An account of the tufa deposits in the Via Gellia, Cromford, Derbyshire, UK.

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For Mercian Geologist.

Abstract.

Detailed mapping, section logging, sampling and petrological description of a tufa deposit in the Via Gellia, Cromford, Derbyshire, UK, has enabled interpretation of the depositional and post-depositional history of the deposit. This has been interpreted in the context of the geomorphology and hydrogeology of the area.

Key words: tufa, hydrogeology, karst environments, anthropogenic influences, Peak District.

Introduction.

Holocene cool water travertine or tufa (secondary carbonate) deposits are relatively extensive and well-studied in Italy (Buccino et al., 1978; Chafetz and Folk, 1984; Conti et al., 1979, and Ford and Pedley, 1996) where they form an extensive resource that is used for construction e.g. Buccino et al. (1978), Conti et al. (1979) and Ford and Pedley (1996). Although widely distributed in the UK (Ford and Pedley, 1996; Viles and Goudie 1990), tufa deposits are generally less extensive. This makes the exceptionally thick and once economically viable deposits of tufa that have formed in the Peak District, all the more interesting. Examples include the barrage deposits of Lathkill Dale and the Wye in Taddington Dale (Pedley, 1993, and Pedley et al., 2000) and the perched spring-line deposits in Matlock (Pentecost, 1999). The exploitation of tufa as a construction material in the Peak District dates back at least to the development of the Peak District thermal waters as Hydros, or Spas, e.g. the opening of Matlock Baths in 1698 (Hey, 2008). A typical example of the use of tufa as a decorative stone has been retained in the grotto of the winter gardens at Derbyshire County Council, Matlock (Figure 1). Historically it was also exploited for land improvement and its use as a source of lime predates its use as a construction material. Farey (1811, volume 1, page 457) reported that: "the softer parts of the Tufa or deposits made by Springs from the Limestone Rocks, [mentioned below,] at Matlock Bath and some other places are called *marl*, and according to tradition, were formerly used as such, but the practice is quite laid aside I believe." More recently, Adam (1851, p 33) observed that the soil above tufa is very fertile and that "many tons of it are annually sent out of Derbyshire", so clearly its exploitation had not been completely set aside by 1811. Evidence of this exploitation is limited to a small number of abandoned quarry sites, for example the Alport Quarry (SK 2212 6471). Of these, the site in the Via Gellia formed the focus for a recent, detailed study which comprised mapping and petrological analysis of the tufa, the findings of which are reported below.

Figure 1: Tufa wall in the Winter Gardens, County Hall, Matlock, Derbyshire. Image taken by University of Derby.

The study area and former quarry are situated close to the south-eastern boundary of the White Peak, in the Via Gellia, near Cromford and approximately 5 km south-south-west of Matlock. Tufa deposits crop out to the west and north-west of “Tufa Cottage” a well-known landmark, comprising as the name suggests, a residential property constructed of tufa (Figure 2). Historic Ordnance Survey maps indicate that the quarry, which once surrounded the cottage, was in existence by 1884 and was disused by 1938. “Tufa Cottage”, formerly known as Marl Cottage, was constructed as a game keeper’s cottage in around 1830. Access to the research area was gained via the A5012, which follows the deeply incised valley from Grangemill in the west to Cromford in the east. There are two springs associated with the tufa deposits, namely the Dunsley Springs (north-SK 26890 56904, and south-SK 25664 56818). The southern spring flows along the northern perimeter of the southern tufa deposit and the northern one along the southern boundary of the northern body of tufa. The two springs meet to the north of Tufa Cottage at SK 26978 56817) and flow along the boundary with Tufa Cottage to the stream in the floor of the Via Gellia (SK 27018 56799).

Figure 2: Tufa Cottage (formerly Marl Cottage), Via Gellia, Cromford, Derbyshire. Image taken by University of Derby.

Legend

Geology 50k bedrock

Geology

- Bee Low Limestone Fm.
- Lower Matlock Lava Member
- Monsal Dale Limestone Fm

Figure 3: Research area geology and spring monitoring points (1-6). (Base Ordnance Survey Copyright/ Licence No 100017897/2013).

Previous references to these deposits, e.g. Ford and Pedley (1996), suggest that the tufa dates to 9000 to 4000 BP. Others have presented information on the stable isotopes (oxygen and carbon) as a means of determining the depositional environment (Thorpe et al., 1980; Viles and Goudie, 1990), but none have included a detailed or systematic account of the tufa. The aim of this piece of work was to map the extent of the tufa, establish its relationship with the underlying geology, examine the morphology, macro- and micro- structure of the tufa and monitor the associated spring chemistry to determine whether active deposition or erosion was occurring. The research was undertaken as a fifth year undergraduate dissertation (Columbu, 2012) through collaborative working between the University of Bologna and the British Geological Survey with additional support from the University of Derby.

Geological and geomorphological context.

An interesting feature of the Via Gellia tufa is its association with the Bee Low Limestone Formation (Figure 3; Table 1), which comprises thickly bedded, shallow water, limestones that are interbedded with volcanic rocks of basaltic composition (British Geological Survey, 1985; Brossler, 1998; Flindall and Hayes, 1971; Macdonald et al., 1984, and Smith et al., 1967). The tufa is formed in the beds immediately underlying the Matlock Lower Lava. This occurs at a stratigraphically equivalent level to the Miller's Dale Member of the Bee Low Limestone Formation in the vicinity of Buxton (to the north-west). The overlying Matlock Group comprise dark grey and grey limestones with fossiliferous bands and, locally, much chert. The research area lies immediately to the south of the Cronkston-Bonsall Fault a significant basement fault (Gutteridge, 1987) that is associated with dolomitization of the limestones. A sporadic cover of superficial deposits includes Head on the valley sides, particularly on the southern side of the valley; pockets of glacial till on the plateau surface; tufa associated with the northern side of the valley (Figure 4), and ribbons of alluvium occupying the valley bottom.

Table 1: Geological Context.

Subsystem	Stage	Group	Formation	Member
Dinantian	Brigantian	Craven	Longstone Mudstone	
		Peak Limestone	Eyam Limestone	
			Monsal Dale Limestone	
	Asbian		Bee Low Limestone	
				Lower Matlock Lava
	Holkerian		Woo Dale Limestone	
	Arundian			
	Chadian			
	Ivorian			

A number of north-west to south-east trending mineral veins cross the area. Many of these are intersected by the north-east to south-west trending Great Rake (Figure 3). The associated lead-zinc mineralization formed the focus for a number of phases of mineral exploitation, possibly even dating back to the Roman occupation of the area (Brossler, 1998). Primary metallic ore minerals include galena and sphalerite, whilst the gangue minerals largely comprise calcite, barite and fluorite.

Secondary alteration of the ore minerals results in the formation of small pockets of ochre, wad and calamine (smithsonite, zinc carbonate). It is reported that calamine was worked in the Bonsall Leys Liberty (Brossler, 1998) for the brass-making industry (Rieuwerts, 2010). Flindall and Hayes (1971) reported on the findings of a survey undertaken on the north side of the Via Gellia by the Mines Survey Group of the Peak District Mines Historical Society (PDMHS). A sketch map of the veins and adit workings under Bonsall Leys (Flindall and Hayes, 1971) shows that the Yule Cheese Vein was drained by the Dunsley Spring Level, approximately 150 m to the south-west of the Dunsley Springs. It should be noted that the southern of the Dunsley Springs aligns with the southern end of one of the north-north-west to south-south-east rakes and the northern spring is closely related to the position of a parallel rake.

The Peak District forms the southernmost extent of the Pennines, comprising an upland terrain dissected by valleys. Limestone crops out as part of a broad anticline over an area of approximately 50 km from north (Castleton) to south and 30 km from west to east (Bakewell); within this area many of the valleys are now dry. The karst geomorphology of the limestone upland includes deep valleys, limestone gorges, scree clad slopes, a range of forms of dolines, ridges, tors and rock pinnacles (Dalton et al., 1999). The area exhibits a complex geomorphology that reflects the long history of uplift and erosion of the sequence; the response to glacial, glaciofluvial and periglacial processes, and considerable anthropogenic modification.

Unusually, for the valleys in the White Peak, the Via Gellia is oriented approximately east-west and forms a wooded, deeply incised valley, which is approximately 100 m deep in the vicinity of the tufa deposit. The profile of the valley is steep sided and symmetrically “V” shaped in form, with a meandering thalweg. Tufa Cottage and the associated tufa deposits occupy the northern side of the valley, effectively on the outside of a meander in the channel. The valley floor supports a covering of alluvium and is currently occupied by an intermittent stream that receives water from both natural and anthropogenic (mine drainage) sources. The stream flows eastwards to its confluence with the River Derwent at Cromford. Its source comprises a number of springs in the vicinity of Shothouse Spring (SK 24210 58931). It is perennial downstream of the Dunsley Springs entry near Tufa Cottage (SK 27020 56799).

At an elevation of approximately 325 m OD the plateau surface above the valley largely comprises fields of pasture that are bounded by stone walls and are interrupted by scars of the former mining activity. Where they are undeveloped the valley sides are thickly vegetated, predominantly by deciduous woodland. Steep slopes (> 25^{o}), attributable to relatively rapid valley incision, have resulted in slope instability, particularly in areas where beds of limestone are underlain by the basalts and valley sides are characteristically associated with areas of landsliding. The literature indicates that the natural karst system is less well developed than in other areas of the Peak District, for example the Good Luck Mine on the south side of the Via Gellia comprises “an extensive series of narrow adits, crosscuts and small stopes of the early 19^{th} century, which have intersected a number of small solution caverns” (Barker and Beck, 2010, p 152).

Anthropogenic impacts on the geomorphology of the Via Gellia are dominated by mineral exploitation, quarrying, agricultural modification and industrial development. Whilst quarrying of the tufa has ceased, the more extensive quarrying for limestone continues. Agricultural modification has included enclosure of fields, which have been primarily used for grazing. Modification to springs to facilitate water supply for mining and industry has been marked. Examples of this are demonstrated by documents held in the Derbyshire County Records Office at Matlock (Table 2). Historically, the springs had always been used as a source for watering cattle and during periods of drought the inhabitants of Middleton and elsewhere fetched water from the springs for their own use. Industrial development in the valley was focused on the watercourse, for example Mr T.H. Walker (of E.H. Badley Limited) was the owner of a Mill or Works (Via Gellia Mill at the junction of Bonsall Road with the Via Gellia Road) and a water wheel, situated in the Via Gellia. In 1936 he alleged that if the waters were taken from the Dunsley Springs the power and efficiency of the wheel would diminish with a consequential loss of value to the mill. In studying the springs the Council (in 1934) noted that in the summer the Via Gellia Stream dries up in the order of 300 m downstream of Marl Cottage and that the loss of this volume of water is coincident with the Whitecliffe Fault through which it is believed water escapes into the Meerbrook Sough.

Table 2: Records pertaining to the Dunsley Springs.

Date	Action	Reference Derbyshire Records Office (DRO)
1935	Monitoring of the Dunsley Springs at Marl Cottage. The discharge ranged between 7.53 and 5.18 l/s between April and August 1935.	DRO D7017/6/32
20.5.1936	Agreement between Thomas Harold Walker of Via Gellia Road, Cromford and the Urban District Council of Wirksworth, which allowed the Council to impound and use water from Dunsley Spring in the Via Gellia in the Parish of Bonsall, in the Urban District of the Matlocks. Given the notice of the Ministry of Health regarding the urgent need for water for the people of Middleton Mr Walker agreed to withdraw his opposition in return for compensation of £127.	DRO D7167/6/30.
14.08.1936	Agreement that with regard to the supply of water to the Marl Cottage the Council shall enclose Spring No.1 and provide a storage tank at Spring No. 2. Mr Key (of Cromford) agreed to the alteration of the line of the pipetrack so as to avoid a newly opened quarry at the line previously intended for the pipeline.	DRO D7017/6/32

Revised mapping of the Via Gellia tufa deposits.

Columbu (2012) re-mapped the extent of the tufa deposits in the Via Gellia with the aim of establishing the relationship between the tufa and the underlying carbonate rocks (Figure 5). Dense, wooded vegetation, paucity of bedrock exposures and the steep slopes made the mapping difficult. Feature mapping was essential and slope angles proved to be particularly useful. The upper surface of the Lower Matlock Lava formed a lower angle, bedding-parallel surface, whereas the limestones formed steep slopes (> 25^{o}) that were modified by the overlying tufa (resting at angles of up to 25^{o}). The revised map (Columbu, 2012; Figure 5) reveals that the tufa comprises two discrete cones. The extent of the tufa has been verified from high resolution photographs. A quarried face in the order of 40 m to the north-east of Tufa Cottage provides a section through the northern cone of tufa (Figure 6). This section shows a fan-shaped form, with higher slope angles on the valley side giving way to lower slope angles lower down the valley side. The presence of erosional unconformities (D1, D2 and D3) in the quarry section suggests that it comprises at least four beds of tufa. The southern cone was described from five exposures and reveals comparable features.

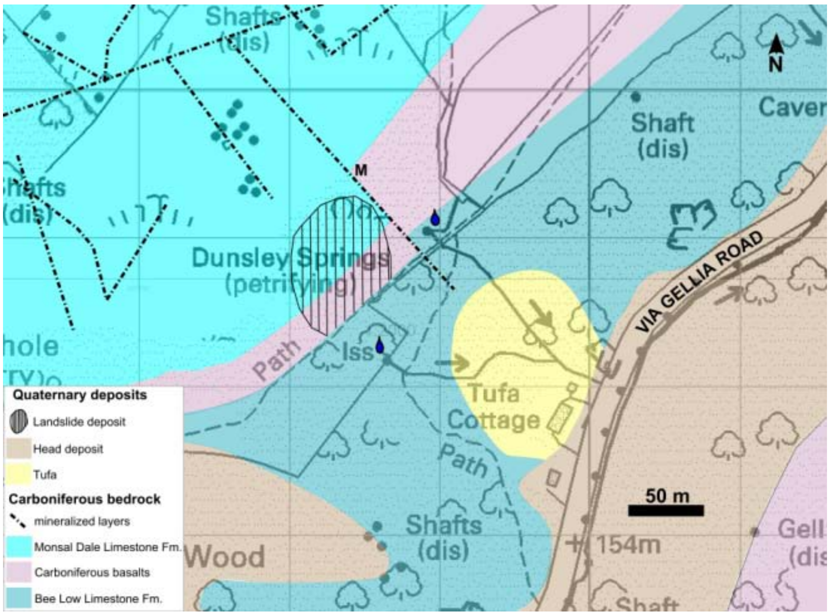

Figure 4. BGS 1: 50 000 geological mapping of the tufa in the Via Gellia.
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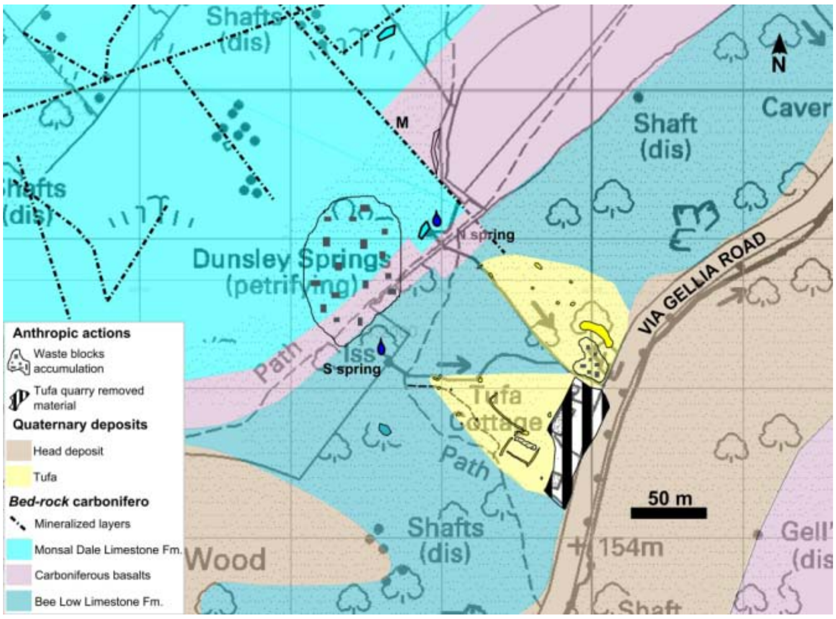

Figure 5: Revised geological mapping of the tufa in the Via Gellia (Columbu, 2012).
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Macroscopic features.

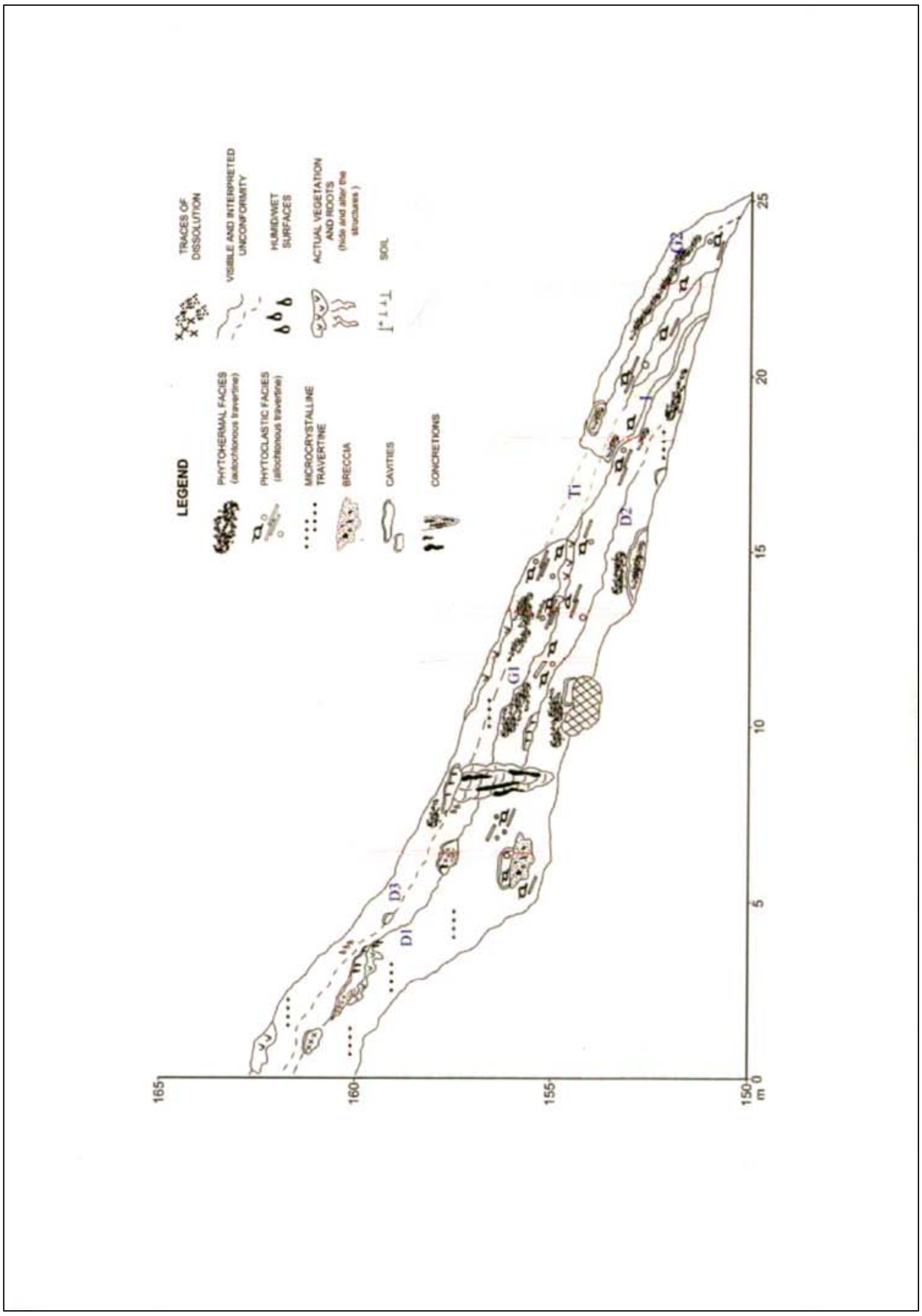
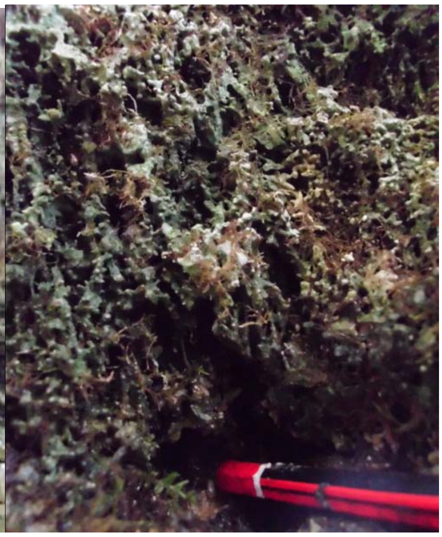


Figure 6: Profile of quarried exposure of tufa at SK 27015 56829. **D1**, **D2** and **D3** are unconformities; **Ti** denotes topographic irregularities; **G** denotes steps in the tufa surface.

The detailed quarry section (Figure 6) shows the range of depositional and erosional macroscopic features that include:

1. Zones of developed (in-situ) phytoherm (Figures 7 and 8) that appear to be more extensive higher in the sequence and comprise interwoven stems of a number of different plant species. Typically the plant stems have diameters of 1 to 5 mm and include *Cratoneurom filicinum* and *Eucladium verticillatum*. These zones are better exposed where they are blanketed by actively growing mosses.

Figures 7 (left) and 8 (right): Autochthonous tufa with bush-like morphology probably derived from cemented *Cratoneurom filicinum* and *Eucladium verticillatum* respectively.

2. Phytoclastic (washed in) facies that include foliage, stems, tree branches and tree trunks (Figures 9 and 10) and comprise fragments of organic matter that were preserved in the tufa at the time of formation.


Figures 9 and 10: Examples of foliage (left) and a tree trunk (right) preserved in the tufa at the Via Gellia.

3. Mircrocrystalline tufa, which is grey in colour, has a sugary texture and has been interpreted as reverting from sparry calcite (Figure 11). This tufa is generally massive and relatively dense, but with local dissolutional porosity.

4. Speleothems and encrustations (Figures 12 and 13) occur in a number of cavities and fractures and can be seen at a variety of scales. Stalactites are common and exhibit a diameter of between 0.2 and 2 cm. Encrustation of pre-existing phytoherm occludes the porosity of the tufa.

5. Breccias were observed locally and were found to be matrix- or carbonate- cemented.

6. Dissolutional cavities, which can be subdivided into: primary and secondary cavities associated with speleothems and encrustations. Pinkish brown clayey silt deposits commonly line a number of the dissolution cavities, a deposit that would appear to have been introduced by vadose flow.

Figures 11 (left)-13 (right): Microcrystalline spar, speleothems and encrustations. Scale bars 2 mm, 100 µm and 5 mm respectively.

Microscopic features.

The following descriptions are derived from the petrological examination of fifteen thin sections supported by scanning electron microscopy that was applied to the samples that were found to be of greatest interest. This work has shown that encrustation commences with a granular micritic layer that hosts an alternating sequence of sub- millimetre spar and micrite layers of variable thickness and frequency (Figures 14 and 15). The deposits are colour banded with darker bands comprising micrite and lighter bands sparite of mosaic, acicular and palisade forms. The porosity of the darker layers is usually high as a consequence of void formation due to the decay of organic matter and the paucity of diagenetic cementation of the resultant voids.

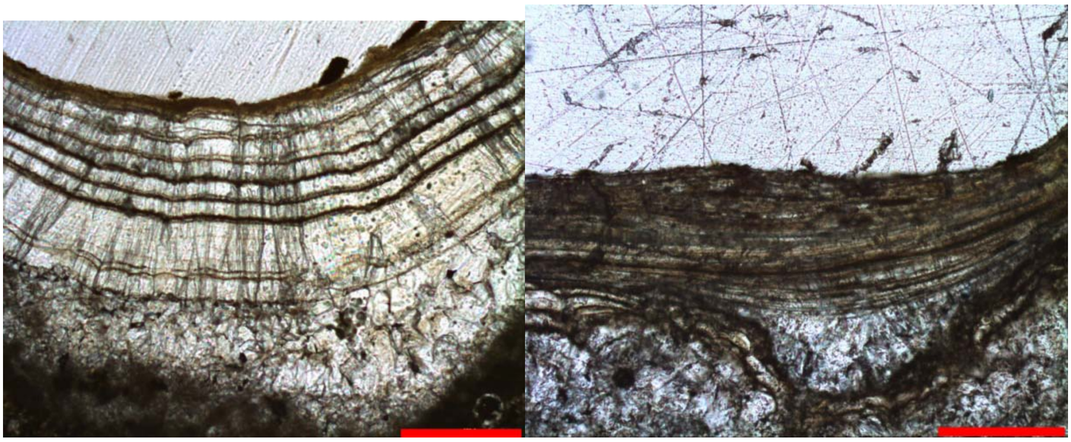
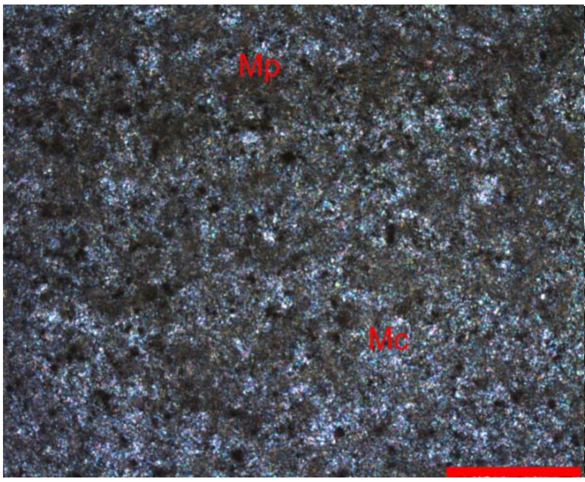


Figure 14 (left): Alternating micrite and sparite. Figure 15 (right): Laminated micrite and sparite. Red bar = 250 µm.

Cementation of the phytoclastic facies differs to the phytohermal facies in that allochthonous (transported) fragments are encrusted with a single, encrusting micritic fringe, rather than a layered sequence. It is suspected that this results from the commencement of cementation during transport of the plant particles, which is followed by further cementation once the particle settles at its point of accumulation. The microcrystalline (mc; Figure 16) facies is dominated by clotted micrite. The resultant micropeloids (mp; Figure 16) are globular with low crystalline resolution and appear dark brown with single and crossed nicols in the polarising microscope. Furthermore, they do not show the normal birefringence colours of micrite, possibly as a consequence of the accumulation of non-carbonate material. Volumetrically less significant is the occurrence of microcrystalline micrite (Figure 17), in which crystals are distinguishable under crossed nicols. The spar occurs as both cement and debris. The microcrystalline facies appear to be associated with bryophyte cementation, debris accumulation and diagenesis. Diagenetic crystallisation can occur as a consequence of dissolution and re-precipitation, which destroys the original fabric of the tufa.



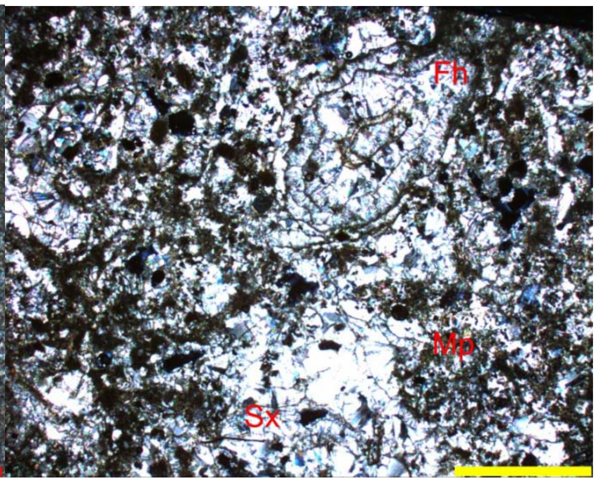


Figure 16 (left): Micrite (mc) and clotted micropeloid (mp) micrite tufa. Figure 17 (right): Microcrystalline tufa. Red bar = 250 µm. Yellow bar = 1 mm. (**Sx** spar; **Fh** Phytohermal)

The analysis of thin sections facilitated classification of porosity types in the tufa (Figure 18; Table 3).

Table 3: Classification of porosity types.

Porosity Type	Description
Organic matter decay	The principal cause of void creation especially in the phytohermal facies, characterised by rounded to rectilinear pores with void size varying with the organic matter, but ranging from millimetre to centimetre scale.
Vuggy	Resulting from the encrustation of bryophytes, usually at the millimetre scale.
Intergranular	The void between the encrusted allochthonous fragments. These pores are commonly visible to the naked eye and tend to be flat and linear with irregular and sinuous boundaries.
Intercrystalline	Micrometric porosity between some crystals, possibly as a consequence of imperfections in crystal growth

Incomplete cementation	Commonly at the millimetre scale.
Degassing	Resulting from the escape of carbon dioxide gas bubbles leaving rounded or flattened “caries-like” sub millimetre voids occurring most commonly in the microcrystalline facies.
Dissolution	Secondary porosity as a consequence of weathering and often acting on pre-existing pores, leaving irregular voids of millimetre to centimetre scale.
Bio-dissolution	The dissolution pores that result from vegetational etching, e.g. lichens and mosses, commonly a consequence of the enlargement of pre-existing pores, associated particularly with tufa that has a high primary porosity and characterised by a dark residual material on the boundaries of the pores.

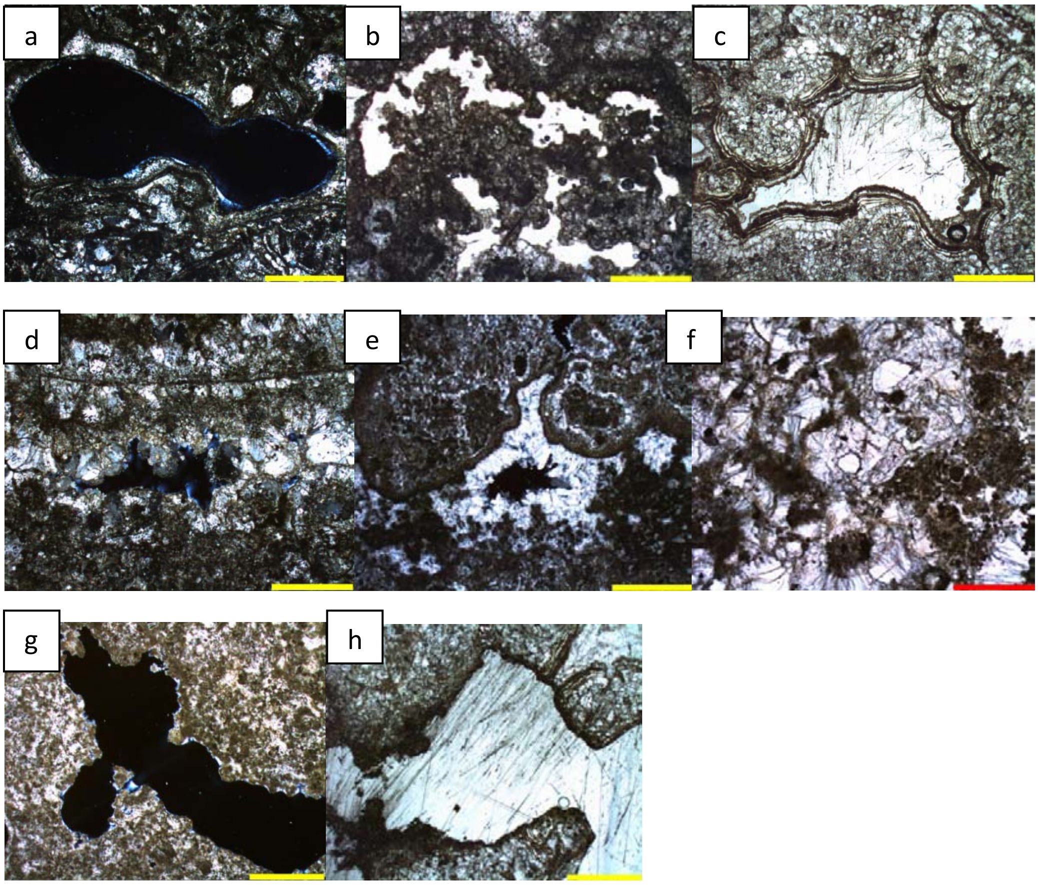


Figure 18: Range of porosity types: (plant decay (a), vuggy (b), intermatrix (c), intercrystal (d), incomplete cementation (e), degassing (f), dissolution (g), biodissolution (h), see text). Red bar = 250 µm. Yellow bar = 1 mm.

Cementation of both the primary and secondary pores has been found to take a variety of forms reflecting the nature and degree of competition for cementation nuclei. Biological mediation of tufa precipitation is evident in the recent deposits where diatoms and bacterial colonies are particularly abundant (Figure 19). Characteristically, cementation commences with a primary rind of dogtooth spar or acicular prismatic crystals that form the nucleus for subsequent, drusy spar growth. Less commonly, botryoidal forms occur. Detrital filling by terrigenous silt, clotted micrite, lithoclasts and organic remains also occurs.

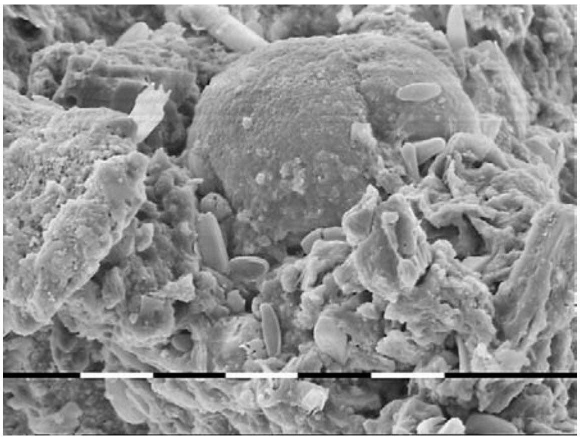


Figure 19: Peloids, tubes and diatoms. Scale bar 10 µm.

Hydrogeochemistry and active tufa deposition.

It was clear from field evidence that in places the springs are actively precipitating tufa. This evidence comprises calcium carbonate encrustations of mosses (Figure 20). The precipitation of tufa from water that is saturated with calcium carbonate occurs as a consequence of inorganic or organic degassing of carbon dioxide. The former may be due to physical agitation of the water, whilst the latter results from biological removal of carbon dioxide from the water. Plant material commonly forms the nucleus for tufa precipitation. In this context plants can have either an active (removal of carbon dioxide) or passive (substrate for precipitation) role in tufa precipitation. Based on field observations, Columbu (2012) plotted the zones of actively precipitating tufa in the springs (Figure 21).

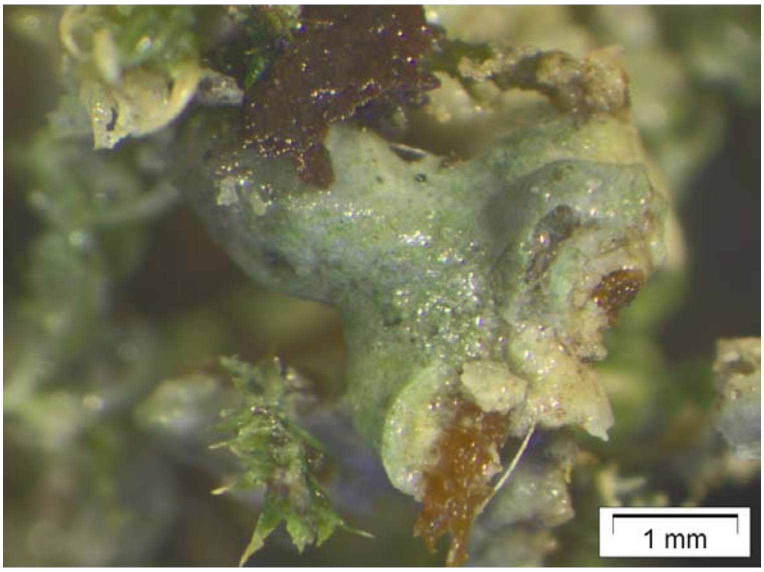


Figure 20: Actively precipitating tufa.

With a view to facilitating an assessment of the extent of tufa precipitation and erosion, synoptic sampling of the spring water and determination of discharges was undertaken on four occasions: 18 May 2011, 3 July 2011, 25 September 2011 and 9 January 2012. Six locations were selected (Figure 3) for sampling for laboratory determination of major cations and anions. Samples 1 and 2 were taken at the Dunsley Springs, sample 3 immediately downstream of their confluence and sample 4 where the stream discharges to the culvert beneath the Via Gellia. The headwaters of two additional springs, situated 250 to 300 m to the north east of Dunsley Springs were also sampled. The samples (120 ml) were split to allow filtration (46 µm) of two subsamples and (1% nitric) acidification of the sub-sample taken for cation determinations. It was considered that the distal springs might provide a base-line against which comparisons with the tufa precipitating springs could be made. At each location, field determinations of the physico-chemical parameters: pH, dissolved oxygen, temperature and electrolytic conductivity were obtained with a portable multi-parameter meter (Hanna Instruments, Inc. HI 9828; Table 4). To enable subsequent flux calculations to be undertaken, a Columbia 2 Digital Stream Meter (an impeller-type flow meter; Educational Field Equipment UK Ltd) was used to measure stream velocity at each location (Table 4). Laboratory testing comprised ICP-AES (Varian Vista Axial) determination of the major and trace elements. The major anions Cl, SO_4, NO_3 and F were determined by ion chromatography (Dionex DX-600) (Table 5). The testing was undertaken in the laboratories of the British Geological Survey and ionic balances in the range 0.06 to 4.34% were achieved. Geochemical modelling (saturation index determinations) was undertaken using SOLMINEQ.GW (Hitchon et al., 1999).

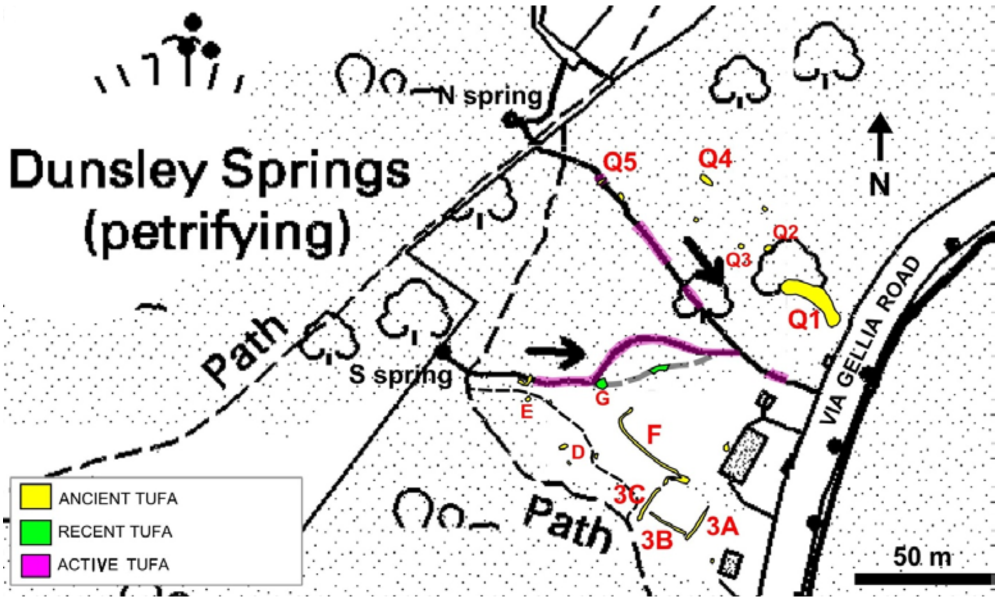


Figure 21: Zones of active precipitation of tufa.

Table 4: Field-derived, physico-chemical parameters.

Sample	Electrolytic conductivity (uS/cm)	Dissolved Oxygen (%)	Dissolved Oxygen (ppm)	pH	^{o}C	Flow (l/sec)
18.05.11						
1	420	94.4	10.7	7.72	8.71	16.4
2	454	89.7	9.99	6.97	8.79	8.5
3	386	115.2	12.51	8.73	9.35	29.2
4	395	95.1	10.69	8.35	9.16	39.5
5	196	87.8	9.97	7.26	8.89	n.d.
6	Flow too low to monitor					
03.07.11						
1	448	116.1	12.57	7.84	10.54	
2	484	79.1	8.9	7.89	8.81	
3	461	94.8	10.45	9.0	10.33	
4	463	94.4	10.33	8.35	10.7	10.0
5	199	99.6	9.51	7.33	14.87	0.056

6	213	132.3	13.4	8.33	18.11	0.002
23.09.11						
1	119	82.6	9.29	8.77	8.79	0.625
2	252	59.4	6.54	8.42	9.32	0.15
3	478	80.3	8.75	8.41	10.33	0.55
4	9	87.4	9.51	8.57	10.42	1.00
5	87	90.4	8.87	7.47	14.74	0.1
6	Flow too low to monitor					
09.01.12						
1	499	92.3	10.47	7.07	8.79	57.13
2	487	94.1	10.66	6.99	8.77	21.78
3	275	134.5	14.64	8.49	8.80	108.67
4	n.d.	104.7	12.0	8.33	8.81	137.54
5	377	92.0	10.36	7.09	9.19	0.571
6	473	83.2	9.25	6.91	9.63	0.086

Table 5: Spring chemistry data.

Date	Sample	pH	Ca	Mg	Na	K	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sr	F^-	Zn	Mn	U	SIc	Ca Flux
			mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	µg l^{-1}	mg l^{-1}	µg l^{-1}	µg l^{-1}	µg l^{-1}		mg s^{-1}
18/05/2011	1	8.11	114	1.62	4.9	0.71	295	6.25	17.2	14.9	114	1.27	153	0.9	0.820	1.134	1869.6
18/05/2011	2	7.94	103	1.44	4.2	0.66	294	6.27	17.2	14.1	103	1.31	165	0.8	0.853	0.935	875.5
18/05/2011	3	7.96	103	1.43	4.1	0.60	276	6.18	17.2	14.7	103	1.27	126	0.2	0.988	0.929	3007.6
18/05/2011	4	8.08	103	1.45	4.2	0.64	281	6.15	17.2	14.9	104	1.28	126	<0.2	0.877	1.050	4068.5
18/05/2011	5	7.91	79.6	1.80	5.8	0.92	208	9.58	24.2	15.7	85.2	1.21	55	10.4	0.718	0.667	
18/05/2011	6	7.89	87.0	2.26	9.3	1.23	222	15.0	24.4	25.5	78.7	0.954	17	8.8	0.480	0.705	
03/07/2011	1	8.24	104	1.44	4.1	0.59	293	6.25	17.4	15.4	103	1.26	160	3.4	0.829	1.218	
03/07/2011	2	8.20	104	1.44	4.1	0.63	293	6.25	17.4	15.1	103	1.30	159	<0.2	0.819	1.156	
03/07/2011	3	8.31	111	1.55	4.8	0.97	291	6.64	17.5	15.8	112	1.27	120	0.7	0.880	1.303	
03/07/2011	4	8.20	104	1.45	4.5	0.98	292	6.78	17.4	17.0	104	1.27	124	0.4	0.866	1.180	1040.0

03/07/2011	5	8.09	80.5	1.81	5.8	1.17	210	10.9	25.0	16.1	84.9	1.21	57	1.4	0.738	0.847	4.5
03/07/2011	6	8.12	85.5	2.13	8.8	1.37	216	14.8	24.6	25.4	77.1	0.964	9	2.3	0.493	0.907	0.17
25/09/2011	1	7.91	109	1.48	4.2	0.65	295	6.46	17.9	16.1	107	1.25	139	0.6	0.831	0.928	68.1
25/09/2011	2	8.09	116	1.54	4.4	0.68	293	6.46	17.9	15.9	113	1.28	151	0.2	0.921	1.119	17.4
25/09/2011	3	8.31	102	1.40	3.9	0.70	291	6.48	17.9	15.6	101	1.25	113	0.4	0.877	1.272	56.1
25/09/2011	4	8.36	112	1.54	4.3	0.76	290	6.51	18.0	15.8	111	1.25	114	0.7	0.821	1.350	112.0
25/09/2011	5	7.99	85.3	1.93	5.6	0.95	208	9.92	25.9	15.3	89.8	1.19	52	11.7	0.742	0.770	8.53
09/01/2012	1	7.93	114	1.70	4.9	0.68	285	7.01	16.7	17.5	111	1.20	153	1.5	0.871	0.950	6512.8
09/01/2012	2	8.02	106	1.59	4.7	0.64	277	7.01	16.8	16.7	107	1.28	142	0.2	0.893	0.998	2308.7
09/01/2012	3	8.37	104	1.53	4.5	0.62	283	7.04	16.8	16.7	106	1.24	126	0.5	0.885	1.322	11301.7
09/01/2012	4	8.34	108	1.57	4.6	0.64	283	7.13	17.0	17.4	109	1.25	130	0.3	0.886	1.309	14854.3
09/01/2012	5	8.00	77.0	1.86	5.2	1.81	193	8.01	20.5	18.3	82.3	1.12	52	0.5	0.598	0.713	43.9
09/01/2012	6	8.07	88.5	2.15	7.8	0.94	230	13.7	21.2	30.5	78.4	0.910	13	0.5	0.467	0.902	7.61
Baseline min and max (Abesser and Smedley,2008)		5.94 9.17	2.36 171	0.269 36.3	3.89 192	<0.5 13.5	21 367	7.32 266	4.96 311	<0.5 12.6	37.1 8440	0.025 1.780	2.2 1840	<0.5 4840	<0.02 5.68		

With the exception of some of the nitrate and chloride concentrations, the spring chemistries fell within the range of the groundwater baseline data for the Derbyshire Dome (Abesser and Smedley, 2008). Whilst the lower chloride concentrations are unusually low for the Carboniferous Limestone, the upper concentrations of nitrate were higher than is usual for the Carboniferous Limestone. It is considered most likely that the elevated nitrate concentrations are derived from cattle silage. In the Peak District fluoride concentrations have been found to be the best indicator of the influence of mineralisation on spring chemistry (Bertenshaw, 1981). This would appear to be evident in the Via Gellia data, where fluoride concentrations of > 1 mg/l (samples 1 to 5) contrast with that of sample 6 (< 1 mg/l), suggesting that the groundwater chemistry of the Dunsley Springs and the southern of the two additional springs are affected by contact with the mineralization. Further evidence that these are relatively elevated concentrations comes from the groundwater chemistry baseline survey (Abesser and Smedley, 2008), which reported Carboniferous Limestone fluoride concentrations in the range 57 to 1780 $\mu g\ L^{-1}$. Calcium, zinc, strontium and uranium concentrations appear to discriminate between the Dunsley Springs (> 100mg/l Ca, >120 µg/l Zn, > 100 µg/l Sr and >0.8 µg/l U) and the two springs immediately to the north-east, albeit they fall within the expected range for the aquifer (Table 5). There is a strong correlation between the calcium and strontium and calcium and zinc concentrations. The Dunsley Springs also differ from those to the north-east by exhibiting lower concentrations of potassium (<1 mg/l), manganese (< 1 mg/l), chloride (<6.5 mg/l), sulphate (<18 mg/l) and nitrate (< 17 mg/l).

Synoptic spring geochemistry provides an indication of the extent and seasonality of water/ rock interaction. This in turn provides an indication of the flow processes in the aquifer. Whilst there are clearly significant changes in the spring discharges, the correlation with the calcium concentrations is not very strong and the spring chemistries show little seasonality. Flux determinations (product of discharge and concentration) show a strong correlation with flow with higher flux occurring during high discharge conditions. With respect to changes in the spring chemistry within the surface watercourse it is evident that there is a downstream increase in the calcium flux and whilst there is a downstream increase in the zinc flux this corresponds with a reduction in the zinc concentration in the stream.

Deposition and erosion of the tufa deposits.

Re-mapping of the tufa (Columbu, 2012) has identified two overlapping cones, which are indicative of a point sources for the dissolved carbonate. This supports classification of the deposit as a cascade (spring-line) tufa (Pedley, 1990). The tufa is unusual in that it is the only significant deposit in the Peak District that is associated with the Bee Low Limestone Formation; the majority are associated with the Monsal Dale Limestone Formation (or south-easterly lateral equivalent the Matlock Group [BGS, 1985]). However, the hydrogeological properties of the upper part of the Bee Low Limestone Formation (Miller's Dale Member to the north-west) are comparable and have been grouped in the same hydrogeological unit (Banks et al., 2009). The Via Gellia tufa is formed immediately beneath the Lower Matlock Lava, towards the top of the Bee Low Limestone Formation, where it is likely to be associated with significant palaeokarstic surfaces and clay wayboards as in the Hoptonwood Quarry where dissolution pits of up to 10 m depth have been reported (Waters et al., 2006).

It would appear that the Via Gellia Valley intercepts south-westerly water flow paths in the limestone immediately beneath the Lower Matlock Lava. Evidence from elsewhere (Banks et al., 2009) suggests that this is related to inception horizons associated with palaeokarst surfaces in the upper levels of the Bee Low Limestone Formation. The source of carbonate is likely to be related to geochemical processes associated with dissolution in the epikarst (during recharge) and anastomosing palaeokarstic surfaces (along vadose zone flow paths). Concentrations of magnesium and sulphate are relatively low indicating that the carbonate is less likely to result from the dissolution of dolomite or be the consequence of sulphate dissolution resulting from the weathering of pyrite. Further to these sources, the relatively elevated concentrations of zinc suggest an additional contribution from the dissolution of the smithsonite (Brossler, 1998). Relatively elevated nitrate concentrations at sampling positions 5 and 6 (Figure 3) are likely to result from more open flow paths and agricultural contamination.

Evidence presented to date suggests that the tufa is a Holocene deposit (Thorpe et al., 1980; Viles and Goudie, 1990). During this period of post-glacial climatic amelioration the proliferation of vegetation would have facilitated carbon dioxide saturation of recharge water, resulting in increased limestone dissolution in the vadose zone. The presence of both dark (micrite) and light (sparite of mosaic, acicular and palisade forms) is comparable with observations in other tufa deposits in the UK and Europe, e.g. Brasier et al., 2011. The occurrence of these two types of calcium carbonate can, at least in part, be attributed to the interplay between physico-chemical precipitation of sparite and biologically mediated precipitation of micrite (Brasier et al., 2011; Pedley et al., 1996). The macro fauna includes leaves and trunks of deciduous trees, which formed the substrate for tufa precipitation. A suspected root bulb was also observed. It comprised a cemented breccia deposit, which together with the local preservation of organic matter suggests rapid deposition of tufa in a relatively unstable environment. It is suspected that high stream flows undercut the banks, thereby triggering tree falls. Such processes may, in part, have been due to rapid incision driven by glacio-isostatic readjustment. Discontinuities in the deposits (Figure 6) indicate that precipitation of tufa during its primary construction stage was not continuous. Progradation of the two tufa cones may have been contemporaneous or represent the migration of deposition from one spring to an adjacent one. Chemical analyses of the current spring waters suggest that it is plausible that the two tufa cones are contemporaneous, representing higher discharge conditions than the present day.

Calculated saturation indices with respect to calcite (Table 5) indicate that the present precipitation of tufa is most likely during the summer months (July and September visits) when increased biological activity results in higher carbon dioxide levels in the recharge water, increasing the limestone dissolution. The saturation indices also appear to confirm active dissolution of the main body of the tufa (sample points 3 and 4). In part this is supported by field evidence, indicating that some cavities in the tufa are primary, representing the voids behind small scale dams or barrages. Other voids are post depositional dissolution cavities that have been interpreted to be a product of weathering (Columbu, 2012) associated with the unconformities in bedding where they commonly form vadose zone flow paths. Consequently a number of the dissolution cavities are lined with speleothems and encrustations. The speleothems and secondary encrustations are regarded as third order deposits with the calcium carbonate being derived from the tufa itself rather than the limestone bedrock, which is the source for the main body of the tufa (secondary carbonate deposit). The distribution of these deposits reflects the vadose zone flow paths, which have been anthropogenically modified in the areas that have been quarried.

Whilst this study has gone some way to understanding the depositional environment of the tufa and its subsequent erosional history there remain a number of unanswered questions. In particular the source of the carbonate has not been fully established. This gap in understanding might be addressed through sampling and petrological analysis of the palaeokarstic surfaces in the limestones immediately beneath the Lower Matlock Lava. The high preservation potential of the tufa lends itself to a more extensive study of the macroflora and the associated depositional environment. Furthermore, the age of the tufa has not been verified and dating of the unconformities in the tufa has yet to be attempted. Additionally, more frequent, monitoring and chemical analyses could be deployed to facilitate mass balance calculations to determine annual rates of precipitation and erosion of the tufa. The physical appearance of the tufa deposits of the Peak District varies considerably and the adoption of a descriptive classification would be of vernacular architectural value, particularly where any future maintenance works may be required.

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List of Figures

List of Tables

Table 5 - Spring chemistry data.