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Actively growing subaqueous stalagmites

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Abstract: In this study, stalagmites have been observed to be forming underwater. The stalagmites are found within a flooded horizontal mine adit, where the poolwater is supersaturated with calcite. Pool and drip water chemistry and hydrology were analysed over an annual field cycle. Stalagmite formation was observed to be from drip waters both undersaturated and supersaturated with calcite. Stalagmites were composed of calcite, and were poorly consolidated: all samples were compact on the side faces but several were unconsolidated underneath the splash impact point. Stalagmite morphology varied with drip fall height and overlying water depth. SEM and XRD analyses demonstrate that the stalagmites comprise calcite crystals of 50-200μm, and show no evidence of biogenic particles or binding. Subaqueous stalagmite formation can be postulated to be caused by the disturbance of the impacting drip of surface calcite rafts formed due to degassing and/or evaporative processes, as well as possible calcite precipitation from the mixing of waters at the drip impact point. The stalagmites form by the slow accumulation of calcite crystals, with occasional collapses until a stable structure is formed, which can ultimately be preserved in the rock record. The stalagmites observed in this study can be considered to be an example of the chemogenic precipitation of calcite by a combination of chemical and physical processes. Such evidence has been rarely reported before in either freshwater or marine environments, and should be preserved in palaeokarst environments.

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INTRODUCTION

Stalagmite deposition is generally reported not to occur in subaqueous conditions. It is accepted that conventional calcite stalagmite formation is subaerial and from the degassing of drip waters that contain elevated carbon dioxide concentrations (Holland *et al.*, 1964; Hill and Forti, 1986; Ford and Williams, 1989). Recently, Davis *et al.* (1990) argued that subaqueous helictites (sinuous growths of calcite 0.2 to 2.0mm in diameter and up to 100mm in length) are actively forming in Lechuguilla Cave, New Mexico. The proposed mechanism was chemogenic (the common-ion effect), where calcite-saturated water comes into contact with gypsum blocks, which dissolve and cause the water to come rapidly to calcite supersaturation. This water forms helictites where it enters a pool as a discreet flow. A similar formation process could apply to subaqueous stalagmite formation, where the drip waters have a different geochemical source, causing calcite supersaturation. Alternatively, the formation process may be more complex than simply a chemical reaction, with physical processes such as the displacement of surface calcite films by the impact of drips or the turbulent mixing of water by drip impacts being important. Either process may form more massive calcite precipitates that are likely to be lithified and thus preserved in the geological record. This report describes an example of calcite deposition that is primarily due to chemogenic and physical processes, forming subaqueous stalagmites within calcite-supersaturated mine waters in SW England.

RESEARCH SITE

Subaqueous stalagmites were first observed by the authors at Sharkham Point Iron Mine, South Devon, England (Grid Reference: SX 737546). The geology at Sharkham Point comprises a sequence of Mid Devonian shales, tuffs and limestones, extensively affected by Hercynian folding and thrust faulting (Smythe, 1973). Iron mineralization occurs within the limestone on the north side of the headland. The ore comprises haematite, with abundant barite and lesser amounts of calcite, dolomite and quartz, infilling irregular dissolution cavities in the limestone. The wall rock adjacent to these

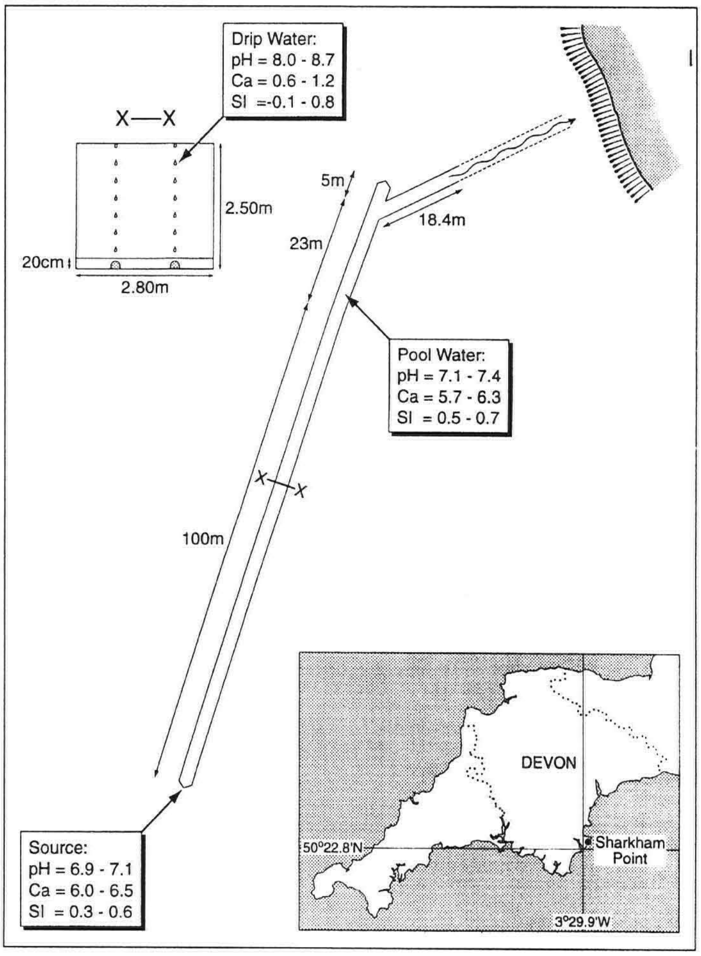

Figure 1. Survey of Sharkham Point Mine. Water geochemical data are shown in terms of pH, calcium concentration in mmol l^{-1}, and saturation index with respect to calcite. Minewater discharges through the mine entrance and flows over a rocky beach into the English Channel.

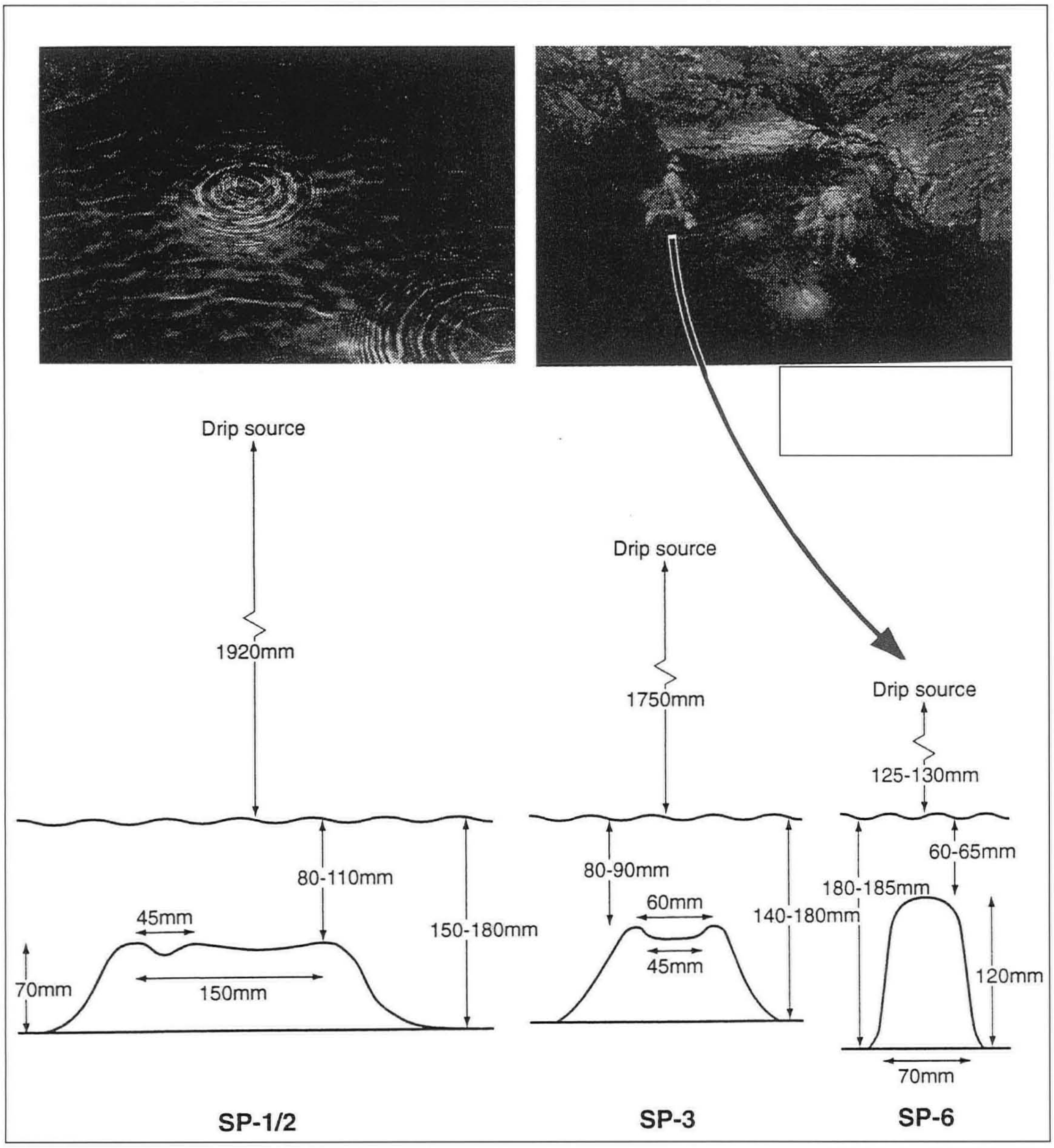

Figure 2. (a) Left: impact of drips with a 2m fall height into the calcite supersaturated pool, subaqueous stalagmites are visible at the base of the pool. Right: subaqueous stalagmites SP-6 and SP-7. (b) Stalagmite morphology of three typical subaqueous stalagmites: SP-1/2 with a double, c.2m fall height drip source, SP-3, with a single, c.2m fall height drip source, and SP-6, with a single, <20cm fall height drip source.

1875 the ore was worked from surface excavations and from adits dug from the coast on the north of the head (Burt *et al.,* 1984). The research site is a horizontal drainage adit (Fig.1) that is approximately 2.2 to 3.0m wide and 1.5 to 2.5m high, containing pooled water 30 to 40cm deep. The pool waters are held back by a tufa-cemented boulder dam near the entrance. Drainage from collapsed old mine workings at the enclosed-end of the adit provides the water supply, and overflow occurs at the adit entrance during the winter months. Calcite rafts form on the pool surface, predominantly at the outward end, and additional flowstone deposition occurs at the enclosed end, whereas tufa is deposited where the overflow water cascades over rocks at the mine exit.

Floor sediments, overlain by the pool water, include stalagmitic deposits. More than 40 such deposits occur; all associated with active drips from the roof of the mine (Figs.1 and 2). Visual inspection of the drip sources demonstrates the absence of stalactites in most cases. The stalagmites are poorly consolidated in their centre, and several have a splash cup on their upper surface. Stalagmite morphology is illustrated in Fig. 2b for stalagmites SP-1/2, SP-3 and SP-6. Significant variation in stalagmite morphology is observed between samples. SP-6 and SP-7 have no drip cup, a smaller diameter and a better consolidation than SP-1/2 and SP-3, which have a greater (2m) fall height (see Figs. 2a and 2b). The stalagmites are also highly friable; stalagmites with splash cups are unconsolidated within the cups to a depth of 2 to 3cm, whereas the remainder of the stalagmite is bound weakly. Those with no splash cup are bound weakly throughout.

SCIENTIFIC METHOD

Three discrete sets of observations were undertaken to confirm that the stalagmites are being deposited subaqueously:

1. The hydrological characteristics of both the pool water and drip waters feeding the stalagmites were observed over both an annual climatic cycle and over a period of several years to confirm subaqueous deposition;

2. The geochemistry of the pool water and drip sources was measured to determine geochemical controls on the deposition of the stalagmites;

3. Subsamples of stalagmite were taken to determine the depositional process and chemical constituency.

The hydrological characteristics of the pool waters were monitored at intervals of 4 to 6 weeks during the 1994 to 1995 period, with additional point samples taken over the period 1994 to 1997. Drip water sources that had associated stalagmites were also monitored for six sites reflecting a range of discharges and calcite saturation. Water samples for geochemical analysis (Ca^{2+}, Mg^{2+}, Na^{+}, SO_4^{2-}, Cl^{-}, K^{+}) were taken from four of the samples (drip sources SP-1/2 and SP-4 and flow sources SP-5 and SP-8) at 3-monthly intervals over the period 1994 to 1995, and analysed using standard MS techniques.

		SP-1 $l\ s^{-1}\ x10^{-5}$	**SP-2** $l\ s^{-1}\ x10^{-5}$	**SP-3** $l\ s^{-1}\ x10^{-5}$	**SP-4** $l\ s^{-1}\ x10^{-5}$	**SP-5** $l\ s^{-1}\ x10^{-5}$	**SP-6** $l\ s^{-1}\ x10^{-5}$	**Pool Depth** cm
19/08/94		5.2	1.9	3.1	0.4			
09/09/94		4.2	0.9	2.0	0.4	60	2.1	17.0
14/10/94		4.1	4.1	1.5	0.3	28	2.1	
11/11/94		31	33	1.7	1.7	1700	1.9	18.0
14/12/94		330	230	3.0	2.0	1100	2.0	
13/01/95		28	22	5.3	1.9	>10,000	2	18.0
17/02/95		38	15	15	2.9	>10,000	2	
16/03/95		26	26	8.8	1.6	>10,000	1.7	17.0
27/04/95		7.8	6.8	0.8	7.9	>10,000	1.8	
14/06/95		2.9	5.8	3.8	0.5	>10,000	1.8	15.0
06/08/95		1.7	3.7	0.1	0.4	63	2.0	
mean		45.5	31.7	4.1	1.8	>492	1.9	17.0
stdev		95.9	66.6	4.3	2.2		0.1	1.3

Table 1. Hydrological data for Sharkham Point Mine. SP-1 to 4 and SP-6 are drip sources, site SP-5 is a flowstone. Drip sources SP-1 and SP-2 are separated by 5cm, and feed one stalagmite (SP1/2). Drip rates are calculated from the time between consecutive drips and assume a constant drop volume of $0.15cm^3$.

Further samples for total ion chemistry (additional measurements of pH and HCO_3^-) were taken during 1994 to 1997. Total ion balances and saturation indices were calculated using PC WatEq (Rollins, 1987).

One stalagmite (that associated with the drip SP-1/2) was chosen for geochemical analysis, and removed from the mine. A subsample was taken for XRD analysis, the remainder cut and prepared for SEM analysis.

RESULTS

Observations of the pool water during the study period demonstrated that a mean depth of 15 to 25cm was maintained at all times, although a seasonal variation was discernible with a slight (<5cm) lowering in summer. This coincided with the decrease in inlet water discharge, overflow at the entrance of the mine ceased, and evaporation may have occurred. Maximum winter outflow was $0.01m^3s^{-1}$; with an estimated total pool water volume in the mine of $60m^3$, flow within the mine is laminar during winter overflow, and stagnant during most of the year. Drip water was monitored from six sites, and the results are presented in Table 1. All of them demonstrated variability typical of drip waters in the unsaturated zone (Smart and Friedrich, 1981), and exhibit active discharge at all sites during the study period.

Geochemical results are presented in Table 2. The pool water is highly supersaturated with calcite. The supersaturation is higher than typical in karst waters due to the high sulphate concentrations, probably derived from nearby mineral deposits. Both the pool waters and the drip waters have a high Na-Cl content, approximately 2% of the seawater mean (Wigley and Plummer, 1976), the source of which is sea-spray from the nearby English Channel. Geochemical results demonstrate that some degassing occurs between source and overflow site, with the poolwater remaining supersaturated at all times. Conversely, drip water samples are supersaturated (SP-5) and undersaturated (SP-1/2, SP-3 and SP-8) with calcite, and these correspond perfectly to whether active subaerial stalactite and

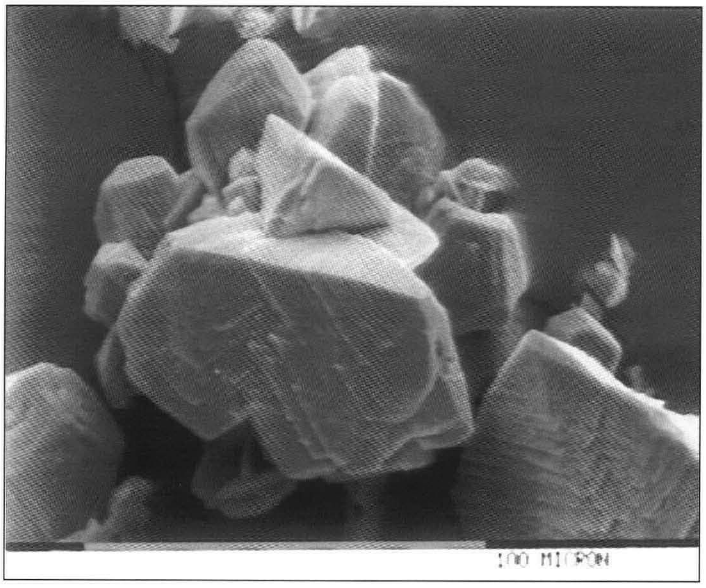

Figure 3. (a) Cross section of stalagmite SP-1/2 under SEM. Calcite crystals demonstrate no preferred orientation and are poorly consolidated, and show no evidence of bacterial action during crystal coalescence.

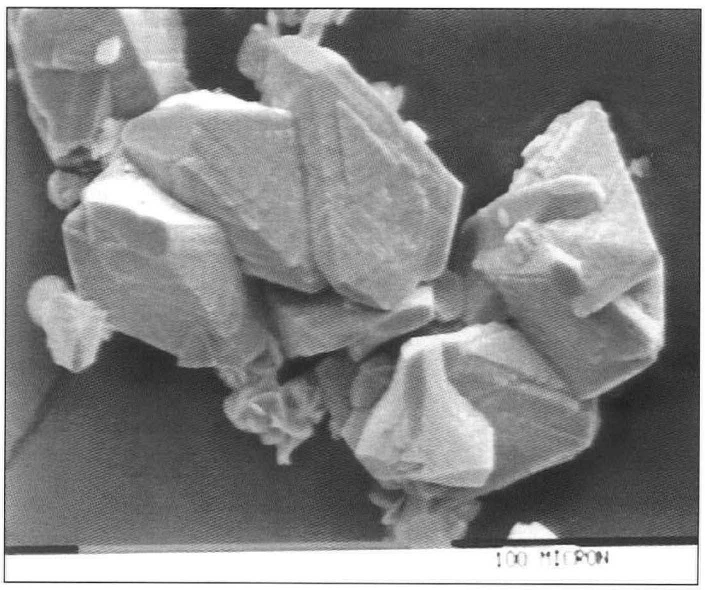

Figure 3. (b) Sample of calcite raft from the same site; note the similarity of form of crystal to that observed in the stalagmite, with the exception of an additional $<10\mu m$ fraction.

Site		Conductivity µS	pH	Ca^{2+} Mmol l^{-1}	Mg^{2+} Mmol l^{-1}	Ca/Mg	Cl^{-} Mmol l^{-1}	Na^{+} Mmol l^{-1}	Na/Cl	K^{+} Mmol l^{-1}	SO_4^{2-} Mmol l^{-1}	HCO_3^{-} Mmol l^{-1}	Ion balance %	Saturation Index calcite	Saturation Index dolomite
SP-1	mean	1794	8.12	0.69	0.59	1.18	9.06	12.22	1.35	0.11	0.90	2.47	0.76	-0.17	-0.50
	sd	177	0.27	0.07	0.07	0.18	0.69	1.65	0.18	0.01	0.26	0.31	0.38	0.16	0.44
SP-4	mean	2322	8.13	0.85	0.84	0.92	12.5	15.10	1.20	0.17	0.92	2.60	4.95	-0.12	-0.26
	sd	32	0.14	0.19	0.07	0.15	0.82	1.62	0.29	0.01	0.62	0.28	2.81	0.05	0.02
SP-5	mean	1068	8.34	0.99	0.64	1.79	5.38	7.25	1.37	0.09	0.63	3.10	4.50	0.44	0.65
	sd	145	0.28	0.16	0.15	0.52	0.51	0.46	0.12	0.06	0.28	0.14	0.30	0.50	0.89
SP-8	mean	908	8.11	1.39	0.57	1.94	5.18	6.43	1.54	0.06	1.37	2.30	11.45	-0.02	-0.34
	sd	406	0.43	0.42	0.03	0.06	2.59	3.06	0.90	0.01	1.18	0.42	9.83	0.18	0.49
Pool	mean	2427	7.34	5.64	2.27	2.54	5.75	8.03	1.59	0.72	1.99	8.40	5.31	0.62	0.80
	sd	317	0.17	0.98	0.55	0.31	3.77	2.93	0.56	0.10	0.29	0.35	4.17	0.09	0.18

Table 2. Mean and standard deviation geochemical data for typical drip waters and pool water for Sharkham Point Mine. SP-1 is one of two drip sources with no associated stalactite formation supplying stalagmite SP1/2; SP-4 similarly has no associated stalactite from its drip source.

flowstone deposition are present. However, several sources that are undersaturated with calcite (particularly SP-1/2 and SP-3) still have associated subaqueous stalagmite deposits.

XRD analysis on a powdered subsample of SP-1/2 confirmed the stalagmite mineralogy to be calcite. Stalagmite morphology observed over the seasonal cycle was seen to remain fairly constant throughout, although the number and size of the splash cups on SP-1/2 did vary with changing drip discharge. This is shown in Fig.3. SEM examination of the samples demonstrates that the stalagmites consist of small (50-200µm) crystals of calcite, which are randomly orientated and show no interrelation to one another or to the height within the sample. The samples display a growth structure distinctly different from that of subaerial stalagmites (Kendall and Broughton, 1978), and biogenic binding of calcite particles is not present.

DISCUSSION

The stalagmites have been demonstrated to have been underwater throughout the 1994 to 1997 period, and the nature of the outlet from the mine suggests that pooling has probably been maintained since a roof collapse and tufa deposition near the entrance dammed the original outflow route. Drip waters feeding the stalagmites have also been monitored throughout the study period. Hence, it is most probable that stalagmite formation is subaqueous. Stalagmites are associated with drip sources that are both undersaturated and supersaturated with calcite, and hence calcite supersaturation of the drip water is not a prerequisite. Both the stalagmite morphology and crystallography attest to a formation process associated with the drip waters impacting upon the calcite-saturated water. One possibility is that calcite rafts form on the surface of the pool, held *in-situ* by surface tension effects, and formed through evaporation and/or degassing of pool water. Upon drip impact, the disturbance of the water overcomes the surface tension effect and the raft material falls to the bed of the pool, where it slowly accumulates to form a stalagmite. Figure 3b, which presents calcite raft material under SEM, demonstrates a remarkable similarity between this calcite and that found in the subaqueous stalagmites. This confirms that the subaqueous stalagmites are at least in part formed from sunken raft calcite, although the <10µm fraction of raft material appears to remain held on the pool surface by surface tension effects rather than become displaced by the falling drips. The terminal velocities of the falling drips can also explain the stalagmite morphology. The velocity of the falling drips is 6ms^{-1} for a 2m fall height, but less than 1ms^{-1} for a 10cm fall height. If the drips can be considered as a point source for raft disturbance, then the energy available to displace the raft per unit time would increase with respect to • v. Hence the observation that wider stalagmites are associated with drips with a greater fall height can be explained by drip impact energies. Localised mixing caused by turbulent flow around the drip impact point may also be significant as a factor increasing calcite precipitation. In particular it must be noted that the lithification of the stalagmites must be caused by a process that is not simply the physical displacement of raft material, and is probably due to calcite precipitation binding the crystals together, with the former raft material providing nuclei for precipitation. SEM analysis of the calcite structure attests to a slow accumulation of settling crystals in a stagnant pool, as no sedimentary structures or preferred orientations are observed. Visual inspection of stalagmites *in-situ* demonstrates that collapses occur, similar to micro-scale screes on the stalagmite sides, until a stable structure is formed. Continual agitation of the upper surface of the stalagmite by the drip impacts maintains an erosive cup in quasi-equilibrium with the depositional process.

From the age of Sharkham Point Mine, the accumulation rate of these stalagmites can be determined to be a minimum of 0.5mm yr^{-1}. Subaqueous stalagmite preservation is not commonly observed, as an increase in pool water flow will prevent the continuation of deposition, or at high discharges, destroy the samples altogether. Similarly, disturbance by humans may also destroy these structures before they can be lithified. The authors have sought similar stalagmites at other cave and mine locations, and to date have found only three other subaqueous stalagmite sites: one in a 0.3 x 0.4m stagnant pool within a 160 year-old freestone mine in Jurassic limestone (Brown's Folly

Mine, Wiltshire), one in a pool of similar size and of Holocene age within a cave in Cambro-Ordovician dolomites (Uamh an Tartair, Assynt) and one in a pool of c.1m x 1m and of Holocene age in Carboniferous limestone (Carrigmurrish Cave, Ireland; Fig.4). All three sites are only visited occasionally, and this might support the argument that the deposits may be destroyed by human activity in caves. Further observations are needed to see if similar material is being deposited in other cave and mine sites. Of interest is the observation that stalagmites have only been observed in sites of 10^2 to 10^3 years antiquity. This could suggest that subaqueous calcite is deposited as the first stage of speleothem deposition where there is a pool of stagnant water, before the pool becomes completely filled with calcite and subaerial stalagmites form. If true, then deposits may be observed in the palaeokarst record.

Figure 4. Subaqueous stalagmite in Carrigmurrish Cave, Co Waterford, Eire.

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