A review of travertines and tufas in Slovakia: Geomorphology, environments, tectonic pattern, and age distribution

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Abstract: Slovakia is rich in the Pliocene, Pleistocene travertines and Holocene tufas and travertines, which were studied in 82 localities. Travertines are developed in the spring mounds (49 %) with central orifices frequently in crater-like forms. Fissure ridges (6 %) with vertical veins were identified. A few mounds and ridges were connected to large coalesced mounds (2 %). Many tufas and travertines were formed in perched springline deposits (21 %). The mounds, ridges, and perched springline deposits have the slopes with prograding cascades, fewer included waterfalls. The dams on slopes were very rare. Most tufas were formed in dams along streams (20 %), usually with waterfalls and caves. The upper Miocene freshwater limestones in 5 localities were originated in lakes and marshes (2 %). The Slovak travertines are usually related to regionally important faults such as the N–S striking Central Slovak Fault System (17 sites). Westwards, NE–SW striking faults related to the travertine occurrences prevailed (3 sites). In northern and eastern Slovakia, the faults have generally W–E to NW–SE strike direction (15 sites). The travertines are often formed on the fault intersections and they are related to the extensional tectonics.

Key words: travertine, tufa, freshwater limestone, morphology, Neogene, Quaternary, neotectonics

1. INTRODUCTION

Slovakia is rich in travertines and tufas. The travertines were found on about 70 and tufas on about 300 sites (Kovanda, 1971). Many travertines were used as the most important ornamental stones of Slovakia. The best of them were mainly exported to Germany, France, Great Britain and also the USA and Australia during the first half of the 20th century. The most representative white 'Spiš travertine' (*spišský travertín* in Slovak) can be seen on public buildings in the most Slovak towns. Numerous unpublished research reports concerning the extraction of travertine were summarised in Čabalová's paper and monograph (Čabalová, 1969, 2013).

Travertines and tufas, as freshwater limestone types, have been intensively studied in recent years (for further information see chapter 2). They were deposited in various continental environments, mainly near mineral spring and in streams. Most travertines were formed from the degassing of CO_2 rich groundwater containing > 2 mol·l^{-1} Ca (Pentecost, 2005). Carbon dioxide is lost from solution on contact with an atmosphere whose CO_2 concentration is lower than in the solution:

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

Groundwater capable of depositing travertine or tufa originates when CO_2 present in water dissolves carbonate rocks to form a solution containing calcium and bicarbonate ions, the reverse of the above reaction. The most important sources of underground CO_2 capable of contacting and dissolving carbonate rocks are the respired soil-zone CO_2 (meteogene) and thermally generated CO_2 (thermogene). Where the evasion of carbon dioxide occurs to the surface atmosphere, additional CO_2 loss frequently occurs through the photosynthesis of aquatic plants and evaporation.

Travertines (thermogene travertines *sensu* Pentecost, 2005) are located near springs, fed with deeply circulating thermal waters, generally over 30°C that are rising along tectonic faults. Travertine water is chiefly characterised by very high HCO_3^- content (> 7 mmol·l^{-1}). The travertines are typified by high depositional rates, regular bedding, low porosity (< 30 %), and an inorganic crystalline and organic microbialite fabric. *Tufas* (meteogene travertines *sensu* Pentecost, 2005; *penovce* in Slovak) are typically produced under ambient temperature, high HCO_3^- content (< 6 mmol·l^{-1}), and water of karstic areas. They are characterised by relatively low depositional rate, producing highly porous bodies (> 40 % of porosity) with poor visible bedding, but containing abundant remains of microphytes and macrophytes. The deposits similar to tufas that form the distal travertine continuation are referred to as *'travitufa'* (Capezzuoli et al. 2014).

Slovakia, as a mountainous country, belongs to the Western Carpathians and partly to the Pannonian and Vienna basins lowlands which comprises the northeastern portion of the Alpine orogenic belt. The internal part of the Western Carpathians is built by nappe stack, which is represented by thick-skinned tectonic units (Tatric, Veporic, and Gemeric units, respectively) covered by thin-skinned nappe system (e.g., Fatric, Hronic, and Meliata-related tectonic units; cf. Hók et al., 2014). The thin-skinned nappe pile is predominantly composed of Mesozoic variable carbonate rocks, which are the source rocks of carbonate-rich waters for 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 the extensional tectonic regime, in which volcanic products covered the Eoalpine nappe stack 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

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Miocene/Pliocene boundary. It was the beginning of the dome morphostructure formation before 4 Ma to 6 Ma, with the main stage of the uplift following in 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 lying under the impermeable Palaeogene or Neogene siliciclastic or volcanic deposits (Fordinál & Nagy, 1997; Ložek, 1992; Gradziński et al., 2015). Small part of travertines and tufas are being formed recently.

Because of the disproportion of travertine, tufa, fen and lake-marsch forms in Slovakia is 70:300:40:10 (Kovanda, 1971), 87 most representative ones were selected and studied for the needs of the paper in the ratio 33:40:9:5. The localities provided the most preserved forms, many of which are protected by the state. Previous knowledge for 50 years was summarised in English for the first time, and new knowledge was added in the light of modern research on morphology and environment, that is the basis for further detailed investigation. The freshwater limestones are composed of different facies. A summary of the new knowledge about the facies in Slovakia will be published in the following article, as the issue is too broad to fit in this article.

2. TRAVERTINE AND TUFA MORPHOLOGY: STATE OF THE ART

The environment and morphology in which travertines were formed were described in numerous papers. Scheuer & Schweitzer (1981, 1985), Schweitzer & Scheuer (1995) illustrated morphologies of many types of thermal travertine cones (mounds), also travertines on valley side, lacustrine-paludal travertine, *tetarata* barrier travertine, and travertines of mixed types on examples from Hungary. The morphology of mainly thermogenic travertines was described by Chafetz & Folk (1984) who recognised basic forms: waterfall, lake-fill, sloping mound, terraced mound, and fissure ridge. Guo & Riding (1998) in Italian Rapolano Terme distinguished slope depositional system with 'smooth slope facies', 'terrace slope facies', and 'waterfall facies', depression depositional system with 'shrub-flat' and 'marsh-pool facies' and mound depositional system with 'reed mound facies'. Özkul et al. (2002) added 'fissure ridge' and 'self-building channel system' to these environments from Turkish Pamukkale. Fouke et al. (2000) defined vent, apron and channel, pond, proximal slope and distal slope facies based on their fabrics in Mammoth Hot Springs (USA). Pentecost (2005) summed up previous knowledge of morphology to spring mounds, fissure ridges, cascades, dams, fluvial crusts, lake and paludal deposits, cemented rudites and clasts, and speleothems. Pedley (2009) improved previous definitions for tufas to perched springline, fluvial, lacustrine and paludal models, and cascade tufas. Morever, he outlined fissure ridge model, terraces and range front sheet model, slope depositional system, depression depositional system, and mound depositional system for travertines. The difference between travertines and tufas was eloquently defined in Capezzuoli et al. (2014), where 'vent environments (proximal)', 'slope environments (intermediate)', and 'distal environments' were assigned to travertines, while 'resurgence environments (proximal)', 'intermediate environments', and 'distal environments' were assigned to tufa. Brogi et al. (2014, 2016) elaborated the fissure ridge environment in more detail.

The most detailed description of freshwater carbonates in Czechoslovakia and a detailed list of references was summarised by Kovanda (1971). He defined travertine and tufa bodies as mounds, additional mounds, craters, valley, and slope cascades. From the previously published papers, it is necessary to mention works of Ivan (1943, 1952), which described approximately 70 Slovak travertine localities with following types: mound with crater pool and possible side springs, terraced travertine, travertines of cold springs with abundant plants and valley travertines. However, the travertines of cold springs with abundant plants and valley travertines would be recently defined as tufas.

Recently, the most known Slovak travertine and tufa sites were studied by Polish (Gradziński et al., 2008, 2013, 2014, 2015, 2018; Wróblewski et al., 2010) and Slovak scientists (Lačný et al., 2018). Dreveník hill is compared with Italian and Turkish fissure ridges. The deposition of lithoclast travertine, as well as the origin of its deformation, is interpreted as resulting from seismic shocks. The papers offer the study of Slovak travertine facies and forms (bodies) in the light of new knowledge of freshwater limestones, of stable isotopes, and radiometric ages (Gradziński et al., 2014, 2015; Wróblewski et al., 2010).

3. METHODS

The Slovak travertines have been studied in detail for 20 years especially from the view as decorative stones on buildings. The research of the 87 important travertine and tufa localities in Slovakia (Fig. 1) has been conducted in the last 5 years. Field research was focused on recent and fossil forms and their sedimentary facies. During the field research, 53 localities with hundreds of forms were examined. The coalesced mounds of Dreveník and Spiš Castle and mounds in their neighbourhood were studied in most detail due to their particular importance among travertine occurrences in Slovakia.

Recent forms and facies of travertine were compared with fossil travertine and tufa in natural outcrops, quarry faces, and building cladding, where vertical and horizontal cuts of structures are visible. Freshwater limestone databases (Ivan, 1943, 1952; Kovanda, 1971) were studied and their terminology had to be transformed to the current one. Transformed information was compared with the field results and the modern descriptions of Slovak sites (Gradziński et al., 2008, 2013, 2014, 2015; Wróblewski et al., 2010). The database of travertine and tufa samples, images of forms, and facies was acquired, in which mutual relations and similarities were observed. The classification into individual depositional environments and forms was mostly based on Pentecost (2005) and Pedley (2009). The missing forms in the classifications were supplemented by Scheuer & Schweitzer (1985), Schweitzer & Scheuer (1995), Guo & Riding (1998), Özkul et al. (2002), Capezzuoli et al. (2014), and Gradziński et al. (2018) (Fig. 2).

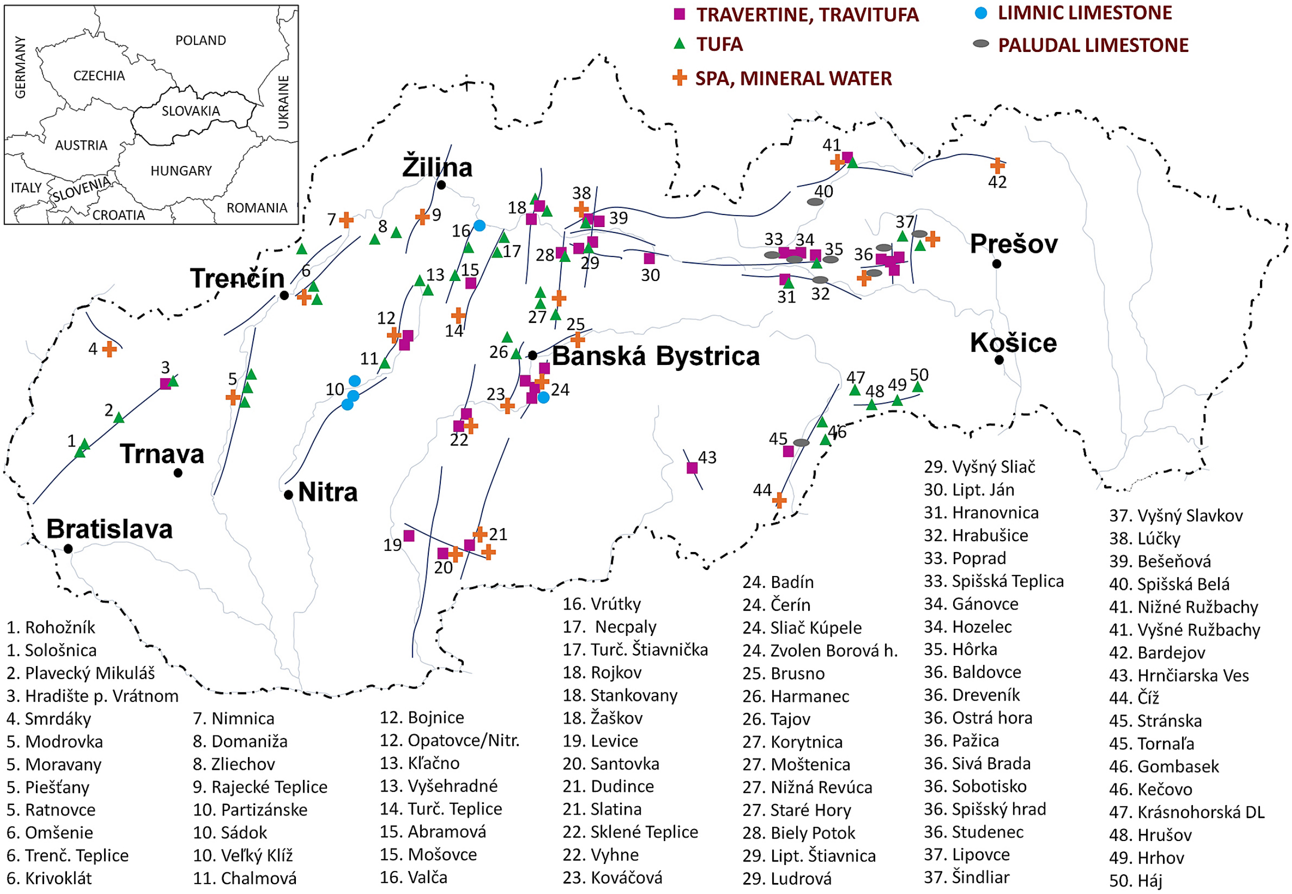

Fig. 1. The map of the most important freshwater limestones and spas in Slovakia. The lines indicate neotectonic faults active during the Late Pliocene to the Holocene (Maglay et al., 1999) that relate to freshwater limestones.

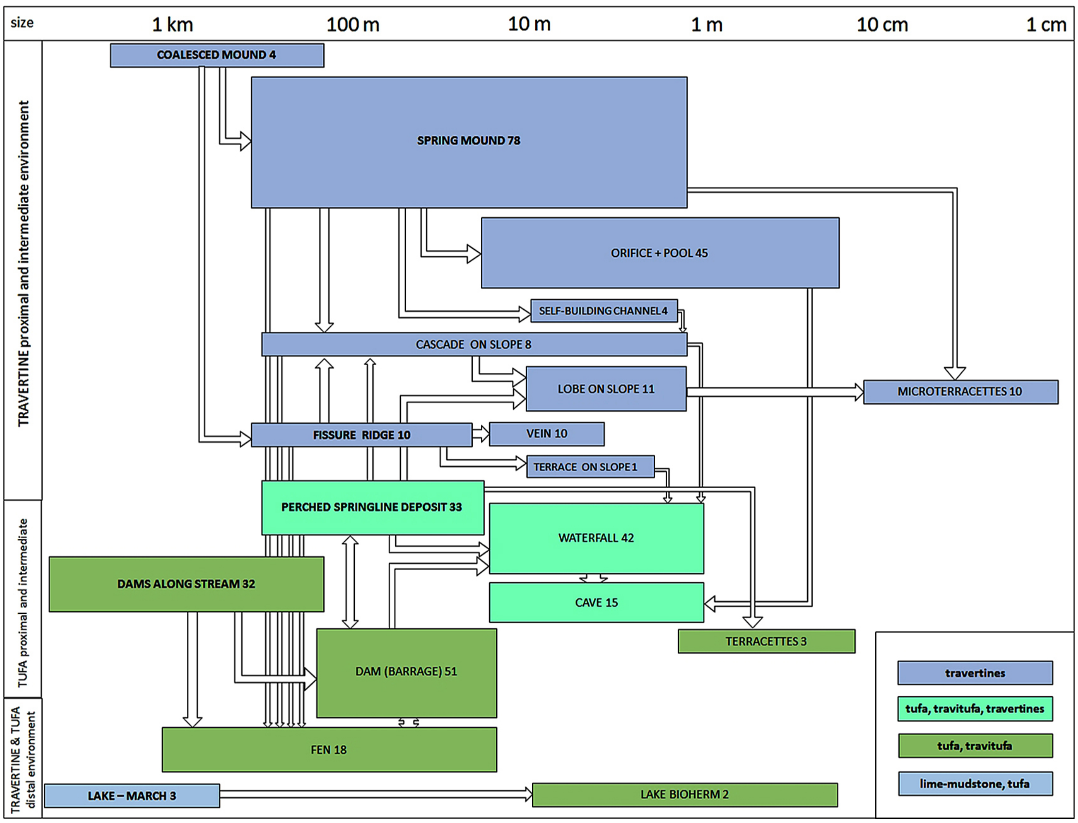

Fig. 2. Hierarchy of freshwater limestone forms. Numbers in boxes and their height express the numbers of examined forms. When an arrow extends from a larger form to a smaller one, it means that it is part of a larger one. The arrows between forms of a similar scale usually point to they can be adjacent with gradual transition. The major forms are indicated with bold letters, while their sub-environments are written with normal letters. Terminology in the first column is according to Capezzuoli et al. (2014).

Large-scale forms in the field were identified and verified in topographic maps, aerial, and lidar images (Fig. 3, Appendix 1). The military maps from the last 18th and the 19th centuries (First Military Survey of Königreich Ungarn 1782 – 1785, Second military survey of the Habsburg Empire – Hungary 1819 – 1869, Third Military Survey of Habsburg Empire 1869 – 1887) satisfactory display travertine forms, a few already exhausted and abandoned. The maps are published online on National geoportal (geoportal.gov.sk) or on Mapire – Historical Maps Online (mapire.eu). Airborne lidar (airborne laser scanning) creates a 3-D point cloud model of the landscape (Cracknell & Hayes, 2007). The measured data is interpolated to digital terrain models using the complex software. This is currently the most detailed and accurate method of performing digital elevation models. Airborne lidar digital elevation model can filter out reflections from vegetation, it can see through the canopy of forest cover, represents ground surfaces, performs detailed measurements of a microrelief. The Geodesy, Cartography and Cadastre Authority of the Slovak Republic has been supplying a new digital elevation model (DMR 5.0) of the whole territory of the Slovak Republic, prepared from airborne laser scanning data since 2017. The part of Slovak territory with the digital elevation model DMR 5.0 is accessible online at zbgis.skgeodesy.sk/mkzbgis (Source of LLS products: ÚGKK SR). Fifty travertine and tufa sites were studied on the digital elevation model.

The paper does not present new dating, but the dating of travertines and tufas is summarised in the discussion from the published data and placed to the neotectonic context of Carpathian structure. Due to the review form of the paper, all data acquired by the research of the authors are complemented by observations and interpretations performed by published studies, when necessary, and are distinguished by referring to the publications.

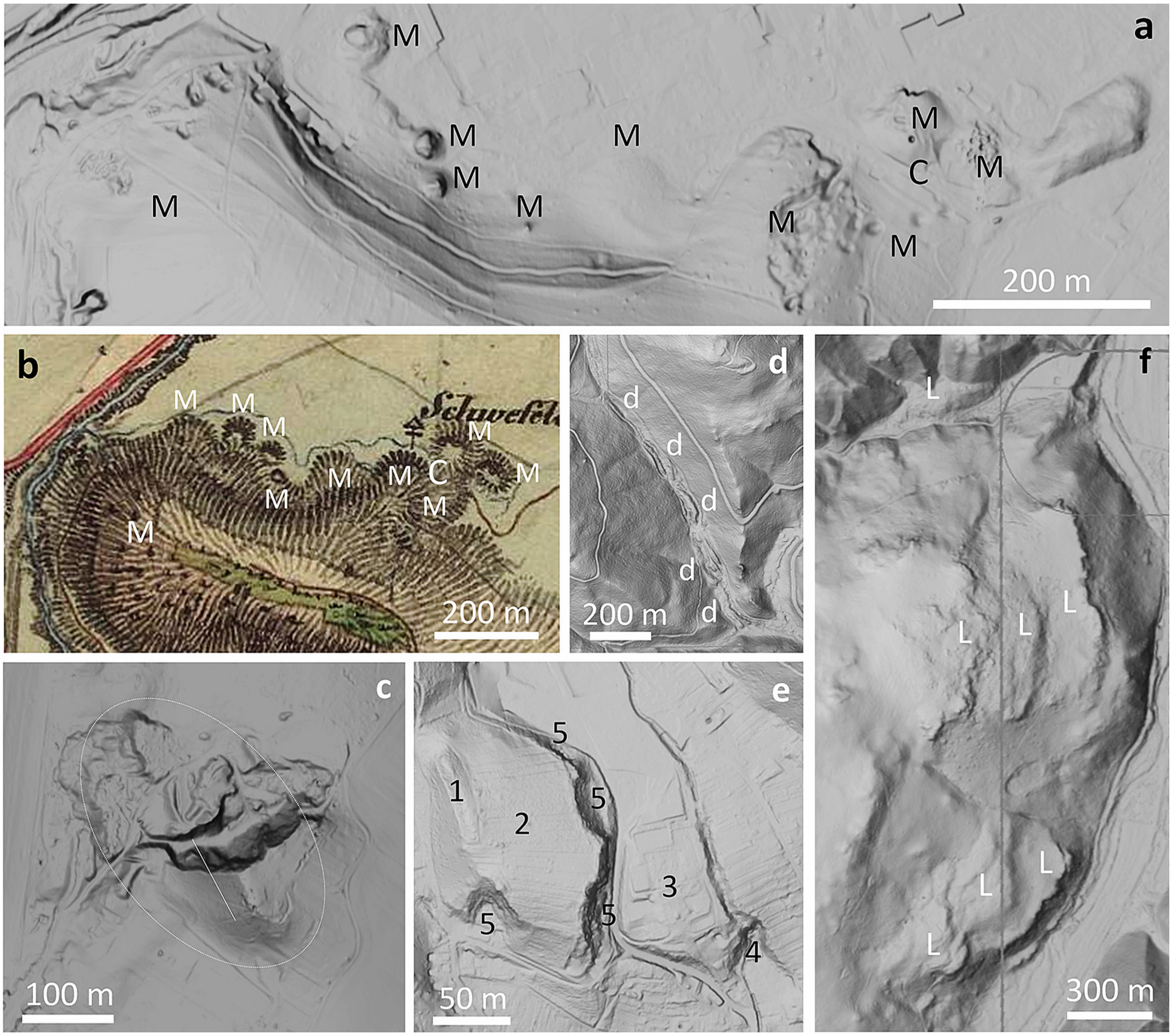

Fig. 3. Travertine and tufa forms on lidar images and historical map: **a, b** – Dudince spa (M – spring mound, C – coalesced mound); **c** – quarried **Vápnik** fissure ridge near Levice; **d** – earlier dam (d) system eroded by stream bellow Fačkov pass near Kľačno; **e** – dam remnants in Lúčky spa (1 – Cretaceous limestones, 2 – Late Pleistocene travitufa dam, 3 – Holocene tufa dam, 4 – waterfall, 5 – quarries); **f** – large lobes on perched springline (L) of Biely Potok Bukovina (a, c–f – lidar images from zbgis.skgeodesy.sk/mkzbgis, b – Hungary 1819–1869, Second military survey of the Habsburg Empire, MAPIRE – Historical Maps Online).

4. MORPHOLOGY AND DEPOSITIONAL ENVIRONMENT

Relations of environments, forms, water source, and deposits in Slovak freshwater limestones are expressed in Tab. 1. The study of recent travertine forms helps to understand the fossil/inactive forms. Some forms have located on a flat surface around a mineral water spring; some of them have placed on slopes. Many others have been developed as barriers in streams. The travertine and tufa forms reach a size from approximately one centimetre to several kilometres. The order of size and hierarchy, as well as genetic subdivision of the forms are described in Tab. 2 and Fig. 2. The basic forms are composed of smaller forms, or can be connected to complex forms. Spring mound is developed with central mound orifices and possible self-building channels. Travertine mound and ridge slopes are smooth with cascades that are moving downward depending on obstacles on the slope. Terraced slope forms are very rare in Slovakia. The cascade lobes are typically covered with microterracettes.

The early forms are often cut by fissures and cracks due to their subsidence into a plastic substratum and a subsequent fissuration or downslope creeping. Block fields with rocky towns (castellated landforms), gorges, and caves were formed on the Pliocene Dreveník mound near Spišské Podhradie town, which has a character of a plateau from aligned coalesced mounds and ridges (Fig. 4d, Appendix 1f). In this chapter, we intend to describe all common primary forms such as travertine mounds, fissure ridges, coalesced mounds and others that are clearly visible on lidar images and historical maps (Fig. 3, Appendix 1). At this point, we want to remark that a description and interpretation were not written in separate chapters for the sake of coherency and simplicity.

4.1. Forms with prevailing travertines

Many Slovak spring mounds, including now defined fissure ridges, were described in previous reviews (Ivan, 1943; Kovanda, 1971). Number of the localities with travertines reaches approximately 17 % of the Slovak freshwater localities (according to Kovanda, 1971). In the paper identified fissure ridges represent a negligible amount of the number. The description of travertine forms has been complemented by map and field research.

4.1.1. Spring mounds

Description: A spring mound or a cone is created around a mineral water spring – mound orifice. The mound is approximately round or slightly oval in plan, with a dome to cone shape. The mound diameters vary from ca. one metre (Čerín, Sivá Brada), through several metres (Dudince, Santovka) up to hundreds of metres (Zvolen – Borová hora, Hrnčiarska Ves; Figs. 3, 4,

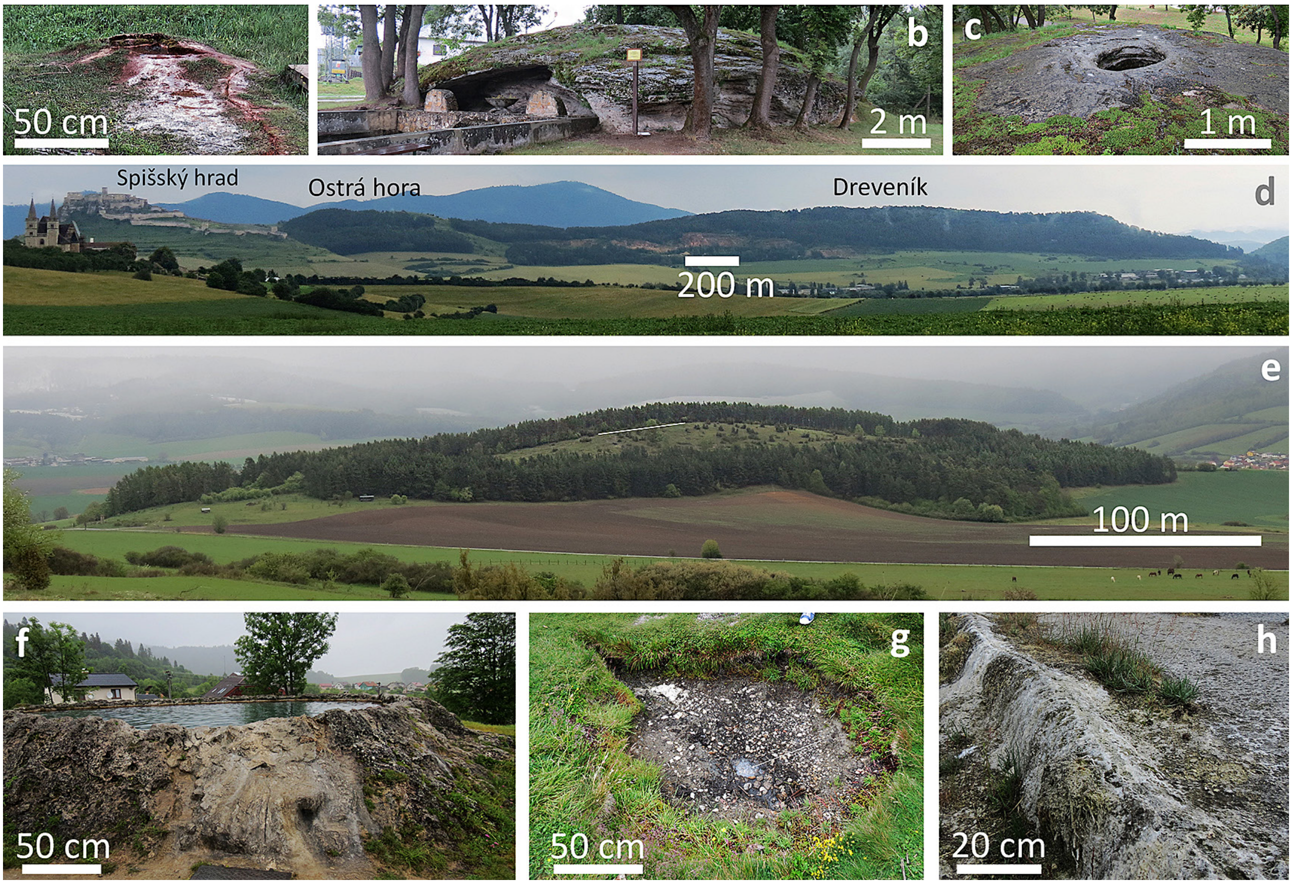

Fig. 4. Spring mound, fissure ridge and associated forms. a – Čerín spring mound ('Mičinské travertíny'), b, c – spring mound with central orifice in Santovka spa near main crossroad, d – Pliocene Spišský hrad castle and Dreveník – Ostrá hora coalesced mounds near Spišské Podhradie, e – Sobotisko fissure ridge with vein (white line), f – Vyšné Ružbachy crater-like orifice, g – Sivá Brada orifice with spring (arrow), and h – self-building channel in Sivá Brada.

Tab. 1. The relations of environments, forms, water source and deposits in Slovak freshwater limestones. Rare forms are in brackets, tufa and lime limestone localities are expressed in italics.

basic form	spring mound	fissure ridge	perched springline deposits	dams along stream	wetland	lake
water source	spring of deeply circulating water	linear spring or springs of deeply circulating water	springs of shallow (deeply) circulating water	stream (spring)	stream	stream (spring)
water temperature	thermal to ambient	thermal to ambient	ambient (thermal)	ambient	ambient	ambient
underlying surface	horizontal or subhorizontal	horizontal or subhorizontal	inclined	subhorizontal	horizontal or subhorizontal	horizontal
partial forms	orifice, parasitic orifice, smooth slope with cascades, self-building channels, microterracettes, (waterfall)	orifices in line, smooth slope with cascades, veins, micro-terracettes, (terraced slope, (waterfall)	waterfall, cave, smooth slope	waterfall, cave, fen	pools	bioherms
connected forms	coalesced mound, mound+fen	ridge+fen, (coalesced mound)	lobe sets, lobe+fen, (coalesced mound)	dam system, dams+fens, (lobe+dams)	marsh+lake, mound+fen, ridge+fen, lobe+fen	marsh+lake
deposits	travertine (*lime mudstone*)	travertine	*tufa*, travitufa, (travertine)	*tufa*, (travitufa, travertine)	*tufa*, *lime mudstone*, travitufa	*lime mudstone* (*tufa*)
examples	Bešeňová, Bojnice, Čerín, Dreveník, Dudince, Gánovce, Hozelec, Hôrka, Hrnčiarska Ves, Ostrá hora, Pažica, Rojkov, Santovka, Sivá Brada, Sliač Kúpele, Spišský hrad Castle, Stankovany, V. Sliač, Zvolen Borová hora, V. Ružbachy	Dreveník, Levice, Ostrá hora, Sobotisko, Vyšný Sliač	Biely Potok, Bojnice, Hradište pod Vrátnom, Hranovnica, Opatovce, Sklené Teplice, Santovka, Vyhne, *Harmanec, Hrhov, Hrušov, Krásnohorská Dlhá Lúka, Omšenie, Tajov, Tr. Teplice, Žaškov Dierová*	*Abramová, Chalmová, Hôrka, Hranovnica, Gombasek, Háj, Kečovo, Kľačno, Lúčky, Moravany, N. Revúca, N. Rudno, N. Ružbachy, Omšenie, Sološnica, Stankovany, Jergaly -Staré Hory, T. Štiavnička, Valča, V. Slavkov Vyšehradné, Zliechov*, Lúčky	*Baldovce, Hozelec, Hôrka, Hrabušice, Sp. Teplica, Sp. Belá, Studenec, Tornaľa, Lipovce,* Ludrová, Stankovany Močiar, Vrútky	*Veľký Klíž, Partizánske, Sádok, Sliač Kúpele, Vrútky*

Tab. 2. Sites of travertine and tufa forms according to size. Italic font is for recent forms.

diameter or length / form	> 1 km	1 km – 100 m	100 – 10 m	10 – 1 m	1 m – 10 cm	10 – 1 cm
coalesced mound	Dreveník	Dudince, Spišský hrad, Vyšný Sliač				
spring mound		*Sivá Brada, Bešeňová,* Bešeňová 2x, Bojnice, Dreveník 5x, Gánovce 2x, Dudince Porošin 2x, Hôrka, Hrnčiarska Ves, Lipt. Ján, Ludrová, Ostrá hora, Pažica, Poprad, Santovka 2x, Spišský hrad 5x, Stránska, Vyšný Sliač, Sliač Kúpele 2x, Vyšné Ružbachy 4x, Zvolen Borová hora	Badín, Hozelec, Hôrka 7x, Levice (?), Mošovce, Poprad, Rojkov, Santovka 7x, Spišský hrad, Dudince 4x	*Čerín 4x,* Rojkov, Čerín 11x, Dudince 2x		
orifice, crater			*Rojkov, Stankovany,* Bojnice, Bešeňová (?), Gánovce (?), Stránska (?), Vyšný Sliač, Vyšné Ružbachy 4x, Zvolen Borová hora	*Bešeňová, Lipt. Ján, Vyšné Ružbachy,* Dudince 2x, Hôrka, Santovka 5x, Sivá Brada 2x, Vyšný Sliač 2x	*Bešeňová, Hozelec, Sivá Brada 4x,* Dudince 5x, Čerín 4x, Vyšný Sliač 3x	
self-building channel				*Hozelec Banícka, Sivá Brada,* Dudince, Santovka Bory		
microter-racette					Dudince Porošin (?)	*Bešeňová, Hozelec, Sivá Brada,* Dreveník, Dudin-ce, Gánovce, Lúčky, Santovka, Vyš. Sliač

fissure ridge		Sobotisko, Levice Vápnik	Dreveník 4x, Levice Gold Onyx, Ostrá hora, Santovka, Spišský hrad (?), Vyšný Sliač			
vein			Dudince Porošin	Dreveník 3x, Levice Gold Onyx, Levice Vápnik, Ostrá hora, Santovka, Sobotisko, Spišský hrad		
cascade on slope		Dreveník, Spišský hrad	*Bešeňová,* Biely Potok, Dreveník, Levice Vápnik	Dreveník, Sivá Brada		
lobe on slope			*Hozelec, Sivá Brada,* Dreveník, Spišský hrad	*Bešeňová, Sivá Brada, Sklené Teplice,* Dreveník, Spišský hrad, Vyšné Ružbachy	*Bešeňová*	
terrace on slope				Levice Vápnik		
terracette				Krásnohorská DL	Biely Potok Krásnohorská DL Hranovnica	
perched springline deposit		*Hrhov, Krásnohorská DL, Necpaly, Sklené Teplice,* Biely Potok 7x, Bojnice 2x, Hradište pod Vrátnom, Hranovnica 3x, Hrušov, Lipt. Štiavnica 3x, Necpaly, Opatovce nad Nitrou, Trenč. Teplice, Vyhne, Žaškov Dierová	*Biely Potok, Harmanec 2x, Tajov,* Biely Potok, Omšenie 2x			
waterfall			*Biely Potok, Hrhov, Lúčky, Tajov,* Bojnice	*Biely Potok 2x, Háj 4x, Krivoklát, Niž. Revúca, Sklené Teplice, Staré Hory 2x, Turč. Štiavnička, Vyhne,* Biely Potok 12x,Domaniža, Dreveník 4x, Hranovnica 5x, Spišský hrad 2x		
cave			Staré Hory	*Háj, Hrhov, Lúčky,* Bešeňová, Biely Potok, Bojnice, Dudince, Dreveník, Hranovnica, Háj, Lúčky, Sklené Teplice, Spišský hrad, Vyšný Sliač		
dams along stream (dam system)	Staré Hory, Valča, Vyšehradné, Vyšný Slavkov, Zliechov -Trstie	*Abramová, Krivoklát, Lúčky, Háj, Hranovnica, Moštenica, Nižná Revúca, Turčianska Štiavnička,* Domaniža, Gombasek, Hôrka Primovce, Kečovo, Chalmová, Kľačno, Lúčky, Modrovka, Moravany, Niž. Ružbachy, Nitr. Rudno, Omšenie, Plavecký Mikuláš, Rohožník, Sološnica, Stankovany 2x, Šindliar, Trenč. Teplice				
dam (barrage)		Plavecký Mikuláš	*Abramová 7x, Háj 4x, Moštenica 6x,* Jergaly-Staré Hory 13x, Kľačno Tmavá 5x, Sološnica 5x, Stankovany 6x, Trenčianske Teplice 4x			
fen	Hrabušice, Spišská Belá	*Baldovce, Hozelec, Stankovany Močiar, Vyšný Sliač,* Dreveník, Lipovce, Lipt. Ján, Lúčky, Ludrová, Ratnovce, Spišská Teplica, Studenec, Tornaľa	*Hôrka Liptovská Štiavnica Sivá Brada*			
march – lake	Vrútky, Partizánske, Nedanovce, Veľký Klíž, Sádok	Sliač – Veľká Lúka				
lake bioherm				Veľký Klíž	Veľký Klíž, Sádok	Veľký Klíž

Appendix 2). The mounds reach the height from a few centimetres (Čerín, Sivá Brada) up to tens of metres (Sivá Brada). A slope dip is usually up to 15°, rarely to 50° and occasionally more (Dudince; Appendix 2a–b). The mound can be free standing on a horizontal or slightly inclined surface (Figs. 3, 4, Appendix 2) or developed as a younger (parasitic) cone on the earlier mound (Appendix 4c). The spring mounds are usually composed of a bedded crystalline crust and microbialite travertine. The central mound orifice can be in a crater shape (Appendix 4).

Interpretation: Travertine forms depend on calcium bicarbonate concentration. When hypersaturated calcium bicarbonate rich water, typically (but not necessarily) hydrothermal in origin is present, the calcium carbonate is precipitated closely to the spring (Kovanda, 1971; Gandin & Capezzuoli, 2014) and creates round convex travertine form on the subhorizontal surface. It is characterised chiefly by a high depositional rate. Such deposits are typical for deeply circulating groundwater in tectonically active areas where geothermal heat flux is high. The mound orifices can move in time as the spring is shifted (Appendix 2e). In Slovakia, the travertine mounds were formed during warmer climates – interglacials with no permafrost according to fauna and flora fossils preserved inside the deposits (cf. Ložek, 1959, 1992).

4.1.2. Coalesced mounds

Description: In regions with long-lasting mineral spring activity in a range of thousands of years, individual mounds and ridges could be joined and mutually overlapped. The general geometric and lithological features are analogous to spring mounds. The double mound was identified in the Vyšný Sliač 'Skala' site (Appendix 2d). The complex coalesced mounds (Scheuer & Schweitzer, 1985; Schweitzer & Scheuer, 1995) consist of several interconnected mounds (Dudince – Močidlá; Fig. 3a–b) or the combination of many mounds and fissure ridges (Dreveník – Ostrá hora with 0.75 km^2 area and Spišský hrad Castle; Fig. 4d, Appendix 1f) in the form of a flat plateau with steep edges formed by cambering.

Interpretation: The area of resurgences of deep-circulating mineral water can occur in the form of several springs with changing position in time. Initially, it is developed as a wet meadow or a carbonate fen with one or several springs (Baldovce), then with a few small spring mounds (Čerín; Appendix 2f). As the small mounds grow, they can be linked to the larger bodies (Dudince, Fig. 3a–b; Sivá Brada, Appendix 2c), where the spring locations also change in time. After thousands of years, when the spring relocated, a massive complex of the coalesced mound can be formed (Dreveník, Fig. 4d, Appendix 1f), where the mounds, ridges, and possibly lobes bellow the parasitic orifices were covered and aligned each other.

4.1.3. Fissure ridges

Description: Fissure ridges are oval with a dome to cone shape growing around a linear spring of mineral water. Fissure ridges, which could be identified by an oval shape, parasitic craters along the ridge axis or upright banded veins of the vent were studied (Brogi et al., 2014; Capezzuoli et al., 2014). The fissure ridges tend to have steeper slopes than the mounds. The slope dip is usually from 30° to 50°, rarely up to 80° (Levice – 'Gold onyx'; Appendices 3b–c, 10f). The ridge size is from several tens of metres (Vyšný Sliač 70 × 30 m, Appendix 3a) up to several hundreds of metres (Sobotisko with dimensions 800 × 500 m, Fig. 4e). The maximal height of the fissure ridge was measured at the Levice – Vápnik site (80 m). The fissure ridges, similarly to the mounds, were formed from the bedded crystalline crust and microbialite travertines.

The spring mound or fissure ridge slopes are usually smooth with prograding cascades (Figs. 4a–e, 5a, Appendix 6). The slopes can be rarely very steep up to 90° with the waterfalls (Spiš Castle; Appendix 10h–i). The recent and fossil mounds and ridges are usually covered by *microterracettes* (Fig. 5f, Appendix 7f–i).

Interpretation: The fissure ridge is typically deposited from deep-circulating groundwater in tectonically active areas with higher geothermal heat flux. Hypersaturated and usually thermal water rich in calcium bicarbonate ascend along the fissure and calcium carbonate precipitates with higher depositional rates close to springs (Brogi et al., 2014; Capezzuoli et al., 2014) developing oval convex forms on a flat substratum. The fissure ridges, like the travertine mounds, were formed during interglacials without permafrost in Slovakia, according to the evidence of fossil assemblages (cf. Ložek, 1959, 1992). Transitional types between mounds and fissure ridges can exist, when the fissure ridge is covered by parasitic craters in parallel to outflow fissure (Vyšný Sliač; Appendix 3a). Whether the spring mound or fissure ridge is developed, depends on the spring character of water ascending along a fault. If the fissure attain the surface, the fissure ridge is formed along the linear spring. If deposits block the fault near a surface, water tends to penetrate them at a singular point and the spring mound is formed. When the fissure on a ridge is obstructed, water will spring on different sites along the fissure. Some fossil travertine accumulations cannot be discerned as a mound or fissure ridge, because of rudimentary preservation of the current (original) body (Appendix 1d–f).

4.1.4. Sub-environments of spring mounds and fissure ridges

Mound orifices

Description: A mound orifice (spring orifice, spring mouth), usually on the top of a mound, occurs very often in a crater-like form with travertine rim with steep slopes between 30° and 80° (Vyšné Ružbachy; Fig. 4f, Appendix 4a–e) or without rim (Santovka, Dudince, Sivá Brada; Fig. 4a,c,g, Appendix 4f–i). The mound orifice has usually rounded shape (Fig. 4, Appendices 1a, 4, 5) with diameter from a few tens of centimetres (Čerín, Sivá Brada, Vyšný Sliač, Dudince; Fig. 3a, Appendices 4c, 5c–e), through several metres (Dudince, Santovka; Fig. 4c,f, Appendices 1a, 4a,g–i), up to several tens of meters (Vyšný Sliač, Vyšné Ružbachy, Borová hora; Appendices 1b, 4j–k, 5f–h). The orifice pool is typically filled with mineral water (Vyšné Ružbachy, Rojkov, Stankovany; Fig. 4f; Appendices 4a, 5a–h) with an oscillating water table (Fig. 4g, Appendix 5a). The orifice can be also dry with possible CO_2 degassing (Vyšné Ružbachy, Vyšný Sliač; Appendix 4e,k). The craters without an active spring are usually filled with a spring deposit (Appendix 4i,k) and a talus from the crater rim (Appendix 4e). The broad crater is usually filled with a calm pool with specific deposits (e.g., lime mudstones, microbialites, and coated grains). Water from the orifice pool overflows in the lowest part/parts of the margin and forms lobes (Vyšné Ružbachy, Appendices 4b, 6h–i) or self-building channels (Santovka Bory; Fig. 4h, Appendix 5i–j).

Interpretation: The mound orifice (Pentecost, 2005) or vent environment (Capezzuoli et al., 2014) develops around a spring of hypersaturated and usually warm water of a deep origin. Overflow water on the mound top creates a pool, which can be fringed by an elevated rim with steep slopes (crater-like) at high depositional rates (cf. Kovanda, 1971). The spring displaced to the mound slope cannot form rim but produces a lobe and/or a small pool (Sivá Brada, Bešeňová, Appendix 6e). Most orifices were seldom influenced by a human impact and excavated for bathing (Rojkov, Stankovany, Appendix 5f,h), as documented by early maps and aerial photos.

Self-building channels

Description: Self-built channels are linear travertine forms growing in a flow direction (Özkul et al., 2002). Several metres long, up to 20 cm wide and a few cm high channels are formed near recent mineral water outflows on a flat surface of cascades (Hozelec Banícka, Sivá Brada, Santovka – Bory, Fig. 4h, Appendix 5i–j). Many of them are influenced by a human activity up to the extreme form of a keeled waterfall (Appendix 5j). The channel walls are usually covered by directed filament cyanobacteria and consist of a crystalline and microbial travertine (e.g., Hozelec Banícka and Bešeňová). Fossil channel deposits have not been identified yet.

Interpretation: The channels are formed near the hypersaturated water orifice with high-discharge streams. Analogously to natural levee of a river, the channel rims are the places of maximal precipitation where current slows at the channel margins or occasionally overflows them.

Veins

Description: Banded veins of vents (Brogi et al., 2014; Capezzuoli et al., 2014) are characteristic feature of fissure ridges. The vein deposits were identified at the Dreveník, Levice, Dudince and Santovka localities (Fig. 3c, Appendix 3d–i). The veins are usually vertical or subvertical (Appendix 3d–g). They can be split to lateral veinlets (Appendix 3g). In Dreveník site, intact, unchanged veins are rare for later dissolution and newly formed speleothems along fractures (Appendix 3b,e). The veins (sills) can be rarely with subhorizontal course, paraller to a bedding (Appendix 3h,i).

Interpretation: The subvertical veins were usually developed in fractures in extension regime of tectonic or gravitational origin. Mineral water ascended along fractures and formed paraller banded travertines. Sheeted subhorizontal veins are a result of overpressured hydrothermal fluids that caused subhorizontal hydrofractures filled with sheeted calcite veins. They have been described by several researchers (Gradzinski et al., 2014; Rimondi et al. 2016; Brogi et al., 2017).

Slope with cascades

Description: The slope with cascades (the first type of cascades *sensu* Pentecost, 2005) can be also named as a smooth slope (Guo & Riding, 1998; Özkul et al., 2002; Pedley, 2009). The slopes of larger mounds (Dreveník, Bešeňová, Vyšné Ružbachy as a whole recent, Fig. 5a, Appendix 6), the fissure ridges (Sobotisko), and a minority of perched springline deposits (Biely Potok Jazierce, Sklené Teplice; Appendix 6c–d) can be covered by convex cascade sets (Pentecost, 2005). The individual cascade lobes have a dip between 0° and 90°, and thus can be transformed

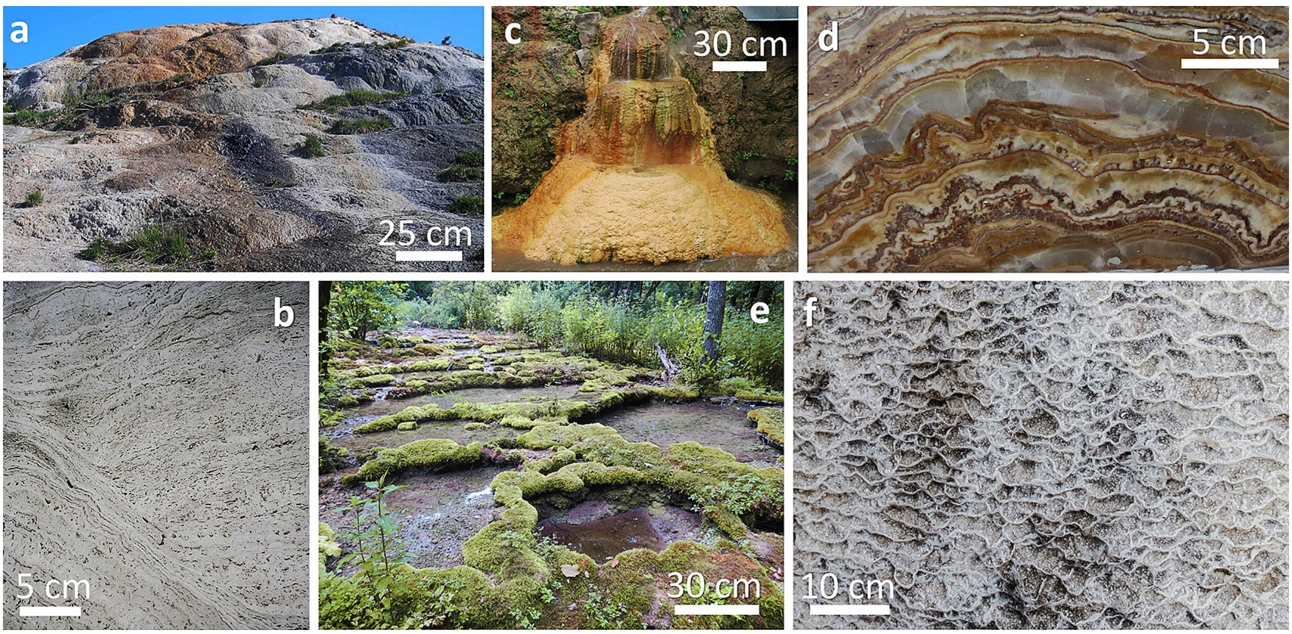

Fig. 5. Mound slopes with cascades or terraces: a – mild cascade in Bešeňová mound; b – angular unconformity in lobes of Dreveník mound (travertine cladding); c – a pagoda-shaped cascade of hot-spring in Sklené Teplice; d – a horizontal cut of fossil hot-spring lobe from Staré Levice 'Gold Onyx', e – moss terracettes on slope lobe in Krásnohorská Dlhá Lúka; f – microterracettes on cascade in Sivá Brada mound.

to the waterfall (Appendix 10h–i). The cascade with long-lasting warm water can reach a cupola- or pagoda-like shape with almost smooth surface (fossil Vyšné Ružbachy, recent Sklené Teplice; Fig. 5c–d, Appendices 4b, 6d,h–i) and/or with lot of irregular dripstones (recent Sklené Teplice, fossil Levice 'Gold Onyx', Fig. 5d, Appendix 6d). The cascades usually consist of crystalline travertine with microbialite portion and locally distributed macrophyte remnants.

Interpretation: The slope with cascades are very similar to a typical example in the Mammoth Hot Springs (Yellowstone National Park, USA). The cascades are approximately paraboloid in the section. The morphology is largely controlled by spate water trajectory typical for high-discharge streams (Pentecost, 2005). The cascades are gradually moved down the slope depends on a mineral water flow. Their shapes are also influenced by standing and fallen trees, fallen travertine blocks, and grass clumps (Appendix 6b,f,j). Angular unconformities visible in the cascades section (Fig. 5b, Appendix 6j–l) record changes in a water flow direction (Fouke et al., 2000; Pedley, 2009; Gradziński et al., 2013). Keeled cascade with waterfall (Pentecost, 2005) can be created with human participation (Appendices 5j, 10d).

Slope with terraces

Description: The terraces composed of pools and waterfalls are metre-sized. The terraces (*sensu* Guo & Riding, 1998) or dams (*sensu* Pentecost, 2005) are formed on a slope along flowing warm water. Recent examples are lacking in Slovakia; however, indications of terraces in depositional record were identified in the Levice Vápnik site with a few metres in size (Appendix 7b–c). Probably artificial terraces were formed in the Stankovany Močiar site (Appendix 7a). Underground speleothem forms from the Domica cave are similar to travertine terraces. The smaller terraces – *terracettes* of a few decimetres to a few metres in size are developed on the recent lobe of Krásnohorská Dlhá Lúka (Fig. 5e, Appendix 7d–e) and Hranovnické pleso. The *microterracettes* are much more common on recent and fossil travertine mounds and ridges. These micro dams reach a few millimetres up to centimetres in size (Fig. 5f, Appendix 7f–k).

Interpretation: Typical example of terraced morphology is Pamukkale in Turkey or Yellowstone Mammoth Hot Spring which consists of terrace sets where each terrace is composed of a pool, rim, and wall with specific facies (Guo & Riding, 1998; Fouke et al., 2000; Özkul et al., 2002; Pedley, 2009). The terraced slope represents the cascades of the second type *sensu* Pentecost (2005). They are accretionary deposits, irregular and prograding, where deposition outpaces erosion over long periods with a slight water flow. The smallest terrace forms – *microterracettes* – result from rapid deposition on slope cascades, when hypersaturated water flows over the entire surface and the physical changes in flow create *microterracette* sets like sinuous and linguoid ripples (Reineck & Singh, 1973), which resemble a wave interference pattern. Gandin & Capezzuoli (2014) point out that the precipitation dominates along the frontal crestline of interference fans of laminar flows. This physical process can be influenced by cyanobacteria net to a variable degree (Sivá Brada, Hozelec, Bešeňová; Appendix 7j–k), resulting in a greater irregularity.

4.2. Forms with prevailing tufa, travitufa and lime-mudstones

The forms with prevailing tufa, travitufa and lime-mudstones represent 83 % of the Slovak localities with freshwater limestones. Tufas and travitufas were mainly formed in dams along stream (37 %; *údolná kaskáda* in Kovanda, 1971), and in perched springline deposits (34 %; *svahová kaskáda* in Kovanda, 1971). Slovak Holocene tufas were formed in the bottoms and slopes of valleys at karstic mountainous regions (Kovanda, 1971; Gradziński et al., 2013, 2015). Lime-mudstones combined with tufa were formed inside fen (10 %) and lake-marsh environments (2 %) (according to Kovanda, 1971).

4.2.1. Perched springline deposits

Description: The perched springline deposits or model were defined by Pedley (2009) as slope tufa environment. Large carbonate accumulations are formed on slopes with a spring line in hilly, mountainous areas with abundant limestone. The accumulations can be tongue-shaped (Hranovnické pleso Hincava 250 × 150 m) or fan-shaped (Hrhov, Hrušov). They are often complex, laterally joined deposits with a rectangular shape (Fig. 3f, Appendix 8a). The width is from a few tens of metres to several hundreds of metres (Hradište pod Vrátnom 140 × 50 m, Biely Potok Bukovina 1000 × 400 m; Fig. 3f, Appendix 8a), the thickness between a few metres and 10–20 m, even up to 40 m (Biely Potok Bukovina, Fig. 3f, Appendix 8a). Several cascades can be arranged along a slope (Harmanec and Omšenie up to six cascades; Kovanda, 1971). The lobes are usually formed from tufa (Fig. 6b, Appendix 8b) and bryophytes (moss) are dominant plants (Fig. 6a,e, Appendices 8f–h, 10b–c). Travitufa with travertine is rather rare (Hranovnica, Biely Potok; Appendix 8c–e). Lobe rims are usually steep with recent (Tajov, Biely Potok; Fig. 6a, Appendix 10b,e) or fossil waterfalls (Hranovnica, Biely Potok; Fig. 6c, Appendix 10f–g) and caves can be developed under them (Fig. 6c, Appendix 10a,g).

Interpretation: The deposits on slopes are developed bellow perched springline (Pedley, 2009; Capezzouli et al., 2014). The calcium bicarbonate-rich groundwaters of shallow-circulation are usually derived from karst water from limestone-rich regions (Gradziński et al., 2013) with ambient temperature (Hrhov, Hrušov, Fig. 5b). A part of water can drain deep-circulating paths (Biely Potok, Hranovnica, Fig. 6e, Appendix 8a,c–e,g–h). The simple lobe or cascade bellow the parasitic orifices on mounds are created in the Sivá Brada (Appendix 6e,g). Similar lobes could be formed in the Dreveník (Fig. 6f) and Spišský hrad Castle mounds. However, these represent a transition to a smooth slope with cascades.

4.2.2. Dams along stream

Description: Dams along streams were formed along stream valleys in the forms of one or several dams (barrages) which can be separated by fens in Slovakia. Early travitufa and travertine valley accumulations are dated back to Pleistocene (Lúčky, Fig. 3e, Appendix 9b–c). The total length of Holocene tufa accumulations in valleys ranges from a few tens of metres up to 6,5 kilometres in the Jergaly – Staré Hory site, with discontinuous deposits reaching length up to 8 kilometres at the Zliechov – Tŕstie site (cf. Kovanda, 1971). Up to 13 dams can be arranged in the downslope direction in some valleys (Jergaly – Staré Hory; Fig. 3d).

Interpretation: The best-known dams or barrages are formed in the Plitvice lakes, where formation of system of several tufa barriers (dams, barrages) led to development of lakes (Srdoč et al., 1985, Pentecost, 2005, Pedley, 2009). Most Slovak tufas were formed in the valleys at a lower altitude (rarely up to 900 m asl.) in mountainous areas created by abundant limestones with shallow-circulating water. Most tufas were formed during wet periods in the Atlantic and less in the Sub-Boreal (Kovanda, 1971; Gradziński et al., 2013). A lot of tufa accumulations are recently destructed by headward erosion or they are cut by a stream (Fig. 3d). Similarly, the Pleistocene tufas have been destroyed for their insufficient lithification. Only those that were more mineralised have been preserved (e.g. Lúčky). Unlike the Plitvice lakes, Slovak dam systems have not developed lakes, only fens. The fluvial tufas were laid down in narrow, steep-sided valleys, where a confined stream flowed with limited lateral migration (Gradziński et al., 2013). The dams were formed in constrictions of a valley or associated with irregularities in the pre-existing valley bottom.

Dam

Description: The recent tufa accumulations are usually developed along valleys as transverse dams (Appendix 9a). The dam width reaches up to several tens of metres, also over 100 metres (Moravany; Appendix 1c). Tufa thickness in dams is from 1 metre to several metres, rarely even more than 10 m, with a maximum of 15 – 18 m (Háj; Appendix 9a). The waterfalls could originate in the head of dams (Háj, Lúčky, Fig. 7d, Appendices 9a,10c) and caves can be formed under the waterfalls (Háj; Appendices 9a,11a,c). The dams are constructed from moss, stromatolitic and phytoclastic tufas, whereas the inter-dam areas comprise chiefly oncoidal and intraclastic tufa facies (cf. Gradziński et al., 2013).

Interpretation: Dam is formed farther from the source in places, where it is more intense oxygenation, more $CaCO_3$ is precipitated than elsewhere. Tufa here grows much faster with the help of moss, grass, algals, and cyanophytes and so they gradually form barrier in the form of dam (barrage), behind which it can be developed pool or fen environment (Kovanda, 1971; Pentecost, 2005).

4.2.3. Sub-environments of the perched springline deposits and dams along streams

Waterfalls

Description: In Slovakia, recent waterfalls are visible in the frontal part of a perched springline deposits (Biely Potok Bukovina, Hrhov; Fig. 6a, Appendix 10a–b). The Hrhov waterfall reaches the height of 14 m. The waterfalls are in the head of dams (Lúčky with the height of 12 m, Háj; Fig. 6d, Appendix 10c) and on the keeled cascades (Vyhne, Turčianska Štiavnička; Appendix 10d). The fossil waterfall deposits were identified in the frontal part of a perched springline deposits (Hranovnica, Biely Potok; Fig. 6c, Appendix 10f–g), a mound slope (Spišský hrad Castle; Appendix 10h–i), on a terrace rim (Levice Vápnik; Appendix 7b–c), or occasionally on a steep crater rim (Vyšné Ružbachy; Appendix 4b). Dripstones and draperies on the waterfalls (Fig. 5c, Appendices 6d, 10a,c,g) and caves behind them (Fig. 6c, Appendices 10a,c,g, 11a,b) are common. A few

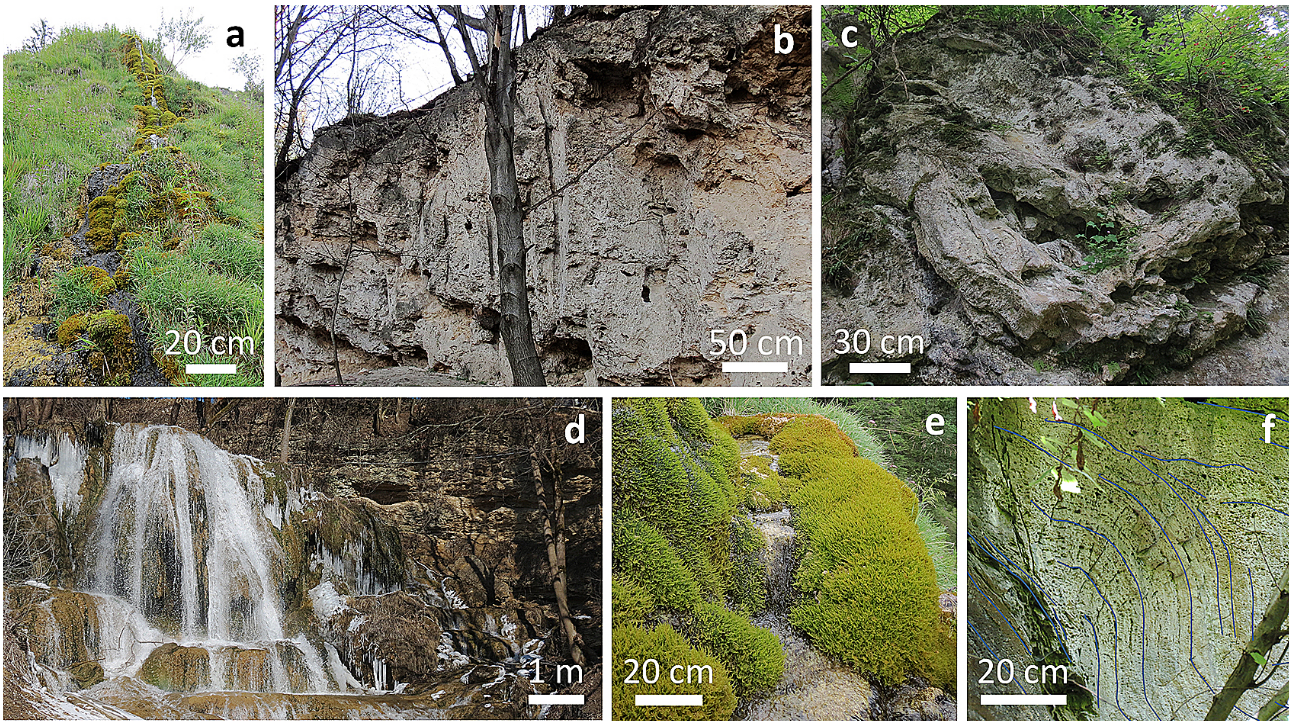

Fig. 6. Perched springline deposits and dams along streams: a – recent slope of perched springline deposit with waterfall, moss, and grass in Biely Potok Bukovina; b – quarry face in Hrhov tufa lobe; c – Pleistocene travitufa lobe with waterfall and voids in Biely Potok Bukovina; d – dam face with waterfall and caves under overhangs in Lúčky spa; e – an active slope of the lobe with moss cushions in Biely Potok Bukovina; f – cut of travitufa moss cushion in Dreveník gorge.

recent waterfalls were developed on quarry faces (Hrhov; Appendix 10a).

Interpretation: The slope depositional environment was described by e.g. Guo & Riding (1998) and Pedley (2009). The waterfall deposits are characteristic of ambient water tufas, but hot-spring waterfall travertines appear to be less common (Guo & Riding, 1992). The perched springline deposits and dams along streams usually have steep heads, where macrophyte overhangs with waterfalls are formed (Appendix 10a). Persistent sprayfall in waterfalls loses its dissolved chemical load rapidly (Pentecost, 2005). Calcium bicarbonate is precipitated on accretional organic cushions, draperies, and drips. Both the recent and fossil waterfalls are usually connected with bryophyte cushions and filamentous cyanobacteria and algae. The waterfall can be also developed on cascade lobes of mounds or ridges. They can be very steep, especially when the upper parts are more reinforced by microbial or moss precipitation (Appendices 6b, 10h–i), steepened by stream erosion (Sklené Teplice; Fig. 5c, Appendix 6d) or rock falls (Appendix 10j).

Caves

Description: Several metres long caves originated under overhangs in the waterfalls (Fig. 6c, Appendices 10a,c,g, 11a–b) rich in moss, cyanobacteria, and algae filaments (fossil Bojnice, Háj, Hranovnica, Biely Potok, recent Háj, Hrhov, Lúčky). The speleothems occur in the form of dripstones in the caves (Appendix 11c). The small caves were developed inside the debris (talus) bellow destructed walls and blocks (Dreveník, Spišský hrad Castle). The voids were often formed after the decay of an organic material (Appendix 11d,f). The vertical cave in the crater is known in Vyšný Sliač (Appendix 4e). The fissure caves with rich speleothems were formed in the Dreveník coalesced mound of the Pliocene age (Appendix 11g–i).

Interpretation: The cushions of bryophytes (moss), draperies and drips of filamentous cyanobacteria are covered by calcite and produce progradational overhangs (*sensu* Gradziński et al. 2018), under which primary caves with speleothems are formed in fluvial tufa (Háj). The longest '*Jelenecká jaskyňa*' cave (65 m) was described by Gradziński et al. (2018). The authors also mentioned a cave in Sklené Teplice travertines. The same cave types were identified in fossil deposits of perched tufa on a slope (Biely Potok, Hranovnica). Aggradational caves formed inside aggraded crater orifices were described in Bojnice (Bojnická hradná jaskyňa), near Bešeňová (Studňa v Záskalí, Studňa pod Drienkom), near Vyšný Sliač, and in Dudince (Očný prameň) (Bella & Vlček 2011, Gradziński et al. 2018). Gradziński et al. (2018) described tree-mould caves in Lúčky. Similar but smaller ones were found in Biely Potok (Trlenská dolina and Jazierce), Žaškov Dierová and Dreveník.

The Pliocene Dreveník mound was subjected to block movements and leaching, and as a result different types of predominantly vertical caves were developed (see Ložek, 1964, 1973).

Fens

Description: Active fens as a type of wetlands in Slovakia are limited due to wetland drainage and water table lowering, but the Pleistocene and Holocene fen profiles were studied in artificial outcrops (Kovanda, 1971). The carbonate fens (*Caslatiny* in Slovak and Czech) are defined with layers of marl alms, sandy intraclast tufa, and macrophyte tufa. The alms are paludal limestones with small-scale irregular horizons of white, grey, and black colour, with different proportions of lime mud and organic material. Much of this material is poorly cemented 'spring chalk', organic detritus (sapropel, humus), and terrigenous material. Overall, the successions are significantly horizontally layered. These deposits are characterised by a distinct assemblage of fen and terrestrial gastropods. The calcareous fens with alms and intraclast tufas were identified e.g. in Spišská Belá (ca. 1.4 km^2), Hrabušice (ca. 0.6 km^2), Spišská Teplica (ca. 0.4 km^2) or Baldovce (ca. 0.3 km^2). The thickness of fen accumulation is up to 3 m, rarely even more (Kovanda, 1971).

Smaller recent fen environment is developed in the Sivá Brada (Appendix 12a–b), Vyšný Sliač (Fig. 7a, Appendix 12e), Hozelec Gánovské lúky (Appendix 12f), Stankovany Močiar, Hôrka (Appendix 12d), and Čerín (Appendix 2f), where wet meadows are formed bellow natural and artificial hypersaturated water springs on a subhorizontal surface. Bellow the springs, crystalline crusts with some portion of cyanobacterial (algal) microbialite are formed transitioning into wet meadows with grass, fewer bryophytes, and reeds.

Interpretation: The fens with paludal tufas (Pentecost, 2005; Pedley, 2009) are developed on valley bottoms and low gradient slopes close to them that are characterised by sluggish or impeded drainage. The deposits can cover the full width of a valley and extend for kilometres of its length. At active upland sites, spring-fed water seeps slowly through bryophyte cushions, reed and grass carpets leaving behind a surficial carbonate coating on all surfaces (Kovanda, 1971; Pentecost, 2005; Pedley, 2009). Under suitable conditions, a fen can last for more than 11,000 years (Mituchovci site; Dabkowski et al., 2019).

4.2.4. Lakes and marshes

Description: The Neogene freshwater limestone of the alluvial lake-march Hlavina Mb. (alluvial plain Volkovce Formation) and lake-march Dubná skala Mb. (long-lived lake Martin Formation, Turiec Group) are developed from subhorizontal calcareous beds consisting of different deposits: mudstone, marl, siltstone of 'lake chalk' character, sandstone and fine-grained conglomerate, organodetrital, lumachella, oncoid, laminate, and peloidal limestone, and porous tufa. Terrestrial and water gastropods, *Chara* detritus, clumpy cyanobacteria *Rivularia,* ostracods and rare bivalves were determined. The thickness of the Hlavina Mb. is ca. 50 m and for Dubná skala Mb. approximately 150 m (Fordinál & Nagy, 1997; Hók et al., 1998; Töröková & Fordinál, 1999; Pipík & Sabol, 2006; Kováč et al., 2011[a]; Pipík et al., 2012, Joniak et al. 2020). Similar deposits were identified near Sliač spa.

The detailed research identified that micritic matrix usually contains scattered intraclasts (bioherm fragments), oncoids (rounded and cylindrical), microbial shrubs, and locally extraclasts (Veľký Klíž including building ashlars of 'Klíž travertine'; Fig. 7b–c, Appendix 12g–h; Dubná skala quarries; Appendix 12j). The clasts and oncoids are often broken. Porous microbial and macrophyte tufas were occasionally found. Recent small lakes (pools or ponds) of different origin are present inside the mound orifices, fens (Fig. 7a, Appendix 12a,e), *terracettes* (Appendix 7e) or in depressions among lobes (Sivá Brada, Appendix 12c). Some of them were influenced by human activity (Appendix 5f–h).

Interpretation: Described deposits of the Hlavina Mb. and Dubná skala Mb. correspond to the lacustrine model of tufa (Pedley, 2009) and the lacustrine crust with lake marl and reefs (Pentecost, 2005). The lake marl or incorrectly 'lake chalk' is a result of $CaCO_3$ precipitation through phytoplankton/macrophyte photosynthesis accompanied by CO_2 evasion and evaporation. Precipitation occurs either within the lake water where it is subsequently deposited as a calcareous mud, or upon submerged benthic macrophytes such as *Chara* (Pentecost, 2005). Microbial laminites, shrubs (dendrites), and mats point to bioherms and crusts on lake bottom (Pedley, 2009). Marshy and littoral lake ostracods and other organisms were identified in freshwater limestone and accompanying deposits of the Dubná skala Mb. (Pipík & Sabol, 2005; Pipík et al., 2012). Freshwater limestone bodies are the products of the hyperconcentrated water springs ascending to the surface along basin border faults (Kováč et al., 2011[a]). The Hlavina Mb. and Dubná skala Mb. are lacustrine-palustrine deposits in changing climatic, tectonic, and water dynamic conditions. Formerly, it was a lake with the bottom flow, occasionally with stream input or without flow. Sometimes beds present marshy lake margin or shallow part of the lake.

Lake bioherms

Description: Irregular bioherms up to several metres in size were identified in Veľký Klíž (Fig. 7b, Appendix 12g,h) and Sádok quarry (Appendix 12i). They are composed of microbial mats and gastropods. In addition to them, small, several centimetres to decimetre-sized microbioherms were found in Veľký Klíž (Fig. 7c), composed of laminites and clusters of millimetre-sized coated holes. The microbialites were found also in the Dubná skala site, but they did not form distinct bioherms. The columnar microbial bioherms were identified in the Levice travertines deposited in shallow pools.

Interpretation: The laminites are a result of microbialite growth and the clusters of millimetre-sized coated holes were formed by caddisfly larvae colonies as their cases (cf. Pentecost, 2005). Stromatolitic mounds (microherms) and large phytoherm reefs may develop in a lacustrine model of tufas (Pedley, 2009). The shoreline microbial bioherms with clotted peloidal micrite boundstone were described in the Great Salt Lake (USA) and laminated stromatolitic boundstone with encrusted caddisfly larvae in the Nine Mile Canyon, Utah (Della Porta et al., 2011; Della Porta & Barilaro, 2012).

5. DISCUSSION OF TRAVERTINE AND TUFA DATING AND NEOTECTONICS

Travertines in Slovakia are regarded as originated during warm and moist climate phases of the Neogene, Pleistocene (interglacials), and Holocene (Ložek, 1992) and Slovak tufas during moist climate Atlantic stage of the Holocene (Kovanda, 1971; Gradziński et al., 2013). These results are based on palaeobotanical (Němejc, 1927, 1929, 1931, 1944), malacological (Petrbok, 1937; Ložek, 1958), and geomorphological data like the degree of weathering and karstification, block movements, and on occurrences of *terra calcis* soil types (Ložek & Prošek, 1957; Ložek, 1959, 1961, 1964, 1973; Smolíková & Ložek, 1962). Recent research confirms, refines, and specifies the previous ones. In the following passages, older research will be discussed with information presented by the authors and the travertine ages are summarised in Fig. 8. Travertines were developed where springs of groundwater occurred, and water accumulated in suitable structures followed by subsequent uplift at along to active faults. The faults are marked on Fig. 1. In central Slovakia, N–S fault system formed, named Central Slovak fault system (Kováč & Hók, 1993). Towards the west, the prevailing orientation of faults is NE–SW. In northern and eastern Slovakia, the faults have a dominant W–E to NW–SE orientation. The travertines are often developed on the fault intersections (e.g., in the Dreveník area).

5.1. Late Tortonian (late Pannonian) to Zanclean

The earliest Cenozoic freshwater limestones were dated back to the late Pannonian, a regional stage, which corresponds to the international Tortonian stage (Fig. 8) (cf. Kováč et al., 2010). They belong to the Hlavina Mb. and were tenuously dated at 8.2 Ma

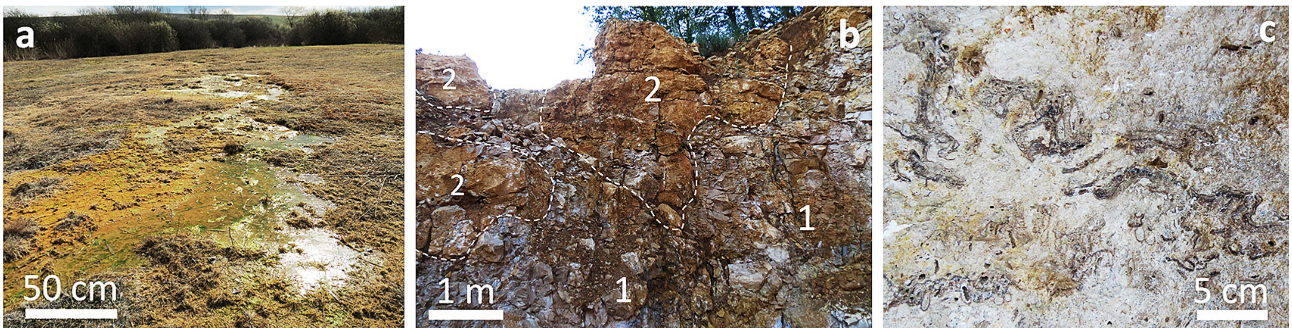

Fig. 7. Wetlands and lakes: a – carbonate fen with grass, algae and cyanophyte filaments near Vyšný Sliač; b – quarry face near Veľký Klíž with the Tortonian lake deposits (1 – fresh-water micrite limestone with small bioherms, 2 – porous microbial bioherms); c – small bioherm with microbial laminite and caddisfly larvae cases in Veľký Klíž.

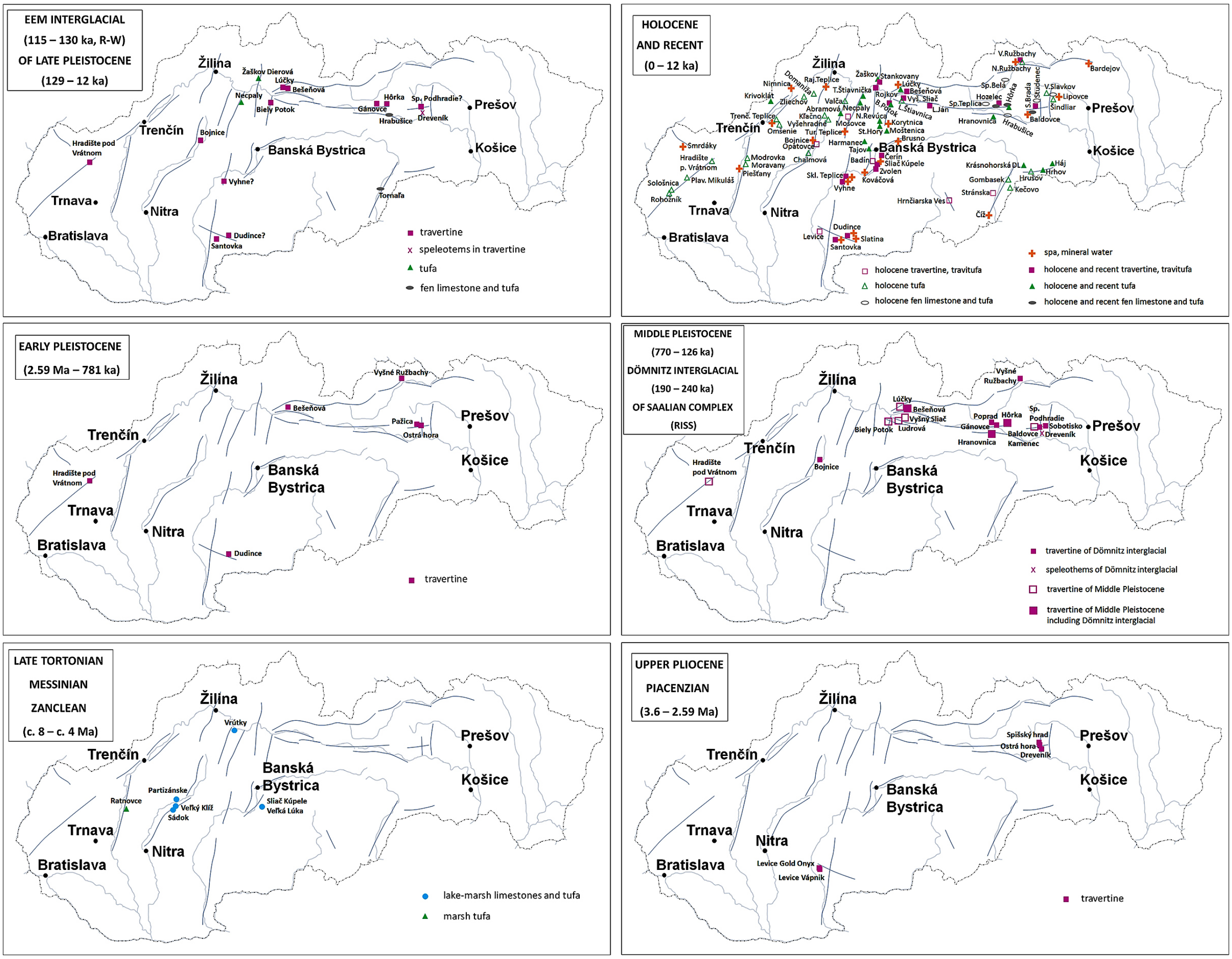

Fig. 8: The age and spatial distribution of Slovak travertines according to Del Tredici (1989), Denk (2004), Fordinál & Nagy (1997), Gradziński et al. (2008, 2015), Hók et al. (1998), Kaminská (2010), Konečný et al. (1998), Kováč et al. (2011a,b), Kovanda (1971), Kvaček et al. (2019), Ložek (1959, 1992), Meschede & Warr (2019), Nemergut (2011), Smolíková & Ložek (1962), Šujan et al. (2017), and Wróblewski et al. (2010).

(Fordinál & Nagy, 1997; Töröková & Fordinál, 1999; Kováč et al., 2010). They were deposited in the lake environment with the bottom flow and bioherms. The deposition happened during the period of the planation of a large part of the Western Carpathians, the formation of the 'Mid-mountain level' (Minár et al., 2011). The Hlavina Mb. is the result of tectonic activity during 9–8 Ma along marginal faults on both margins of the Považský Inovec and Tribeč Mts. (Fordinál & Nagy, 1997; Šujan et al., 2017).

Although similar to the Hlavina Mb., the Dubná skala Mb. is not clearly defined in terms of age. Hók et al. (1998) and Pipík & Sabol (2006) considered it to be of a same age as the Hlavina Mb., but Kováč et al. (2011[a]) dates them to the Messinian (ca. 5.7 Ma) and Králiková et al. (2014[a]) to lower Pliocene (ca. 4.5 Ma). The most probably longer duration (ca. 1 Ma) of travertine formation in the Dubná skala is evidenced by gradually decreasing dip of bedding from the bottom (≈ 40°) to the top of sedimentary sequence (basically subhorizontal). This structure is interpreted as syntectonic and is linked with a normal displacement of the N–S striking Hradište fault, which divides the upper Miocene deposits of the Turiec Basin to the east from the Tatric crystalline basement to the west. The bedding planes are inclined generally westwards. The latter two age data are consistent with the commencement of a rapid domal uplift in the Western Carpathian mountain chain documented between 6–4 Ma (Kováč et al., 2011[a], 2011[b]; Minár et al., 2011) connected with an extensional tectonic regime with the orientation of σ_3 in the NW–SE direction (Vojtko et al., 2019). However, the precise time span of travertine formation of the Dubná skala Mb. is still yet to be precisely determined.

5.2. Late Pliocene

Two important travertine areas in Slovakia originated in the Pliocene (Fig. 8): The Drevenik site near Spišské Podhradie (Ložek, 1992) as the largest coalesced mound in Slovakia and the Levice area with hot spring travertines (Konečný et al., 1998). The travertines of the Dreveník mound can be compared with the Rapolano Terme travertines (Italy) based on palaeoenvironments, facies, and stable isotopes (cf. Gandin & Capezzuoli, 2008; Gradziński et al., 2014). The weathering phase is characterised by intensive karstification associated with *terra rossa* and strong cambering (Ložek, 1992). The occurrence of large forms of travertine in the Pliocene may be related to the late Pliocene (≈ 4.1–2.6 Ma) and Quaternary acceleration of the Western Carpathian chain uplift which led to the formation of the current landscape and development of the river network. Travertine mounds and fissure ridges at both sites are located on the 'River level', the upper Pliocene to the lower Quaternary pediment (Bizubová & Minár, 1992; Michaeli, 2001; Minár et al., 2011; Bella et al., 2019). However, the Dreveník site can also be related to the W–E trending Vikartovce fault (cf. Vojtko et al., 2011).

In the Dreveník travertine, teeth of *Mammut borsoni* were found (Holec, 1992), later redefined to *Anancus arvernensis* (Tóth & Krempaská, 2008). The species lived from the early Turolian to the Villafranchian (ca. 9 to 1 Ma), so the finding cannot be used to specify the exact age (cf. Boscato et al., 2008).

A tree leaf community (Němejc, 1927, 1944) and pollen analysis (Gradziński et al., 2015) refer to the late Pliocene age between 3.5 Ma and 2.6 Ma. *Fagus pliocenica* and *Ginkgo*, was determined among leaves (Němejc, 1944) and Denk (2004) included *Fagus pliocenica* within *Fagus haidingeri* that was widespread in Europe from the late Miocene to the Pliocene. *Ginkgo* was abundant in Europe at the start of the Pliocene and it was gone from that region by about 2.5 million years ago (cf. Del Tredici, 1989; Taylor & Edith, 1993). The leaf and pollen assemblages from the Dreveník (Němejc, 1944; Gradziński et al., 2015) is similar to the assemblage from the Frankfurt am Main site (Kvaček et al., 2019), that is considered to be the late Pliocene (ca. 3.6 Ma to 2.6 Ma) with the same species: *Ginkgo, Picea, Carya, Fagus, Liquidambar, Quercus, Torreya, Tsuga, Zelkowa,* and *Celtis.* In the late Pliocene – Mid Pliocene Warm Period (3.3 to 3 Ma), glaciers retreated in Antarctica and in Greenland and sea level rose by more than 20 m (De Schepper et al., 2014), and tropical forests expanded in the Pannonian Basin area from 4 to 3 Ma (Schweitzer, 2015).

Based on previous plant community studies, it is possible to specify the age of the Dreveník travertine to the late Pliocene (Piacenzian; 3.60 to 2.59 Ma). This is consistent with the results of the palaeomagnetic study which proved that travertine has normal polarity (Gradziński et al., 2015), thus it most likely belongs to the Gauss chron (3.59 to 2.59 Ma) in Geomagnetic Polarity Time Scale (Cande & Kent, 1995). The majority of the Dreveník – Ostrá hora coalesced mound is probably of the late Pliocene in age, but in the upper parts of the Ostrá hora, the Early Pleistocene malacofauna was also found (Kovanda, 1971). Since the coalesced mound base of Spiš Castle is at a similar height to the Dreveník coalesced mound, and the stage of weathering is very similar for both sites then the same age of their origin is considered.

5.3. Early Pleistocene

Several Spiš and Liptov travertines, Dudince and Hradište pod Vrátnom travertines (Fig. 8) (Tab. 3) were dated to the Early Pleistocene, based on cambering, height above the recent erosive base, karstification with *terra fusca* and locally *terra rossa* (Ložek, 1959, 1992; Smolikova & Ložek, 1962; Kovanda, 1971). Gradziński et al. (2015) found out that pollen assemblage from Bešeňová Baňa (old quarry) was typical for the warm climate. The Early Pleistocene (Gelasian and Calabrian) was the period without distinct glacials and interglacials. U-series dating (Gradziński et al., 2015) suggests that Bešeňová travertines are older than 350 ka but younger than 1.2 Ma. Palaeomagnetic study showed that they are normally magnetised, which implies the age younger than 780 ka, but also Jaramillo subchron (1.06 to 0.90 Ma) which belongs to the Early Pleistocene (Cande & Kent, 1995).

At the transition between the Pliocene and the Pleistocene, the direction of extensional axis changed from NW–SE to NE–SW in the western part of Slovakia (Vojtko et al., 2008, 2019). The tectonic stress change could cause the initiation of new deep circulating water systems with travertines in the sites of Bešeňová, Vyšné Ružbachy, and Hradište pod Vrátnom. The Bešeňová and Vyšné Ružbachy localities are near Sub-tatra fault with higher activity between 6.5 to 1 Ma (Vojtko et al., 2010; Králiková et al. 2014[b]). Certain phase of its movement probably occurred in the Early Pleistocene.

5.4. Middle Pleistocene

Some Spiš and Liptov travertine localities, Hranovnica, Sliač Kúpele, and Hradište pod Vrátnom travertines (Tab. 3; Fig. 8) were dated to the Middle Pleistocene, based on insignificant cambering, height above recent erosive base, and *terra fusca* (Ložek, 1959; Smolíková & Ložek, 1962; Kovanda, 1971). For the mentioned localities, the earlier part of the Middle Pleistocene is assumed. Hranovnica Hincava travertine body (Kovanda, 1971) was dated to Günz–Mindel interglacial (ca. 0.5–0.6 Ma).

The late part of middle Pleistocene, Saalian Complex (Riss), Dömnitz interglacial (ca. 190–240 ka; Meschede & Warr 2019) age is assigned to some Spiš and Liptov travertine sites, and Bojnice travertines (Tab. 3) based on the height above recent erosive base and *terra fusca* soil (Ložek, 1959; Smolíková & Ložek, 1962; Kovanda, 1971). The affiliation of Vyšné Ružbachy Horbek, Hranovnica (over road), Hôrka, and Sobotisko to this period was also confirmed by the Neanderthal tool occurrences (Kaminská, 2010; Nemergut, 2011). The dating results by means of U-series disequilibrium allowed to determine the age of the Vyšné Ružbachy Horbek site that was finished approximately 200 ka (Gradziński et al., 2008), which correspond to the Dömnitz interglacial. During this time span, the study area was controlled by the youngest palaeostress phase with the extensional tectonic regime, where the principal minimum σ_3 axis was oriented in the NE–SW to E–W direction in the Western Carpathians (Sůkalová et al., 2012; Vojtko et al., 2019). The inherited fault structures from older phases were used as a feeder of mineralised and thermal saturated underground water.

5.5. Late Pleistocene

The Eem interglacial (115–130 ka, Riss–Würm) of the Late Pleistocene was, like the Dömnitz interglacial, marked out by the formation of numerous travertines in the Spiš and Liptov region, as well as at Bojnice, Santovka, and Hradište pod Vrátnom (Tab. 3) (Fig. 8). The sites are characterised by minor traces of karstification, frost weathering, rendzina, and local *terra fusca* soil (Ložek, 1959, 1992; Smolíková & Ložek 1962; Kovanda, 1971). The dating of the sites was determined by the Neanderthal tool occurrences in Hôrka, Gánovce (extending to the end of Saalian/Riss glacial), and Bojnice (extending to the beginning of the Vistulian/Würm) glacial (Kaminská, 2010; Nemergut, 2011). The bottom part of Lúčky travertine was dated based on U-series to 139 (–14+15) ka (Gradzinski et al., 2008) which can also fit into the Eem interglacial.

The extensional tectonic regime with the principal minimum σ_3 axis was oriented in the NE–SW to E–W direction same as in the Middle Pleistocene (Vojtko et al., 2019). In the Spiš region near Poprad, the W–E striking Vikartovce fault restarted its activity ca. 135 ka (Vojtko et al., 2011), which could influence the travertine sites near Gánovce and Hôrka. The regional pattern of the tectonic regime locally fluctuated and the NNW–SSE extension prevailed in some places (Sůkalová et al., 2012). The travertine site were also formed on the normal faults, which were related to the Central Slovak fault system border fault along the core mountains.

5.6. Holocene and recent

The Holocene as warm interglacial period restored deep circulation of mineral waters after last glacial stagnation. The travertine mounds, fissure ridges, and lobes were formed on valley bottoms or the slopes near them (many of them are still active; Tab. 3). The regions and sites with most abundand occurences are the Poprad – Spišské Podhradie region, Liptov region, Vyšné Ružbachy site, Banská Bystrica – Zvolen region, and Levice – Dudince region.

During the Holocene, carbonate fens developed (e.g., Spišská Belá). Hrabušice and Tornaľa started at the late Vistulan glacial (Kovanda, 1971). The large fens are abundant near the High Tatras, where the depressions formed between large alluvial fans. The depressions also formed behind horst barriers (e.g., Hrabušice) or behind large travertine mound (Spišské Podhradie) on an impermeable basement.

Most tufa localities formed during the warm Atlantic period (Kovanda, 1971). Radiocarbon dating proves that the Slovak Karst tufas grew during the Atlantic and Sub-Boreal periods (ca. 7.5–3.5 ka BP; Gradziński et al., 2013), which corresponds to the most balanced part of the speleothem moisture records in Spain caves during the Holocene, relatively stable conditions between dry and wet climate (Smith et al., 2016). Recently many tufa accumulations are being destructed by headward erosion. The older tufas were probably also destroyed by weathering and erosion.

6. CONCLUSIONS

This paper updates knowledge for 87 the most representative sites of Slovak travertines and tufas by describing and interpreting depositional environments and morphologies described in the recent publications. Recent and fossil travertines and tufas were studied and compared. Basic forms as spring mounds (1 to 500 m; 49 %) with mound orifices, fissure ridges (30 to 500 m; 6 %), perched springline deposits (20 to 400 m; 21 %), and dams along the stream (20 m to 6.5 km; 20 %) were identified on lidar images and historical maps.

The basic forms contain smaller forms, or can be connected to complex forms. Typical spring mounds are developed with central mound orifices (20 cm to 20 m), mostly in crater form. Travertine mound and ridge slopes are smooth with cascades that are moving downward depending on obstacles on the slope such as grass clumps, standing and fallen trees, and slipped travertine blocks. Terraced slope forms are very rare in Slovakia. The spring mounds can contain small self-building channels on the surface. Parasitic orifices (mouths) are usually formed on larger mounds. The cascade lobes are typically covered with *microterracettes*, which are formed by physical process with possible biogenic influence. Transitional types between mounds and fissure ridges can occur when a fissure ridge is covered by parasitic craters in parallel with fissure (e.g., Vyšný Sliač).

Slovak travertines are at a different stage of mound and ridge formation. The ideal sequence is: springs on fen (Baldovce), small spring mounds on fen (Čerín), several larger mounds (Dudince), the connection of mounds (Dudince, Hozelec), and finally a massive complex coalesced mound (Dreveník) associating several.

Perched springline deposits were described for tufas, travitufa, and sporadically travertines. Tufa dams along the stream occur in several hundred cases in Slovakia. The lobe or dam faces are often built from moss tufa, filamentous cyanobacteria, and algae with typical waterfalls, caves, and rare moss *terracettes*.

The freshwater limestones (Hlavina Mb. and Dubná skala Mb.) form when the mineral water rising along the active fault was accumulated in the grabens and alluvial lake with marginal marshes is formed with a variety of different limestone deposits, occasionally with bioherms. The large bioherms up to a few metres are composed of microbial mats with gastropods and the small bioherms up to a few dm consist of the colonies of caddisfly larvae cases and laminated or dendritic microbialites (Veľký Klíž).

The older published data of the Slovak freshwater limestone ages were summarised and discussed in context of the recent knowledge. The earliest freshwater limestones of lakes and mashes are the Tortonian and Messinian. True travertines were deposited in warm periods of the late Pliocene, the Early Pleistocene, in the interglacials of the early Middle Pleistocene, the late part of the middle Pleistocene (Dömnitz interglacial, ca. 240–190 ka), the Late Pleistocene (Eem interglacial, ca. 130–115 ka), and Holocene. Some of travertines and tufas are still forming presently. According to previous research, Slovak tufas were mostly developed during the Atlantic and the early Sub-Boreal periods, which corresponds to the period of relatively stable conditions between dry and wet climate during the Holocene, measured on the speleothems in Spain. Pleistocene and earlier tufas were almost all destroyed for their insufficient lithification.

The Bešeňová and Vyšné Ružbachy sites were very active in the Early Pleistocene. This probably indicates increased activity on the sub-Tatra fault, beside which the sites are located. The travertines of Dreveník, Vyšné Ružbachy, and partly Bešeňová mounds. are very similar to Rapolano Terme travertines in Italy with the environments, facies and stable isotopes.

The N–S Central Slovak fault system relates to 17 travertine sites. Towards the west, the faults with travertines (3 sites) turn in the direction NE–SW. In northern Slovakia, the faults have a W–E orientation (15 sites) and travertine mounds are developed along the strike of the Vikartovce fault. The territory of Slovakia contains all common forms of travertine and tufa described in the world literature. They are being developed over a period of 8 million years, but especially in the Quaternary.

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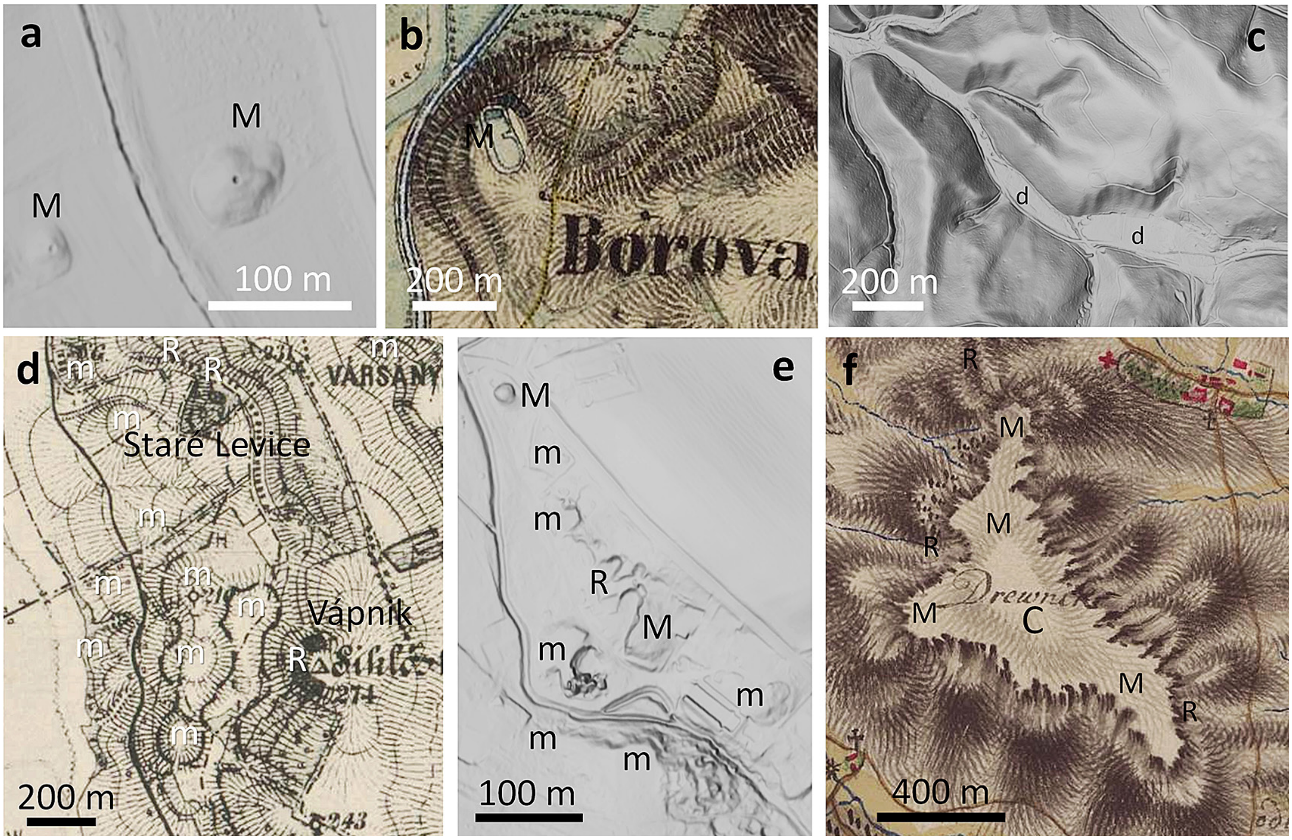
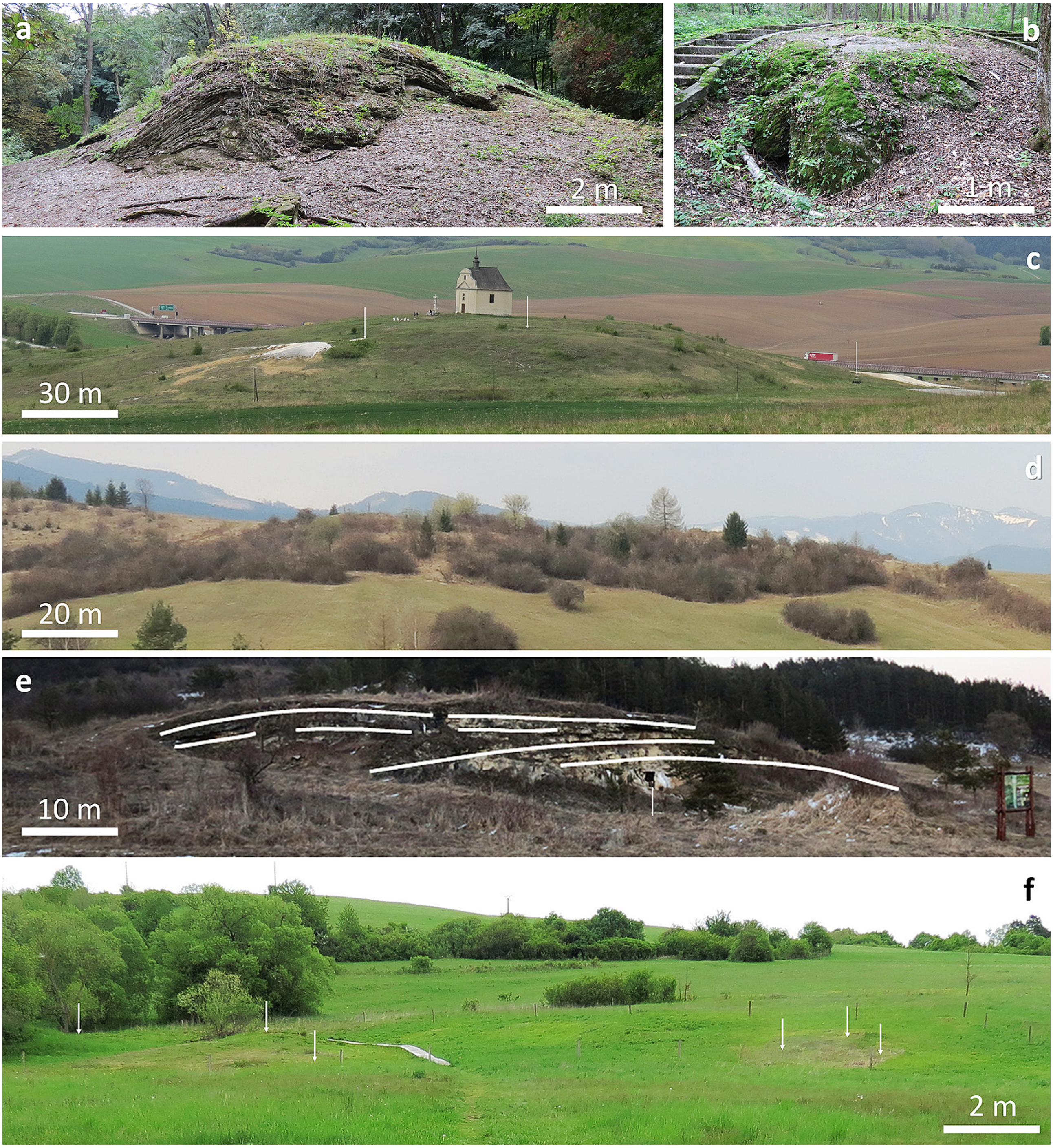
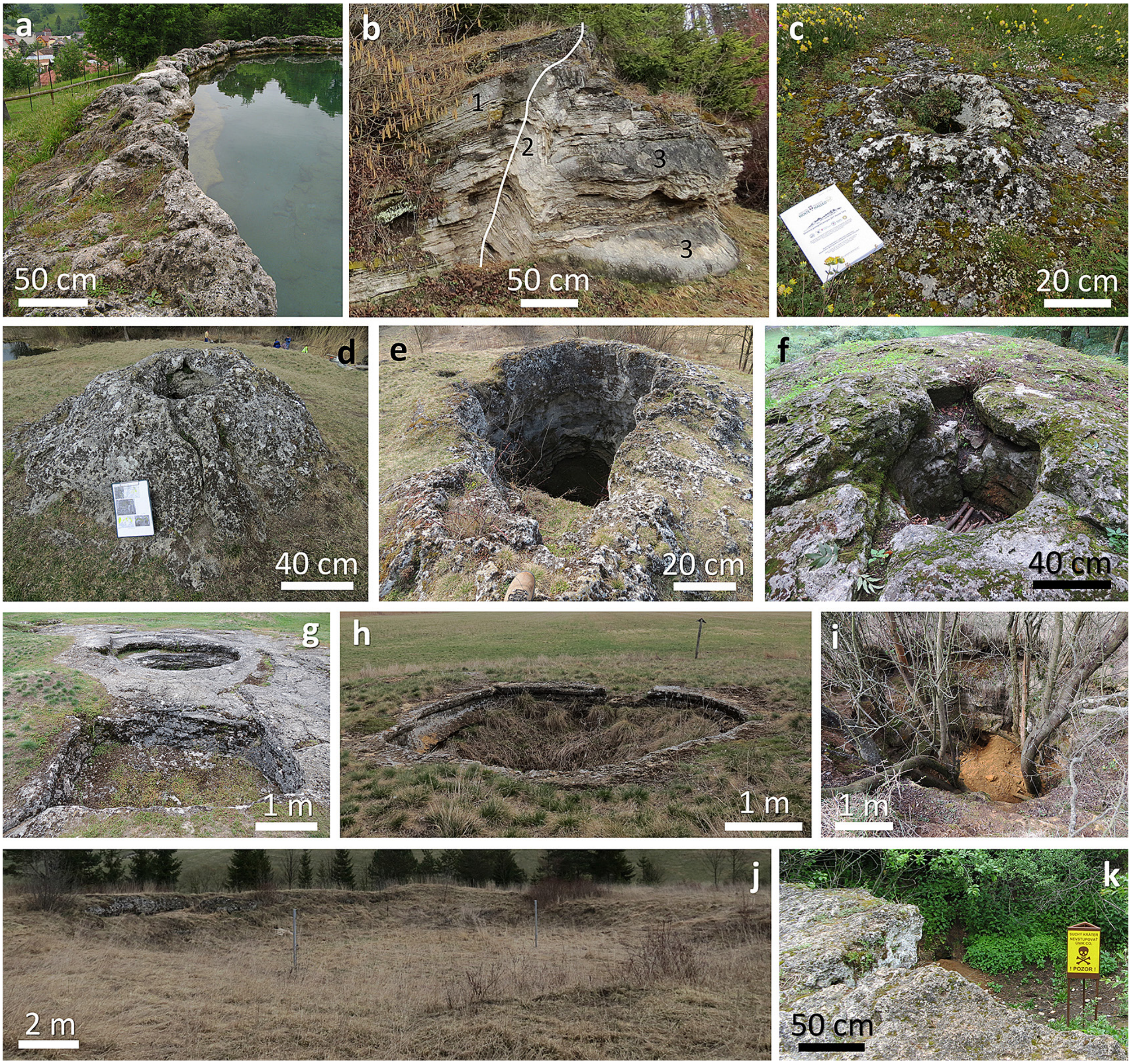


Appendix 1 – Travertine and tufa forms on lidar images and historical maps (M – spring mound, R – fissure ridge, m – mound or ridge, C – coalesced mound, d – dam): **a** – spring mounds with orifices on alluvium between Santovka spa and Bory; **b** – spring mound of Borová hora hill near Zvolen with pool in the orifice; **c** – dams along the stream in Striebornica valley near Moravany; **d** – spring mounds and/or fissure ridges in Staré Levice with Vápnik hill; **e** – spring mounds and/or fissure ridges in Santovka spa; **f** – coalesced mound Dreveník hill near Spišské Podhradie with connected spring mounds and fissure ridges (a, c, e – lidar images from zbgis.skgeodesy.sk/mkzbgis, f – Königreich Ungarn 1782-1785, First Military Survey, b – Hungary 1819-1869, Second military survey of the Habsburg Empire, d – Habsburg Empire 1869-1887, Third Military Survey, MAPIRE - Historical Maps Online; mapire.eu).



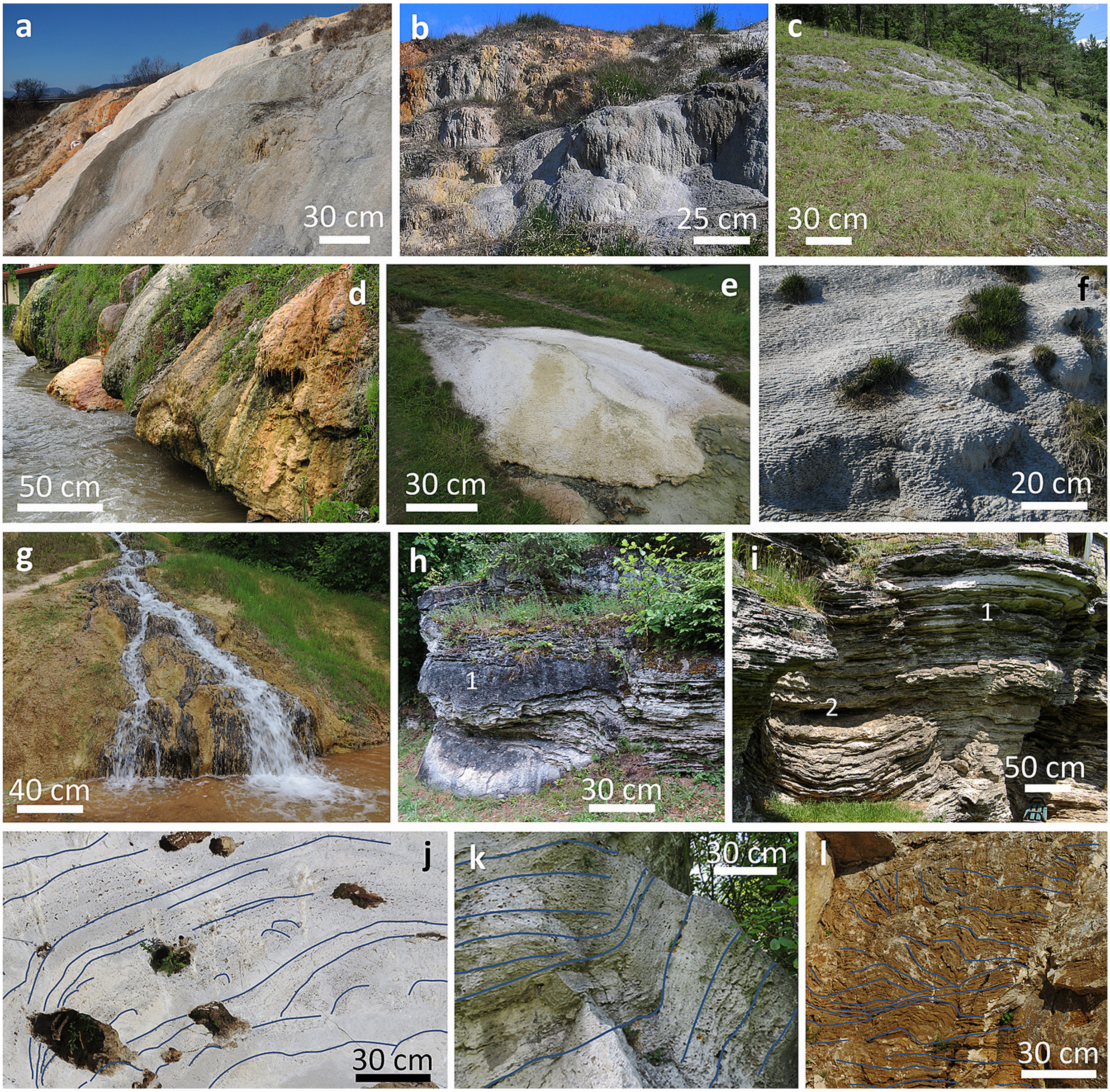
Appendix 2. Spring mounds (arrows show recent springs): **a** – 'Hostečný prameň' mound in Dudince spa; **b** – 'Očný prameň' mound in Dudince spa; **c** – Sivá Brada mound with recent parasitic orifices and slope lobes; **d** – Vyšný Sliač Kalvária mound – a wooded hill in the foreground; **e** – quarried Hozelec 'Banícka' mound with a lateral shift; **f** – 'Mičinské travertíny' site with many small springs mounds in Čerín cadastre.

Appendix 3. Fissure ridges and veins (white lines; 1 – slope travertine, 2 – vein, 3 – lateral veinlets, 4 – speleothems, 5 – *terra rossa* and breccias, 6 – gravitational crack or fissure, 7 – slip breccia): **a** – Vyšný Sliač ridge with orifices along the fissure; **b** – a fragment of fissure ridge in Dreveník mound; **c** – a steep slope of fissure ridge in 'Levice Gold Onyx' quarry; **d** – a fragment of fissure ridge and vein in Santovka spa; **e** – vein in 'Peklo' gorge of Dreveník mound; **f** – vein in Vápnik quarry; **g** – vein and veinlets in Spišské Podhradie quarry (Dreveník mound); **h,i** – sheeted veins (sills) in Dudince Porošin.

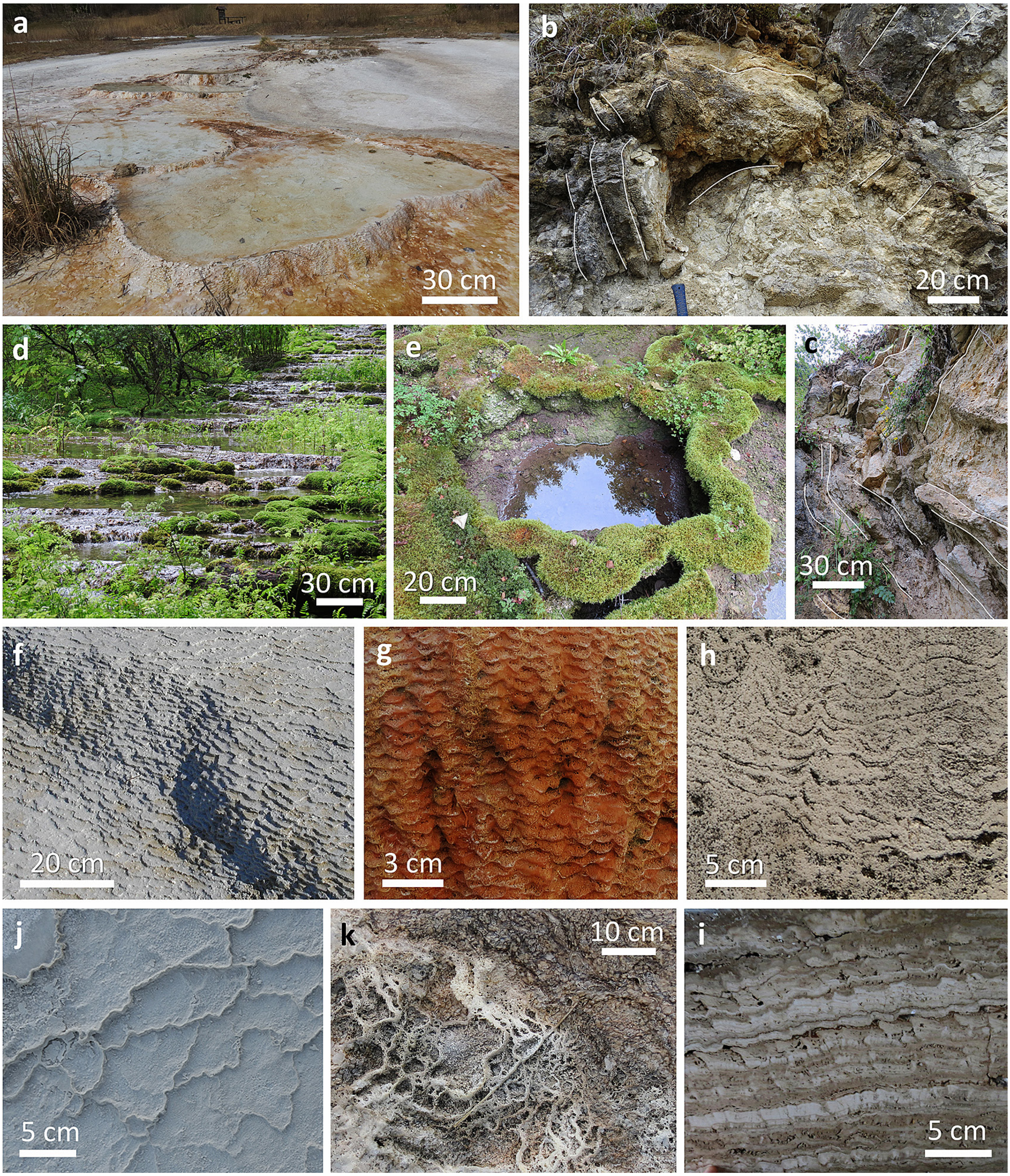


Appendix 4. Mound orifices: **a** – crater-like orifice in Vyšné Ružbachy; **b** – crater cut in Vyšné Ružbachy (white line - crater rim, 1 – crater inner slope, 2 – crater outer slope, 3 – cupola-like lobe); **c** – parasitic crater on Sivá Brada mound; **d** – Vyšný Sliač crater (smaller); **e** – Vyšný Sliač crater (larger); **f** – partly modified mound orifice on 'Tatársky prameň' mound in Dudince; **g** – mound orifice (back) and washing basin (front) in Dudince 'Močidlá'; **h** – mound with orifice between Santovka spa and Bory; **i** – wooded mound orifice with lime mud between Santovka spa and Bory; **j** – inactive broad orifice in Vyšný Sliač 'Kotlisko'; **k** – crater orifice in Vyšné Ružbachy with carbon dioxide escape.

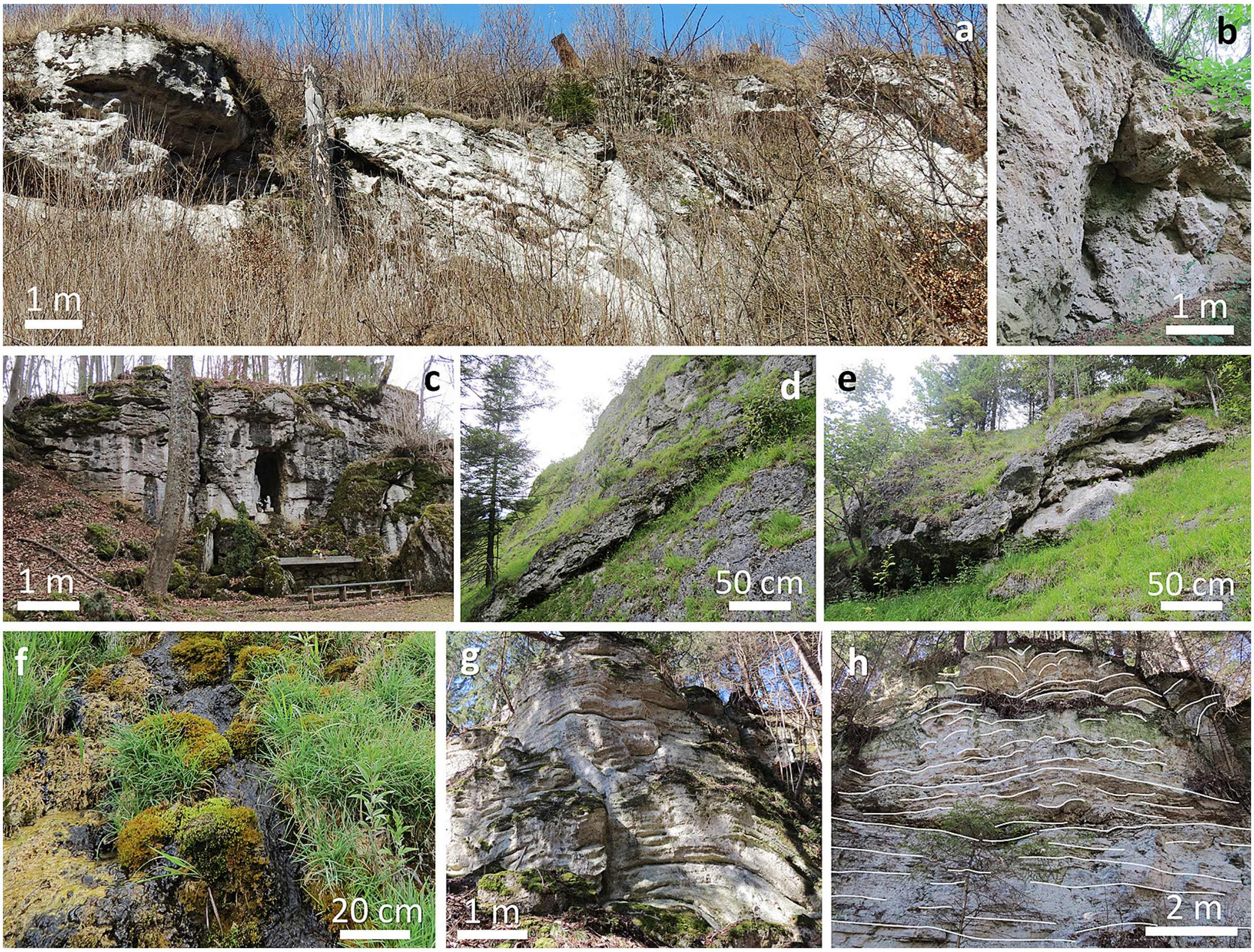
Appendix 5. Mound orifices and self-building channels: **a** – Sivá Brada orifice with pool (arrow - spring); **b** – Sivá Brada orifice (formerly a borehole); **c** – parasitic orifice in Sivá Brada; **d, e** – small mounds with orifices in Čerín ('Mičinské travertíny'); **f** – man-influenced orifice pool in Stankovany Močiar; **g** – orifice pool in Borová hora mound near Zvolen; **h** – man-influenced orifice pool in Rojkov; **i** –self-building channel in Sivá Brada bellow parasitic orifice (back); **j** – self-building channel terminated by keeled waterfall in Vyhne.



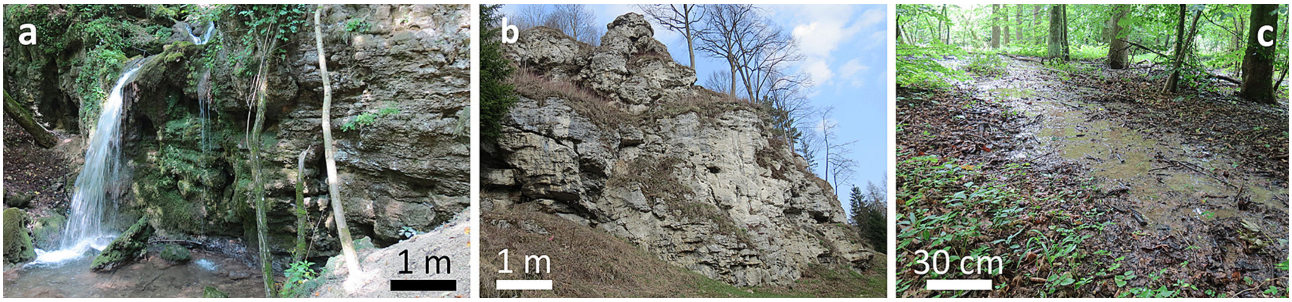
Appendix 6. Mound slopes with cascades: **a** – active and inactive cascade in Bešeňová; **b** – steep cascade in Bešeňová mound; **c** – an inactive cascade in Biely Potok Jazierce; **d** – cupola-like and pagoda-like cascade in Sklené Teplice; **e** – active lobe below parasitic orifice in Sivá Brada; **f** – cascade surface in Sivá Brada; **g** – cascade with biogenic facies in Vyšné Ružbachy; **h** – cupola-shaped lobe (1) in Vyšné Ružbachy; **i** – cut of the cupola-shaped lobe (1) and interlobe depression (2); **j** – a horizontal cut of lobes with trees in Dreveník; **k, l** – angular unconformities in lobes of Dreveník.



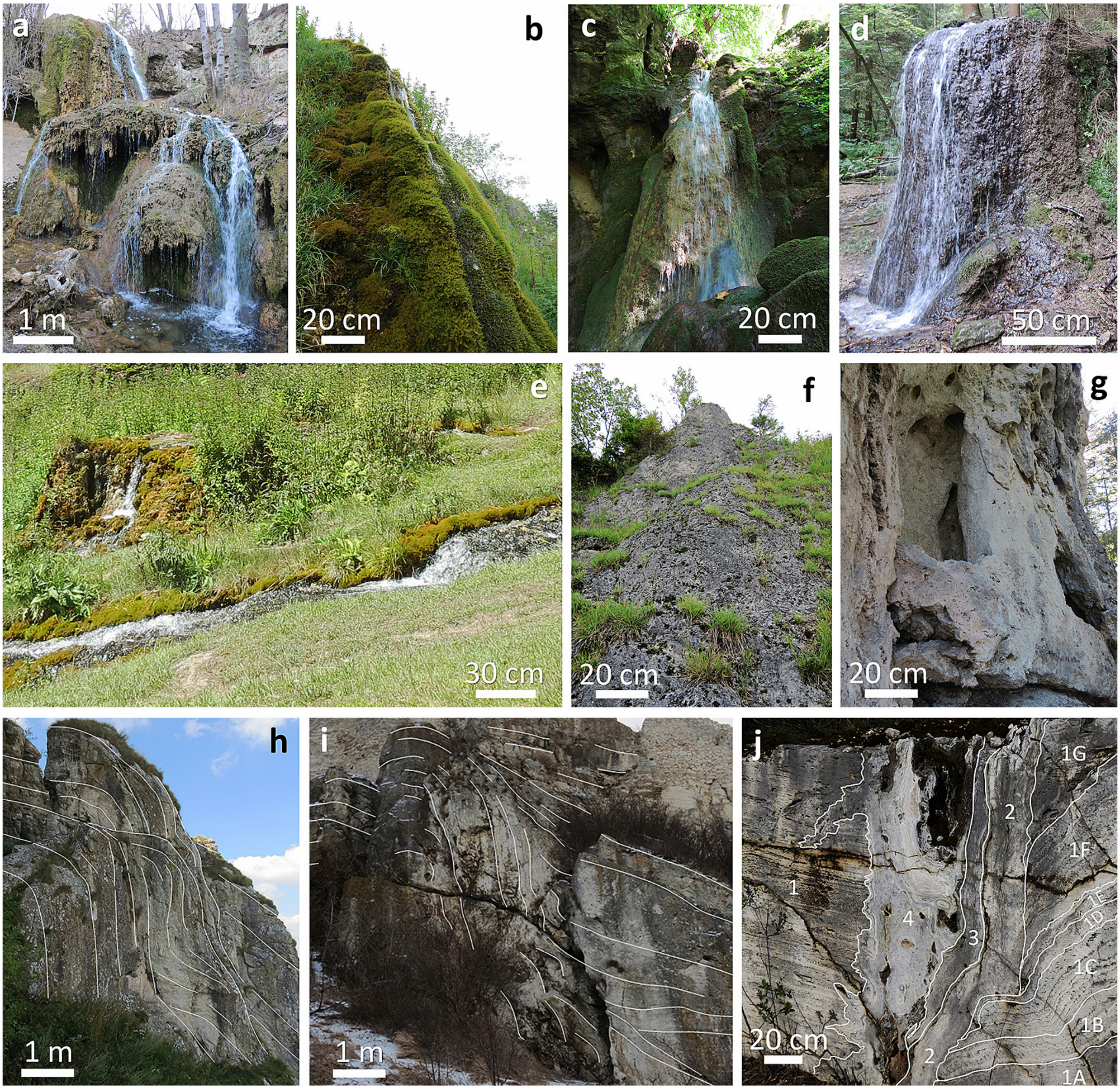
Appendix 7. Terraces, teracettes, microterracettes: **a** – man-influenced terraces in Stankovany Močiar; **b, c** – cuts of probable terrace rims in Levice Vápnik quarry; **d** – moss terracettes (dams) on slope lobe in Krásnohorská Dlhá Lúka; **e** – pool behind terracette in Krásnohorská Dlhá Lúka; **f** – microterracettes on cascade in Sivá Brada mount; **g** – microterracettes on steep cascades in Bešeňová; **h** – a horizontal cut of microterracettes from Drevenik quarry; **i** – a vertical cut of microterracettes from Lúčky quarry; **j** – microterracettes on subhorizontal surface mildly influenced by cyanobacteria; **k** – microterracettes on subhorizontal surface strongly influenced by cyanobacteria net.



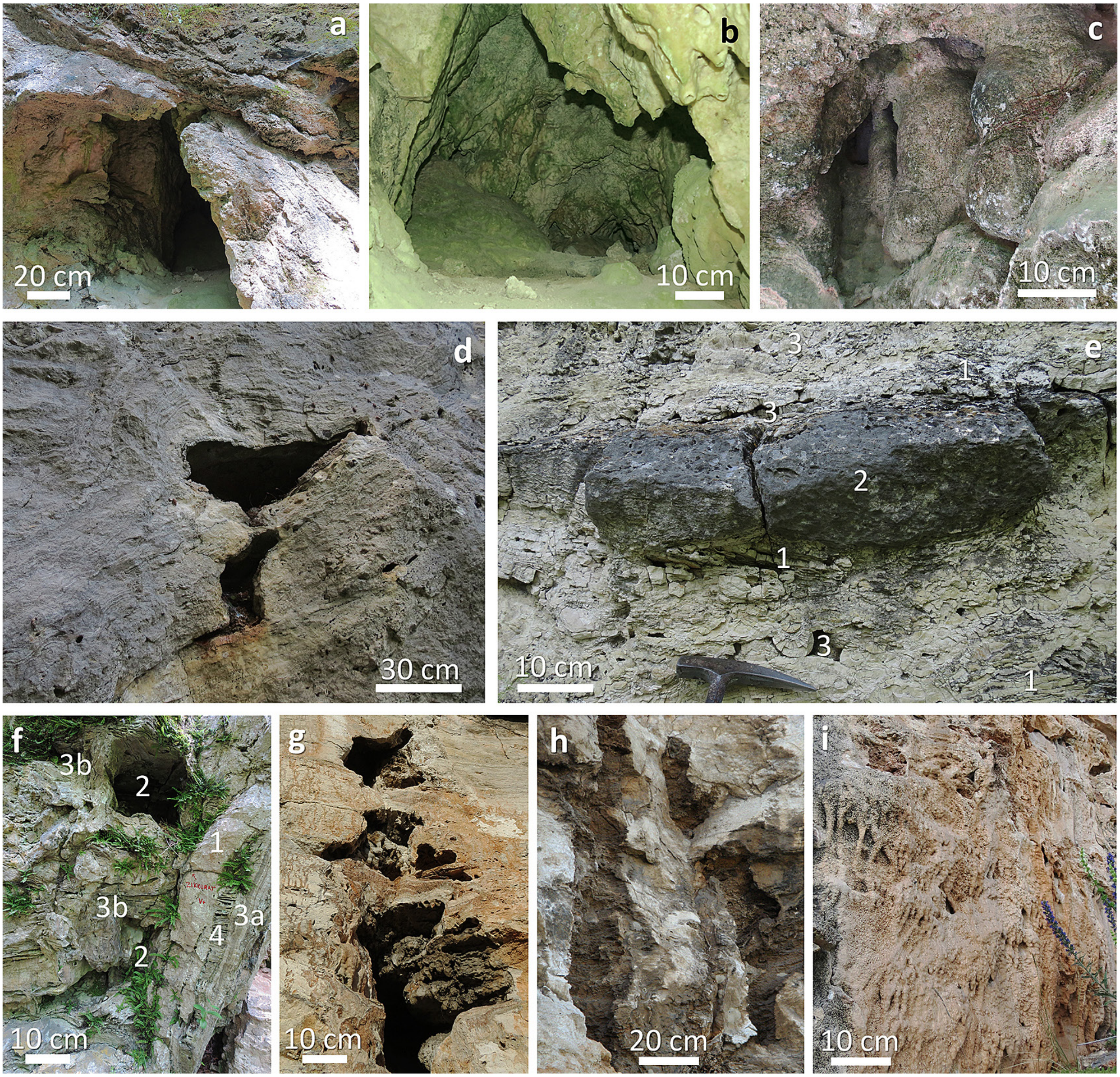
Appendix 8. Lobes on perched springline: **a** – gravitationally destructed face of large travitufa lobe near Hranovnica; **b** – quarry face in Hradište pod Vrátnom tufa lobe; **c** – quarry face of travitufa lobe in Biely Potok 'Vlčia skala'; **d, e** – slopes of moss travitufa lobe in Biely Potok Bukovina; **f** – an active slope of the lobe with moss cushions and grass in Biely Potok Bukovina; **g** – quarry face with moss travitufa regular beds in Biely Potok Trlenská valley; **j** – quarry face with moss travitufa irregular travitufa beds in Biely Potok Trlenská valley.



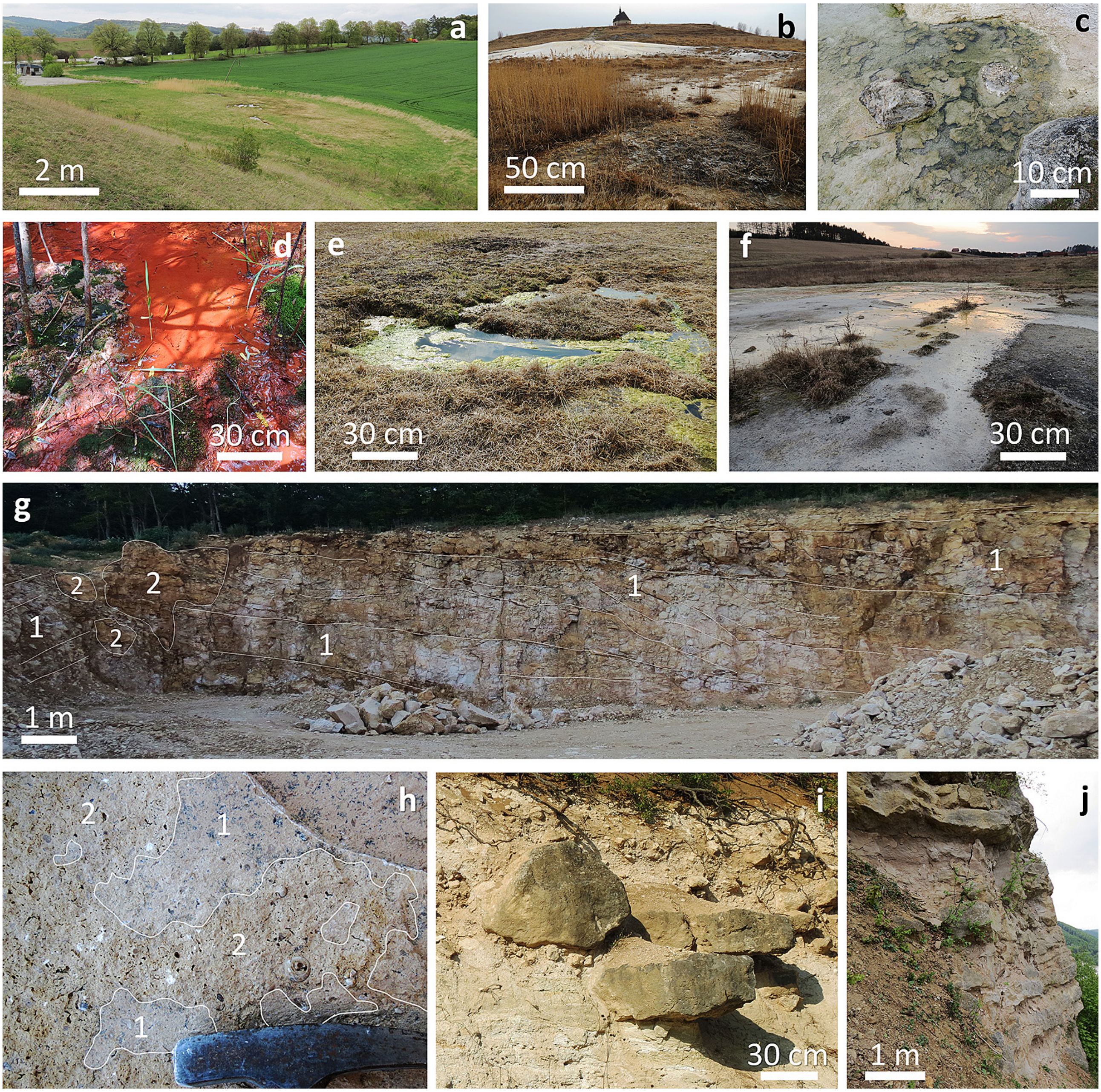
Appendix 9. Dams along streams: **a** – Holocene tufa dam with waterfall and caves in Háj; **b** – Pleistocene travitufa dam cut in Lúčky spa; **c** – flat wet surface between two dams near Krivoklát.



Appendix 10. Waterfalls: **a**– stepped waterfall from tufa in Hrhov; **b** – upper part of the waterfall with moss cushions in Biely Potok Bukovina; **c** – tufa waterfall in the head of the dam in Háj; **d** – waterfall on keeled tufa in Turčianska *Štiavnička*; **e** – stream with and without waterfall on lobe on perched springline in Biely Potok Jazierce; **f** – former tufa waterfall in Biely Potok Bukovina; **g** – Pleistocene travitufa waterfall with caves in Hranovnica Hincava; **h, i** – Pliocene travertine waterfalls in Spišský hrad coalesced mound; **j** – quarry face with waterfall and speleothems in Dreveník (1 – travertine cascade, 1A-G – travertine cascade with the erosion of 1C and later 1E-G, 2 – waterfall, 3 – the earlier speleothem, 4 – the later speleothems).



Appendix 11. Caves: **a**, **b** – caves under overhangs inside tufa dam in Háj; **c** – speleothems inside cave in Háj tufa dam; **d** – void after decay of organic slipped material on ridge slope in Dreveník; **e** – subhorizontal cave created in travertine (1) by flowing water (2) and later filled by speleothems (3); **f** – fissure ridge slope in Dreveník (1) with voids after decay of organic fallen material (2) covered by travertine beds (3b) and with vein (3a) and floes on former water levels inside fissure (4); **g** – karst cavities with speleothems along fissure in Dreveník; **h** – karst chimneys in Spišský hrad travertine; **i** – speleothems of the fissure surface in Dreveník travertines.



Appendix 12. Wetlands and lakes: **a** – carbonate fen with grass next to Sivá Brada mound; **b** –carbonate fen with reed next to Sivá Brada mound; **c** – pool with cyanophyte mats between lobes on Sivá Brada mound; **d** – carbonate fen with grass next to lobe on perched springline in Biely Potok Bukovina; **e** – carbonate fen with grass, algae and cyanophyte filaments near Vyšný Sliač; **f** – carbonate fen and pools in 'Gánovské lúky' (Hozelec) with grass, reed, cyanophyte filaments, algae filaments, and charas; **g** – quarry face near Veľký Klíž with the Tortonian lake deposits (1 – fresh-water micrite limestone with small bioherms, 2 – porous microbial bioherms); **h** – irregular contact of micrite limestone (1) with microbial boundstone limestone (2) in Veľký Klíž quarry; **i** – porous microbial bioherms in soft micrite limestone near Sádok; **j** – the Messinian lake and marsh deposits near Vrútky.