Facies
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ORIGINAL ARTICLE

Spring-associated limestones of the Eastern Alps: overview of facies, deposystems, minerals, and biota

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Abstract In the Eastern Alps, both fossil spring limestones and actively limestone-depositing springs are common. The geological context and a few radiometric age data of fossil spring-associated limestones (SAL) mentioned herein indicate that they accumulated subsequent to the Last Glacial Maximum in the Eastern Alps (24–21 ka BP). Prevalent facies of the SAL deposits, active and fossil, including phytoclastic tufa, microbialites *s.l.*, springstone, and moss tufa form, or formed, from (a) waterfall/creek systems, (b) hillslope-paludal systems, (c) moss-tufa systems, and from (c) foreland-type systems. Precipitated minerals include calcite and, at springs of elevated Mg/Ca ratio, magnesian calcite and aragonite. In a few limestone-depositing, oxygen-deficient springs with dissolved Fe^{2+}, downstream, iron oxide precipitates ahead of $CaCO_3$ (mineralogical zonation). Biota associated with calcium-carbonate deposition include cyanobacteria, green micro-algae, macro-algae, and mosses. Calcium-carbonate precipitation may be speeded by biological mediation, but mineralogy and polymorphy of precipitated $CaCO_3$ are not biotically controlled. In the Eastern Alps, SAL deposits in total range from 190 to 2,520 m a.s.l., corresponding to mean annual temperatures of 10°C to less than 0°C. In altitudes below the continuous permafrost line (about 2,600–3,000 m a.s.l., depending on location), SAL deposition is chiefly controlled by proper balance between water supply and sufficient supersaturation for $CaCO_3$, rather than by mean annual temperature.

Keywords Alps · Tufa limestone · Travertine · Springs · Freshwater carbonates

Introduction

Because of their wide spectrum in morphological setting, water chemistry, and biota, limestone-precipitating springs provide ‘natural laboratories’ of carbonate deposition. In addition, spring-associated limestones (SAL) accumulate under influence of climatic conditions at spring emergence (Pentecost 2005). For European regions outside the Alps, it is demonstrated that SAL deposition practically ceased during glacials and re-established during interglacials (Hennig et al. 1983; Baker et al. 1993; Frank et al. 2000; Zak et al. 2002). Climate records from age-dated SAL deposits thus may support the interpretation of or may help to bridge gaps in speleothem records (Andrews et al. 1993; Andrews 2006; Anzalone et al. 2007). Aside of physico-chemical processes pertinent to all spring-limestone deposystems, such as CO_2-degassing, however, regional concepts of SAL formation must take into account the physiographic and climatic setting (Ford and Pedley 1996;

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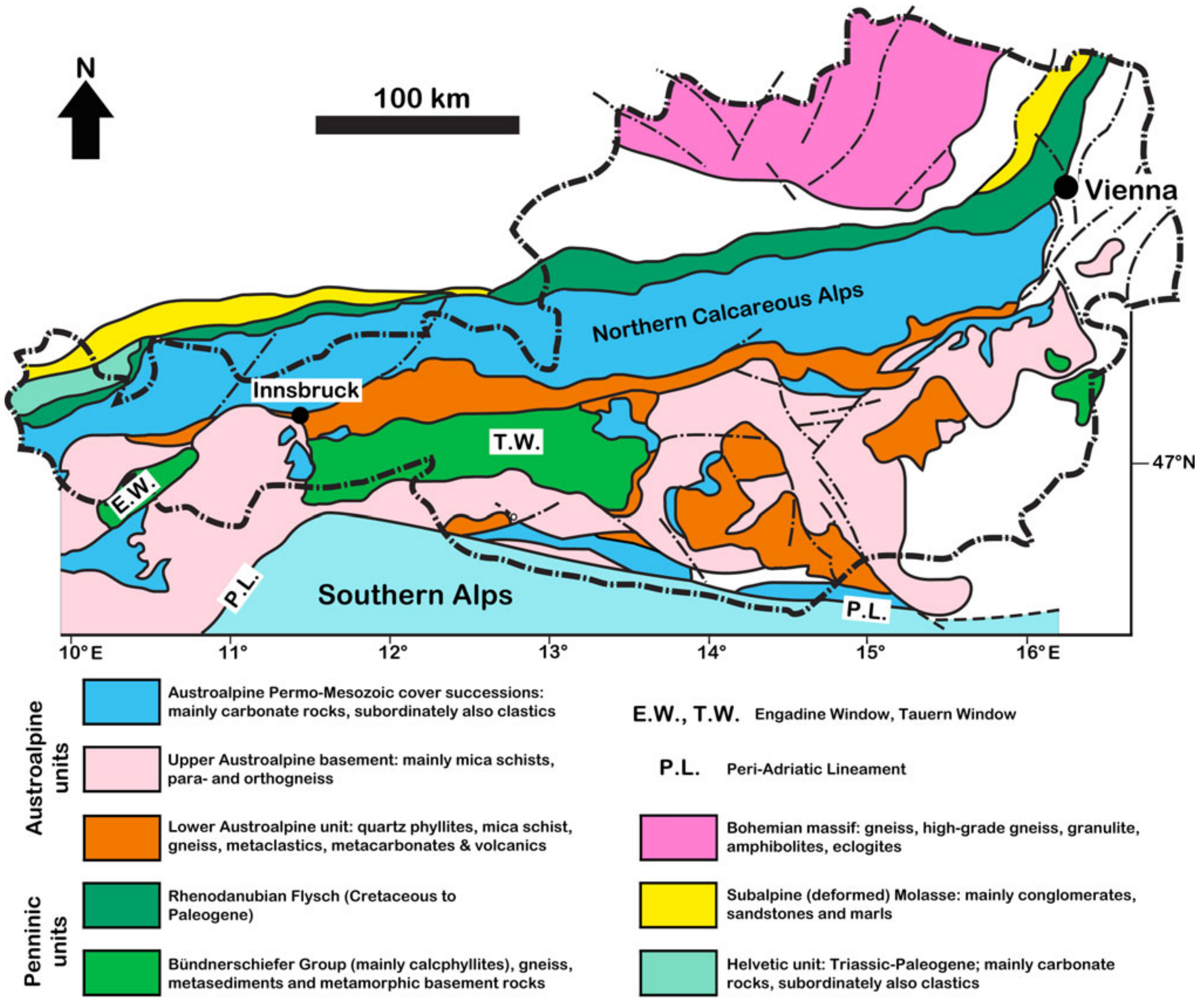


Fig. 1 Geological map of the Eastern Alps showing main tectono-stratigraphic units (see text and Table 3 for characterization of units). In the Eastern Alps, spring limestones are present on each of the main structural units, but are particularly common in the vicinity of and within two large tectonic windows (Engadine Window, Tauern Window), and in the Rhenodanubian Flysch zone

Carthew et al. 2003, 2006). As late as 1995, however, even the magnitude number of SAL deposits in the Eastern Alps (Fig. 1) was practically unknown: A mere five sites are mentioned in the compilation of Pentecost (1995, pp. 1013–1014), and similarly few deposits are listed in Ford and Pedley (1996, p. 142 f). For the Eastern Alps, a preliminary database established mainly by inspection of geological maps and by field trips lists nearly 300 deposits (Sanders et al. 2006a), and even a few more will be identified in future. Because these deposits are of a typical extent of a few tens to a few hundreds of meters, they tended to be viewed as marginal features not worthwhile investigation. The purpose of this paper is to provide an overview of the SAL deposits of the Eastern Alps with emphasis facies, deposystems, minerals, and biota. The climatic impact on deposition of Eastern-Alpine spring limestones is discussed by means of a comparison of SAL deposits versus altitude and mean annual temperature; the comparison shows that SAL deposition is mainly steered by water chemistry and much less so by climate.

Background to deposition of spring limestone

Limestone may precipitate from: (a) thermal (warm) springs with a temperature at emergence of ≥20°C, (b) cool springs with a temperature at emergence representing the mean annual temperature of the topographic recharge area, and (c) from subthermal springs with a temperature clearly above the mean annual temperature of the topographic recharge area, but less than 20°C (Zötl and Goldbrunner 1993; Pentecost 2005). Our descriptions of Eastern-Alpine SAL refer to cool springs, and to exhausted (former) springs that probably shed cool to, perhaps, subthermal waters (see below for discussion). Precipitation of spring limestone mainly results from the following processes: when groundwater with elevated concentrations of Ca^{2+} and HCO_3^- (and with CO_2 supersaturation due to elevated hydrostatic pressure within the aquifer) emerges, CO_2-degassing may lead to sufficiently high supersaturation for precipitation of $CaCO_3$:

$$Ca^{2+} + 2HCO_3^- = CO_{2(g)} \uparrow + CaCO_3 \downarrow + H_2O \quad (1)$$

(Heimann and Sass 1989) degassing is driven by physical effects of pressure release and water turbulence, by warming and, less commonly, by evaporation (Chen et al. 2004). Withdrawal of HCO_3^- due to photosynthesis, simplified to:

$$Ca^{2+} + 2HCO_3^- = CaCO_3 \downarrow + 'CH_2O'(' \times 6 = \text{glucose}') + O_{2(g)} \uparrow \quad (2)$$

(Heimann and Sass 1989; Konhauser 2007) at least at many springs is much lower in rate relative to physical CO_2 degassing (Merz-Preiß and Riding 1999; Chen et al. 2004; Shiraishi et al. 2008). In addition, bryophytes and several cyanobacteria can directly take up CO_2 for photosynthesis. Other, uncommon chemical pathways of spring-limestone formation are outlined in Pentecost (2005). Downstream of spring emergence, $CaCO_3$ precipitation proceeds until supersaturation is sufficiently lowered; even after termination of $CaCO_3$ deposition, however, many stream waters still are weakly supersaturated for calcite, but further precipitation is prevented by kinetic factors (Pentecost 1992; Berner and Berner 1996). The most widespread mineral of SAL deposits is low-magnesian calcite (Julia 1983; Heimann and Sass 1989; Sancho et al. 1997), a result confirmed by our data from the Alps.

Definitions

Pentecost (2005, pp. 2–18) discussed in detail previous classifications or ad hoc terminologies of spring- or stream-associated limestones. He defined ‘travertine’ as (Pentecost 2005, p. 3): “A chemically precipitated continental limestone formed around seepages, springs and along streams and rivers, occasionally in lakes and consisting of calcite or aragonite, of low to moderate intercrystalline porosity and often high mouldic or framework porosity within a vadose or occasionally shallow phreatic environment. Precipitation results primarily through the transfer (evasion or invasion) of carbon dioxide from or to a groundwater source leading to calcium carbonate supersaturation, with nucleation/crystal growth occurring upon a submerged surface.” We agree with this definition focused on loci and processes of formation; yet we found it less useful in communicating the main geological characteristics of spring-produced *rocks*, particularly in case of fossil deposits. For a fossil deposit, it is not always obvious whether it represents a thermogene (=warm spring), meteogene (=cool spring), or superambient (≈subthermal) travertine (cf. Pentecost 2005, pp. 11–18); in fossil deposits, even detailed geochemical investigations may lead to inconclusive results with respect to this classification (Boch et al. 2005).

Spring limestones in many cases are ‘tufa’ (from Latin *tophus*, meaning ‘light-weight porous rock’, irrespective of composition; Pedley 2009) with a porosity of more than about 10–15% (Heimann and Sass 1989; Ford and Pedley 1996). Ford and Pedley (1996) proposed to reserve the term tufa for freshwater low-magnesian calcites precipitated at low or near ambient temperature; this is unfortunate because cool-spring limestones may also consist of aragonite or magnesian calcite (Sanders and Wertl 2009; Sanders et al. 2010a). Some authors would designate limestones deposited from waters ≥20°C as travertine (from Latin *lapis tiburtinum*, meaning ‘the stone of Tiburtinum’; Pedley 2009). Many such travertines, however, show a porous fabric of dendrites and/or of crystal skeletons of $CaCO_3$. Conversely, low-porous and typically laminated ‘springstones’ may form, both, from warm and cool springs, at the day-lit surface of a spring creek. Many springstones are demonstrably of primary origin; in other cases, springstone fabric resulted from rapid recrystallization of original laminated tufa limestone combined with further, abiotic crystallization of calcium carbonate (Golubic et al. 1993; Pentecost 2005; ‘combispar crystallization’, Sanders and Rott 2009). Low-porous limestones formed at the day-lit surface of a spring creek previously were designated by some authors as ‘flowstones’; this term, however, should be reserved for speleothems precipitated from a water film (see Fairchild et al. 2007). To avoid mixing of interpretative with descriptive criteria, we herein use the term ‘tufa’, or ‘tufa limestone’, for all spring- or stream-related limestones with a porosity of more than about 10–15%, irrespective of mineralogy, polymorphy, and assumed temperature of precipitation (Table 1). The term springstone is used for *low-porous*, typically (but not necessarily) laminated limestones of calcium carbonate formed at the day-lit, water-run surface of the deposit, with no connotation on mineralogy, polymorphy, or temperature of formation (Table 1). With respect to the physiographic position of stream-related freshwater-limestone deposystems, two major categories were distinguished (cf. Magnin et al. 1991; Ford and Pedley 1996): (1) systems perched on valley flanks or hillslopes (‘perched-spring systems’), and

Table 1 Terminology of spring-associated limestones used in the present paper

Modifier according to water temperature	Major category of spring limestone, based on porosity	Subcategories, based on features from field to cut slab
'Cool-spring': spring temperature <20°C	Tufa limestone, tufa	Laminated tufa
'Chilled-water': water cooled down to <20°C in the distal part of thermal-spring systems	Limestone with porosity more than about 10–15%, and formed in springs	Moss tufa
		Phytoclastic tufa
'Warm-spring': spring temperature >20°C		Intraclastic tufa
		etc.
'Heated-water': water heated to >20°C after emergence from a cooler spring (e.g., Spötl et al. 2002)	Springstone	Laminated springstone:
	Limestone with porosity less than about 10–15%, and formed in springs	consists of stacked, subparallel laminae of dense calcium carbonate, typically of prismatic to fibrous $CaCO_3$ (calcite, magnesian calcite, aragonite)
'Superambient' (Pentecost 2005), or 'subthermal':		Laminated springstone forms at the day-lit, water-run surface
spring water <20°C, but warmer than the mean annual temperature in the topographic recharge area of a spring		Bedded to unbedded springstone:
		includes moss springstones, phytoclastic springstones, intraclastic springstones, etc.

For other fabrics, such as cements formed in pores of spring limestones, or speleothems (flowstones) formed upon karstification, or for microbialites accumulated within dark pores, the conventional terminology of carbonate fabrics applies (see Flügel 2004)

(2) river systems or valley systems accumulating within the stream that drains a valley. All of the limestone-precipitating deposystems, active or fossil, described in this paper represent perched-spring systems.

The size categories of SAL deposits used herein (section A in Table 2) are established with a perspective to the typical extent of Eastern-Alpine deposits. To designate the activity of limestone-depositing springs as well as of SAL deposits, two different categories are introduced. The activity status of individual springs with respect to limestone deposition is subdivided into three types (section B in Table 2): (1) *Active springs*. Active limestone precipitation is indicated by litho- and phytoclasts of the season, green moss tufts, human litter, etc., coated by calcium carbonate (Fig. 2a). Moss tufts may be heavily calcified and indurated in their understorey, such that only the tips of green

Table 2 Characterization of size, formation, and activity of spring limestone deposits used in present paper

A: size	
Small	Longest measure: up to 20 m
Moderate	Longest measure: 20–100 m
Large	Longest measure: >100 m to 1 km
B: Activity, with respect to limestone deposition, of individual spring	
Active	Overrun by water plus significant actual $CaCO_3$ precipitation on surface. Resulting deposit grows
Inactive	
Dormant	Overrun by water, but no or insignificant $CaCO_3$ precipitation at surface of deposit. Deposit does not grow or undergoes local, limited erosion
Fossil	Limestone deposit undergoes karstification (where fallen dry), or significant erosion by non-limestone precipitating water
	Ratio of active/inactive areas
C: Activity status of an entire spring-limestone deposit	
Active	Active area $\geq 3-4 \times$ inactive area, or entire deposit is active
Moderately active	Active area $\approx$ inactive area
Low-active	Inactive area $\geq 3-4 \times$ active area
Inactive	Inactive area $\geq 10 \times$ active area
Fossil	Entire deposit inactive

shoots remain visible. In active systems of the Eastern Alps, litho- and phytoclasts become encrusted by calcium carbonate within weeks to months (Sanders and Rott 2009). (2) *Dormant springs*. This category designates springs may intermittently (years to?tens/?hundreds of years) achieve a state of zero or extremely slow net accumulation of calcium carbonate. Dormant spring creeks show a bed of uneroded or scarcely eroded spring limestone, with poorly calcified moss tufts growing alongside or within the stream (Fig. 2b), and/or by uncalcified or weakly calcified microbial assemblages (cyanobacteria, green microalgae) or macroalgae (e.g., *Vaucheria*). Dormant systems are best identified by placing of precipitation substrates. (3) *Fossil springs*. For SAL deposits that today are dry, more-or-less-vegetated and/or undergoing erosion, fossil status is obvious (Fig. 2c, d). In many cases, field mapping allows to identify the exit of the former spring, or springs, that once had supplied spring-limestone deposition. A few deposits are still overrun by a spring creek, yet cessation of carbonate precipitation perhaps hundreds to thousands of years ago is indicated by fluvial incision into spring limestones plus lack of evidence for active precipitation (Fig. 2e, f). From the perspective of limestone precipitation, thus, such systems are fossil. 'Water-run' fossil systems may be colonized by facultative calcifyers, such as cyanobacteria or algae, but these are uncalcified (Fig. 2f, g). The activity of individual springs in limestone deposition not necessarily reflects the activity of an entire SAL deposit. The observation that, in the Eastern Alps, all large SAL deposits containing active limestone springs also comprise fossil sectors thus requires an additional categorization of activity status of an entire deposit (section C in Table 2). Herein, high-altitude SAL deposits are defined as such that form, or formed, at and above 1,500 m a.s.l.; in the Eastern Alps, this altitude generally corresponds to the height at which July temperature can occasionally drop below 0°C (Fliri 1980; Steinhauser and Nowak 1963).

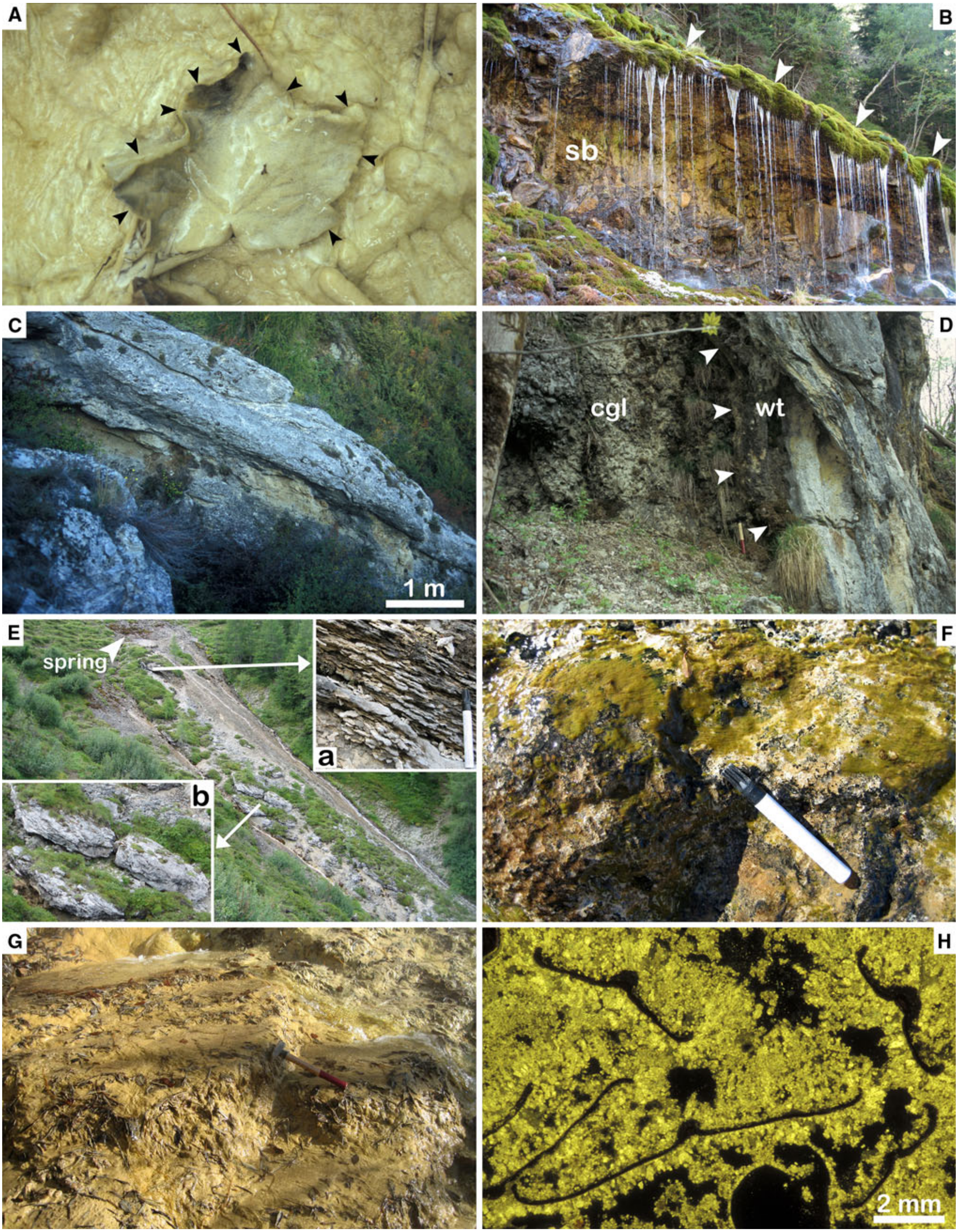
Geological setting

The Eastern Alps consist of a pile of thrust nappes derived from the northern margin of the Apulian microcontinent, in the south, to the Helvetic shelf along Meso-Europa in the north (Fig. 1; Table 3). Letting aside the vagaries of Alpine orogenesis (see, e.g., Schmid et al. 2004, for overview), from North to South, the Eastern Alps consist of the following major tectonostratigraphic units (Table 3): (1) the Molasse Zone, composed mainly of marls, sandstones and conglomerates derived from the rising Alpine edifice, (2) the Rhenodanubian Flysch, characterized by deep-marine marls and turbidite sandstones accumulated in the northern foredeep of the Alps, and (3) the Austroalpine units derived from the northern margin of the Apulian microcontinent. The Austroalpine, in turn, consists of: (a) the Northern Calcareous Alps, a stack of cover thrust nappes dominated by Triassic carbonate rocks, and (b) the Central Alps, composed of metamorphic basement nappes, and of basement/cover nappes. (4) In the Central Alps, the structurally lowest Penninic unit is exposed in tectonic windows (Engadine Window, Tauern Window; Fig. 1) characterized by thick successions of calcphyllites ('Bündnerschiefer Group'). In the strongly telescoped frame zone of the tectonic windows, the calcphyllites or Bündner Schiefer contain intercalated slivers of Triassic sulfate evaporites and metacarbonates; these latter two are derived from the paleogeographical transitional belt between the Austroalpine and the Penninic unit. SAL deposits, fossil to active, are found on each of the mentioned tectonostratigraphic units, but are particularly common in the Rhenodanubian Flysch Zone and on the Bündnerschiefer Group of the Penninic unit.

The geological context of the SAL deposits, both fossil and active, described herein indicates that their accumulation commenced after the Last Glacial Maximum (LGM) in the Eastern Alps (24–21 ka BP; Ivy-Ochs et al. 2009). In the eastern sector of the Eastern Alps, a few SAL deposits assigned to the Miocene are indicated in geological maps; these limestones are excluded from consideration. Aside of the potential Miocene SAL deposits, to date we found no evidence for Quaternary SAL deposits pre-dating the LGM. The few numerical ages produced for Eastern-Alpine SAL deposits furthermore all indicate post-LGM accumulation (cf. Boch et al. 2005; Ostermann 2006). In the Eastern Alps, to our knowledge, all limestone-precipitating thermal springs are inaccessible because fully captured. If not otherwise noted, thus, all statements below apply to cool springs. To date, for the Eastern Alps, we did not identify an unequivocal example of a subthermal limestone-depositing spring.

Methods

Active to fossil SAL deposits were investigated with a range of different methods since year 2000 (Table 1 in Electronic Supplementary Material). Aside of information taken from geological maps, a total of 36 SAL deposits were investigated in the field, with a variable spectrum of methods employed, and with a total duration of investigation ranging from a single day to repeated visits over six years. A total of 354 thin-sections (status March 2010) supported documentation of facies and microfacies. Selected deposits were mapped in the field and, in active systems, samples of biota were taken. At six locations with active SAL deposition, experimental substrates were


A
B
sb
C
1 m
D
cgl
wt
E
spring
a
b
F
G
H
2 mm

◀ **Fig. 2** Record of activity status of spring limestone deposits. **a** Fallen maple leaf (outlined by *black arrowtips*) of the season, encrusted by yellowish layer of calcium carbonate, and 'cemented' towards its substrate of phytoclastic tufa. Lingenau, Austria. **b** Cemented slope breccia (*sb*) veneered by a layer of moss tufts (indicated by *white arrowtips*); the moss tufts show only very scarce calcification in their understorey. Pfitsch valley, Italy. Width of view about 8 m. **c** Fossil deposit of spring limestone undergoing erosion. U/Th age of an aragonitic cementstone in the rock substrate about 30 cm below the spring limestone: 13.4 ± 0.2 ka (Ostermann 2006). Vinschgau, Italy. **d** Fossil waterfall tufa (*wt*) coating a cliff of Molasse conglomerates (*cgl*). Lingenau, Austria. Width of view about 4.5 m. **e** Fossil tufa deposit undergoing erosion, and partly overrun by a creek with 'non-limestone depositing' water. *Insets a* and *b* show erosion of tufa limestone. Navis valley, Austria. Width of view about 120 m. **f** View onto surface of fossil spring-limestone deposit overrun by creek. Although the surface is colonized by filamentous cyanobacteria (*green* patches), these do not show evidence for calcification. Note also pitted, irregular surface of fossil spring-limestone deposit, and compare with **a**. Schmirn valley, Austria. *Pen* is 14 cm long. **g** Ensemble of phytoclastic shelfstones and rimstones in active formation. Lingenau, Austria. *Hammer* is 35 cm long. **h** Thin-section of phytoclastic tufa limestone shown in preceding image. The limestone contains moulds of *Salix* leaves; the former leaves became overlain by calcite precipitated from the desmid micro-alga *Oocardium stratum* ('*Oocardium* calcite', see text). Crossed nicols

placed along the system and checked in periods that ranged in duration between two months to more than one year. Total observation times of experimental substrates range from more than one year to six years (status September 2009). For purpose of interpretation, the limestone fabrics of Eastern Alpine SAL were compared with limestones sampled in thermal-spring deposystems in Switzerland (Leukerbad, Cantone Wallis), and in Italy (Rapolano Terme, Bagno Vignoni, Bagni San Filippo).

Facies types

Both the active and the fossil SAL deposits of the Eastern Alps consist of: (a) springstones, and/or (b) diverse types of tufa limestones (Table 4). Common and distinct facies of spring-associated limestones are illustrated in Figs. 2, 3, 4, 5, and are characterized in Table 5. Other facies, such as breccias resulting from spring-associated cementation of hillslope colluvium or of talus slopes, vadolithic limestones, micritic freshwater stromatolites (some with chironomid larval casts), characean tufa, and cementstones formed in karstic veins and caverns within spring limestones are very rare and subordinate in abundance. At a few locations, permineralization of phytoclasts by calcium carbonate is observed (Fig. 4d, e) (Sanders et al. 2006c). The morphological elements of SAL deposystems such as limestone-coated waterfall cliffs, plunge pools and pool rims, or shelves and steps, may consist of different field facies and, in turn, of different microfacies. For instance, pool rims may be composed, either, of phytoclastic tufa, or of springstone, or of moss tufa, of 'algal tufa' (e.g., *Vaucheria* tufa) or, finally, of tufa formed by calcification of cyanobacterial tufts.

Table 3 Main tectonostratigraphic units of the Eastern Alps, listed downward from north to south

Unit (time range of succession of Alpine cycle)	Subunit (time range)	Characteristics	Remarks
Molasse Zone (Paleocene to Miocene)		Neritic marls, sandstones, conglomerates of rising Alpine edifice	Prevalently hilly terrain
Helvetic unit (Triassic to Paleogene)		Neritic marls, shallow-water limestones, deep-water limestones deposited on southern shelf of Meso-Europa	Eastern Alps: exposed mainly as tectonic slivers; outcrop widens near western end of Eastern Alps
Penninic unit (total range: Permian to Paleogene)	Rhenodanubian Flysch (Cretaceous to Paleogene)	Deep-water marls and turbidite sandstone deposited in Alpine foredeep	Prevalently hilly terrain
	Bündnerschiefer Group (Jurassic to Paleogene)	Calcphyllites, metapelites to metapsammites deposited in Alpine foredeep	Steep-flanked terrain. Bündnerschiefer Group exposed in frame zone of Engadine Window and Tauern Window (Fig. 1)
Austroalpine unit (Permian to Paleogene)	Lower Austroalpine (Permian to Lower Cretaceous)	Metamorphic basement and, locally, metamorphic cover units (mainly Triassic metacarbonates)	Hilly to steep-flanked terrain
	Upper Austroalpine (Permian to Paleogene)	(a) Metamorphic basement nappes, (b) metamorphic basement nappes plus metamorphic and non-metamorphic cover units mainly of Triassic carbonates, (c) cover thrust nappes mainly of Triassic shallow-water carbonates	Cover thrust nappes: Northern Calcareous Alps Mainly steep-flanked terrain

Table 4 Field-based subdivision of common types of cool-spring limestones, Eastern Alps

Main group	Type	Characteristics	Remarks
Tufa limestones	Phytoclastic tufa	Tufa limestone rich in phytoclasts or phytomoulds coated by (a) other types of tufa lst., and/or (b) by fringes of springstone	Phytoclasts provide substrate for microbially induced calcification and ‘abiotic’ cement precipitation
	Laminated tufa	Limestone composed of stacked, subparallel, distinct to faint laminae to very thin beds of tufa; deposits of laminated *‘Oocardium* tufa’ may attain a few tens of meters in lateral extent	Limestone precipitated in association with desmid microalgae (*Oocardium stratum*); small patches may also be formed by cyanobacteria (*Scytonema*, *Phormidium* probably also *Rivularia*)
	Moss tufa	Tufa limestone initially formed by calcium-carbonate precipitation on moss tufts; intrinsic pore space may be filled by infiltrated sediment, by microbialites, and/or by cement	Initial calcification of moss tufts, (a) induced by microbes living on the moss, and/or by (b) formation of cement by evaporation and CO_2 degassing of spray and drip water, and (c) by photosynthetic CO_2 uptake by moss
	‘Algal’ tufa	Patches up to a few decimeters in size of tufa limestone with micro- to small-sized macropores of more-or-less constant width	Unlaminated to, rarely, indistinctly laminated limestone formed in association with macroalgae, such as *Vaucheria*
	Intraclastic tufa, clast- to matrix-supported	Composed of intraclasts of tufa and/or of springstone; clasts embedded in matrix of micrite, or coated by cement fringes	Veneers of intraclastic tufas typically present near base of steep hillslope-paludal deposystems; may show gradual compositional transition into intra/extraclastic breccias
Springstones	Laminated springstone	Dense limestone of stacked, subparallel laminae of ‘abiotically’ precipitated $CaCO_3$, commonly fibrous low-magnesian calcite, less commonly high-magnesian calcite and/or aragonite	Springstone forms by ‘abiotic’ precipitation of $CaCO_3$ at the day-lit, water-run surface of the spring creek Relative abundance of springstone ranges from insignificant to abundant among different springs
	Bedded to unbedded springstones	Low-porous limestones commonly formed in a similar fashion than most tufas, but more heavily calcified	Bedded to unbedded springstones are common both in active and fossil systems
Breccias lithified by limestone-precipitating spring	Mixed intra/extraclastic hillslope colluvial breccias, clast- to matrix-supported	Breccias composed of (a) intraclasts of tufa lst and/or of springstone, and (b) lithoclasts from local rock substrate; matrix is porous micrite to vadolithic grainstone; phytoclasts/phytomoulds may be admixed	These breccias are typically present near the base of or intercalated in ravines into some steep hillslope-paludal deposystems and of some waterfall/creek systems
	Talus-slope breccias	Breccias of steep (20–35°) dipping strata of angular clasts from local rock substrate; lithified by micritic cements and/or by sparitic cement fringes	Waters precipitating the cements within the talus slope emerge from limestone-precipitating spring above the talus-slope surface (Sanders et al. 2010b) Talus-slope breccias are present at the base of or intercalated (in ravines) into some steep hillslope-paludal deposystems and of some waterfall/creek systems

Deposystems

Waterfall/creek system

This class of spring-limestone deposystem is characterized by a waterfall and/or a very steep creek with a cascade channel to step-pool channel (Figs. 2g, 4f). Small systems consisting only of waterfall tufa, that is, a tufa limestone formed where the water flows down subvertically, are only a few decimeters to a few meters in length; in all the other, longer systems a creek reach with limestone precipitation is typically situated downstream of the waterfall, or between successive waterfalls (Fig. 6a). In the Eastern Alps, the overwhelming number of waterfall/creek tufas documented so far forms directly downstream of spring emergence; only a single creek tufa system is known to the author that receives significant supply of limestone-precipitating waters by seeps and springs emerging laterally alongside the creek (Abtenau). Waterfall tufas, and tufas formed on vertical steps of cascading creeks, consist of highly variable relative proportions of *Oocardium* tufa, cyanobacterial tufa, and abiotic laminated springstones. Locally, tufts of the moss *Eucladium verticillatum* may grow within creek steps, or along the lower edge and in the overhang underneath the tufa curtains. Alongside of waterfall-creek systems, calcified moss tufts (e.g., the widespread *Palustriella commutatum*) may be common. A rare subtype of waterfall/creek deposystems is represented by iron oxide/carbonate systems (Fig. 6a1) (Sanders et al. 2010c). The outstanding feature of this type of deposystem is a 'mineralogical zonation', that is, directly downstream of spring emergence, only iron oxide precipitates first; downstream, however, precipitation of iron oxide fades out within a short distance, and limestone formation starts. Precipitation of laminae of iron oxide and laminae of limestone interfinger for some distance downstream. The distal part of each of these deposystems, by contrast, is characterized by pure limestone deposition.

Moss-tufa system

These systems are comparatively rare, but highly distinct (Fig. 6b). Moss-tufa systems form along very steep, well-illuminated slopes. Moss-tufa systems are distinguished from mere moss-rich patches in other SAL deposystems in that the former are dominated by calcified moss tufts at surface, and moss calcification determines the morphology of the entire deposit (Fig. 4g). Moss-tufa systems build intervals of tufa limestone up to at least a few meters in thickness, hence are well suited for quarrying. Moss-tufa systems consist of an array of subvertical, moss-covered 'cliffs' a few decimeters to about two meters in height, intercalated by gently sloping to horizontal 'steps'. A typical feature of moss-tufa systems is that the creek runs over most of its extent *within* the lithosome of tufa limestone, but often re-emerges on steps. Where the creeks re-emerge, small ponds (here called 'step ponds') are common (Fig. 4h). The ponds may be limited by rimstones of cyanobacterial tufa and/or of moss tufa. Another, rare variety of moss-tufa systems are elevated, moss-fringed, narrow channels that became progressively built up by moss calcification.

Hillslope-paludal system

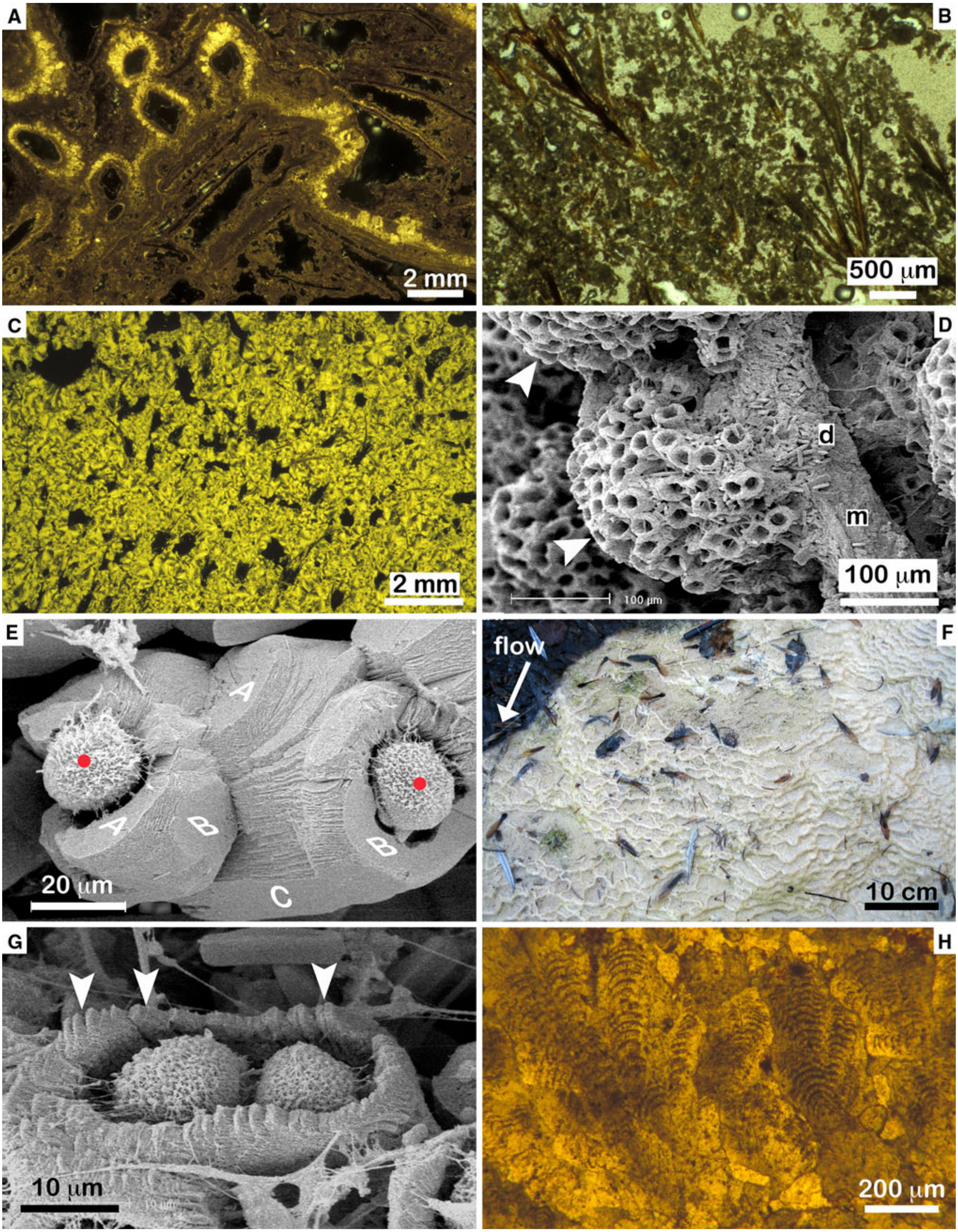
Ford and Pedley (1996) indicated that many European 'tufas' form on poorly drained slopes vegetated by moss, grass, and bushes; they proposed the term paludal (Latin *palus* = swamp) for these deposits. We retain the term paludal but add 'hillslope' to indicate that, in the Alps, many of these deposystems are situated on moderately steep to very steep, swampy slopes with seepage of limestone-precipitating waters over a larger area (Fig. 6c). Hillslope-paludal systems typically are vegetated by grass and moss, but trees (*Pinus*, *Alnus*, *Salix*) and shrubs locally are common, too (Fig. 5a). Hillslope-paludal systems may be a few hundreds of meters in lateral extent; conversely, the limestone formed in these systems typically is of very high porosity and friable when freshly excavated. Hillslope-paludal systems are dominated by moss tufa and/or by phytoclastic tufa; in addition, a high proportion of lime ooze is typical for these systems. The swampy hillslope may be intercalated by small ponds or by small creeklets running over a limited distance downslope, before vanishing again by percolation in the very shallow subsurface. Hillslope-paludal systems are fairly common, not only in the hilly terrains of the Flysch Zone and Molasse Zone, but also at hillslopes in the Central Alps.

Fossil systems

In the Eastern Alps, most of the fossil SAL deposits are comparable in size, facies inventory and architecture to the previously described systems. A few fossil deposits, however, are up to about one kilometer in downslope extent, i.e., they are of significantly larger total extent than presently active systems (Figs. 6d, 7). Such large fossil systems are typical for the frame zone of the Tauern and Engadine Window, respectively (Fig. 1); there, the fossil systems are located on strongly telescoped successions of calcphyllites ('Bündnerschiefer') with intercalated slivers of sulfate evaporites and metacarbonates (cf. Brandner et al. 2008). In a few cases, groundwater percolated through fossil spring limestones may give rise to: (a) karstic caverns with flowstones or cements, and/or (b) to small 'secondary' spring-limestone deposystems perched on the older limestones (Watzdorf 2008). In a few cases, fossil foreland-type systems are present within the Eastern Alps (Fig. 6e). The name of these systems is derived from the northern foreland (approximately from Baden-Württemberg via Bavaria to Lower Austria) of the Eastern Alps, where systems of comparable architecture and facies inventory are common. The foreland-type systems are primarily distinguished by the following combined features: (a) morphological position below the brink of plains or gently dipping terrain veneered by proglacial outwash and glacial till, and (b) presence to prevalence of limestones of lacustrine, paludine, and lentic-fluvial environments. Examples for such systems within the Alps are provided by the fossil deposits of Peratschitzen (Carinthia) and Plainfeld (Salzburg).

Altitude range of spring limestone deposits

A compilation of the altitudinal position of 272 deposits of the Eastern Alps shows that SAL range from 190 to 2,520 m a.s.l. (Fig. 8). The majority of SAL deposits is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flow
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◀ **Fig. 3** Microfacies and microfabrics of spring-associated limestones. **a** Thin section of phytoclastic tufa characterized by micritic encrustation of former phytoclasts recorded by mouldic pores. The *light-grey* crust of sparitic calcium carbonate represents a layer of *'Oocardium* calcite'. Tugstein, Austria. Crossed nicols. **b** Thin section of micropeloidal variety of moss tufa. The moss *Palustriella commutatum* is overlain by a highly porous aggregate of micritic micropeloids. Vomper Loch, Austria. Parallel nicols. **c** Thin section of moss tufa formed of aggregated, submillimeter-sized botryoids to spherulites of fibrous calcite. Vinschgau, Italy. Crossed nicols. **d** Moss stem (*m*), locally overlain by aggregates of diatoms (*d*), and by hemispherical clusters (indicated by *white arrowtips*) of calcite tubes formed by calcification of the desmid alga *Oocardium stratum*. SEM image. Weiherburg, Innsbruck, Austria. **e** Two cells (highlighted by *red dots*) of *Oocardium stratum*, each attached to an incipient tube of calcite induced by the alga ('*Oocardium* calcite'). The surfaces labeled *A* to *C* represent different crystal surfaces of the calcite rhombohedron. Critical-point SEM image. Lingenau, Austria. **f** Microterracettes of cool-spring tufa limestone formed by calcification of *Oocardium stratum*. Lingenau, Austria. **g** Two cells of *O. stratum*, closely after division, within their tube of calcite. Note serrated upper end of calcite tube (labeled by *white arrowtips*) that here consists of fibrous calcite. Critical-point SEM image. Weiherburg, Innsbruck, Austria. **h** Thin section of coarse-crystalline springstone showing subparallel laminae. Trebesing, Austria. Parallel nicols

situated at altitudes below 1,500 m a.s.l., whereas a total of 49 high-altitude deposits formed above 1,500 m a.s.l. were identified. Most of the SAL deposits between 1,000 and 2,000 m a.s.l. form in areas with a mean annual temperature in the range of 0–5°C; SAL above 2,000 m a.s.l. form in areas with a mean annual temperature below 0°C.

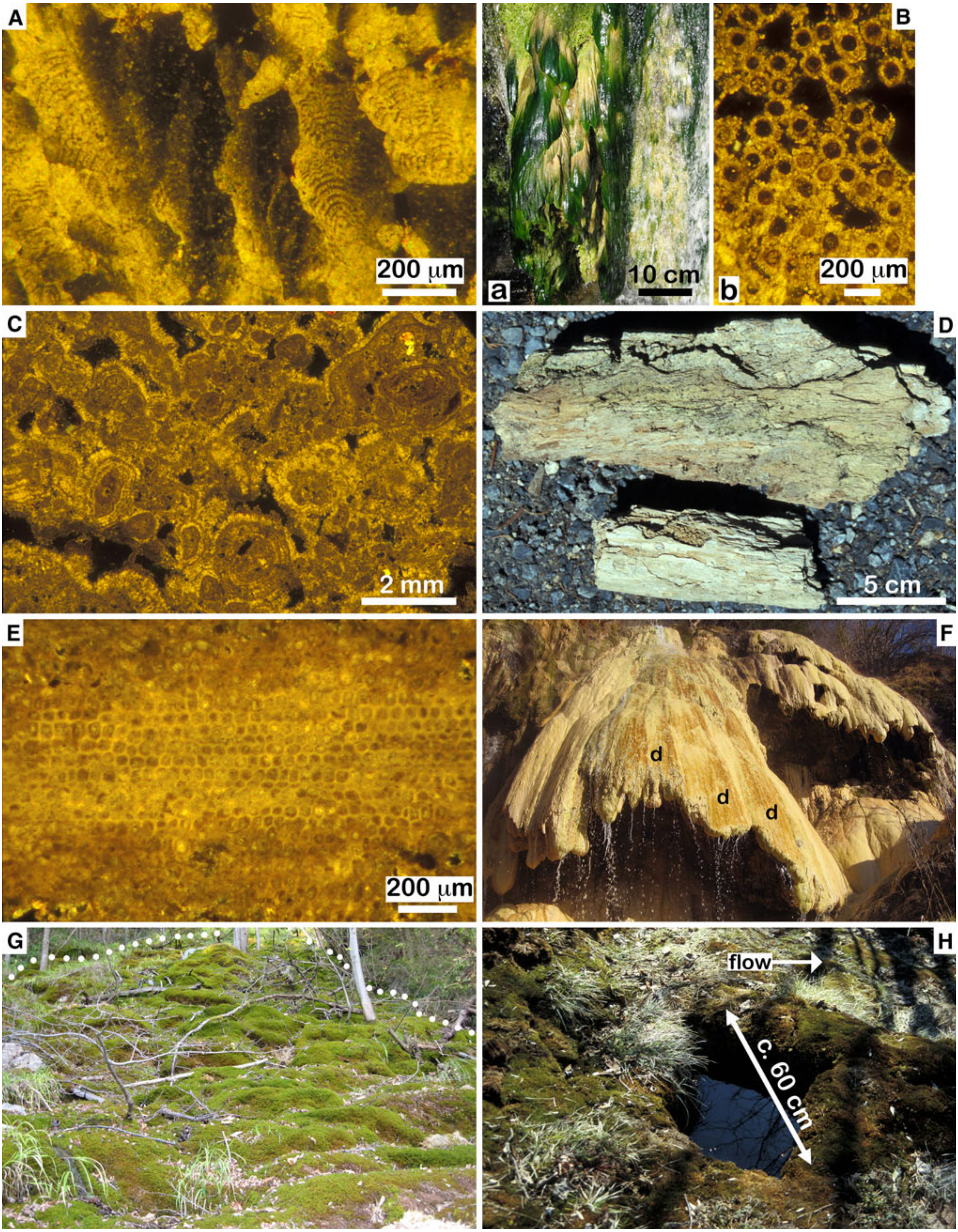
Mineralogy

The most widespread mineral of both the active and fossil SAL deposits of the Alps is low-magnesian calcite (LMC). In most cases, at active springs, LMC precipitates directly as such, typically as (sub)rhombohedral crystals (Fig. 3e). At other springs, LMC precipitates as fibrous LMC (Fig. 5b, c). A few fossil SAL deposits are characterized by a prevalence of magnesian calcite (MC) and aragonite (see Electronic Supplementary Material). Aside of fine-grained fabrics hardly resolvable with light microscopy, in springstones, these two minerals form fibrous to botryoidal fabrics similar to fibrous LMC. At a few active SAL deposits, MC and aragonite precipitate from cool springs (Fig. 5d–f); these springs shed waters of elevated Mg/Ca ratios, up to 5 (highest value recorded by us to date) (Sanders et al. 2010a). As mentioned, at a few active springs, iron oxide precipitates directly at and downstream of spring emergence while $CaCO_3$ deposition starts only farther downstream, where iron oxide is exhausted.

Biota

In most cases, the shrub- and tree flora surrounding springs comprises elements of azonal vegetation, with specific features comparable to the riverine vegetation along rivers. Depending on altitude, many limestone-depositing springs of the montane and subalpine areas are fringed by *Salix*- and *Alnus* species with *Picea* and *Pinus* mainly in the surrounding zonal vegetation and, at springs situated in lower altitudes, *Fagus*; phytoclasts of these taxa thus prevail in the tufa limestones. Bryophytes are common elements of the spring-associated plant communities, with *Palustriella commutata* and *Eucladium verticillatum* most frequently encountered in montane settings (*Cratoneuretum commutati* Aichinger 1933; Grabherr and Mucina 1993, p. 233). As a result, these two mosses prevail in moss-tufa formation (Figs. 3b, 4g; Table 6). Several groups of green algae *s.l.* may contribute to spring-limestone formation: Of the desmidiacean algae (all of them micro-algae), *Oocardium stratum* is locally abundant, and may control the formation of a few SAL deposits (Fig. 3d–g). For *O. stratum*, different calcification structures as a result of a different water chemistry of springs were documented (Sanders and Rott 2009; Rott et al. 2009). Many other green (micro-)algae, such as the desmid *Cosmarium* or zygnematalean micro-algae, were identified but seem to be insignificant in limestone formation, at least from active sites. Tufts of the xanthophyte macro-alga *Vaucheria* are locally common on steeply dipping to vertical substrates (Fig. 4b).

Cyanobacteria are present in all of the active deposystems inspected by us, however, nowhere prevail in limestone formation. Most characteristic and widespread calcifying cyanobacteria include *Rivularia* and *Scytonema*. *Rivularia* may comprise calcified hemispherical aggregates, and arrays of laterally merged hemispheres. The intensity of *Rivularia* calcification ranges from loose aggregates of micrite to microsparite to coarse-crystalline springstone (Obenlüneschloss 1991; Sanders et al. 2006b). *Scytonema*, by contrast, forms tufts of long filaments. On south-facing, sun-lit waterfalls, *Scytonema* tufts tend to be black; conversely, in more shaded creeks, they are of grey to greenish-grey color. *Scytonema* tufts are most common in waterfalls, along rims of pools, and on vertical steps of rimstone-pool ensembles. Pool rimstones may consist of '*Scytonema* tufa' that in fact may be largely formed by calcification induced by diatoms and other microbes thriving on and between the cyanobacterial threads. In addition, other filamentous and coccoid cyanobacteria, respectively, were identified (e.g., *Phormidium*, *Schizothrix*, *Plectonema*, *Pseudoscytonema*, *Nostoc*, *Gloeocapsa*, *Gloeothece*, *Aphanothece*), but these are subordinate in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◀ **Fig. 4** Facies, microfacies, and deposystems of spring-associated limestones. **a** Same thin section as in Fig. 3h, crossed nicols. The springstone consists of fibrous low-magnesian calcite with sweeping extinction. **b** Calcification of the xanthophycean macro-alga *Vaucheria*. *Subfigure a* (*left*): Field view of calcifying *Vaucheria* tufts in a waterfall. Lingenau, Vorarlberg. *Subfigure b* (*right*): Thin section of sample of '*Vaucheria* tufa' from the waterfall shown in **a**. The tufa shows circular moulds of algal threads that became encrusted by rhombohedral calcite spar. Locally, the pore space between the calcite tubes is also filled by calcite spar. Crossed nicols. **c** Thin section of vadolite from the highest known spring-limestone deposit of the Eastern Alps, at 2,520 m a.s.l. in Fimber valley, Tyrol, Austria. Crossed nicols. **d** Two pieces of conifer wood permineralized by aragonite and magnesian calcite (tested by XRD). Flath Alm, Austria. **e** Thin section of permineralized conifer wood shown in preceding image. Note good preservation of cell walls. Crossed nicols. **f** Waterfall tufa system. This tufa is mainly built by calcification of the desmid micro-alga *Oocardium stratum* during summer. During winter, the activity of *O. stratum* ceases, and diatom mats (brownish streaks labeled *d*) spread out. Photo of December 15th, 2006. Lingenau, Austria. Width of tufa curtain in foreground about 3.5 m. **g** View up slope an active moss-tufa deposystem (delimited by *white dots*). The moss tufa is situated on a very steep slope, shows a positive relief, and consists practically entirely of calcifying moss tufts. Weiherburg, Innsbruck, Austria. **h** View down slope an active moss-tufa deposystem, showing a characteristic small pond rimmed by calcifying moss tufts. These ponds are subject to slow throughflow of water. Andelsbuch, Austria

abundance and overall insignificant in spring-limestone formation.

Diatoms adapted to circumneutral to slightly alkaline pH also induce calcium-carbonate precipitation. Between late autumn and spring, diatom mats spread out over spring limestones (Fig. 4f). Calcite rhombohedra may nucleate while floating freely within diatom-secreted mucus; in addition, diatom frustulae provide nuclei to calcite crystals (Sanders and Rott 2009). Also the surface of diatom mats may be coated by a thin lamina of calcium carbonate crystals. Upon shrinking or waning of diatom mats in summer, however, it seems probable that diatom calcification ultimately results in loose, micritic to sparitic calcium-carbonate sediment rather than representing a significant source of limestone preserved in situ. To date, we could not identify a microfacies that can unequivocally attributed to diatom-induced calcification preserved in situ.

Interpretation and discussion

Mineralogy

As mentioned, most SAL deposits of the Eastern Alps consist of low-magnesian calcite (LMC), but fossil and active deposits consisting of magnesian calcite and aragonite are present, too. Because mineralogy is controlled by water chemistry, this hints on different chemical compositions of limestone-depositing waters. Overall, validated data from literature and our own data indicate that Alpine spring limestones commonly precipitate from waters of Ca–HCO_3 to Ca–(Mg)–HCO_3–SO_4 to Ca–(Mg)–SO_4–HCO_3 characteristic (cf. Carlé 1975; Kahler 1978; Wexsteen et al. 1988; Zötl and Goldbrunner 1993; Unterwurzacher 2001; Rüf 2006; Sanders and Rott 2009). Groundwaters of Ca–HCO_3 characteristic, with variable amounts of sodium, magnesium, sulfate and chloride, are widespread and can form in different rock substrates as well as in unlithified sediments, such as glacial till; this is underscored by the observation that SAL deposits are present in all major tectonostratigraphic belts of the Eastern Alps, notwithstanding their lithological differences (Sanders et al. 2006a). Springs with Mg $\geq$ Ca are rare, but if the Mg/Ca ratio is sufficiently high (up to 5; the highest value recorded by us to date), aragonite and magnesian calcite (MC) may precipitate (Sanders et al. 2010a). Aragonite is common in thermal springs (cf. Fouke et al. 2000; Minissale et al. 2002; Pentecost 2005), but may also precipitate from subglacial waters (Aharon 1988). In most natural environments, at low temperatures and also at low Mg concentrations, the threshold between precipitation of LMC versus aragonite + MC is located at Mg/Ca ratios of commonly 1.2–4 (Gonzalez and Lohmann 1988; Gutjahr et al. 1996a, b; Morse et al. 1997; Stanley and Hardie 1998; Dean et al. 2006). For Mg incorporation into calcite, even at relatively low Mg concentrations, temperature and alkalinity are of minor importance relative to Mg/Ca ratio (Berner 1975; Morse et al. 1997; Lopez et al. 2009). The 'mineralogically zoned' springs precipitating iron oxide ahead of calcium carbonate shed anoxic to dysoxic waters (Sanders et al. 2010c); this is consistent with the fact that iron oxides are practically insoluble in oxygenated water (Berner and Berner 1996). In addition, the rate of precipitation of Fe^{3+} probably is speeded by iron-oxidizing bacteria, such as *Gallionella ferruginea* (cf. Søgaard et al. 2001; James and Ferris 2004). In the fossil, dry-fallen SAL deposits known to us we did not observe petrographic evidence for widespread calcitization of aragonite and magnesian calcite. The U/Th ages of fossil, dry SAL deposits rich in aragonite and MC, up to more than 13 ka (see Electronic Supplementary Material), also argue against widespread Mg leaching and aragonite conversion. Nevertheless, fossil SAL deposits that today are overrun by a non-limestone depositing creek may undergo some mineralogical conversion, depending on permeability (cf. Spötl et al. 2002).

Facies and microfacies

Warm-spring tufas sampled by us in the proximal sector of five active thermal springs (Italy, Switzerland) consistently show two distinctive crystal fabrics, including: (a) laminae

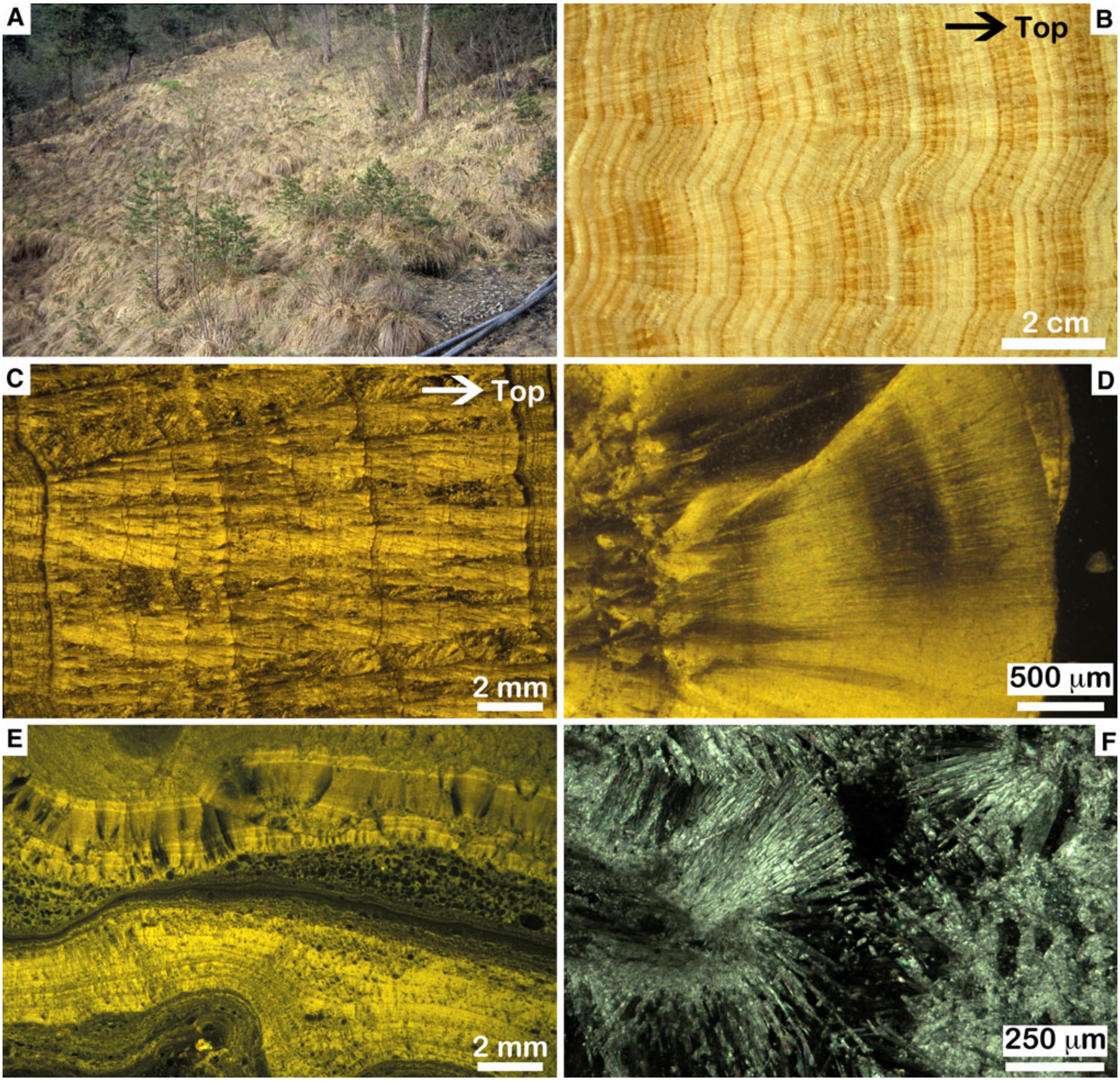


Fig. 5 Deposystems and crystal fabrics of spring-associated limestones. **a** Hillslope-paludal deposystem situated on a gentle slope. The bumpy, swampy meadow is underlain by a veneer of: (a) phytoclastic tufa limestone formed mainly by calcification of grass and wood fragments of the forest (*Pinus*, *Alnus*, *Salix*, *Corylus*) growing on the slope, and (b) of moss tufts growing in the understorey of the grass. Ludesch, Austria. **b** Cut slab of laminated springstone of fibrous calcite. Feistritz, Austria. **c** Thin section of sample shown in preceding photo. The springstone consists of fibrous low-magnesian calcite without evidence for biological mediation of precipitation. Crossed nicols. **d** Springstone of fibrous magnesian calcite, from the active surface of a waterfall. This springstone precipitated on an experimental substrate placed by the authors. Vinschgau, Italy. Crossed nicols. **e** Infilling of a macropore of a slope breccia directly below a fossil spring-limestone deposit. The pore is filled by isopachous fringes of aragonite (tested by XRD), and a geopetal fabric of peloidal grainstone. Flath-Alm, Austria. Crossed nicols. **f** Fibrous aragonite cement within a macropore of a fossil spring-limestone deposit. Gschließ, Italy. Crossed nicols

to thin beds of tufa composed of calcium-carbonate dendrites, and/or (b) laminae to thin beds of tufa of $CaCO_3$ 'feather crystals' or crystal skeletons (see Fouke et al. 2000; Jones et al. 2000; Pentecost 2005; for illustrations). Such crystal fabrics are typical for thermal-spring deposits (Pentecost 2005); they suggest rapid crystallization far off equilibrium (Sunagawa 2005), mainly due to water chilling and CO_2 evasion. To date, we did not observe these fabrics neither in the field nor in thin-sections of SAL from the Eastern Alps. As mentioned, in the Eastern Alps, all

Table 5 Main textural types of investigated spring-limestone deposits

Textural class	Textures	Presence	Interpretation	Remarks
1 Moss framestone to bafflestone	(1.1) Micropeloidal moss frst to bafflest (1.2) Springstone moss frst (1.3) *Oocardium* calcitic moss frst Most common: (1.4) Combined texture of (1.1)–(1.3) above	Forms on moss tufts, and in the understorey of moss tufts	Moss provides framework for (a) microbially induced tufa precipitation, (b) large surface for 'abiotic' precipitation of springstone	Common to widespread, may prevail in tufa deposits
2 Phytoclastic rudstone	(2.1) Springstone phytoclast rudst (2.2) Micritic phytoclast rudst (2.3) *Oocardium*/cyanolithic phytoclast rudst (2.4) Combined texture of (1)–(3) above	Forms around phytoclasts (wood fragments, leaves, conifer needles)	Phytoclasts provide substrate for abiotic and biologically induced tufa formation	Common, may comprise large part of tufa deposits
3 Sparry *Oocardium* tufa	Sparry, laminated tufa limestone formed in associated with the desmid alga *Oocardium stratum*	Forms mainly waterfall tufas, may also comprise an accessory to significant portion in moss tufas	Large calcite crystals formed around *Oocardium* cells while these grow upward and multiply by cell division (Wallner, 1933; Sanders and Rott, 2009)	Abundance highly variable (from nil to abundant) between different tufa deposits; lamination is of seasonal origin (Sanders and Rott, 2009)
4 Cyanobacterial framestone	(4.1) Coarse-sparry springstone formed around *Rivularia* sheaths or filaments (4.2) Micro- to orthosparitic cementstone formed around *Rivularia* sheaths or filaments	Mainly in waterfall/creek systems	Calcite orthospar crystals to micrite formed along sheaths and/or along filaments of cyanobacteria	Common, but always subordinate in abundance Sparry type (4.1) forms at loci of water impact, and by 'combispar crystallization' (recrystallization plus further crystallization)
5 Cyanobacterial bafflestone	Peloidal grainstone, with grains supporting each other, or floating freely and supported only by organic mucus	Mainly in waterfall/creek systems and moss-tufa systems; typical locations: On vertical surfaces, on pool rims	Peloidal grainstone formed by trapping of peloids and, probably, by calcification of microbes (e.g., diatoms) thriving within tufts of filamentous cyanobacteria (e.g., *Scytonema Schizothrix semiglobosa*, *Plectonema wollei*)	Common, but subordinate in abundance
6 *Vaucheria* framestone	Framestone formed by precipitation of crust of calcite crystals on a framework provided by filaments of macroalgal tufts (in described case: *Vaucheria*)	In waterfalls, and on the brink of pool rims	Precipitation of calcite crystals probably directly mediated by macro-algal photosynthesis, and/or by organic compounds on surface of alga	Uncommon, but relatively persistent in tufa systems characterized by swift-flowing waters (waterfall/creek systems)
7 Laminated springstone	Springstone of subparallel laminae of fibrous calcite, of magnesian calcite, or of aragonite	Mainly in waterfall/creek systems	'Abiotic' precipitation of calcium carbonate directly from spring water, at the daylit surface of the creek;	Common in some waterfall/creek systems; may prevail in large, fossil waterfall/creek systems Lamination most probably of seasonal origin

Table 5 continued

Textural class	Textures	Presence	Interpretation	Remarks
8 Micritic to microparitic limestone (Lime mudstone)	(8.1) Crusts, laminae and patches of micrite to microsparite formed demonstrably in association with microbial activity	Widespread in all types of tufa systems	Processes of microbiological mediation of micrite-microspar precipitation may range into organo-mediated precipitation and inorganic precipitation	Widespread but rarely prevalent
	(8.2) Crusts, laminae and patches of micrite to microsparite of now definite origin	Pore-fills of micrite to microspar may result from activity of microbes and/or from passive infill of micrite		
	(8.3) Matrix of intraclastic tufas, and of colluvial breccias			

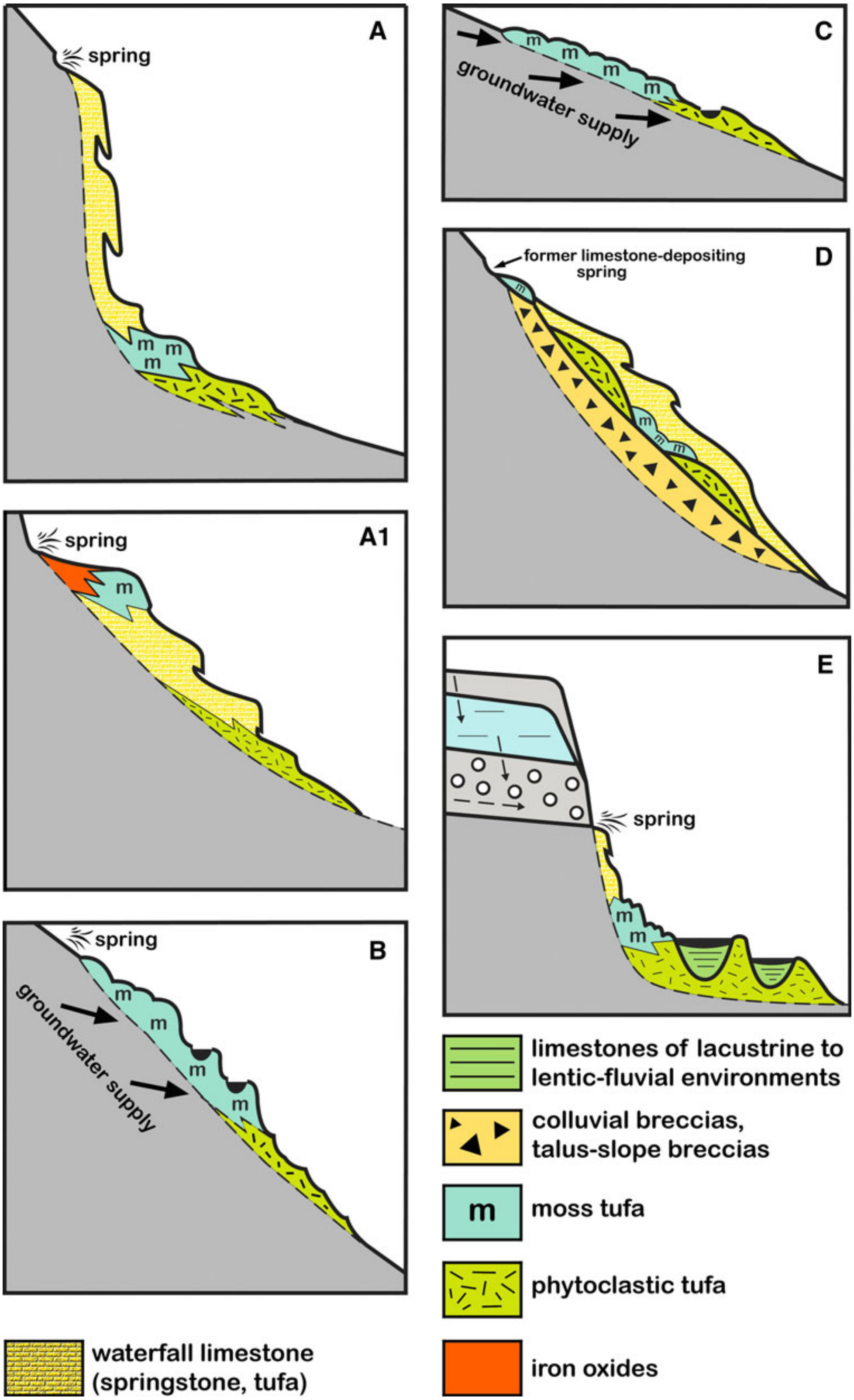
limestone-precipitating warm springs are captured and overbuilt by spas. Also in three fossil SAL deposits rich in aragonite and (magnesian) calcite, we did not identify high-porous fabrics of dendrites and crystal skeletons. Conversely, we found that laminated springstones such as illustrated in Fig. 5b, c form commonly in the distal, chilled-down (<20°C) sector of thermal-spring systems, but also at cool springs. The 13.5-ka fossil SAL deposit of Ainet, Eastern Tyrol (see Table 2 in Electronic Supplementary Material) is composed of, both, aragonite and calcite, in form of laminated springstones and tufas (Boch et al. 2005). The springstones consist of laminae of fibrous aragonite, intercalated with laminae of fibrous calcite. Stable isotopes of oxygen and carbon indicate that the deposit did not form from thermal waters; the calculated paleotemperatures of precipitation might, at most, suggest precipitation from low-subthermal waters (Boch et al. 2005).

At least most of the other facies and microfacies described herein are basically similar to facies described previously by other authors for deposits outside the Alps. The relative percentage of facies, however, in many cases seems to be different. For instance, SAL deposits of moderate to large size composed nearly entirely of '*Oocardium* tufa' may be typical for some locations in the Alps and their northern foreland (Wallner 1933; Sanders and Rott 2009), as well as for some locations in the Apennines (Golubic et al. 1993). On the British Isles and in Belgium, in contrast, *O. stratum* seems to be rare (cf. Pentecost 1991, 2005; Janssen et al. 1999); overall, however, much more comparative data on the biology of Alpine versus extra-Alpine springs were needed (Rott et al. 2009). Experimental determination of spring limestone formation at three locations in the Eastern Alps indicates rates of about 1–10 mm per year; this is within the range documented for spring/stream-deposited limestones at many locations outside the Alps (cf. Pentecost 2005; Sanders et al. 2006b).

Deposystems

There are no sharp limits between the described types of deposystems; each deposystem may rather be considered an 'empiric end member' in a continuum. This reflects the prevalence of physico-chemical processes in controlling saturation state and precipitation (see above). As a consequence, the initial morphology of the substrate a limestone-depositing spring creek descends influences the ensuing architecture of the deposystem. The lateral scale of deposystems, of course, is quite variable (cf. Table 2). Some of the fossil systems in the central Alps as well as some foreland-type systems (Fig. 6d, e) are distinguished by large size; the other systems, however, may range from small to large in extent (with corresponding smaller-scale

Fig. 6 Spring-associated limestone deposystems typical for the Eastern Alps. See text for description and discussion



variability in large systems). Waterfall/creek deposystems as well as hillslope-paludal and moss-tufa systems, respectively, are widespread in hilly terrains outside the Alps, too (see Ford and Pedley 1996). Because of their steep inclination and size of up to about 1 km, the large fossil waterfall/creek systems of the central Alps (Fig. 6d)

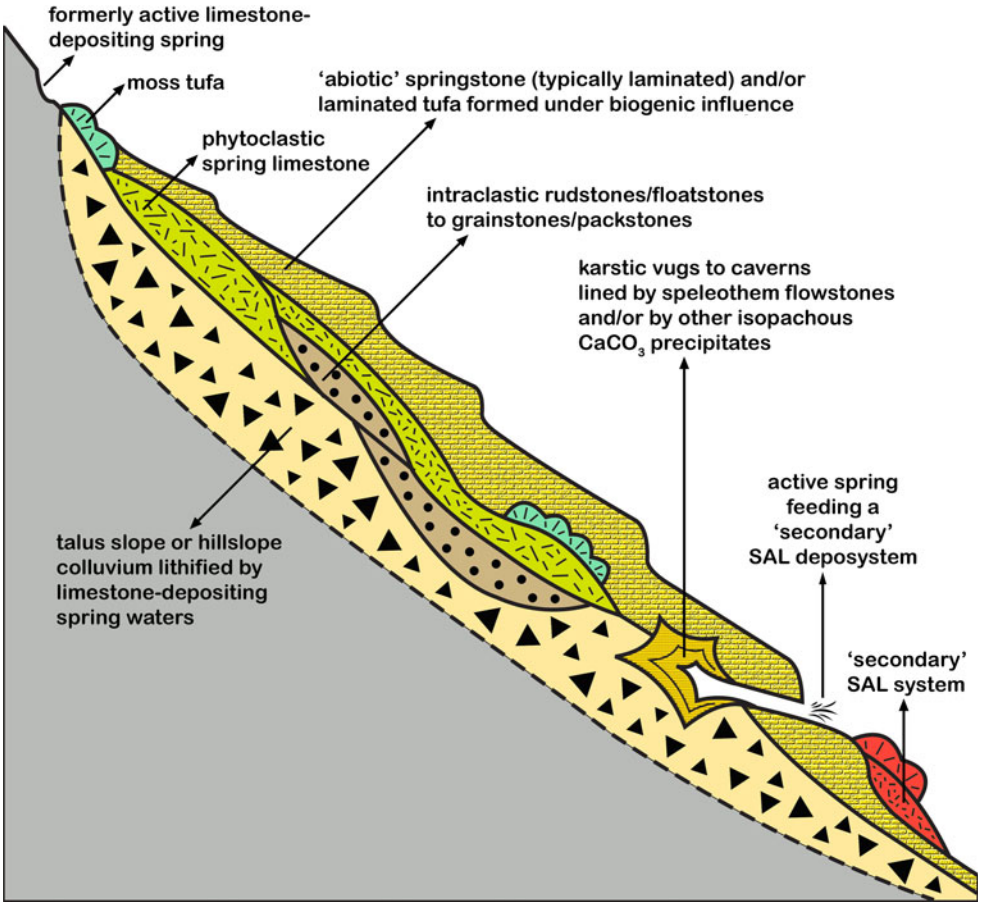


Fig. 7 Schematic section of a typical fossil spring-limestone deposystem situated on metamorphic rock terrains, within and in the frame zone of large tectonic windows (Tauern Window, Engadine Window; Fig. 1) of the central Alps. These systems may be up to more than a kilometer in length. Today, in the Eastern Alps, no active systems of comparable size are known to us. Upon emergence, groundwaters percolated through spring limestone-covered mountain flanks may locally give rise to much smaller, 'secondary' spring-limestone systems (*indicated red*)

may be considered characteristic of mountain flanks; in addition, these systems typically are associated with intervals of breccias of talus slopes and/or of hillslope colluvium that are rare in the other systems. The fact that the Eastern Alps do not show a SAL deposystem that is uniquely 'montane', or strictly confined to a mountain range such as the Alps, is explained by the small extent of the deposystems relative to the typical scale of landscape elements such as the length, inclination, and height of hillslopes.

Spring limestones versus altitude and mean annual temperature

Compilations of age-dated SAL of European regions outside the Alps show that spring limestones form mainly during interglacials; during glacials, spring activity was restricted by permafrost resulting in decrease of limestone formation (Hennig et al. 1983; Baker et al. 1993; Frank et al. 2000). During dry interludes, even during interglacials, however, SAL deposition is limited, too (Baker et al. 1993; Zak et al. 2002). Yet in more detail, the data of Hennig et al. (1983) record notably persistent SAL deposition: over the entire marine isotope stage (MIS) 6, the total number of active limestone springs dropped only to some 50% of the preceding, warmer MIS 7; even during the Riss pleniglacial, some limestone springs remained active (see Pentecost 2005, his fig. 79). Thus, even during cold climatic phases, such as MIS 5.3, intermittent SAL deposition may have been possible by short interruptions of permafrost (Frank et al. 2000).

In the Western Alps, on NE- to NW-exposed slopes, continuous permafrost may be present above roughly 2,600 m a.s.l.; conversely, on South-facing slopes, continuous permafrost starts at about 3,000 m a.s.l. (Nötzli and Gruber 2005). In the Eastern Alps, no permafrost monitoring as in Switzerland exists (see www.permos.ch), but similar altitudes for onset of continuous permafrost most probably apply also for the Eastern Alps; *discontinuous* permafrost, however, may reach down to about 2,400 m a. s. l. or even less, depending on site-specific factors (K. Krainer pers. comm.; see also Nötzli and Gruber 2005). The altitude distribution of Eastern-Alpine SAL deposits up to 2,520 m a.s.l. (Fig. 8) indicates that, for all locations below the *continuous* permafrost height, SAL deposition is not primarily coupled with mean annual temperature. The vertical distribution of Alpine SAL rather indicates that water supply and chemistry are the overriding controls.

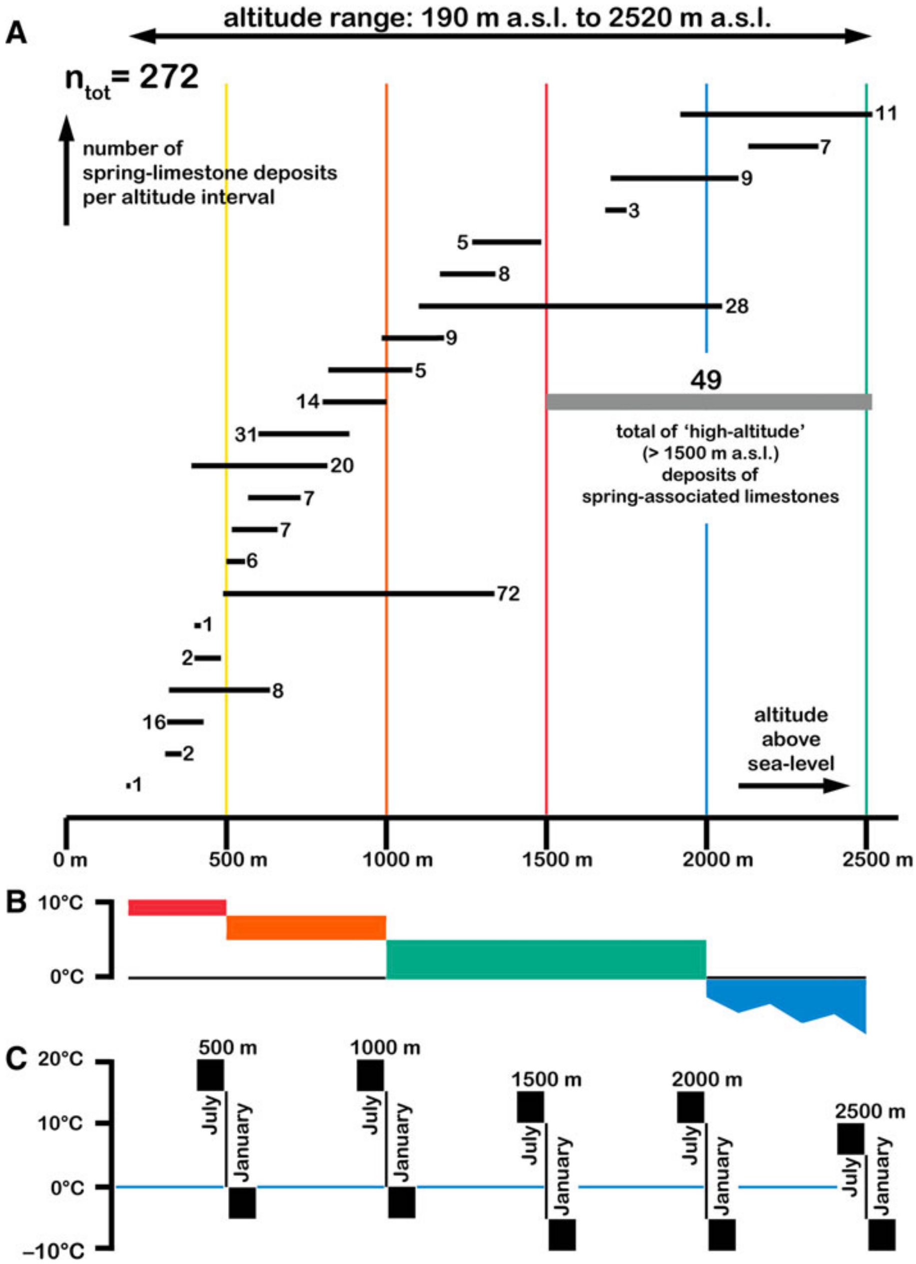


Fig. 8 Spring limestone deposits versus altitude. **a** Compilation of altitude range of 272 spring limestone deposits in the Eastern Alps, including fossil and active deposits. **b** Range of mean annual temperatures (1901–1950) in 500-m altitude increments (from Steinhauser and Nowak 1963). **c** Mean annual temperature range (1931–1960) in the western eastern Alps, with maximum-minimum values indicated for January and July (from Fliri 1980). See text for discussion

On the Tibetan Plateau, Zhang and Li (2002) found a warm-spring limestone deposit dated to about 20 ka BP, when the mean annual air temperature for the region is estimated between −1 and −3°C. In view of our results from the Eastern Alps, this is not exceptional. For periglacial areas, the broad correlation of SAL deposition with interglacials may chiefly result from more efficient water cycling (as typical for European interglacials) and less so from warmer climatic conditions.

In tropical Australia, fluvial tufas tended to accumulate during glacials, when monsoon was attenuated and water supply lowered; conversely, during interglacials, as a result of intensified monsoon and increased runoff and dilution of stream waters, the tufas typically became eroded (Carthew et al. 2003, 2006). In other low-latitude regions where SAL deposition may be considered 'water-limited', deposition increased during pluvial phases associated with glacials, and decreased or ceased upon drier interglacial conditions (e.g., Szabo 1990; Crombie et al. 1997; Auler and Smart 2001). On a south-facing slope (between 900 and ca. 1,300 m a.s.l., Sonnenberg, Italy) that is among the peak warmest and driest places of the entire Alps, with an annual precipitation comparable to some locations in Sicily, Spötl et al. (2002) had determined a seasonal gauge of limestone-precipitating spring on a thinly overrun, sunlit waterfall (ca. 1,000 m a.s.l.) between +6 and +29°C; such high summer water temperatures clearly favor limestone precipitation. Many other active SAL deposits of the

Table 6 Common taxa involved in $CaCO_3$ precipitation in Eastern-Alpine spring creeks

High-level taxon	Genus, species	Products	Remarks
Desmidiaceae (Chlorophyta)	*Oocardium stratum*	'*Oocardium* tufa' (laminated tufa limestone)	Builds significant to prevalent portion of some SAL deposits; is rare to absent in others
Cyanobacteria	*Rivularia*	*Rivularia* calcified in variable intensity	Widespread, but subordinate in abundance
	Scytonema	*Scytonema* bafflestone (faintly laminated micropel grsts)	Common at some locations in specific sites (e.g., pool rims, waterfalls)
Bacillariophyceae	Diatoms (e.g., *Navicula*, *Meridion*, *Gomphonema*)	Microsparitic to sparitic calcite crystals, (micro)sparitic crusts	Diatoms may calcify mainly during cold season
Bryophyta	*Palustriella commutata*, *Eucladium verticillatum*, and other, less widespread taxa	Moss tufa	Minor amount of moss tufa is common, but moss-tufa systems are relatively rare
Xanthophyceae	*Vaucheria*	'*Vaucheria* tufa'	Common, but does not comprise major portion of SAL deposits

Eastern Alps, however, are situated in persistently cooler locations, such as in dense forest, or on very steep north-facing mountain flanks or on low-lit, north- to east-facing cliffs within canyons. At Sonnenberg, Spötl et al. (2002) had U/Th-dated fourteen samples of speleothems from six sites. Most of the ages fell into the early to middle Holocene, but three late Holocene ages also were determined. Because the U/Th ages showed some fit with glacial advances in the Alps, and because post-glacial alluvial fans along the southern slope of Sonnenberg are abandoned and vegetated, Spötl et al. (2002) suggested that increased deposition of speleothems and, by inference, of spring limestones coincided with phases of more humid climate. For the comparatively extreme, semi-arid setting of Sonnenberg where deposition of speleothems and spring limestones may be considered as 'water-limited', this is feasible. For many other locations in the Alps, however, a correlation at least of SAL deposition with precipitation seems doubtful; many springs may become too dilute upon an increase in precipitation, such that limestone deposition ceases. For instance, on limestone terrains of the British Isles, the chemistry of a statistically significant number of springs showed a *negative* correlation between spring discharge and, both, calcite saturation and pH (Pentecost 1992). With respect to the Alps, deposition of spring limestones controlled mainly by a balance, within a 'spring-limestone window', between water supply and chemistry is consistent with, both, the altitude distribution of SAL in the Eastern Alps and glacial-interglacial accumulation patterns in European periglacial areas.

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