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# MICROBIALLY INDUCED CALCIUM CARBONATE IN TUFAS OF THE WESTERN EASTERN ALPS: A FIRST OVERVIEW

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With 1 figure, 4 plates and 2 tables

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## Abstract

Most of fourteen tufa locations mainly in the western part of the Eastern Alps contain a significant to prevalent portion of microbially-induced calcium carbonate.

The investigated tufas are situated on substrata of limestone, dolostone, marlstone, conglomerate, gneiss, phyllite and slate. Most larger tufa occurrences comprise significant areas wherein tufa formation is low or had halted. Two major groups of "microbial tufas" are distinguished, (1) crystalline microbial calcium carbonate, and (2) micropeloidal to micritic calcium carbonate. Crystalline microbial calcium carbonate is present in two major fabrics. (1A) Calcified "microbushes" of outward-radiating clusters of slightly tangled tubuli each encased by a single crystal of calcite of subrounded to subcircular cross-section. Larger volumes of tufa may be composed of stacked laminae built by laterally arrayed microbushes. (1B) Knobs to crusts that, internally, consist of fan-like arrays of tubuli encased within large single crystals of calcite. Both the microbushes and the microfans are interpreted as calcified cyanobacterial aggregates of *Rivularia* type. The crystalline microbial calcites may readily recrystallize and provide a substrate for further, "inorganic" calcite growth, resulting in cementstone texture that shows little evidence of its microbially-induced origin.

(2) Micropeloidal to micritic calcium carbonate includes micropeloidal grainstone, "filamentous-micropeloidal" grainstone, (fenestral) lime mudstone with stromatolithic or cauliflower lamination, and thrombolithic lime mudstone. The micropeloids and the filamentous-micropeloidal arrays may have been produced by coccoid and filamentous cyanobacteria, at or near the tufa surface. A major portion of calcium carbonate of this category, however, is present within the pore space of tufas, where it formed in association with light-indepedent microbes and/or with dead microbes, small phytoclasts and organic compounds. Deduced rates of present tufa formation are within the range of known rates, but show distinct variations both within and among locations.

## Zusammenfassung

Die meisten von vierzehn Kalktuff-Vorkommen vorwiegend in den westlichen Ostalpen bestehen aus einem bedeutenden bis überwiegenden Anteil aus Kalziumkarbonat, dessen Fällung von Mikroben induziert wurde.

Die untersuchten Tuffe liegen auf verschiedenen Gesteinsuntergründen wie Kalkstein, Dolomitstein, Mergel, Konglomerat, Gneis, Phyllit und Schiefer. In den meisten Vorkommen findet noch aktive Tuff-Bildung statt, jedoch enthalten die meisten der grösseren Vorkommen auch Bereiche, in denen kaum oder keine Tuff-

Neubildung stattfindet. Wir unterscheiden zwei Hauptgruppen "mikrobieller Tuffe", (1) kristallines mikrobielles Kalziumkarbonat (zumeist Kalzit), und (2) mikropeloidales bis mikritisches Kalziumkarbonat.

Das kristalline mikrobielle Kalziumkarbonat zeigt zwei Gefüge. (1A) Verkalkte "Mikrobüsche" aus Büscheln von leicht unregelmässigen und "verfilzten" Röhrchen, deren jedes von einem stark gelängten, im Querschnitt rundlichen Einzelkristall meist aus Kalzit eingehüllt wird. Die Mikrobüsche können alleine vorkommen oder zu Laminae aufgereiht stehen, zusammen mit anderen Arten von Tuff, oder bilden selbst Tuffe, die aus vielen Laminae aufgereihter Büschchen bestehen. Jeder Mikrobusch besteht aus einem einzigen oder wenigen Kristallen von Kalzit; innerhalb jedes Mikrobusches sind daher ganze ganze Bündel von Röhrchen oder die Röhrchen des gesamten Mikrobusches von Kalzit umgeben, der trotz des diskreten Wachstums der Röhrchen eine einzige optische Orientierung zeigt. Die Mikrobüsche starten an ihrer Basis von "keulenförmigen" Kalzitkristallen, die an ihrer Oberseite die Öffnungen der Röhrchen zeigen. (1B) Knoten bis Krusten, die im Schnittbild aus regelmässigen "Fächern" von gleichmässig aufgefächerten, diskreten Röhrchen bestehen. Jedes Röhrchen wird von Kalzit umgeben. Büschel von Röhrchen oder ganze Fächer von Röhrchen sind von Kalzit mit einer einzigen optischen Orientierung umgeben, sodass jedes Röhrchen-Büschel bzw. jeder Fächer in einen grossen Einkristall aus Kalzit eingebettet ist. Die Krümmung der Aussenseite der Kalzitkristalle ist parallel der Krümmung der Röhrchen. Die Organismen, die die beschriebenen Typen 1A und 1B von kristallinem Kalzit bilden, werden der Gattung *Rivularia* (Nostocales, Cyanobacteria) zugeordnet. Die Kalzite der Typen 1A und 1B sind von sub-Millimeter dünnen, zueinander in etwa parallelen Laminae von Mikrit bis Mikrosparit durchsetzt. Das "Wachstum" jeder Lage von Rivularien geht von einer dieser Mikrit/Mikrosparit-Lamina aus. Auf diese Weise werden Laminae von wenigen Millimetern bis etwa 1 cm Dicke von verkalkten Rivularien gebildet. Feldexperimente legen nahe, dass die Mikrit/Mikrosparit-Laminae Unterbrechungslagen darstellen, die sich meist in Verbindung mit einem winterlichen Aussetzen bzw. Verringern der Rate der Kalkfällung bzw. des Rivularien-Wachstums bilden. Bei Lingenau (Vorarlberg) besteht der weitaus grösste Anteil des gesamten aktiven Tuffvorkommens aus Rivularien-Tuff, der die beschriebene Lamination zeigt, die wahrscheinlich auf jahreszeitliche Schwankungen der Kalkfällungsrate in Verbindung mit dem Wachstum der Cyanobakterien zurückzuführen ist. Feldexperimente und die erwähnte ?jährliche Lamination der Tuffe machen sehr wahrscheinlich, dass die Fällung des Kalkes in ursächlicher Verknüpfung mit dem Wachstum der Cyanobakterien steht, diese also entscheidend die Kalkfällung beeinflussen.

(2) Mikropeloidales bis mikritisches Kalziumkarbonat umfasst im wesentlichen mikropeloidale grainstones, "filamentös-mikropeloidale" grainstones, (fenestrale) lime mudstones mit stromatolithischer oder "blumenkohl-artiger" Lamination, und thrombolithische lime mudstones. Die Arten des Kalziumkarbonats der zweiten Gruppe bildeten sich wahrscheinlich im Zusammenhang mit coccoiden (Mikropeloide) und filamentösen Cyanobakterien ("filamentös-mikropeloidale" Aggregate) an oder nahe der Oberfläche der Tuffe, zu einem grossen Teil aber auch durch licht-unabhängige Mikroben, die im Porenraum der Tuffe leben, sowie durch Kalkfällung in Verbindung mit unbelebter organischer Substanz (z. B. tote Mikroben, Phytoklasten, organische Verbindungen) im Porenraum. Ein seltener Typ von Tuff, der sich möglicherweise unter signifikanter Beteiligung von Mikroben bildete, ist durch einen fossilen Vadolith vertreten. Die ermittelten Raten heutiger Tuff-Bildung liegen im Bereich bekannter Raten, zeigen jedoch zwischen verschiedenen Tuff-Lokalitäten als auch auch innerhalb einer "Lokalität" starke Unterschiede. Unter intensivem Wasserzutritt, wie etwa an den Prallstellen frei fallender Wasserfäden oder an Vorsprüngen von wasserüberronnenen Tuff-Vorhängen rekristallisiert der kristalline mikobielle Kalzit meist rasch und dient als Unterlage für weitere, "anorganische" Kalzitfällung, was zu einem mehr oder weniger homogenen, sehr harten cementstone-Gefüge führt, das kaum noch Spuren seines mikrobiell induzierten Ursprungs zeigt.

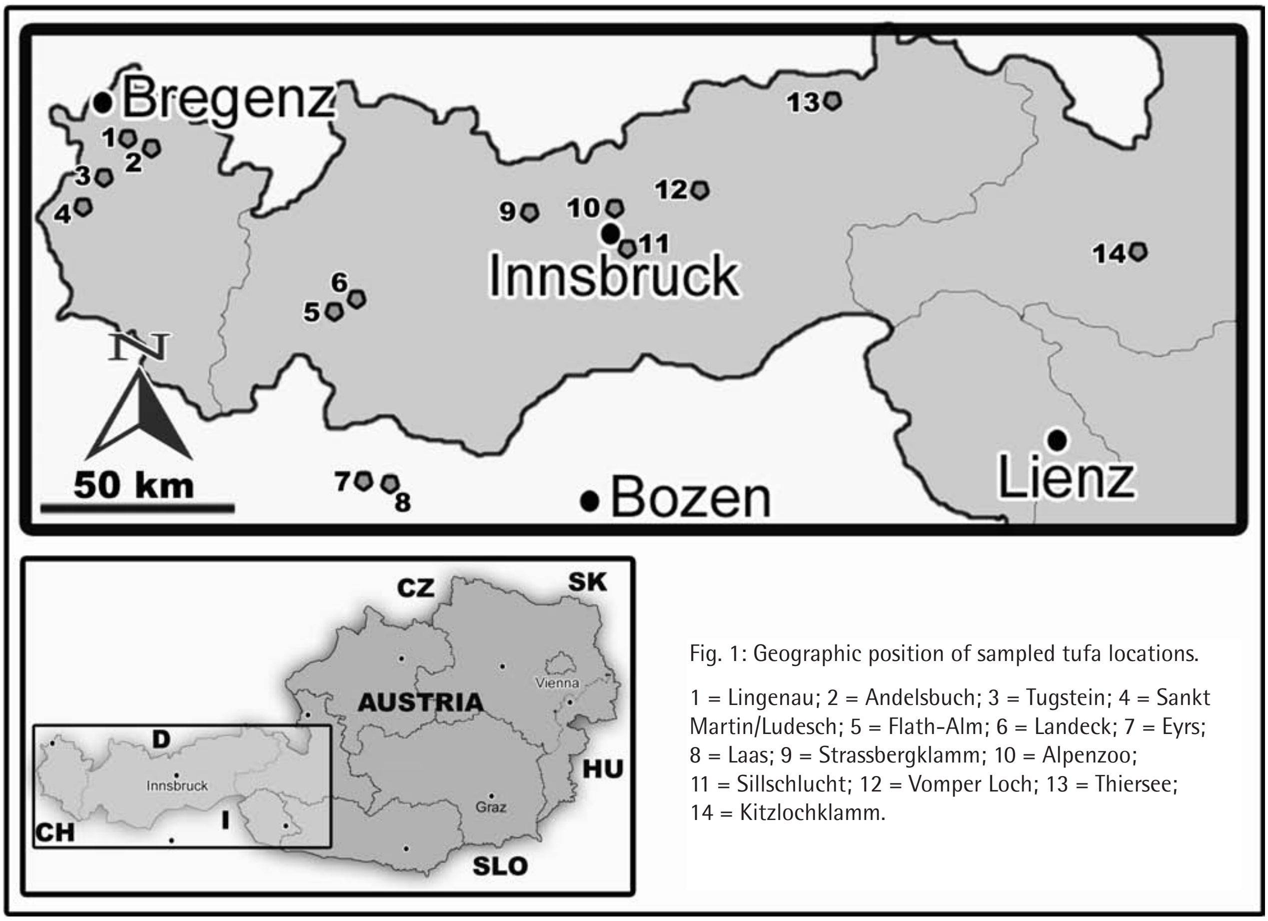

Fig. 1: Geographic position of sampled tufa locations.

1 = Lingenau; 2 = Andelsbuch; 3 = Tugstein; 4 = Sankt Martin/Ludesch; 5 = Flath-Alm; 6 = Landeck; 7 = Eyrs; 8 = Laas; 9 = Strassbergklamm; 10 = Alpenzoo; 11 = Sillschlucht; 12 = Vomper Loch; 13 = Thiersee; 14 = Kitzlochklamm.

## 1. Introduction

In the days before concrete, tufa limestone was a highly appreciated building stone. By contrast to travertine limestone (lapis tiburtinum) that forms around hot springs associated with volcanism, calcareous tufa forms by precipitation of calcium carbonate from "cool" spring and river waters (Ford & Pedley, 1996). Tufa limestone was widely used in masonry as a light-weight yet stressable, easily workable stone resistant to frost cracking. Numerous are the castles, churches and other buildings that contain or even largely consist of blocks of tufa. By contrast to all other building materials except for wood, tufa "re-grows" after quarrying by precipitation of calcium carbonate. In addition, in many cases, a single or several locations of tufa were situated (relatively) near the building site, hence costs for transport were low. Aside of these profane considerations, tufas are interesting for other reasons, too. First of course stands the question "Why precipitation of calcium carbonate just here and not at every other spring?", touching upon hydrology, water chemistry, climate, type of geological substrate, and ecology and biochemistry of the organisms involved. Spring tufas form by precipitation of calcium carbonate from waters supersaturated up to about 10 times. Supersaturation is mostly attained, or is highest, some distance downstream the emergence of the spring or, in large tufa-precipitating systems such as Plitvice, also within-stream to downstream of rapids and water falls. There is general aggreement that degassing of $CO_2$ out of the water is the single most important process in producing the necessary degrees of supersaturation for precipitation (Viles & Goudie, 1990; Chen et al., 2004).

To a carbonate sedimentologist, however, a simple yet tackling question is "How do these tufas look like in thin section and how do the observed fabrics form?" All geologists can predict how a thin section of oolite should look like and how the constituent ooids originate. For spring tufas, despite investigations into their water chemistry and aspects of fabrics (Emeis et al., 1987; Sancho et al., 1997; Janssen et al., 1999; Freytet & Verrecchia, 1999), we are as yet still off a concept relating the field appearance of different types of tufas to their microfabrics and, finally, from establishing a predictive concept of formation of spring tufa fabrics (cf. Merz-Preiß & Riding, 1999). This holds in particular for calcium carbonate precipitation induced by microbes. Cyanobacteria, for instance, secrete extracellular polymeric substances that might profoundly modify the shape of crystallized calcium carbonate (cf. Cölfen, 2003). In the present paper, major types of microbially-induced tufa observed at locations visited by us are characterized and discussed. Microbially-induced tufa is widespread and, at a number of locations, comprises the major part of total carbonate volume. For spring tufas of the Eastern Alps, the significant to prevalent contribution of microbially-induced calcium carbonate to date has not been appreciated, and bears implications for the general mode of tufa formation. This contribution is in acknowledgement to the first author's (D. S.) first academic teacher, Rainer Brandner, who accompanied his first steps into the wide world of carbonate rocks.

## 2. Methods and settings

A total of fourteen locations of spring tufas situated in Vorarlberg, Northern Tyrol, Southern Tyrol, and Salzburg was documented and sampled (Fig. 1). For a short characterization of the sampled tufa locations, the reader is referred to table 1. In order to include as many different types of tufa-depositing systems (fossil to active) as possible, no specific selection of tufa locations was made. Each location is classified with respect to its prevailing tufa deposystem (e. g. springline tufa) and the types of tufa as identified on the surface (e. g. waterfall tufa, moss tufa) (Tab. 1). The different types of tufas as classified in the field were sampled. Cut slabs and thin sections of resin-indurated samples provided documentation of microfabrics. A total of 134 thin sections has been investigated. SEM investigation of selected samples provided additional information on surfaces and internal fabrics. The investigated spring tufas are situated on different rock substrata (Tab. 1). In addition, at most locations, the substrate is overlain by glacial till, or reworked glacial till, or glacial till is present in the environs of the tufa formation. Where tufa occurrences are situated on substrata of gneiss or phyllite, these rocks typically are riddled by more-or-less wide cataclastic to phyllonitic zones.

## 3. Types of microbially induced calcium carbonate

Based on descriptive features, herein we distinguish two major classes of calcium carbonate precipitated under microbial mediation, (1) crystalline microbial calcium carbonate, i.e. microbially-induced tufa composed of $CaCO_3$ crystals that are recognizable by standard light microscopy, and (2) micritic microbial calcium carbonate, in which the crystals are so small that they can hardly be resolved with a petrographic microscope.

### 3.1. Crystalline microbial calcium carbonate

#### 3.1.1. Laminated "microbush" tufa

In this category, the most conspicuous facies and microfacies is represented by laminated, porous tufas. These laminated tufas may build steep to overhanging, yellowish tufa curtains up to a few tens of meters in height associated with water falls (Pl. 1/1-3). Individual tufa laminae typically are between about 4 to 8 mm in thickness (Pl. 1/4, 5). The laminae are vertically separated by very thin intercalations typically less than a millimetre thick of microsparite and/or of micrite; the microsparite consists of more-or-less equigranular calcite rhombohaidra. Each tufa lamina consists of laterally arrayed, more-or-less dense "microbush-like" arrangements of calcite crystals that are obvious as "microbushes" also under crossed polars (Pl. 1/5). Individual branches of the calcite microbushes are bifurcating (Pl. 1/6). Upon bifurcation, the optical orientation of the calcite crystals commonly remains constant. In laterally adjacent microbushes, however, the calcite is typically of different optical orientation, giving rise to microbushes of distinct extinction under crossed polars (Pl. 1/5-7). Within the center of the calcite crystals that comprise individual microbush branches, elongate tubes parallel to the vertical extent of the crystals are present (Pl. 1/6). In cross-section, the calcite crystals that comprise the individual branches of the microbushes show a subcircular to circular pore in their center, corresponding to the mentioned tubes (Pl. 1/7). In young, "fresh" samples of laminated tufa, the space between the calcified branches is open pore space (Pl. 1/6, 7). In SEM, the surface of the described tufa laminae of microbushes consists of a dense array of round, tower-like calcite crystals each with a subcircular hollow in its center, resulting in very small calcite tubelets (Pl. 1/8). Whereas the upper and outer surface of the calcite tubelets shows crystal growth surfaces according to the rhombohaidral symmetry of calcite, the inner surface of the tubelets is round and/or slightly rugged (Pl. 2/1, 2). The outer boundary of these calcite may show numerous sub-micron sized steps according to the rhombohaidral calcite symmetry or, in the best-preserved samples, the boundary of the laminae is nearly perfectly smooth and round (Pl. 2/2). At Laas, a similar spectrum of microstructures of inferred microbial origin is observed, but is preserved within more-or-less calcitized aragonite. At March 18th, 2005 at Lingenau (Vorarlberg), an active pavement of laminated tufa as described was sampled, by excavating a cavity with a chisel. The same spot was re-sampled on September 8th, 2005, i. e. nearly six months later. Because the first sampling had truncated the laminae of the tufa, any newly precipitated calcium carbonate should be easily recognizable by geometrical relations in thin section. Indeed, the truncated laminae of previous years became overlain by a lamina up to about 6 millimeters of calcified microbushes identical to those in the older, underlying laminae (Pl. 2/3, 4). This proves that this style of tufa formation is still active at Lingenau. The tufa lamina formed between 18.3.-8.9.2005 shows lateral variations in the intensity of calcification. Within densely calcified portions, the tubuli of the microbushes are enveloped by dense calcite of low porosity. In scarcely calcified portions, it is just the tubuli - or some stretches thereof - that are enveloped by elongate to "worm-like" curved, optically single crystals of calcite.

At several locations, laminated tufas of the described type comprise the major portion of total tufa volume. At Lingenau, the light-yellow cascades and curtains of waterfall tufas consist practically entirely of this type of tufa. This laminated tufa seems to form on well-sunlit, steep to vertical substrata overrun by thin sheets of water. By contrast, under impacting water from water falls or water "shoots", and under shooting water more than roughly 1-2 cm in depth, this type of tufa is intercalated with and is replaced by a brown, massive calcite with a botryoidal surface (Pl. 1/2). At Lingenau, however, also the major part of phytoclastic tufa of the moderately steeply inclined creek downstream the upper waterfalls consist of laminated microbush tufa (Pl. 2/5). There, this type of tufa also commonly forms "mini-rimstones", with rims up to a few millimeters high and pools are a few centimeters to about 10 cm in width (Pl. 2/6, 7). In thin section, the mini-rimstones also consist of microbush tufa as described above (Pl. 2/8). Also at other locations, however, the described type of tufa may locally represent a significant portion of the total volume.

**Interpretation**: For the described laminated "microbush calcite", the elongate organic structures that comprise the nucleus for calcite precipitation are identical in size and growth pattern to calcified filamentous cyanobacteria, probably *Rivularia* (cf. Obenlüneschloß, 1991; Riding, 1991; Kano et al., 2003). Within the described tufa, the regular interruptions of growth along thin laminae of micrite to microsparite may represent a seasonal or quasi-seasonal pattern. This is indicated by the absence of a lamina of micrite to microsparite along the contact to the laminae artifically truncated by us in spring 2005, followed by growth of a summer-2005 lamina of rivularian calcite. The thickness of this lamina of about 4 to 8 mm compares well with that of the older laminae (see Pl. 2/3). Thus, during a single spring to summer cycle, cyanobacterially-induced calcification adds a few millimeters at least to the tufa surface. Whereas calcified cyanobacterial microbushes and laminae built thereof were observed also within moss tufas and in phytoclastic tufas, massive laminated tufas of this type form mainly in association with water falls. The described "mini-rimstones" of rivularian tufa in such abundance to date were observed only at Lingenau. Seasonally laminated cyanobacterial tufas similar to those described by us have been described, for instance, from Belgium (Janssen et al., 1999) and Japan (Kano et al. 2003). Growth thicknesses of up to 1 cm/a of these laminated tufas are considered as likely (Janssen et al., 1999, p. 83), and this is supported by our data (see also below). In most laminated cyanobacterial tufas, however, the cyanobacterial filaments are encrusted by calcitic micrite and/or microsparite (cf. Arp et al., 1999; Janssen et al., 1999; Kano et al., 2003), not by optically single calcite crystals (but see Obenlüneschloß, 1991). Cyanobacteria secrete protective, mucus-like, extra-

| **No. in figure 1**<br>**Name of location**<br>**Size**<br>**Rock substrate in immediate environs** | **Field classification of tufa deposystem (acc. to Ford & Pedley, 1996)**<br>**Prevalent tufa on active surface, field classification** | **Abundance of microbially-induced tufas** | **Prevalent types of microbially-induced tufa** | **Active/Inactive relation** |
|---|---|---|---|---|
| | | | | |
| 1<br>Lingenau<br>Large<br>Conglomerates, sandstones, marlstones | Proximal springline tufa<br>Waterfall tufa | Abundant | Microbush calcite, microfan calcite | Moderately active to low-active |
| | | | | |
| 2<br>Andelsbuch<br>Moderate<br>Marlstones | Fluvial barrage tufa (of perennial creek)<br>Moss tufa | Common to abundant | Micropeloidal grainstones, crystalline microbial calcites, thrombolites | Moderately active to fully active |
| | | | | |
| 3<br>Tugstein<br>Small<br>Limestone | Proximal springline tufa<br>Moss tufa | Common to few | Micropeloidal grainstones, thrombolites (in pore space) | Fully active |
| | | | | |
| 4<br>St. Martin (Ludesch)<br>Large<br>Sandstone, marlstone | Paludal tufa<br>Moss tufa | Abundant | Micropeloidal grainstones, thrombolites (in pore space) | Moderately to ?fully active |
| | | | | |
| 5<br>Flath-Alm<br>Moderate to ?large<br>Gneiss and slate, glacial till | Fossil.<br>Proximal springline tufa.<br>Phytoclastic tufa | Uncommon | Micropeloidal grainstones, crystalline microbial calcites | Fossil |
| | | | | |
| 6<br>Landeck<br>Moderate<br>Quartz phyllite | Springline tufa, paludal tufa<br>Phyto/lithoclastic tufa, moss tufa (few) | Uncommon | Micropeloidal grainstones, lime mudstones in part of ?microbial orgin | Moderately active to ?low-active |
| | | | | |
| 7<br>Eyrs<br>Moderate<br>Gneiss with shear zones, glacial till | Fossil.<br>Springline tufa, paludal tufa<br>Lithoclastic tufa | not identified in our samples; perhaps uncommon to rare | (not specified) | Fossil |

Tab. 1: Locations sampled for tufas (see Fig. 1 for location). Field classification of tufa deposystems is based on Ford & Pedley (1996). The size of tufa locations (including both actively forming tufa and older, inactive to fossil tufa at each location) is here subdivided into four categories. Very small: up to a few meters; Small: a few meters to about 20 m (longest measure); Moderate: 20 m to about 100 meters; Large: distinctly more than about 100 meters in longest measure. For each location, because of limitations of outcrop, the relation of active tufa-depositing area relative to inactive tufa occurrence (Active/Inactive relation) provides a semi-quantitative impression only, and is subdivided into four categories. Fully active: Inactive areas absent or of insignificantly small size relative to active areas; Moderately active: Active and inactive areas roughly of the same size; Low-active: Active area much smaller than inactive area; Fossil: no active tufa formation.

| No. in figure 1<br>Name of location<br>Size<br>Rock substrate in immediate environs | Field classification of tufa deposystem (acc. to Ford & Pedley, 1996)<br>Prevalent tufa on active surface, field classification | Abundance of microbially-induced tufas | Prevalent types of microbially-induced tufa | Active/Inactive relation |
|---|---|---|---|---|
| | | | | |
| 8<br>Laas (several occurrences)<br>Moderate (for most occurrences)<br>Gneiss with shear zones, glacial till (locally) | Springline tufas<br>Lithoclastic tufa, waterfall tufa, phytoclastic tufa | Abundant: waterfall tufas<br>Common: litho/phytoclastic tufas (in part fossil) | Active waterfall tufa: Microbush aragonite, microfilamentous aragonite<br>Litho/phytoclastic tufas (in part fossil): micropeloidal grst-pkst, lime mudst (thrombolites), microbush aragonite, microfilamentous aragonite | Total of all occurrences: low-active |
| | | | | |
| 9<br>Strassbergklamm<br>Large<br>Dolostones | Springline tufa<br>Waterfall tufas, moss tufas | Common to abundant | Micropeloidal grainstones | Low-active to fossil |
| | | | | |
| 10<br>Alpenzoo<br>Moderate<br>Lodgement till, cellular dolostone | Springline tufa<br>Moss tufa | Abundant | Crystalline microbial calcites, micropeloidal grainstone, thrombolites | Moderately active to ?low-active |
| | | | | |
| 11<br>Sillschlucht (several occurrences)<br>Small and very small (two occurrences are fossil)<br>Quartz phyllite | Springline tufa<br>Waterfall tufa, moss tufa | Common to abundant<br>(as pore fills and as crusts) | Stromatolithically to cauliflower laminated lime mudst, fenestral lime mudst, micropeloidal grainstones, Crystalline microbial calcites, | Total of all occurrences: low-active |
| | | | | |
| 12<br>Vomper Loch<br>Very small<br>Limestones | Springline tufa<br>Moss tufa | Abundant | Micropeloidal grainstones, laminated lime mudstones | Fully active |
| | | | | |
| 13<br>Thiersee<br>Fossil part: Large<br>Active part: Very small<br>Limestones | Fossil part: waterfall tufa, fluvial barrage tufa?<br>Phytoclastic tufas, waterfall tufas<br>Active part:<br>Moss tufa (small) | Common to abundant | Waterfall tufas: Microbush calcite, micropeloidal grainstone<br>Vadolithic tufas: micropeloidal to clotted-micropeloidal grainstone, lime mudstone | Low-active to fossil |
| | | | | |
| 14<br>Kitzlochklamm<br>Small<br>Slates | Springline tufa associated with short cave<br>Moss tufa, with lateral transition into speleothems | Overall few, confined to spring tufa, in cave only flowstones | micropeloidal grst-pkst, cauliflower/stromatolithically laminated lime mudst, lime mudst (thrombolites) | Fully active |

Tab. 1 (continued)

cellular polymeric substances (EPS) rich in polysaccharides and in organic acids, such as aspartic amino acid (Obenlüneschloß, 1991; Decho et al., 2005). Biopolymers within gels or gel-like substrates, such as provided by EPS embedding cyanobacteria, are efficient modifiers of the shape of crystallizing calcium carbonate (cf. Cölfen, 2003). Aspartic amino acid, for instance, binds to specific step edges of calcite crystal surfaces; this, in turn, results in curved to finely stepped crystal edges and surfaces. The resulting "chiral" modifications of crystal shape (see Cölfen, 2003, p. 24) are broadly reminiscent to the curved to very finely serrated outer surface of the observed *Rivularia* calcite.

### 3.1.2. Microfan tufa

A similar, less widespread type of tufa of this category is primarily associated with subhorizontal to steeply inclined to overhanging, wet (spray water and/or seep water) but not intensely water-run portions of water fall tufas (e. g. at the location Lingenau), but also at locations dominated by moss tufas and phytoclastic tufas, where it is present as well-indurated, dense carbonate crusts on gravels, tufa intraclasts and phytoclasts (e. g. at the locations Ludesch, Andelsbuch, Alpenzoo). In the field, this tufa is present in small, protruding, cream to yellow to pink or light brown-coloured, calcified patches or crusts a few millimeters to a few square meters in size. Small patches of crust are of knobby to hemispherical shape; wider crusts up to 10 cm and more in extent may show a mammillated to pustular-"meandroid" surface (Pl. 3/1). The crusts may be present in isolated knobs to small patches, or may comprise areas up to a few square meters in size (e. g. at the location Andelsbuch). The crusts are present on bare rock surfaces, but are equally common on lithoclasts, tufa intraclasts (Pl. 3/1-3) as well as on phytoclasts. In thin sections oriented vertical relative to the surface of the crusts, they consist of a highly regular array of outward-fanning calcite crystals (Pl. 3/4, 5). Within the calcite crystals, a highly regular array of branched, curved, outward-fanning tubelets is present, forming "microfans" of tubuli. The curvature and extent of the tubelets is concordant with extent and curvature of the calcite crystals (Pl. 3/6). Each individual microfan as defined by the patterns of the tubelets consists of several curved calcite crystals, i. e. outwards, each crystal becomes larger as the tubelets fan out. Near their outer termination, individual calcite crystals as identified by extinction under crossed polars are up to about 10 mm in width. The outer surface termination of individual crystals of calcite is the same surface than that of the entire crust, i. e. of convex and concave shape in thin section. In addition, also within the calcite fans, individual bush-like arrays of calcite crystals may terminate sharply along a curved surface.

**Interpretation**: The calcitic knobs to crusts are interpreted as calcified cyanobacterial aggregates, but of a different type than the above-described calcite. In this type of tufa, the fans built by the tubuli are of quite smooth and continuous curvature, and of highly regular arrangement. Additionally, individual calcite crystals extend across the concentric lamination, resulting in large single crystals. Three extant species, or morphospecies, of *Rivularia* are known to produce such regular, radially-fanning sparry calcite (Obenlüneschloß, 1991; see also Janssen et al., 1999, p. 81). *Rivularia* is very similar to the fossil genus *Cayeuxia* (see also Kershaw & Guo, 2003, their Fig. 4), and is considered by some authors as a synonym (Flügel, 2004, p. 409, 410). *Cayeuxia*, or *Rivularia*, for that matter, consists of a radially-fanning array of tubuli very similar to the fans of calcified tubuli observed by us. We thus assign the described, regularly-fanning tubuli/calcite crystal aggregates to *Rivularia*. The close correspondence of calcite crystals with the shape, curvature and fanning of the cyanobacterial filaments indicates that calcite crystallization is influenced or steered by the cyanobacteria. The precise reasons for the changes, or apparent changes, in the optical orientation of calcite crystals during growth and outward-fanning are not known. The optical orientation of the calcite crystals may be set since the start of growth of a cyanobacterial aggregate (calcification with different orientations on different sides of the cell?), or it may result from changes in orientation during later growth of the crystal/cyanobacterial-ensemble. The formation of both of the described types of crystalline microbial calcite in association with photosynthetic organisms is also indicated by the microstratigraphy observed in thin sections; calcified fabrics of these kinds always are form first during the formation of tufa fabric successions, and no calcified rivularians or other cyanoids were observed within macropores of tufa.

## 3.2. Micropeloidal to micritic calcium carbonate

### 3.2.1. Micropeloidal grainstones

Aside of both "inorganically" precipitated cements (not treated herein) and the above-described tufas, micropeloidal grainstone to, subordinately, packstone and non-geopetal crusts of stromatolithically laminated/fenestral lime mudstones are the most significant types of microfacies types in the investigated spring tufas. In the field, micropeloidal grainstones to packstones appear as light brown to ocre-coloured crusts to masses a few millimeters to more than 10 cm in thick. Such crusts have been found also in low-lit locations such as short, artifically excavated caves or below overhangs, below thin sheets of flowing water and on permanently wet spots around drip impacts or at water seeps. In general, in locations of low to moderate illumination, such as in caves, half-caves and below overhangs, crusts more than 10-20 square meters in size of microbial calcium carbonate may comprise the largest part or all of the tufa calcium carbonate, like at Andelsbuch. Crusts and patches of micropeloidal grainstone/packstone are common to widespread in all types of spring tufas, but typically this lithology is most abundant in moss tufas and in phytoclastic tufas. In moss tufas, micropeloidal grainstone may have formed first in the diagenetic succession. Conversely, in phytoclastic tufas, the first stages of diagenesis typically are represented by crystalline microbial calcites and/or by fringes of cement, whereas the remaining abundant pore space is partly to entirely filled by micropeloidal grainstone to packstone. Overall, the micropeloidal grainstones to packstone show little variation with respect to fabric. They consist of a more-or-less porous grainstone composed of micropeloids cemented by fringes of very finely crystalline rhombohaidral calcite spar. (Pl. 3/7) In thin section, some micropeloidal grainstones show a more-or-less systematic, "pearl-necklace" like arrangement of micropeloids (Pl. 3/8), or an array of tangled, very narrow "tubes" encrusted along all or most of their extent by micrite (Pl. 4/1). In the grainstones, fenestral pores and/or dissolution veins less than a millimeter to more than a centimeter in width may be common. Some of the micropeloidal grainstones to packstones also contain layers of fenestrae that probably result from larval conducts of insects, such as of chiromonids and/or trichopterids. In addition, phyto- and zooclasts (e. g. gastropod shells) may float within the grainstone. The micropeloidal grainstone to packstone may comprise entire thin sections, i. e. patches built exclusively of this lithology are at least about 6 cm in width, or it is present as one of several spring tufa fabrics (e. g. cement crusts, moss stems) within the same sample. To simulate moss tufa formation, at Tugstein (Vorarlberg), a hair brush was fixed on March 18th, 2005 onto a wall of tufa thinly overrun by water. About six months later, on September 8th, 2005, the bristles of the brush were completely clogged and overgrown by indurated calcium carbonate (Pl. 4/2). In thin section, the calcium carbonate that clogs the bristles is a fenestral micropeloidal grainstone as described, and relatively rich in very small-sized phytoclasts. At the surface of the indurated clogging of micropeloidal grainstone, beyond the extent of the bristles, "mini-stromatolites" and micritic crusts of calcium carbonate had formed (Pl. 4/3). By contrast to moss tufas (not described herein), however, the bristles of the brush are not immediately overlain by a layer of micrite to microsparite, or cement. At waterfall tufas, on steeply-dipping to overhanging surfaces of tufa and/or of substrate rock, crusts up to a few centimeters thick of stromatolithically to cauliflower-like laminated or fenestral lime mudstone to micropeloidal grainstone locally are common. At the toe of tufa-encrusted rockwalls, chips of tufa spalled off by frost action may accumulate. These chips, in turn, may be coated by laminated crusts of lime mudstone to micropeloidal grainstone as described, giving rise to a specific type of intraclast coated grain.

**Interpretation**: Micropeloids formed by calcification of clumps (probably mostly consortia) of non-filamentous microbes are among the most widespread types of microbially-induced calcium carbonate, and have been described from numerous habitats ranging from deep-marine to terrestrial (e. g. Reid, 1987; Reitner, 1993; Camoin et al., 1999; Rivadeneyra et al., 2000, 2004). In calcium-rich environments such as sea water and tufa-precipitating waters, active expellence of calcium out of the cell is a physiological must. Because the cell surface of microbes is negatively charged, particularly dead microbes are attractors of calcium ions; in addition, most microbial aggregates or consortia are embedded in extracellular polymeric substance rich in bicarbonate (from respiration). Microbial calcification thus proceeds in habitats both lit and dark, albeit at different rates. Furthermore, precipitation of calcium carbonate may proceed in association with dead microbes, small phytoclasts and organic substances within the pore space of tufa. This at least in part explains the widespread presence of micropeloidal grainstone to packstone both in surface and subsurface habitats, and both on the surface of actively forming tufas and in the pore space of tufas.

### 3.2.2. Thrombolites

Lime mudstone, typically with a highly variable proportion of small phytoclasts, small tufa intraclasts and/or a few extraformational grains derived from the local rock substrate, is widespread in larger pores of all types of tufa. The possible contribution of microbially-mediated micrite precipitation to these mudstones, however, is difficult to assess. A portion or all of the lime mudstone may have been passively spilled into the pore space via the typically swift pore water flow within spring tufa lithosomes. In some cases, however, faint cauliflower-like laminae within relatively pure mudstone, and a close association of micropeloidal grainstone interfingering, in a non-geopetal fashion, with lime mudstone suggest that at least some of the lime mudstone may represent thrombolithic microbialites. Whether passively infilled or precipitated, the lime mudstones within micro- to macropores make up a significant proportion of the total rock of many tufas.

**Interpretation**: Because the described thrombolites are present within the pore space of tufas, this type of microbially-induced calcium carbonate results from non-photoautotrophic organisms. At the present state of investigations, precipitation of isolated crystals and/or "dark calcification" of thoroughly micrite-calcified biofilms may be assumed, but is difficult to prove. A portion or all of the lime mud may have been produced by microbially induced precipitation, whereas another portion probably represents a fine-grained sediment passively swept in. That passive sweep-in was active in at least many cases is suggested, but equally not proven, by common presence of small phyto-, intra- and extraclasts in the lime mudstone. Conversely, non-geopetal, homogeneous to faintly clotted masses of micrite, and cauliflower-like, non-geopetally laminated masses of lime mudstone are ascribed to dark calcification of biofilms. A few groups of cyanobacteria also are capable to thrive in the dark by facultative chemoautotrophy on sugars (Schwoerbel, 1999), but as yet it is not known whether the interstitial waters of spring tufas contain enough (poly)saccharides to sustain sizeable dark-cyanobacterial populations. Aside of the potential presence of interstitial cyanobacteria, the pore space of tufa may be colonized by light-independent, aerobic to facultatively anaerobic, heterotrophic and chemoorganotrophic bacteria. These bacteria thrive within a wide range of pH, T and oxygen, and are quite resilient against changes in these parameters (cf. Schwoerbel, 1999). Aerobic or anaerobic oxidation of organic compounds such as carbohydrates and organic acids results in release of carbon dixoide and/or of bicarbonate which, in association with expellence of calcium out of the cell, leads to precipitation.

## 3.3. Vadoid grainstones to rudstones

At the location Thiersee, aside of fossil phytoclastic waterfall tufas and Recent moss tufa, a type of tufa is present that to date (November 2005) was observed by us in abundance only there. This tufa consists exclusively, or nearly so, of subspherical to ellipsoidal vadoids and cyanoids a few millimeters to more than a centimeter in diameter (Pl. 4/4). The nuclei of the vadoids commonly are or were phytoclasts. The vadoid cortices typically show an inner, subspherical part and an outer layer that may abut with fitted boundaries (reminiscent of compromise boundaries within freely precipitated cement) to the adjacent vadoids (Pl. 4/5). In addition, along point contacts or along the described fitted boundaries, the vadoids are cemented by micrite and/or by finely crystalline fringes of equant calcite spar. The vadoid cortices consist of numerous, very thin laminae of micrite and/or of micropeloidal grainstone, and/or of laminae of micropeloidal grainstone or clotted lime mudstone, and/or of micro-dendrolithic to "cloudy" aggregates of micrite within a finely crystalline equant calcite cement (Pl. 4/6). Many of the piso- to macro-vadoids are aggregates built by smaller-sized vadoids of similar to identical type (Pl. 4/6). Along the surface of megapores (e. g. after tree trunks) to cavern-sized framework pores in phytoclastic tufas, the cement crusts that merge the grains together laterally coalesce, resulting in distinctly botryoidal surfaces (Pl. 4/7). The botryoids consist of numerous very thin laminae of cement, and/or of laminated micrite, and/or of micropeloidal grainstone, or of micritic micro-dendrolites embedded within finely crystalline equant calcite spar (Pl. 4/8).

**Interpretation**: The described coated grains are interpreted as vadoids that formed in an episodically to near-permanently turbulent vadose surface environment (cf. Flügel, 2004). Within the vadoid cortices, the inner subspherical portion records a first, mobile phase when the vadoids were still subject to episodic overturning. By contrast, the outer layers of cortices, i. e. the layers that abut the adjacent vadoids along "compromise-like" boundaries, record a subsequent immobile phase during which the grains became bound to each other. This second phase may have resulted from very shallow burial within the vadolithic sediment, in a depth no longer affected by episodic sediment reworking, or resulted from a prolonged phase of sediment immobility. Within the vadoid cortices, the diversified laminae of clotted wackestone to micropeloidal grainstone may represent microbialites. Conversely, the micrite micro-dendrolite/calcite cement fabrics and for the "cloudy" micrite patches within laminae that consist of very finely crystalline calcite spar cement, may not be of primary origin, but more probably resulted from recrystallization of the micrite. The spring tufa occurrence near Thiersee once probably was a few hundreds of meters in size at least, perhaps even more. Today, except very minor precipitation of moss tufa and of thin calcareous crusts on rock surfaces of waterfalls of local creeks, nearly no precipitation of calcium carbonate takes place. Erosional relicts of tufa still adherent to a cliff of limestones consist of tufas as described, and contain moulds of tree branches and trunks, and locally show indistinct subhorizontal bedding. Most of the tufa occurrence consists of an interval at least about 5-10 meters thick down to base of outcrop, but today is subject to erosion and is largely covered by forest. The spring tufa from this location had been quarried to build the Josefsburg, the western outlier of the fortress of Kufstein; this underscores the volume of this occurrence. The spring tufas at Thiersee perhaps accumulated from a fluvial barrage tufa system, within a lentic fluvial reach with vadolithic tufas and at least one waterfall with both phytoclastic tufas and vadolithic tufas. Today, lacustrine oncoids still form in lake Thiersee.

## 4. Rates of tufa formation

Experimental precipitation substrata placed at three tufa occurrences (Strassbergklamm, Lingenau, Tugstein, see Fig. 1 and Tabs. 1, 2) in spring 2005 and removed in fall 2005 indicate highly different rates of tufa formation depending on location, exposition and field type of tufa formed (e. g. moss tufa, waterfall tufa). Artificial precipitation substrata include (a) hard substrates such as flower pots of burnt clay, stones, or formatted rods of wood, and (b) soft substrata, such as a hairbrush and small paint rollers with very thin, soft hair.

In Strassbergklamm, flower pots placed within water-run tufa curtains and in water shoots immediately below the curtains showed only a thin film of calcium carbonate formed closely above the level of standing water within the pots, and closely above the impact halo of the water on the outer surface. Similarly, paint rollers were impregnated by an ocre-coloured, firm (but not hard) substance that consists only in part of micrite. Thus, in Strassbergklamm, tufa formation at present is very slow to halted.

At Lingenau, by contrast, all artifical substrata became covered by crusts of rivularian tufa up to about 8 mm in thickness during the time between 18.3.05 (placement of substrates) to 8.9.05 (removal of some substrata). The growth of the filamentous cyanobacteria probably halts somewhen in late fall and starts during spring, thus the rate of tufa formation of about 8 mm/6 months will be close to the maximum present rate of local tufa formation. This is underscored by the thickness of the laminae in the rivularian tufas, which do not exceed a thickness of about 6-8 mm.

At Tugstein, a hair brush was fixed on 18.3.2005 onto a wall of tufa thinly overrun by water. On 8.9.2005 (date of removal), the bristles (25 mm in length) of the brush were completely embedded by and overgrown by cemented, hard micropeloidal grainstone and other types of microbialites (see above). This indicates that micropeloidal grainstone may accrete, by combined baffling and precipitation, at rates of at least about 2-2.5 cm per year, provided that a suitable substrate is present.

In Vomper Loch, a low rock cliff blast in 1966 upon road cutting is covered by a spring tufa about 4 m in length and 3.8 m in height. Types of tufas include moss tufa and, subordinately, phytoclastic and cyanobacterial tufa. In May 2001, the

| Location | Type of tufa | Rates of growth | Reference |
|---|---|---|---|
| | | | |
| Strassbergklamm | waterfall tufa | close to zero | this paper |
| | | | |
| Lingenau | cyanobacterial waterfall tufa | up to 8-10 mm/a | this paper |
| | | | |
| Tugstein | waterfall tufa (at site of artificial substrate) | micropeloidal tufa: 25 mm/a (experimentally deduced rate) | this paper |
| | | | |
| Vomper Loch | moss tufa | 8.5 mm/a (maximum 35 years average of a single station)<br>5 mm/a (average of several stations) | this paper |
| | | | |
| England (several locations) | cyanobacterial (Nostocales) tufa built by *Rivularia haematites* | 5 mm/a: summer growth rate<br>0.7 mm/a: winter growth rate | Pentecost (1987) |
| | | | |
| Global review of tufa locations with rate data | all types of "cool spring" tufa | 1-50 mm/a, up to 52 mm/a<br>(last figure: Drysdale & Gillieson, 1997) | Viles & Goudie (1990) |
| | | | |
| Stuttgart (Germany) | spring tufas (Pleistocene interglacial) | average rate: up to 5 mm/a | Frank et al. (2000) |
| | | | |
| Louie Creek (Australia) | fluviatile tufas | average rate: 4.15 mm/a | Drysdale & Gillieson (1997) |
| | | | |
| Two tufa creeks in Germany | fluviatile tufas | 2 mm/a on artificial substrates | Merz-Preiß & Riding (1999) |
| | | | |
| Mijares gorge (Spain) | fluviatile tufas | average long-term rate: 1-5 mm/a | Pena et al. (2000) |
| | | | |

Tab. 2: Comparison of rates of tufa precipitation

thickness of the tufa was determined at 17 sites. For the maximum thickness of 30 cm of moss tufa, with an age of 35 years of the artificial cliff, this transfers to a mean accretion rate of about 8.5 mm/a. The average thickness of sites with a cover of apparently pure moss tufa is about 18.5 centimeters, corresponding to an average rate of moss tufa formation of 5 mm/a. After excavation of the rock wall, a colonization phase of unknown duration must be assumed before moss cover and efficient precipitation started to develop. Not withstanding this uncertainty in the rate estimate, the deduced rates of moss tufa formation in Vomper Loch compare well with the rates as determined by the experimental substrata, and with short-term (years) to to long-term (hundreds to thousands of years) rates of tufa formation of other areas (see Tab. 2).

## 5. Discussion

Cyanobacteria are among the most significant biological inducers of calcium carbonate precipitation, but are considered as facultative calcifiers in that both external, inorganic factors and biological factors must be set to allow for precipitation (Riding, 1992; Merz-Preiß & Riding, 1999). In tufa-depositing systems, the prevalence of cyanobacteria over other photosynthetic microbes can be explained by the fact that the latter are both obligate anaerobes and most commonly depend on hydrogen sulfide which, in oxygenated freshwater, is practically absent. Moreover, cyanobacteria are best-adapted to thrive in oligotrophic waters (Schwoerbel, 1999). As mentioned, the actively forming cyanobacterial tufas are of ocre to yellow tints. By contrast, except for a single red species, uncalcified cyanobacterial accumulations show dark green to blackish-blue or brown tints (Schwoerbel, 1999). This fits with our observation that permanently or episodically wet tufa curtains that are inactive or of very low activity with respect to $CaCO_3$ precipitation are typically coated by a greenish to dark brown to blackish biomat that is only slightly calcified or uncalcified, such as in Strassbergklamm and in the inactive portions of Lingenau and Laas (see Tab. 1).

At all investigated locations, microbially-induced tufa makes up a significant to even prevalent portion of tufa volume. Equally, the tufa curtains of Lingenau, Strassbergklamm and Laas would not exist (in that style) without microbially induced precipitation. Because the crystalline microbial calcites readily "age" to more-or-less equicrystalline cementstones, the contribution of microbially-induced calcium carbonate to total tufa volume might be underestimated. The microbially-induced tufas also act as a template for further precipitation of calcite by recrystallization of microbial tufa accompanied by additional, inorganic $CaCO_3$ precipitation. The resultant final fabric may show little record of microbial induction of precipitation. At the waterfall of Lingenau, if an accretion rate of 5-10 mm/a is back-extrapolated, this implies that a tufa layer 5-10 m thick formed within only 1000 years. If the spring that nourishes present-day tufa formation at Lingenau was active at that location since about 5000 ka b. p., this would imply that a tufa 25-50 m in thickness had accreted; scattered small outcrops of subsurface rocks, however, suggest that the tufa cover is up to a few meters in thickness only. At Lingenau, the total area covered by inactive tufa is significantly larger than the presently active one, and inactive waterfall tufas are as widespread as the active one. In Strassbergklamm, as mentioned, an array of tufa curtains is present over hundreds of meters along the left flank of the gorge, yet the present rate of calcification is very low to zero. At Laas, several occurrences of inactive and of fossil tufas are present, but active tufa formation still takes place. Thus, locations with active tufa formation, locations of inactive tufa but overrun by water, and fossil "dry" tufas today all may co-exist within the same geographic area, and at the same location.

Although the data base is limited, for the tufa occurrences investigated so far, an overall correlation between total size and active/inactive ratio (in the following shortly: activity) is suggested (Tab. 1). Whereas for very small and small occurrences, their typical full activity may in part also be an artefact of distinction, the clear-cut prevalence of low and zero total activity in the moderately large and large occurrences is not. The negative relation between size and total activity perhaps reflects the perceived „late Holocene tufa decline" (Goudie et al., 1993; Ford & Pedley, 1996), and might result from three factors. (1) Moderately large and large tufa systems are produced by cumulation of small active systems in time and space, thus necessarily will be characterized by a lower total activity. In this view, small active systems comprise the „building blocks" of larger systems. Such a concept would necessitate changes, in space, of spring emergence or of levels of spring emergence. (2) The moderate to large systems result from environmental conditions no longer verified today. In this context, it is notable that most, but not all, of the tufas visited by us are associated with glacial till either in their directly underlying substrate or in the supposed recharge area of tufa-depositing waters. The glacial till probably favoured the formation of groundwater supersaturated for calcium carbonate. Our hypothesis that calcium carbonate from glacial till may nourish most of the investigated tufa occurrences is supported by cementation patterns in the Quaternary of northwestern Germany, where glacial till is the major source of calcium carbonate (Elbracht, 2002). Fine-grained glacigenic calcium carbonate is vulnerable to dissolution because particle surfaces are not coated by iron hydroxides, organic substances, or biofilms (Elbracht, 2002; see also Fairchild et al., 1994). In addition, in glacial tills, very fine-grained carbonate particles produced by shear-induced cataclasis below glaciers may contain residual strain in their lattice. Both, the "edge effect" of very small crystallites and residual lattice strain, render such particles highly soluble (cf. Bathurst, 1975). Thus, progressive exhaustion of soluble carbonate particles from glacial tills may lead to an overall decline of tufa deposition over time. (3) The moderate- to large-sized tufa occurrences relate to former climatic conditions that, perhaps, were more wet and warmer (cf. Goudie et al., 1993). In Northwestern Europe, however, tufa-depositing systems became rapidly established early after post-glacial ice retreat, before the establishment of extensive forests (Taylor et al., 1994). For the fossil tufas at Flath-Alm and some locations near Laas (e. g. Gsalerweg), a limitation of activity to the pre-forestation interval can be excluded because these contain coarse phytoclastic tufas including calcium-carbonate metasomatized tree fragments (Ostermann et al., 2006).

There is probably no straightforward relation between climate and deposition of calcareous tufa. A comparison of the annual gauges of shedding, temperature and conductivity of 54 springs monitored by the federal hydrographic services of Austria shows that many "groundwater springs" are characterized by comparatively high *and* comparatively stable values of electrical conductivity (conductivity = rough proxy for anorganic ions in solution) (see: Quellbeobachtung im Hydrographischen Dienst in Österreich, 2005, for data and terminology of spring classification). By contrast, karst springs and talus springs show marked fluctuations in both shedding and conductivity up to more than one order of magnitude, within hours to days. For most but not all karst and talus springs, conductivity inversely correlates with shedding. For talus springs as well as for karst springs fed by shallow subsurface waters, snow melt can lead to a marked lowering of conductivity over weeks to months (cf. Quellbeobachtung im Hydrographischen Dienst in Österreich, 2005). For these latter spring types, thus, the overall lower (relative to many "groundwater springs") and fluctuating conductivity seems less favourable to mineral precipitation. For such spring types, a mere increase of shedding may do little to propel tufa precipitation. In addition, the marked and rapid changes in conductivity probably are hostile to microbes involved in induction of calcium carbonate precipitation. Conversely, for many groundwater springs, increased shedding under a more humid climate may still result in waters supersaturated enough to allow for precipitation.

The above-mentioned potential causes of the late Holocene tufa decline are not mutually exclusive, because there is more than a single way to produce as well as to quench tufa-depositing spring. One of the major obstacles to better understand the origin and environmental significance of tufa is the lack of absolute ages and the lack of precise hydrogeological information of individual tufa-depositing springs. Absolute age-dating by the Th-U method of a number of tufa occurrences will be indispensable to better understand the relation between Holocene climate and tufa formation. In the marine realm, with marked fluctuations, microbial carbonates became more rare until at present, they are nearly absent and limited to special habitats, most probably mainly as a result of a decrease in oceanic saturation state (Arp et al., 2001; Riding & Liang, 2005). Most tufa occurrences differ from common carbonate factories in that they do not have a significant source of metazoan- and/or plant-controlled calcium carbonate. Tufa-depositing systems are more similar to carbonate systems driven only by microbially induced precipitation and by physico-chemical conditions. Startling perhaps, however, is the fact that cyanobacteria and other microbes also are among the most aggressive biodegraders of buildings (Warscheid & Braams, 2000; Gaylarde & Gaylarde, 2005). Investigations into biodegradation, from a geological perspective, may help in a better understanding of the relation between microbes and carbonates.

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## Plate 1

1: Tufa curtains along and below the emergence of a spring line (Strassberg gorge, Tyrol). The rock substrate is Hauptdolomit. Width of view about 6 meters.

2: Ocre-coloured aragonitic waterfall tufa in active formation (Laas, Southern Tyrol). The darker grey (brown in the field) patches represent coarsely-crystalline botryoidal aragonite; this type of aragonite forms mainly at locations of water impact and along steep to vertical runs with shooting water flow. Width of view about 1 metre.

3: Overhanging tufa curtain (Lingenau, Vorarlberg). This curtain consists of tufa as shown in the next thin section photograph. Height of view about 1 m.

4: Thin section of tufa curtain shown in Pl. 1/3. The tufa consists of laminae each a few millimeters thick of „bushy" calcite that are vertically separated by thin, intercalated laminae of micrite and/or microsparite. Width of view 17 mm.

5: As preceeding photo, but with crossed polars. Individual tufa laminae consist of arrays of elongate-"bushy" calcite crystals that branch towards the upper surface of the tufa carbonate. The "bushy" calcite arrays internally consist of patches of calcite with uniform optical orientation. The laminae of bushy calcite are vertically separated by laminae of micrite to microsparite. Note that each array of calcite "bushes" starts from the intercalated, very thin micrite-microsparite laminae, and branches upward. Width of view 17 mm.

6: Laminated tufa from a tufa curtain overrun by a sheet of water with shooting flow (Lingenau, Vorarlberg). Detail of a tufa lamina that consists of an array of "bushy" calcite aggregates. Section is slightly oblique to the lamination. Note that the optically uniform calcite crystals are slightly curved, and that they are centered by an elongate "channel". Petrographic thin section, crossed polars. Width of view 3.2 mm.

7: Laminated tufa from a tufa curtain overrun by a sheet of water with shooting flow (Lingenau, Vorarlberg). Detail of a tufa lamina that consists of an array of "bushy" calcite aggregates. Section is subparallel to the lamination. Note that each of the thin calcite tubes is centered by a subcircular hollow space. Petrographic thin section, crossed polars. Width of view 4.2 mm.

8: SEM image of calcite crust on a phytoclast (Ludesch, Vorarlberg). The calcite consists of numerous narrow tubes that locally appear to branch or to „bud" onto each other. Elongate forms are diatomeans.

# Plate 1

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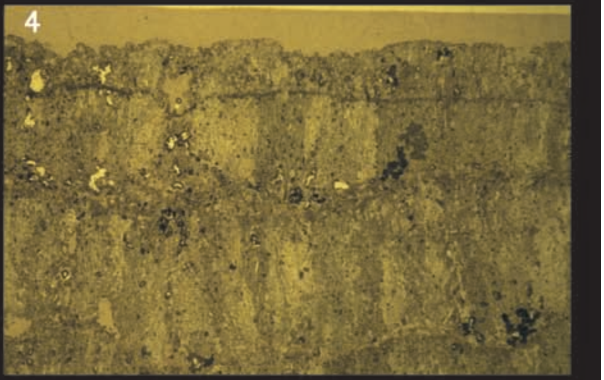

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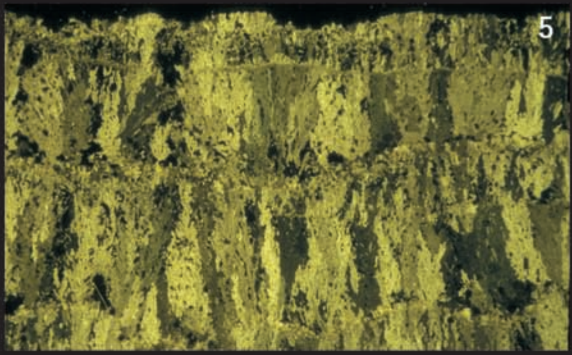

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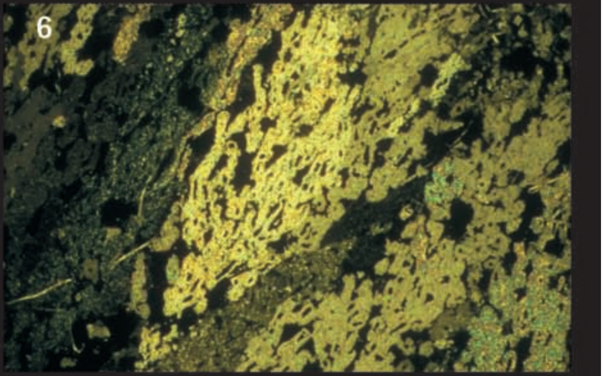

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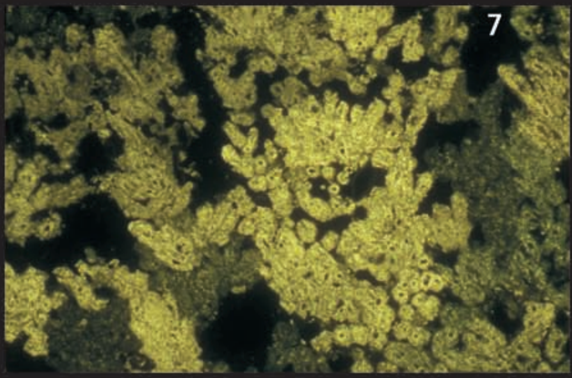

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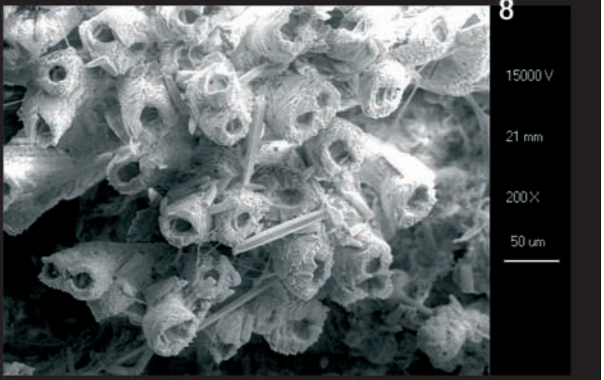


## Plate 2

1: SEM image of calcite crust on a leave (Lingenau, Vorarlberg). The calcite consists of numerous tiny tubes that, on their outer surface, show the characteristic surface steps according to the rhombohaidral shape of crystalline calcite. The inner surface of the tubes is relatively rough and does not show crystal surfaces.

2: SEM image. Detail of calcite tubes as shown in Pl. 2/1. The inner surface of the tube does not show crystal surfaces, but is relatively irregular and rough. The outer surface shows numerous, tiny steps according to the symmetry of calcite. The steps, however, disappear towards the debouch of the tube, where the calcite surface appears completely smooth and nearly perfectly circular. The entire structure seems to be built by subcircular, stacked lamellar units of subcircular calcite rings less than 1 micron in thickness.

3: Laminated tufa of tufa curtain (Lingenau, Vorarlberg). The tufa was excavated with a chisel on 18.3.2005, and resampled on 8.9.2005 (nearly six months later). The truncated older laminae of "bushy" calcite became unconformably overlain by a lamina of "bushy" calcite that precipitated during nearly six months. Petrographic thin section, crossed polars. Width of view 17 mm.

4: Detail of previous photograph. Note that the newly-grown (=18.3. - 8.9.2005) lamina of "bushy" calcite is not underlain by a lamina of micrite to microsparite. Petrographic thin section, crossed polars. Width of view 6.5 mm.

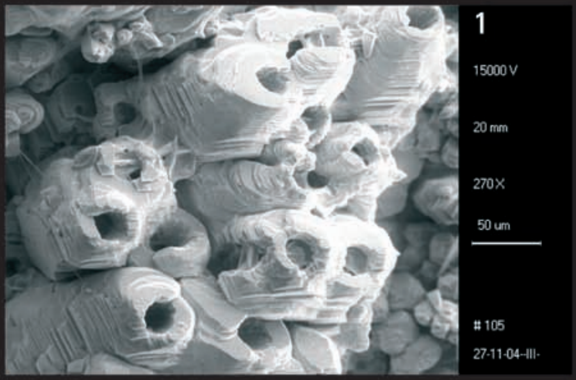
5: "Big brother is watching you": Phytoclastic tufa (Lingenau, Vorarlberg). Cross-section through two twigs, overgrown by calcitic tufa as also illustrated in Plate 1. Note, within the calcite crystals, the thin elongate grey traces. Cross polars. Width of view 17 mm.

6: Detail of tufa creek (Lingenau, Vorarlberg) paved by inactive, dry "mini-rimstones", i. e. by a grey calcium carbonate crust with numerous elevated rims oriented subperpendicular to water flow. One-cent coin for scale.

7: Actively forming "mini-rimstone" (Lingenau, Vorarlberg), i. e. by a yellow calcium carbonate crust with numerous rims oriented subperpendicular to water flow. In thin section, these mini-rimstones consist of the same calcite than illustrated in plate 1. Five-cent coin for scale.

8: Cross-section of "mini-rim" from a mini-rimstone as shown in previous photograph. Width of view 3.2 mm.

# Plate 2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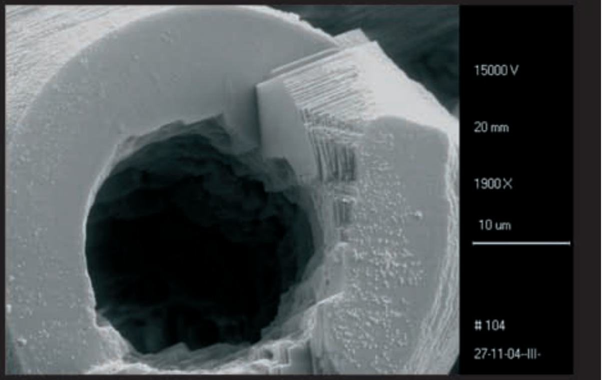
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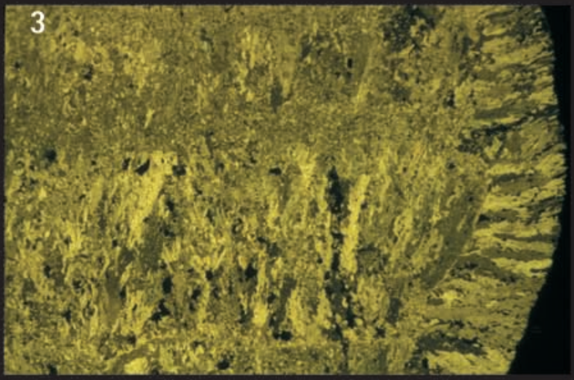
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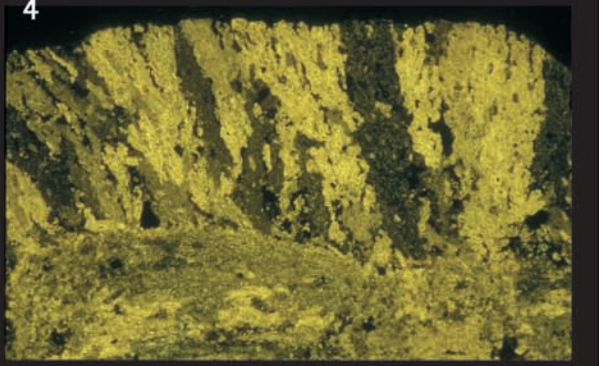
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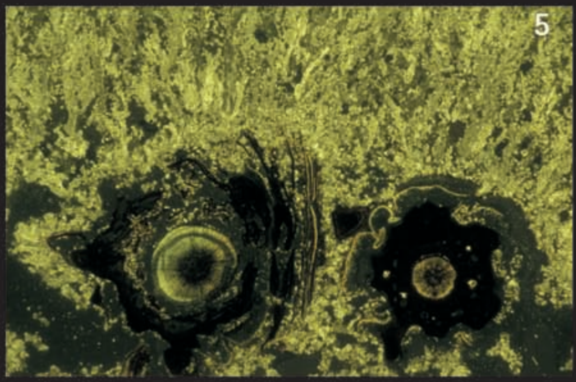
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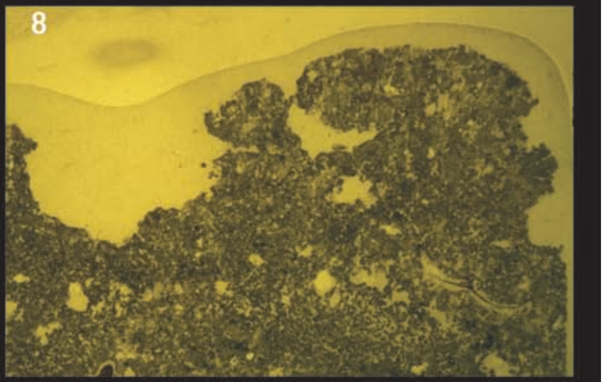
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## Plate 3

1: Carbonate crust on permanently wet, well-lit, but not intensely water-run location (Lingenau, Vorarlberg). The crust shows a pustular to mammillated to "meandroid" surface. Such crusts, albeit in most cases not very conspicuous, are common in many of the investigated spring tufa occurrences. Width of view about 20 cm.

2: Lithoclasts coated by crust of dense, light-ocre calcium carbonate (Andelsbuch, Vorarlberg). In thin section, the crust shows as well-preserved "*Rivularia*". Clast is about 10 cm in size.

3: Tufa intraclast, coated by mammillary crust of ocre-coloured calcium carbonate (Andelsbuch, Vorarlberg). Such encrusted clasts (tufa intraclasts, lithoclasts, phytoclasts) locally are common. Width of view about 15 cm.

4: Section through carbonate crust on lithoclast (Andelsbuch, Vorarlberg). Note the outward-fanning appearance of the carbonate. Width of view 5.3 mm.

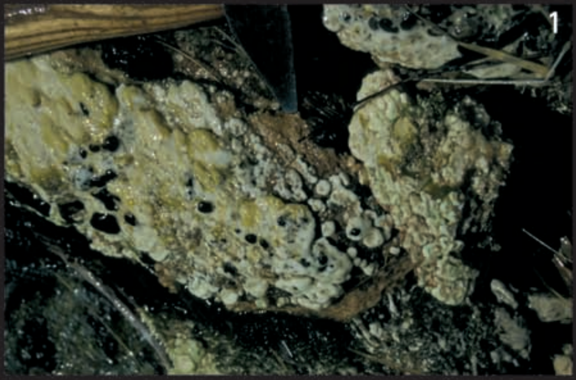
5: Same as Pl. 3/4, but with crossed polars. Note the outward fanning of calcite crystals of discrete optical orientation, and the indistinct lamination subparallel to upper surface of the crust. Width of view 5.3 mm.

6: Thin section through the crust shown in Pl. 3/1. Crossed polars. The crust consists of patches of outward fanning calcite crystals that are arranged into patches each of distinct optic orientation. Width of view 12 mm.

7: Micropeloidal grainstone from an occurrence of moss tufa (Alpenzoo, Tyrol). Width of view 8.5 mm.

8: Thin section of a white, mammillary crust a few centimeters thick (field appearance) (Andelsbuch, Vorarlberg) that consists of micropeloidal grainstone, with the micropeloids arranged in "string fabrics". This crust has been found at the floor of a low-lit location of a short cave excavated by man, in the course of a very small "creeklet" along the floor. Width of view 6.5 mm.

# Plate 3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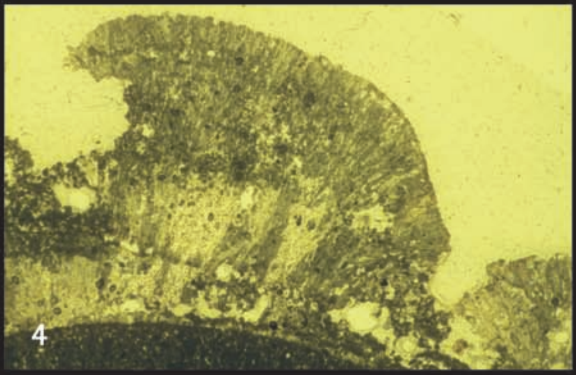
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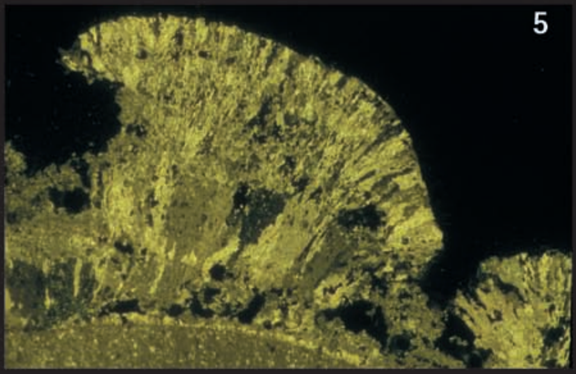
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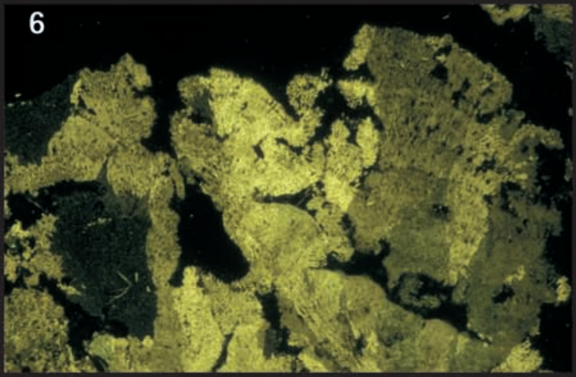
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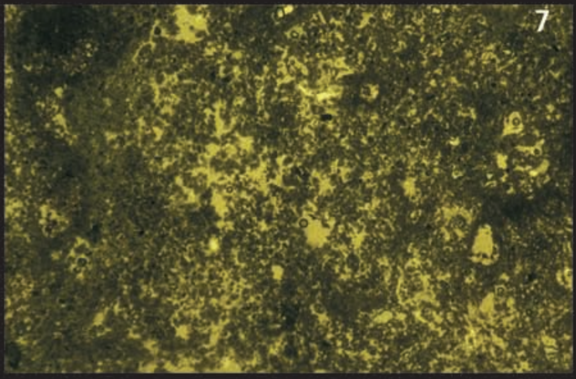
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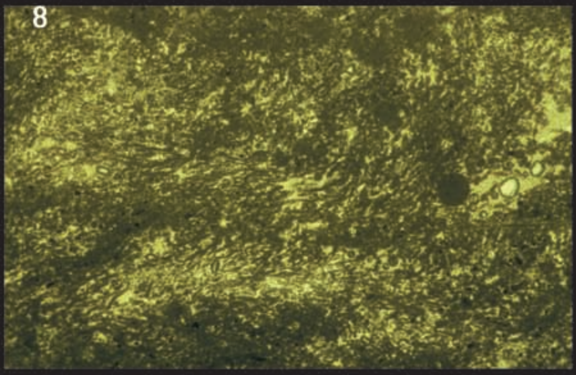
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## Plate 4

1: Detail of a tufa from a moderately lit location below a natural overhang (Andelsbuch, Vorarlberg). This tufa consists of tangled, very small-sized tubes encrusted along their extent by micrite. Crossed polars. Width of view 6.5 mm.

2: Wooden brush (turned outside from the vertical tufa wall to take the photograph) with bristles clogged by an indurated mass of micritic calcium carbonate (Tugstein, Vorarlberg). The brush was placed on 18.3.2005, and was removed on 8.9.2005, i. e. nearly six months later.

3: Thin section of the calcium carbonate within the bristles of the brush shown in Pl. 4/2. The bristles are clogged by a micropeloidal grainstone relatively rich in small-sized phytoclasts, and with open fenestrae. At the top of the grainstone, a lamina to microdendrolithic overgrowth of micropeloidal to micritic calcium carbonate had formed. Width of view 17 mm.

4: Micro- to piso-oncolite consisting of coated grains built by laminae that consist of micrite and/or of micropeloidal grainstone to micro-dendrolithic grainstone (Thiersee, Tyrol). The oncoids are cemented to each other. Crossed polars. Width of view 17 mm.

5: Fine-grained vadoid rudstone (Thiersee, Tyrol). Note that the vadoids show an inner cortex fringed by more or less dense micrite, and an outer cortex of porous micrite. The outer cortices of the vadoids abut each other along boundaries broadly reminiscent of compromise boundaries of cement crystals. The vadoids are locally cemented to each other by the porous micrite. Width of view 8.5 mm.

6: Macro-oncoid composed of laminae of micrite to micropeloidal grainstone, within oncolite composed mainly of piso-oncoids (Thiersee, Tyrol). Note that the oncoids are cemented to each other. Width of view 17 mm.

7: Botryoidal surface of tufa that consists of calcium carbonate as illustrated in Pls. 4/4, 4/6. Note the cracks both within and between individual botryoids. Two-cent coin for scale.

8: Micro-dendrolithic micrite, separated by patches and layers of finely crystalline cement. Locally, the micro-dendrolithic micrite shows faint subparallel lamination. Crossed polars. Width of view 6.5 mm.

# Plate 4