A review of Slovak travertine and tufa facies and their environment

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Abstract: Eighty principal Slovak travertines, tufas and lacustrine/palustrine limestones were studied in terms of facies and their environment. Travertines are most frequently formed on spring mounds and less fissure ridges with the alternation of crystalline crust and microphyte beds in different proportion. Macrophyte tufas were abundant in valley dams and on perched springline deposits often with accompanied microphytes. Crystalline crust facies on fixed substrate are represented by crystalline crust travertines with fan- to feather-like, laminated fan, and banded palisade crystals, radiating dendrites, rafts, and coated bubbles. Microphyte facies on fixed substrate occur in the forms of microbial mats, cruststones and shrubs. Abundant macrophyte tufas contain coated moss and vascular plant remnants. Gastropoda, ostracoda and caddisfly larvae cases were identified. Granular facies of abiotic/biotic origin are developed in lime-mudstone facies, coated grain travertine facies, and intraclast facies of diverse origin.

Key words:fresh-water limestones, Western Carpathians texture, crystalline crust, microphyte, macrophyte

1. INTRODUCTION

Slovakia is rich in fresh-water carbonates, especially in travertines and tufas. According to list of Kovanda (1971), travertines are situated on about 70 sites and tufas on about 400 localities. Many travertines were used as ornamental or building stones, the most important in Slovakia. Substantial white Spiš travertine and several others can be visible on public buildings in all Slovak towns, where excellent facies are presented.

Travertines and tufas, a type of freshwater limestones, have been intensively studied recently worldwide. They are deposited in many continental environments, mainly near mineral springs and in streams. Travertines are formed from the degassing of CO_2 rich groundwater containing >2 mol.l^{-1} Ca (Pentecost, 2005). Carbon dioxide is lost from solution at water/atmosphere interface if CO_2 concentration in atmosphere is lower than in the water solution or the most important due to high flow velocity, water agitation or turbulence. Biogenic travertines and tufas were formed due to photosynthesis-induced $CaCO_3$ precipitation, acidity of cyanobacterial extracellular polymeric substances (EPS), and non-calcifying cyanobacteria possessing non-acidic EPS contributed to the trapping/binding of suspended particles (Shiraishi et al., 2019, 2020).

$$Ca^{2+} + 2(HCO_3)^- = \downarrow CaCO_3 + \uparrow CO_2 + H_2O \qquad [1]$$

Travertine and tufa deposition is dependent on groundwater capacity for rock weathering and incorporation of Ca and bicarbonate ions (Rodríguez-Berriguete et al., 2012; Rodríguez-Berriguete & Alonso-Zarza, 2019) by the reverse process as in reaction [1]. The most usual sources of underground CO_2 capable to dissolve carbonate rocks are soils (meteogene source; e.g, Ford & Williams, 2007; Fairchild & Baker, 2012) and deep thermal waters (thermogene source; Pentecost & Viles, 1994; Capezzuoli et al., 2014; Pentecost, 2005). The CO_2 evasion to the atmosphere is often accompanied by additional CO_2 loss due to photosynthesis of aquatic plants and evaporation (Pentecost & Coletta, 2007).

Travertines (thermogene travertines *sensu* Pentecost, 2005) are located near springs and fed with deeply circulating thermal waters, generally over 30°C, ascending along tectonic faults (Gandin & Capezzuoli, 2008; Capezzuoli et al., 2014). The waters associated to travertines are chiefly characterized by very high HCO_3^- content (>7 mmol.l^{-1}). Travertines are typical by high depositional rates, regular bedding, low porosity (<30 %), an inorganic crystalline and organic microbialite fabric. *Tufas* (meteogene travertines *sensu* Pentecost & Viles, 1994; Pentecost, 2005; *pěnovce* in Czech*; Ložek, 1963; penovce* in Slovak) are typically produced under ambient temperature, with high HCO_3^- content (<6 mmol.l^{-1}) in groundwater, and from water of karstic areas. They are characterized by relatively low depositional rate producing highly porous bodies (>40 %) with poor bedding but containing abundant remains of microphytes and macrophytes. Tufas can form a distal travertine continuation.

Slovakia as a mountainous country belongs to the Western Carpathians and partly to the Pannonian Basin, which are northeastern portion of the Alpine Orogeny Belt. The internal part of the Western Carpathians is built by nappe stack, which is represented by thick-skinned tectonic units (*Tatricum, Veporicum,* and *Gemericum*, respectively) covered by thin-skinned nappe system (e.g., *Fatricum*, *Hronicum*, and *Meliaticum* related tectonic units). The thin-skinned nappe pile is composed of predominantly Mesozoic variable carbonate rocks, which are the source rocks for carbonate rich waters to freshwater limestone formation. During the Palaeogene, the nappe stack was covered by marine flysch sediments in the north. Horst and graben system in the internal zones of the Western Carpathians was the results of the Neogene strike-slip to extensional tectonic regime in which volcanic products covered the earlier tectonic units, especially in central Slovakia (Hók et al., 2019). The modern relief formation relates to the planation of a large part of the Western Carpathians at the Miocene/Pliocene boundary. It was the beginning of the dome morphostructure formation before 4 to 6 Ma with the main stage of the uplift to the Late Pliocene. The last, more active stage started in the Middle Pleistocene (Minár et al., 2011).

In the presented tectonic pattern, the freshwater limestones including travertines were originated from the deep circulating mineral waters through the Mesozoic carbonates, which are

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lying under the impermeable Palaeogene or Neogene siliciclastic or volcanic deposits (Ložek, 1992; Fordinál & Nagy, 1997; Gradziński et al., 2015). Some travertines and tufas are formed recently. The Mesozoic carbonates produce Ca-Mg-HCO_3 waters such as in Hozelec. Some nappe sequences also contain Mesozoic and Permian gypsum and anhydrite evaporites generating transient Ca-Mg-HCO_3-(SO_4) waters such as in Vyhne and Hôrka, Ca-Mg-HCO_3-SO_4 waters such as in Vyšné Ružbachy, Liptovský Ján, Vyšný Sliač, Stankovany, and Bešeňová, Ca-Mg-SO_4-HCO_3 waters as in Lúčky, Sliač, and Sklené Teplice. An increased amount of Na and Cl indicates mixed waters with relic marine water contribution. The Na-Ca-HCO_3-CI waters come from Dudince, Santovka, and Slatina, Ca-(Mg-Na)-HCO_3-(SO_4-CI) from Sivá Brada, and Ca-(Mg-Na)-HCO_3 from Čerín (cf. Franko & Melioris, 1999).

In the paper, the principal Slovak travertine and tufa localities were studied. Previous knowledge was summarized, and extensive set of new information was added in the light of modern research on facies and environment with the basis for further detailed investigations. The paper follows a study of Slovak travertine and tufa forms and ages (Pivko & Vojtko, 2021). Figures in the text are extended by supplementary figures.

2. PREVIOUS KNOWLEDGE

Travertine facies, environment and morphology in which travertines were formed were described in many papers. Facial analyses of travertines in a hydrothermal system began to emerge in Italian localities in the 1990s. Guo & Riding (1998) allocated the following facies: crystalline crust, shrub travertine, pisoid travertine, paper-thin rafts, lithoclast, reed travertine, palaeosol and coated bubble travertine. The very similar facies were presented on the basis of Turkish travertines (Özkul et al., 2002). Pentecost & Viles (1994) and Pentecost (2005) discussed in more detail calcite fabric of individual facies. Rainey & Jones (2009) more precisely resolve feather and radiating dendrite facies. Jones & Renaut (2010) in the monography chapter point to common facies in calcareous spring deposits including plant, insect, shrub, coated grain, stalactite, lithoclastic–bioclastic, micritic, raft, coated bubble, and crystalline tufa or travertine. The most detail and comprehensible paper about travertine facies is Gandin & Capezzuoli (2014). Except for summary of previous knowledge, they define, e.g., tree types of crystaline crusts, microbial mats and laminites. Biotic shrub facies were elaborated to six morphological types (Erthal et al., 2017).

Classical paper of tufa facies (Pedley, 1990) recognises the following five types: perched spring line, cascade, fluviatile, paludal, and lacustrine facies. Previous knowledge of fluvial, lacustrine and palustrine facies was concisely summarized in 'Carbonates in continental settings' book (Arenas-Abad et al., 2010, Alonso-Zarza & Wright, 2010, Gierlowski-Kordesch, 2010). Fluvial tufa facies in river systems are controlled by karstic spring inputs, river slopes, morphology, water flow conditions, and seasonal changes (Arenas et al., 2014, Oste et al., 2021). Travertine and tufa facies were found also in volcanic area (Rodríguez-Berriguete et al., 2012; Rodríguez-Berriguete & Alonso-Zarza, 2019).

Ivan (1943, 1952) described ca. 50 Slovak travertine localities among which are included occurrences presently considered as tufa and lacustrine/palustrine limestones. Zýka & Vtělenský (1960) defined 15 structural types of travertines and tufa without their genesis. Their simple description without pictures was based on shape and size of crystals, grains and pores. Ložek (1963) and mainly Kovanda (1971) provides the most detailed description of fresh-water carbonates in Czechoslovakia and comprehensive list of references. The monography defined travertine and tufa facies as 'pramenit' in Czech (loosely translated as spring rock), basal facies, crater facies, tufa travertine, tufa and alm facies. Freshwater limestones from Slovakia were briefly commented in a review of Mišík & Reháková (2009).

Some important Slovak travertine and tufa localities have been recently studied by Polish geologists (Gradziński et al., 2008, 2013, 2014, 2015; Wróblewski et al. 2010). They defined some facies in Spiš travertine of Dreveník, such as crystalline crust, lithoclast travertine, paper-thin rafts travertine and coated bubble travertine. The deposition of lithoclast travertine, as well as origin of its deformation is interpreted as a result of seismic shocks. Moss, stromatolitic, phytoclastic, oncoidal, intraclastic tufas and colluvial breccia were identified in tufa localities from Slovenský kras Mts.

The present study describes and explains 20 basic facies of more than 50 Slovak travertines and tufas in the light of new knowledge of fresh-water limestones and their environments (Figs. 1, 2). This first summary can be a starting point for more detailed studies.

3. METHODS

The author of the paper studied Slovak travertines in detail for 20 years especially from the view as building/decorative stones. The detailed study of important travertine/tufa (37), tufa (29) and lacustrine/palustrine limestone (14) localities in Slovakia (Fig. 1) has been conducted in the last 5 years. Selected sites are important in terms of a preservation of forms and facies, so many of them are protected. Field research was focused on recent and fossil facies and environments which were observed macroscopically and by magnifying glass from 2x to 30x. The most studied site was Dreveník coalesced mound and surrounding mounds, being substantial travertine sites in Slovakia. The observations of 10 recent travertines took place in warm and cold months, when the temperature was even below 0° C to see changes depending the seasons. Taken samples were studied by optical microscope and USB microscope with a magnification to 300x. Many structures in travertines are very difficult to observe with the naked eye due to their very similar shade. If images were darkened and contrasted, many structures have become visible.

Recent facies were compared with fossil travertine and tufa in natural outcrops, quarry faces and building cladding, where structures and textures were cut both in vertical and horizontal directions. Cut travertine tiles offer excellent examples and enable understanding of facies, even already exhausted in the quarries. The data of fresh-water limestones in Kovanda (1971) and Ivan (1943, 1952) were studied to identify the most preserved localities and the terminology used by them was transformed to the recently valid one. The transformed information was compared with results of field study and with the modern descriptions (Gradziński et al., 2008, 2013, 2014, 2015; Wróblewski et al. 2010). The database of travertine and tufa samples, images of facies and environments were developed, in which mutual relations and similarities were searched. The classification into individual facies and environments was mostly based on Gandin & Capezzuoli (2014), Capezzuoli et al. (2014) and Pentecost (2005).

4. DEPOSITIONAL FACIES

In recent decades, the fresh-water limestone facies have been described together with their genesis (e.g., Guo & Riding, 1998; Pentecost, 2005; Jones & Renaut, 2010; Özkul et al. 2014; Gandin & Capezzuoli 2014). Some travertine facies are formed by abiogenic physical-chemical precipitation and the others by the precipitation with the participation of living organisms. Thermal water travertines are usually composed of bedded travertines with crystalline crust and microphyte alternation (Dreveník; Fig. 3). The beds could be formed by abiotic or biotic facies (Fig. 3, Appendix 1).

Deposited travertines and tufas were exposed to syngenetic or early diagenetic processes, comprising: sparmicritization in the crystalline facies; cementation well-developed in the granular facies and more incomplete within the microbialites; shrinkage and soft sediment deformations in

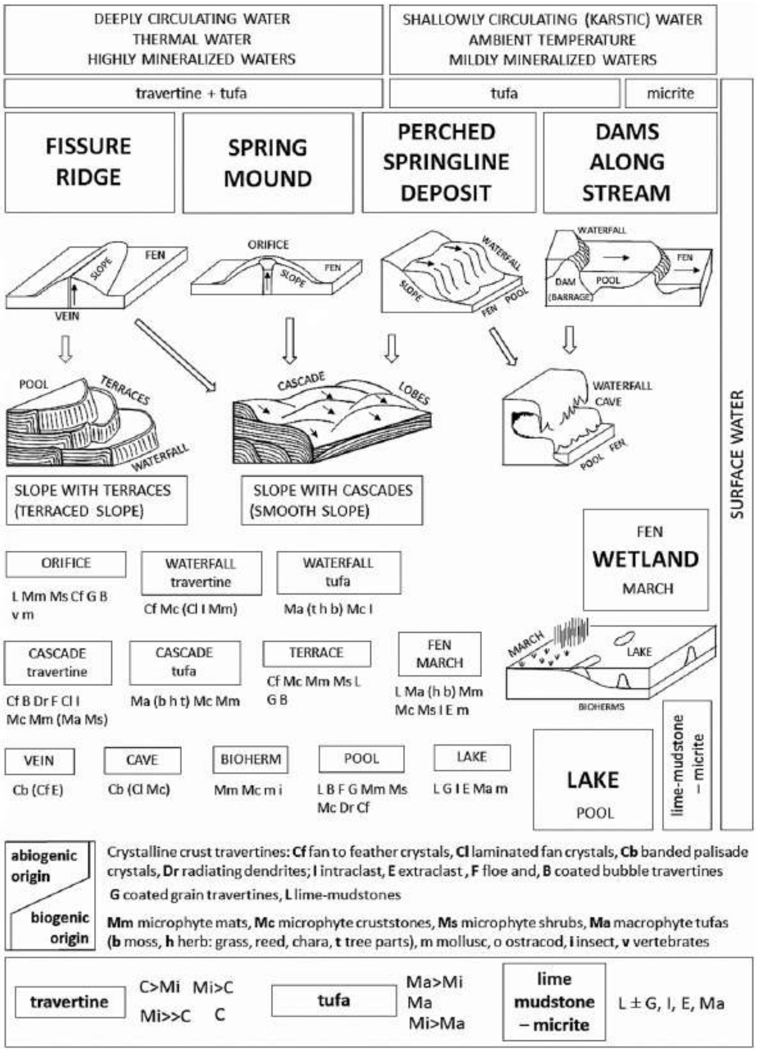


Fig. 2. Relations of forms, environments and facies of tufa and travertine deposits in Slovakia.

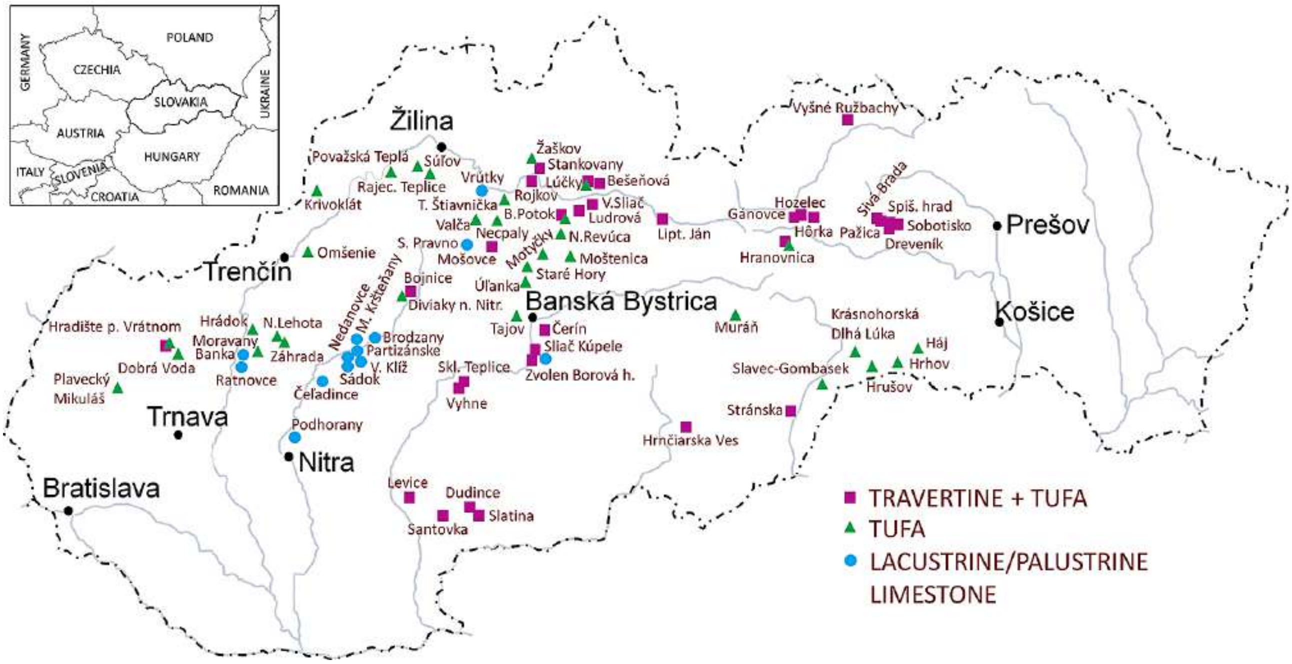


Fig. 1. The map of the most important freshwater limestones in Slovakia. Selected localities are important due to a preservation of forms and facies.

lime-mudstone facies; and pedogenetic modification of silty mudstones. Post-depositional processes comprise fracturing of the brittle travertine crusts by desiccation or block movements and karstic processes (Gandin & Capezzuoli, 2014).

Depositional facies are genetically linked to spring water chemistry and precipitates, to the environment and topographic features present in the area of deposition (Fig. 2), for the mentioned reasons the facies were divided to three subchapters according to fixed substrate or loose particles, abiotic or biotic origin.

4.1. Crystalline crust facies on fixed substrate

The dominant crystalline lithofacies, consisted of aggregates of well-packed calcite crystals, are represented by fan to feather crystals precipitated in the environment near mineral water springs and banded palisade crystals typical for undersurface vent conduits (Gandin & Capezzouli, 2014; Jones & Renaut, 2010; Guo & Riding, 1998; Folk et al., 1985). Less frequent crystalline deposits consist of coated bubbles or of thin calcite rafts (Gandin & Capezzouli, 2014), being developed at the surface of stagnant waters.

4.1.1. Crystalline crust facies with fan to feather crystals (Cf), laminated fan crystals (Cl) and radiating dendrites (Dr)

Description: The crystalline crusts were observed in the form of layers with a thickness of a few mm to 15 cm (Fig. 3, Appendix 1) in Slovak travertines. They consist of white calcite sparite crystals in *fan-shaped, shrub-shaped, dendrite-shaped, feather-shaped* or *plume-shaped crystals* (Cf; Fig. 4a-d, i-o, Appendix 2). There is a continuum between different crystal shapes. Fan-like crystal were described from Dreveník (Gradziński et al., 2013). The crystals are often very delicate, hardly visible by naked eye (Appendix 2i-j). Fan-like and dendrite-like crystals are related to mound and fissure ridge slopes, waterfall rollovers (Spišský hrad), cascades on the slopes and microterracettes on them. The crystals grow usually perpendicular to beds. If they are part of microterracette rims, their course can go also obliquely to beds and can be crooked (Appendix 2n,o). Feather-like crystals were exceptionally developed in fissure ridge veins (Dreveník Peklo) (Fig. 4o).

Fan-like crystals can be highlighted by laminae perpendicular to crystals (Cl; Fig. 4p,q, Appendix 3). These beds have range between a few and 30 cm (Dreveník; Fig. 3, Appendix 1). *Laminated fan crystals* grew in syntaxial continuity. Sharp or gradual transitions (Appendix 3a-b) were presented from fan crystals to fan-laminated crystals. Laminae can be rarely connected with feather-shaped crystals (Fig. 4q). Laminae are sometimes undulated and are visually more noticeable than fan crystals (Ostrá hora) (Appendix 3f). The thickness of individual laminae is mostly about 1 mm. Tooth-like shrubs with fan-like and laminated fan-like crystals occur along channels with thermal water in Dudince and Santovka (Appendix 3m-v).

In microterracette pools, *radiating dendrites* (Dr) are recently developed (Rainey & Jones, 2009; radial pisoids according to Guo & Riding, 1998). Their spherical and sub-spherical shape is up to a few mm in size. They are covered by branching calcite crystals that radiates from nucleus (Fig. 4r,s, Appendix 4).

Interpretation: Feather-like, dendrolitic crystals were well described by Gandin & Capezzuoli (2014 and references therein) and Slovak crystalline crusts also correspond to them. In present travertine systems, the feather-like crystalline crusts precipitate directly from very thin sheets of very high supersaturated water running on variably steep surfaces, with smooth, laminar flow (Guo & Riding, 1998, 1999; Gandin & Capezzuoli, 2008). Dendritic, fan crystals are influenced by mineral habit, but some portion of bacterial influence at crystallization is possible (Chafetz & Guidry 1999, Jones & Renaut 1995, Jones 2017). Tooth-like shrubs in Dudince and Santovka (Appendix 3u-v) display mineral habit influenced by cyanobacteria filament growth. Microbially influenced shrub crystals are described in Microphyte shrub chapter.

Smooth transitions exist between fan and dendritic crystal crusts on one side and radiating dendrites on the other (Rainey & Jones, 2009). The radiating dendrites often bind and grow into massive calcite crust (Appendix 4p,t-w). Fan crystals (crystal shrubs) and fan-laminated crystals (ray-crystal crust) were formed in very high supersaturated environments of abiotic

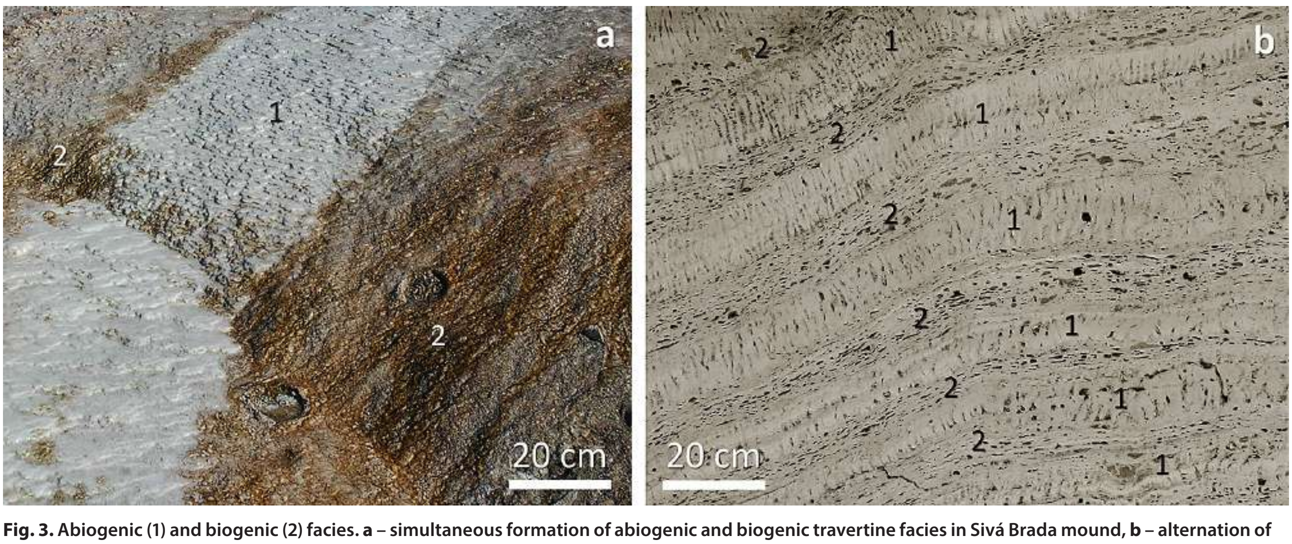


Fig. 3. Abiogenic (1) and biogenic (2) facies. **a** – simultaneous formation of abiogenic and biogenic travertine facies in Sivá Brada mound, **b** – alternation of abiogenic and biogenic layers in Spiš travertine.

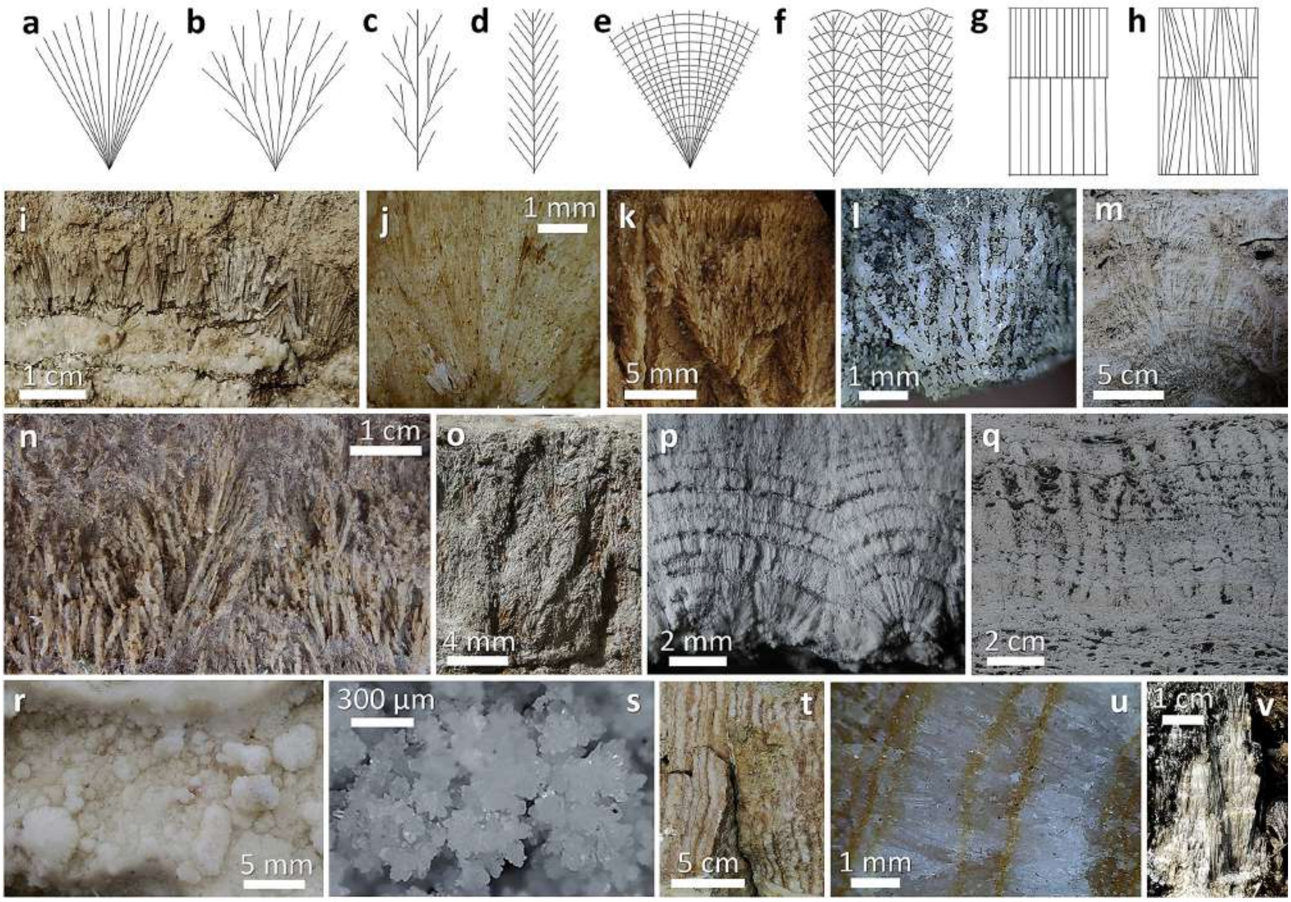


Fig. 4. Calcite crystal shapes in travertine crystalline crusts and veins. a – fan-shaped, b – shrub-shaped, c – tree-shaped (dendrite), d – feather-shaped, e – laminated fan-shaped, f – laminated feather-shaped, g – palisade-shaped, h – opposite fan-shaped, i – calcite fans in Dudince Porošin, j – calcite fan in Levice Gold Onyx, k – calcite shrub in Levice Gold Onyx, l – calcite shrubs in Levice Vápnik, m, n – calcite trees (dendrites) in Spiš travertine, o – calcite feathers in Dreveník, p – laminated fans in Ostrá hora, q – laminated feathers in Spiš travertine, r – radiating dendrite creation in recent microterracettes of Sivá Brada, s – calcite shrubs on radiating dendrite surface in Hozelec, t – vein composed of banded travertine with palisade crystals in Levice Vápnik, u – banded travertine with palisade and opposite fan crystals in Levice Gold Onyx, and v – opposite fan crystals in Dudince Porošin.

precipitation (Chafetz & Guidry, 1999), but fan-laminated crystal require faster water flow, greater spring yield (cf. Gandin & Capezzuoli 2014). Such environment is not present in recent Slovak travertines.

4.1.2. Crystalline crust facies with banded palisade crystals (Cb)

Description: Vertical, sub-vertical or rarely subhorizontal veins with onyx-like banded carbonates were studied in Dreveník, Levice, Santovka and Dudince. They consist of juxtaposed vertical sheets of closely packed palisade columnar or radiating acicular crystals in syntaxial continuity, perpendicular to the fracture walls (*sensu* Gandin & Capezzuoli, 2014; Altunel & Hancock, 1996; Gradziński et al., 2014; Brogi et al., 2014). The calcite crystals commonly form alternating bands of limpid and rusty-red stained crystals (Fig. 4t, Appendix 5a,b). The crystals are parallel and perpendicular to bands (Fig. 4g,t) or in the shape of opposite fans (Fig. 4h,v, Appendix 5e,f). The mentioned types often occur together inside one bed (Fig. 4u, Appendix 5c,d). Crystalline crust with banded palisade crystal beds was identified in travertine mound slope in Dudince Porošin (Fig. 4v). Vertical vein with extraclasts from travertine basement were identified in Spiš travertine. Speleothems (Cs; cf. Gradziński et al., 2014, 2018) with dominant banded palisade crystals are very abundant in Dreveník travertine (Appendix 4l-t) and occur in many older travertines and in caves under overhangs of tufas.

Interpretation: The banded palisade crystals occurs as vertically formed bands, veins that fill fractures and represent the undersurface conduits that fed open fissure springs (Altunel & Hancock 1996). In Dreveník site, intact, unchanged veins are rare for later dissolution and newly formed speleothems along fractures. It is sometimes difficult to distinguish between conduit vent or speleothems. The veins have usually sharp straight contacts with fissure ridge travertines and their banding used to be vertical and straight (Appendix 5a), but the speleothems deposited on corroded irregular travertines with typically botryoid shapes (Appendix 5l,q). The veins (sills) can be rarely with subhorizontal course, parallel to a bedding (Appendix 5g-k). They are a result of overpressured hydrothermal fluids that caused subhorizontal hydrofractures filled with sheeted calcite veins grown from both sides. Subhorizontal veins have been described for other travertines by several researchers (Brogi et al., 2017; Gradzinski et al., 2014; Rimondi et al. 2016).

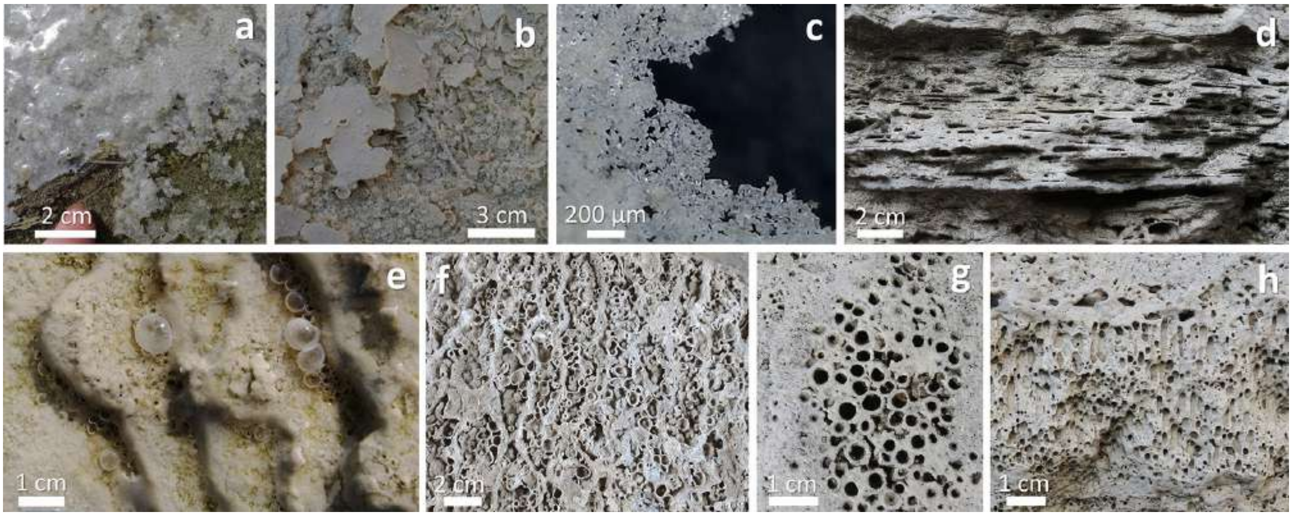


Fig. 5. Raft (floe) and coated bubble facies. **a** – thin calcite cover and rafts on pool surface in Stankovany Močiar, **b** – calcite rafts and coated bubbles in dry pool in Sivá Brada, **c** – calcite crystals of raft edge in Bešeňová, **d** – thin layers of raft origin in Spiš travertine, **e** – microterracettes with coated bubbles formation in Sivá Brada, **f** – microterracettes with coated bubbles in Gánovce travertine, **g** – microterracette with coated bubbles in Spiš travertine, and **h** – set of vertical coated bubbles in Spiš travertine.

4.1.3. Raft facies (R)

Description: Travertine rafts (Gandin & Capezzuoli, 2014; Folk et al., 1985) or floes (Pentecost 2005) are very thin pieces of calcite crystalline crusts (from 1 mm to some mm) precipitated on calm water surface (Fig. 5a-d, Appendix 6). Recent rafts with possible bubbles are developed near spring orifices especially during cold dry weather (Fig. 5a, Appendix 6a,d,k). The raft is composed of microsparite crystals (Fig. 5c, Appendix 6i). In Dreveník locality, the calcite rafts are frequently developed in narrow fractures (Appendix 6p,q).

Interpretation: Calcite sheet is formed at water–air interface of still-water ponds by evaporating and cooling of supersaturated water, frequently sheltering gas bubbles. The cover is commonly broken to rafts by the movement of the water surface caused by currents, when increasing spring discharge can destroy crystalline crust on water surface. The bubbles accumulating under thin crystalline crust can also broke it to pieces (Fig. 5b, Appendix 6b,d-h,j) by pressure of individual increasing bubbles (Appendix 6c). Another way of breaking is wind or frost. Very thin crust can be plastically deformed by flow to tiny wrinkles, folds (Appendix 6k-m), which reminds the formation of rope (pahoehoe) lava or folded protein film on boiled milk. The rafts may be enveloped by microbial coatings which are linked to microbial laminite travertine (Appendix 6h,j).

4.1.4. Coated bubble facies (B)

Description: Coated bubble travertine or foam rock consists of aggregates of lithified gas bubbles (Jones & Renaut, 2010) arranged in subvertical, closely fitted pipes constricted at regular intervals (Gandin & Capezzuoli, 2014) or covered individual bubbles are also present (Fig. 5e-g, Appendix 7). Recent coated bubbles are occasionally developed in Sivá Brada, Hozelec and Bešeňová (Fig. 5e, Appendix 7a-h). Recent and fossil bubbles are covered with sparite to microsparite calcite crystals (Appendix 7e-h). Subvertical bubbles were identified in the Pliocene travertines from Dreveník and Levice (Fig. 5h, Appendix 7l,m).

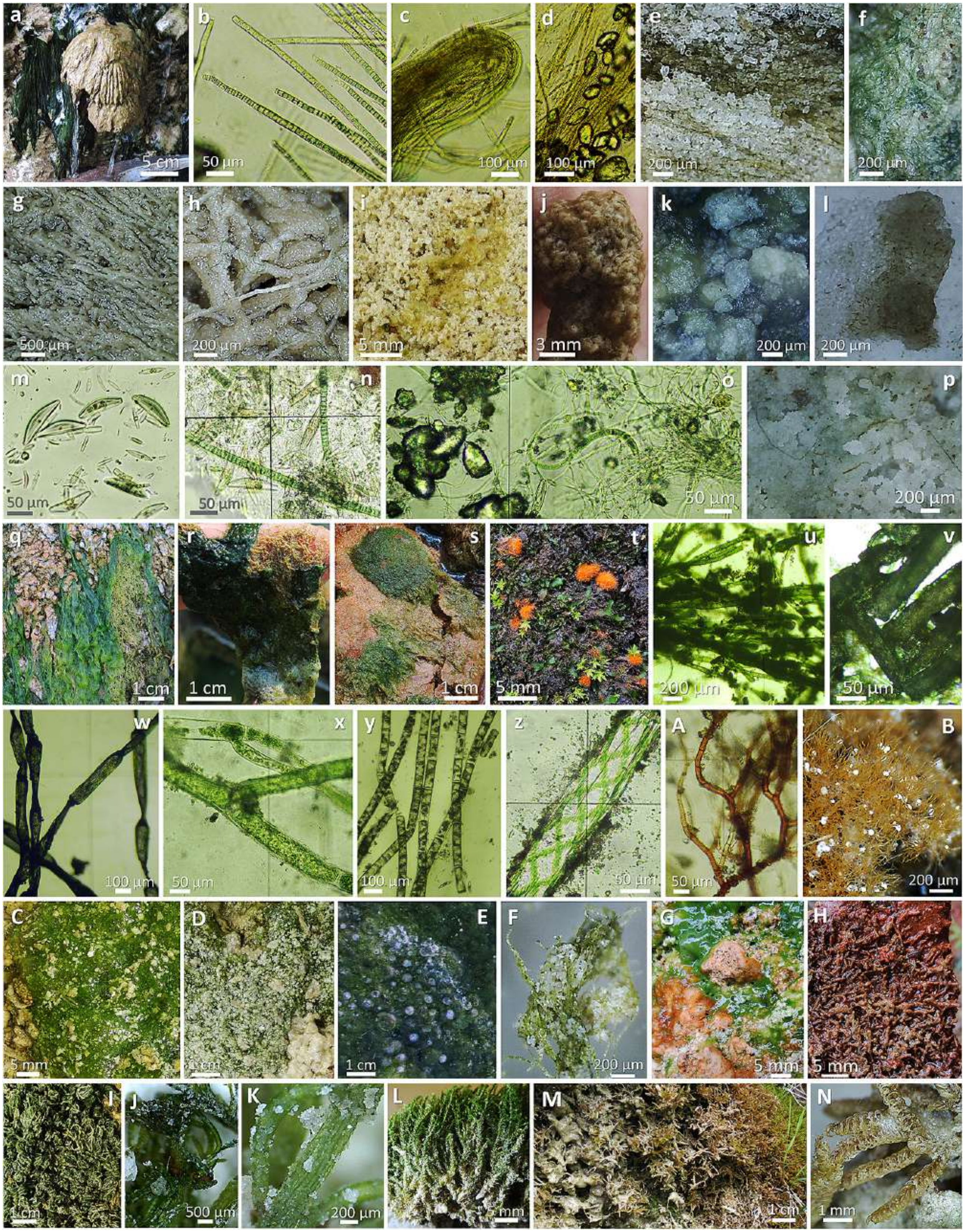
Interpretation: The coated bubble travertine with vertically stretched bubbles or better gas escape structures were formed near thermal springs on the bottom of shallow ponds where the carbonate film envelops bubbles. The bubbles are produced by gas discharge from superconcentrated water or originated by

Fig. 6. Organisms and biogenic facies: **a** –cyanobacterial cruststone formation in Krivoklát, **b-e** – filamentous cyanobacteria in Hozelec Banícka (b – cyanobacterial filaments, c – bundle of filaments, d – calcite crystals formed on mucilage EPS of filament bundle, e – calcite cruststone with parallel filaments, **f-h** – calcified filamentous cyanobacteria in Krivoklát (f – coated filaments overgrown with new filaments, g – coated parallel filaments, h – unequally old calcified filament with different diameter), **i-n** – diatom and cyanobacterial EPS in Stankovany Močiar (i – partly calcified bunchy diatom mucilage in pool, j – lumpy calcified diatom mucilage, k – lumpy diatom-cyanobacterial mucilage, l – mucilage with visible brown diatoms, m – diatoms in mucilage, n – diatoms and filamentous cyanobacteria in mucilage), **o-p** – diatom and cyanobacterial mucilage (EPS) with calcite crystals in Hozelec Banícka (o – mucilage with calcite crystals, p – calcite replaced mucilage), **q-r** – partly calcified algal filaments in Vyhne (q – parallel curly filaments changed to calcite mamelons, r – calcified algal net), **s** – partly calcified *Vaucheria* bunches in Hôrka Tarnovský potok brook, **t** – *Trentepohlia* bunches (orange) and bryophytes in Tajov, **u-v** – *Vaucheria* filaments in Lúčky waterfall (u) in Hôrka Tarnovský potok brook (v), **w-x** – *Cladophora* filaments in Motyčky Jelenec, **y-z** – *Spirogyra* filaments in Hozelec meadows (y) and in Vyšné Ružbachy (z), **A-B** – *Trentepohlia* filaments (A – branched filaments in Krivoklát, B – filament with calcite crystals trapped on mucilage), **C-E** – *Spirogyra* filament net in Hozelec meadows (C – early and D – advanced stage of growing calcite crystals in mucilage, E – coated bubbles with calcite inside mucilage), **F** – *Cladophora* filaments with attached calcite crystals in Tajov, **G** – orange calcite mamelons from *Trentepohlia* bunches and green mucilage with *Cosmarium* algae, diatoms and cyanobacterial filaments in Tajov, **H** – calcified *Vaucheria* filaments in Hôrka Tarnovský potok brook, **I-K** – calcite crystals attached to *Chara* stems and branches in Hozelec meadows, **L-M** – gradually calcified moss in Hôrka Tarnovský potok brook (L) and Tajov (M), and **N** – thin coated moss in Tajov.

microbial metabolism or organic decay and are coated by microcrystalline calcite (Chafetz et al., 1991; Gandin & Capezzouli, 2014). The coated bubbles are often the only one component of crystalline crust facies, especially among radiating dendrites or in granular facies.

4.2. Microphyte and macrophyte facies dominantly on fixed substrate

Biogenic facies were mainly formed by calcium bicarbonate precipitation in a connection with organisms (Fig. 6, Appendix



11-18), actively or passively involved in final microphyte deposit (*sensu* Pentecost, 2005). Microphytes (microbialites) are joined with microscopic single cells (coccoid) or colonial filaments of cyanophytes (Fig. 6a-p), heteroconts including diatoms (Fig. 6i-p,s,u,v,H), chlorophytes (Fig. 6t,w,x,A,B,F,G), some charophytes (Fig. 6y,z,C-E,G) and somewhere iron bacteria. The microphytes correspond to bindstone (Embry & Klovan, 1971) containing microbial mats, shrubs (dendrolites) and cruststones (laminites). Macrophyte tufas are formed *in situ* or from macroscopic fragments of charophytes (Fig. 6I-K), bryophytes (Fig. 6L-N) and vascular plants (Appendix 17) as branches and leafs. Macrophyte tufas contain also changeable portion of microphytes.

Cyanobacteria, yellow-green algae, diatoms, chlorophytes and charophytes were observed in recently formed travertines such as Sivá Brada, Hôrka, Hozelec, Vyšné Ružbachy, Bešeňová, Stankovany and Čerín) and tufas such as Lúčky, Hrhov and Háj (Kovanda, 1971; Hindák & Hindáková, 2013, 2014; Hindáková & Hindák, 2015, 2016; Hindáková, 2017, 2018; Gradziński et al., 2015). *Phormidium* or *Microcoleus* filamentous cyanobacteria are present at all sites, forming coatings and clumps of green-blue, grey-green, grey-brown and brown-black colour. *Leptolyngbya* and *Pseudanabaena* (filamentous cyanobacteria), *Vaucheria* (yellow-green algae), *Cladophora, Trentepohlia* and *Chara* (charophytes) are less represented. Many species of pennate diatoms were identified in recent travertine and tufa sites. The most abundant are *Encyonopsis, Achnanthes, Navicula, Cymbella* and *Nitzschia* genera.

Some diatoms, cyanophytes and algae produce a continual secretion of adhesive EPS (*sensu* Chen et al., 2019), which is important during carbonate formation, because represents crystalization cores for carbonate crystals (Fig. 6d,i-p). Some travertines and tufas contain mollusc shells (Kovanda, 1971), ostracod valves (Pipík et al., 2012) and larvae cases (Fig. 8k,w,x, Appendix 18).

4.2.1. Microphyte mat facies (Mm)

Description: Microphyte mat represents (microbial mats *sensu* Gandin & Capezzuoli, 2014) thrombolitic or agglutinated fabrics (Fig. 7k,q,r) made of microbial peloids (coccoid clusters) and filamentous assemblages (cyanophytes, heteroconts, chlorophytes, some charophytes and iron bacteria) arranged in spongy cellular, reticular or vacuolar networks (Fig. 7a,i-r, Appendix 11). Their filaments are intertwined with minimal preferred orientation (Fig. 6f,p). The porous fabrics produce soft, mucilaginous bodies at the bottom of still water shallow pools or large pancake-like rafts with bubbles at the water surface (Fig. 7i-m, Appendix 11a-p). In fossil travertines, the fabric forms irregular beds, eliptic or lenticular bodies irregularly alternated with the other microbial facies (Fig. 7n-p, Appendix 11s-J) or crystalline facies (Fig. 3b, Appendices 1b,c, 11G). Thicker homogenous layers up to several decimetres were identified in very steep slopes of fissure ridges (Dreveník, Ostrá hora; Appendix 10f-k). A vertical transition of homogeneous into microphyte layers can be observed (Ostrá hora; Appendix 10i). and microphyte net can be sometimes visible after surface weathering (Appendix 10k).

Interpretation: Firstly, gas bubbles were entrapped inside filament tangles with EPS. Mats were floating on quiet pool water lightened by bubbles (Fig. 7i, Appendix 11a,b,d,e,n,o). The carbonate crystals gradually coated bubbles and filaments (Fig. 7j, Appendix 11o,p) and finally spongy-like mat sink to the bottom (Fig. 7k, Appendix 11p,q). If the mats were attached to the bottom by EPS or water surface was very low (Fig. 7l,m, Appendix 11c,f-m), a gradual lithification carried out on bottom (Fig. 7l,m, Appendix 11g-j). The soft mats can be crumpled by heavy rainfall or strong wind (Appendix 11i,l). The organisms do not participate in this process actively but act only as a substrate for growing crystals. The microcrystalline carbonate fallout (whitings), previously precipitated in water column, is entrapped by filaments or cohesively fixed by EPS (Fig. 6d,o) and can bury the organic mats, crusts and shrubs (cf. Gandin & Capezzuoli, 2014; Gradziński et al., 2015).

Homogenous thick micrite layers on steep slopes are startling (Ostrá hora, Dreveník; Appendix 10f-k). An adhesion of slurry lime mud to the slopes can be explained by entrapping microsparite and micrite crystals to EPS produced by microbial network of cyanobacteria and algae. Similar process is visible on steep slope of the Tajov waterfall (Fig. 6G). The beds had to be subjected to early lithification. A transition of homogeneous into microphyte layer can supports previous statements (Ostrá hora; Appendix 10i). Microphyte net can be sometimes macroscopically visible after surface weathering (Appendix 10k).

4.2.2. Microphyte cruststone facies (Mc)

Description: Unlike microbial mats, microbial cruststones or laminites (*sensu* Gandin & Capezzuoli, 2014) consists of distinct flat to curled laminae sheets (Fig. 7s-B, Appendices 12, 13). The sheets can be split up by mostly lenticular voids (Fig. 7v,x, Appendix 13a-h,m,q,y,z) to composite structures similar to puff pastry bakery product (Gandin & Capezzuoli, 2014) or similar to cabbage section. Individual filament bundles are separated by oval to lenticular voids from top view (e.g., Fig. 7v,w,y, Appendices 12k,l, 13w) and lenticular or irregular long voids from side view (Fig. 7x, Appendix 13a-d). Trapped bubbles (Appendices 12e,j,n, 13o) and crystalline rafts (Appendix 13k,l) can be part of the cruststones. Bent parallel laminae and voids of convex (Appendix 13i) and concave (Appendix 13j-l) shape are formed in some travertines. Very narrow laminae are rarely developed among laminated fan crystals (Appendix 13E-G). Some cruststones are knoll-shaped almost without voids, similar to marine stromatolites (Fig. 7z, Appendix 13g,p,r-v), rarely with a columnar shape (Appendix 13s). Cruststone knolls can be stacked repeatedly (Appendix 13o,p,D). Microbial cruststones are formed also on dripstones grown on slope lobes or inside waterfalls (Appendices 12r-v, 13A,B). Recent and fossil travertines frequently present transitional types between microbial mats and cruststones (e.g., Appendix 13d,h).

Interpretation: Unlike microbial mats, microbial cruststones are principially formed in flowing water, e.g., in channels or in shallow pools with moving water. The filaments of cyanobacteria or algae are stretched with preferred orientation along the current (Fig. 7s-u,w, Appendix 12a-c). Thin cyanobacteria colonies can be arranged by flowing water to spotty, fibrous or reticulate pattern (Appendix 12l-q), which can be the basis for the cruststone formation. The stretched organic network was gradually reinforced by carbonate precipitation to microphyte film (crust) or some films above each other. Smooth transitions between microbial mats and

Fig. 7. Microphyte mat, cruststone and shrub facies. **a-h** – schematic microphyte facies (a – mat facies, b – cruststone facies, c – narrow dendriform shrub facies, d – wide dendriform shrub facies, e – fili dendriform shrub facies, f – arborescent shrub facies, g – arbustiform shrub facies, h – pustular shrub facies, c-h – improved according Erthal et al. 2017), **i-k** – cyanobacterial mats in shallow pool in Sivá Brada (j – spongy network with bubbles and filaments gradually coated and replaced by calcite, k – the resulting spongy calcite network), **l** – green algae filament mat replaced by calcite in Hozelec Banícka, **m** – cyanobacterial mats impregnated by calcite in Hozelec meadows, **n** – microphyte mat facies with transition to cruststone facies (left) in Spiš travertine, **o** – microphyte mat facies in Santovka, **p** – cruststone (bottom) and mat (top) facies in Klíž travertine, **q, r** – mat facies of microsparite crystals in Klíž travertine, **s** – travertine lobe covered by cyanobacterial net in Hozelec, **t** – current directed cyanobacterial and algal filaments in Hozelec, **u** – current directed cyanobacterial filaments with bubbles in Bešeňová, **v** – current directed microphyte filament network in Sivá Brada, **w** – dry filament network hardened by calcite in Gánovce, **x** – puff pastry-like laminated facies in Dreveník, **y** – horizontal cut of cruststone facies in Spiš travertine related to (v) and (w), **z** – mat (bottom) and cruststone (top) facies in Levice travertine, **A, B** – peloid micrite and microsparite network of cruststone facies in Spiš travertine, **C** – microphyte shrubs partly coated by calcite in Stankovany, **D-F** – wide dendriform shrub facies in Stankovany (D), Santovka (E) and Vrútky (F), **G, H** – narrow dendriform shrub facies in Spiš travertine, **I, J** – fili dendriform shrub facies in Levice travertine (I) and Hranovnica (J), **K, L** – arborescent (K) and arbustiform (L) shrub facies in Spiš travertine, and **M** – pustular shrub facies in Vrútky.

cruststones can be explained by changeable intensity of water flow. Some organic films can be twisted and shrinked by strong water flow or drying (Appendix 10a). Bent parallel laminae and voids of convex shape (Appendix 13i) are related to waterfalls. Concave shape (Appendix 13j-l) is associated with crystalline rafts formed on water level inside fissures and among collapsed blocks. Very narrow laminae among laminated fan crystals (Appendix 13E-G) were probably developed in shrink fissures among botryoids with fan laminated crystals (*sensu* Gandin & Capezzuoli, 2014). Knoll- to columnar-shaped cruststones (Fig. 7z, Appendix 13r-v) were probably formed in deeper quiet pools and lakes. Calcium carbonate network from Dudince spring (Appendix 12h) can be formed on unknown microphyte network, which is not observable. This would require further detailed research.

Microphyte cruststones can be compared with stationary buildup stromatolites (Freytet & Verrecchia, 2002). The authors defined the stromatolites as laminated rocks, resulting from the induration of a felts of bacteria, cyanobacteria, eucaryotic algae, etc., trapping and binding particles and precipitating minerals.

4.2.3. Microphyte shrub facies (Ms)

Description: In Slovak travertines, the microbial shrubs are rarer than microbial mats and cruststones. Rare recent microphyte shrub-like forms were found on Stankovany Močiar (Fig. 6i, 7C, Appendix 14a) and supposed on Hozelec meadows (Appendix 14b-e). Fossil shrub-like forms were identified mainly in Spiš and Levice travertines (Appendices 14, 15). The microbial shrubs consist largely of peloidal micritic aggregates engulfed in spar calcite, ranging in average from 1 to 3 cm in height (*sensu* Chafetz & Folk, 1984; Chafetz & Guidry, 1999; Erthal et al., 2017). Morphology types of shrubs (Erthal et al., 2017) were identified in Slovak travertines (Fig. 7C-M, Appendices 14, 15) as narrow (Fig. 7c), wide (Fig. 7d), and fili (Fig. 7e) dendriform shrub facies, arborescent (dendriform, treelike; Fig. 7f), arbustiform (bushlike, shrublike; Fig. 7g) and pustular (Fig. 7h) shrub facies. Dendriform shrub facies are characterized by distinct branches, arborescent and arbustiforms by indistinct and converging branches. There are smooth transitions between the different types. Some arborescent and arbustiform types are bent and twisted (Appendix 15f,k,n,p,r,s,u) or are developed with loop shape filled with micrite (Appendix 15q,t). Broken plant stems are rarely covered by radial bacterial shrubs (Appendix 9c).

Interpretation: Typical bacterial shrub or dendrolite fabric formed by colonies of densely packed microphyte clumps are very abundant in Italy (Gandin & Capezzuoli, 2014; Chafetz & Folk, 1984; Guo & Riding, 1994; Rainey & Jones, 2009). During travertine formation from calcium carbonate precipitation, mineral habit can be influenced by microphyte growth. Biogenic influence tends to disturb regular crystal shapes. Microphyte shrub morphology essentially displays no evident mineral habit, whereas the crystal shrubs range from a minimal crystal habit, at one extreme, to a pronounced crystal habit, at the other extreme (Chafetz & Guidry, 1999).

Steeply inclined cascades with high flow velocity are typical by the sparitic fabric due to more significant CO_2 degassing and consequent higher saturation state, leading to the dominance of abiotic precipitation. On the contrary, sub-horizontal pools with low flow velocity are characterized by the micritic fabric due to less significant CO_2 degassing and consequent lower saturation state, leading to the prevalence of microbially-influenced precipitation (Shiraishi, 2019).

Microphyte shrubs are reported from very shallow pools, shallow extensive waterlogged slightly inclined flat areas with a flowing water, and on the subvertical walls of semi-dried channels. Depositional settings are characterized by the rapid evaporation of very thin films of supersaturated waters (Chafetz & Folk, 1984; Guo & Riding, 1994; Chafetz & Guidry, 1999; Rainey & Jones, 2009; Erthal et al., 2017). Unlike present Slovak climate, for bacterial shrub formation, warm dry climate is necessary which enables rapid evaporation of supersaturated water and suitable conditions for cyanobacteria like *Dichothrix, Rivularia, Schizothrix* or charophyta *Oocardium* (Pentecost, 2005). Shrub facies are more widespread in Spiš travertine and possibly in Levice travertine. Both travertines were formed during the Late Pliocene, when relatively warm climate was appeared (Pivko & Vojtko, 2021). Recent shrub-like forms in Stankovany are formed from EPS produced by diatoms and cyanobacteria inside a shallow pool (Figs. 6i, 7C, Appendix 14a).

4.2.4. Macrophyte facies (Ma)

Description: Typical macrophyte tufas contain the macrophyte casts of vascular plants, such as leaves (Fig. 8h,u, Appendix 17C-G), stems and branches (Fig. 8d-g,q-t, Appendix 17a-A), less trunks (Fig. 8v, Appendix 17H-L), seeds (Appendix 17B), and pollen assemblages (Kovanda, 2011). The same association could be observed in tufas as well as in distal travertines. Moss (bryophyte) tufas are very abundant on slopes in recent and fossil deposits, characterized by moss cushion sets (Fig. 8b,c,m-p, Appendix 16e-H). Tufa-like deposits with charophyte casts were found in pools with a slow flowing water near spring orifice (Fig. 8a,l, Appendix 16a-d). Fresh-water limestones rarely contain remnants of terrestrial and aquatic gastropods (Fig. 8x, Appendix 18a-h), ostracod valves (Fig. 8k, Appendix 18i-l) and caddisfly larvae cases (Fig. 8w, Appendix 18m-r). Vertebrate bones (Appendix 18s; Bojnice) including Neanderthal bone cast and tools were also found (Vlček, 1955).

Interpretation: Some plant remnants are autochtonous, in situ growing plants, e.g., moss cushions (Fig. 8b,m, Appendix 16e-y), standing trees (Fig. 8v, Appendix 17J-L), reed and grass clumps (Fig. 8d,e,s,t, Appendix 17a-d). Part of them are suballochtonous, fallen trees and their parts transported to small distance (Fig. 8h, Appendix 17C-I), and allochtonous, brought by water flow especially during floods or by strong wind. After mineralisation, the remnants remained mostly in place. The macrophyte tufas are characterized by highly porous fabrics (Fig. 8c,e,n, Appendix 17e,j). There are large voids with air trapped to the structure and voids after plant remains, that were degraded by decay. High porous macrophyte fabric of some tufas can be gradually changed by continued calcium bicarbonate precipitation (Fig. 8b,c, Appendices 16h, 17j-m) inside open voids after decay of tissues, around coated remnants (Appendix 17b-d) and then inside the open voids that remained (Appendix 17m). The deposit is similar in hardness and density to travertine but without bedding typical for travertine.

Fig. 8. **Recent plant incrustation, fossil macrophyte tufa facies and related animals. a –calcite precipitation on *Chara* brenchlets in Hozelec meadows, b-c – prograding calcite precipitation (2-4) on moss cushion (1) in Krásnohorská Dlhá Lúka, d – incrusted bunch of flowering plant in Sivá Brada, e – incrusted grass stems in Biely Potok Bukovina, f – advanced calcite precipitation on flowering plant stems in Sklené Teplice, g – advanced calcite precipitation on tree branchlets in Krásnohorská Dlhá Lúka, h – leafs covered by precipitated calcite in Sliač spa, i-j – stem incrustation composed of radiating dendrites, lime mudstone, plant detrit, quartz grains and ostracods in Vyšný Sliač, k – ostracods from Stankovany Močiar pool, l – molds of *Charales* branches in Levice travertine, m – moss facies with cushion section in Biely Potok Bukovina, n – incrusted moss stems in Hranovnica tufa, o-p – incrusted moss stems in Biely Potok tufa, q – macrophyte tufa facies with incrusted stems in Likava Castle, r – incrusted perpendicular and oblique sections of probably *Typha* stems and leafs in Spiš travertine, s – lateral section of plant stems growing in microphyte cruststone in Spiš travertine, t – perpendicular sections of incrusted bunch of plant stems in Spiš travertine, u – leaf molds in Gánovce travertine, v – tree trunk mold in Spiš travertine, w – caddisfly larvae cases in Klíž travertine, and x – gastropoda endocasts in Klíž travertine.**

4.3. Granular facies

In contrast to the previously mentioned facies substantially developed *in situ*, granular facies were formed from loose particles from mud to gravel size. Before deposition, the particles were subjected to vertical and/or horizontal movement.

4.3.1. Intraclast (I) and extraclast (E) facies

Description: Travertines are fragile and can be fractured to blocks separated by calcite veins up to some milimetres (Appendix 8d,f). Intraclast travertine, brecciated travertine or lithoclast travertine (Gradziński et al., 2013) is composed of angular to subangular pieces of previously deposited travertine (Fig. 9a-d, Appendix 8). The size of broken pieces is between a few mm and several m. The intraclast travertines with larger clasts over some centimetres are grain-supported (Fig. 9c,d) with finer matrix (Appendix 8j,m), calcite cement and/or open spaces (Fig. 4l, Appendix 8n), together with rafts (Appendix 8o) and microbial laminites. The thickness of intraclast travertine bodies with large intraclasts in Dreveník are between 0.5 and 2.5 m (Gradziński et al., 2013). The thickness of intraclast travertine beds with the clasts up to several centimetres is between a few cm and several dm. The broken pieces sometimes remained autochtonous or subautochtonous position (Fig. 9a,b). Some travertine breccias are situated inside fissures together with *terrae calcis* (Fig. 9g) or with deform clasts (Fig. 9h).

Interpretation: Deposited travertine beds on mound or ridge slopes were subjected to dessication, frost (Fig. 4i, Appendix 8d-f,h), and bending which resulted in the fracturation of fragile travertines and creeping of large blocks on plastic basement (e.g., Dreveník). Inactive depressions were exposed to pedogenic processes (Fig. 4j, Appendix 8g,i). Subsequently, the intraclast travertines were originated especially by gravitational processes (Fig. 9c,d). Loose pieces were exposed to mass wasting and torrential rains (Fig. 9c,d, Appendix 8j-o). Heavy rains can cause debris flow with extraclast breccia deposition (Hranovnica, Fig. 9e). Gradziński et al. (2013) points to earthquakes as a possible mechanism of rockfall avalanche. Destructed travertine microtteracettes with radiating dendrites are occasionally washed and worked out with episodic streams (Appendix 8a,b). When tufas are formed on slopes, flowing spring water rounds tufa pieces to pebbles (Appendix 8c). Some breccias *in situ* or tepee-like structures (Bešeňová, Vyšné Ružbachy; Fig. 9f) or large clasts from basement incorporated to fresh-water sediment (Veľký Klíž; Appendix 8p) could be caused by gas pressure eruptions (Brogi et al. 2017). As mentioned in the subchapter 4.1.2, overpressured hydrothermal fluids induced subhorizontal hydrofractures filled with broken pieces of original beds and sheeted calcite veins (Dudince-Porošin; Appendix 8u). Some travertine breccias are a result of cave collapse (Fig. 9g, Appendix 8q,r). Cohesive slip breccias were developed inside obliquely inclined slip surfaces of a fissure ridge (Levice-Vápnik), probably formed by creeping, a process generally comparable to formation of a mylonite (Fig. 9h, Appendix 8s,t).

4.3.2. Coated grain facies (G)

Description: The coated grain travertines consist of spherical, oval or cylindrical grains composed of nucleus covered by thin regular or unregular laminae. The nucleus is usually intraclast or fossil fragment. *Oolitic limestone* consist of spherical *ooids* with regular laminae (*sensu* Flügel, 2010). Well-developed oolitic limestone with ooids (0.5 to 1.5 mm) were found only on one locality (Dudince-Porošin, Fig. 9j,k). The coated grains, probably some pisoids or ooids were rarely identified in Dreveník travertine (Appendix 9a,b; also Hudáček et al. 1976). Recent pisoids are originated in small pools in lower part of slope cascade with hot mineral water (Sklené Teplice; Fig. 9i). Other type of coated grains, *radiating dendrites* (radial pisoids according Guo & Riding 1998) was described earlier at crystalline crusts (4.1.1) because of similar origin. Their spherical and sub-spherical shape is up to several milimetres in size. They are covered by branching calcite crystals that radiates from nucleus. More abundant *oncoids* with irregular laminae between a few mm and 3 cm, max. 8 cm were found in Neogene travertines (Veľký Klíž, Sádok, Vrútky; Fig. 9l-n, Appendix 9g-s). Intraclasts and plant fragments (Appendix 9c-e) can serve as oncoid cores. The oncoids are mostly scattered in micrite together with organic fragment, but the layers filled with oncoids were also found. Coated grains, especially plant fragments, similar to oncoids, are typical for many recent tufa localities, where the coated grains move downstream or form flat dams (e.g., Úľanka, Valča; *piesčité penovce* in Kovanda 1971, Fig. 9n).

Interpretation: The pisoids and ooids occur in pools near hot supersaturated water orifices situated along tectonic faults. The ooids of Dudince-Porošin are similar to '*Karlsbad Sprudelstein*' (*hrachovec* in Czech) (Flügel, 2010). The oncoids were originated as tangles of microbial filaments (Gandin & Capezzuoli, 2014) in dynamic environments of river channels or lake shores (Arenas-Abad et al., 2010; Alonzo-Zarza & Wright, 2010). Slovak Neogene fresh-water limestones with coated clasts and fossils are very similar to Hungarian Süttő travertine locality (*sensu* Török et al., 2017).

4.3.3. Lime-mudstone facies (L)

Description: Lime-mud and lime-mudstones consist of micrite/microsparite calcite with possible oval aggregates – clots and peloids (*sensu* Freytet & Verrecchia 2002; Fig. 9t, Appendix 10f,o,p). The lime-mud forms in shallow pools on slopes of travertine mounds and fissure ridges or inside crater pool around spring mouths (Fig. 9o-q, Appendix 10a-e). In fossil travertines, homogenous lime-mudstones are present in subhorizontal beds, sometimes with mottled appearance (e.g., Bešeňová, Levice Vápnik, Dreveník, Ostrá hora; Fig. 9r-t, Appendix 10m-q). The lime-mudstones occasionally contain scattered coated bubbles and/or radiating dendrites (Appendix 10d,e). They are rarely penetrated by vertical stems of charophytes (Levice Vápnik; Fig. 7l), algae or reed (Dreveník, Appendix 17g). In Veľký Klíž quarry, the lime-mudstones were accumulated in the beds of several metres in thickness. They are enriched with scattered fossil fragments (gastropods, plants, ostracods), whole and broken oncoids, organic particles, microbial mats and microbial laminites (Appendix 10x-z). Homogenous microsparite beds with centimetre to millimetre brown laminae were formed inside slope crystalline crusts with a variable content of iron hydroxides (Levice Vápnik; Fig. 9u,v). Dessication features (mud cracks Lc) locally occur in some lime–mudstone beds (Appendices 8d,f, 10A,B; cf. Brogi et al., 2017), which are frequently connected with yellow-orange-red mottling

(Lm marmorisation; Appendix 10C-E), nodulisation and brecciation (Ln; Appendix 8e,g, Appendix 10F-H), irregular cavity network (Lk pseudomicrokarst; Appendix 10I,J), and root cavities in e.g., Sádok, Sliač Kúpele, Podhorany, and Ratnovce (*sensu* Alonso-Zarza & Wright, 2010; Appendix 10K,L). Irregular layers of brown-grey lime-mudstones are locally developed between crystalline crust beds with scattered crystalline crust fragments up to several dm in diameter (Dreveník; Fig. 9b,c, Appendix 8g,i).

Interpretation: The lime-mudstones consist of micrite and microsparite calcite with a different number of organic particles

Fig. 9. **Intraclast, coated grain and lime mudstone facies. a – weathered travertine bed by dessication and frost in Sivá Brada, b – fragments of weathered beds in darker soil horizon in Spiš travertine, c – mass wasting of weathered travertine clasts mixed with darker soil particles in Spiš travertine, d – mass wasting of weathered travertine clasts without matrix in Spiš travertine, e – extraclast shale layer of debris flow inside travertines near Hranovnica, f – tepee-like structure of gas escape (arrow) in Bešeňová travertine, g – partly weathered and collapse breccia of crack in Dreveník, h – interformational slip breccias in Levice Vápnik, i – shallow pool with coated grains in Sklené Teplice hot spring lobe, j, k – pisoid facies in Dudince Porošin, l – oncoid facies in Klíž travertine, m – microsparite and micrite layers in oncoids in Vrútky, n – loose coated plant fragments in Úľanka, o – whiting, as calcite crystal fallout, in shallow pool with radiate dendrites in Gánovce meadows, p – overflowed lime mud in Sivá Brada, q – microsparite aggregates from lime mud in Bešeňová, r – lime mudstone in Bešeňová, s, t – lime mudstone with scattered larger particles in Veľký Klíž, u – color laminated lime mudstone from Levice Vápnik, and v – finaly laminated microsparite lime mudstone from Levice Vápnik.**

(Flügel, 2010) such as clots of bacterial filaments and microbial aggregates – peloids (Chafetz, 1986). Microscopic crystals nucleate and are released during fallout, also called whiting, in the water column (Riding, 2000). The fallout is due to microbial metabolic process or abiotic evaporation. The crystals are subsequently accumulated from suspension as lime-mud at the bottom (Fig. 9o, Appendix 10a,b) and is rapidly incorporated into loose microbial aggregates and their sticky extracellular polymeric substances (EPS; Fig. 6d,o), to form a microbial micrite that may evolve into regular microbial mats (Gandin & Capezzuoli, 2014; Capezzouli et al. 2014). Very thin layers of lime mudstones (Levice Vápnik) can be the result of rapid change in mineral water characteristics (Fig. 9u,v).

Very thick layers of lime-mudstones (Veľký Klíž, Vrútky; Fig. 9s,t, Appendix 10x-z) with fossil and oncoid fragments were originally formed in lakes with a supply of calcium carbonate saturated water and a flow on bottom. Calcium bicarbonate deposited during whiting and throught precipitation in oncoids. The lime–mudstone beds frequently occur with mud cracks, marmorisation, brecciation, pseudomicrokarst, and root cavities are typical marks of palustrine facies and environment. Original lacustrine lime-mud was subjected to subaerial exposure related to fluctuations in water level (Freytet & Verrecchia, 2002; Alonso-Zarza & Wright, 2010).

Irregular darker beds between crystaline crust accumulations (Fig. 9b,c, Appendix 8g,i), relate to sedimentary unconformities,

Tab. 1: Slovak freshwater carbonates with typical forms and facies: crystalline crust travertines (C) with fan to feather crystals (Cf), laminated fan crystals (Cl), banded palisade crystals (Cb), speleothems (Cs), radiating dendrites (Dr), raft travertine (R), coated bubble travertine (B), microphytes (Mi) with microphyte mats (Mm), microphyte cruststones (Mc), and microphyte shrubs (Ms), macrophytes (Ma) with moss (b), herbs: grass, reed, chara (h), tree parts (t), molluscs (m), insect (i), ostracod (o), vertebrates (v), intraclast (I) and extraclast (E) travertine, coated grain travertine (G), lime-mudstones (L), mud cracks (Lc), yellow-orange-red mottling-marmorisation (Lm), nodulisation and brecciation (Ln), and irregular cavity network - pseudomicrokarst (Lk). Previous papers are Kovanda (1971) and Gradziński et al. (2008, 2013, 2014, 2015). Typical forms and facies are highlighted.

recent and fossil localities	traver-tine	tufa	lime-stone	forms, environments (Pivko & Vojtko 2021, previous papers)	facies, facies in previous papers
Levice-Vápnik	+	+		**fissure ridge: cascades,** terraces, pools, vein	**C**>**Mi: Cf, Mm, Mc, L,** I, Cb, B, Ms, G, Ma (b, h), *v*
Levice 'Gold onyx'	+	+		**fissure ridges: cascades, veins,** pool	**C**>**Mi:** Cf, Cb, Ma (b, h, t), Mc, L
Levice Margita-Ilona	+	+		**fissure ridge?: cascade,** pool, vein	**C**>**Mi: Cf, Mm, Mc, L, Cb,** I, Ms, Ma (t), Lm, Lc
Sobotisko	+	(+)		**fissure ridge: cascades,** veins, caves	C>Mi: Cf, Cb, Mm, Mc, I, Ma?, *m*
Dreveník - Ostrá hora	+	(+)		**coalesced mound: mounds, cascades,** fissure ridges, lobes, veins, pools, waterfalls, fen, caves	***C>Mi*** (Mi>C, C): ***Cf*, Mm, Mc, *I*,** Dr, Cl, Cb, Cs, *B, R,* Ms, L, Lm, Lc, G, Ma (t, h, b), *m, v*
Spišský hrad	+	(+)		**coalesced mound: mounds, cascades,** fissure ridge, lobes, veins, waterfalls, caves	**C**>**Mi** (Mi>C, C): **Cf, Mm, Mc,** Cb, Cs, I, Ma (b, h, *t*), E
Pažica	+	(+)		**coalesced mound: mounds, cascades**	**C**>**Mi: Cf, Mm, Mc,** Ma?, *m*
Sivá Brada	+	(+)		**mound: cascades, lobes,** orifices, parasitic orifices, pools, channels, fen	**C**>**Mi: Cf, Mm, Mc, B, Dr,** R, L, I, Ma (h)
Bešeňová *Bešeňová*	+	(+)		**mounds: cascades, lobes,** orifice, channel	**Mi**>**C** (C): **Mm, Mc, Cf,** Dr, B, I, R, L, Cb, Ma (h, b)
Santovka *Santovka*	+	+		**mounds, orifices,** fissure ridge, vein, channels, perched springline deposit	**Mi**>**C** (C): **Mc, Mm, Cf,** Ma (b, t), Cl, L, G, Ms, Dr, Cb, B, I, v
Dudince *Dudince*	+	+		**mounds, orifices,** pool, fen, lobes, channel	**Mi**>**C: Mc, Mm, Cf, L,** Ma (b, t), Ms, Dr, I, Cb, Ln
Dudince-Porošin	+	+		**mounds, veins,** orifice, pool, fen	**Cb, Dr,** Cf?, Mm, G, L, m, Lm, Lc
Vyšné Ružbachy	+	+		**mounds, orifices,** lobes, craters, pools	**Mi**>**C: Mc, Mm, Cf,** Ms, Ma (b, h, t), I, B, L?
Gánovce	+	+		**mound, orifice,** pool, fen	**Mi**>**C: Mm, Mc, Cf,** B, Ms, Ma (b, t), I, *m, v*
Hozelec-Banícka & other	+	+		**mounds,** lobes, orifice, channel	**Mi**>**C: Mm, Mc, Cf,** Ma (b, h), E
Hôrka	+	+		**mounds,** lobes, pool, fen, stream	**Mi**>**C: Mm, Mc, Cf,** Ma (b, h, t), Ms, G, I, L, m, Lm
Rojkov *Rojkov*	(+)	+		**mounds, orifices,** fen	**Mi**>**Ma: Mm, Mc, Ma (h, t,** b?**),** Cf, L
Vyšný Sliač *Vyšný Sliač*	(+)	+		**mounds, orifices,** fissure ridge, fen	**Mi**>**C: Mm, Mc, Cf,** Ma (b, h, t), I, B, Ms, L
Liptovský Ján	(+)	+		**mound, orifice,** stream	**Mi**>C>Ma**: Mm, Mc, Cf,** Ma (b, h, t), E
Stránska	(+)	+		**mound, orifice**	**Mi**>**Ma**+C**: Mm, Mc,** Ma (h, b), Cf, L, E, Ln, Lm?
Hrnčiarska Ves	+	+		**mound, lobes,** orifice	**Mi**>**C: Mc, Mm, Cf,** Ma (h, b, t), I
Mošovce	(+)	+		**mound,** fen	**Mi**>**C: Mm,** Mc?, Ma (h, t, b?), Cf, L, R
Slatina	(+)	+		**mound,** pool, fen	**Mi**>**C: Mm, L,** Mc, Cf, I, Cs, Lm, Lk, Ln, Lc?
Ludrová	+	+		mound (?), **fen,** pool	**Mi**>C>Ma: **Mm, Mc,** Cf, Ma (b, h), *m*
Sliač Kúpele	?	+		**mounds,** lobes, pools	**Ma**>**Mi: Ma (b, h, t),** Mm, Mc
Čerín – Dolná Mičiná	+	+		**mounds, orifices,** channels, fen	**Ma**>**Mi: Ma (b, h,** t), **Mm, Mc,** B, Cf?, I, L?
Zvolen, Borová hora	?	+		**mound, orifice**	**Ma**>**Mi: Ma (b, h), Mm, Mc**
Hozelec (meadows)	+	+		**flat lobe, orifice, pool, fen**	**Mi**>**C: Mm, Mc, Cf,** B, Dr, Ms?, Ma (h), L, R
Hozelec Banícka	+	+		**flat lobe,** channels, pool	**Mi**>**C: Mm, Mc, Cf,** Dr, Ms?, L, I, R
Stankovany Močiar	+	+		**flat lobes,** orifice, lobes	**Mi**>**C: Mm, Mc, Cf,** B, Dr, Ms, Ma (h), L, R

recent and fossil localities	**traver-tine**	**tufa**	**lime-stone**	**forms, environments (Pivko & Vojtko 2021, previous papers)**	**facies, facies in previous papers**
Sklené Teplice	+	+		**perched springline deposits**	**Mi**>**C: Mc, Cb,** Ma (h, t), Cf?, Mm, G
Hranovnica *Hranovnica*	(+)	+		**perched springline deposits,** waterfall	**Ma**>**Mi**: **Ma (b,** h, t), **Mc, Mm,** Cf, Ms?, E
Ružomberok Biely Potok	(+)	+		**perched springline deposits,** waterfall, fen	**Ma**>**Mi**: **Ma (b, h**, t), **Mc, Mm,** Cf, Ms?, Cl, B, I
Hradište pod Vrátnom	?	+		**perched springline deposits**	**Ma**>**Mi**: **Ma (b, h**, t?, m), **Mm,** Mc
Bojnice	(+)	+		**perched springline deposits,** waterfall, mound, caves	**Ma**>**Mi**: **Ma (b, h**, t?, *m, v*), **Mm,** Mc, I, Cf, Cs, E
Vyhne *Vyhne*	(+)	+		perched springline deposit?, keeled lobe	**Ma**>**Mi** (Mi>C): **Ma (b, h**, t?), **Mc,** Mm, I, Cf,Cs, m
Moštenica	?	+		**perched springline deposits**	**Ma**>Mi: **Ma (b, t),** Mc?, Cf?, Cs, G, E
Lúčky Kúpele *Lúčky*	(+)	+		**dams along stream**, waterfall, lobes	**Ma**>**Mi: Ma (b, h,** t), **Mm, Mc,** Cf, I
Lúčky - Kalamenová	(+)	+		**dams along stream**	**Ma**>**Mi: Ma (b, h,** t), **Mm, Mc,** Cf, R
Necpaly *Necpaly*	?	+		**perched springline deposits**	**Ma**>Mi: **Ma** (**b, t**), Mc, Mm, Cf?
Tematín castle (Hrádok, Stará Lehota)		+		**perched springline deposits**	**Ma**>Mi: **Ma** (**b, t**), Mc, Mm?, *I*
Tajov		+		**perched springline deposit,** waterfall	**Ma**>Mi: **Ma** (**b, h, t**), Mc, Mm, G?, *I*
Hrhov		+		**perched springline deposits,** waterfall	**Ma**>Mi: **Ma** (***b*, h,** t), *Mc,* Mm?, G, *I*, *m*
Krivoklát (Vršatec castle)		+		**dams,** lobes	**Ma**>Mi: **Ma** (**b, h, t**), Mc, Mm?, G, I
Motyčky, Staré Hory		+		**dams,** waterfalls, caves	**Ma**>Mi: **Ma** (**b, h, t**), Mc, I, G, Cs, *m*
Háj		+		**dams,** waterfalls, caves	**Ma**>Mi: **Ma** (***b*, h, t**), *Mc,* Mm?, *I, G*, Cs, *m, i*
Žaškov Dierová	?	+		**perched springline deposits**	**Ma** (**b, h, t**), Mc, G, I
Dobrá Voda		+		**perched springline deposits**	**Ma (t,** b), Mc, Mm?
Diviaky nad Nitricou		+		**perched springline deposits**	**Ma** (**t, b**), G?, *I*, *m*
Omšenie		+		**perched springline deposits**	**Ma** (**b, h,** t), Mc, G, I, *m*
Hrušov		+		**perched springline deposits**	**Ma** (**b**, h, t), Mc?, G?, *I*, *m*
Muráň		+		**perched springline deposits**	**Ma** (**b, t**), Mc, G?, *I*
Slavec Gombasek		+		**perched springline deposits**	**Ma** (**b, t**), Mc, G?, *I*, *m*
Moravany - Striebornica		+		**dams**	**Ma** (**b**, t), **G, I**
Nižná Revúca - Teplá		+		**dams**	**Ma** (**b, t**), G, I, Cs, E
Nová Lehota - Zváracá		+		**dams**	**Ma** (**h,** b, t), **G, I,** m
Záhrada - Zľavy		+		**dams**	**Ma** (**h**, t), **G, I,** m
Stankovany		+		**dams**	**Ma** (**h, t,** b), **G, I**, E
Staré Hory - Košiar		+		**dams,** terracettes	**Ma** (**b, t**), **G, I,** Mc, E
Plavecký Mikuláš		+		**dams**	**Ma** (**b, t**), Mc, Mm?, G?, *I*, *m*
Turčianska Štiavnička		+		**dams,** waterfall	**Ma** (**b,** h, t), Mc?, I
B. Bystrica Úľanka		+		**dams**	**Ma** (**t,** b), **G, I,** Mc
Považská Teplá (castle)		+		**dams**	**Ma** (**b, t**), Mc, G?, *I*
Súľov (castle)		+		**dams**	**Ma** (**b, t**), Mc, G?, *I*
Rajecké Teplice (Stránske)		+		**dams?**	**Ma** (**b, t**), Mc, G?, *I*
Krásnohorská Dlhá Lúka		+		**perched springline deposit**, terracettes, pools	**Ma** (**b**, h, t), G, I
Valča Slovianska		+		**dams**	**G, I,** *Ma* (t?, h?)
Hôrka		+	+	**fen**, lobe	**L, Mm, Ma** (**b**, h, t), Mc, E?
Veľký Klíž		(+)	+	**lake,** marsh, pool, bioherm	**L,** G, I, Mc, Mm, E, m, i, Ma?
Sádok		(+)	+	**lake,** marsh, pool, bioherm	**L,** I, Mc, Mm, G, E, *m*, Ln, Lm
Nedanovce Bošany		(+)	+	lake, marsh	**L,** Lm, Lc, Lk, m, Mm, Mc
Ratnovce		(+)	+	lake, marsh	**L,** Lm, Lc, Lk, Mm, I, G, Mc, m, i
Banka		(+)	+	lake, marsh	**L,** Mm, Mc, G, I, Lm
Vrútky		(+)	+	**lake, marsh**	**L,** I, Mm, Mc, Ms, E, *m*, G, Ln, Lm, Lk, C
Sliač Kúpele, Veľká Lúka		(+)	+	**lake, marsh**	**L,** Lm, Lc, Lk, Ln, I, *m*, E, Mm, Mc?
Slovenské Pravno		(+)	+	lake, marsh	**L,** I, m, Ln, Lm, Mm, Ma (h, t)
Brodzany		(+)	+	lake, marsh	**L,** m, Lc, Lk, I, Lm
Partizánske Veľké Bielice		(+)	+	lake, marsh	**L,** I, Lm, m, Lc, Mm, Ln
Malé Kršteňany		(+)	+	lake, marsh	**L,** Lc, Lk, m, I, Mm, Lm, Ln
Čeľadince		(+)	+	lake, marsh	**L,** Lm, Ln, Lk, m, Mm
Podhorany		(+)	+	lake, marsh	**L,** Lm, Lk, Ln, Lc, I, Mm, E

are a result of interruption in travertine deposition. The beds can be originated in shallow cool ephemeral ponds with palustrine conditions (Gandin & Capezzuoli, 2014), with eroded crystalline crust, eolian and fluvial input. Darker horizons are buried paleosols, which can be flushed to karstic cavities.

5. FACIES ASSOCIATIONS AND RELATIONS

A summary and generalization of all facies depending on water source, environments and forms is expressed in Tab. 1 and Fig. 2. In Slovak travertines and tufas, the relations between environment and facies are like others world travertines and tufas.

5.1. Travertine facies associations Mi>C, C>Mi, C>>Mi, C

The travertines are characterized by the centimetre layer alternation of microphyte facies with *microphyte mats* to *microphyte cruststones* and crystalline facies with *fan- to feather-like crystals*. Microbial mats occur mostly in calm water environment and microphyte cruststones in dynamic environment with a flowing water. Alternated layers of abiotic crystalline crusts and biotic microbialites can express seasonal (annual) cycles or the cycles in spring yield during year. Thin millimetre laminae can reflect probably daily variations or changes in local flow conditions (Gandin & Capezzuoli, 2014; Rainer & Jones, 2009; Pentecost, 2005; Shiraishi, 2019).

Cascade lobes on spring mound slopes are commonly formed in recent travertines, covered with microterracettes composed of fan to feather crystal rims, containing coated bubbles and/or radiating dendrites. During cold weather in winter or during cold nights and mornings, the microterracettes are covered by calcite film, used to be later destructed and becomes part of microtteracette pools. When spring yield decrease, the lobe is colonized by cyanobacteria and diatoms, later by algae and herbs. In fossil travertines, radiating dendrites are rare due to their recrystallization to crystalline crust.

Rare facies in travertine environments are vein fillings, crater deposits, and terraced slopes. Veins were exposed only in quarries due to their subsurface formation (e.g., Levice, Dreveník). Fossil crater deposits with mud limestones were rarely observed due to their small volume against slope deposits. Few active craters are strongly controlled by a human impact (e.g., in Vyšné Ružbachy and Rojkov). Terraced slopes with metre sized terraces and typical facies was identified only in Levice Vápnik fossil travertine from the warm late Pliocene epoch (Pivko & Vojtko, 2021). In the Pliocene epoch, the greatest volumes of travertines with the most developed facies and the greatest volumes of crystalline facies were produced in Dreveník and Levice. The smaller travertine volumes were formed during interglacials with no permafrost.

Abiotic crystalline crust travertines *with banded palisade to opposite fan crystals* were identified in vertical and horizontal veins, in caves and rare on fossil mound slope with thermal water. Abiotic *ooids* were also found in thermal travertines. Alternate opening of fissures perpendicular to each other form interlaced veins in Levice Gold Onyx. The veins have usually sharp straight contacts with fissure ridge travertine and their banding used to be vertical and straight, but the speleothems deposited on corroded irregular travertines with typically botryoid shapes (Dudince-Porošin, Bešeňová). Fossil hot spring travertine facies were identified in Dudince-Porošin, Staré Levice and rarely Dreveník, recent in Sklené Teplice. Dudince-Porošin can be compared with Karlovy Vary spa with a presence of palisade crystals (*vřidlovec* in Czech) and oolitic limestones (*hrachovec* in Czech).

Slovak travertines, especially Dreveník travertines can be compared with the Rapolano Terme travertines (Italy) based on palaeoenvironments, facies, and stable isotopes (cf. Gandin & Capezzuoli, 2008; Gradziński et al., 2014). Travertine facies, except for missing terrace facies, are similar to Denizli (Pamukkale) travertines in Turkey (Altunel & Hancock, 1996; Özkul et al., 2002) and Angel Terrace in Mammoth Hot Springs, Wyoming, the USA (Fouke et al., 2000). The real hot spring travertines are rare in surrounding countries as Hungary, Poland and Czechia. The fossil travertines near Přerov (Tučín) in Morava (Kovanda et al., 1971) and recent travertine around thermal well near Eger in Hungary (Egerszalók; Kele et al. 2008) are exceptions.

5.2. Tufa facies association Ma>Mi, Ma, Mi>Ma

Tufa facies association with dominant macrophyte tufas were abundant in valley dams and perched springline deposits, frequently with accompanied microphytes. Typical macrophyte tufas are developed with moss cushions and terracettes of decimetre sized, leaf, branch and stem tufas (cf. Gradziński et al., 2013). Bryophyte tufas are typical for forests (e.g., Krásnohorská Dlhá Lúka, Biely Potok, Staré Hory) and stem tufa for meadows and wetlands (e.g., Nová Lehota, Stankovany). Tufa with loose coated macrophyte clasts are very frequent in tufa localities (cf. Kovanda, 1971; e.g., Úľanka, Valča). Characteristic high porous macrophyte fabric can be gradually changed by continued calcium bicarbonate precipitation to dense travertine like deposit. The dense and coherent tufas of the Pleistocene are the oldest preserved fluvial tufas in Slovakia (e.g., Biely Potok, Hranovnica, Bojnice), reffered to as travitufas in Pivko & Vojtko (2021), and as travertines in Kovanda (1971) and Ivan (1943). Most preserved tufas were formed during wet and relatively warm periods in the Atlantic and less in the Sub-Boreal (Kovanda, 1971; Gradziński et al., 2013; Pivko & Vojtko, 2021). Older tufas were destroyed by erosion due to their low cohesion, and similar to the Atlantic tufas are being recently eroded (e.g., Staré Hory - Jelenec).

Similar tufa facies were described in surrounding countries as Hungary, Poland and Czechia (Kovanda, 1971; Schweitzer & Scheuer, 1995; Mastella & Rybak-Ostrowska, 2012). The tufas are common in the karstic regions of the Alps and the Dinarides (Pentecost, 1995).

5.3. Lacustrine/palustrine limestone facies associations L ± G, I, E, Ma

The most lacustrine/palustrine limestones were produced during warm period of the late Tortonian (late Pannonian) to Zanclean as horizontal beds. The limestones were a part of the fluvial/lacustrine/palustrine carbonate system (cf. Arenas-Abad et al., 2010). Basic lime-mudstone facies of shallow lacustrine origin tends to be enriched by coated grains, gastropods, intraclasts, and rarely extraclasts. Locally, microphyte bioherms with mat or cruststone facies were developed in shallow water similar to microphyte tufas. The lacustrine deposits can be accompanies by sandstone, mudstone and conglomerate beds (e.g., Vrútky, Sádok). The lacustrine environment was closely associated with palustrine conditions. Lake levels were fluctuated and lacustrine deposits were subjected to Fe and Mn diffusion (marmorisation), reed growth (root cavities), dessication features (mud cracks) and fragmentation (pseudomicrokarst and brecciation).

The palustrine (lacustrine) systems are known from the early Holocene in intermountain basins (*Ca-slatina* and *alm* in Kovanda, 1971). The deposits are enriched by organic sediments and locally by terrestrial gastropods. Irregular alternation of white, grey, and black streaks is typical feature of the deposit.

The Tortonian and Zanclean fluvial/lacustrine/palustrine carbonate systems can be compared with higher levels of the Gerecse and Buda travertines and fresh-water limestones in Hungary (Scheuer & Schweitzer, 1988; Schweitzer & Scheuer, 1995). Similar intermontane systems were described in Spain (Arenas-Abad et al., 2010; Alonzo-Zarza & Wright, 2010; Vazquez-Urbez et al., 2013).

5.4. Facies relations

The individual facies represent endpoints of continuous process, complex system that is sensitive to fine environmental changes such as spring yield, HCO_3^- content, water and air temperature, relief and slope dip, the presence of rainfall and surface water.

The most common relation is a gradual transition from travertine to fluvial tufa or lacustrine/palustrine limestone facies associations. Macrophyte tufas and palustrine limestones tends to be distal environments of proximal travertine environment, where HCO_3^- content and current speed is decreased. The relations occur in recent travertines (e.g., Sivá Brada, Stankovany and Hozelec) and in fossil ones (e.g., Dreveník). Darker facies with abundant reed and coarse grass growths (Appendix 17n-r,t-w) can correspond to reed mound facies and appear where water issues from the base of low-angle slopes (Guo a Riding, 1992; Pedley, 2009). Such reed mounds could form at the base of Dreveník spring mounds during the Pliocene.

Over time, changes in total dissolved solids and overflow of waters can occur. As a result, the sedimentation of travertines on the spring mound may turn into moss cushions as in the fossil record on Spiš castle hill. On the contrary, crystalline crust facies were rarely identified in perched sprinline tufa, near a spring (e.g., Hranovnica and Biely Potok), due to increased total dissolved solids in some periods. Banded crystalline crusts inside waterfall tufas point to speleothems in caves under overhangs in waterfalls. Occasionally laminated lime-mudstones can be very closely connected with crystalline crust facies and microphyte mats. The deposits were formed inside a crater or a terrace pools of spring mound (e.g., Levice Vápnik).

In Slovak travertines, the *microphyte shrubs* are rare in contrast to Italian travertines which were originated in warmer dry climate (Gandin & Capezzuoli, 2014; Chafetz & Folk, 1984; Guo & Riding 1994; Rainey & Jones, 2009). Recent microphyte shrub-like forms were identified only on Stankovany Močiar, and real shrubs in Dudince and Santovka travertine lobes with thermal water. Fossil shrub-like forms were found mainly in Spiš and Levice travertines which were originated during warmer climate in the Late Pliocene (Pivko & Vojtko, 2021).

It is possible to observe a continuum between *crystalline shrubs* and *microphyte shrubs*. Bacterial shrub morphology essentially displays no evident mineral habit whereas the crystal shrubs range from a minimal crystal habit, at one extreme, to a pronounced crystal habit, at the other extreme (Chafetz & Guidry, 1999). Dendritic, fan crystals are influenced by mineral habit, but some portion of microphyte growth influence at crystallization is possible (Chafetz and Guidry, 1999). Mainly biogenic control tends to disturb regular crystal shapes. Typical bacterial shrubs or dendrites can be compared in shape to tree or shrub with leafs, but abiotic or mainly abiotic ones to shrub or tree without leafs, rounded vs. pointed (sharp) terminations (Fig. 4, 7c-h, 7C-M).

Slovak travertines, especially Spiš travertine, display many genetic *breccia types*, intraclast travertines. Individual breccias can be distinguished based on e.g., surroundings rocks, matrix, graded bedding, and deformation. The most common breccias were originated by gravitational processes. Deposited travertine beds on slopes were subjected to weathering (dessication, frost, pedogenic processes), block creeping on plastic basement. Loose pieces were exposed to mass wasting caused by torrential rains, occasionally by earthquakes (Gradziński et al., 2013). The heavy rains could bring extraclasts (Hranovnica). Some breccias *in situ* or tepee-like structures (Bešeňová, Vyšné Ružbachy, Dudince Porošin) or large clasts from basement incorporated to freshwater sediment (Veľký Klíž) could be caused by gas pressure eruptions or overpressured hydrothermal fluids. Some travertine breccias were the result of cave collapse. Interformational slip breccias like mylonites were developed inside large fissure ridge (Levice Vápnik).

6. CONCLUSIONS

The most complex and known Slovak recent and fossil travertines were object of their origin and conditions study. Almost 40 fossil and recent travertines, 30 tufas and 15 lacustrine/palustrine limestones were studied in the field and on building stones. Depositional environments are composed of almost 20 abiotic and biotic facies that were described and explained. Summarized knowledge about Slovak freshwater limestones offers material for more detailed and sophisticated climate and tectonic research.

Travertine facies association was identified in spring mounds and fissure ridges with supersaturated water, consisting usually of alternating travertine beds with crystalline crust and microphyte facies, and rare coated bubble facies, raft facies, banded palisade crystal facies, intraclast facies, lime-mudstone facies, laminated fan crystal subfacies, coated grain facies (ooids), and shrub facies. Microphyte mats occur mostly in shallow pools (calm water) and microphyte cruststones in channels (flowing water). Microphyte shrubs were formed during relatively warm climate in the late Pliocene and recent channels with thermal water. There is a continuum between crystalline shrubs with a pronounced crystal habit and microphyte influenced shrubs. Intraclast travertines were primary developed by dessication, frost, pedogenic processes, block creeping on plastic basement, overpressured fluid and gas, and secondary by gravitational and fluvial processes.

Tufa facies association with macrophyte tufa and frequently accompanied by microphytes were abundant in valley dams and perched springline deposits bellow karstic springs. Typical macrophyte tufas are developed with moss cushions, stem, leaf and branch molds, and coated clasts. Characteristic high porous macrophyte fabric can be gradually changed by continued calcium bicarbonate precipitation to dense travertine like deposit.

Palustrine/lacustrine limestone facies association were typically formed in shallow ponds, lakes, marches and soil. The lime-mudstones are accumulated in the beds of several metre thickness that can be enriched with tufa-like reefal microbial mats and microbial cruststones with caddisfly larvae cases, and scattered fossil fragments (gastropods, plants, ostracods) and oncoids.

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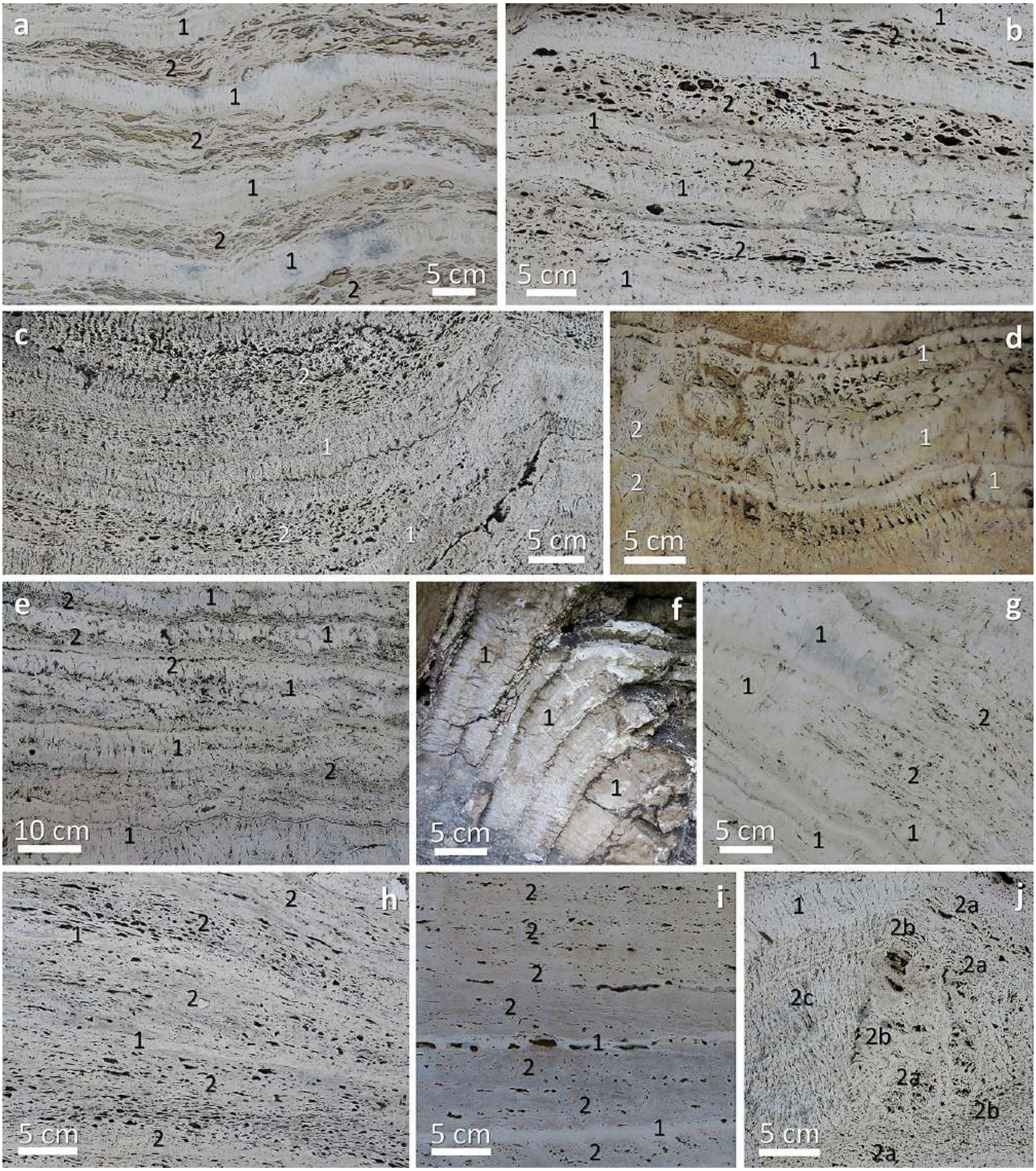
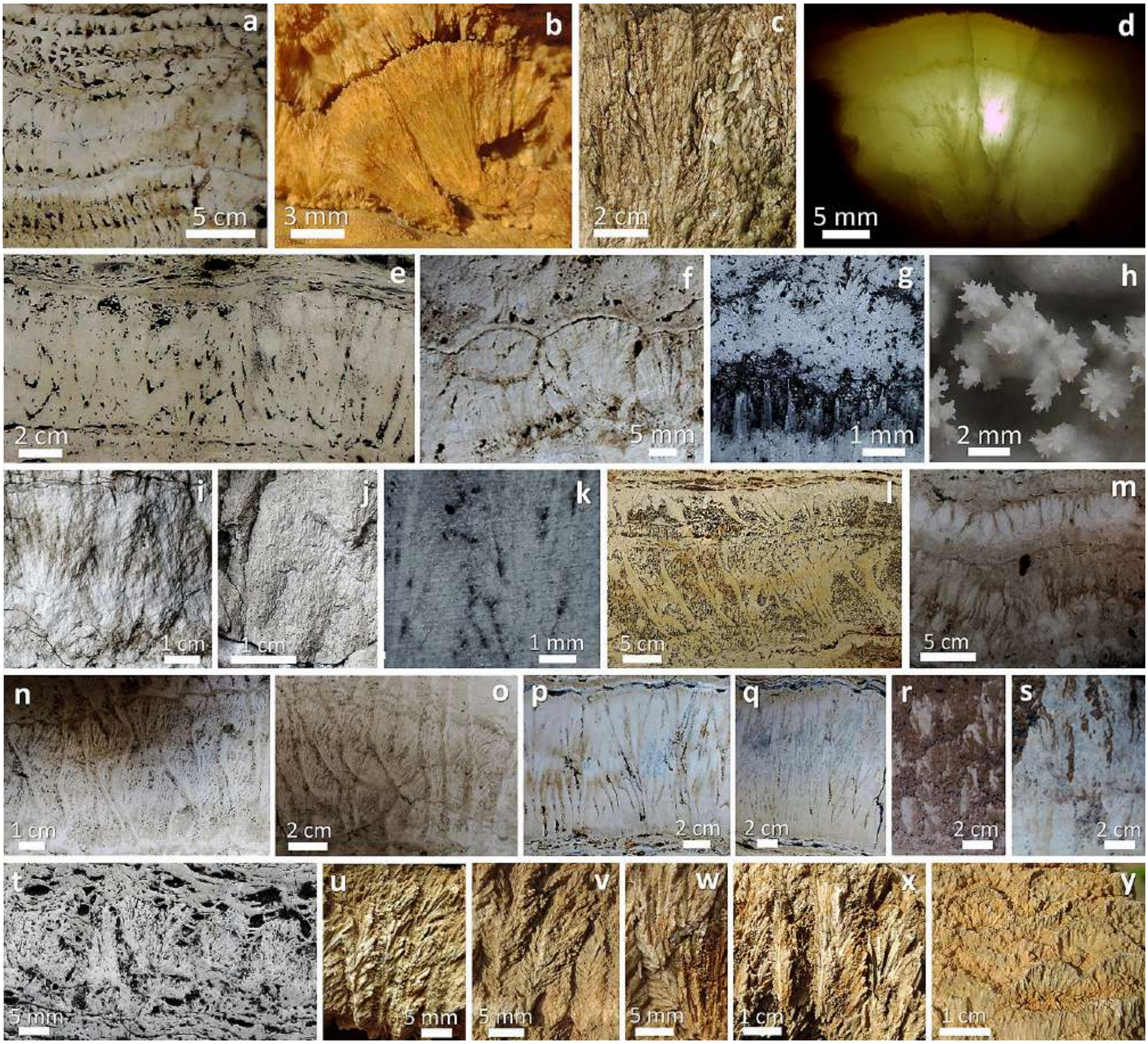
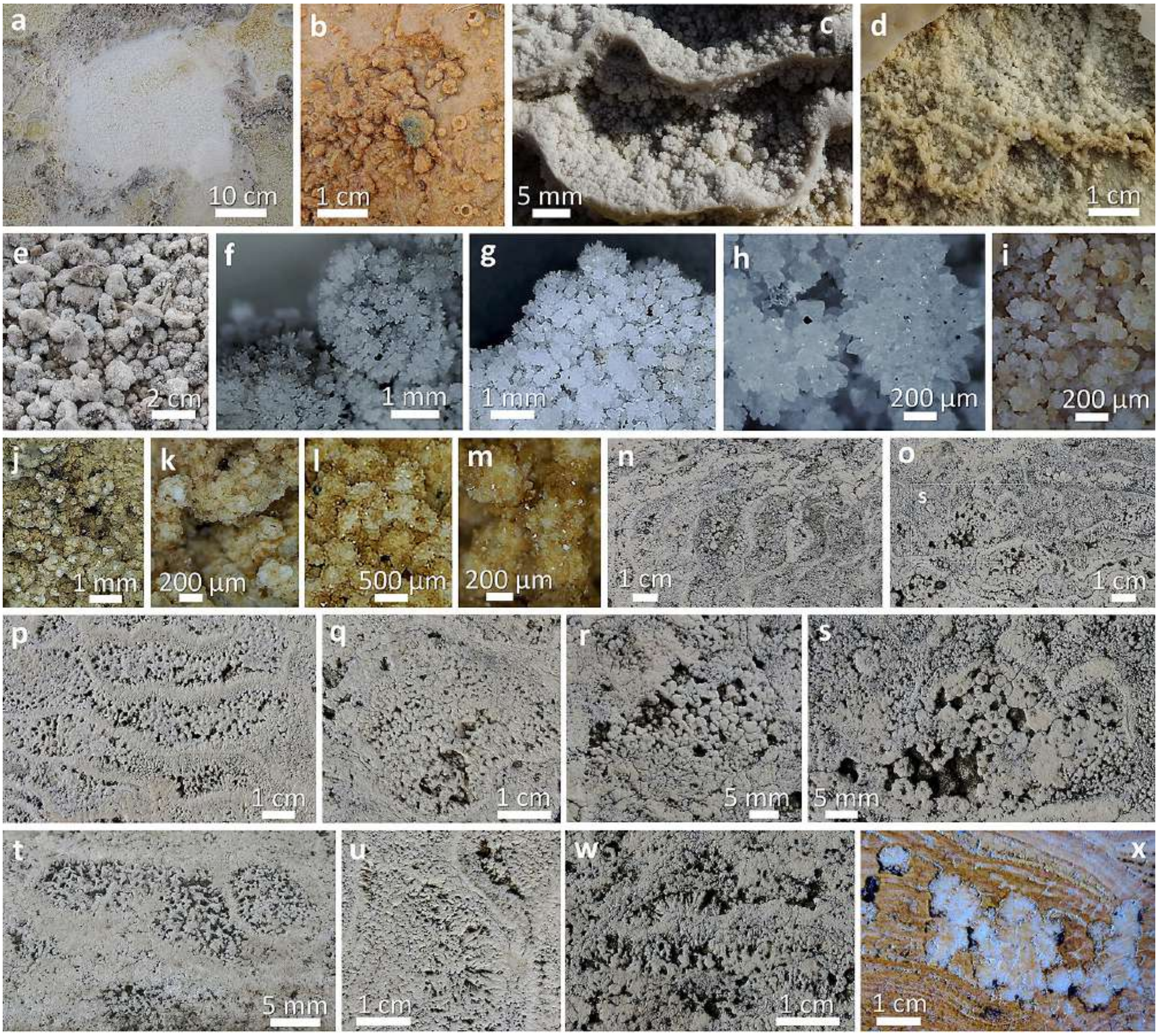


Appendix 1. Alternating and/or simultaneous formation of abiogenic and biogenic facies (1 – mostly abiogenic and 2 – mostly biogenic facies, 2a – microbial mats, 2b – microbial cruststones and 2c – microbial shrubs). **a-b** – relatively regular alternation of abiogenic and biogenic beds in Spiš travertine, **c** – alternating and simultaneous formation of abiogenic and biogenic facies in Spiš travertine, **d** – prevailing of abiogenic facies and simultaneous formation of biogenic facies in Levice Vápnik, **e** – prevailing of abiogenic facies in Spiš travertine, **f** – abiogenic facies in Spiš castle, **g** – simultaneous formation of abiogenic and biogenic facies in Spiš travertine, **h-i** – prevailing of biogenic facies in Spiš travertine, **j** – simultaneous formation of different biogenic facies in Spiš travertine.

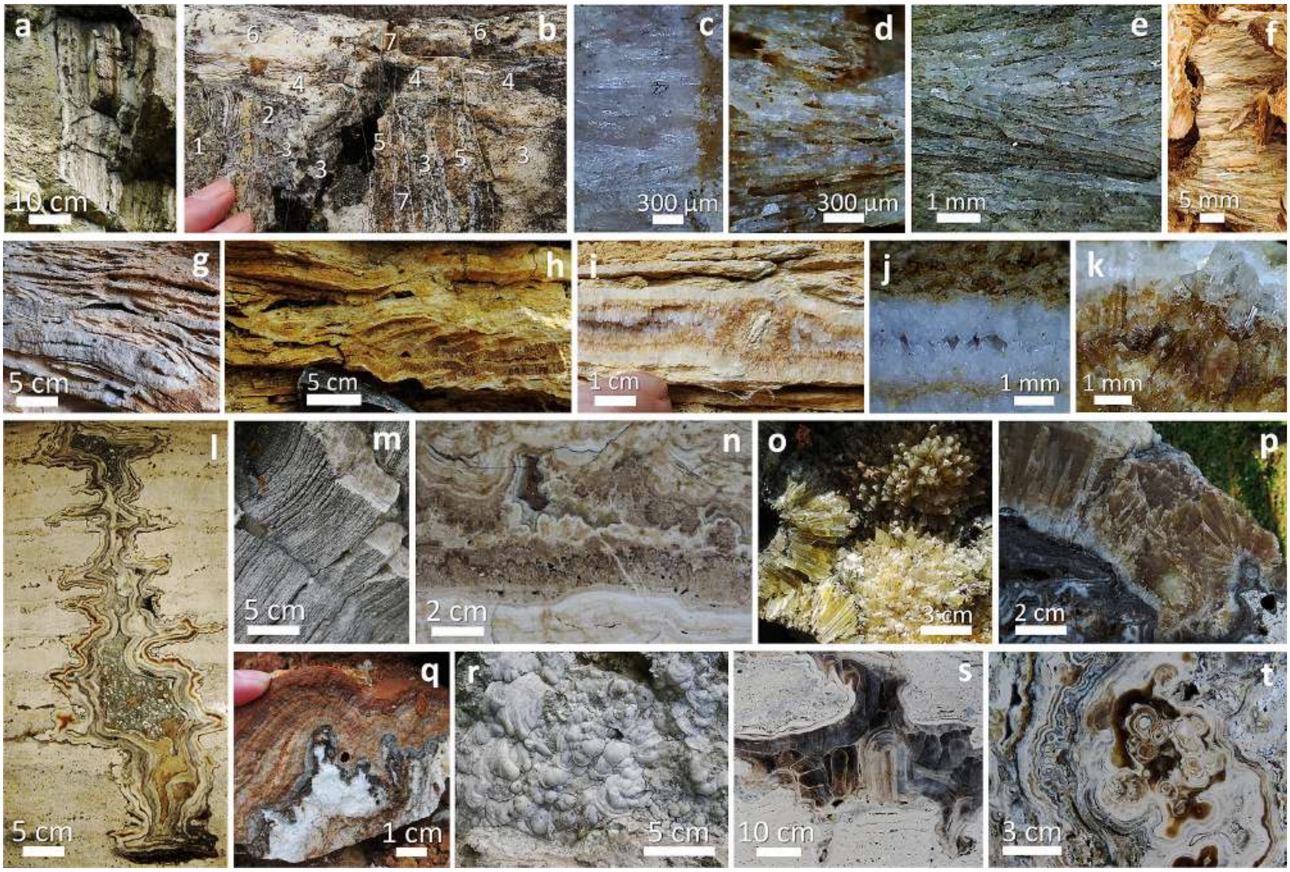


Appendix 2. Calcite crystal shapes in travertine crystalline crusts. **a** – different fan to feather-shaped crystals in Levice Vápnik, **b** – fan-shaped crystals in Levice 'Gold Onyx', **c** – narrow fan-shaped crystals with cleavage in Levice 'Gold Onyx', **d** – backlit fan with indication of lamination in Levice 'Gold Onyx', **e** – overlapping fans in Spiš travertine, **f** – fan to shrub-shaped crystals in Spiš travertine, **g** – shrub-shaped and palisade-shaped crystals in Spiš travertine, **h** – shrub-shaped crystals in recent spring in Dudince spa, **i-j** – inconspicuous shrub crystals in Spiš castle, **k** – touching calcite shrubs in Spiš travertine, **l** – rib-like and shrub-like crystaline calcite separated by biotic facies in Levice Vápnik, **m** – shrub and dendrite crystals in Spiš travertine, **n-q** – dendrite crystals in Spiš travertine, **r-s** – dendrite crystals in Levice Vápnik, **t** – calcite dendrites and shrubs inside microbial laminite in Spiš travertine, **u-v** – asymmetric and symmetric feather crystals in Levice 'Gold Onyx', **w-x** – feather to dendrite crystals in Levice 'Gold Onyx', and **y** – crests with fan crystals going perpendicular to feathers (fig. u-v) in Levice 'Gold Onyx'.

Appendix 3. **Fan-laminated and dendrite-laminated crystals. a – fan-laminated crystals superposed shrub-crystals in Spiš travertine, b – fan-laminated crystals superposed dendrite crystals in Spiš travertine, c – fan-laminated crystals in Spiš travertine, d –fan crystals with indistinct laminae in Spiš travertine, e – dendrite-laminated crystals in Spiš travertine, f – fan-laminated crystals with distinct wavy lamination and invisible to the naked eye dendrite crystals in Ostrá hora (original dip), g – fan-laminated crystals in possible spelethems in Spiš castle, i – shrub crystals passed to fan-laminated crystals in Levice Vápnik, j – fan-laminated crystals in Hranovnica Malacinová, k – dendrite-laminated crystals in Dreveník quarry, l – fan-laminated crystals in Ostrá hora, and m–v – tooth-like shrubs with fan-laminated and dendrite-laminated crystals (m – shrubs along a channel in Dudince, n–o – shrub clusters with and without cyanobacterial growth in Santovka, p – tooth-like shrubs in Dudince, q–r – fan-laminated crystals in Santovka, s–t – dendrite-laminated crystals influenced by cyanobacteria in Santovka, u–v – mineral habit influenced by cyanobacteria filaments in Santovka).**

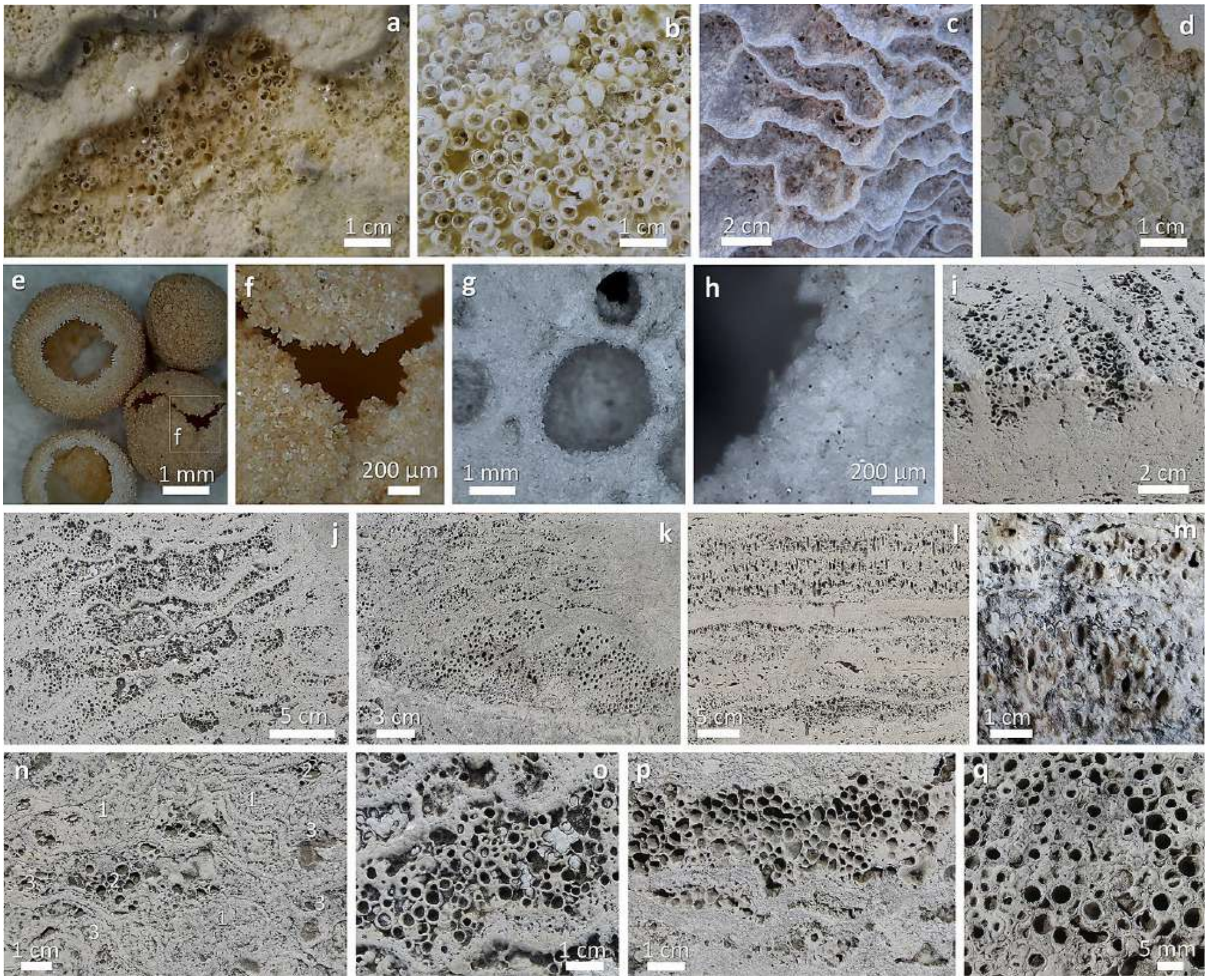


Appendix 4. Radiating dendrites. **a** – shallow pool with radiating dendrites formation in Hozelec meadows, **b** – unregular radiating dendrites with lime mud and coated bubbles in Bešeňová, **c** – radiating dendrite formation inside microterracettes in Sivá Brada, **d** – radiating dendrite and microtteracette rim formation with broken calcite rafts in Sivá Brada, **e** – radiating dendrites in Hozelec meadows, **f** – radiating dendrite detail in Hozelec meadows, **g-h** – radiating dendrite details in Stankovany Močiar, **i** – partly worked radiating dendrites in Bešeňová, **j-m** – two types of radiating dendrites in Dudince Porošin, **n-w** – horizontal sections of microterracettes with radiating dendrites in Spiš travertine (p-s – coalescence of radiating dendrites, s – radiating dendrites with originally organic matter, t-w – relation of microterracette rims with lateral calcite dendrites and intramicroterracette radiating dendrites), and **x** – radiating dendrites inside laminated lime mudstone in Levice Vápnik tile.



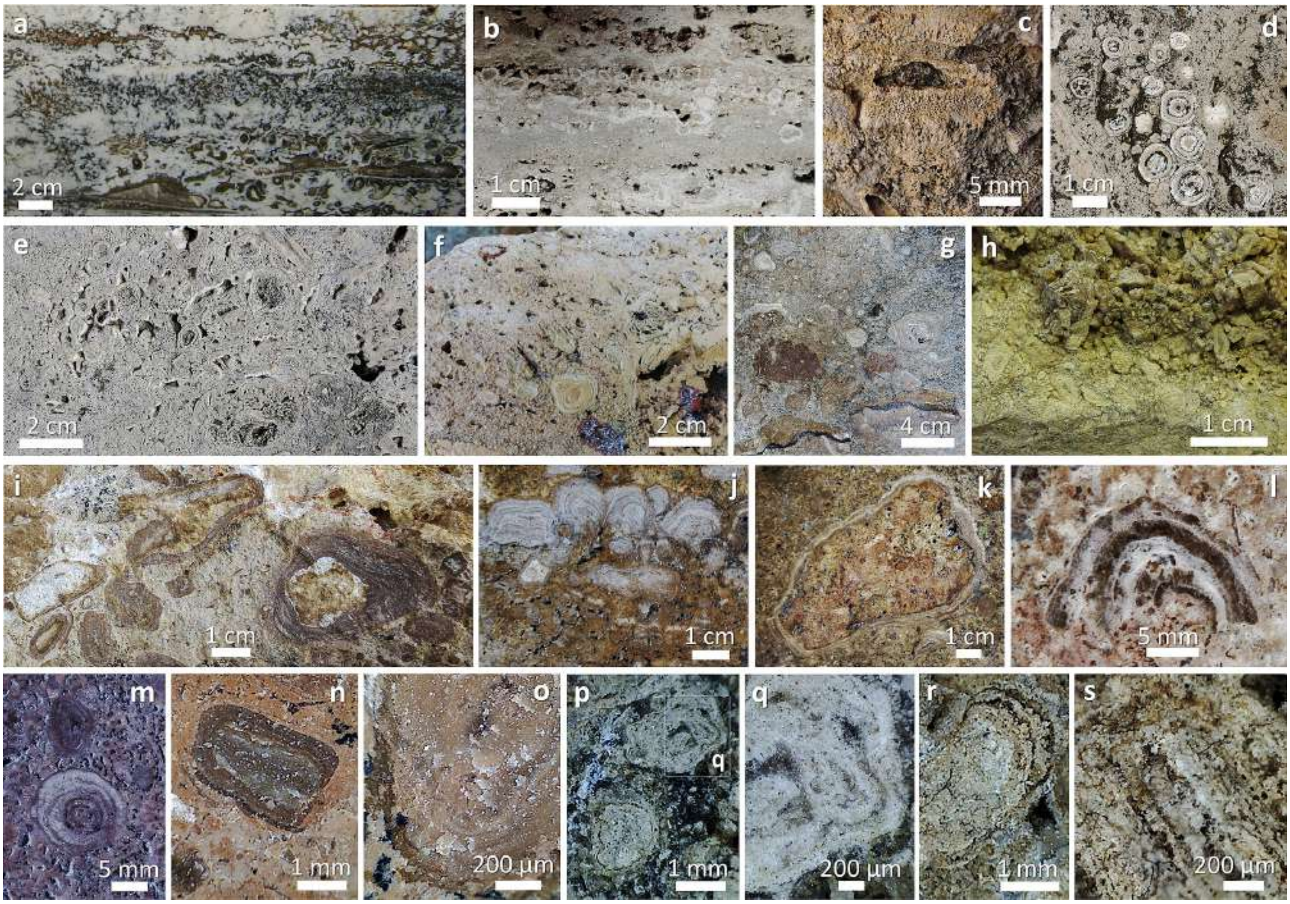
Appendix 5. Banded palisade crystals in veins and speleothems. **a** – vein with banded palisade travertine in Levice Vápnik, **b** – alternate opening of fracture with perpendicular vein fillings in Levice 'Gold Onyx', **c, d** – preserved and corroded columnar and opposite fan crystals in Levice 'Gold Onyx, **e** – opposite fan crystals in Dudince Porošin, **f** – fragments of fibrous opposite fan crystals in Sklené Teplice, **g-k** – sheeted calcite veins with palisade columnar to fan crystals in Dudince Porošin (g – subparallel sheeted veins, h – imbricated veins and original travertine fragment, i – jammed fragment of original travertine inside vein, j – vein filling grown from both sides, k – changeable iron content in vein filling), **l-t** – speleothems in Spiš travertine from Dreveník (l – karstic void parly filled with banded calcite crystals, m – regular laminae with palisade and fan crystals, n – banded and dendritic speleothems, o – fan crystals with scalenohedral termination, p – palisade and fan crystals, q – banded fan crystals on unregularly corroded travertine surface, r – botryoid surface of banded fan crystals, s, t – banded speleothems of dripstones in karstic voids).

Appendix 6. Recent calcite coatings, rafts (floes) and fossil raft facies. **a** – thin calcite coating with trapped bubbles on pool surface in Bešeňová, **b** – broken calcite coating with rafts in Hozelec Banícka, **c** – breaking of calcite coating with big bubble in Hozelec Banícka, **d** – microterracettes partly covered by calcite coating in Bešeňová, **e** – microterracette coating broken to rafts in Bešeňová, **f, g** – brittle microterracette coatings broken to rafts in Sivá Brada, **h** – calcite rafts influenced by cyanobacterial film in Hozelec Lúky, **i** – calcite crystals of raft edge in Stankovany Močiar, **j** – mixture of calcite rafts, cyanobacterial crusts and radial dendrites in Sivá Brada, **k** – very thin calcite film deformed by bubbles and flow in Stankovany Močiar, **l** – very thin ductile calcite film influenced by bacteria in Sivá Brada, **m** – deform fragments of ductile calcite film in Stankovany Močiar, **n,o** – raft facies influenced by cyanobacterial coatings in Spiš travertine, **p** – predominantly abotic (A) and biotic rafts-crusts (B) inside karstic (K) void in Spiš travertine, and **q** – relatively thick abiotic-biotic rafts inside narrow fissure in Dreveník.



Appendix 7. Recent coated bubbles and fossil coated bubble facies. **a** – coated bubble formation inside microterracettes in Sivá Brada, **b** – coated bubble formation inside shallow pools in Hozelec meadows, **c** – coated bubbles in dry microtteracettes in Hozelec Baníčka, **d** – coated bubbles and rafts in dry microtteracettes in Sivá Brada, **e-h** – coated bubbles covered by microsparite to sparite crystals in recent Bešeňová travertine (e, f) and in fossil Spiš travertine (g, h). **i** – microtteracettes filled with coated bubbles in 3D image of Spiš travertine, **j-k** – horizontal cut of coated bubble facies with narrow (j) and wide (k) microterracettes in Spiš travertine, **l-m** –vertical cut of coated bubble facies in Spiš (l) and Levice (m) travertine, **n** – microterracettes with radiating dendrites (1), coated bubbles (2) and microbial mats (3) in Spiš travertine, and **o-q** – horizontal cut of coated bubble facies in Spiš travertine (o – wide, p – narrow and q – multiply calcite coatings).

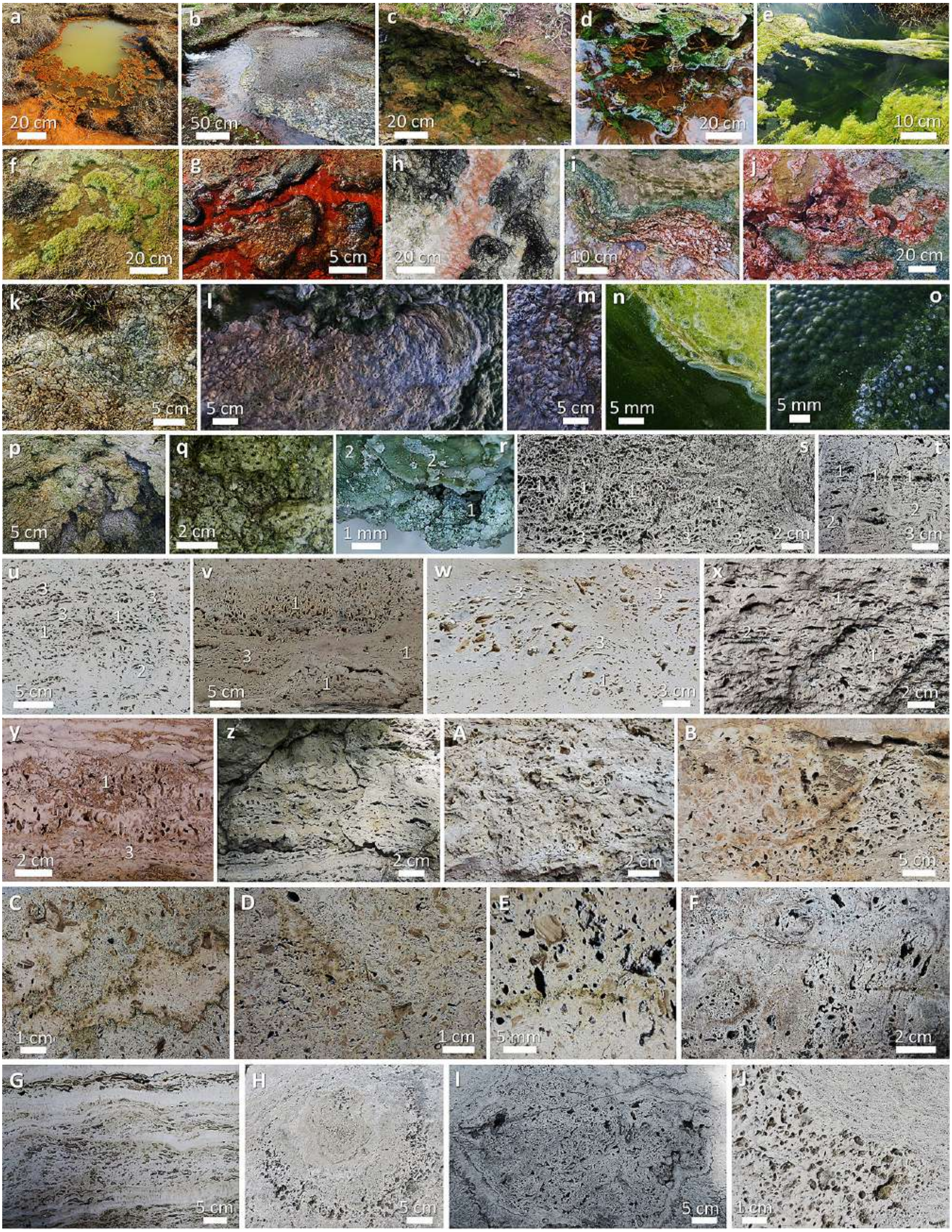
Appendix 8. Different types of intraclast facies and extraclasts. a, b – partly rounded intraclasts (radiate dendrites, crystalline clast fragments) in recent Sivá Brada (a) and in fossil Spiš travertine (b), c – partly rounded tufa intraclasts by stream in Omšenie, d-e – fractured and fragmented crystalline crust in Spiš travertine, f – by drying fractured lake limestone between Sliač spa and Lukové, g – soil with fragments of crystalline travertine and subsequent crystalline travertine beds intruded to unconsolidated soil in Spiš travertine, h – probably by frost fractured travertine bellow Spiš castle, i – weathered crystalline crust and partly displaced fragments in 3D cut of Spiš travertine, j – intraclast facies with matrix and angular fragments in 3D ashlar of Spiš travertine, k – intraclast facies formed by mass wasting of weathered travertine clasts, l – microterracettes filled with intraclasts moved downward in Spiš travertine, m-o – intraclast facies in Spiš travertine (j – with matrix, k – without matrix and l – with raft fragments), p – limestone extraclast inside lime mudstone of fossil lake in Veľký Klíž, q-r – partly weathered and collapse breccia in fissures of Dreveník, s-t – interformational slip breccias in Levice Vápnik with big fragment of vein (white line) and slip surfaces (black dashed lines), with brittle and ductile deformed deposit fragment (before injected from superposed deposits into fractures), and u – hydrothermal breccia in Dudince Porošin.



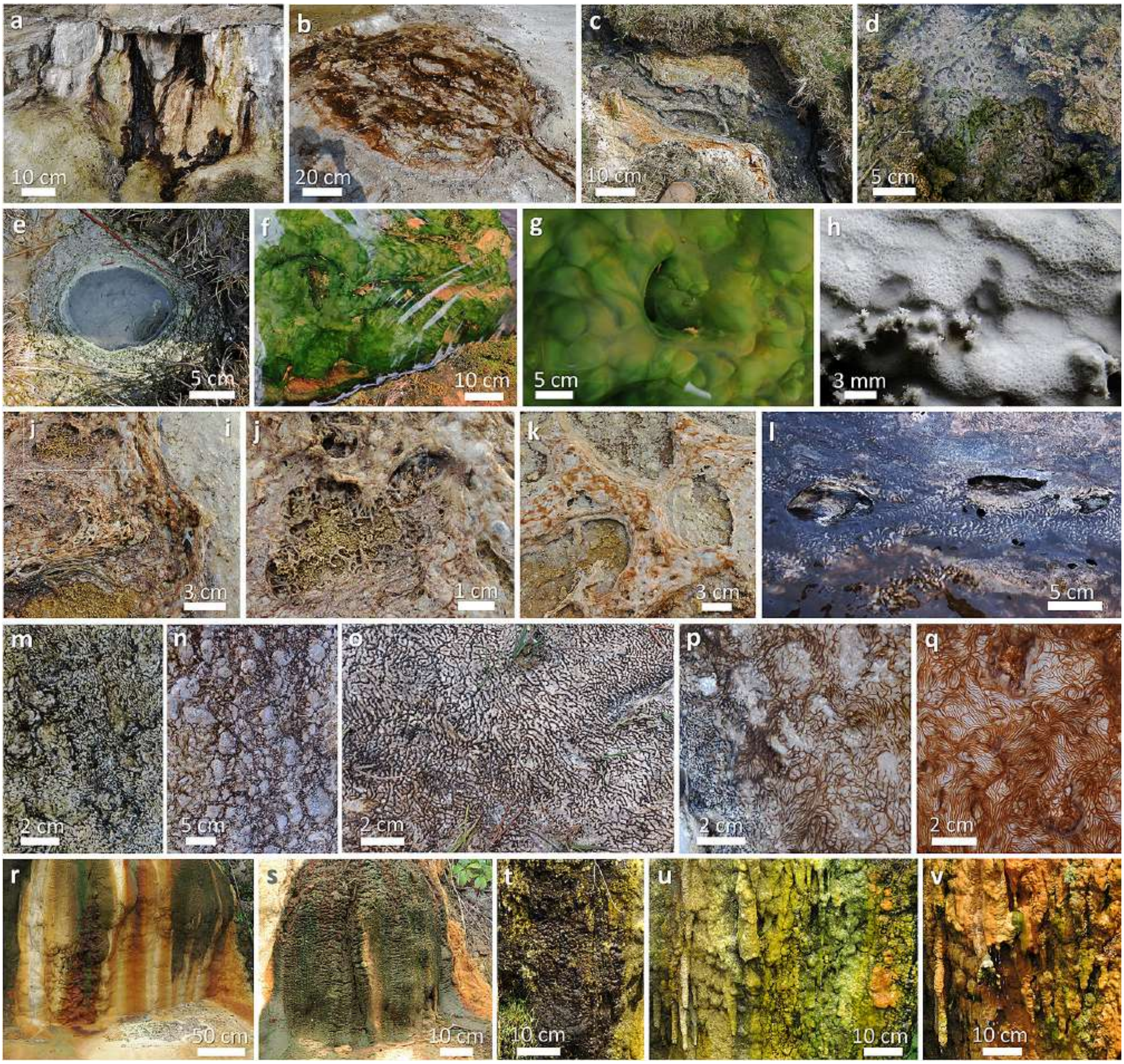
Appendix 9. Coated grain facies. **a** – shrubs, coated grains and radiate dendrites in Spiš travertine, **b** – coated grains with radiate dendrites in Spiš travertine, **c** – microphyte shrub coatings of macrophyte fragments in the Tortonian limestone of Nitra Castle, **d** – pisoid-like coatings of stems in Spiš travertine, **e** – complex macrophyte coatings of different thickness in Spiš travertine, **f** – oncoids and big coated intraclast in Levice Vápnik, **g** – oncoids and intraclast facies in Klíž travertine, **h** – oncoidal facies in Vrútky, **i** – coated grain facies in Veľký Klíž, **j** – unilateral oncoids attached to microbial bioherm in Klíž travertine, **k** – big coated intraclast in Klíž travertine, **l** – broken oncoid in Klíž travertine, **m** – oncoid with white shrub growths in its layers in Klíž travertine, **n, o** – microsparite and micrite layers of oncoids in Veľký Klíž, **p-s** – microsparite and micrite layers of oncoids in Vrútky freshwater limestone.

Appendix 10. **Lime mudstone facies. a – shallow pool with microbial cruststones and lime mud in Hozelec meadows, b – cloudy water, as calcite crystal fallout (whiting) in shallow pool with radiate dendrites in Hozelec meadows, c, d – intraclasts and lime mud in Sivá Brada, e – lime mud with coated bubbles in Bešeňo-vá, f-h – steep beds with lime-mudstones in Dreveník travertine (h – undulate lamination), i-k – lime mudstone facies in Ostrá hora travertine (1 – crystalline crusts, 2 – lime-mudstones, 3 – indistinct microphyte facies, k – visible microphyte net in weathered part), l – microsparite of lime mudstone in Ostrá hora, m – lime mudstone facies in Levice 'Gold Onyx', n – lime mudstone facies in Levice Vápnik, o-q – microsparite and micrite of lime mudstone in Levice Vápnik (o – with sparite vein), r – lime mudstone facies in Vrútky, s – microsparite and micrite of lime mudstone in Vrútky, t – lime mudstone facies in Dudince Porošin, u, v – microsparite of lime mudstone in Dudince Porošin, w, x – lime mudstone facies with scattered biotic fragments in Veľký Klíž, y, z – microsparite of lime mudstone in Veľký Klíž, A, B – dessication features – mud cracks (A – in Veľká Lúka, B – in Malé Kršteňany), C-E – yellow-orange mottling – marmorisation (C – in Podhorany, D – in Ratnovce, E – in Čeľadince), F-H – nodulisation (F – in Veľká Lúka, G – in Veľké Bielice, H – in Slovenské Pravno), I, J – irregular cavity network – pseudomicrokarst (I – in Malé Kršteňany, J – in Veľká Lúka), and K, L – root cavities (K – in Veľká Lúka, L – in Dudince-Porošin).**

Appendix 11. **Recent and fossil microphyte mat and mat facies. a –cyanobacterial mats on shallow pool surface in Bešeňová, b-d – microphyte mats inside artificial pools in Sliač spa (b – floating on surface, c – growing on bottom, d – green algae mats), e – green algae mats (bottom) and directed filaments (top), f – microphyte mats with green algae and bubbles in Vyšný Sliač, g – cyanobacterial mats with bubbles bounded by current directed filaments in Bešeňová, h – sessile cyanobacterial mat mounds, in Sivá Brada, i, j – cyanobacterial (red-brown) and green algae (green) mats partly impregnated by calcite in Hozelec meadows (i – wrinkled mats by stronger input or by wind), k – partly dried cyanobacterial mat with abundant bubbles in Stankovany Močiar, l-m – partly dried microphyte mats with bubbles in Hozelec meadows, n – green algae filaments directed by current (left) and floating mat with bubbles (right) in Vyšný Sliač, o – algal mat rich in bubbles partly impregnated by calcite (right), p-r – cyanobacte-**

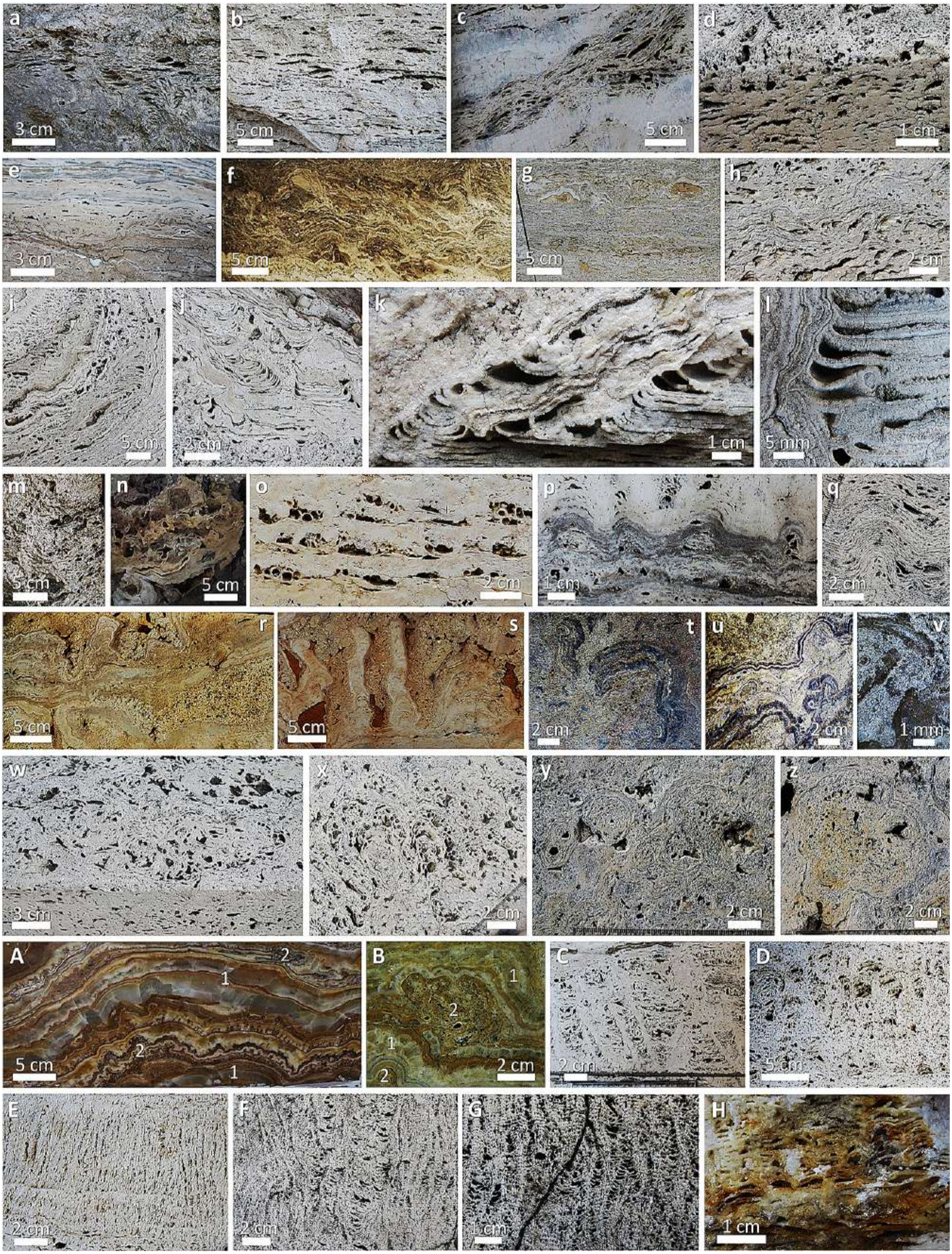


rial mats in shallow pool in Sivá Brada (q – spongy network with filaments and bubbles gradually coated and replaced by calcite, r detail image of (1) mat and (2) cruststone), **s-y** – mostly microphyte mat facies (1) of different appearance in Spiš travertine (2 – cruststone facies, 3 – transition to cruststone facies), **z** – mat to cruststone transition facies in Ostrá hora, **A-B** – mostly microphyte mat facies in Levice travertine, **C-F** – microphyte bioherms with mat facies in Klíž travertine (C unregular porous mat facies with voids filled by lime mudstone facies, E – contact of mudstone facies (bottom) and mat facies (top), F – unregular small bioherms of mat facies inside lime mudstones facies), **G-J** – sharp mat facies contact with crystalline crust facies in Spiš travertine (horizontal section except for G).



Appendix 12. Recent microphyte biofilms and cruststones. **a** – current directed cyanobacterial biofilms around spring in Hozelec Banícka, **b, c** – current directed cyanobacterial biofilms in Stankovany Močiar (b – in open pool, c – in channel), **d** – current directed network of cyanobacterial filaments between cyanobacterial mats in Sivá Brada, **e** – cyanobacterial filaments with bubbles directed to a circle around water outflow in Stankovany Močiar, **f, g** – directed algal coatings on channel bottom in Sliač spa, **h** – microphyte-like net without visible organisms and calcite shrubs in thermal spring in Dudince spa, **i-k** – dried calcite cruststones, previously current directed cyanobacterial biofilms, **l** – current directed cyanobacterial colonies in channel of Hozelec Banícka, **m-q** – cyanobacterial colonies with different pattern (m – Sivá Brada, n, o, p – Hozelec Banícka, q – Hozelec meadows), and **r-v** – microphyte influenced cruststones in coatings and dripstones on lobe bellow thermal outflow in Sklené Teplice.

Appendix 13. Fossil cruststone facies. **a** – vertical sections of cruststone facies in Biely potok, **b-h** – vertical sections of cruststone facies with dominant convex shapes in Spiš travertine (d – 3D ashlar with cruststone downand shrub facies up), **i** – convex cruststone facies grown on bottom part of waterfall of crystalline crusts in Spiš travertine, –d – 3D ashlar with transition to mat facies, **j-l** –concave cruststone to raft facies inside voids of intraclast facies in Spiš travertine, **m** –cruststone microphyte to macrophyte facies in Gánovce travertine, **n** – cruststone microphyte to macrophyte facies in Plavecký hrad tufa, **o** – cruststone facies with coated bubbles in Levice travertine, **p-q** –stro- ▶



matolite-like cruststone in Spiš travertine, r-s – **microphyte stromatolites with intraclast facies from shallow pools in Levice travertine (r – subhorizontal cut, s – subvertical cut), t-v – laminar cruststone facies of lake bioherms in Klíž travertine, w-z – subhorizontal sections of stromatolite-like cruststone in Spiš travertine, A-B – subhorizontal cut of travertine lobe with curtains and dripstones composed of palisade crystal facies (1) and microphyte-macrophyte cruststone facies (2) in Levice 'Gold Onyx', and C-H – microphyte cruststone columns grown among calcite crystals in Spiš travertine.**

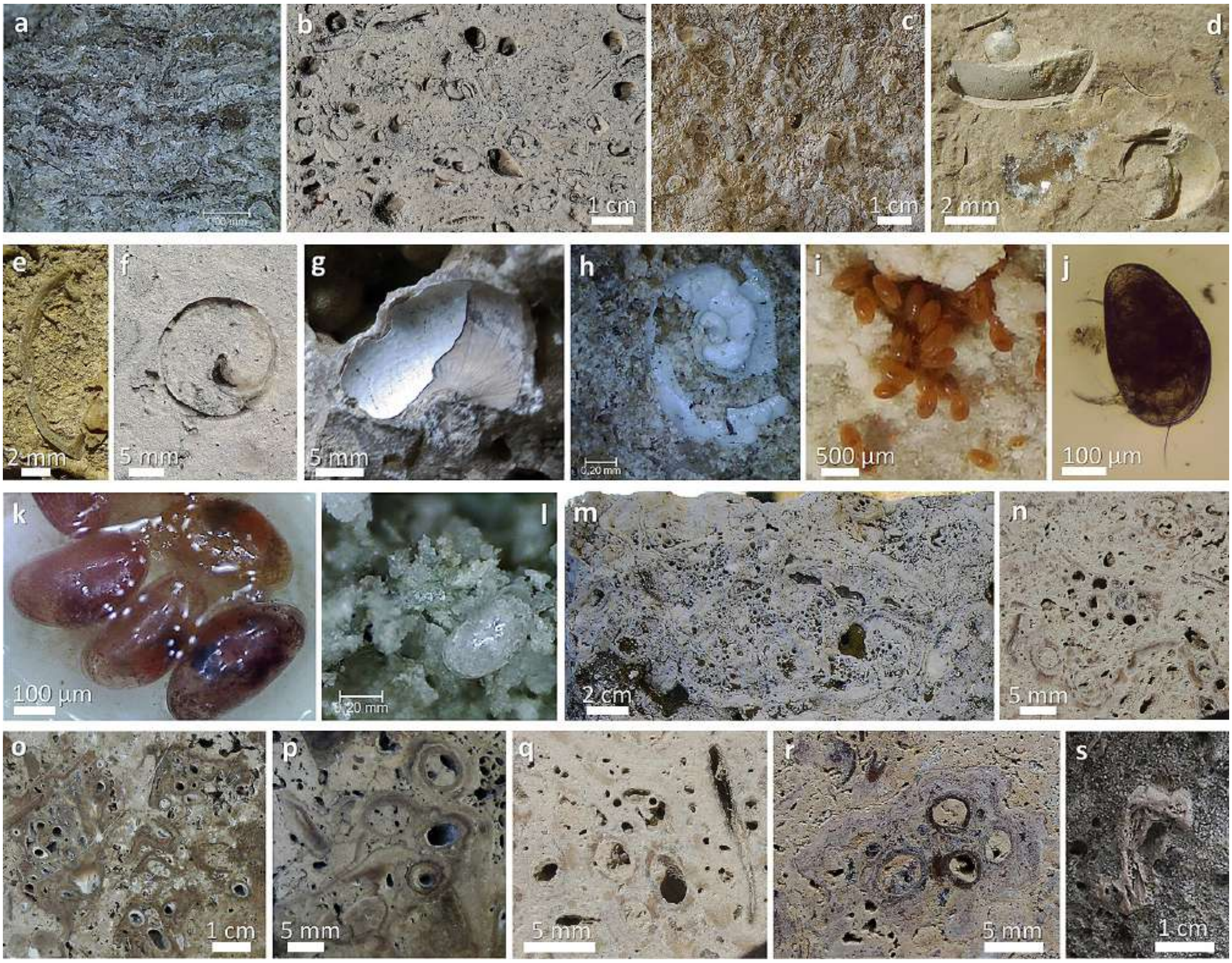
Appendix 14. Microphyte wide, narrow and fili shrub facies. **a** – shrub formation from EPS of diatoms and cyanobacteria in Stankovany Močiar, **b-e** – shrubs formation in shallow pools with cyanobacteria and diatoms in Hozelec meadows (b-c), Hozelec (d) and Sivá Brada (e), **f** – filament cyanobacterial or algal shrubs in tufa near Topoľčany, **g-l** horizontal section of microterracettes filled with different shrubs influenced by abiotic and biotic processes in Spiš travertine, **m-n** – shrubs influenced by abiotic and biotic processes in Stankovany Močiar (m) and Vrútky (n), **o-A** – vertical section of Spiš travertine with different types of wide shrub facies, **B** – wide and narrow shrub facies in Spiš travertine, **C-L** – vertical section of Spiš travertine with different types of narrow shrub facies, and **M-Q** – vertical section of Spiš (M-P) and Levice (Q) travertine with different types of fili shrub facies.

Appendix 15. Microphyte arborescent, arbustiform and pustular shrub facies. **a-h** –arborescent shrub facies in Spiš travertine (a,b,f,h – with transition to fili shrub facies), **i-k** – arborescent shrub facies in Levice travertine, **l-u** – arborescent shrub facies with bent deform shrubs in Spiš travertine, **v-w** – arborescent to arbustiform or wide shrub facies in Levice travertine, shrub facies in Spiš travertine, **x** – wide shrub to arbustiform shrub facies in Spiš travertine, **y-z** – arborescent to arbustiform shrub facies in Spiš travertine, **A-E** – arbustiform shrub facies in Spiš travertine, **F-K** – pustular and pustular relative shrub facies in Vrútky (F), Spiš (G-J) and Vyšné Ružbachy travertine (K).

Appendix 16. Macrophyte facies of *Charales* (stonewort) and *Bryophytes* (moss, livewort). **a-b** – molds of stonewort branches in Levice travertine, **c-d** – molds of stonewort branches and tiny oogoniums in Spiš travertine, **e** – moss and cyanobacteria curtains in Hrhov waterfall, **f-g** – moss (f) and liverwort (g) curtains in Háj waterfall, **h-i** – prograding calcite precipitation (2-4) on moss cushion (1) in Krásnohorská Dlhá Lúka, **j-q** – thin encrustation of moss stems with visible morphology in tufas of Hrhov (j), Ludrová (k), Omšenie (l-m), Hradište pod Vrátnom (n-o), Štítnik castle (p), Uhrovec castle (q), **r-z** – thick encrustation of moss stems without visible morphology in tufas of Vyšný Sliač (r), Hranovnica (s), Hrhov (t), Háj (u), Omšenie (v), Biely Potok Bukovina (w-x) , Lúčky spa (y), Plavecký hrad castle (z), **A-D** – encrusted moss stems in Biely Potok Trlenská tufa (C-D with visible morphology, and **E-H** – moss stems in Levice Gold Onyx.


a
5 mm
b
5 cm
c
3 cm
d
2 cm
e
1 cm
f
5 cm
g
3 cm
h
3 cm
i
1 cm
j
2 cm
k
5 cm
l
5 cm
m
5 cm
n
1 cm
o
1 cm
p
1 cm
q
2 cm
r
2 cm
s
1 cm
t
1 cm
u
2 cm
v
2 cm
w
2 cm
x
1 cm
y
5 mm
z
1.00 mm
A
1.00 mm
B
5 mm
C
5 cm
D
5 cm
E
5 cm
F
5 cm
G
2 cm
H
50 cm
I
20 cm
J
20 cm
K
20 cm
L
10 cm

Appendix 17. Macrophyte facies of vascular plants. **a** – fine calcite precipitation on stems and leafs in Bojnice tufa, **b-e** – thick calcite precipitation on stems in Sklené Teplice travertine/tufa (b), Hrhov tufa (c), Motyčky tufa (d-e), **f-g** – bunch of plant stems in growth position in Spiš travertine, **h-i** – stem pieces in Spiš travertine, **j** – mildly encrusted stems in Motyčky tufa, **k-m** – gradual filling of space by calcite precipitation in Bojnice tufa (k – spaces among encrusted stems were filled with calcite, l – voids after rotten stems were parly filled with calcite, m – almost all smaller voids were filled with calcite), **n-r** – encrusted stems in Spiš travertine (n – crystalline shrub encrustation in growth position, p – probably inside rotten *Typha*, q-r – multiply encrustation in growth position), **s** – stem pieces encrustation in Hlavina Member fresh limestone, **s** – lateral section of plant stems growing in microphyte cruststone in Spiš travertine, **t-w** – encrustation of reed stems in Spiš travertine (u-w – probably *Typha* stems and leafs), **x** – horizontal sections of encrusted bunch of plant stems in Spiš travertine, **y-z** – encrusted stems in recent tufa (y – in Hranovnica Malacinová, z – Stankovany Močiar), **A** – incrusted stems in Klíž travertine, **B** – seed molds in Vyšný Sliač tufa, **C** – leaf encrustation in recent Tajov tufa, **E-G** – leaf molds and leaf encrustations in Vyšné Ružbachy (D), Motyčky (E), Krivoklát (F-G), **H-I** – tree trunk molds in Biely Potok Jazierce, and **J-L** – empty and filled (by breccia) mold after tree trunk in growth position in Spiš travertine.



Appendix 18. Animal remnants inside freshwater limestones. **a** – detrit of mollusca shells in Vrútky freshwater limestone, **b-h** – gastropod shells in Spiš travertine (b,f), in Hlavina Mb. used in Nitra castle (c), in freshwater limestone near Sliač spa (d,e), in Hradište pod Vrátnom tufa (g), in Vrútky freshwater limestone (h), **i-l** – living ostracods (i-j) and their valves (k,l) in Stankovany Močiar (i,k), in Hozelec meadows (j), in Sivá Brada recent travertine (l), **m-r** – caddisfly larvae cases in Klíž travertine (Hlavina Mb.), and **s** – part of a vertebrate bone in Klíž travertine used in Bojnice castle.