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Hydrogeological Significance of Secondary Terrestrial Carbonate Deposition in Karst Environments

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1. Introduction

A significant hydrogeological characteristic of karst environments is the precipitation of a proportion of the dissolved calcium carbonate derived from limestone dissolution. The study of such secondary deposits is important because they provide information on the palaeohydrogeology of the unsaturated zone at the time of precipitation. They also offer the potential to provide information with respect to climatic conditions through the study of stable isotopes and dating through the study of radiogenic isotopes. This chapter introduces the formational processes, depositional environments (hydrogeological, hydrogeochemical, biological and geomorphological) and post depositional history of secondary terrestrial carbonate deposits. Consideration is given to the associated research themes and techniques, in particular to the current research focus on the role of microbial communities in present day sediment-water interface processes (Pedley and Rogerson, 2010) and the implications for furthering the understanding of climate change and landscape evolution. These deposits have a world-wide distribution (Ford and Pedley, 1996; Viles and Goudie, 1990) and include speleothems, travertines, tufas, calcareous nodules, calcretes and carbonate cements, such that speleothems and tufa represent two end members of a continuum of freshwater carbonate (Pedley and Rogerson, 2010). They form in a range of climatic conditions, but are best developed in warm humid climates. Examples cited in the text include case studies from the White Peak, Derbyshire UK, which currently experiences a temperate humid climate and hosts a range of deposits as a consequence of its recent geological history. The White Peak was not subjected to glacial erosion during the most recent (Devensian, MIS 2-4) glaciation, therefore there is a potential for an extensive record of Quaternary palaeoclimatic conditions to be preserved in the secondary carbonate deposits.

2. Types of secondary carbonate deposit and their classification

Secondary terrestrial carbonate deposits include four major groups: (i) *Speleothems* that are characteristically deposited in caves above the water table (vadose or unsaturated zone) from saturated mineral solutions and can be seen at scales that range from millimetres to tens of metres. Typically, they are formed of calcium carbonate by the precipitation of calcite

or aragonite from water as excess dissolved carbon dioxide is diffused into the cave atmosphere. Aragonite is a metastable polymorph of calcite, which predominantly occurs as acicular crystals in speleothems. Its occurrence is generally attributed to depletion of calcium ions in magnesium rich solutions. Other minerals, for example gypsum, can also be precipitated in this environment. They occur as *dripstones*, formed by water dripping from the ceilings or walls of caves (*stalagmites* or *stalactites*), or as *flowstones* formed on the walls or floors of caves. Speleothems can also form carbonate cements and cemented rudites in the cave environment. Typically they form as elongate (columnar) crystals perpendicular to the growth surface (palisade calcite, Kendall and Broughton, 1978), which may be visible as a series of growth layers. Speleothems commonly comprise alternations of soft and hard calcite (Ford and Williams, 2007) with most hard calcite occurring as palisade calcite, or as microcrystalline calcite. They also occur outside the cave environment, e.g. the anthropogenic flowstone precipitating from lime-rich cement at Lindisfarne Castle, Northumberland, UK (Figures 1 and 2). (ii) *Tufa* (ambient temperature, freshwater carbonate with carbon dioxide derived from the soil atmosphere) and *travertine* (carbonate precipitating from water that is hot as a consequence of deep circulation with carbon dioxide being derived from magmas and decarbonisation). These carbonates result from a combination of biologically moderated physicochemical processes and accumulate in a range of settings. They may take the form of cones, cements, barrages at metre to kilometre scale or minor, localised plant encrustations. Growth increments in tufas occur as contrasting laminae of dense micrite and more porous sparry crystalline calcite (Andrews and Brasier, 2005). (iii) *Carbonate cements* comprise minerals that fill pore spaces and bind particles together. Most terrigenous clastic sediments (rudites, arenites and argillites) have the potential to become cemented by minerals that fill the pore spaces. Although beyond the remit of this chapter, common cementing materials also include silica, iron oxide and sulphates. Carbonate cements occur externally to and within cave environments. Within caves they typically occur as cave breccias (deposits of calcium carbonate formed where cave water percolates into clastic sediments) and externally they typically comprise a greater variety of cemented rudites (e.g. fluvial gravels or screes; Figure 3). (iv) *Pedogenic carbonates* encompass caliche, soil nodules and rhizome (root) coatings, which may also exhibit incremental growth patterns. Fossilised forms include algal burrs, such as those of upper Jurassic age in Dorset, UK (Francis, 1984). These carbonates can be either inorganic or as consequence of biomineralization. Subsequent dissolution can lead to the development of third-order forms.

Secondary carbonate deposits attract a plethora of terminology (Ford and Pedley, 1996; Pentecost, 1995; Pentecost and Viles, 1994; Viles and Goudie, 1990, and Viles and Pentecost, 2007). Field descriptions are largely derived from the terms that are applied to microbialites (biolithite of Folk, or boundstone of Dunham [Tucker, 2011]), encompassing stromatolites and bioherms (Tucker, 2011; Viles and Goudie, 1990; see glossary). They may adopt columnar, planar, or oncolite forms. According to Pedley (1990) tufas can be described as either autochthonous (forming in-situ), e.g. phytoherm framestone (anchored) and phytoherm boundstone (dominated by the heads of skeletal stromatolites), or clastic (not anchored). Clastic tufas include: phytoclasts, oncoids, detritus, peloids and palaeosols. Petrological descriptions of cements are usually based on the extent of micrite (carbonate particles <4µm diameter) or sparite (clear, or white coarser equant calcite precipitated in

pore space between grains; Tucker and Wright, 1990). Reference should be made to the literature for more unusual cement forms.



Fig. 1. Speleothem (flowstone) attributed to carbonate leaching from lime rich mortar, Lindisfarne Castle, Northumberland, UK.



Fig. 2. Speleothem (flowstone) attributed to carbonate leaching from lime rich mortar, Lindisfarne Castle, Northumberland, UK.



Fig. 3. Cemented scree at Ecton, Manifold Valley, Staffordshire, U.K.

Classification and interpretation of depositional environments is fundamental to the applied geological aspects of secondary carbonate deposits. Owing to the breadth of depositional environments and their global distribution, a number of potentially useful classification schemes have been developed. Classifications that have been applied to the major groups follow.

2.1 Speleothems

Speleothems are generally classified according to their morphology or their origin (Hill and Forti, 1995). The former is used more frequently and Hill and Forti (1995) use the term *speleothem type morphology* to define a distinct morphology that is controlled by one or more hydrological mechanisms, e.g. dripping, flowing, pool, geyser, capillary, condensation and aerosol water. More broadly, speleothems can be classified as gravitational (dripstones and flowstones), which are the key focus for this chapter, or as non-gravitational erratic forms, including coverings or shields, helictites (capillary-fed), botryoidal forms, moonmilk, pendants, straws, cave pearls, rimstones and pool deposits. Each of these is associated with a specific setting within the cave environment (Ford and Williams, 2007; Hill and Forti, 1995). Whilst stalactites and stalagmites are formed by dripping water, flowstone is formed layer upon layer by water flowing over surfaces. Draperies (e.g. curtains) may be formed by both processes separately or in combination. As a consequence of their layered structure, gravitational speleothems can be dated and contribute evidence of local and regional tectonic histories. They can also be used in conjunction with stable isotope analyses for the interpretation of climate change (section 6). Where flowstones occur, indicators of historic flooding may be preserved on cave walls as erosional features or inclusions of detritus.

2.2 Travertine and tufa deposits

The basis for the classification of the depositional environments associated with travertines and tufas comes from the work of Chafetz and Folk (1984) who defined five main classes: waterfalls; lake-fill; sloping mound or fan; terraced mound and fissure ridge. A number of classification systems have followed, which are broadly based on depositional setting, geomorphology or biology (Pazdur et al., 1988; Pedley, 1990; Pentecost and Lord, 1988; Pentecost and Viles, 1994; Viles and Pentecost, 2007). Additionally, classifications have been devised for engineering purposes; such classifications need to take account of the heterogeneous nature of tufa, e.g. the engineering classification of tufa in the Antalya area, SW Turkey (Dipova, 2011), which was derived from a consideration of primary fabric, diagenesis and strength. Pedley (1990) subdivided tufas on the basis of their environmental setting (Table 1) and this provides the reference point for subsequent descriptions in this chapter.

Some tufa deposits occur where deep hydrothermal flow resurges, commonly in association with faults. Due to the absence of associated assemblages of deposits, these tufas would likely be classified in the perched spring-line model. Examples include the deposits at Matlock Bath, Derbyshire, UK (Pentecost, 1999). As with speleothems, growth couplets have been identified as representing annual seasonality (Andrews and Brasier, 2005), which offer the potential for palaeoclimatic and palaeoenvironmental interpretation (section 6). An unusual non-biogenic occurrence of tufa occurs in ultramafic rocks in northern Oman, where hyperalkaline groundwaters precipitate tufa (Clarke and Fontes, 1990).

Pentecost and Viles (1994) classify tufa as a form of travertine and they distinguish between meteogene and thermogene travertine on the basis of the source of the carbon dioxide (soil and deep crustal sources respectively). Thermogene travertine is associated with volcanic centres, high carbon dioxide discharges and high geothermal gradients (section 3.5). Pentecost and Viles (1994) presented a further classification for thermogene travertines, subdividing: spring (fissure ridge or mound, including those of saline lakes) river (cascade, cemented rudites and barrages) and lake deposits (crusts).

Model	Deposits
Perched springline. (resurgences part way up slopes). Cascade.	Proximal: dominated by liverworts and bryophytes; colonisation by cyanophytes and diatoms. Distal: Fine intraclast tufa and microdetrital tufa.
Braided fluviatile.	Curtains of moss associated with waterfalls. Notable absence of upstream lake sediment and biotal associations.
Fluviatile barrage.	Braided cyanolith-dominated deposits comprising oncoids and micro-detritus.
Lacustrine.	Phytoherms that obstruct stream flow forming barrages with associated upstream lake sediment and biotal associations.
Paludal.	Macro- and microphytes that characterise lake margins; stromatolite, oncoid and intraclast tufas characterise the shallow water and micro-detritus the marginally deeper water.
	Surface coatings of tufa on vegetation in marshy localities, where resurgences occur on poorly drained slopes or alluvial valley bottoms.

Table 1. Classification of tufa based on environmental setting (Pedley, 1990).

An outcome of an investigation of calcretes and speleothems in deep time (Brasier, 2011) was the observation that the relative absence of biogenic soils prior to the evolution of vascular plants implies that different processes were associated with the deposition of terrestrial carbonates during the Archaean, Proterozoic, Cambrian, Ordovician and Silurian. Accordingly, Brasier (2011) has suggested that the term tufa cannot really be applied to deep time; instead, more descriptive classifications, e.g. spring carbonate, stream carbonate and lacustrine carbonate may be more appropriate.

2.3 Carbonate cements

A range of clastic sediments can be cemented, but coarser sediments contain larger pore spaces, which allow thicker cement rinds to form and render them more favourable for research purposes. Detailed petrological descriptions facilitate classification on the basis of vadose or phreatic cementation. A good case study by Strong et al. (1992) described the range of vadose fabrics associated with the cementing of glacial gravels in North Yorkshire, England, UK. This case study also includes a description of some of the terms used to describe pedogenic carbonates, including rhizocretions (the tubiform cements that form around plant roots). Additional pedogenic forms (Tucker, 2011) include duricrusts (lithified, pedogenic surface layers), laminated layers and vadoids (laminated spherical grains that are commonly biologically mediated).

2.4 Pedogenic carbonate

These carbonates primarily occur in arid, semi-arid, or subhumic climates and can be classified on the basis of either morphology or formational process. Irrespective of climatic conditions, formational processes can be subdivided into: per descensum, per ascensum, in situ and biogenic models (Curtis, 2002).

2.5 Third order deposits

Regional lowering of groundwater levels can induce dissolution of secondary carbonate cements. Given their topographical setting, cascade tufa deposits are particularly vulnerable to this form of weathering. However, active dissolution can also result in saturation and supersaturation of the infiltrating water with a potential for re-precipitation, particularly in association with biological mediation. Typical of this process are the third order speleothem deposits observed in the Via Gellia, near Cromford, Derbyshire, UK, which take the form of micro-stalactites (Figure 4) and flowstone. Similarly, inundation of calcareous aeolianites is often characterised by vertical piping because dissolution occurs where percolation is guided by tree roots (Ford and Williams, 2007).

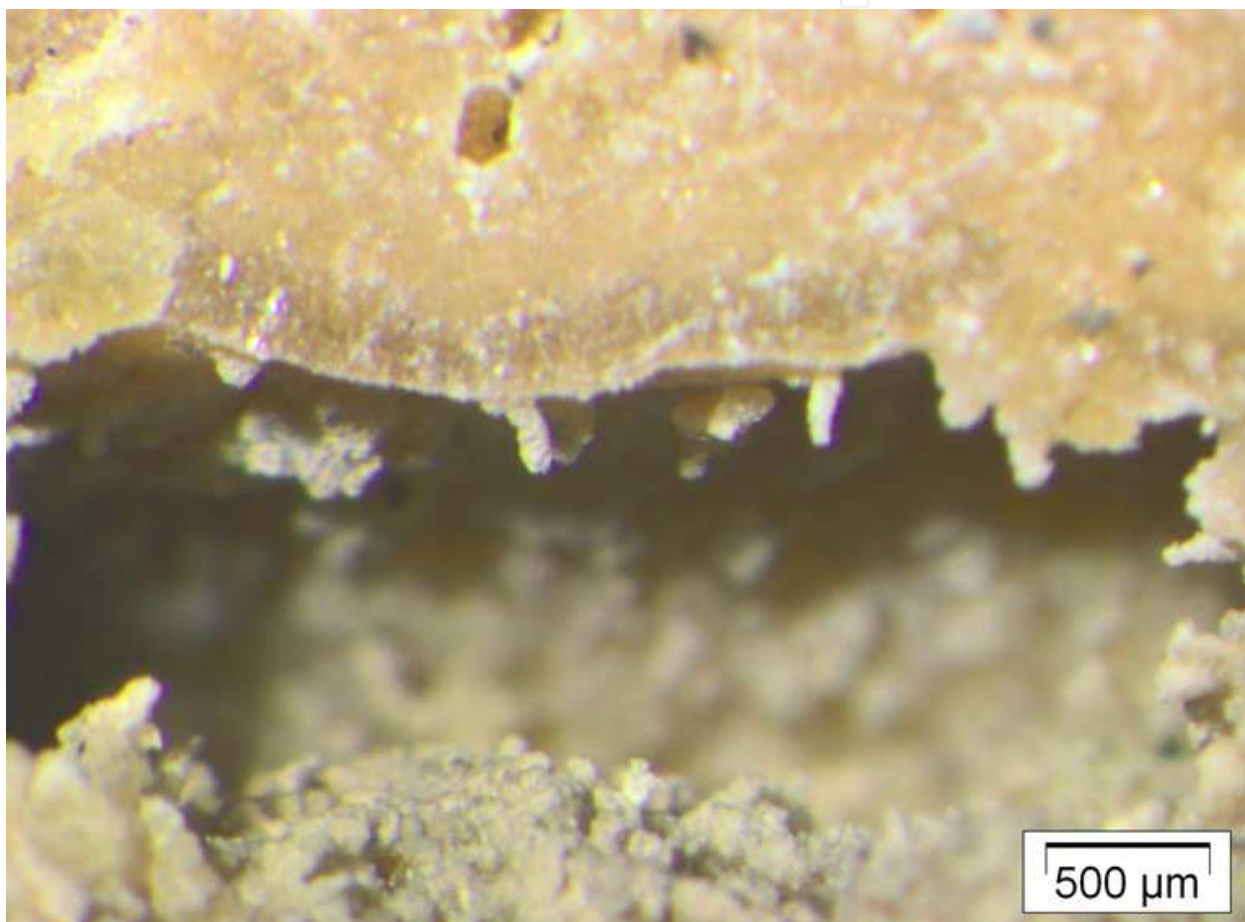


Fig. 4. Micro-scale third order speleothems in tufa in the Via Gellia, near Cromford, Derbyshire, UK. Larger examples also occur. Binocular microscope image: the British Geological Survey Mineralogy and Petrology Laboratories.

3. Depositional processes associated with secondary carbonate precipitation

Secondary carbonates result from a carbonate source-pathway-receptor system that operates at or very close to the Earth's surface. This generally involves dissolution of an existing deposit of calcium carbonate followed by transport of the dissolved species via surface and groundwater flow paths to a point of precipitation. Favourable conditions for precipitation

include supersaturation with respect to calcium carbonate and sites where the physical perturbation of water promotes carbon dioxide outgassing.

3.1 Hydrogeochemistry

The hydrogeochemistry of secondary carbonate deposits is fundamental to understanding their formation. The following comprises a brief overview of the carbonate system. The interested reader is recommended to refer to additional texts, including: Ford and Williams (2007) and Kehew, (2001), as well as the other references cited.

Limestone dissolution has been studied extensively in the context of karst geomorphology (Appelo and Postma, 2005; Ford and Williams, 1989 and 2007; Gunn, 1986). The controlling chemical equations with respect to the dissolution of calcium carbonate are:



This equation represents the absorption of carbon dioxide in water. At equilibrium, the activity of dissolved carbon dioxide is proportional to the partial pressure of carbon dioxide in the gas phase in contact with the aqueous phase containing the dissolved carbon dioxide. Atmospheric P_{CO_2} is $10^{-3.5}$ atm., whereas the P_{CO_2} values for groundwater are typically an order of magnitude higher (up to approximately 6%, Ford and Williams, 2007), as a consequence of the addition of biologically (plant respiration) derived carbon dioxide (Atkinson, 1977). The variation in the production of carbon dioxide is primarily related to the temperature, moisture content and amount of organic matter in the soil and therefore it reflects climate and seasonality (Ford and Williams, 2007; Kehew, 2001).



Aqueous carbon dioxide dissolves in water to form carbonic acid, which is a weak acid with a potential for dissociation. The theoretical assumption is that all of the CO_2 occurs as carbonic acid, whereas in practice, most of the CO_2 is present as dissolved CO_2 . The reaction between aqueous CO_2 and water is slow compared to reactions involving H_2CO_3 , thus it becomes rate limiting (Kaufmann and Dreybrodt, 2007). Carbonic acid is a diprotic acid, i.e. it can dissociate twice:



The three inorganic carbon species that result from the dissolution of carbon dioxide in water are active over differing pH ranges: H_2CO_3 predominates in acid conditions (pH 1 to 6.4); at pH 6.4 the activities of HCO_3^- and H_2CO_3 are equal; from pH 6.4 to 10.33 HCO_3^- is more active; at pH 10.33 the activities of HCO_3^- and CO_3^{2-} are equal, with CO_3^{2-} being most active where the pH exceeds 10.33.

Additional hydrochemical factors to be considered in the context of limestone dissolution include: (i) The common ion effect, whereby a common ion derived from the dissolution of a more soluble mineral will reduce the solubility of the less soluble mineral, e.g. the addition of sodium bicarbonate to a solution in equilibrium with calcite would cause an increase in the saturation index for calcite, thereby resulting in calcite precipitation. (ii) Incongruent

dissolution, which can occur because of the differing activities of minerals at different temperatures or as a consequence of differing reaction rates. An example of the former is the incongruent dissolution of dolomite and simultaneous precipitation of calcite as a consequence of the common ion effect imparted by anhydrite, which results in dedolomitization (Bischoff et al., 1994). (iii) Increases in ionic strength, which cause reductions in activity coefficients and consequential increases in solubility.

Dissolution in karst environments (karstification) can result in surface lowering or an increase in the underground permeability. Rates of dissolution can be calculated from the product of the discharge volume and solute (calcium carbonate) concentration. Both ground surface and underground dissolution are not uniform processes. Dissolution is greatest: at points of convergence where mixing corrosion can occur; in zones of more intense biological activity; where soil moisture is high, and in areas with a sunny aspect (Ford and Williams, 2007). As a consequence, dolines can become the focal point for higher rates of surface dissolution. In the UK, dissolution rates of $83 \text{ m}^3 \text{ km}^2 \text{ a}^{-1}$ have been quoted for Derbyshire and Yorkshire (with 0% and 50% respectively being derived from underground sources; Pitty, 1966 and Sweeting, 1966). A rate of $69 \text{ m}^3 \text{ km}^2 \text{ a}^{-1}$ was measured by Gunn (1981) for Waitomo, New Zealand (37% from the soil profile and the remainder from up to 5- 10 m of bedrock) where the epikarst is better developed than Derbyshire and Yorkshire. Any assumption of 100% surface lowering is likely to be in error. More recent developments in the understanding of carbonate dissolution, in particular that of kinetic thresholds (see below) and the importance of flow convergence, suggest that an underground component should be expected in all environments. Ford and Williams (2007, p82) note that *"hundreds of studies of solutional denudation have been completed since 1960. A major shortcoming of much of the work is that autogenic rates have often not been distinguished from mixed autogenic-allogenic rates so that there is still no unequivocal answer to the question posed long ago by climatic geomorphologists: in which climatic zone does karst evolve most rapidly?"*

Initial openings in unconfined karst settings are slowly enlarged by groundwater that is close to saturation with respect to calcium carbonate. The routes conducting the highest discharge are subject to greater dissolution (Palmer, 1991, 2002). Consequently, conduit development is enhanced by larger initial openings and increased hydraulic gradients such that conduit initiation is commonly attributed to base level lowering, which may be a consequence of uplift. For a given partial pressure of carbon dioxide, the initial rate of dissolution decreases in an approximately linear manner with increasing calcium carbonate content, but at 60-90% saturation the dissolution rate decreases rapidly (the kinetic threshold). Whilst the slow uniform dissolution that delays the final stage of saturation with respect to calcite facilitates the gestation of long conduit flow paths and enables deeper penetration of nearly saturated water, it may inhibit supersaturation with respect to calcite. Whereas flow in pre-dissolutional openings is laminar, as dissolution proceeds and openings are enlarged to the hydrodynamic threshold (generally considered to be 10 mm, Fetter, 2001), turbulent flow develops and the rate of carbonate rock dissolution increases rapidly as circulating water becomes less saturated. The hydrodynamic threshold also coincides with the kinetic threshold and the onset of clastic sediment transport, which further contributes to dissolutional enlargement (White, 2002). The rate of dissolution increases with discharge until a maximum is achieved. Flooding increases flow rates and flood water is generally more aggressive being characterised by a lower pH and lower concentration of calcium. During

flooding, additional flow paths will be activated, both in the vadose and the phreatic zones, facilitating rapid dissolution and increasing the efficiency of the system.

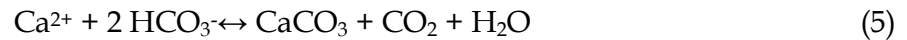
Even without topographical and hydrological focusing of flow, limestone dissolution would be non-uniform because some limestones have a greater propensity for dissolution than others. For example, dissolutional activity (speleogenesis) tends to focus on inception horizons (Lowe, 2000; Banks et al., 2009). Typically, inception horizon-guided dissolution focuses on incipient physical, lithological, or chemical differences that form a focal point for conduit gestation. These differences include: breaks in sedimentary style or bedding; variation in trace chemistry; fossil bands, or contrasts in permeability (e.g. boundaries between limestone and chert, shales or clays). Given sufficient residence time, rock-groundwater interaction ensures that the groundwater chemistry reflects the chemistry of the host geology. Thus inception horizons may also form a source of calcium carbonate, despite the fact that the rates of dissolution quoted above suggest that conduit sources generally provide less than 50% of the dissolved calcium carbonate in a catchment.

Other sources of calcium carbonate include soils, superficial deposits and a range of anthropogenic materials. Soil and superficial deposits derived from limestone terrains can contain a significant proportion of leachable calcium carbonate. Typical artificial sources of carbonate with a greater propensity for dissolution include former waste tips resulting from lime processing, quarrying or mining. For example, the source of the artificial tufa barrages in Brook Bottom (Figure 5), which are in the order of 1 m high (Ford and Pedley, 1996), and the source for a nearby, rapidly accumulating speleothem in Poole’s Cavern, near Buxton, Derbyshire, UK (Baker et al., 1999) comprises waste heaps related to the former lime manufacturing industry (Figure 6). The formation of pedogenic carbonate with carbonate derived from artificial sources such as slag, construction materials and cement has been described by Manning (2008).

Locality	Secondary carbonate deposit type	Rate (mm/annum)	Reference and notes
Caves of Niue Island, South Pacific.	Speleothem	0.23-0.34	Aharon et al., 2006.
Lathkill Dale, Peak District, Derbyshire, UK.	Tufa	2.5	Andrews et al., 1994. Holocene accumulation rate.
Poole’s Cavern, Peak District, Derbyshire, UK.	Speleothem	2.1 – 5.0	Baker et al., 1999. Associated with former lime kilns. 1910 – 1996.
Palaeozoic caves of Wallonie, Belgium.	Speleothem	0.5 – 2.17	Genty and Quinif, 1996.
Malham Tarn, North Yorkshire, UK.	Tufa	0.01-1.30	Pentecost, 1978.
Goredale Beck, North Yorkshire, UK.	Tufa	1-8	Pentecost, 1978.
Mato Grosso, Brazil.	Speleothem	0.012	Soubiès et al., 2005. Variable growth rate.

Table 2. Examples of secondary terrestrial carbonate accumulation rates.

The precipitation of calcium carbonate can be summarised by:



A state of supersaturation is required for carbonate precipitation. This can be brought about by the degassing of calcium carbonate enriched waters (Chen et al., 2004; Lorah and Hermon, 1988) that may be associated with cooling and physical or biological degassing of carbon dioxide, reducing the amount of calcium carbonate that can be held in solution. A further process leading to supersaturation is that of evaporation, which is considered to be



Fig. 5. Anthropogenic tufa barrages, Brook Bottom, Derbyshire, UK.



Fig. 6. Cemented lime kiln waste, Brook Bottom, Derbyshire, UK.

the cause of tufa precipitation near many cave and mine entrances (Ford and Williams, 2007). However, a solution that is supersaturated with calcium carbonate does not necessarily give rise to carbonate precipitation if appropriate nucleation sites are not present. Rates of carbon dioxide out-gassing can exceed rates of calcium carbonate precipitation resulting in supersaturation, with a potential to mask any groundwater mixing effects (Thraillkill, 1968). In the case of speleothems, where there is a lower partial pressure of carbon dioxide in the cave atmosphere than in the incoming water, degassing of carbon dioxide leads to supersaturation and consequential precipitation of calcium carbonate.

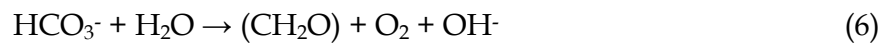
Accumulation rates for secondary terrestrial carbonates can provide valuable information with respect to landscape evolution. The relatively rapid accumulation rates are such that measurements can be determined in mm per year; examples are presented in Table 2.

3.2 Biological mediation

The nature and extent of biological mediation (enabling) of secondary carbonate precipitation reflects the physical setting of the deposit. Various microbes, flora and fauna contribute to tufa deposition. Cyanobacteria are usually the dominant microbial component (their calcification being associated with the mucopolysaccharide) in fast-flowing streams supersaturated with respect to calcite, where sheath encrustation is the dominant form of calcification (Riding, 2000). Cyanobacteria mineralization is extensively associated with tufa precipitation (Andrews and Brasier, 2005; Brasier et al., 2011; Pentecost, 1988). Photosynthesis causes alkalinization, while exopolymeric substance (EPS) acts as binding site for calcium (less so in freshwater tufas; Dittrich and Sibling, 2010) and the consequential focus for calcium carbonate precipitation. Similarly, microbes are also present in many cave systems, varying between the twilight and aphotic zones of caves (Jones, 2010). They include a diverse range of algae, actinomycetes, bacteria, fungal hyphae and cyanohyphae. Cave microbes contribute to the destructive (dissolutional substrate breakdown, boring and degradation) and constructive processes (trapping and binding of detrital particles, calcification and precipitation) that influence the growth of speleothems (Jones, 2010). Evidence of these processes comes from the presence of fabrics (e.g. microbial stromatolites), mineralized microbes and geochemical markers (e.g. lipid biomarkers; Jones, 2010). Cave microbial processes reflect the habitat, particularly the light distribution.

When microbes are encrusted and replaced by calcite, they become part of the substrate. This process results in a range of calcite crystal forms, in both tufas and speleothems. Biomineralization is associated with: bacterial cells, including picocyanobacteria (unicellular cyanobacteria with a cell diameter of 0.2 to 2.0 μm); sheaths, and EPS. Biogenic mineralization can occur through either biologically controlled or biologically induced processes (González-Muñoz et al., 2010). Biologically controlled mineralization occurs in isolated compartments within a living organism, resulting in highly ordered mineral structures (González-Muñoz et al., 2010), which are more typical of shells, but uncommon in bacteria. Biologically induced mineralization is the result of microbial metabolism. There are two stages involved: firstly, active modification of the physical chemistry in the environment of the bacteria leading to an increase in ion concentration (supersaturation; equations 6 to 7); secondly, nucleation of mineral (equation 7). Homogeneous nucleation requires a higher degree of supersaturation, whereas heterogeneous mineralization results from nucleation on bacterial cell walls, bacterial EPS or the new mineral phase (González-

Muñoz et al., 2010). The geochemical equations involved in bacterial ion concentration (González-Muñoz et al., 2010) can be summarised as:



This equation represents the photosynthetic bacterial conversion of bicarbonate into reduced carbon. Similar effects can be produced by bacteria that produce ammonia by oxidative deamination of amino acids. Where carbon dioxide is generated by the bacterium, supersaturation with respect to bicarbonate or carbonate may result (González-Muñoz et al., 2010).



Equation 7 results from the exchange of intracellular hydroxide ions for extra cellular bicarbonate ions across the cell membrane. Alkalinization around the bacterial cells induces carbonate generation.



Equation 8 represents the precipitation of calcium carbonate on the cell surface. Calcium carbonate may first be precipitated as vaterite. Evidence for a two phase process in active tufa deposition in the Via Gellia, Derbyshire, UK, can be seen in Figures 7 to 9. However, different cyanobacterial species exhibit different calcification fabrics (Pentecost, 1991).



Fig. 7. Active tufa precipitation in the Via Gellia, Near Cromford, Derbyshire, UK. Binocular microscope images: the British Geological Survey Mineralogy and Petrology Laboratories.

Dittrich and Sibling (2010) analysed and modelled the functional groups of extracellular polysaccharides of three picocyanobacteria establishing the presence of five to six surface sites, corresponding to: carboxyl, phosphoric, sulphhydryl, amine phenol, and hydroxyl

groups. The carboxyl and carboxyl-phosphoric groups dominated in all strains, closely followed by the hydroxyl groups. Polysaccharides were found to be negatively charged at a

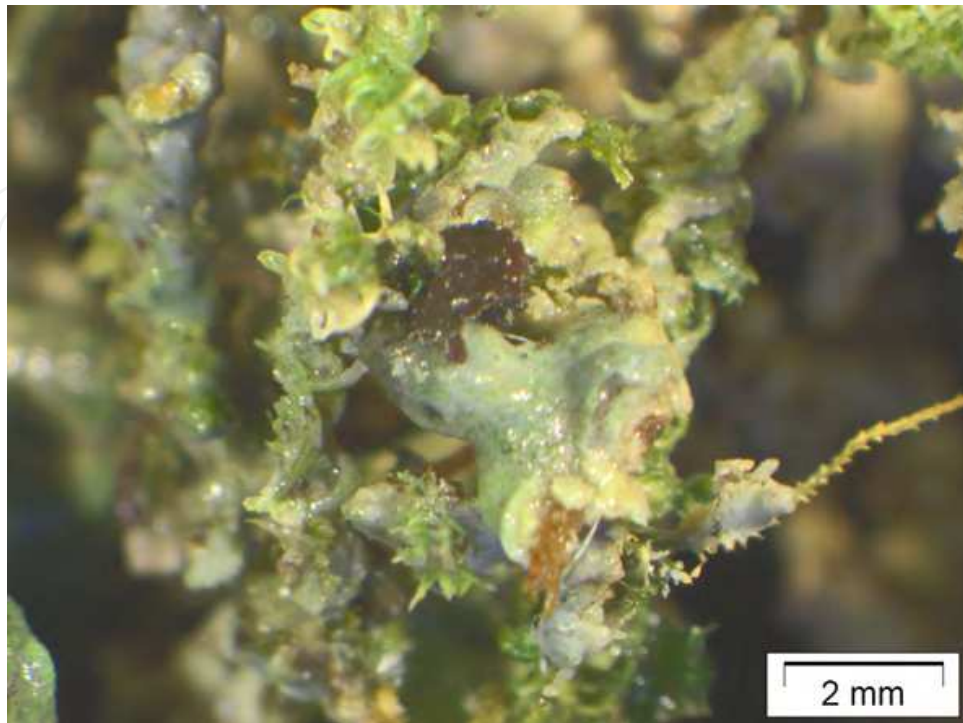


Fig. 8. Active tufa precipitation in the Via Gellia, Near Cromford, Derbyshire, UK. Binocular microscope images: the British Geological Survey Mineralogy and Petrology Laboratories.



Fig. 9. Active tufa precipitation in the Via Gellia, Near Cromford, Derbyshire, UK. Binocular microscope images: the British Geological Survey Mineralogy and Petrology Laboratories.

pH range of 6 – 7. Therefore, calcium ions can easily be attracted to them. However, removal of calcium reduces the degree of saturation, thereby inhibiting calcium carbonate precipitation. The presence of the carboxyl groups offers the potential to remove metals, thereby overcoming the inhibition to calcium solubility resulting from the presence of low concentrations of metals (Terjesen et al., 1961; Dittrich and Sibler, 2010). Decomposition of the EPS releases bicarbonate and calcium ions, which increases the calcium carbonate saturation state and promotes precipitation.

3.3 Geomorphological and tectonic mediation

A number of deposits are representative of specific geomorphological and tectonic settings, as acknowledged in Pedley's (1990) classification of tufas (section 2.2) and as evident in the

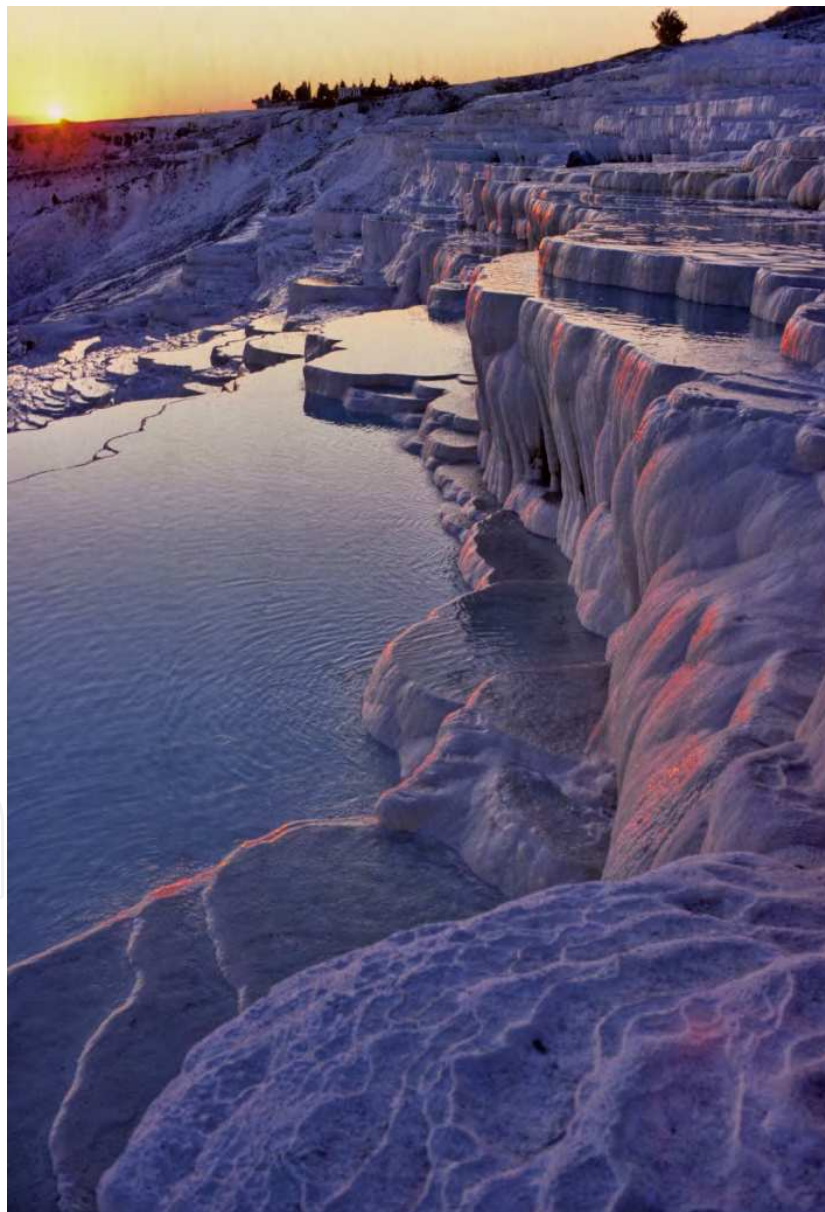


Fig. 10. Pamukkale Travertine, SW Turkey. Photograph: Anthony H Cooper, British Geological Survey.

Antalya area of south-west Turkey, where tufa terraces have been related to glacio-eustatic sea level change (Glover and Robertson, 2003). Similarly, Forbes et al. (2010) described a number of tufa deposits in the south-western coastal zone of Western Australia. These deposits are characterised by cascade to barrage pool and perched spring line to barrage pool situations, which are associated with coastal waterfall and supratidal geomorphological settings respectively. Geomorphology and tectonic setting can also influence the carbonate source and flow paths through uplift and erosion. As an example, a rock slide in the Fern Pass, Austria produced carbonate rock flour which formed the carbonate source for subsequent cementation of the rockslide breccias (Ostermann et al., 2007). As thermal deposits, travertines are also likely to be moderated by tectonic events, particularly given that the location of these deposits is commonly related to faults (Pentecost, 1995). Similarly, fissure ridge travertine deposits, associated with listric faulting in the Gediz Graben extensional province of Turkey have been explained by their tectonic setting (Selim and Yanik, 2009). The Pamukkale travertine (Figure 10) in Turkey occurs in a different extensional tectonic regime (Selim and Yanik, 2009; Şimşek, 1993). In the case of the Lapis Tiburtinus travertine, Central Italy, travertine cycles reflect water table fluctuations associated with fault and volcanic activity between 115 000 and 30 000 BP (Faccenna, et al., 2008).

3.4 Anthropogenic influences

As well as providing artificial sources of calcium carbonate, anthropogenic influences can affect flow paths and the depositional rates of secondary carbonates that are commonly encountered in infrastructure, mines and industrial areas. The growth of speleothems has been reported in a number of such settings, e.g. railway arches and disused water reservoirs. Recent work in opening the disused railway cuttings between Buxton and Bakewell in the White Peak, Derbyshire, UK, has exposed occurrences of speleothems, flowstone and tufa associated with the engineered structures, including tunnels, bridges and cuttings. Occurrences of this kind may be a consequence of either the opening of new flow paths, or the interception of pre-existing ones, as observed in a cutting (Figure 11) where tufa precipitation is clearly associated with water discharging from exposed inception horizons. Flow rates associated with these deposits are generally low, with flow commonly occurring as minor seepages in the unsaturated zone. The nature of anthropogenically mediated secondary deposits would appear to reflect the significance of biological mediation, with tufa forming in moist locations where mosses and bryophytes establish themselves, commonly associated with shade and good ventilation. As the majority of the engineered structures can be dated, secondary carbonate deposits in these settings provide an opportunity for assessing minimum rates of precipitation. Cemented kiln waste encountered in Brook Bottom, Derbyshire, U.K (Figure 6), provides further evidence for the occurrence of anthropogenically moderated calcite precipitation. Underground, rapid rates of calcium carbonate precipitation are implicit in the occurrence of tufa deposits above a skeleton discovered in historic mine workings in Lathkill Dale, Derbyshire, UK in 1744 (Rieuwerts, 2000).

Anthropogenic influences have been linked with a range of factors that may have contributed to the post-Holocene decline in tufa deposition (Goudie et al., 1993), which in Derbyshire, UK, primarily occurred approximately 4000 years BP. This coincides with Neolithic to Early Bronze Age deforestation (Taylor et al., 1994), which may have influenced barrage type (section 2.2) tufa deposition in one or more of the following ways (Goudie et al., 1993): reduced availability of carbon dioxide in the vicinity of areas of groundwater

recharge; less woody material available to form dams; induced soil erosion, associated with further reductions in the availability of carbon dioxide; alteration to the shade causing stress to mosses or cyanobacteria at resurgences; increased access for grazing with consequential changes to groundwater chemistry, including eutrophication, and turbidity, thereby inhibiting the bacteria and mosses responsible for tufa accumulation, and increased surface run-off causing increased turbidity and dissolution potential during periods of high discharge. Tufa formation is severely limited when the mean annual air temperature falls below 5°C (Pentecost, 1996; Pentecost and Lord, 1988), which suggests that a component of the late Holocene decline may be associated with lower mean air temperatures.



Fig. 11. Tufa formation below an inception horizon in a railway cutting between Buxton and Bakewell, Derbyshire, UK. 1 m length of tape measure for scale.

3.5 Travertine forming processes

Pentecost (1995) summarised the distribution of Quaternary thermogene travertine formations in Europe and Asia Minor. Of the 93 sites identified, 56 are known to be active and many of the European deposits date to the Pleistocene or late Pliocene. A significant proportion of the active sites occur in Italy and Turkey, where they correspond with volcanic centres and high carbon dioxide discharges, associated with high geothermal gradients. The precise relationship between volcanism and travertine formation has yet to be established. On the basis of isotope analyses, it has been hypothesised that carbon dioxide enriched fluids derived from the upper mantle and from limestone decarbonation dissolve sedimentary carbonate (Pentecost, 1995). However, in the case of the Lapis Tiburtinus travertine, Tivoli, Central Italy, carbon isotope analysis of the travertine suggests

a hydrothermal origin for the fluids that precipitated the tufa (Faccenna et al., 2008). The majority of hydrothermal springs rise on faults (Pentecost, 1995). The largest depositional region extends from Greece, through Turkey and across the Caucasus Mountains into Russia, where convergence of the Eurasian and Afro-Arabian plates is believed to be responsible for the recent volcanism and hot spring activity.

3.6 Diagenesis

Diagenesis of carbonate sediments can occur through cementation, dissolution, microbial micritization or neomorphism. The metastable condition of many carbonate minerals, such as aragonite, renders them susceptible to recrystallization. Potentially, this may result in changes that cause the deposits to be less useful for interpreting climate change or depositional environments. Recrystallisation may occur through changes to the isotopic signature or fractionation of elements used for dating. Thus, understanding of diagenetic processes is important. Martín-García et al. (2009) demonstrated this in the case of speleothems from the Castañar Cave, in the southern part of the Iberian Massif in Spain. Here speleothems in dolomite hosted karst were found to have undergone micritization and neomorphism thereby modifying the primary features including the stable isotope, strontium and magnesium contents. Similarly, in a study of the diagenesis of aragonite in speleothems in Korea, Woo and Choi (2006) found that aragonite inversion to low magnesium calcite was associated with the remobilisation of stable isotopes and trace elements, with a notable difference in the carbon isotope signature.

In contrast, in a petrographic examination of Greek tufa deposits with a significant development of sparite over micrite, the relative absence of diagenetic processes was established (Brasier et al., 2011). This disproved a formerly held view that the extent of sparite was likely to be a secondary feature (diagenetic aggrading neomorphism, e.g. Love and Chafetz, 1988) of the tufa. The study of the distribution of sparite and micrite in two Greek Pleistocene tufa stromatolites (Brasier, et al., 2011) revealed primary columnar calcite spar in a younger deposit (ca 100 ka) from Zemenos occurring immediately above chironomid larval tubes with which its growth was associated, whilst an older tufa (ca 1 Ma) from Nemea comprised proportionately more sparite with some chironomid tubes and cyanobacterial filaments. Comparison of stable isotopic trends (section 5.2) revealed that both deposits supported resolvable seasonal responses, suggesting that there had been limited post-depositional alteration of either tufa. The higher proportion of sparite in the Nemea deposit has been attributed to abiotic, speleothem-like growth of near hemispherical laminations from thin films of water (Brasier et al., 2011).

4. Spring and cave drip geochemistry

The use of seasonal signatures derived from carbonate deposits, particularly as a source of high-resolution palaeoclimate data, drives the need to understand how this is expressed in the supply waters. Spring geochemistry is of interest to the research of secondary terrestrial carbonate deposits, because it reflects the source of the carbonate as well as the processes operating during transport of the solutes between the points of dissolution and precipitation. Drip and cave air geochemistry is of equivalent interest in the case of cave deposits (Baldini et al., 2006). Calibration of speleothem oxygen isotopes in current calcite deposits at Tartair cave, Sutherland, North West Scotland with the oxygen isotope

signatures of precipitation and percolating waters (Fuller et al., 2008) demonstrates the benefit of speleothem research to climate studies.

4.1 Flow path geochemistry

Groundwater can be characterized by the degree of equilibrium between the water and the wall rock (Drake and Harmon, 1973; Richardson, 1968; Shuster and White, 1971, Smith and Atkinson, 1976). Factors that influence flow path geochemistry include: flow-through time (water-soil contact or water-rock contact time); atmospheric conditions, including temperature; thickness and type of superficial cover; bedrock geology, and epikarst thickness. These variables are reflected in the range of proposed classifications, based on: individual parameters, ratios of parameters (Downing, 1967 and Vervier, 1990), flow-through times, as indicated by hardness and P_{CO_2} (Drake and Harmon, 1973; Pitty, 1966), seasonal variation of parameters (Shuster and White, 1971) and variation with discharge (Jacobson and Langmuir, 1974). Kehew (2001, p. 16) suggested, *"By knowing the state of equilibrium between the water and minerals within the aquifer, we can predict the type of reactions that are occurring or would be likely to occur"*, but it is rarely possible to sample a karst system along its flow path, instead use is made of springs and geochemical modelling to assess the likely processes within the system.

Conceptually, speleothems form within a flow path, thereby providing information on flow path geochemistry in the vadose zone. It has been established that the five main controls on their growth rates are: drip rate, activity of calcium in the drip water, air temperature, cave air P_{CO_2} and film thickness (Fairchild et al., 2001). In this context, cave drip water chemistry and cave air chemistry is important for understanding the hydrological controls on speleothem growth rates. This has been demonstrated in studies of hourly resolved cave P_{CO_2} and cave drip water hydrochemical data, in Crag Cave, SW Ireland (Baldini, et al., 2006; Sherwin and Baldini, 2011; Tooth and Fairchild, 2003). These studies demonstrated that calcite deposition on stalagmites can be moderated by prior calcite precipitation on short timescales. Given relatively constant conditions (air temperature, film thickness and low drip rates) controls on speleothem growth were most strongly influenced by cave air in winter, whilst drip water dilution caused by rain events may play a more significant role during the summer. In a separate study of the same cave system, Tooth and Fairchild (2003) established that some speleothems at this site may record a signal of palaeohydrology determined by variations in Mg/Ca ratios, with higher Mg/Ca ratios indicating lower flow conditions when base flow is maintained by long residence time storage water.

4.2 Spring geochemistry

Geochemistry can be used to assess the functioning of karst springs, for instance the degree of equilibrium between the groundwater and the wall rock has been taken as an indicator of the type of flow feeding the spring (e.g. Atkinson, 1977a; Shuster and White, 1971; Worthington and Ford, 1995). Shuster and White (1971) classified diffuse and conduit flow waters; Bertenshaw (1981) vadose and phreatic, or open and closed systems, and Worthington (1991) underflow and overflow systems. The terms "open" and "closed" are defined by Appelo and Postma (2005), Ford and Williams (2007), Gunn (1986) and Smith and Atkinson (1976). The open system is one in which gas, water and rock are all in contact with one another such that carbon dioxide is available to replace that used up in

the reaction of limestone and carbonic acid. The closed system is one in which gas and water come into equilibrium, but a replacement supply of carbon dioxide is not continuously available during the reaction between limestone and carbonic acid. There is a gradation between fully open and fully closed systems. In the closed system, the concentration of carbonate species with changing pH is non-linear and less than in open systems. Karst systems are also described as diffuse or focused, which again may be reflected in the spring chemistry. Further understanding of aquifer processes can be derived from the seasonality of spring data.

4.3 Seasonality in spring and groundwater geochemistry

Seasonality in biogenic activity results in fluctuation in the biogenic production of carbon dioxide with a consequential seasonality to the partial pressure of carbon dioxide in infiltrating groundwater. Additionally, maximum evapotranspiration associated with the summer months concentrates constituents entering the ground to as much as twice that measured in the atmospheric precipitation (Edmunds, 1971). The extent to which seasonality is exhibited in spring water chemistry has been the subject of debate, possibly in part due to the method of monitoring (analogue versus digital). Shuster and White (1971) were able to use seasonality as an indicator of flow type in the Central Appalachians. More specifically, they related the variability of total hardness (expressed as a percentage coefficient of variation i.e. standard deviation/mean) to the type of resurgence. Springs with a variability of greater than 10% were interpreted as conduit flow, whilst those with less than 5% as diffuse, or percolation flow. However, in the Central Appalachians the variation in carbon dioxide pressures was more closely related to source areas (Shuster and White, 1971) than to seasonality. Deriving comparable coefficients of variation with respect to total hardness, Jacobson and Langmuir (1974) concluded that discharge was a more important influence on water chemistry than season, particularly for dispersed recharge type springs. In a more recent study in subtropical areas of SW China, Liu et al. (2007) collected data over two years of continuous monitoring of pH, conductivity, temperature and water stage from two epikarst springs (Nongla and Maolan springs). This was used to calculate partial pressures of carbon dioxide and the saturation indices with respect to calcite and dolomite. The study identified marked seasonal, diurnal and storm-related variations in the monitored and modelled parameters. Coefficients of variation of the parameters indicated that the greatest variation was at the seasonal scale, whilst storm scale exceeded diurnal variation. The variation was marked by higher conductivity and lower pH in the summer and daytime. Co-variation with temperature indicates that this influences the production of carbon dioxide in the soil. High rainfall events mask the seasonality as a consequence of the dilution. Monthly monitoring, over a 5-year period at fourteen localities along a tufa bearing stream on Carboniferous to Permian limestone at Shimokuraida, Niimi City, in southwest Japan, identified seasonal variation in the soil and spring water partial pressures of carbon dioxide. The variation was higher in the summer to autumn and lower in the winter to spring (Kawai et al., 2006).

4.4 Relationships between supply water chemistry and carbonate precipitation

Individual studies have demonstrated how supply water chemistry influences carbonate precipitate geochemistry. For example, the oxygen isotope content of speleothems in Tartair

Cave, Sutherland, North West Scotland corresponds with the oxygen isotope signatures of precipitation and percolating waters (Fuller et al., 2008; section 4). Leybourne et al. (2009) demonstrated that rapidly deposited tufa Sr/Ca ratios were controlled by spring water Sr/Ca ratios in a carbonate rock aquifer in the Interlake Region of Manitoba, Canada. They showed that whilst the $\delta^{18}\text{O}$ in the tufa is in equilibrium with the water, the $\delta^{13}\text{C}$ is enriched compared with the groundwater. In a case study in the Wye catchment, Derbyshire, UK, Banks et al. (2009) defined a number of formationally-based hydrogeological domains. These were derived from the results of dye tracing tests, analysis of water well monitoring and spring geochemistry and established that occurrences of barrage tufa are associated with only one of the domains. The implication was that the inception horizons in this unit provided a source of calcium during tufa precipitation (Banks et al., 2011).

4.5 Stream chemistry

Whilst spring chemistry provides an indication of the functioning of the karst aquifer, stream or river chemistry in karst terrains provides a catchment scale indication of dissolution and landscape erosion. A study of the river geochemistry of the Wujiang and Quingshuijiang rivers in the Guizhou Province of southern China (Han and Liu, 2004) demonstrated that dissolution in the catchments was attributable to both carbonic and sulphuric acids. Isotope studies ($^{87}\text{Sr}/^{86}\text{Sr}$) and the presence of nitrates indicate an anthropogenic source for a proportion of the sulphuric acid; thereby the implication is of anthropogenically accelerated erosion rates (43 to 49 mm per annum). Given the vulnerability of karst aquifers to contamination (Vesper et al., 2001), which results from the existence of open fast flow paths in the form of conduits, closely spaced monitoring in rivers can provide useful information with respect to point and diffuse sources and sinks of contaminants. A study of this type was undertaken by Banks and Palumbo-Roe (2010) in Rookhope Burn, a lead-zinc mining impacted karst catchment and tributary of the River Wear in northern England. This identified previously unrecognised resurgences of zinc-contaminated groundwater.

5. Geochemistry of secondary carbonate deposits

5.1 Secondary carbonate geochemistry

Secondary carbonate cements formed by meteoric water are representative of the local environmental conditions at the time of precipitation. Speleothems form in the vadose (unsaturated) zone by water dripping from the ceilings or walls of caves or from the overhanging edges of rock shelters. The precipitation of calcium carbonate is caused by the degassing of carbon dioxide into the cave, resulting in supersaturation of the groundwater with respect to calcium carbonate and consequential precipitation, which may also be biologically mediated. Seasonal lamination may occur as a consequence of seasonal variations in: drip rate (potential for variation in layer thickness); drip water supersaturation with respect to calcium carbonate, and cave climate (temperature, humidity and carbon dioxide concentrations). Lamination thickness measured in Belgian stalagmites by Genty and Quinif (1996) varied both between and within stalagmites, in the range 0.47 to 2.17 mm. Laminae were defined by variations in the density of the intercrystalline pores and inclusions. The pores were elongate parallel to the growth direction with their length ranging from 0.05 to 1 mm. Annual laminations formed as couplets of white porous laminae

and dark compact laminae of palisade calcite. The dark laminae, which have a lower pore density, form during periods of moisture excess with insufficient time for surface degassing of carbon dioxide, resulting in run-off and precipitation on the sides of the speleothems. This causes an overall thinning of the laminae and localised widening of the stalagmite. During drier periods, the narrow white porous calcite laminae are attributable to a chemically efficient flow rate that allows sufficient time for carbon dioxide outgassing and precipitation of calcium carbonate at the top of the stalagmite.

Annual trace element variation within speleothems, in part attributable to colloid transport, provides valuable information that can be used to investigate climate change. Fairchild et al. (2001) used ion microprobe analyses of speleothems from five western European cave sites to demonstrate seasonality in concentrations of magnesium, strontium, barium, fluoride, hydrogen and phosphorus (as phosphate). The caves studied were: Crag Cave, County Kerry and Ballynamintra, County Wexford in Ireland; Uamh an Tartair, Sutherland, Scotland; Grotte Pere-Noël, Belgium, and Grotta di Ernesto, north-east Italy. It was established that: i) Magnesium, strontium and barium substitute directly for calcium. ii) Magnesium/ calcium ratios reflect the supply ratio, tending to be lower under high flow conditions, because of prior calcite precipitation along the flow path. iii) In cave environments with low sodium and magnesium/calcium ratios, and with a constant temperature, the key variables affecting strontium partitioning are the supply ratio of strontium/calcium and the growth rates, with more strontium being incorporated at higher flow rates. iv) The concentration of sodium and fluoride was found to reflect the growth rate (more sodium and fluoride at higher growth rates) rather than variations in the supply water chemistry, a consequence of the rapid incorporation of these elements, but results in charge imbalance (growth defect) that can be satisfied by the further incorporation of more trace elements and suggests greater concentration of trace elements during periods of rapid speleothem growth.

Comparable findings have been made in studies of tufa deposits which also comprise calcium carbonate that is representative of the local environmental conditions at the time of precipitation. This particularly applies to biologically moderated tufas, where the cyanobacteria do not have a direct influence on the rate, mineralogy, or geochemistry of the calcium carbonate that precipitates around them (Andrews and Brasier, 2005). The seasonality of tufas results from cyanobacterial blooms in the early spring, which facilitates nucleation of densely calcified darker layers. As the nutrient supply (diatoms) reduces, cyanobacterial growth slows and filaments aggregate into scattered bundles separated by cavities resulting in a lightly calcified, porous layer (Andrews and Brasier, 2005). Strontium, magnesium and manganese concentrations in summer precipitates have been shown to be higher than those in winter (Chafetz et al., 1991). Magnesium geochemistry is more complex than indicated by Chafetz et al. (1991); as with speleothems, upstream precipitation of calcite has been shown to have a minor effect on magnesium chemistry, and magnesium concentrations appear to be controlled by aquifer processes rather than temperature (Andrews and Brasier, 2005).

5.2 Stable isotopes (carbon and oxygen) – Environmental and hydrological implications

The ratio of $\delta^{18}\text{O}$ to $\delta^{16}\text{O}$ measured against a standard gives an indication of mean annual surface temperatures at the time of speleothem precipitation. Similarly, ratios of carbon

isotopes may provide evidence for seasonality. Given no direct contact with the external atmosphere and constant temperature due to the limitation of air circulation, calcite precipitated in the resultant speleothem will form in isotopic equilibrium with the water from which it is precipitated. Changes in surface atmospheric conditions will be reflected in the percolating water and isotopically preserved in the speleothem and any fluid inclusions. However, not all speleothems can be studied in this way. For example, some may undergo diagenesis, or the speleothem may be contaminated by detrital matter (section 3.6).

Associated with the seasonality in tufa precipitation is a $\delta^{18}\text{O}$ trend to isotopically heavy winter-time tufa and isotopically light summer-time tufa. This is attributed to changing water temperature. $\delta^{13}\text{C}$ also shows seasonality with the summer-time sparry calcite exhibiting lower values than the micritic winter laminae. Matsuoka et al. (2001) suggested that seasonality in $\delta^{13}\text{C}$ in their Japanese study was attributable to winter degassing of carbon dioxide from groundwater fed spring water. In winter, the subsurface karst conduit air is warmer and less dense than the atmospheric air, so ventilation of the conduit air decreases the subsurface air Pco_2 and causes degassing of isotopically light $^{12}\text{CO}_2$ from the groundwater (Andrews and Brasier, 2005).

In a study of Quaternary pedogenic carbonates, designed to assess their usefulness as environmental indicators in Texas, Zhou and Chafetz (2010) undertook stable isotope analyses on a range of host strata. In the Gulf Coastal Plains, the Southern Highland Plains and the west, $\delta^{13}\text{C}$ values were found to vary in response to changes between C_4 -dominated and C_3 -dominated plants. Additionally, $\delta^{18}\text{O}$ values of the late Quaternary pedogenic carbonates decreased gradually from east to west, mimicking the spatial variation of $\delta^{18}\text{O}$ in modern meteoric water and increased distance from the Gulf of Mexico. However, the stable-isotope values developed on marine limestone and calcareous alluvium in central and southern Texas contained isotopic signatures that were derived from the host strata. These findings imply a variable potential for the interpretation of pedogenic carbonate stable isotope signatures.

5.3 Fractionation of isotopes

Fractionation of isotopes occurs where there is a change to the speleothem drip water chemistry prior to or during precipitation. This may occur in the soil, vadose zone, epikarst or in the cave environment. Potentially, fractionation may result in misinterpretation of isotope analyses. Fractionation effects can be estimated by analysing the variation in hydrogen isotopes, which are unaffected during crystal formation (Lauritzen, 1993). Additional information may be obtained from multi-proxy approaches, including non-conventional isotope systems, such as magnesium fractionation (Immenhauser et al., 2010). Fractionation can also occur as a consequence of post-depositional weathering of secondary carbonate deposits.

5.4 Isotopes and dating of secondary carbonate deposits

Radiometric dating methods are based on the decay of natural radio isotopes with a fixed decay constant (λ) for a given isotopic species. Cosmogenic isotopes are formed through cosmic reactions, e.g. with atmospheric nitrogen to generate carbon-14 (^{14}C), or rocks and

soil (^{10}Be , ^{14}C , ^{26}Al and ^{36}Cl). The application of the appropriate techniques is based on the geochemistry and suspected age of the dateable material. The suspected age is considered because each of the isotopes has a different half-life e.g. 5730 \pm 40 years for ^{14}C . ^{14}C ages are generally determined from atom counts undertaken in an accelerator mass spectrometer. The principal dating technique used for secondary carbonate deposits is uranium-thorium dating. Radioactive uranium (^{238}U and ^{235}U) generates daughter isotopes ^{206}Pb and ^{207}Pb through radioactive decay (of α , β and γ particles) via intermediate daughter species including ^{234}U , and ^{230}Th . Uranium is soluble in carbonate waters; rock weathering results in the preferential removal of ^{234}U , whereas thorium is far less soluble and bonds preferentially to clay particles. Consequently, whilst ^{234}U may be incorporated in secondary carbonate cements, thorium will not be represented, thereby enabling dating from the U/Th ratio. For U/Th dating it is necessary that samples contain sufficient uranium with low ^{200}Pb concentrations. This dating technique has been extensively applied to speleothems (Baker et al., 2008; Richards and Dorale, 2003), tufas (albeit with the difficulty of low uranium concentrations in young tufas, Garnett et al., 2004) and increasingly to cemented rudites (Sharp et al., 2003). In interpreting the results, consideration needs to be given to the potential for sample contamination or for fractionation to have taken place, i.e. whether the system is open or closed to post depositional migration of constituent nuclides (Richards and Dorale, 2003). The use of other intermediate uranium daughter isotopes for dating, e.g. protactinium 231 (Edwards et al., 1987), forms the subject of ongoing research. Another research direction is the use of laser ablation linked ICPMS for determining uranium isotope ratios (Eggins et al., 2005). However, at present the precision of conventional TIMS or solution MC-ICPMS techniques has not been achieved. Other dating techniques include: optically stimulated luminescence (OSL), electron spin resonance (ESR; Grün, 1989) and amino acid racemisation. The latter is obtained from changes to the structure of organic matter, a process that is temperature controlled. Longer established dating techniques include palaeomagnetism (Rowe et al., 1988) and biostratigraphy, using fauna, flora and pollen.

Isotopic dating offers the potential for determining the minimum age of the surfaces (geological or anthropogenic) upon which the secondary carbonate deposits lie. For example, critical dating evidence (455 ka BP) has been derived from U/Th dating of tufa overlying an exposure of the Anglian Lowestoft Formation (a glacial till) at a Palaeolithic site at West Stow Suffolk, UK (Preece et al., 2007). At this locality the land snail assemblage identified in the tufa comprised woodland taxa indicative of a wetter and potentially warmer climate than the present day.

6. Secondary carbonate deposits as indicators of palaeohydrogeology, climate change and landscape evolution

6.1 Karstification and secondary carbonate deposition

The sources for secondary terrestrial carbonates are of interest to the karst hydrogeologist because of the potential to establish the palaeohydrological conditions at the time of precipitation (section 4.4). The spatial distribution of dissolution is of interest both to the hydrogeologist as an indicator of palaeo flow conditions and to the karst geomorphologist as it contributes to our understanding of landscape evolution.

6.2 Implications for interpreting climate change

The presence or absence of speleothems provides valuable information regarding sufficiency of water supply and soil carbon dioxide for their growth. As their growth is restricted to the vadose zone, they provide constraints on the opening of passages and water table fluctuations (Richards and Dorale, 2003). In the context of glacial-interglacial cycles, speleothem growth is at a maximum during warm periods. It is limited by frozen ground conditions, ice cover and subsequent melting. Frozen ground and lower biogenic carbon dioxide supply limit growth in permafrost conditions (Lowe and Walker, 1997). Growing from meteoric water, speleothems and tufa preserve a continuous record of climate change for the duration of their formation, albeit that this may be moderated by ground storage of the water. If certain conditions are satisfied, speleothems may contain annual laminae, generally of 10 to 1000 μm (Baker et al., 2008). The necessary conditions include: an annual cyclicity of the surface climate (e.g. seasonal monsoon, annual migration of the inter-tropical convergence zone, or a seasonal moisture deficit); a cyclic signal expressed in the speleothem as a consequence of groundwater, or cave atmosphere signal transfer, and a depth of speleothem such that groundwater moderation does not mask the climatic variation (Baker et al., 2008). Thus, detailed studies of annual growth laminae offer the potential to provide evidence of past precipitation, temperature, or atmospheric circulation. This can be done using a number of techniques (Table 3). Annual laminae, which are a function of palaeoclimate, define speleothem growth rate. Warmer, moister conditions are associated with increased growth, except under peat soils where warmer, drier conditions promote growth (Fairchild et al., 2001). Laminations represent a change in chemical composition of the speleothem that can be made visible by imaging or chemical mapping (Baker et al., 2008; Table 3). Visibility of the laminae depends on alternation of the crystal arrangement with a well-defined morphology. In some examples, e.g. Genty and Quinif (1996) there is an alternation between dark compact calcite and white porous calcite.

Providing laminae periodicity can be established and it can be demonstrated that the change in annual lamina thickness reflects surface climate variations through speleothem growth rate and geochemistry, then quantitative reconstruction of climate from stalagmite growth layers, or lamina-climatology (Baker et al., 2008) studies can be undertaken. Using this technique, Genty and Quinif (1996) distinguished 11-year cyclicity in speleothem growth in a pre-Holocene Belgian stalagmite, which they suspected of being linked to sunspot activity. Not all laminae are annual. Sub-annual laminae are more likely to be present in speleothems that grow closer to the ground surface without moderation by groundwater. Investigation of the periodicity of the laminae can be undertaken using: dating techniques; laminae counting between events; drip water chemistry monitoring (including fluorescence) or a comparison of observed with theoretical prediction of lamina width. Attention has also been given to the application of hyperspectral imaging, the opportunity for which lies in the potential to use the near infra-red range to map out areas of stalagmite where fluid inclusions are present. The sensitivity of speleothem growth to local conditions is such that there can be variation in drip chemistry within a single cave system, e.g. Pitty (1966) in Poole's Cavern, Derbyshire, UK. This results from the variation in individual flow paths and the consequential climate filtering, which may give rise to poor correlation between individual speleothems within the same cave system. This difficulty is best overcome using a multi-parameter investigative approach (Baker et al., 2008), e.g. lamina thickness, stable isotope investigation and trace element geochemistry.

Technique	Application	References
Measurement of change in laminae width using conventional transmission and reflected light microscopy on polished and thin sections. Scanning electron microscopy to look at pore spaces. Studies of trapped pollen.	Speleothems from across the world including, Belgium; Brazil and Ethiopia.	Genty and Quinif, 1996; Soubiès et al., 2005, and Baker et al., 2007.
Ratios of stable isotopes.	Speleothems.	McGarry and Caseldine, 2004.
Calcite-aragonite couplets.	Speleothems, tufa, cements.	Andrews and Brasier, 2005; McDermott, 2004.
Variations in trace element ratios.	Speleothems, examples studied from north-west Botswana and Nepal.	Railsback et al., 1994, and Denniston et al., 2000.
Optical luminescence.	Speleothems.	Fairchild et al., 2001.
Hyperspectral imaging used to discriminate laminar density contrasts.	Speleothems; examples include Poole’s Cavern, Derbyshire, U.K.	Baker et al., 1999.
	Speleothems; examples studied from north-east Turkey.	Jex et al., 2008.

Table 3. Secondary carbonate imaging techniques.

Remnant organic acids trapped within the calcite growth rings can be investigated using luminescence studies and UV microscope technology. Fluorescence can be observed using reflected light microscopy to detect emission wavelengths of between 400 and 480 nm with a mercury light source to provide UV excitation at wavelengths of between 300 and 420 nm. Trace element and UV-fluorescent laminae studies provide information at a finer resolution (annual to subannual level) than the other techniques listed in Table 3, thereby offering the potential to research the changing nature of seasonality through time. During periods of higher or more intense precipitation, organic material can be washed on to the surface of speleothems. By applying these techniques to investigate growth laminae, conclusions can be drawn regarding the frequency of cyclonic storms and hence the changing atmospheric circulation patterns (Baker et al., 1999; 2008; Soubiès et al., 2005).

Stable isotope studies of speleothems and tufas are now well established proxies for interpreting climate change (Andrews, 2006; Baker et al., 2008; Andrews and Brasier, 2005; McDermott, 2004, Richards et al., 1994). Garnett et al. (2006) carried out stable isotope analyses of Late-glacial and early Holocene tufa deposits from Caerwys, North Wales, UK, demonstrating that Late-glacial tufa (pre-9000 years BP) probably formed during a period of climatic warming with summer water temperatures in the range 13 to 16.5°C, followed by a period of cooling associated with the cessation of tufa precipitation. Analysis of oxygen isotope ratios from pedogenic carbonates can also provide useful palaeoclimatic information, reflecting changes in the humidity and frequency of soil wetting (Lowe and Walker, 1997; Pendall et al., 1994).

Whilst laminar growth patterns have not been reported in secondary carbonate cements, more than one type or phase of cement can be present and these can be used to interpret depositional environments. For example, in a detailed petrological study carried out in conjunction with stable isotope analyses, Strong et al. (1992) identified a range of cement fabrics in carbonate cemented Late Devensian glacial gravels.

6.3 Incision and the interpretation of groundwater base-levels

Speleothems have been used to determine sea level change, e.g. in the Bahamas (Gascoyne et al., 1979 and Richards et al., 1994). Dating of secondary carbonate deposits also offers the potential for determining rates of landscape incision. Where cemented rudites have formed on a geomorphic or anthropogenic surface, dating of the cement provides a minimum age for the host surface. This has been found to be particularly relevant to the dating of glacial tills, e.g. Preece et al. (2007). In the situation that a dated surface has been incised, the opportunity arises to calculate the rate of incision. It should be noted that the rate of incision may equate to either surface lowering, or to glaciogenic or tectonic uplift. Calculations of this type have been undertaken using dated tufa deposits in Lathkill Dale, Derbyshire, UK (Banks et al., 2011).

Similarly, although it is feasible that more than one cave level can be hydraulically operational at a given time, dating of speleothems has demonstrated that the oldest material is commonly found in the higher caves and that the onset of speleothem formation is progressively later in lower caves (Ford and Williams, 1989; Lowe and Walker, 1997). This may be a response to the progressive lowering of the water table and therefore another potential means of calculating rates of incision.

6.4 Carbon dioxide budgeting

The cycle of dissolution and precipitation of calcium carbonate involves carbon dioxide cycling. Consequently, bacterial carbonate precipitation in terrestrial environments may be crucial for atmospheric carbon dioxide budgeting (González-Muñoz et al., 2010).

6.5 Discriminating between point and diffuse contaminant sources

Monitoring the flux of dissolved species in streams in karst environments can provide useful information regarding the functioning of karst aquifers, in particular to determine sources and sinks of calcium carbonate. Associated with this, there is the potential to discriminate between diffuse and point source contaminants in the stream environment. Flow networks in karst aquifers facilitate the focusing of contaminants (Vesper et al., 2001). The flux associated with the latter has a more discrete, spiky impact on water quality, which is readily discernible with customised monitoring networks (Banks and Palumbo-Roe, 2010).

6.6 Dating of catastrophic events

Catastrophic events, such as earthquakes, can damage speleothems for which U-series dates can be obtained (Forti, 1997; Ford and Hill, 1999). Equally, the occurrence of geohazard events may be associated with secondary carbonate precipitation, e.g. the Fern Pass rockslide, Austria (Ostermann et al., 2007). This provided new sources of carbonate and new

flow paths, facilitating precipitation of secondary terrestrial carbonate deposits and providing a means of dating such events in the geological record.

7. Conclusions

This overview of secondary terrestrial carbonate deposition in karst environments demonstrates that the carbonates have a widespread distribution, display a variety of forms and result from a range of depositional and diagenetic processes. Such variability has resulted in numerous descriptive terms for the deposits as well as some complexities in classification. Examples cited in this chapter illustrate how detailed studies of the depositional setting, form and geochemistry of the carbonates can provide important information about formative processes, age and past environmental conditions (climatic, hydrogeological, hydrochemical, biological, geomorphological and anthropogenic). Such studies have particular relevance to interpretations of climate change and landscape evolution. Recent research has focused on the study of: terrestrial carbonate deposits in deep time (Brasier, 2011); diagenetic processes (Brasier et al., 2011; Martín-García et al., 2009); refining dating techniques for tufas and carbonate cements (Sharp et al., 2003; Garnett et al., 2004); dating using laser ablation linked ICPMS (Eggins et al., 2005); hyperspectral imaging of secondary carbonate deposits (Jex et al., 2008); furthering understanding of depositional processes, particularly the biological processes (Dittrick and Sibler, 2010; González-Muñoz et al., 2010, and Jones, 2010); cave atmosphere and drip chemistry (Baldini et al., 2006); collecting and interpreting continuous monitoring data (spring chemistry), and analysing the reasons for tufa decline, e.g. eutrophication (Forbes et al., 2010). The ongoing description and interpretation of “new” exposures of secondary carbonate deposits, e.g. Forbes et al. (2010) has the potential to underpin the conceptual understanding of the hydrogeology of these deposits.

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9. Glossary

Activity constant:	The ratio of the apparent to the actual concentrations of ions that results from the inter-ionic forces of attraction in more concentrated solutions of a solute.
BP:	Before present.
Columnar:	Upright, elongate growth form.
Deamination:	Removal of an amine group (organic compound or functional group containing an N atom) from a molecule.
Dissociation constant:	Dissociation is a process whereby a single compound splits into two or more smaller products that can easily recombine to form the reactant. The dissociation constant reflects the extent of incomplete dissociation.

Doline:	Enclosed depression centred on a sink hole, or intercepted cave passage.
Epikarst:	Karst zone that lies close to the surface, encompassing the soil and weathered bedrock.
EPS:	Extracellular polymeric substances, which are characterised by the presence of different proteins, uronic acids, pyruvic acid and sulphate groups.
ICPMS:	Inductively coupled plasma mass spectrometry.
Inception horizon:	Part of a rock succession that is particularly susceptible to the earliest cave forming processes.
Luminescence:	Light that usually occurs at low temperatures.
MC ICPMS:	Multi collector inductively coupled plasma mass spectrometry.
Mucopolysaccharide:	Polysaccharide containing an amino group.
Oncolite:	Carbonate encrusted nodules developed around a stone, or another nucleus (Tucker, 2011; Viles and Goudie, 1990).
Palisade calcite:	Calcite that is formed with elongate crystals perpendicular to the growth surface.
Picocyanobacteria:	Microscopic (0.2-2.0 µm) bacteria.
Polysaccharide:	Carbonate comprising a chain of sugars (monosaccharides) that be of more than one type.
Pyruvic acid:	An organic acid and ketone (CH ₂ COCOOH).
Sheath:	A bacterial sheath surrounds certain filamentous bacteria, particularly those in water.
Uronic acids:	A sugar with carbonyl and carboxylic acid function.
Speleogenesis:	Cave forming processes.
Stromatolites:	A term that is used to describe cemented algal mats from the coastal zone and is commonly applied to freshwater deposits of a similar form (Tucker, 2011; Viles and Goudie, 1990).
TIMS:	Thermal ionization mass spectrometry.
Twilight zone:	Portion of the cave that forms the transition between the unlit cave interior and the outside world (Jones, 2010).
Vaterite:	Metastable polymorph of calcium carbonate.

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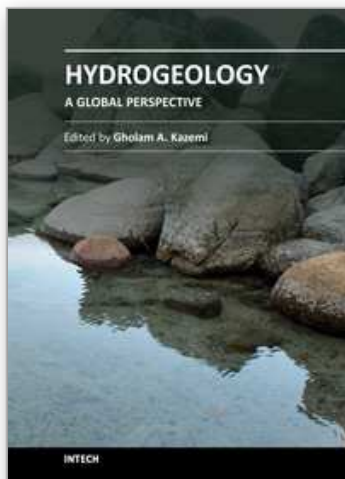
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The field of groundwater hydrology and the discipline of hydrogeology have attracted a lot of attention during the past few decades. This is mainly because of the increasing need for high quality water, especially groundwater. This book, written by 15 scientists from 6 countries, clearly demonstrates the extensive range of issues that are dealt with in the field of hydrogeology. Karst hydrogeology and deposition processes, hydrogeochemistry, soil hydraulic properties as a factor affecting groundwater recharge processes, relevant conceptual models, and geophysical exploration for groundwater are all discussed in this book, giving the reader a global perspective on what hydrogeologists and co-scientists are currently working on to better manage groundwater resources. Graduate students, as well as practitioners, will find this book a useful resource and valuable guide.

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