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Alteration of Triassic carbonates in the Buda Mountains – a hydrothermal model

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Large, irregular volumes of altered, friable Triassic dolomite with poorly recognizable depositional fabrics crop out in the Buda Mountains, Hungary. These rock volumes are characterized by powder-like, chalky, soft, whitish gray microporous carbonates, referred to as "pulverized dolomite". This is interpreted as the result of corrosion of carbonates along microfractures. The pulverized dolomite is commonly associated with silica and clay cementation ("silicification") and "mineralization" of iron-rich minerals, barite, sphalerite, galena, fluorite, calcite, dolomite and others, clearly pointing out hydrothermal Mississippi Valley Type (MVT) conditions.

The pulverization, silicification and mineralization are considered to be a diagenetic facies association (PSM facies). Tectonic shear corridors played an important role in the development of PSM facies as carriers of hydrothermal fluids, but the geometry of the altered units is very irregular and cross-cuts different Triassic depositional facies in addition to Eocene limestone and Middle–Upper Miocene sediments. The PSM facies represents the early stages of hydrothermal alteration (i.e. the burial phase) that was later modified by thermal mixing zones. Pulverized dolomite bodies that reached the surface were strongly affected by meteoric fluids; peculiar speleo-concretions were formed by calcite cementation of the powdery dolomite clasts.

The altered carbonates show major porosity development whereas the unaltered carbonates present only minor porosity. The size and lithologic contrast of the altered geobodies makes them detectable by geophysical methods of mineral and hydrocarbon exploration.

Key words: diagenetic, non-stratabound, alteration, dolomite, Buda Mountains, hydrothermal, pulverization

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Introduction

The widely-exposed, 2 km-thick Triassic carbonates are preserved in many areas of the Buda Mts, in the northeastern segment of the Transdanubian Range (Fig. 1) and have been extensively studied (Hofmann 1871; Wein 1977; Haas et al. 2000). Locally, however, these depositional facies and textures are intensively altered, obscured and erased, resulting in significant rock volumes of friable, disintegrated dolomitic and calcitic geobodies without stratification. This alteration is traditionally referred to as "pulverization" and the rock "pulverized dolomite". Previous authors suggested different processes, from surface weathering (Szabó, 1858; Hofmann, 1871) to thermal spring activity (Scherf 1928; Horusitzky and Wein 1962; Nagy 1979; Kovács and Müller 1980), to be potentially involved in the alteration.

This paper reviews the extensive published documentation on the "pulverized" carbonates in the Triassic of the Buda Mountains. In addition, it presents the results of detailed geologic mapping which was carried out on two selected pilot areas (Fig. 2) in order to understand the geometry, petrography and stratigraphy of the altered rock bodies. The relationship between the altered carbonate geobodies and the unaltered Triassic carbonates and younger stratigraphic units is carefully studied. The goal is to provide a comprehensive overview of these complex outcrops, with the large-scale diagenetic processes affecting the Triassic and younger stratigraphic units, on the basis of field relationships. Specialized petrologic and diagenetic studies are under development (Esteban et al., in preparation) and not included in this paper.

Geologic setting

The Buda Mts are in the northeastern segment of the Transdanubian Range (Fig. 1). The central massif of the Buda Mountains consists of Middle to Upper Triassic dolomite and limestone (Fig. 2.) with a total thickness of about 1,500–1,800 m (Fig. 3). The Budaörs Dolomite (late Anisian to earliest Carnian age) represents the oldest outcropping part of the Triassic platform carbonates. The Carnian-Norian basin facies (Mátyáshegy Fm.) is a 200 m-thick gray, slightly bituminous cherty dolomudstone and dolowackestone. It contains marl intercalations in the south (Sashegy Dolomite Mb.), and well-bedded to laminated, bioclastic, bituminous cherty limestone and marl in the north (Mátyáshegy Limestone Mb.). The platform carbonates are made up of cyclic sequences of Carnian Sédvölgy Dolomite ("Vadaskert Dolomite"), upper Carnian to Norian Hauptdolomit Fm. (both with a maximum thickness of 600 m), and the oncoidal thick-bedded upper Norian-Rhaetian Dachstein Limestone (500 m thick).

The Mesozoic strata of the Buda Mountains were uplifted during the Late Cretaceous times (Alpine Orogeny). The compressive movements caused gentle, NE–SW striking folding in the Triassic limestone, and abundant fractures in the dolomite (Wein 1977). The top of the Triassic carbonate section is a significant

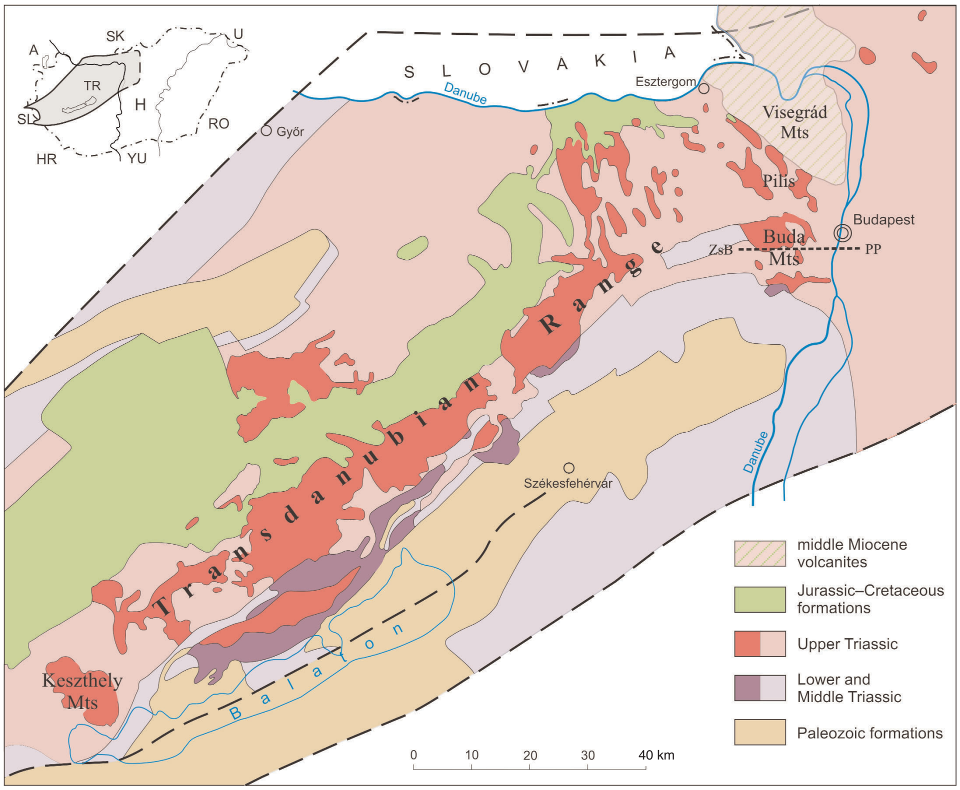


Fig. 1
Simplified pre-Tertiary map of the Transdanubian Range showing the location of the Buda Mountains (after Haas and Budai 2004) and the Miocene volcanites of the Visegrád Mountains. Dashed line corresponds to the general stratigraphic section of Fig. 3. ZsB – Zsámbék Basin PP – Pest Plain

palaeokarst surface. Subaerial exposure, intense meteoric karstification and erosional truncation affected the Mesozoic sequence from the Late Cretaceous until the late Eocene. Subvolcanic dykes of ultrabasic rocks (Budakeszi Fm) and red shale (locally with minor bauxite deposits) are considered as remnants of Cretaceous formations.

After this long subaerial exposure, the first marine sediment in the Buda Mountains is the upper Eocene basal conglomerate, breccia and sandstone (some tens of meters thick), with clasts mainly derived from Upper Triassic dolomite and limestone (andesite and rhyolite clasts are also present; Hofmann, 1871).

The basal unit, a fan delta complex (Fodor et al. 1994), is overlain by the upper Eocene Szépvölgy Limestone, deposited as a carbonate slope apron along a narrow, dissected, mobile shelf. The shallow water limestone (Szépvölgy Limestone) gradually changes into deepening upward, hemipelagic, pelagic marly limestone and marl (Buda Marl), indicating that sedimentation took place in a transgressive environment. The 60–120 m-thick Buda Marl is laminated; flaser-beds and limestone turbidites are common.

Eocene–Oligocene volcanoclastic deposits, shallow intrusive bodies and dykes are also present in the region (Schafarzik and Vendl 1929; Horusitzky and Wein 1962; Wein 1974); however, the presence of Middle Triassic volcanics cannot be excluded (Horváth and Tari 1987).

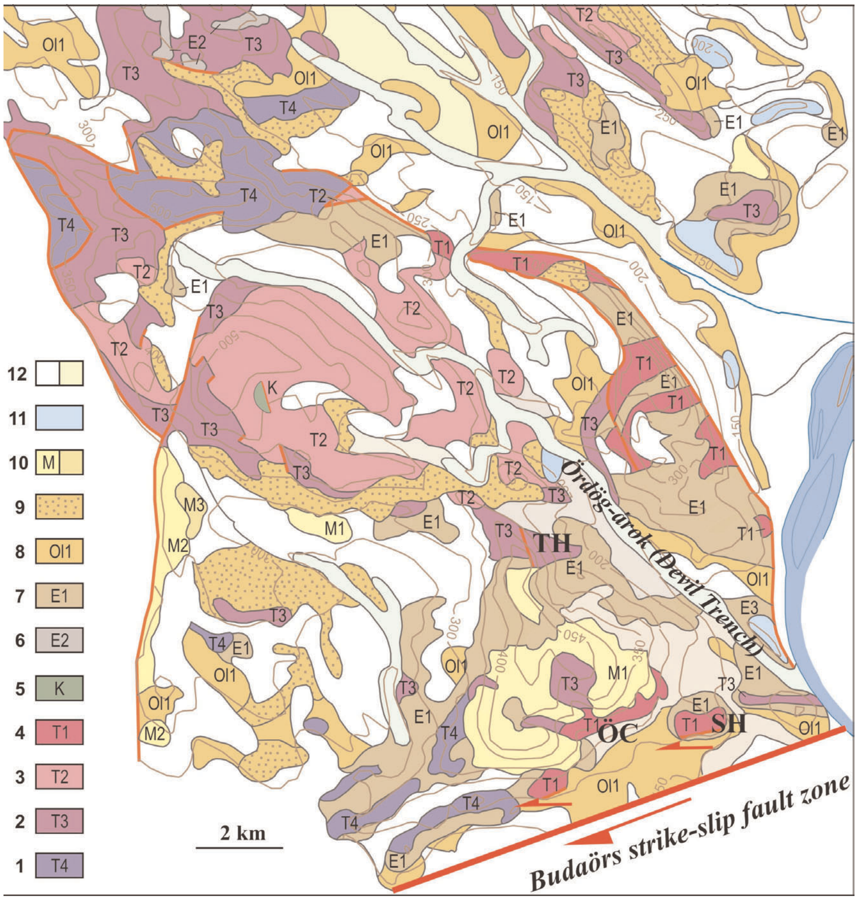


Fig. 2
Geologic map of the Buda Mts (modified after Budai and Gyalog 2009). 1. Anisian–lower Carnian platform dolomite (Budaörs Fm); 2. Carnian–Norian platform dolomite (Sédvölgy and Hauptdolomit Fms.); 3. Norian-Rhaetian platform limestone (Dachstein Fm.); 4. Carnian–Norian basinal carbonates (Mátyáshegy Fm.); 5. Upper Cretaceous volcanic dykes (Budakeszi Fm.); 6. Middle Eocene formations; 7. Upper Eocene formations; 8. Lower Oligocene formations, 9. Lower Oligocene siliceous sandstone (Hárshegy Fm.); 10. Miocene formations; 11. Pleistocene freshwater limestone, 12. Quaternary formations. Abbreviations: TH – Tündér Hill (Tündér-hegy); ÖC – Ördög Cliff (Ördög-orom); SH – Sas Hill (Sas-hegy)

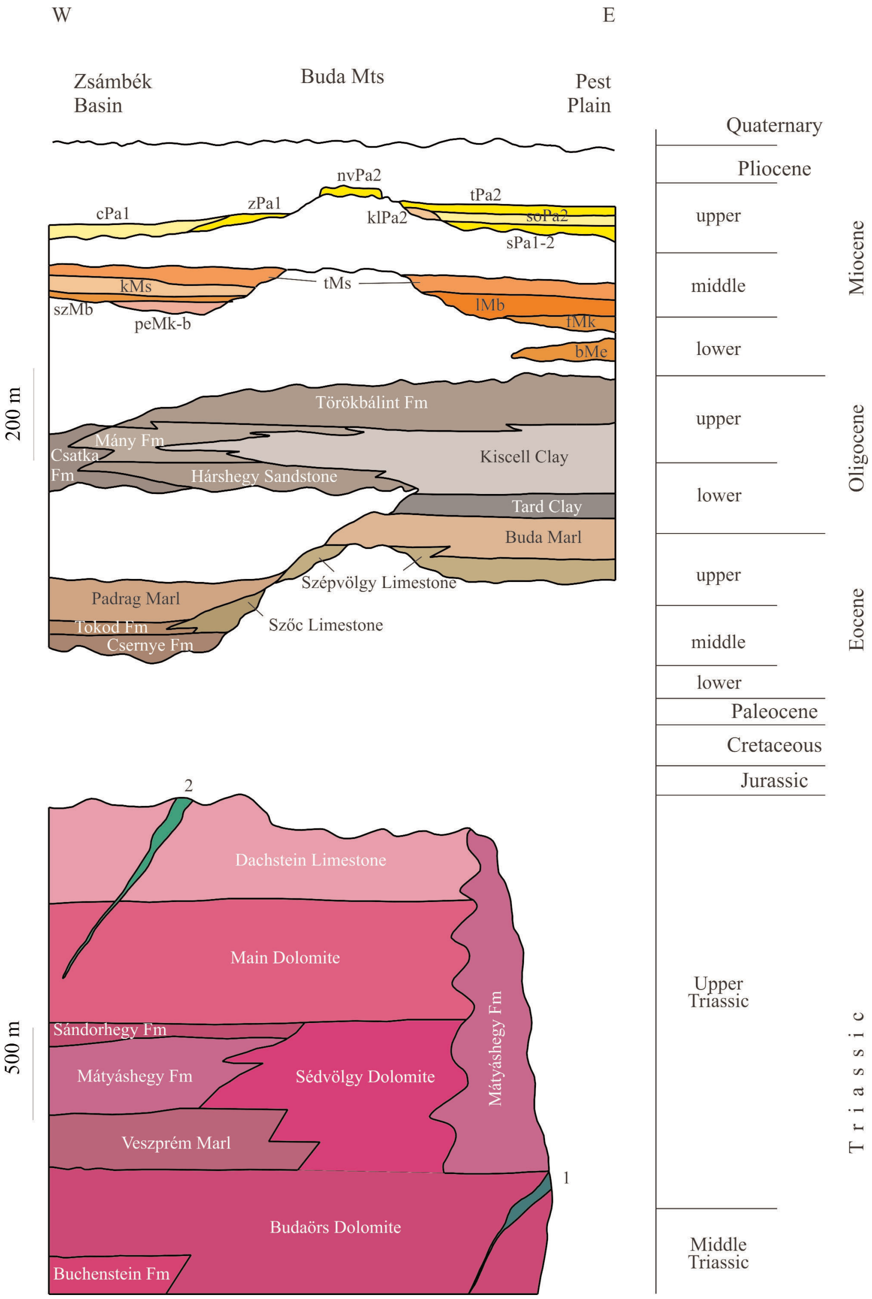


Fig. 3
General stratigraphic section of the Buda Mountains and the adjacent basins (the location of the section can be found as a dashed line in Fig. 1). 1. Middle Triassic volcanic dykes; 2. Upper Cretaceous subvolcanic dykes

During the Early Oligocene the product of pelagic carbonate sedimentation (marl) became shaly and the former shelf became an epicontinental basin. The Jánoshegy Antiform (parallel to the Buda Line) divided the basin into two parts (Fodor et al. 1994), separating the prograding siliciclastic delta front (Hárshegy Sandstone) in the west from a euxinic basin (Tard Clay) in the east. In the southeastern part of the Buda Mts an 800 m-thick sequence of shallow bathyal clay was deposited during the Early Oligocene (Kiscell Clay). Fine-grained sand and silt deposition took place during the Late Oligocene (Törökbálint Fm). The area was gradually uplifted along NW-SE oriented normal faults, and became subaerially exposed by the end of the Oligocene and Early Miocene.

At about 15 MYBP volcanism began north of the Buda Mts, forming the stratovolcano of the Visegrád and Börzsöny Mts (Balla and Korpás 1980; Korpás 1998).

The basal strata of the shallow marine Neogene sediments around the Buda Mountains do not contain any clasts from the Triassic and Eocene carbonates. It is assumed that at this time, these carbonates were still covered by thick Oligocene shaly sediments.

The late Miocene period is represented by a shallowing upward sequence: sandstones and siltstones are overlain by freshwater limestones of lacustrine facies (Nagyvázsony Fm.). The Oligocene sedimentary rocks continued to be eroded and by the end of the Miocene the area of the Buda Mts became a morphologically rather dissected terrain.

Karst and thermal karst processes were active in Pliocene and Pleistocene times. This is demonstrated by the travertine formed in thermal springs and lakes (Schréter 1912, 1953; Scheuer and Schweitzer 1988). The precipitation temperature of the travertine was in the range of 31–55 °C (Deák in Nádor 1992). The altitude of the travertine bodies indicates an estimated minimum of 360 m for the amplitude of the Buda Mts uplift (Scheuer and Schweitzer 1988).

Previous studies on altered carbonates of the Buda Mountains

The authors of early surveys of the Buda Mts (Szabó 1858; Hofmann, 1871) believed that the friable, "pulverized" character of the dolomite could be simply explained by surface weathering processes. Schréter (1912) recorded the first evidence of hydrothermal activity in the Buda Mts, with a precise description of diverse minerals (barite, fluorite, pyrite, etc.) associated with silicified rock bodies, such as dykes or other geometries.

The detailed study of Scherf (1928) provided an extensive description of the occurrences and characteristics of friable, "pulverized" dolomite in the Buda Mountains. He believed that friable dolomite in the Buda Mts (and also in the Pilis Mts; see Fig. 1) were formed as a result of recrystallization by hot waters of geyser-like thermal springs. The overpressured thermal waters were rich in carbonic acid, and on their way up along fracture zones produced intense mineralization. Based on the composition of the accompanying mineral assemblage (and on experiments on the formation of dolomite), Scherf estimated the water temperature to be around 120–130 °C. He found remnants of eroded vents of thermal springs in several regions of the Buda Mts. Based on the stratigraphic distribution of these eroded clasts of the vents, Scherf pointed out that the lateral migration of the ascending thermal waters within the sequence depends upon the impermeable overlying formations (Buda Marl, Kiscell Clay, etc.).

According to Schréter (1912) and Scherf (1928), hydrothermal activity clearly took place after the Oligocene. They believed that it was a postvolcanic phenomenon and its origin was connected mainly with the middle Miocene andesite volcanism of the Visegrád Mountains (see Fig. 1). Vendl (1923), Ferenczi (1925), Schafarzik (1926), Schafarzik and Vendl (1929), Van Amerom (1932), Bokor (1939), Földvári (1933), Vígh and Horusitzky (1940) and Semptey (1943) mapped the different areas of the Buda Mts and adopted the interpretations of Schréter (1912) and Scherf (1928) regarding the origin of the "pulverized" dolomite.

Later authors agree with the overall hydrothermal interpretation but have different opinions regarding the timing and type of hydrothermal processes. Horusitzky and Wein (1962) suggested that the thermal water activity in the Buda Mts was not connected with postvolcanic processes, mainly because such rock alterations cannot be observed in the close vicinity of the Miocene volcanics (Visegrád Mountains). In their opinion intensive hydrothermal flows occur (and occurred) along the margins of the Transdanubian Range in fault contact with the subsiding Tertiary basins (e.g. Hévíz). Based on the mineralogy and trace elements of the thermal spring precipitates, Horusitzky and Wein (1962) assumed the presence of a magmatic rock body (granite) beneath the Permian–Triassic sequence of the Buda Mts. Wein suggested (in Báldi et al. 1973) that hydrothermal alteration took place in the Pleistocene. He considered that the associated mineral paragenesis was derived from the hydrothermal re-dissolution of Eocene subvolcanic rocks (known in numerous localities in the Buda Mts). Báldi and Nagymarosy (1976) also believed that the mesothermal (310–320 °C) silica-bearing hydrothermalism was related to the Eocene volcanism, but they related it directly to the postvolcanic activity that ended in mid-Oligocene times. This opinion was mainly based on the absence of silicification in middle Oligocene sediments (note: formations younger than the Oligocene were not studied by Báldi and Nagymarosy 1976).

The excellent geologic map of Wein (1977) provided a detailed Triassic stratigraphy, including the distribution of "pulverized" geobodies. These altered geobodies are defined (at least in part) as Ladinian (^{d}T1) and Carnian (Tk) loose and silicified (^{k}Tk) dolomite units.

Nagy (1979) also proposed that thermal waters, circulating along fractured and crushed zones, could cause the pulverization of the dolomite. He thought that the alteration process resulted from a combination of: (i) the reactivity and (ii) the heat flux and the circulation of the hot waters.

Kovács and Müller (1980) considered that thermal water activity in the Buda Mountains occurred in two phases: (i) the early phase, triggered by postvolcanic activity during the late Eocene (Budaörs Zone) and middle Miocene (Szabadság Hill, Ezüst Hill); (ii) the second phase, in connection with the subsidence of the Pannonian Basin, triggered by a significant heat flux due to the thinning lithosphere.

Korpás and Kovácsvölgyi (1996) and Korpás et al. (2002) believed that hydrothermal alterations were connected with the activity of the late Eocene–early Oligocene 'Wein' paleovolcano (hypothetical).

Juhász et al. (2006) suggested a complex burial diagenesis involving pulverization, silicification and mineralization (PSM facies) resulting in intense alteration and obliteration of carbonate depositional facies and textures into non-stratabound geobodies. This burial diagenetic facies took place before the development of the spectacular thermal mixing cave system of Buda (not included in the present paper; for details see Müller 1989; Nádor 1994 and Juhász et al. 2006).

Gál et al. (2008) concluded that silicifying hydrothermal processes that produced chalcedony veins in the Hárshegy Sandstone (also known in the Buda Mts) can be related to a Paleogene volcanic intrusion.

Study areas

Two areas of the Buda Mountains were selected for a detailed survey: two segments of the so-called Budaörs strike-slip fault zone (Ördög Cliff – Ördög-orom and Sas Hill – Sas-hegy) in the southern part, and the Zugliget area (Tündér Hill – Tündér-hegy and Hunyad Cliff – Hunyad-orom) in the central part of the Buda Mts (Fig. 2). To the south the Upper Triassic carbonates are made up of thin-bedded cherty dolomite of basinal facies (Mátyáshegy Fm., Sashegy Dolomite Mb.), while in the central part they consist of shallow subtidal to peritidal cycles of platform dolomite (Hauptdolomit).

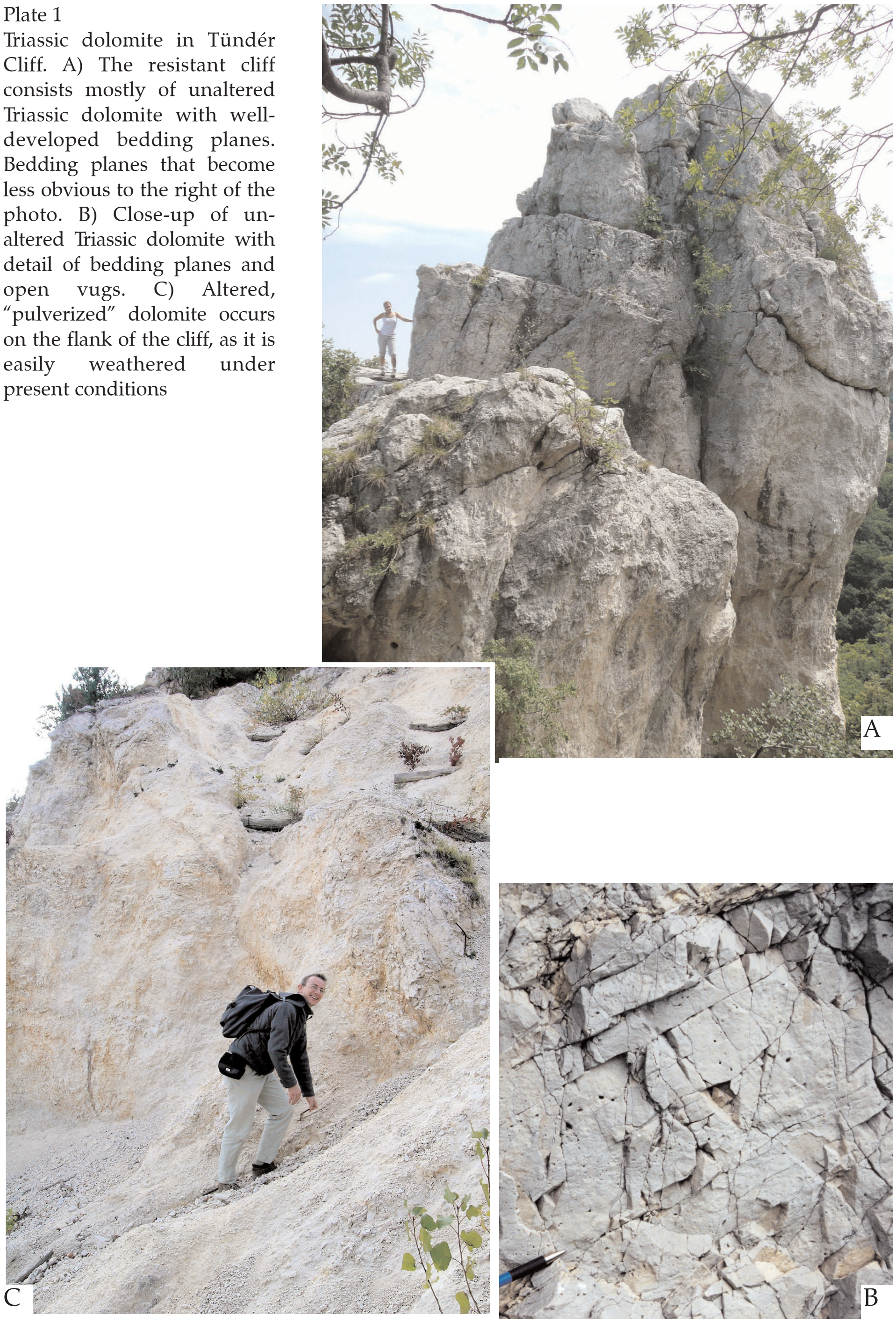
In both areas the following rock types were distinguished:

Non-altered, original rocks

The lower parts of both the platform interior (Plate 1, A) and basinal facies packages are pervasively dolomitized. Available exposures suggest a stratabound dolomitized body in the platform interior facies, but little is known regarding the nature or timing of the dolomitization event(s). Early diagenetic peritidal dolomitization models are commonly suggested; late diagenetic dolomitization overprints, however, cannot be excluded. The basinal facies are also dolomitized, showing more gradual or transitional boundaries, favoring the interpretation of late burial dolomitization models.

The non-altered, original Triassic rocks are characterized by easily recognizable bedding and depositional fabrics (Plate 1, B). There may be locally intense

Plate 1
Triassic dolomite in Tündér Cliff. A) The resistant cliff consists mostly of unaltered Triassic dolomite with well-developed bedding planes. Bedding planes that become less obvious to the right of the photo. B) Close-up of unaltered Triassic dolomite with detail of bedding planes and open vugs. C) Altered, "pulverized" dolomite occurs on the flank of the cliff, as it is easily weathered under present conditions



fracturing and brecciation, but without the typical degradation of depositional fabrics or physical disintegration in the outcrops.

Altered rocks

The term "altered" rock is informally used in the local literature to refer to outcrops of Triassic dolomite with poorly recognizable depositional bedding or other depositional fabrics, characterized by "loose" or "powdery" degradation of the dolomite (Plate 1, C). Altered rocks are white to very light gray; lighter than unaltered dolomite. The altered dolomite commonly has reddish stains indicating oxidation of iron-rich minerals (Plate 1, C, Plate 2, B). Altered rock bodies are "soft" under present weathering conditions, forming valleys and depressions in morphological contrast with the unaltered rock bodies. At least in part, alteration is clearly controlled by some major fault corridors with important shear zones, suggested by the rhomboidal or lensoidal shape of relatively unaltered relicts of the original dolomite (Plate 2, A). This pulverized Triassic dolomite is commonly associated or adjacent to zones of ore-mineralization and/or silicification (Scherf 1928), which may provide local physical consistency or rigidity to generally "loose rubbly" outcrops (Plate 1, C). Both the Budaörs zone and the Zugliget area are extensively dominated by "altered" Triassic dolomite, with only minor enclaves of the original rock.

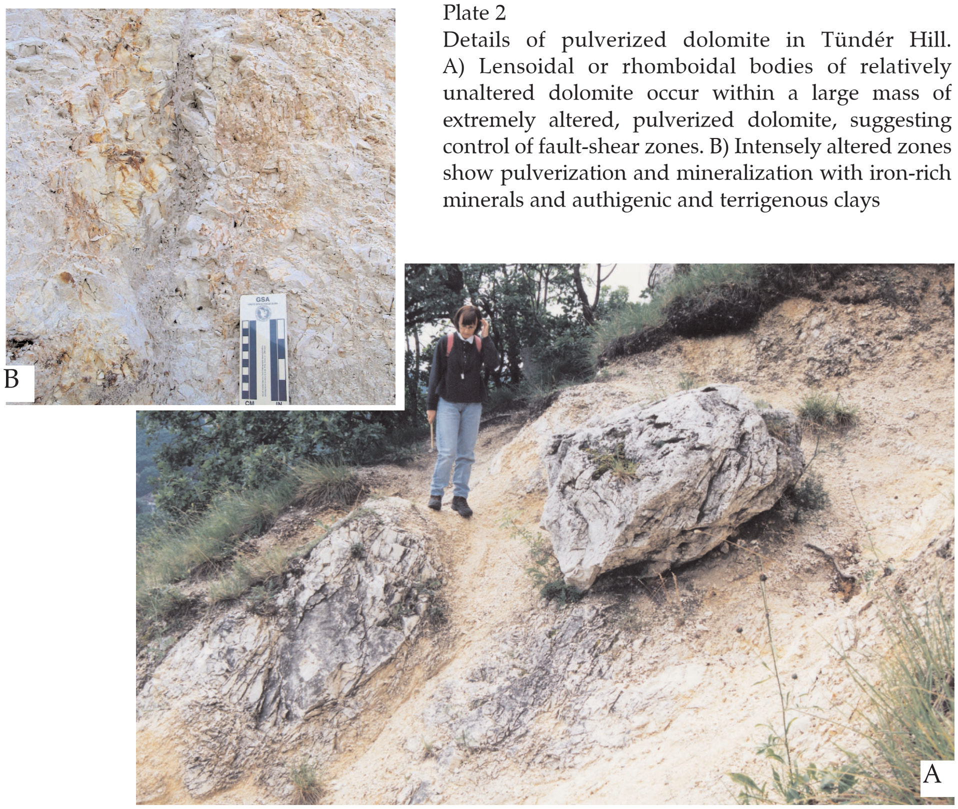
Other rocks

In the Budaörs and the Zugliget regions there are other rock types that differ from the original, non-altered and altered dolomite, and play an important role in the understanding of the diagenetic process. They are: (1) upper Eocene conglobreccia/conglomerate, (2) upper Eocene carbonates (limestone and marl) and (3) speleo-concretions that we suggest calling "Hunyad-type" speleo-concretions or "Hunyad facies".

1) Different types of carbonate conglobreccia and conglomerate occur above the altered and unaltered Triassic carbonates. The coarse detrital deposits contain abundant Triassic elements, locally abundant rounded chert pebbles and locally minor volcanoclastics. The conglobreccia is bedded to non-bedded, medium sorted or unsorted, mostly matrix supported; it is considered to represent mass and debris flows of the weathered slopes of the Triassic mountains (scree, hillsides, sinkholes, fans). Locally, the conglobreccia is capped by Eocene marine conglomerate and sandstone or by Pannonian sandy conglomerate. The conglomerate is medium-thick bedded, sorted, clast-supported, containing subrounded clasts, locally with organic borings and is considered as the basal conglomerate of the Eocene transgression (beach).

2) Bedded nodular limestone of late Eocene age (Szépvölgy Fm.). It is characterized by rock-forming quantity of large foraminifera, i.e. discocyclinids

Plate 2
Details of pulverized dolomite in Tündér Hill. A) Lensoidal or rhomboidal bodies of relatively unaltered dolomite occur within a large mass of extremely altered, pulverized dolomite, suggesting control of fault-shear zones. B) Intensely altered zones show pulverization and mineralization with iron-rich minerals and authigenic and terrigenous clays



C) Hunyad-type concretions in the quarry of Tündér Hill. These irregular concretions are developed at a late stage within pulverized dolomite as result of late calcite cementation under vadose meteoric conditions and nummulitids, as well as by corallinacean algae. The limestone succession is overlain by marl and often shows siliceous concretions and/or cements in connection with the pulverized zones (Buda Marl, containing the so-called bryozoan marl).

3) The term "Hunyad-type" speleo-concretion (or "Hunyad facies") is proposed to refer to irregular bodies, at least 20 m thick, consisting of calcite-cemented concretions of different shapes and sizes, occurring "within" some of the intensively pulverized dolomite areas and forming characteristic cliffs in the outcrops (as in Hunyad Cliff). Some of the concretions are clearly reminiscent of stalactites, stalagmites and botryoids; others depart from verticality and display important curvatures (Plate 2, C). At least in part, these calcitic speleo-concretions grew within a matrix of intensely pulverized dolomite and dolomite breccia, as suggested by the occurrence of abundant patches of pulverized dolomite within the concretions. These concretions are very similar to the groundwater concretions extensively described in the literature (Pomar et al. 2004). Nevertheless, late stages of concretional growth could occur along the walls of open channels and caves rather than within the pulverized dolomite body. The Hunyad speleo-concretions occur as cliffs at different elevations on the flanks of the Buda Mountains (valley down-cutting) and are tentatively interpreted as the result of vadose meteoric karstification within exposed pulverized dolomite. It is critically important to distinguish the Hunyad-type cliffs from the characteristic cliffs dominated by remnant boulders of "unaltered" dolomite (e.g. Tündér Cliff; see Plate 1, A and B) or silicified breccia within the pulverized dolomite zones (e.g. the towers of Sas Hill) and from sinkholes filled with upper Eocene sediments (e.g. on Ördög Cliff).

Ördög Cliff and Sas Hill area

The E–W elongated, narrow range of Ördög Cliff (Fig. 4) is situated on the southern side of the Farkas Valley. It is built up by well-bedded laminated cherty dolomite of the Sashegy Mb. (Mátyáshegy Fm.). The dolomite is intensely fractured and altered on the northern side, along the road cut of Edvi Illés Street. The host rock crops out only at some blocks where the well-bedded cherty dolomite shows folding and dipping to the SW at 50 degrees (Plate 3, A). The narrow ridge of the area is made of well-cemented (silicified and calcitized) breccia and conglobreccia containing rounded to subangular clasts of dolomite and chert. The blocks of the breccia are embedded within the pulverized dolomite, weathered as tower-like cliff at the northern edge of the ridge. Pulverization seems to be stronger on the southern slope of the range.

Breccia-conglomerate-sandstone beds overly the Triassic dolomite. They belong to the base of the upper Eocene succession. In the abandoned quarry along the southern slope of the hill silicified dykes penetrate the upper Eocene conglomerate along a SE–NW direction. Another population of dykes is filled

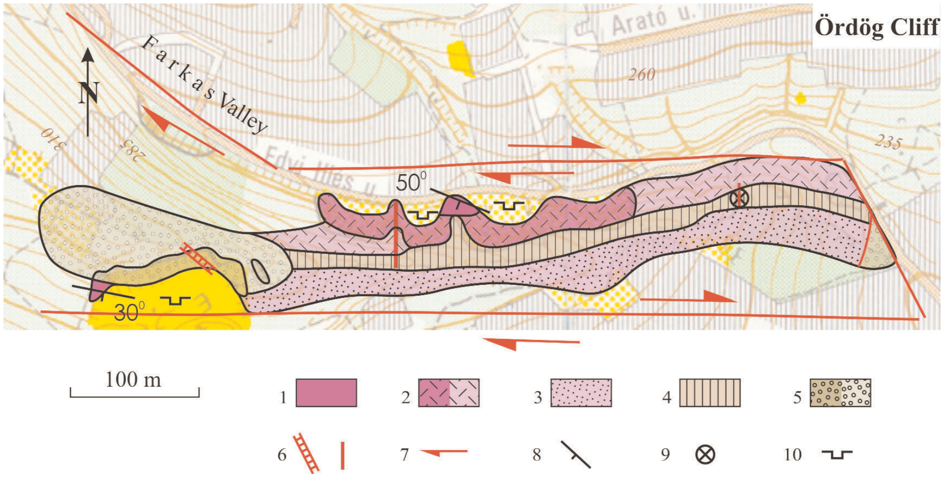


Fig. 4
Geologic map of Ördög Cliff (regional tectonic elements from Fodor et al. 1994)
1. Sashegy Dolomite; 2. brecciated dolomite, 3. pulverized dolomite; 4. cemented dolomite breccia; 5. upper Eocene conglobreccia and sandstone; 6. silicified dykes and upper Miocene (Pannonian) sandstone dykes; 7. strike-slip faults; 8. dipping; 9. tower-like cliff; 10. abandoned quarry

with coarse-grained upper Miocene sandstone (see also Fodor and Kázmér 1989; Magyari 1996) and penetrates both the Triassic and the upper Eocene rocks. These dykes strike in a N–S direction as a rule. Their age is Pannonian (late Miocene). Báldi et al. (1973, p. 21) considers them as evidence of post-Pannonian pulverization because the dykes do not contain altered dolomite material; the opening of these dykes had to be prior to pulverization. An alternative hypothesis takes into account that: (i) the lack of pulverized or any other carbonate in the dykes could represent intense pulverization and complete dissolution of any carbonate material, and/or (ii) that the pulverized dolomite had become hard rock by intense silicification and replacement before the formation of the dykes.

Sas Hill (Fig. 5) is built up by the Sashegy Dolomite. The lower part of the sequence is thick-bedded (uppermost part of the Sédvölgy Dolomite), and it becomes bedded with chert nodules upward. The Triassic rocks are covered by eroded remnants of the upper Eocene breccia forming small patches on the top. The heavily tectonized range is controlled by dextral strike-slip faults of E–W direction while the smaller hills are separated by sinistral strike-slip faults of SE–NW direction (Fodor and Magyari 2002). The dolomite dips to the SW at angles of 30–50 degrees.

The alteration of the dolomite shows similar regional features as on Ördög Cliff. The less tectonized bodies of the dolomite make up the hilltops, while the valleys between them are filled by dolomite breccia. Both the northern and the southern side of the range is heavily tectonized. The southern part is more

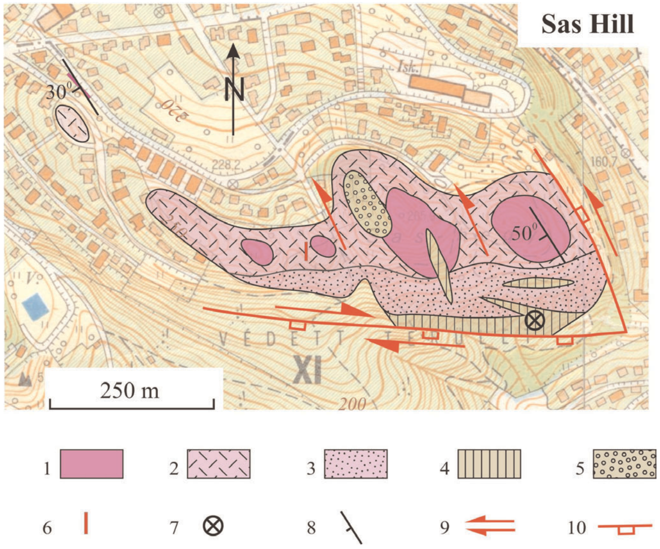


Fig. 5
Simplified geologic map of Sas Hill (modified after Fodor and Magyari 2002)
Upper Triassic dolomite (Sédvölgy and Sashegy Dolomite); 2. brecciated dolomite, 3. pulverized dolomite; 4. cemented (calcitized or silicified) dolomite breccia with patches of silicified upper Eocene "bryozoan marl"; 5. upper Eocene conglo-breccia and sandstone; 6. upper Miocene (Pannonian) sandstone dykes; 7. tower-like cliff; 8. dipping; 9. strike-slip faults; 10. normal faults

pulverized. The pulverized dolomite is impregnated by silica cement along E-W striking zones. Dykes are commonly filled with siliceous upper Eocene Buda Marl (Magyari 1996). Tower-like cliffs, resulting from differential weathering, are also common in this zone (see Plate 3, B).

These localities demonstrate that the characteristic alteration ("pulverization") is independent of Triassic facies, affecting both platform and basinal facies. Silicification is commonly associated with pulverization, but appears concentrated in dykes and affects different Eocene and Pannonian lithologies; this is explained by the lack or scarcity of carbonate lithologies in some Tertiary formations. In addition intense lithification re-cemented loose pulverized rock into hard dolomite. It can be concluded that altered Triassic carbonates are not restricted to the pre-Tertiary unconformity.

Tündér Hill

The Upper Triassic sequence of Tündér Hill (Zugliget area) is made up of more than 1.5 km thick platform carbonates, predominantly of dolomite (Sédvölgy and Hauptdolomit Fms) with a thin Dachstein Limestone cover on János Hill (János-hegy). The main part of the region is covered by Cenozoic sediments, i.e. upper Eocene limestone and marl, various types of Oligocene siliciclastics, upper Miocene sandstone and freshwater limestone. The most significant alteration of Triassic carbonates can be observed along the northeastern side of the range, on Tündér Hill and Hunyad Cliff (Fig. 6).

Most of this region is built up by strongly fractured, brecciated dolomite of the Hauptdolomit Fm. Remnants of the relatively "unaltered" rocks are present only

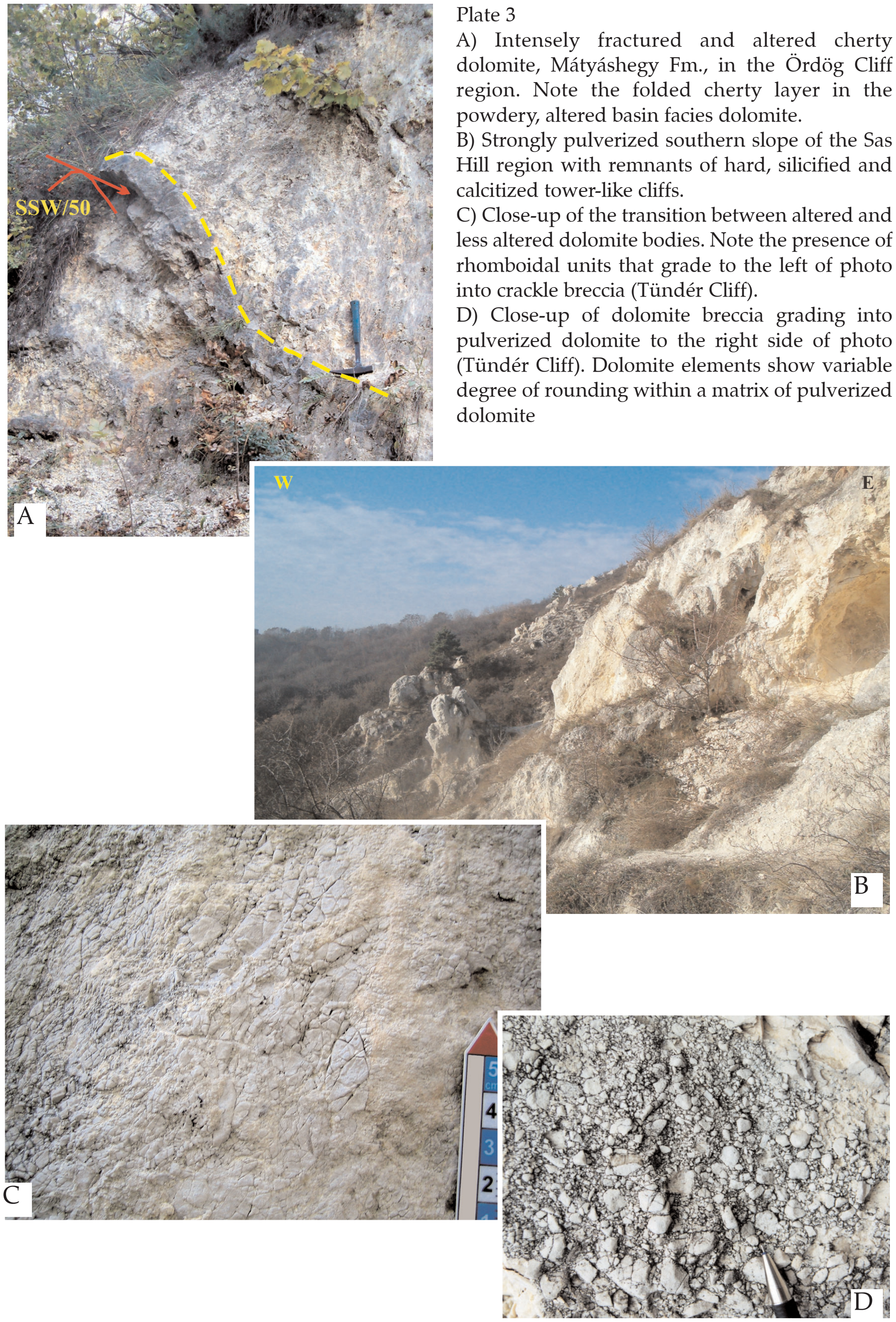


Plate 3

A) Intensely fractured and altered cherty dolomite, Mátyáshegy Fm., in the Ördög Cliff region. Note the folded cherty layer in the powdery, altered basin facies dolomite.

B) Strongly pulverized southern slope of the Sas Hill region with remnants of hard, silicified and calcitized tower-like cliffs.

C) Close-up of the transition between altered and less altered dolomite bodies. Note the presence of rhomboidal units that grade to the left of photo into crackle breccia (Tündér Cliff).

D) Close-up of dolomite breccia grading into pulverized dolomite to the right side of photo (Tündér Cliff). Dolomite elements show variable degree of rounding within a matrix of pulverized dolomite

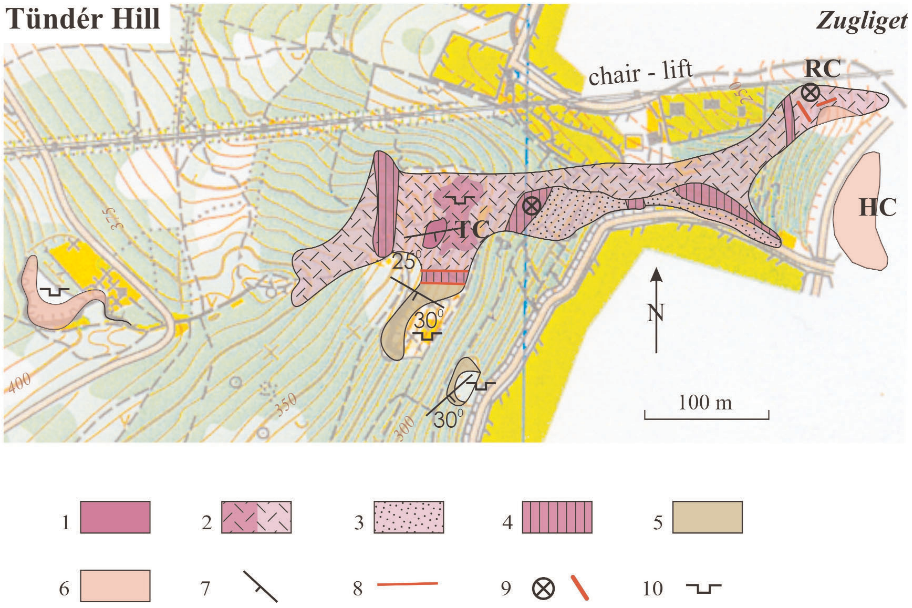


Fig. 6
Geologic map of Tündér Hill. Abbreviations: HC – Hunyad Cliff; RC – Remete Cliffs; TC – Tündér Cliff. 1. Hauptdolomit; 2. brecciated dolomite, 3. pulverized dolomite; 4. cemented dolomite breccia; 5. Upper Eocene conglobreccia and limestone; 6. “Hunyad-facies”; 7. dipping; 8. tectonic contact; 9. tower-like cliffs, silicified dykes; 10. abandoned quarry

on Tündér Cliff, where the thick-bedded dolomite dips to the south at angles of 20–25 degrees (see Plate 1, A and B).

The strongly brecciated dolomite is widespread over the entire range (Plate 3, C and D). The transition between unaltered and altered pulverized dolomite bodies is rather abrupt at mapping scale, but very gradual at the scale of hand specimen or thin section. There are less altered rhomboidal elements present in different scales that grade into crackle breccia or the totally pulverized dolomite (see Plate 2, A and Plate 3, C). Dolomite elements show variable degree of rounding within a matrix of pulverized dolomite (Plate 3, D); this is interpreted as the result of dissolution by diagenetic fluids.

The best outcrops are in the abandoned quarries at the foot of Tündér Cliff. The brecciated dolomite is cemented by silica or calcite. Narrow (20–50 cm wide) dykes are present. The strike of these sub-vertical dykes show E–W or NW–SE and SW–NE direction. The silica or calcite cemented breccia bodies stand up from the loose rock as tower-like cliffs as a result of differential weathering.

The dolomite underwent intense pulverization on the southern side of the range (see Plate 1 C). This rock was mined in small quarries along Zugliget Street. Here, the pulverized dolomite contains calcite cemented breccia dykes.

The southern side of Tündér Hill consists of upper Eocene sediments in tectonic contact with the Upper Triassic altered dolomite (Vígh and Horusitzky

1940; Fodor et al. 1994; Magyari 1996). The strike of the fault zone shows an E–W direction. The basal part of the Eocene sequence is breccia and conglobreccia impregnated by silica cement (as was already observed by Hofmann in 1871).

The youngest diagenetic facies of the Tündér Hill region is the calcite-cemented pulverized dolomite. It contains speleo-concretions of different morphologies: botryoidal, stalactite and other precipitates of vadose karst processes. We call it "Hunyad-type speleoconcretions" or "Hunyad facies", as its best outcrop is located at Hunyad Cliff, on the southeastern side of the Zugliget Valley (between 250–230 m asl). This rock type also crops out in the quarry above Tündér Cliff between 380–400 m asl (see Plate 2). Calcite-cemented concretions are also common, as in the pulverized zones in the Hauptdolomit of the Keszthely Mts (Gyalog and Budai 1985).

This area shows large-scale distribution of altered carbonates and corroborates the main patterns outlined in the Ördög Cliff–Sas Hill study area. In both areas the alteration appears more intense in the southern flanks of the hills, suggesting a relationship with the main fault corridors separating the basinal areas to the south.

Discussion

The above-described "altered" rock types of the Buda Mountains are defined as a diagenetic facies association consisting of variable amounts of pulverization, silicification and mineralization (PSM facies association). This facies is present in the form of large rock volumes in the Buda Mts (Fig. 7).

PSM facies are not restricted to the interior platform Triassic dolomite only; PSM facies also occur in the Triassic limestone (albeit not as intensively) and basinal facies of the Sashegy Dolomite. Furthermore, these PSM facies occur in Eocene limestone and younger units, as it is well known from the literature (Hofmann, 1871; Scherf 1928; etc.).

– The term "pulverization" refers to degradation of originally bedded/tight carbonates into a homogeneous mass of powder-like, chalky, whitish gray microporous carbonates. In the case of pulverized dolomite there are common fragments, granules, pebbles or boulders of "hard", unaltered dolomite, commonly as a crackle breccia with more or less rounded breccia elements within a matrix of pulverized dolomite. The larger unaltered elements within the mass of pulverized dolomite contribute to the characteristic cliff morphology in the outcrops. The pulverized limestone tends to be much finer grained than the dolomite. Pulverization occurs along major fault corridors, fractures and microfractures; the lensoidal or rhomboidal shape of remnants of less altered dolomite suggests the involvement of tectonic shear in the process of pulverization. There is a wide range of pulverized carbonate types, from loose breccia with pulverized microfractures to homogeneously pulverized masses. Pulverized bodies may be also affected by late fracturing and other diagenetic processes (silicification, mineralization). Pulverization is interpreted as the result of micro-dissolution (micro-corrosion) associated to fluids along fractures post-dating the main dolomitization event.

– The term "silicification" is traditionally used as an ambiguous expression to refer to (or infer) the presence of silica-rich minerals, including chert, chalcedony,

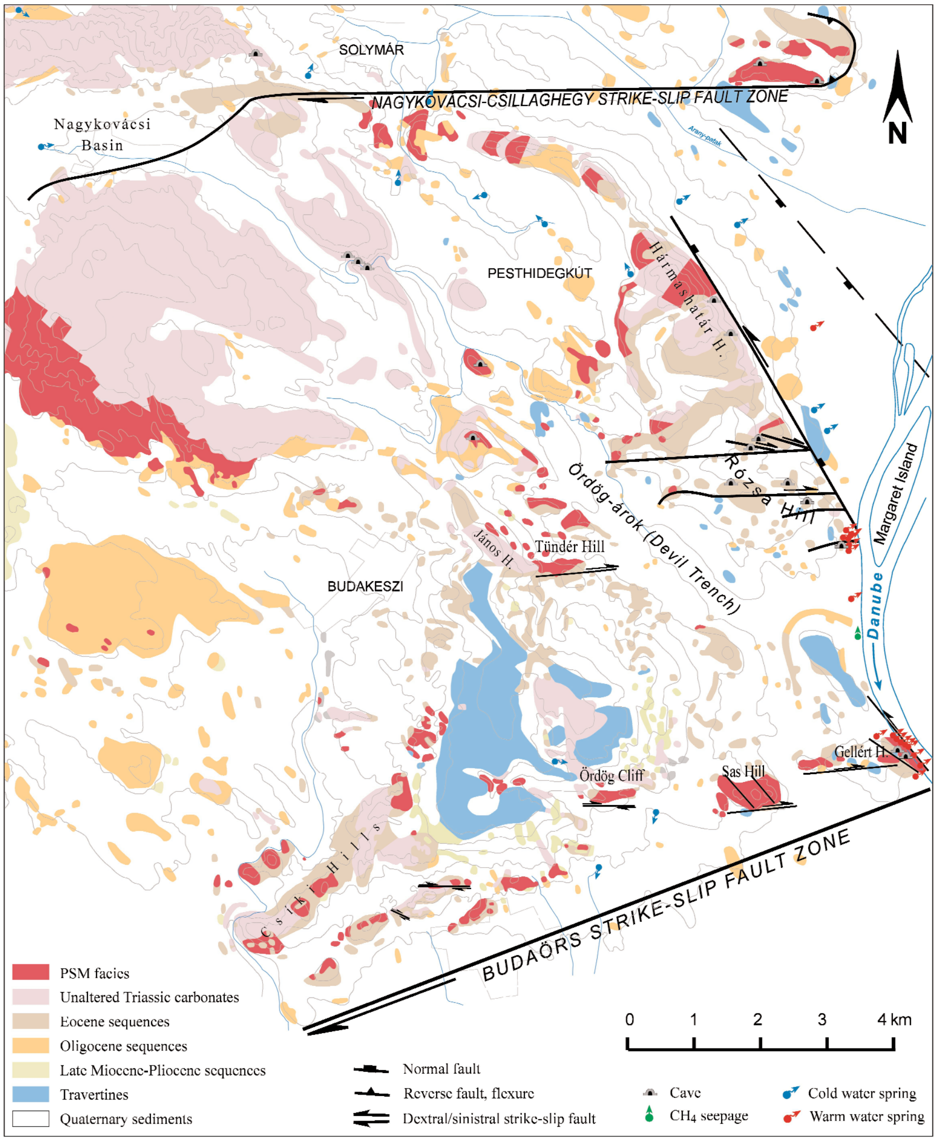


Fig. 7
Distribution of PSM facies in the Buda Mountains, extensively modified from Wein (1977); Fodor et al. (1994); Benkovics and Dudko (1993)

micro-quartz and clay. The silicified rock or siliceous alteration can occur as large distinctive patches or as finely disseminated micro-particles in the carbonate-rich matrix. The silicification is commonly considered to "harden" previously "altered" or pulverized carbonate bodies. In general, silicification contributes to the characteristic cliff morphology in the outcrops (together with remnants of original dolomite). Primary or early diagenetic biogenic silica concentrations (related to radiolarians or sponge spicules) are expressly excluded from this type of silicification, which is essentially attributed to hydrothermal processes. Fault or fracture control is obvious in the silicified zones in Triassic and Eocene carbonates, also expressed as dykes. However, there is also stratabound silicification at the base of the Buda Marl and in some of the coarse siliciclastic sandstone of the Oligocene and Miocene in the Buda Mountains. It is unknown (see the summary of the previous studies) whether silicification is a single diagenetic event in the late Neogene or if there are repeated silicification events during the Cenozoic, in relationship with the Alpine evolution in the area. In any event, pulverized carbonate outcrops are commonly associated with silicification; most of it along faults and chimneys. In addition, unaltered carbonates do not show silicification only. Finally, some silicified Tertiary sediments are not pulverized because they lack carbonate lithologies. Intense silicification of previously "pulverized" dolomite results in silica-cemented hard rock; this may be misinterpreted as silicification without pulverization.

– "Mineralization" is characterized by concentrations of iron-rich minerals, barite, sphalerite, galena, fluorite, calcite, dolomite and other ore minerals, clearly pointing out hydrothermal Mississippi Valley Type (MVT) conditions. Mineralization commonly occurs within, adjacent to or closely associated with pulverized and silicified facies, suggesting a common diagenetic environment or, at least forming part of a common diagenetic evolution. The mineralized facies are common in the "altered" Triassic carbonates, but also affect the fractures in Eocene carbonates and as lenses in Oligocene and Miocene sandstone. It is unknown if the mineralization is a single diagenetic event in the late Neogene or if there were repeated mineralization events during the Cenozoic.

A hypothetical diagenetic model

Subaerial karstification

Triassic carbonates underwent long subaerial exposure and intense karstification during the Early Tertiary. There is a major stratigraphic gap between the Upper Triassic and middle Eocene successions. Red lateritic breccia and cavity fills in the Buda Mountains are commonly attributed to Upper Cretaceous and Eocene karst deposits. They are widely known in other areas of the Transdanubian Range (Bárdossy 1977; Szantner et al. 1987; Mindszenty et al. 2001). These early diagenetic processes probably created a vast pore network of different types and sizes, controlled by gravitational flow regimes, both stratabound and non-stratabound. There is no evidence of preservation of this early porosity. It is fully obliterated by subsequent compaction, cementation and internal sedimentation.

Late Eocene transgression

During the late Eocene the exposed Triassic carbonates were progressively onlapped by coastal marine deposits, reducing the area of subaerial exposure (Fig. 8). This transgressive trend continued during the early Oligocene, controlled by tectonic movements. This marine transgression reworked and fossilized the previously weathered Triassic regoliths and paleokarst. It can be assumed that the meteoric karst system was intensively rejuvenated, with abundant evidence of Tertiary sediments infiltrating the enlarged fractures and karst cavities within the Triassic carbonates ("dykes"). There is also the possibility of hypothetical coastal karst development in the coastal-marine mixing zone. However, there is no record of preservation of any type of porosity likely to have been produced during the transgression phase. Erosional truncation, cementation and internal sedimentation appear to have obliterated most of the porosity generated or enhanced during this period.

Burial diagenesis

The burial of Triassic carbonates continued during the Oligocene and early Miocene, with thick sections of basinal clay (Tard Clay Fm., Kiscell Clay Fm.) covering the Buda Mountains. Burial diagenesis involved ascending compactional and thermobaric fluids that evolve in time (and/or space) as producing a sequence of diagenetic events characterized by: 1. dolomitization, 2. pulverization, 3. silicification, 4. mineralization, 5. late spar calcite (coarse white crystals).

There can be one or three episodes of this 1-to-5 diagenetic cycle of events, with a variable degree of intensity for each one of the 1–5 processes. This could be referred to as deep or pure hydrothermal; "late burial diagenesis" is the preferred term in the paper. Pulverization involved the generation of proto-caverns in areas of preferential thermobaric flow (fracture corridors).

Deep burial diagenetic processes may have already started along the flank of the structure during the deposition of the Hárshegy and Tard units during earlier Oligocene times. It can be assumed that the PSM facies were gradually affecting structurally higher units during the burial, controlled by the different tectonic movements and reactivation of fault corridors. Upper Eocene and locally Oligocene sediments were also strongly affected by the PSM facies.

Mixing hydrothermal phase

In the middle Miocene major structural inversion began and led to the progressive uplift and dismantling of the present-day Buda Mts. A mixing zone of cold meteoric waters with hydrothermal burial fluids was initiated in the higher parts of the structure, and was progressively displaced toward the flanks during the Pliocene and Quaternary. It can be assumed that mixing with meteoric aquifers constantly increased during the uplift, reducing thermal mixing toward the flanks (present Danube river bed). Thermal mixing produced most of the spectacular cave system, extensively modifying the pore network generated during burial diagenesis. Typical thermal cave conduits, cupolas, botryoids, rafts, and folias characterize this phase. It is possibly dominated by convectional flow and mixing of deep thermobaric fluids with compactional fluids and deep phreatic meteoric influx. Fault and fracture corridor control is very obvious.

Late meteoric overprints

The uplift and exposure to meteoric aquifers is recorded as late meteoric overprints on the Triassic and Eocene carbonates. The terraced travertine deposits, with associated fluvial deposits and erosion, are the reflection of this progressive uplift. Altered Triassic carbonates were partly cemented by "Hunyad-facies" (speleo-concretional bodies). Minor meteoric vadose speleothems such as stalactites and stalagmites are present on superficial parts of the cave system. Typically this meteoric cementation is controlled by exposure topography, with diffuse flow in "altered" carbonates and conduit flow along previous caverns and fault corridors. Local cavern collapse and infill are also characteristic. These late meteoric overprints are locally important in reducing considerable amounts of porosity in the upper few meters of the present-day exposure surface. However, these overprints are considered as minor or volumetrically insignificant at a regional scale.

Barriers to diagenetic fluids

The main stratigraphic barriers are the Buda Marl, Tard Clay, and Kiscell Clay (Fig. 8). The possible role of occasional clay-rich intercalations in the Triassic carbonates requires further investigation. These main stratigraphic barriers would have provided relative seals for the ascending thermobaric fluids, forcing lateral fluid migration. Only where these barriers are intensely fractured would it be possible for diagenetic fluids to proceed upward. These stratigraphic barriers would act as aquitards or aquicludes for the gravity-controlled meteoric fluids.

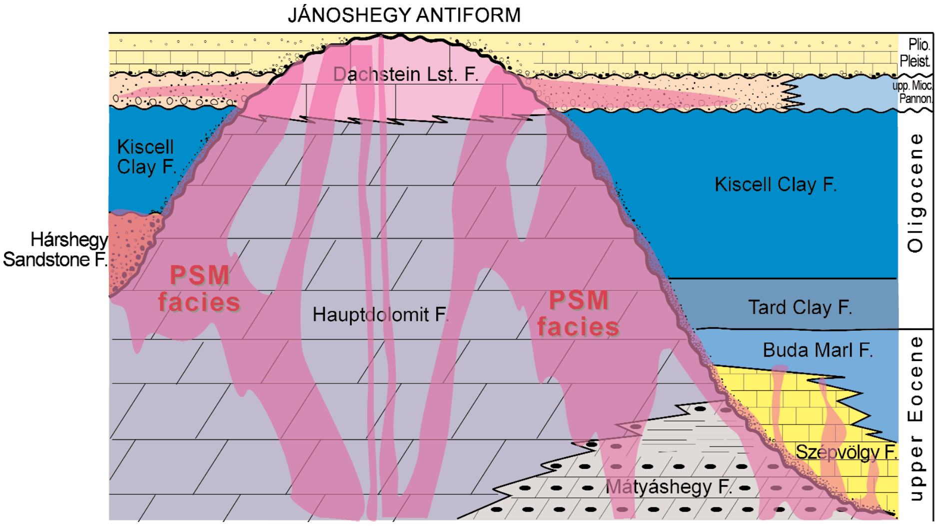


Fig. 8
Generalized Cenozoic onlap with irregular and non-stratabound diagenetic bodies of the Buda Mts

Geometry of the diagenetic bodies

The early diagenetic processes would tend to result in stratabound diagenetic bodies. The burial diagenetic processes are primarily controlled by fault and fracture patterns. However, in areas of intense fracturing or beneath effective top seals (stratigraphic barriers) the resulting diagenetic bodies could be massive, irregular and non-stratabound (Fig. 8). Finally, in units with preferential permeability (like the basal Eocene conglomerate or the coarse Oligocene and Miocene sandstone) burial diagenetic bodies can become stratabound. Also, the erosion surface at the top of the Triassic is perceived as a general onlap surface for the Cenozoic units. We can assume that there is a conglomerate or breccia (or conglobreccia) along the onlap surface, and that this surface (and related deposits) was extensively altered by burial diagenesis (PSM facies).

For the thermal mixing karst, fracture-fault bound diagenetic bodies are predominant. The final stage of meteoric diagenesis is controlled by exposure topography and old cave patterns (fault patterns).

Correlation with other areas of the Transdanubian Range

The more than 2,000 m-thick Middle to Upper Triassic carbonate sequence is widespread along the Transdanubian Range (see Fig. 1), from the Keszthely fault zones (large-scale longitudinal overthrusts of the Balaton Highland and of the

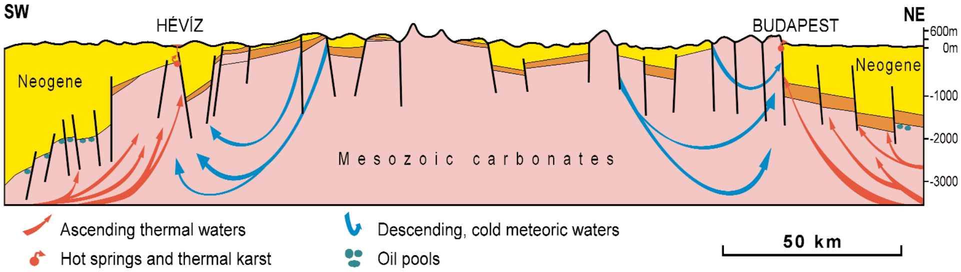


Fig. 9
Strongly simplified geologic section of the Transdanubian Range showing basic hydrogeologic similarities between the two edges

Bakony Mts) to the large-scale strike-slip faults of the Keszthely, the Bakony, the Vértes and the Buda Mts. The dolomite is fractured and brecciated along these fault zones but strong pulverization occurs only at the two edges of the Transdanubian Range, namely in the Keszthely Mts and in the Buda Mts. Comparing these two regions several similarities can be found in their geologic framework (Fig. 9). Both mountains are predominantly built up by Upper Triassic carbonate sequences overlain by thin remnants of Cenozoic cover; they have a sharp tectonic contact (major deep-seated faults) with deep Neogene basins in their surroundings; calcite-cemented and silicified bodies in connection with pulverized dolomite are common (Gyalog and Budai 1985); fire clay of hydrothermal origin can be found in karstic sink-holes, both in the Keszthely Mts (Csillag and Nádor 1997) and in the Buda Mts (Scherf 1928); morphological elements (caves, conduits, etc.) of modern karst processes are present; recent hydrothermal activity is ongoing (warm lake of Hévíz to the SW and thermal springs of Buda to the NE).

Wider implications

The occurrence of the altered carbonate geobodies in the Buda Mts has wider implications. The altered Triassic dolomite (PSM facies) forms large-scale irregular geobodies that are markedly non-stratabound, "softer" and have significantly better porosity (intercrystalline microporosity, micro and macro-vuggy porosity, caverns, enlarged fractures, etc.) than the unaltered Triassic carbonates. The unaltered carbonates show only minor porosity (scattered mouldic, fenestral keystone, residual intergranular porosity). This implies that the PSM geobodies have good potential for detection by geophysical (seismic) techniques and may provide important models in hydrocarbon and mineral prospection. This has been well recognized at least since the 50s (i.e. IFP 1959), and is reported in numerous publications in Europe (i.e. Elf Aquitaine 1991; Ardaens 1992; Zempolich and Hardie 1997; Lopez-Horgue et al. 2005), the Middle East (i.e. Broomhall and Allan 1987; Nader et al. 2004), the Far East (Sattler et al.

2004) and North America (i.e. Hurley and Budros 1990; Wickstrom et al. 1992; Boreen and Davies 2004; Lynch and Trollope 2001; Reimer et al. 2001; Strecker et al. 2004; Smith and Davies 2006; Wierzbicki et al. 2006). In all of these cases the critical implication is that major reservoir units are non-stratabound and developed independently of depositional facies/textures and sequence stratigraphy control. In addition, reservoir development takes place at a much later geologic time than the age of the deposition of the reservoir. In our case the Triassic dolomite developed its reservoir potential during the late Miocene or early Pliocene. Ancient fault corridors acted as preferential carriers for late diagenetic fluids that migrated in cross-formational (non-stratabound) patterns. Only shale-rich lithostratigraphic units are barriers to this type of fluid migration and reservoir development. This could give the local appearance of stratabound control in reservoir development; the study of the large-scale geometry of the porous units is essential to evaluate the genetic controls in reservoir development.

Conclusions

Based on a detailed mapping survey of large-scale lithological units and the critical re-evaluation of the vast amount of published material referring to “pulverization” of the Upper Triassic carbonates in the Buda Mts, the following conclusions are outlined:

1. The type and intensity of alteration (PSM facies association) are independent of the original carbonate facies. Both basin and platform facies dolomite are dolomitized and intensely altered, forming huge volumes of massive, irregular and non-stratabound pulverized geobodies. Triassic limestone appears less intensively affected than the dolomite, but this needs to be corroborated with additional observations. The PSM facies also affects upper Eocene limestone, but with less intensity than the Triassic dolomite. Tertiary non-carbonatic lithologies are not “pulverized” but only show intense silicification and mineralization.

2. The Triassic dolomite has been strongly fractured along strike-slip tectonic zones and normal faults. Occurrence of rhomboidal remnants, or blocks of the unaltered, and/or less altered dolomite bodies of various scales within the PSM zones, suggest the involvement of shear zones. This does not imply that the PSM facies was produced by tectonic shearing; it only indicates that the involved diagenetic fluids circulated along fracture corridors characterized by shear zones.

3. Alteration of the Triassic dolomite appears to be better developed along the flanks of hills with currently preserved Paleogene or Neogene clay-rich cover. This suggests that the occurrence of seals or barriers played a role in the distribution of late diagenetic fluids involved in the generation of PSM facies.

4. The better development of PSM facies along the southern flanks of the studied hills could also indicate preferential flow patterns of diagenetic fluids

from the southern basins. Alternatively, these flanks are commonly gentler than the northern flanks, and could just be the result of better preservation.

5. The PSM diagenetic facies are non-stratabound at large mapping scale; it cross-cuts different lithologies and stratigraphic units. The final geometry appears to be controlled by the interaction of fracture corridors and other preferred conduits (exposure surfaces, conglomerates) with high porosity/permeability and with barriers and seals of clay-rich units.

6. It is unclear if the PSM facies is a single or multiphase diagenetic event. Silicification (and mineralization) appears as bands or dykes within pulverized dolomite, suggesting a 2-phase process, but never occurs in unaltered carbonate. In addition, intense silicification results in re-cementation of previously pulverized dolomite; this could be misinterpreted as unaltered and silicified dolomite. Nevertheless, silicification (and mineralization) does occur without pulverization in sediments without carbonate constituents, confirming the interpretation of pulverization as a micro-dissolution process.

7. The PSM facies is interpreted to represent the early stages of hydrothermal alteration (i.e. the deep burial phase) that was later affected by near-surface, phreatic thermal mixing zones as part of continued uplift. The PSM facies could have formed in deep burial environments at the same time as the spectacular thermal mixing caverns of the Buda Mts developed in the shallower parts of the system. In the Transdanubian Range there are huge volumes of Triassic carbonates with very intense tectonic fracturing, brecciation and dolomitization, but without traces of PSM facies or thermal caves. This hydrothermal alteration occurs exclusively in local areas adjacent to major, deep Neogene basins.

8. Pulverized dolomite bodies that reached the vadose zone have been strongly affected by meteoric fluids. Stalactite, stalagmite and other speleo-concretions were formed by calcite cementation within the pulverized dolomite geobodies.

The altered dolomite of the Buda Mts provides a good setting in which to study the development of large-scale non-stratabound porous units with potential for subsurface exploration. Further work is required for an improved understanding of these complex geobodies.

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