The Geomorphic Evolution of Karsts and Karstic Surfaces

János Móga and Márton Veress

Abstract

In this chapter the geomorphic evolution of Hungarian karst areas and the history of current karstification are overviewed. The denudation surfaces of the karst areas and their development, as well as their development age and subsequent transformation and the beginning of present karstification are described. Karstification started in the Pleistocene in the Aggtelek-Rudabánya Mountains (maybe in the Upper Pannonian or in the Pliocene) and it began in the Early-Sarmatian in the Bükk Region. In the Western-Mecsek Karst, the landforms of older soil-covered karst is overlain by the landforms of concealed karst and the beginning of concealed karstification dates back to the Würmian or it is older than it. In the Transdanubian Mountains this characteristic feature is also present, but it is less widespread and concealed karstification started in the Würmian or earlier, but its beginning is also different on the blocks belonging to various types.

Keywords

Cover formation • Exhumation • Tropical peneplain • Pediment • Abrasion platform

1 Introduction

The karst type of a karst area, its karst features, and the character and intensity of karstification depends on the factors influencing karstification and on its geomorphic evolution too. The beginning of the development of Hungarian karst surfaces and the interpretation of its present image are mostly traced back to the Upper Jurassic and to the end of the Cretaceous. There is no way to reveal surfaces older than this age or if there is any, that surface is in a buried state today thus, it does not belong to the topic of this chapter, but it belongs to chapter "Paleokarst in Hungary".

The development of karst surfaces is determined by several factors which are the following:

- Geological built-up (rock quality, thickness, structure and their age).
- The type and change (degree, velocity) of the climate during development stages.
- Altitude, vertical movements (frequency, degree, velocity).
- Surface forming forces during development stages (their sort, number, intensity, duration).

We are going to see that in Hungarian karsts tropical karstification, fluvial surface formation, abrasion, burial, and exhumation affected mainly the formation of karst surfaces.

- The effect of karstification, the interaction of surface and subsurface karst processes.
- The duration of a stage of geomorphic evolution.

The geology, vertical elevation, and climate of the areas were controlled by movements of plate tectonics. The present surface of a karst area developed as a result of the above-mentioned factors. The difference of the facies of some karst areas is primarily caused by geological structure and the frequency, degree and speed of vertical movements.

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Here will be described the role of loess in karstification and landscape evolution since the karstification of the Transdanubian Mountains and the Western Mecsek Karst are significantly influenced by this cover. Loess is denuded easily thus, it thins out in some places, which favours karstification (see chapter "An Interpretation of Karstification and Karst Processes by Hungarian Researchers"). Mixing with other sediments, the denuded loess becomes impermeable. It accumulates in depressions (in epigenetic valleys) where valley floor concealed karstification may happen. Dolines developing on valley floors promote the transportation of valley floor loess into the karst and thus, the valleys can be separated into areic parts. The loess mantle became an important karst genetic factor, it disrupted the karstification of the limestone terrain which on the one hand became covered (concealed) karst, on the other hand—because of the high carbonate content of the typical loess—it makes the waters percolating through it saturated thus, preventing karst corrosion even if the percolating water reaches the limestone beds situated below it. The complete or partial dissolution, the loam formation and soil formation of the carbonate content of the typical loess that deposited onto the karst terrain is important as regards karst development. Experiments prove the quality differences of the water percolating through the soil and the loess which play a crucial role in karstic processes. The waters percolating through the loessy sediment affected by soil formation covering the peneplain blocks and the plateau may have a limestone dissolving capacity of various degree depending on the soil quality, the thickness, and porosity of the subsoil loess bed.

Where the cover is thin, the loess can be completely affected by leaching and soil formation in its total depth even to the bedrock therefore, significantly increasing the dissolution capacity (aggressivity) of the meteoric water percolating through it which reaches the carbonate rocks. If there is loessy sediment below the soil cover, the water percolating through this loses its limestone dissolving capacity to a significant extent by dissolving the calcium carbonate content of the loess (Kiss et al. 2007). After all, it depends on the absolute amount of the carbonate content of the loess and on its change in the loess whether dissolution takes place in the bedrock. Self-generating processes may have an effect on loessy terrains. Surface waters flowing into the developing depressions increase decalcification, which increases surface runoff and thus, the development of the depression (Veress 1982, 2000b). The passages of depressions become plugged, intermittent lakes develop and the slowly seeping water of lakes increases the duration of dissolution (Veress 2000b).

Depending on its clay content, the loess mantle may have different behaviour regarding waters originating from precipitation: they drain some of the waters enabling them to infiltrate into deeper beds, while the other amount of precipitation increases surface runoff.

The grain size of loess influences doline development. In case of small grain size, the infiltrating water moves laterally, while in case of a larger grain size, it moves vertically (Deák et al. 2015; Veress et al.) and gets into the karst. The relation between the loess and the epikarst affects the development of subsidence dolines. Where the epikarst is well-developed due to former karstification, the loess may be washed-in into its passages without their plugging. On the loessy surface a lot of dolines are formed therefore, during its denudation the loess accumulates in the dolines. The loessy surface only becomes dissected to a small degree. Such concealed karst is the Western Mecsek Karst. Where the epikarst is underdeveloped, the loess may be washed-in into the passages of the epikarst to a small degree or it may not either. The development of the epikarst will be local, few shafts develop, and thus, the number of dolines (situated above the dolines) will also be low. Therefore, the catchment area of the dolines will be relatively large, and by this the waters flowing towards them create creeks contributing to the dissection of the loess mantle. Such concealed karst terrains occur in the Transdanubian Mountains.

2 Karst Areas

2.1 Aggtelek-Rudabánya Mountains (Aggtelek-Rudabánya Hills)

The Aggtelek Karst is plateau karst according to its dissected character, renewed allogenic covered karst from evolutionary point of view, mixed allogenic-autogenic karst hydrologically and morphologically and mostly soil-covered karst according to coveredness (Jakucs 1956, 1977; Hevesi 1991a, b; Móga 2002a, b; Veress 2016, see chapter "A General Description of Karsts in Hungary"). Valleys with doline rows, dolines (drawdown dolines), uvalas, ponors with blind valleys (with karst marginal ponors and ponors inside the karst), depressions of superficial deposit, subsoil karren (Zámbó 1998a, b; Móga 2002a, b; Veress 2010, 2017, see chapter "The Surface Morphology of Karsts in Hungary") are characteristic karst features in its area.

According to Láng (1955a, b), the Aggtelek Karst (and its plateaus) are built up of peneplanated surface parts which developed by the end of Miocene and during the Pliocene. Sásdi (1998) states that in the former terrestrial part of the karst, the tropical-subtropical peneplain developed at the boundary of the Oligocene and the Miocene. The opinion dating back its tropical karstification to the Cretaceous and Late Cretaceous is more predominant (Jakucs 1977; Gyurica and Sásdi 2009). The mounds of the plateaus are probably but not provably the remnant features of tropical karstification. The solution dolines of the karst, except if they are not on valley floor, are mostly situated on such mounds (Móga

2002a). According to Jakucs (1977), the surface was affected by continuous karstification from the Cretaceous to our present days since he thinks that the terra rossa (or any weathered material of such character) being widespread on the karst is the final product of tropical karstification. However, the theory of continuous karstification is hardly valid since the karst was covered by sediment many times (see below). According to Gyurica and Sásdi (2009), the karst became covered with marine sediment in the Oligocene at least partially, which is indicated by the distribution border of the abrasion conglomerate of the Bretka Gravel Formation: its northern border can be marked along the line between the settlements of Aggtelek and Égerszög (Fig. 1).

During the Miocene, rhyolite tuff accumulated originating from volcanic activity taking place in several stages (Gyurica and Sásdi 2009), from which a terra rossa like mantle of chemical weathering material developed (Bidló and Maucha 1964). However, according to other opinions, the terra rossa which is still widespread on the karst, mainly in the depressions of the karst and has a significant role in karstification processes (see chapter "The Surface Morphology of Karsts in Hungary") redeposited (Andrusov et al. 1958), and developed during karstification (Jakucs 1964; Stefanovits 1976; Less 1998).

Jakucs (1977) states that the Medve-szikla (Bear Cliff) being exposed on the slope of Lake Vörös is a tropical karst remnant feature. A notch being similar to the features of the South-Chinese stone forest can be seen on the cliff with terra rossa environment, and these morphological characteristics refer to a development under a climate warmer than today's maybe Tertiary, subtropical one. The quartz crystalline transformations of the ferricrete fills of the karren here indicate that the fill is several million years old (Beck and Borger 1999). According to the above-mentioned authors,

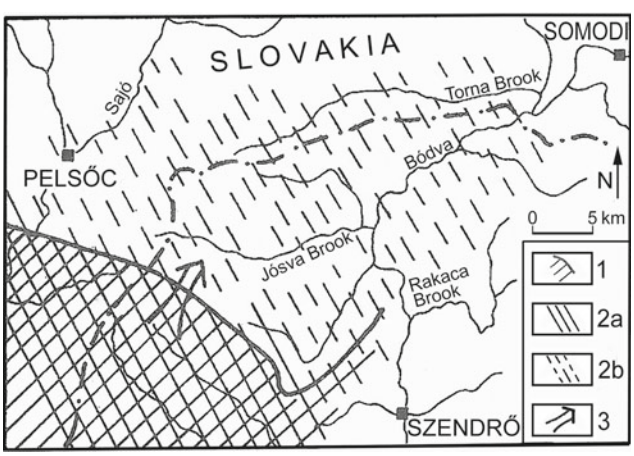

Fig. 1 Former distribution of Oligocene-Miocene sediments (Sásdi 1990). Legend: 1. Bretka Formation (limestone and conglomerate), 2. Putnok (=Szécsényi Slir) Formation (a = certain, b = supposed), 3. direction of transgression

the host material is of crystalline origin, which reached its present place by fluvial transportation and was transformed by chemical weathering. They think that this latter process took place on a former tropical peneplain of Cretaceous/Early Eocene age.

The flow of karstwater was of NS direction both in the Oligocene (disregarding transgression) and the Miocene (Gyurica and Sásdi 2009). This also refers to the presence of karstification although Sásdi (1998) dates the karstification of this time to the end of the Miocene when the superficial deposit denuded.

In the Pannonian age karstification related to karstwater took place: there are Pannonian cover cavity fills around the settlements of Alsótelekes and Felsőtelekes (Sásdi 1998). The freshwater limestones occurring in the karst marginal Pannonian beds (Teresztenye Plateau) also refer to karstification (Sásdi 1998; Gyurica and Sásdi 2009). However, according to Sásdi (2005), the Pannonian freshwater limestones are not related to the karstification of the mountains. It has to be mentioned that according to Zámbó's calculations (1986), there are dolines on the karst which started to develop in the Upper Pannonian.

In the Early Pannonian age a newer transgression took place which spread to the present terrains with an elevation of 300 m and only the more elevated parts of the plateaus protruded from this (Sásdi 1998, Fig. 2). As already mentioned, the mountains became covered with rhyolite tuff in the Middle Miocene (Jakucs and Móga 1997). In the Late Pannonian-Pliocene the alluvial cone of Ős-Sajó (Ancient Sajó) developed on the currently covered karst part, but on the plateaus as well and the latter became covered with gravel thinly (Sásdi 1998, Fig. 3). According to Zámbó (1998a), in the Pannonian the mountains were transformed into pediment and then later it became dissected and getting into various elevations it constituted the plateaus though as it will be seen below, other authors date pediment development later.

From the beginning of Pliocene, vertical and horizontal movements of significant degree began (Gyurica and Sásdi 2009) which continued in the Pleistocene: the degree of elevations was 50–100 m (Mezősi 1998), it may even have reached 300 m in the northern part of the karst (Zámbó 1998a). Láng (1955a) states that the final (today also existing) morphological separation of the currently covered karst and buried karst took place at the end of the Pliocene, and then in the Pleistocene, the plateaus became elevated to such extent that surface karstification could have begun and karst hydrography could have developed. If shaft caves developed from ponors situated at former rock boundary (Dénes 1972, see chapter "An Interpretation of Karstification and Karst Processes by Hungarian Researchers"), during the denudation of the cover, the plateau of Alsó Hill may also have lost its cover at this time since there are several karst features of

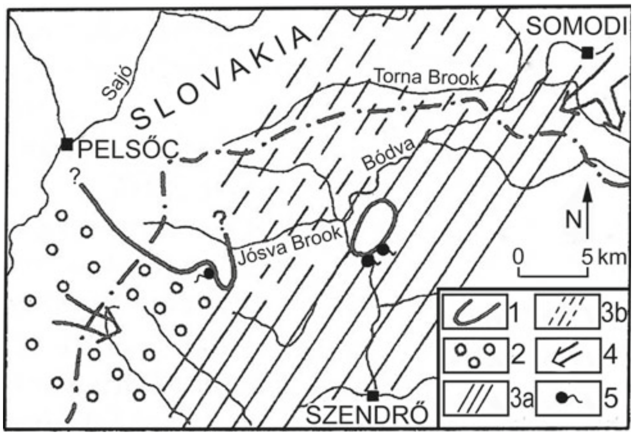

Fig. 2 Former distribution of Pannonian rocks (Sásdi 1990). Legend: 1. uncovered karst, 2. clayey gravel beds, 3. clayey, sandy groups of beds with lignite (a = certain, b = supposed), 4. direction of material transport, 5. traces of spring activity

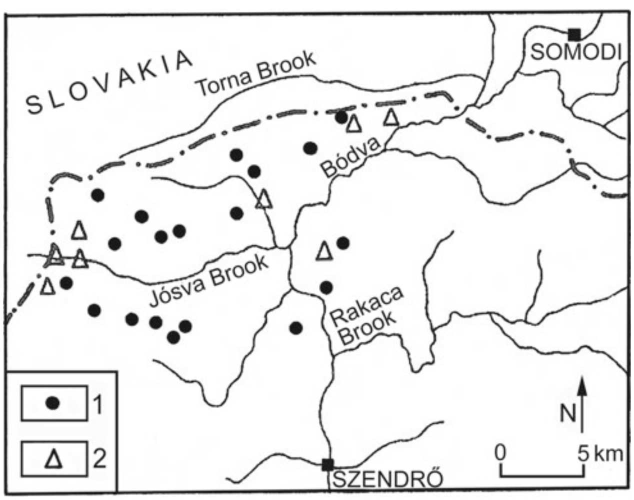

Fig. 3 Sporadic remnants gravel occurrences on the karst (Sásdi 1990). Legend: 1. quartz gravels on the surface, 2. quartz gravels in the cave

such character. However, the degree of elevations is indicated by the fact that the Late Pliocene freshwater limestones are at an altitude of 250–280 m, while those of Pleistocene age are at an altitude of 145 m (Alföldi et al. 1975). The inheritance of the valleys of the karst onto the limestone began at the end of the Pliocene (Sásdi 1998).

Bella et al. (2016) think that the Jósvafő paleopolje continued its development in the Late Pliocene by horizontal dissolution taking place on the surface of former pediment. The pediment (the authors do not give a development stage) probably developed during the formation of the Borsod Gravel Formation on the karst. The development of the pediment also means that the already existing karst features (primarily depressions) may have been destroyed as a result of the significant planation taking place in its area.

According to Jakucs (1956), in the Pannonian, the valleys with NS direction being situated on the northwards inclining surface of the area of the Aggtelek Karst (he meant Aggtelek Plateau by this) and currently having doline rows (for example Baradla Valley, Mész Valley, Hideg Valley) inherited (the author calls this Stage I), the cover became destroyed in these valleys and in their environs. The rock boundary with ponors of blind valleys developed at the interface of the soil-covered karst and covered karst by this. He thinks that this process resulted in the further erosional development of the large caves of the karst (Baradla-Domica, Béke Cave, etc.). However, on the contrary, the karst tilted at the Pliocene-Pleistocene boundary (Sásdi 1990), or in the Pontian stage (Gaál 2014) and its surface became tilted in SSE direction (Sásdi 1990). As a result of this, gravel material (Borsod Gravel Formation) was transported from NW and W (Gaál 2014), from the Slovak Ore Mountains (Móga 2002a) to the uncovered terrains and to the Pannonian terrains. This gravel cover refers to the Pliocene development of the pediment similarly to the case of other Hungarian mountains (Pécsi 1980). The age of the accumulation of the Borsod Gravel Formation is Pliocene according to Jaskó (1932), while Gaál (2014) dates it to the Pontian stage. On the floor of epigenetic valleys (the already mentioned Baradla Valley, Mész Valley, Hideg Valley) with a southern orientation developing on this surface, the ancestors of today existing ponors were formed contributing to the development of the Baradla-Domica cave system (Veress 2010, 2012, Fig. 4). Subsequently, the Aggtelek Plateau tilted oppositely during the separation of the karst into blocks (plateaus) thus, its surface began to dip in northern direction, but partly also the plateau part eastwards, the western part of Galyaság and also the covered karst situated south from them (Veress 2010, 2012). As a result of this tilting, surface waters flowed and flow towards the Aggtelek Plateau from the southern covered part of the karst (Fig. 4). This resulted in the development of newer ponors at the rock boundary and the further erosional development of the Baradla-Domica cave system (Veress 2010). At the ponors of the capture line along the Baradla-Domica cave system, basin-like depressions (depressions of superficial deposit) are arranged (Láng 1971; Veress 2017; Fig. 15 in chapter "The Surface Morphology of Karsts in Hungary"). Below them, closed depressions can be found on the bedrock (chapter "The Surface Morphology of Karsts in Hungary"). The development of basin-like depressions took place by the partial destruction of the fill of the depressions. The material of the fills was transported into the cave since the fill is the material of the Borsod Gravel Formation there (Piros and Gyurica 1986). According to

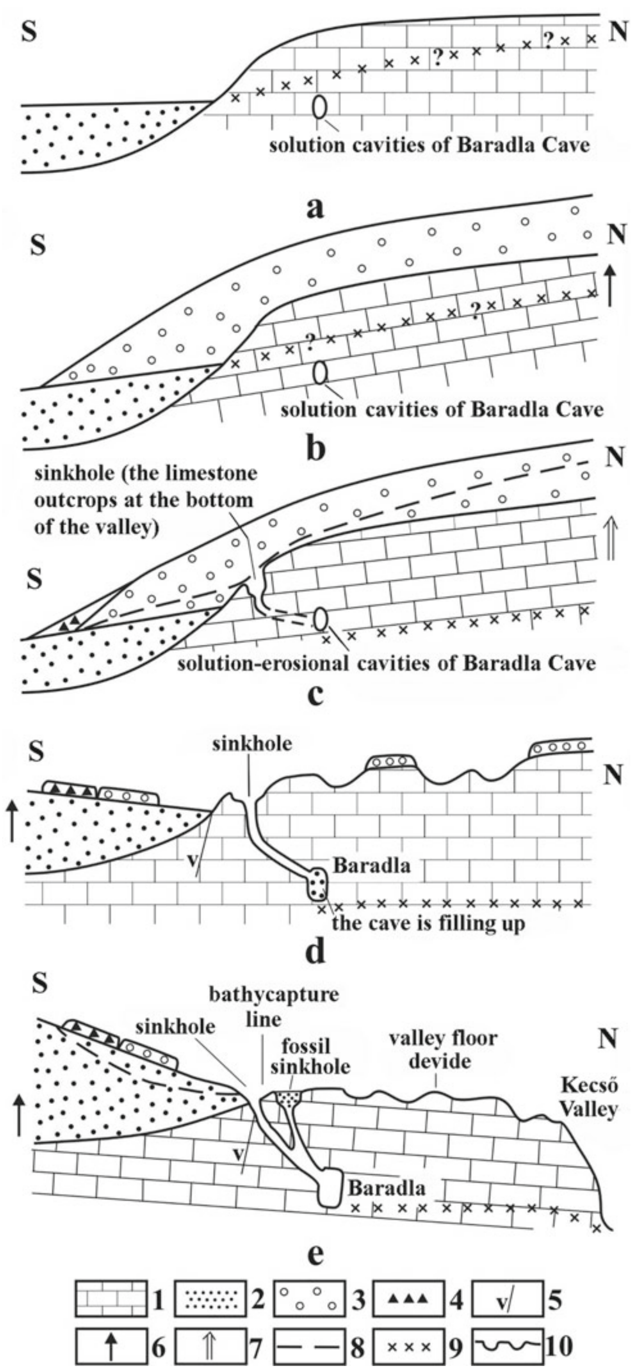

Fig. 4 Surface development and valley development on the Aggtelek Plateau (Veress 2012). Legend: a. uncovered features are formed on the Aggtelek Plateau, features of the Edelény Formation develop southwards from the plateau, b. Pliocene-Pleistocene: the plateau tilted, its SSE inclined surface inclined, but the surface of the covered karst which was covered by the material of the Borsod Gravel Formation also inclined, c. Pleistocene (?): the southern margin of the plateau and the areas in a southern direction from this (the present covered karst) lifted, the plateau had an almost horizontal position, but its valleys had inherited to the limestone in their total by this time, solution dolines were formed on valley floors, e. end of Pleistocene and beginning of Holocene: tilting continued, the plateau is inclined in northern direction, the second generation of ponors developed at the margin of the plateau, 1. limestone, 2. gravel, sand, clay (Edelény Formation), 3. gravel (Borsod Formation), 4. reworked gravel, 5. fault, 6. tilting, 7. uplift, 8. valley floor, 9. karstwater level, 10. dolines and uvalas

Veress (2017), cave development and the exposure of paleokarstic depressions were connected through the ponors and took place affecting each other (Fig. 16 in chapter "The Surface Morphology of Karsts in Hungary"). The gravel material was transported from the depressions into the Baradla-Domica cave system thus, maintaining erosion there. When the denudation reached fine-grained beds in the fill, accumulation increased in the cave system. The cave growth reacted upon the deepening of the depression since the cave system was able to receive the denuded sediment. The transformation of the catchments area of the ponor(s) into a basin also increased the amount of water getting into the ponors (Veress 2017).

Focusing on Aggtelek Plateau and Jósvafő Plateau, Jakucs (1964) distinguished the following stages of karstification related to landscape evolution.

– Pre-pannonian stage: the karst is separated into plateaus.
– Pannonian stage: the karst (or some of its parts) become covered.
– Post-pannonian stage: Valley development on Aggtelek Plateau and Jósvafő Plateau from the end of the Pannonian. The latter is transformed into a polje.
– Pleistocene stage: Downcutting of the River Jósva, the ponors of the capture line develop.
– Early Holocene stage: The Jósvafő polje opens. The lower levels of the large caves of the karst develop. Tributary valleys develop which divide up the floor of the Jósvafő polje. Doline development begins on the floor at this time.

2.2 The Bükk Region

There are diverse karst types in the area of the Bükk Region thus, soil-covered karst, mixed allogenic-autogenic karst (Bükk Plateau, Southeastern Bükk). Concealed karst is not significant, some larger and smaller patches can be mentioned from the floor of karst depressions. Its karst features are diverse (Fig. 5). Solution dolines with various morphology and morphological environment can primarily be mentioned, but some collapse dolines (Fig. 6) and ponors with blind valley occur too.

According to Láng (1954), the Bükk Region is a peneplain remnant where the parts of former peneplain got into different elevations. In the Late Jurassic and Early Cretaceous, the mountains were situated in great depth and their structure was transformed (Hevesi 2002). Sásdi (1997) thinks that it has been a terrestrial area since the middle of the Eocene and then sediment formation began in the Oligocene. In the Eocene the area of the mountains had hot climate (Andreánszky and Kovács 1955) therefore, tropical peneplanation happened (Bulla 1968); Pinczés 1968, 1980; Láng et al. 1970; Hevesi 1978, 1980, 1990). According to Tóth (1984, 2001), Fejes and Tóth (1984), the area of the

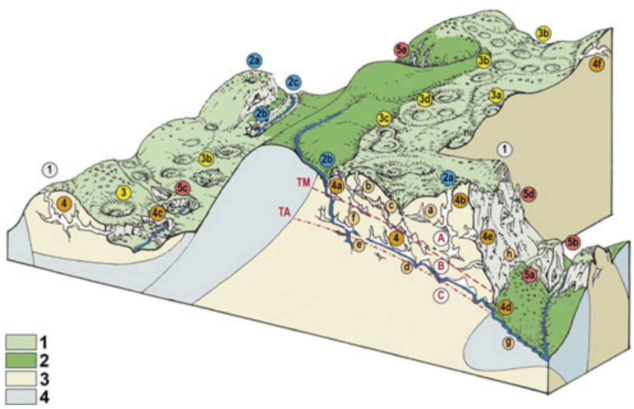

Fig. 5 Karst landform of Bükk Mountains after Baráz Cs. Legend: A—Vadose zone, B—Epiphreatic zone, C—Phreatic zone, TA—Low karstwater level, TM—High karstwater level, Surface landform: 1—karren (lapies), 2—swallow, 2a—opening of a shaft on the summit, 2b—sinkhole with active cave, 2c—blind valley with a resurgent stream, 3—doline, 3a—lonely (hanging) doline, 3b—series of dolines, 3c—uvala, 3d—polje, Underground landform: 4—cave, 4a—sinkhole cave (active), 4b—shaft (inactive vertical cave), 4c—active stream cave, 4d—uplifted collapsing cave, 4e—ruin cave, 5—Surface destroyed karst landforms: 5a—cave, rock gate, 5b—karst gorge, roofless cave, 5c—collapsed doline, 5d—stone pillars, 5e—cuesta, Surface and subsurface Karst relicts and traces: a—collapsed chamber with avens, b—aven with collapsed rockfield, c—syphon, d—inner cave swallow hole passages, e—inactive tetaratas, f—travertine deposit, g—rockfall and debris flow

Central Bükk is the remnant of several peneplanation lasting from the Cretaceous to the Middle Eocene and on this peneplain an older Pliocene denudation level develops at an altitude of 850–870 m and then a younger Pliocene surface is formed at an elevation of 650–700 m (Fig. 23 in chapter “The Surface Morphology of Karsts in Hungary”).

A general view exists that the mountains were peneplanated into a tropical peneplain under hot climate (Bulla 1964; Pinczés 1968, 1980; Láng et al. 1970; Hevesi 1978, 1980, 1990). Therefore, the unevenly denuded surface of the Triassic became overlain by the Early Tertiary rocks (Bércziné Makk 1980). According to Hevesi (2002), the Bükk Plateau is the remnant of this peneplain and qualifying the development age of the peneplain he considers it to be Early-Middle Eocene. He believes that the peneplain continued its formation by terrestrial denudation (karstification), the features preceding tropical karstification were destroyed because of this, between the Lower Eocene and Middle Oligocene. Thus, karstification affected almost the same surface. He thinks that this view supports Jakucs’s (1977) opinion that on karsts of Aggtelek character, present surface karst features are well-developed and of great density because karstification took place on their karst surfaces without interruption for a long time. However, as it can be seen below, the mountains became covered subsequently thus, the Lower Eocene-Middle Oligocene karst surface is not the direct ancestor of the current karst surface. Hevesi (2002) thinks that in the Oligocene, the middle parts of the mountains protruded from the sea that flooded their margins. According to him, the gravel beds of the marginal parts of the mountains and the sand-gravel beds around Noszvaj also refer to this (Báldi 1983). However, on the Kis Plateau (Csókás) there are Upper Oligocene sediments. Sásdi (1997) thinks that this refers to the fact that the mantle of the Kis Plateau thrust over the Palaeozoic rocks of North-eastern Bükk after the Oligocene, but according to Hevesi (2002), it refers to transgression in the mountains at the end of the Oligocene. However, with a newer uplift the mountains became dry land again and during the Eggenburgian age debris was formed under less warm climate, which promoted valley development and cave development (Hevesi 2002). Along the Répáshuta limestone stripe (South-eastern Bükk) red clay with debris accumulated and filled the dolines here and buried the inselberg karst in their environ (Hevesi 2002).

In the Miocene, rhyolite tuff covering took place many times (Jámbor 1959; Balogh 1964). The tuff was denuded within a short time and accumulated in karst features (cave, fissure) (Sásdi 1997).

In the Ottnangian-Carpathian era, the mountains were covered by the sea transgrading from a north-eastern direction (Hevesi 2002). In the Eggenburgian and Ottnangian age, tuffs of volcanic origin accumulated in the south (Pantó 1961; Hámori et al. 1978). In the Carpathian stage, sea cover became complete (Nagymarosy 1981), then pediment formation took place in the northern part of the mountains (Hevesi 2002) after the marine regression under warmer Mediterranean climate (Andreánszky and Kovács 1955)

In the Badenian the uplift of the mountains happened by upwarping (Moldvay 1972). In the inner area of the mountains, the denudation of the substratum is indicated by the limestone gravels of the Badenian beds of the marginal areas, while the calcareous sinters of the beds refer to their karstification (Bohn and Kiss 1978). The uplift by upwarping could have been accompanied by the rejuvenation of karstification towards the margins (Veress 2000a).

According to Andreánszky and Kovács (1955), the climate was Mediterranean (with an amount of precipitation of 850 mm, then 1500 mm, the average temperature in July was 24.5 °C) in the Sarmatian-Early Pannonian age. Hevesi (2002) thinks that the remaining superficial deposit denuded from the karst and tuff accumulated as a result of volcanic activity (Varga 1981).

Sásdi (1997) states that as a result of the significant uplift in the Pannonian, buried mounds were exposed on Nagy Plateau. However, he believes that Miocene sediments occurred on the plateaus even in the Pleistocene.

Fig. 6 Collapsed doline in the Bükk Mountains (Udvar-kő cave) (Photo Baráz Cs.)

By the end of the Miocene, the Bükk Region or some of it was transformed into mountains with significant elevation which separated from its environment and was dissected by valleys (Balogh 1964; Pinczés 1968, 1980; Hevesi 1978, 1990), and already had an individual drainage network at this time (Kerekes 1936; Pinczés 1957, 1980; Hevesi 1978, 1990).

Although according to Dunkl et al. (1994), at the end of the Miocene there was still thick, non-karstic cover in the mountains, several researchers (Kleb 1976; Pinczés 1957) reported on terrestrial limestone gravels from the margins due to drillings. Based on the latter data, Hevesi (2002) thinks that the karstification of the mountains lasting to present day began in the Sarmatian. They could have been transformed from buried karst into mixed allogenic-autogenic karst.

The doline fills and the freshwater limestones refer to their partial exposed character and karstification. Based on Pannonian flora elements, Pannonian fill was found in one of the dolines of the South-eastern Bükk (Vitális 1977; Láng et al. 1970). Sásdi (1997) described Miocene and Late Oligocene doline fill from the mountains, particularly from the South-eastern Bükk. The Lower Miocene karstification of the South-western Bükk is also proved by the freshwater limestone ruins of sediments of such age (Sásdi 1993).

According to Hevesi (2002), the surface karst features of Late Oligocene-Early Miocene were completely destroyed and only those cave parts and features could have survived which had developed below the karstwater level. However, since we think that the mounds of Nagy Plateau could have developed by karstification, these relict landforms partially survived. Hevesi (2002) thinks that the exposure of the mountains continued in the Sarmatian (valley development), but he also assumes pediment development, though it was accompanied by dissection since the climate became wetter.

At the beginning of the Pannonian, the mountains became elevated significantly (Sásdi 1997), but according to other opinions, sinking took place and the uplift only happened at the end of the Early Pannonian (Hevesi 2002). Sásdi (1997) states that as a result of the uplift, the mounds of the Nagy Plateau became exposed, while Hevesi (2002) believes that sinking was accompanied by the retardation of denudation. The average temperature in January was 6–8 °C, in July it was 22–24 °C, and the amount of precipitation was 1100–1200 mm in the mountains (Andreánszky and Kovács 1955).

Surface waters mainly flowed in northern and north-eastern direction (Hevesi 2002), which fact coincides with the opinion that the entrances of the spring caves in the environs of Nagymező (Nagy Plateau) have a northern direction (Sásdi 1997). The northern orientation of streams is proved by the fact that the sediment transportation from the mountains took place in northern direction. Since there are no gravels originating from the substratum in the Southern Bükk until the Pliocene (Pinczés 1968). Another evidence for this is that the streams of the valleys with doline rows of Nagy Plateau also left the karst in the above-mentioned direction (Hevesi 1980). According to Hevesi (2002), the beheadings of the streams of the plateau happened at the end of the Early Pannonian.

At the time of the Late Pannonian-Pliocene, the climate became drier (Pécsi 1980). The development of the

Fig. 7 One of the Bükk rocks, Őr-kő (Photo Baráz Cs.)

pediments of Bükkalja and Bükkhát started (Pinczés 1957, 1977; Hevesi 1986, 1990). However, at the end of the Pliocene, the climate became wet (Kretzoi and Pécsi 1972), and because of the sinking of the Great Hungarian Plain (Sümeghy 1944) and the uplift of the mountains, the erosional dissection of pediments began (Hevesi 2002). The karstification being significant from the Late Sarmatian to the Early Pannonian, and then slowing down, became more intensive in the Late Pliocene (Hevesi 2002). The valleys with doline rows of the Nagy Plateau were formed by the end of the Pliocene (Hevesi 1980, 1990). Hevesi (2002) states that the pattern of the current valley network developed by the end of the Pliocene which was accompanied by the development of streams with a southern orientation in the Southern Bükk. This is proved by the fact that the entrances of younger spring caves already look to the south (Sásdi 1997). By the end of the Pliocene, the mounds of the southern margin of the plateau developed (the "Rock", Fig. 7), and its regions (micro regions) became separated.

The inactive spring caves refer to the Pleistocene state of the mountains. Jánossy (1979) thinks that the archaeological findings (fossils) of the fill of the karstic fissure of Köves--Várad which are situated below and near Pungor-lyuk cave are of Günz-Mindel interglacial age. Therefore, the Pungor-lyuk was already above the karst water level at that time and according to Hevesi (2002), it is a representative of the older spring caves generation of the mountains (Hevesi believes that it developed at the end of the Pliocene.) According to the archaeological findings, the fill of the younger spring cave generation of the mountains (for example, Istállóskő Cave, Subalyuk) developed in the Early and Middle Würmian (Jánossy 1979). Thus, the development of these caves must be older than this. Sásdi's opinion (1997) is that there are fills referring to ponor activity in several inactive spring caves, but he did not give their age. This refers to an activity of katavothron character and to the fact that the karstwater level was close to the surface. According to Pinczés (1977) and Hevesi (1978, 1980), the pediments of Late Pliocene widened in the glacials. The spring caves became destroyed, the dolines functioned as snow traps and gorge development became more intensive (Hevesi 2002).

The older spring cave generation developed in the Günz-Mindel interglacial and then the younger generation was formed in the Mindel-Riss interglacial and the current, active spring caves appeared in the Riss-Würmian interglacial (Hevesi 2002). Newer gorges were formed in the Würmian by collapse of caves (Kerekes 1936).

2.3 The Transdanubian Mountains

As a result of the different elevation, structure, and extent of exposure of horsts, various karst types occur in the mountains (Veress and Vetési-Foith 2019a, b). Thus, on horsts covered with loess there is concealed karst (Tés Plateau, Hárskút Basin, Gerecse, etc.) with subsidence dolines, on horsts with impermeable cover there is cryptokarst (Kab Mountain, some parts of Pilis Mountain, Naszály?) with

Fig. 8 One of the largest basalt depressions, Macska-lyuk (Cat Hole) ponor on the Kab Mount

caprock dolines, on horsts partly covered with impermeable beds, mixed allogenic-autogenic karst occurs with ponors with blind valleys (Kab Mountain, Figs. 8 and 9), on horsts of lower elevation if they are uncovered, soil-covered karst is present (Tapolca Karst, some dolomite terrains) with solution dolines (Fig. 10), in case of cover (the karst in the environs of Devecser) there is soil-covered karst with partly filled solution dolines or conglomerate karst (among Magyarpolány, Városlőd and Farkasgyepű), with depressions that developed in superficial deposit.

Fig. 9 Regression valleys joined to basalt ponor on Kab Mount

Fig. 10 Tapolca karst (with solution dolines, basalt buttes in the background)

Láng (1952) and Bulla (1958, 1964) interpreted the horsts of the Transdanubian Mountains with different age (and elevation) as peneplain levels since they think that tropical peneplanation took place from the Upper Cretaceous to the Middle Miocene continuously. However, in other earlier works peneplanation and lowering was dated later. According to Leél-Őssy (1958), it took place during the Miocene-Pliocene in the Pilis Mountains and according to Láng (1956) in the Miocene in the Gerecse Mountains.

However, Pécsi (1980) thinks that patches of gravel cover also occurring on the roof levels of horsts are not tropical chemical weathering products, but they indicate pedimentation taking place under warm, sub-humid and semi-arid climate (the gravel material originated from the adjacent mountains of crystalline material that subsided by now). According to Pécsi (1980), the surface of the horsts of the Transdanubian Mountains developed through Mesozoic peneplanation during tropical karstification as a result of which surfaces of cone karst (inselberg karst) developed. He thinks that peneplanation took place from the Upper Jurassic to the Lower and Middle Cretaceous. During planation, the surface denuded almost to the base level of erosion and some areas of the mountains got below transgression. The inselberg karst did probably not develop uniformly and varieties of various maturity were formed (Veress 2000b). The exposure of surface parts with dolines by manganese and bauxite mining at Úrkút (Szabó 1956), Nyirád and Iharkút (Pataki 1983) refer to this.

According to Pécsi (1980), the peneplain started to dissect tectonically at the end of the Cretaceous. The separating horsts could have risen, sunk, or oscillated. Pécsi (1987a) thinks that the peneplain remnants could be covered with Eocene limestone (Bakony Region), with Oligocene sandstone (Buda Mountains, Pilis Mountains), with Miocene (Middle Oligocene—Lower Miocene) gravel completely (Bakony Region, the area among Magyarpolány, Városlőd, and Farkasgyepű and some of the basins) or partially (Eastern Gerecse).

The mounds of inselberg karst could only have survived at places where the caprock protected them against denudation, but it is also probable that they were also destroyed to a great extent as a result of permanent karstification. The more elevated a horst (at an absolute or relative altitude), the greater the chance of the denudation of its karstic landforms at its surface and thus, of the truncation of various degrees of the mounds was. At present, surface features remaining from tropical karstification are probable only at some sites. These are the following:

– On Kab Mountain, where outcrops of limestone patch occur at the surface with basalt cover (Németh 2005; Móga and Németh 2005; Veress and Unger 2015, see chapter "The Surface Morphology of Karsts in Hungary"). These are the karstic mounds of the dissected bedrock whose outcrop is very young if they became covered. However, if they were not covered, they could not have been destroyed significantly either since its degree is determined by the denudation of the basalt surface. Though, the extent of the denudation of the latter is insignificant because of the little elevation difference of the basalt surface.
– On horsts covered with Middle Cretaceous limestone in the Bakony Region where the exhumation of the mounds

takes place from below the superficial deposits (see chapter "The Surface Morphology of Karsts in Hungary").

- The surfaces built up of Triassic Main Dolomite such as the Veszprém-Devecser Graben or the environs of Nyirád and Ódörögd are dissected by mounds and groups of mounds. Csillag and Sebe (2015) interpreted their development by Early Miocene tropical planation. However, some parts of the dolomite surface (Veszprém Plateau) were transformed by Pliocene pedimentation (Pécsi 1987b). The survival of the landscape with mounds can be explained by two factors: since they are not of mountain front position, pedimentation affected the above-mentioned areas less or it did not affect them at all and/or because of their low position (at least at present), denudation was less intensive.

Between the Middle Oligocene and Lower Miocene, terrestrial sediment formation took place (Csatka Gravel Formation) on the low surface being more or less separated into horsts and disrupted by archipelago parts (Middle Eocene limestones were formed and at the north-eastern part of the mountains, Oligocene sandstones were formed). In the area of terrestrial sediment formation, the gravel was accumulated by rivers arriving from the south and the southeast (Korpás 1981) since the mountains were a low piedmont zone at that time (Láng 1958). Gravel formation gradually ceased until the beginning of the Pannonian (Pécsi 1980). The widespread distribution of this gravel in the Transdanubian Mountains (it occurs in the Bakony Region and in Gerecse too) indicates that the mountains were a uniform, hardly dissected area at that time. Pécsi (1980) regards this gravel accumulation as the development age and development of the older pediment of the Transdanubian Mountains. He thinks that its age is of Middle Oligocene and Middle Miocene. The patches of gravel cover are at different altitudes now (Láng 1955b, 1958) disregarding the reworked occurrences. This refers to the fact that since the development of the gravel cover the peneplain has become tectonically dissected definitively and the peneplain parts got into various altitudes. The Late Pannonian calcareous sinter occurrence at an altitude of 340–350 m below the Pisznice Cave (situated at an altitude of 460 m) in the Central Gerecse also refers to this (Scheuer and Schweitzer 1983). Thus, the cave was already inactive at this time and this also marks the elevated position of the bearing block (Nagy Pisznice) and also the fact that karstification took place in some parts of Gerecse.

According to Pécsi (1980), the gravel developed under warm, sub-humid, and semi-arid climate during pedimentation and pediplanation. Pécsi (1963, 1970) states that the horsts of the Transdanubian Mountains were alternating the sedimentary basins and pediments of the surrounding mountains that subsided into the depth by now. He also establishes that the recurring gravel covers refer to recurrent pedimentation. The surface features of older karstification may have been destroyed particularly during this latter process.

In the Pannonian, abrasion levels (Lóczy 1913; Prinz 1926) and Pannonian limestones were formed in the mountain front areas and in the basins inside the mountains such as in the Zirc Basin and Bicske Basin as well as in their grabens for example in the area of the Veszprém-Nagyvázsony Graben (Pécsi 1980).

In the Pliocene, pedimentation occurred again (Pécsi 1980) due to the streams leaving the mountains (Pécsi 1963). As a result of the uplifts, the pediments can be situated at various altitudes and may also form two levels because of their transformation in the Pleistocene (Pécsi 1987a). The pediment formation happened on the Pannonian sediments, but it also spread onto older surfaces (Pécsi 1980) or it developed on the Pontian abrasion platform (Pécsi 1987a) and penetrated into some valleys too (Pécsi 1963). The piedmont half-planes were overlain by Upper Pliocene calcareous sinters and the older terraces of the River Danube and its tributary rivers (Pécsi 1980, Fig. 11). Pliocene

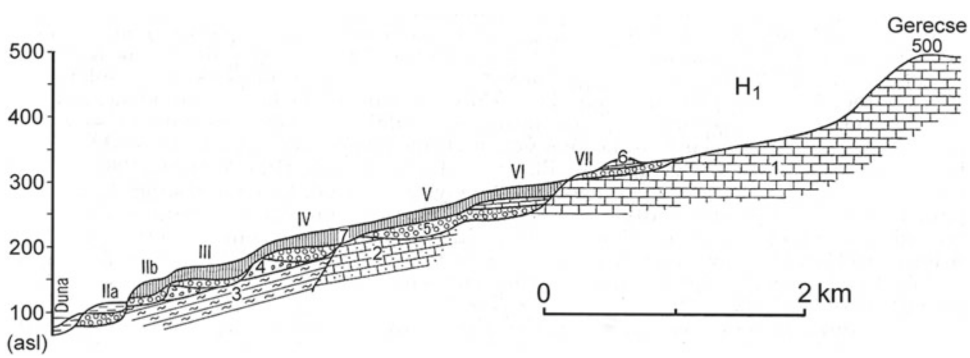

Fig. 11 Danube terraces and Upper Pliocene pediments at Lábatlan at the margin of the Gerecse Mountains (Pécsi 1980). Legend: H_1 Upper Pliocene pediment, IIa-VII Danube terraces, VII Late Upper Pliocene terrace (?) covered with calcareous sinter, VI. Pre-günz (Danube terrace with freshwater limestone), V. Günzian terrace, IV Mindel glacial terrace, III. Riss glacial terrace, IIa-IIb. Würmian glacial terraces, 1. Mesozoic rocks in general, 2. Cretaceous sandstone, 3. Eocene marl, 4. Oligocene gravel, conglomerate, 5. terrace gravel, 6. freshwater limestone, 7. slope loess

freshwater limestones for example in Gerecse occur at various altitudes as a result of the upheaval of different degree of some horsts (Láng 1956).

In the south-western part of the Transdanubian Mountains, the basalt lava covered Pannonian surface (Tapolca Basin), Pliocene pediments and probably Cretaceous peneplains (Kab Mountain) (Pécsi 1980) during the Late Pliocene basalt volcanism (Lóczy 1913; Jugovics 1954), whose absolute age is 2.7 million years (Balogh et al. 1987). The peneplain of the Kab Mountain was probably transformed by that time. According to Láng (1958), the basalt lava covered a surface dissected by valleys and mounds.

It is probable that the development of the older epigenetic valleys of the mountains and the dissection of denudation levels already started in the Pliocene. In the Pleistocene, valley development became more intensive particularly in the interglacials. The gravelly terrains and Pannonian surfaces (especially in the basins) were dissected by a valley network. In the Pleistocene, the Pliocene pediments were dissected by valleys in the interglacials and preceding it, a newer pediment may have developed on the already existing pediments in the glacials (Pécsi 1963). Loess was formed in the mountains which dates back to the Würmian in the Bakony Region. Pécsi (1982) states that the loess is younger than 30 thousand years in the Bakony Region (but it may be older than this on other mountain parts). Therefore, particularly in the Bakony Region, the development age of syngenetic subsidence dolines that were formed on non-reworked loess is younger than 30 thousand years (Veress and Vetési 2019a, b). The development age of postgenetic dolines may also be older than this.

According to Veress and Vetési (2019b), the relative age of the development of subsidence dolines is different. In case of dolines with a valley floor position, this age is younger than the sediment lining the valley floor, on the terrains between exhumed mounds it is younger than the development of the surrounding valley (superficial deposit was transported into them from the mounds and their environs), and it is also younger on the floor of solution dolines than the accumulation of floor sediments. Since valley development on the horsts and in their environs is of various time, the beginning of concealed karstification of horsts also took place at a different time.

Postgenetic karstification is characteristic of the Tés Plateau (Bakony Region). Here, mixed allogenic-autogenic karst developed at the patches of the Oligocene Miocene gravel cover (at present, its material exists in the form of sporadic gravel mostly in the caves of the plateau) following the dissection of the cover. After the denudation of gravel cover patches and the development of loess, former, filled ponors redeveloped as subsidence dolines (Veress 2000b).

Taking into consideration the geomorphic evolution of horsts, Pécsi (1980, 1991) distinguished the following horst types in the Transdanubian Mountains (Fig. 46 in chapter "The Surface Morphology of Karsts in Hungary"):

- Cryptopeneplain: the altitude of its surface is below 300 m. The cryptopeneplain is covered with Pliocene gravel and Middle Miocene limestone and gravel. The peneplain (block) may occur at the mountain front or inside the mountains. In the latter case, the block (or block group) is a basin or graben morphologically.
- Low threshold surface: the altitude of its surface is below 300 m (400 m) and it is built up of old (mainly Triassic) carbonate rocks. The blocks of this type lost their superficial deposits by pedimentation.
- Horst elevated to summit position: the altitude of its surface may be between 400 m (maybe 300 m) and 550 m. Several varieties of this type can be distinguished. Thus, in the area of the covered horsts elevated to summit position, Middle Eocene limestone and Oligocene sandstone covers the Mesozoic (Triassic, Jurassic) substratum which often has a surface of cone karst. (We think that the horsts where the cover is Cretaceous limestone can also be put into this type.) In the area of half exhumed horsts elevated to summit position, the Tertiary cover only survived in patches, while the exhumed horsts elevated to summit position are terrains where Tertiary sediments were completely destroyed.
- Horst in summit position: the altitude of its surface is 600–700 m and it is built up of Triassic and Jurassic carbonate rocks.
- The above classification can be supplemented by the block type with basalt cover (Kab Mountain) which occurs in the southern part of the Bakony Region.

The blocks belonging to the above types will have a different degree of coveredness and thus, various karstification as well (see chapter "An Interpretation of Karstification and Karst Processes by Hungarian Researchers"). The surfaces of horsts are being karstified now if the circumstances are suitable there particularly the denudation (or accumulation surfaces) of various horst types. The type of karstification depends on whether there is non-karstic cover and if there is, of what type it is. On horsts in summit position, peneplain surfaces are karstified where the patches of permeable superficial deposit (loess) survived. Its condition is only present at few sites for example on the floor of old depressions (see chapter "The Surface Morphology of Karsts in Hungary"). On horsts elevated to summit position, concealed karstification is more widespread. Here, there are karstifying patches where the superficial deposit survived between the exhuming karstic mounds (horst covered with Middle Cretaceous limestone) in a thinned out state or at that place where covered mounds occur under the loose superficial deposit (Tés Plateau) or below consolidated cover (Kab Mountain) (Veress 2000b, Veress and Vetési-Foith 2019a, b). It has to be highlighted that the lower parts of this horst type being stripped of gravel cover belong to the older pediment. Karstification may also happen here mainly on the lined floors of epigenetic valleys (Hárskút Basin, maybe some parts of Tés Plateau, the environs of Márvány Valley, see chapter "The Surface Morphology of Karsts in Hungary").

On lower threshold surfaces, the peneplain (dolomite terrain), the older pediment, but the younger one may also be karstified. Tapolca Karst (which is mostly uncovered soil-covered karst) or the karst being covered with reworked superficial deposit in the environs of Devecser may be mentioned as examples for the latter.

The horsts with cryptopeneplains of the mountains are buried karsts. Either conglomerate karst developed (during the dissolution of the limestone material of the cover) on these or waters flowing from surfaces with gravel cover contribute the development of the gorges of the mountains and the opening-up of karstic cavities there (Veress 2000b; Veress and Vetési-Foith 2019a, b).

2.4 The Western Mecsek Karst

The Western Mecsek Karst is situated at the northern margin of the Mecsek Mountains which are surrounded by badly karstifying carbonate rocks and non-karstic rocks from the south (Barta and Tarnai 1997, Fig. 63 in chapter "The Surface Morphology of Karsts in Hungary"). The whole Mecsek is a system of peneplain surface parts (Pécsi 1963; Lovász 1981). Pécsi (1963) thinks that peneplanation took place at the end of the Cretaceous, but according to Lovász (1981), Eocene–Oligocene tropical peneplain remnants also occur (Fig. 12, Jakab Mountain, Misina-tető). The peneplain parts were later elevated into different altitudes by tectonic movements. Particularly the peneplain parts of marginal areas and within these the parts built up of karstic rocks were transformed by outer forces.

During Cretaceous-Early Tertiary karstification, polje development happened and the polje was transformed by the Orfű Valley (Szabó 1956). In the Carpathian stage, the area of the karst was transformed into pediment (its remnant is at an altitude of 450–470 m), which or a part of which developed into abrasion platform during transgression in the Middle Miocene (Lovász 1981). During the uplift of the mountains, the northern margin of this platform was also transformed into an abrasion platform due to a newer transgression in the Pannonian (Lower Pannonian). The two levels are separated from each other by a steeper slope (Fig. 62 in chapter "The Surface Morphology of Karsts in Hungary").

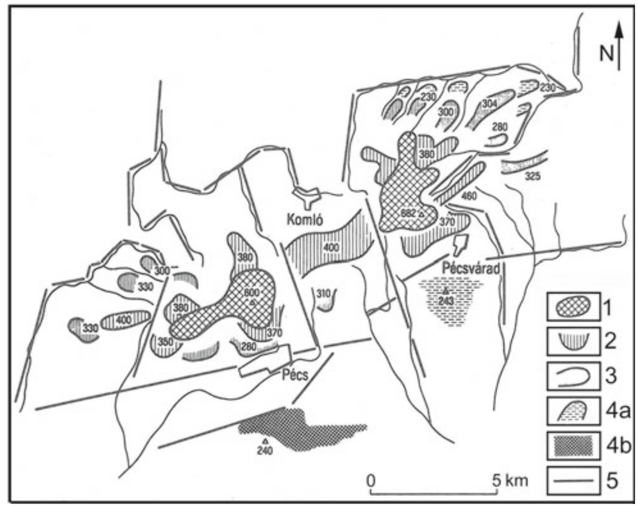

Fig. 12 Main structural lines and denudation surfaces of the Mecsek Mountains (Lovász 1981). Legend: 1. Eocene–Oligocene surface, 2. Carpathian abrasion surface, 3. Lower Pannonian abrasion surface, 4a. piedmont half-planes, 4b. buried alluvial cones, 5. main structural line

Valleys with a SN orientation go transversely to the area of the karst, the valleys primarily received and still receive their streams from the surrounding non-karstic terrain. These valleys either inherited from superficial deposits being denuded by now to the karstifying rock or they developed because the karstwater level situated close to the surface and they could deepen following the lowering of this level (Hevesi 2001). The beginning of their development is younger than the Pannonian, but older than the Pleistocene (Lovász 1977; Hevesi 2001). According to Hevesi (1991a, b), the older abrasion level became covered in the Middle Miocene.

Loess, but clay and sand occurring together with loess are widespread in the Mecsek Mountains and thus, in the karst area too (Veress 2011). The latter probably originates from the sandstone of Jakab Mountain.

The karstification represented by the development of solution dolines may have begun after the formation of the valleys, which is proved by the fact that the distribution of dolines is determined by valleys to a great degree (for example doline rows occur in the continuation of valley heads). However, there are no solution dolines on valley floors which, as already mentioned, may refer to the fact that during their development the valley floors were situated at the karstwater level. According to Hevesi (1991b), karstification is continuous on the upper abrasion level from the Sarmatian and on the lower abrasion level from the Pliocene to these days. Szabó (1968) dates back the development of solution dolines to the Early Tertiary. However, as there are no solution dolines on the upper level (Lovász 1971, 1977), they were destroyed and at most the surviving shafts of former dolines can represent this.

In the Pleistocene, loess was formed which developed uniformly and since it does not contain limestone thus, it may have been dissolved for a longer time and it is probably older than the Würmian. The subsidence dolines of the karst developed in the loess. Thus, concealed karstification is young (Szabó 1968; Lippmann et al. 2008), it is younger than the development of the loess (Veress 2011) and its beginning is probably Würmian and younger than this.

3 Conclusions

It is a common character in the history of Hungarian karst areas that denudation terrains with low inclination (peneplains, pediments, and abrasion platforms) developed during the geomorphic evolution of karst areas. These surfaces are primarily the tropical karst peneplains whose geomorphic evolution was very different. Therefore, the degree of exposure and denudation as well as the elevation of peneplain parts also differs. However, no tropical peneplain can be found on the Western Mecsek Karst. Fluvial surface formation always plays a role in the past of karst areas. On the one hand, it denuded the superficial deposit, on the other hand, the developing valleys, being inherited to the karstic bedrock had a significant influence on karstification.

The duration and frequency of periods with terrestrial areas, the degree and frequency of coveredness, the type, thickness, and present distribution of the covering non-karstic rocks are different on various karst areas.

The present surface of karst areas developed during extremely different landscape evolution. The transformation of former denudation surfaces is very different. Karstification also played a role in geomorphic evolution. The time from which karstification is continuous until the present is uncertain to determine. The present surface karstification seems to be continuous from the Pleistocene (maybe from the Upper Pannonian or the Pliocene) on the Aggtelek-Rudabánya Mountains, while in the Bükk Mountains it may be continuous, being present from the Late Sarmatian or from the Pannonian though not with the same intensity. The beginning of the concealed karstification of the Transdanubian Mountains and the Western Mecsek is young. In case of the Transdanubian Mountains, it is Würmian or younger, and it began at a different time on blocks of various blocks, while in case of the Western Mecsek, it may also be older than the Würmian. On the latter karst a change of karst type happened since the older soil-covered karst was overlain by concealed karst. This overlying character occurs less frequently in case of the karsts of the Transdanubian Mountains. Such karst terrains can be mentioned from the Bakony Region (Tés Plateau, Kab Mountain).

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