves, cliff-top springs and man-made modifications, dating back to at least the late 18th Century, have produced a distinctive suite of tufa and speleothem deposits. Flowstones and coralloids, only identified in Stackhouse Cove, can be dated to the historic period. Tufa deposition predates the speleothems and the final stages of the postglacial sea level rise and has continued into the historic period. Analyses were undertaken on tufa and speleothem samples, which included coralloids, using scanning electron microscopy (SEM), energy-dispersive spectrometry (EDS) and powder X-Ray diffraction (XRD). The analyses revealed tufas mainly composed of calcite and coralloids, associated with biofilms, containing monohydrocalcite and gypsum.

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INTRODUCTION

In Britain tufas and their underground equivalents, speleothems, usually occur in inland areas, where massive limestones form the bedrock and are characterised by karst and surface springs. However, Howie and Ealey (2009, 2010), drew attention to the widespread occurrence of coastal calcareous tufa/speleothems (Figure 1) on the cliffs and in sea caves of Cornwall where limestone beds are relatively sparse or absent.

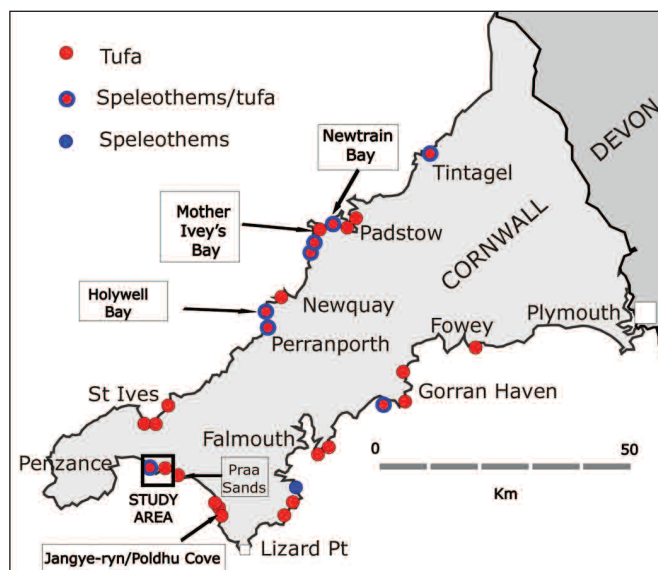


Figure 1. Tufa and speleothem map showing locations of sites mentioned in text. Mount's Bay refers to the area between Penzance and Lizard Point.

Howie and Ealey (2009) reported the presence of tufa in Prussia and Stackhouse coves, on the South-West coast of Cornwall (Figure 1). In this paper, these tufa occurrences and their setting are described in more detail and their origin discussed. The area contains an almost complete Mid-Late Pleistocene record, hitherto virtually undocumented, of former Quaternary sea levels, and has been subject to considerable man-made historical modification, allowing the age of the tufa bearing cliff faces to be estimated with some confidence. Speleothem occurrences, confined to Stackhouse Cove, have formed entirely on historically dated man-made structures and are reported for the first time.

BACKGROUND

History

The names Prussia Cove and Stackhouse Cove reveal their 18th Century history. Prussia Cove is not a single cove, but comprises Piskies, Bessy's, King's and Coules's coves (Figure 2). The overall name Prussia Cove for these four coves, lying in the lee of Cudden Point, is derived from the Carter brothers who used this area as a smuggling base in the mid-late 18th Century. John Carter (1738-1803), the second oldest, greatly admired Frederick The Great (1712-1786) in his youth and self-styled himself the King of Prussia (Waugh, 1991), hence the overall name Prussia Cove, and King's Cove for the easternmost cove where he had his house. Bessy's Cove is named after Bessy Bussow who kept the local alehouse during the time of the residence of the Carter brothers.

Stackhouse Cove is named after John Stackhouse (1741-1819) who is probably best known for his treatise on seaweeds – *Nereis Britannica*, published in a number of volumes between

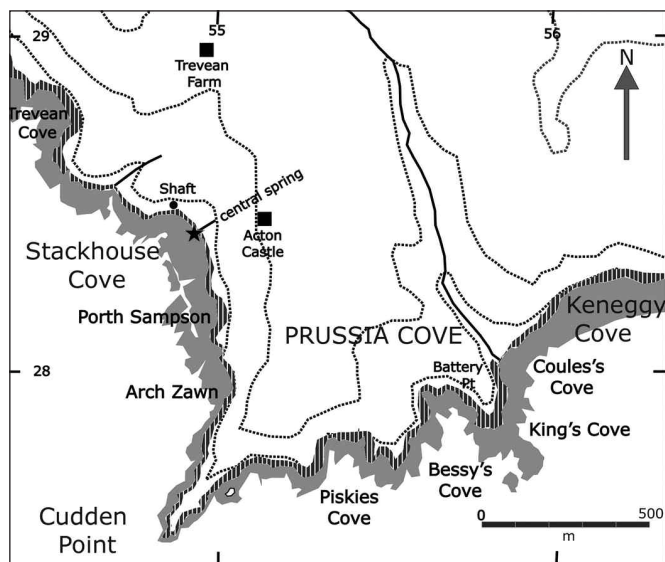


Figure 2. Sketch map of Prussia and Stackhouse coves. Shore platform shaded grey. Asterisk marks Rock-cut bath no 2.

1795 and 1802 (Caldwell, 2008). Between 1773 and 1775 he had purchased land above the cove and built Acton Castle, (named in memory of his wife's father) essentially as a privately owned field centre for his subsequent seaweed studies in the cove below. Large-scale holding tanks for his seaweed specimens survive in the grounds around the house.

Geology

Prussia and Stackhouse coves lie to the east and west respectively of Cudden Point, in areas dominated by slates of the Devonian Porthleven Breccia Member of the Mylor Slate Formation (Leveridge and Hartley, 2006) and minor masses of synsedimentary metabasic rock (Goode and Taylor, 1988), all dipping in a west to northwest direction. Cudden Point itself projects south-westwards into Mount's Bay and is formed of a massive metadolerite/gabbro sill, the northern faulted limit of which (Floyd *et al.*, 1993) runs between Arch Zawn and Piskies Cove (Figure 2). Similar metabasic rocks are developed immediately to the east and west of the area (BGS map sheets 351 & 358, 1984) where they dominate the higher ground landward of the coast. The Devonian strata are cut by numerous faults, trending NNW-SSE and WSW-ENE, related to Carboniferous-Triassic extensional faulting (Shail and Alexander, 1997).

The geology clearly controls the coastal geomorphology and development of the shore platforms in the area. The shore platforms are poorly developed around Cudden Point with its basic rocks, but are wider in the Mylor Slate Formation on either side. The coastal erosion of the extensional faults is clearly seen on the shore platform extending landwards into the cliffs, where they form numerous caves. These closely (35-70 m) spaced faults appear to have been equally as important in coastal erosion as the contrasting lithologies. On south-facing coasts the NNW-SSE trending faults and on west facing coasts the WSW-ENE trending faults have been preferentially eroded.

QUATERNARY EVOLUTION OF COASTAL CLIFFS

The Quaternary geology of this coastal section has received little attention in the literature to date. It receives no mention in the British Geological Survey memoirs of the area (Reid and Flett, 1907; Goode and Taylor, 1988). James (2003) noted sea-level notches at 4 m in Stackhouse Cove and at 6-11 m around Cudden Point. Our investigations indicate that these differing levels reflect two former sea levels that are traceable throughout the Prussia/Stackhouse cove area. Evidence for the higher sea-level is discontinuous. On the east side of Bessy's Cove,

northwest of Battery Point, there is a well developed - manganese cemented raised beach, well above the current high water mark (HWM), 1 m thick and characterised by subangular-subrounded clasts up to metre-scale. It is overlain by ~ 3 m of medium to coarse grained sand, capped by ~ 4 m of slaty head. In terms of elevation and lithofacies this section appears very similar to that described by James (1975) at Godrevy Fishing Cove (SW 654222). Northwest of Cudden Point (SW 550278), there is a good example of a raised beach developed on the dolerite sill, with a lateral abrasion notch, basal abraded sea floor hummocks and iron-cemented beach deposits, overlain by 'head' with vertically aligned clasts, interpreted as aligned due to periglacial freeze-thaw processes. The higher raised beach deposits reappear on either side of the cove at Porth Sampson (Figure 2) and continue to the southern margin of Stackhouse Cove. They reappear northwest of Stackhouse Cove on the higher shore platform there.

The lower sea-level, just above current HWM, is widely represented with good exposures of discontinuous raised beach deposits and cliff parallel palaeo-cliff notches around the cliffs between Coules's and King's coves, a well-developed palaeo-cliff notch and smaller cave notch confined raised beaches on the western side of Bessy's Cove. Farther west, Piskies Cove is characterised by current sea-level caves. To the west of Cudden Point at Porth Sampson there is a well developed raised beach, at least a metre thick, just above HWM and characterised by clasts up to metre-scale in an iron/manganese-cemented gravelly matrix. It is overlain by ~10 m of 'head', almost entirely covered by vegetation and subject to extensive landslips. At Stackhouse Cove evidence for the lower sea level stand is represented by a marked lateral abrasion notch at its southern end and raised beaches confined to mushroom-shaped caves.

'Head' deposits are not as well developed as they are farther west between Penzance and the study area (Figure 1) where thick sections dominate the coastal cliffs. In the Prussia/Stackhouse cove area they are generally confined to the upper levels of the cliffs where they overlie weathered slates with the exception of Porth Sampson where thick head deposits dominate. However, since the 'head' in this area has been extensively landslipped, the true distribution and thickness of 'head' is not known for certain. The erosion of well developed coastal head terraces in the area between Stackhouse and Coules's coves is considered to be the result of the increasing exposure to the SW waves and swell as the coastline projects increasingly south-eastwards away from Penzance (Figure 1). The preservation of 'head' aprons in more sheltered environments has been documented elsewhere in the South-West by Keene (1996) and Ealey and James (2011). It cannot, therefore, be assumed that there was no coastal 'head' terrace deposition; the current cliff faces in the area may well have been exhumed during the postglacial rise of sea level.

TUFA AND SPELEOTHEMS

Sampling and analytical methods

In this study samples of tufa and speleothem (Table 1) were carefully removed after field observations from selected localities in Bessy's and Stackhouse coves so as to ensure minimal damage to the sites. Finely ground samples were prepared for powder X-ray diffraction (XRD) analysis using a Siemens D5000 X-ray Diffractometer. After visual inspection using low power microscopy (Summit MicroFix USB Digital Microscope) selected samples were stub mounted and carbon coated for scanning electron microscopy (SEM). Imaging was undertaken with a Jeol JSM-5400LV Scanning Electron Microscope fitted with an Oxford ISIS Energy Dispersive Spectrometer (EDS) system for X-ray analysis. Field measurements of the pH of spring and cliff side/cave water run-off/drips were carried out using a Tecpel pH703 portable pH meter. API 5 in 1 test papers were employed in the field to indicate general water hardness ($\text{Ca}^{2+} + \text{Mg}^{2+}$ ppm).

Sample number and location	Sample description	Powder XRD analysis
ST1 Stackhouse – cliff-side dry zone SW 54894 28468	White indurated tufa	Calcite - major
ST2 Stackhouse – cliff-side wet zone above modern cliff notch SW 54928 28425	Buff/cream indurated tufa enclosing angular quartz grains	Calcite - major Quartz - minor Aragonite - trace Chlorite - trace Muscovite - trace
ST3 Stackhouse adit SW 54894 28468	Cream coloured brittle flowstone with outer layer of eroded coralloid	Calcite - major Monohydrocalcite - minor Quartz - trace Chlorite - trace
ST4 Stackhouse adit SW 54894 28468	Hard white crystalline laminated tufa/speleothem	Calcite - major
RCB1 Stackhouse – roof of rock-cut bath SW 54928 28425	Pale pink/green brittle branched coralloid	Monohydrocalcite - major Calcite - minor Gypsum - minor Quartz - minor
PC1 Bessy's Cove - cliffside above palaeonotch SW 55623 27925	Grey/white soft tufa	Calcite - major Quartz - trace
BST1 Bessy's Cove slipway SW 55633 27913	Hard white tufa	Calcite - major Quartz - trace

Table 1. Summary of the location, main characteristics and mineral constituents of tufa and speleothem samples.

Prussia Cove

In this part of the coast only tufa is present and is restricted to the central Bessy's Cove which lies landward of a saddle between Battery Point and the higher ground to the west (Figure 2). The cove is some 120 m wide at its mouth and extends landward 160–190 m and comprises two sub-coves (Figure 2), formed by the erosion of two prominent NNW-SSE faults. The cliffs surrounding the cove are some 15 to 20 m high. Two slipways are located on the west side and one on the east side, which is connected to a track, shown on the 1880 Ordnance Survey (OS) map, leading east around Battery Point to the former residence of John Carter at King's Cove. Drill marks, with diameters of 4–5 cm and depths of up to 50 cm clearly visible on their landward faces, suggest that blasting was involved in their construction. These slipways are connected on the rocky foreshore by a rutway (Smith-Grogan, 1998) made by/for carts. The majority of these structures almost certainly date at least back to the smuggling activities of the Carter family.

Tufa exposures are confined to the western sub-cove, the narrowest and most incised. Spring water (pH range 8.0 to 8.5 and hardness ≥ 180 ppm $\text{Ca}^{2+} + \text{Mg}^{2+}$) seepage occurs in the upper parts of the cliffs at the head of the cove and on its western flank. Tufa occurs on the rock-cut landward wall of the steeper inner slipway and the slipway itself and continues landwards on a natural cliff with a well developed palaeo-cliff notch, formed during the lower of the two former higher sea levels (Figure 3). Here tufa attains a maximum thickness of 10 cm. The cliff inland of this palaeo-notch has been subject to rockfall and tufa is present only as a coating. Fallen blocks close to the cliff base exhibit indurated tufa, with a thickness of up to 1 cm. Green filamentous algal mats cover the tufaceous seeps in the lower parts of the cliff but are replaced by moss higher up the cliff face. At the landward end of this narrow sub-cove, well above current HWM, moss covered tufa is forming on a bouldery raised beach and overlying boulder sized breccia. Powder XRD analyses of samples of tufa taken from the slipway (BST1) and above the palaeo-cliff notch (PC1) indicate major calcite content along with minor quartz (see Table 1).

Stackhouse Cove

Stackhouse Cove faces SW and is some 200 m long and fronted by a 120 m wide inter-tidal shore platform. The cove is backed landward by a low area between Acton Castle and



Figure 3. West side of Bessy's Cove, showing slipways and tufa coating cliff base palaeo-notch.

Trevean Farm with cliffs ~ 15 m high which are characterised by a subdued concave slope over wall profile. The concave upper slope may possibly reflect the degraded presence of the higher sea level. A spring occurs on the eastern side of this low area, which forms a series of lateral seeps in the upper cliffs here at the centre of Stackhouse Cove and is referred to in this study as the central spring. Flanked on either side by higher supra-tidal shore platforms, developed by the former two sea levels, this lower part of the shore platform is interpreted as a postglacial transgression feature. The former lower high sea level stand is clearly evidenced by the relic caves above present HWM in its cliffs. In pursuit of his seaweed studies in this cove below Acton Castle, Stackhouse left a remarkable rock-cut infrastructure, first described by Tangye (1997). It includes a slipway down to the cove, which the 1880 OS map indicates connecting to a track to Acton Castle above, a rectangular shelter, also shown on the same OS map, a remarkable bath cut some metres into the cliff, and on the shore platform another slipway and rock-cut bath, all located in the south eastern part of the cove. During this study an additional vertical shaft and horizontal mine adit were found in the northwest corner of the cove, apparently not reported or described to date, and probably not related to the activities of John Stackhouse.

Discontinuous tufa cascades extend from the southeast access slipway to the mine workings in the northwest part of the cove and onto the higher parts of the shore platform bordering the cove to the north. In the vicinity of the slipway they are widely spaced, thin, and vary in texture from brown to green active vegetated spongy forms to grey-white indurated encrustations. Mosses and grasses dominate the flora in this supratidal location. The presence of tufa on the landward side of the rock-cut slipway and on the edges of the rock-cut shelter indicates that it has formed here in historical times.

Tufa is particularly well developed in the area immediately seaward of the central spring (Figure 2). The intervening area between the spring and slipway is relatively barren. This area is indented and is interpreted as more subject to active coastal erosion. In the central spring area the tufas are cream to buff in colour, of gritty texture and are undoubtedly the best developed and thickest (20-50 cm) in the whole area. They are clearly visible from a distance as a variety of green filamentous algae grow in close association with the tufa. These include *Blidingia minima*, *Cladophora glomerata*, and *Rhizoclonium hieroglyphicum*. In places these green algae host blue-green algal cm-sized blebs. Higher up the cliffs mosses and grasses predominate. The tufa deposits extend from where the upper concave slope steepens to the base of the lower slope over wall cliff, where they are undercut by a modern basal cliff abrasion notch (Figure 4) and locally exhibit rillenkarren (Lowe and Waltham, 2002). Powder XRD analysis of a sample of this tufa (ST2) gave major calcite, minor quartz and trace aragonite, chlorite and muscovite (see Table 1). Farther west, the vegetated active tufaceous seeps die out, but the remains of former white indurated tufa cascades are observed descending the cliffs. Powder XRD analysis of a sample of this indurated tufa (ST1) indicates the presence of calcite only (see Table 1). Present day exposures of speleothems are entirely confined to Stackhouse Cove where they occur in the rock-cut bath no. 2 of Tangye (1997) and man-made voids farther west, probably associated with mining.



Figure 4. Stackhouse Cove. Modern cliff base notch with rillenkarren in associated tufa overhang. Decimetre spaced scale pole.

Rock-cut bath no. 2

This structure (Figure 5) lies immediately beneath the low point of the cliff and coincides with seeps originating from the central spring above, the water of which is slightly alkaline (pH 7.5-8 and hardness ≥ 180 ppm $\text{Ca}^{2+} + \text{Mg}^{2+}$). It appears to have been first described by Tangye (1997) on whom the dimensional data here are largely based. It is approached via an adit-like tunnel, the entrance of which lies ~ 2 m above the present beach to which steps, now largely eroded by the sea, were cut. This tunnel, 4 m long, 0.4 m wide, and 1.8 m high, and coated with green/purple algal biofilms (Figure 6), leads into a square (2.44 m) rock-cut chamber, into the floor of which

a rectangular rock cut bath (1.83 m x 0.84 m) and 0.75 -1.25 m deep has been cut. On the northern side of the inner chamber a rectangular feed shaft some 6 m deep has been cut to capture the seeps on the cliff above which enter the chamber below through a smaller (0.84 m x 0.48 m) oval hole. This sophisticated freshwater fed rock-cut bath was undoubtedly constructed on the instructions of John Stackhouse and differs from the more common 18th-19th Century sea water baths in Cornwall and farther east. It is likely that this was the bath that he employed a mason from Bath to cut rather than the double-bed sized sea water bath cut on the foreshore (Rock-cut bath no.1 of Tangye, 1997) as Caldwell (2008) suggests. Stackhouse had already employed the Bath architect John Wood, the younger, to design Acton Castle and later had a house in this spa town.

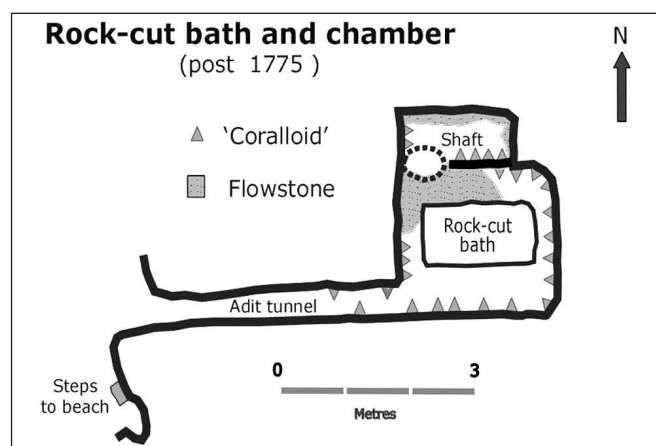


Figure 5. Sketch of rock-cut bath no.2, adapted and modified after Tangye (1997).



Figure 6. Green/purple biofilms in the entrance of Rock-cut bath no.2. The red algae have been identified as *Audouinella hermanni* and *Chroodactylon ornatum*, which flourish in low light conditions. Tunnel height 1.8 m. Photograph: Geoff Purcell.

Speleothems (hard dripstones and flowstones) coat the west and north walls of the chamber around the rock-cut bath in the vicinity of the hole connecting the shaft above and the chamber and rock-cut bath below. They have a mamillated (dm-scale) appearance in their lower part around the bath and become more nodular (cm-scale) with vertical and horizontal ribbing higher up and into the north and west wall of the shaft itself. Here they pass upwards into vegetation covered tufa. Away from the influence of flowing water from the feed shaft the speleothems are developed as popcorn (Figure 7a) and fragile

spiked coralloids (Figure 7b) which can be seen on all walls of the chamber and its roof. Coralloids are also well developed on the shaded south and west walls of the vertical feed shaft. The environment within the bath chamber is constantly humid due to the flow of spring water down the feed shaft. Daylight penetration is direct through the entrance tunnel to the chamber and down the feed shaft, diffuse at the back of the chamber with around half the roof receiving no light. There is limited percolation of spring water through the bedrock walls and roof of the bath chamber and entrance tunnel. These areas

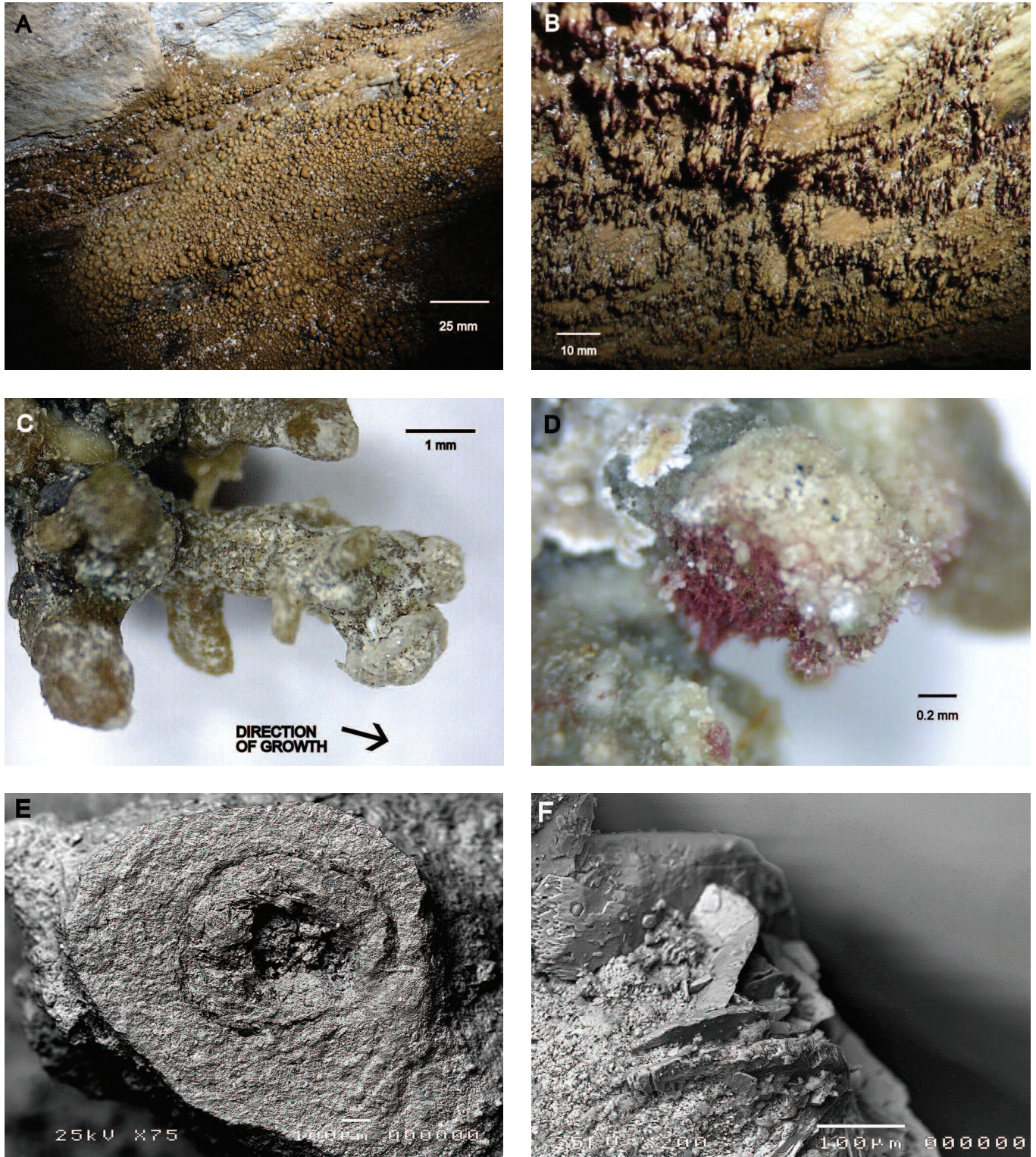


Figure 7. Photographs of popcorn coralloids (a) on walls and elongated 'spiked' coralloids (b) on roof of Rock-cut bath no.2 chamber. Digital microscope images of individual roof 'spiked' coralloids showing branched structure (c) and tip and side coated with colony of purple to red algae (d). (e) SEM image of fractured roof coralloid branch showing concentric growth structure. (f) SEM image of uneroded roof coralloid branch terminating in growth of gypsum crystals with curved habit.

are continuously wetted, presumably by capillary action and splashing. Powder XRD analysis (Fig. 9) of a roof spiked coralloid sample growing in diffused light (RCB1) indicates the presence of predominantly monohydrocalcite, along with minor calcite and trace quartz and gypsum (see Table 1). The individual spiked coralloids, which are each separated by a few millimetres, are about 5 to 10 mm in length and, at low magnification, are noticeably arborescent in structure with round to oval branches or horns of sub-millimetre to 1-2 mm length and diameter (Figure 7c). The tips and sides of the coralloid branches are commonly coated with colonies of purple to red coloured algae (Figure 7d). These coralloids give the appearance of being phototropic, *i.e.* elongated growth towards the light which enters through the horizontal adit and the shaft (Figure 7b). Another factor in their growth may be deflection of growth tips by predominant air movement in the chamber from the entrance to the shaft and *vice versa*. Individual coralloid branches exhibit concentric growth

structure (Figure 7e). Figure 7f shows the smooth surface of an uneroded roof coralloid branch terminating in growth of gypsum crystals exhibiting unusual curved habit. EDS analysis of this sample shows that gypsum terminates the coralloid branch, which is composed of monohydrocalcite and calcite (Figure 10). The intimate relationship between coralloids and algae is clearly seen where surface colonies adhere via filaments to the coralloid (Figure 8a).

Adit

This adit or exploratory horizontal mine shaft lies at the back of small cave 3 m wide, 2 m high and 6 m deep, cut by current sea level into the base of the cliff. The roof of this cave is formed by iron-cemented raised beach deposits, with traces of green copper mineralization. These raised beach deposits can be discerned through a coating of white tufa in the cliffs above, infilling what appears to have been a relict former higher sea

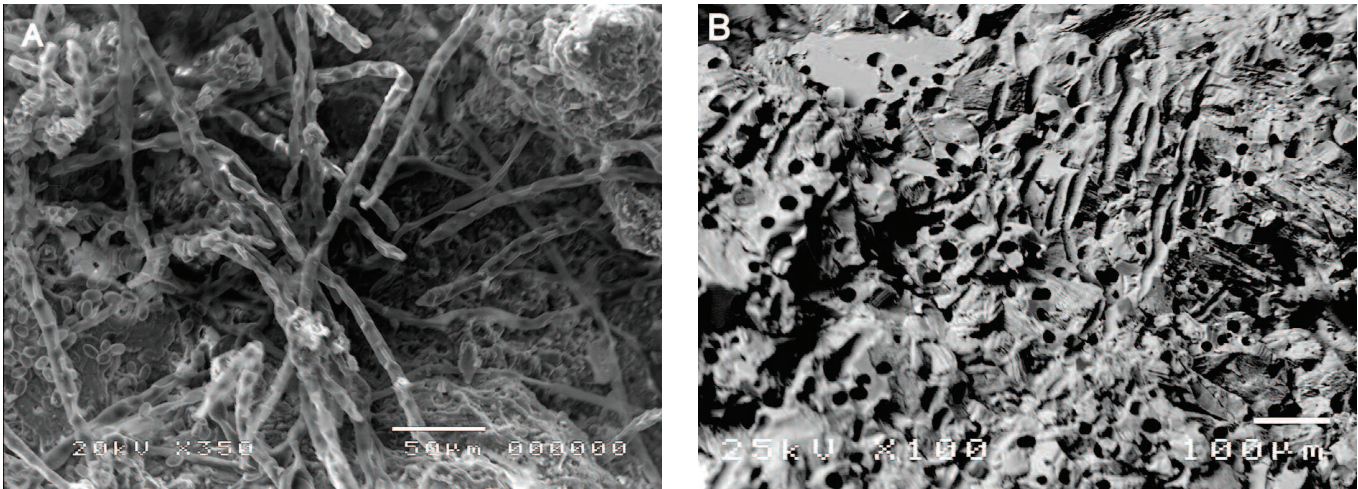


Figure 8. (a) SEM image of 'spiked' coralloid branch with adhering algal filaments. (b) SEM image of Stackhouse adit laminated speleothem showing dissolution by burrowing/boring organisms or carbonate precipitation around filamentous algae which have subsequently decayed.

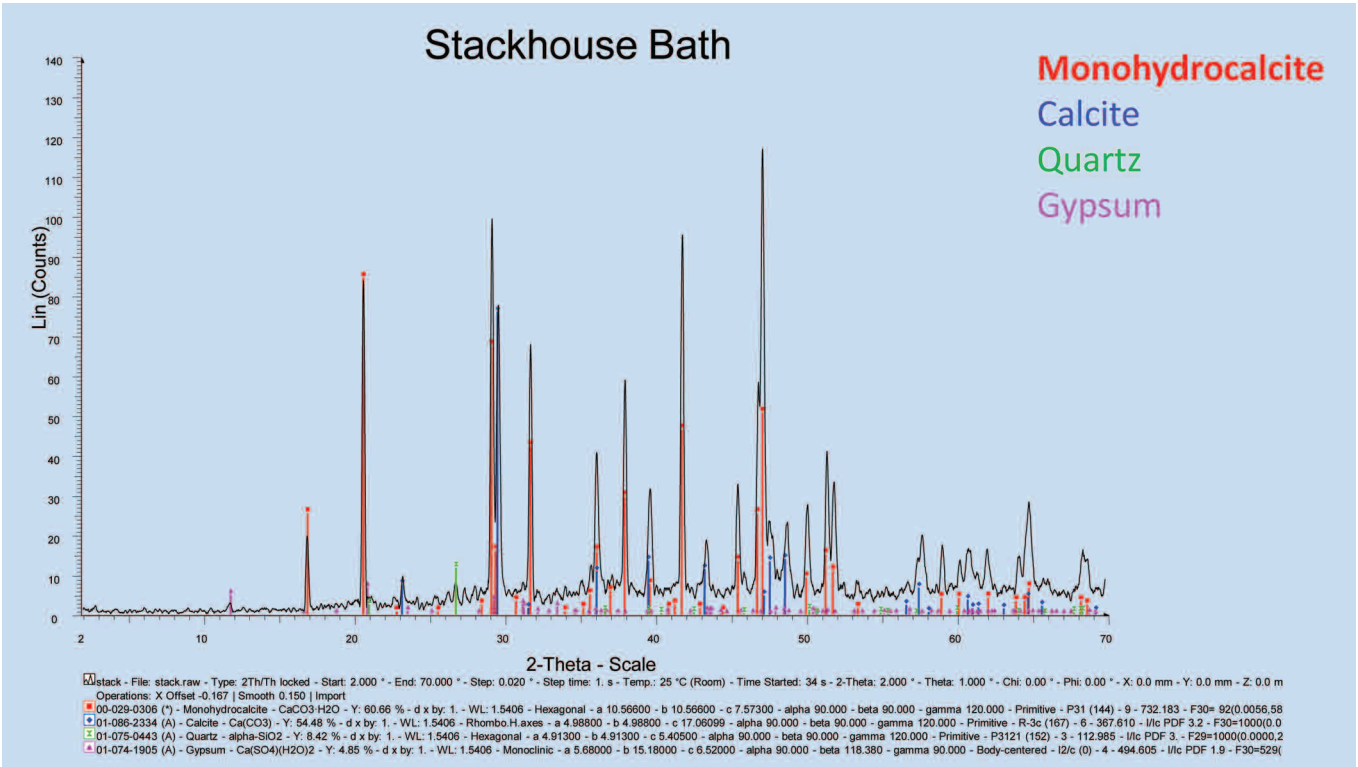


Figure 9. Powder XRD of 'spiked' coralloid from roof of bath chamber indicating composition of monohydrocalcite, calcite, gypsum and quartz.

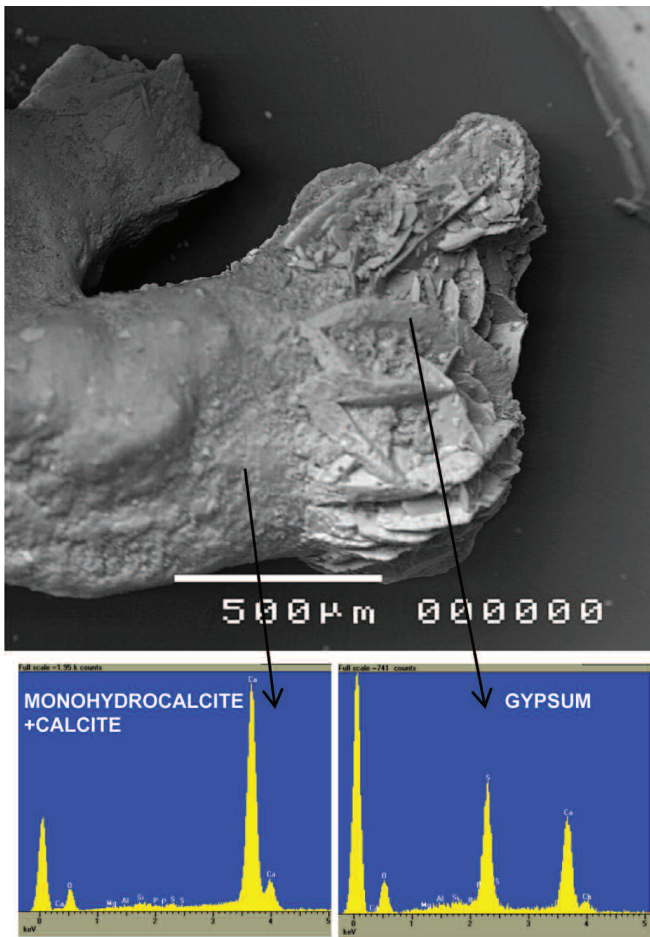


Figure 10. SEM image of coralloid from roof of bath chamber with two EDS analyses: left at the spot arrowed indicating monohydrocalcite/calcite in the coralloid stem (Ca and O peaks prominent), right at the spot arrowed on the terminal crystal indicating gypsum (Ca, O and S peaks prominent). Specimen carbon coated.

level cave with similar dimensions to the current sea level cave (Figure 11). The adit itself has been driven some 30 m into the cliff along the trace of a northwest trending normal fault, exhibiting green copper mineralization in places. Its floor on the west side is undercut by the current sea level so that it is some 30 cm above the modern beach of quartz vein-derived rounded clast gravels/pebbles. Both the former higher and higher modern caves follow the hade of the fault as does the recent erosion of the adit floor. Speleothems in the form of dm-scale vertical sheets coat the east wall of the adit and locally cover its floor, indicating that they post-date the construction of the adit. The sheets comprise laterally alternating areas of thin flowstones and mm-scale coralroids, considered to be the result of erosional flaking (Figure 12). Powder XRD of a bulk sample of this material (ST3, see Table 1) reveals major calcite, minor monohydrocalcite, along with trace quartz and chlorite. Here and elsewhere in the adit there are indications of oscillating conditions, sometimes favouring coralloid formation and at other times flowstone layers. At the adit entrance the speleothems are associated with green/purple algal biofilms on the partially daylight walls (Figure 13). Near the entrance and on the side of the modern cave there are indications that the speleothems are being actively eroded. The speleothems here are thicker and exhibit well developed lamination. Powder XRD of a sample of this material (ST4, see Table 1) reveals calcite only. SEM examination of a sample from this area has perforated texture indicating either a degree of dissolution, possibly caused by burrowing or boring by organisms, or carbonate precipitation around filamentous algae which have subsequently decayed (Figure 8b).



Figure 11. Adit cave entrance and relict former higher sea level cave above, outlined in black, and fault trace in red. 33 cm long hammer for scale.

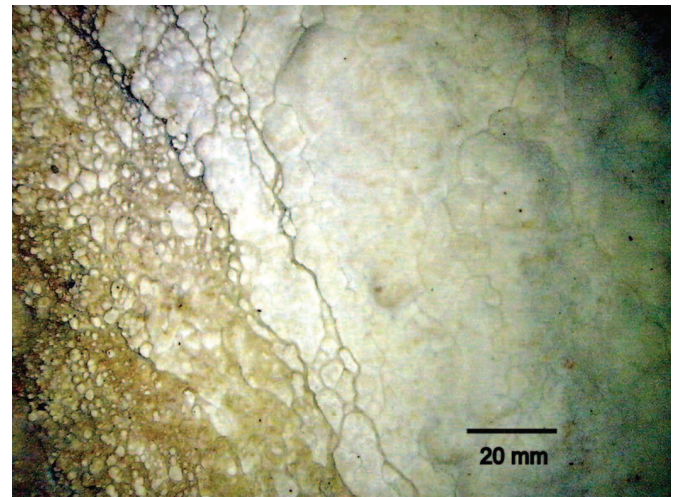


Figure 12. Laterally alternating mm scale coralroids and flowstone layers, revealed by erosional flaking and indicating changes in the speleothem environment during deposition.



Figure 13. Biofilms on outer adit walls.

Vertical shaft

This lies in the north-west corner of the cove where the cliffs start to rise. It occurs in a composite cave, which has formed along a low-moderate west dipping fault parallel to the bedding/foliation and comprises a former higher sea level cave ~15 m deep which is undercut by a wider modern cave. Howie and Ealey (2009) drew attention to tufa/speleothems coating the higher cave iron oxide-cemented raised beach deposits. Re-examination of this exposure indicates that the central part of these raised beach deposits, now confined to the sides of the former cave, have been eroded or removed by human activity and that the tufa/speleothems coating the east side of the breach are heavily coated in green and purple coloured algae (see Howie and Ealey, 2009; figure 4b). At Pargodonnell Rocks hosting the well known Giant's Rock erratic, immediately west of Porthleven, similar cave confined iron oxide-cemented raised beach deposits (Ealey and James, 2001) have been breached in the construction of an adit. Therefore the breaching is tentatively attributed to mining activities in the cove, clearly evidenced by the adit, discussed above.

The vertical shaft is approached through the west side of the modern cave which is some 25 m long, and lies some 12 m from the entrance of the cave. The shaft is cut into the roof of the cave some two metres above the floor and is rectangular (1.2 m x 1.85 m). Daylight is seen at its top. The shaft is entirely covered by flowstone with local evidence of black cyanobacterial staining. The flowstones clearly coat a blast shot hole, ~4 cm in diameter and 30 cm long (Figure 14). Coralloids occur on the seaward side roof of the modern cave where it is contiguous with the bottom of the shaft. The much overgrown surface expression of the shaft is located immediately north of the SW Coastal Footpath at an elevation of at least 20 m OD where it is shown as a shaft on the 1880 Ordnance Survey map. This shaft is clearly older than 1880 and given the blast hole diameter could date back to the 18th Century. When the use of gunpowder shot hole blasting was introduced into the mines of the area in 1689 (Earl, 1978), the holes were wider than the commonly used one inch (2.54 cm) of the 19th Century (Paris, 1818). The construction of this shaft may well have diverted calcium carbonate-rich waters from the cliffs immediately east and thus explains the observed lack of active tufa seeps in this sector.



Figure 14. Flowstones coating vertical shaft walls and gunpowder blast shot hole. Decimetre spacing highlighted on tape measure. Photograph: Geoff Purcell.

DISCUSSION

The coastline in the area is characterised by three vertically juxtaposed sea levels, ranging from well above sea level to the current level. Each successive lower level has incised its

predecessor, either as a result of sequential drops in eustatic interglacial sea level rises or regional uplift. The importance of pre-existing faults in coastal development during the Quaternary is striking and has resulted in the relatively common lateral displacement of the coastal sea caves in the area in the fault down-dip direction (Figure 8) with progressively lower sea-levels. The presence of tufa/speleothems acts to highlight ongoing coastal erosion during the historic period at the base of the cliffs and landward erosion of fault aligned caves in the area.

Powder XRD analysis of the tufa and speleothems (Table 1) indicates that the dominant mineral is predominantly calcite with indications in the Stackhouse rock-cut bath coralloids that monohydrocalcite ($\text{CaCO}_3 \cdot \text{H}_2\text{O}$) is the major carbonate mineral. The established mechanism for calcite tufa and speleothem deposition is via rainwater permeating the CO_2 -rich soil environment becoming super-saturated with CO_2 and effectively an acidic solvent. Where this CO_2 -rich water meets limestone CaCO_3 is dissolved and when this super-saturated solution emerges as a spring or in a cave CO_2 is degassed as a result of the pressure drop and CaCO_3 is precipitated. In the area investigated here spring water and cliff side seeps pass through soil and 'head' and will become saturated with CO_2 , however, here there is no obvious immediate bedrock source of calcium. The field measured hardnesses of the Stackhouse Cove central spring water and cliff side seeps/drips in Stackhouse and Prussia coves ($\geq 180\text{ppm Ca}^{2+} + \text{Mg}^{2+}$) coupled with pH ~ 8.0 indicate that these are the source of calcium carbonate for speleothem and tufa deposition. As such the source appears to be groundwater based and derived from the adjacent hinterland, and is unlikely to be Holocene coastal dunes as is probably the case in other neighbouring sites on the south coast (Howie and Ealey, 2010) like Praa Sands, Gunwalloe Church Cove, and Poldhu Cove (Figure 1). Possible sources of calcium are calcite mineralization, associated with the Carboniferous-Triassic extensional faulting (Power *et al.*, 1997), weathering of the pre-Variscan metabasites as observed elsewhere in Cornwall (Reid, 1907), or Last Glacial loess (Bristow, 2005). Speleothems and tufa are known to form in basalt-rich terrains elsewhere. L  veill   *et al.* (2000) describe speleothems from Quaternary caves developed in Pliocene basalts in Hawaii and Pawar *et al.* (1988) describe Holocene tufa from Deccan-Trapp basalts.

Tufa occurrences and their thicknesses in the study area not surprisingly reflect the availability of seeps and age of the faces on which they are developed. They are generally thin on historical man-made slopes associated with the slipways in Bessy's and Stackhouse coves and areas of recurrent cliff instability, caused by coastal erosion. The thickest tufas lie seaward of the central spring in Stackhouse on a cliff, interpreted to have formed during the last Ipswichian/Eemian interglacial. Given the caveat that the cliffs in this area were probably subject to periglacial processes, the tufa here is unlikely to be older than Holocene. The ecological zonation, identified in this investigation, of filamentous algae in the lower part of the cliffs and mosses higher up or more landward of the splash zone is also characteristic of other tufa sites in Cornwall (e.g. Mother Ivey's Bay, Holywell). Provided that these macroscopic biofacies can be identified at the microscopic level, this zonation may provide a potential proxy for the Post-Glacial rising sea level in coastal tufa sites.

The speleothems reported in this investigation have clearly formed over the last 200-300 years in man-made voids and are characterised by flowstones and coralloids. Stalactites and gour pools, seen elsewhere in natural coastal caves of Cornwall (e.g. Holywell and Newtrain Bay), are noticeably absent, presumably because of the steepness of the rock-cut faces and largely channelised vertical feeds. Their value as climate proxies is clearly limited. The speleothems of Stackhouse Cove are considered of greater significance for their association with green and red algae and for their well-developed coralloids with unusual mineralogy (monohydrocalcite and gypsum). The role exerted by organisms on the formation and dissolution of speleothems, for both of which there are some indications in

the man-made voids of Stackhouse Cove, is currently a matter of considerable discussion (Taboroši, 2006; Jones, 2010; Jones, 2011).

Monohydrocalcite is a relatively rare mineral that has been reported from lake sediments (Taylor, 1975; Armenteros, 2010), an arctic fjord (Dahl and Buchardt, 2006), beachrock (Swainson, 2008) and, more significantly for this discussion, in speleothems (Fischbeck and Müller, 1971; Broughton, 1972; Hill and Forti, 1997; Lévillé *et al.*, 2000). The chemistry, mineralogy and biomineralogy of monohydrocalcite is currently the subject of wide-ranging investigation (Neumann and Eppe, 2007; Kimura and Tomoyasu, 2011). Differing modes of monohydrocalcite formation have been advocated in limestone caves: (1) chemical precipitation from either airborne water droplets/aerosols or at the solution/atmosphere interface (Fischbeck and Müller, 1971) or (2) biological activity (Broughton, 1972). However, the formation of monohydrocalcite described by Fischbeck and Müller (1971), Broughton (1972) and, in basalt caves, by Lévillé *et al.* (2000) is associated with dolomite and hydrated magnesium carbonates including magnesite, hydromagnesite and nesquehonite. Additionally monohydrocalcite in the lacustrine environment occurs with early dolomite, in waters with high Mg/Ca ratio and pH >8.6 (Taylor, 1975), when magnesium or phosphate ions, or organic material, inhibit the formation of calcite and aragonite, at water temperatures of <40°C or in water supersaturated with respect to monohydrocalcite (Kelts and Hsü, 1978). In this study powder XRD reveals no evidence of magnesium mineralisation in any of the samples analysed. The popcorn and spiked coralloids reported here are growing in effectively permanent humid air and on moist non-limestone substrates, probably as the result of highly calcareous and alkaline (pH of 8-8.5) water entering the chamber. These conditions, together with the biological activity (algal growth) observed on the lit walls and roof of the chamber, are considered to be the reasons for the formation of monohydrocalcite here at Stackhouse Cove.

Although the association of calcite with gypsum in speleothems is well known (Hill and Forti, 1997), the association of monohydrocalcite with gypsum is rarely reported. Smith and Huntington (2010) noted this association in XRD analysis of haematic clays in drill cores from the Birrindu Basin, Northern Australia and Shahack-Gross and Finkelstein (2008) in experimental work on ashed *Tamarix aphylla* wood and leaves soaked in water. Gypsum and monohydrocalcite in speleothems is noted by Lévillé *et al.* (2000) in analyses of dried crusts in secondary deposits in basaltic caves where they suggest that 'both phases formed directly from evaporating water'. The association reported here would appear to indicate overgrowth of gypsum on monohydrocalcite under saturated conditions.

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