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Predicting Potential Sites of Covered Karstification

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Abstract

Our aim was the prediction of karstification. We measured the karstic bedrock and the overlying superficial cover in four areas of Hungary and one area in Romania. One of our tools was the widely used geophysical techniques i.e. VES and multi-electrode method. We also made observations on mountainous, Mediterranean and tropical karsts. In these areas the occurrence of covered karsts, of either syngenetic or postgenetic type, is high. Based on the measured data we determined the conditions under which covered karst formation is possible. For example the conditions that induce syngenetic karstification are: cavities, caves, and shafts within the bedrock, places where the superficial cover is locally thinner, or places where the impermeable beds edge out. An indicator of postgenetic karstification is the presence of lenticular intercalations in the superficial cover (sites of former dolines). Knowing these conditions in any karst area we can readily identify the potential sites where covered karst formation is possible in the near future. If these sites are known, engineering structures can be planned so that potential dangers due to karstification are avoided.

Keywords: covered karst, shaft, passage, syngenetic karstification, postgenetic karstification, potential covered karstification, map of sites of potential karstification

1. Introduction

The investigation of karst regions has many important applications. For example, the development of covered karst features as well as non-karstic processes involve subsidence or collapses, which can damage engineering structures or their components, as was presented in detail by Beck (2005) and Ford and Williams (1989, 2007). Collapses and suffosions are also common if karst water or groundwater is extracted rapidly, as was shown by Chen (1988) and Guo (1991). Waltham et al. (2005) not only present the complete characteristics and classification of dolines, but also provide numerous case studies of the damage caused by the collapse of man-made structures. Various technological approaches have been developed to preserve constructions potentially threatened by karstification. The collapse of the ground surface in areas susceptible to karst may be prevented if buildings are constructed with appropriately designed foundations (Destephen & Wargo, 1992) or if the bedrock cover is excavated above the cavities and filled with rock aggregate (Beck & Stephenson, 1997), or if a concrete plug is installed into the depression (Sowers, 1996). These methods are, however, expensive. Furthermore, engineers must locate the voids in the limestone precisely, which can be difficult and expensive if there are no indications of the depression on the ground surface (subsidence depressions do not necessarily develop over cavities). Therefore, engineers would benefit if a method were developed that can identify sites where karstification might occur. Knowing these sites the location of man-made structures can be selected carefully, to avoid the potentially dangerous areas and thus make all the above mentioned and expensive procedures unnecessary.

The aforementioned facts motivated us to develop a method that can identify the locations where covered karstification is possible in any karst area. We define potential covered karstification sites as locations where dolines might form in the near future.

2. Review of Karst

Covered karsts develop if non-karstic rock covers a rock mass suitable for karstification. The covered karst may be cryptokarst (if the superficial deposit is impermeable) and concealed karst (if the superficial deposit is permeable). Above the bedrock in the basal subsoil usually there is an area of broken and weathered unconsolidated rock. In the case of concealed karst the material deficit is caused by dissolution of the limestone bed, which induces the redistribution of the material of the sedimentary cover and, as a consequence, dolines form in the superficial deposit.

Dolines in the cover deposits are referred to three types (Cvijič, 1893; Cramer, 1941; Thomas, 1954; Jennings, 1985). According to Jennings (1985) subsidence dolines (in modern terminology they are referred to as suffosion dolines) and dropout dolines develop if the depression is formed in a non-karstic, unconsolidated superficial deposit, because part of the cover material is transported into the karst. According to Jennings (1985) subjacent dolines (in modern terminology they are called caprock dolines) develop if non-karstic rock (e.g. basalt or sandstone) enters an underlying limestone cave through a rapid and periodic process (e.g. collapse). Alluvial streamsink dolines develop if surface waters wash the unconsolidated superficial cover into the shafts of the karst. This latter form generally develops close to the piezometric surface, as in poljes (large, flat-floored depressions within the karst). Lately two types of subsidence dolines have been distinguished (Drumm et al. 1990; Tharp, 1999; Waltham & Fookes, 2003). A dropout doline (cover collapse doline) develops if the superficial deposit is consolidated and part of it caves-in into a shaft. Such collapse can have different causes – for example, the cover might be very loosely consolidated, or a material deficit rapidly develops in the lower part of the superficial cover or in the limestone. Material deficit can also develop if the lower part of the cover is affected by solifluction (Drumm et al., 1990; Tharp, 1999; Waltham & Fookes, 2003). The sides of the resulting doline are steep failure scarps. A suffosion doline develops if a non-indurated (loose) superficial deposit subsides but does not collapse (Williams, 2003; Waltham & Fookes, 2003). The process can happen if larger slabs of the superficial deposit sink, if a finer sediment subsides, if the grains of the superficial deposit are displaced by suffosion (Drumm et al., 1990; Williams, 2003; Veress, 2005, 2006b), if the sediment is redeposited by sheetwash (Cramer, 1941; Drumm et al., 1990; Tharp, 1999) or through compaction. Yet another type of doline, a buried doline (a shallow depression of the surface of the superficial deposit) may develop if the accumulating sediment of an older karst depression becomes compacted. It can also happen if sediment is washed into the karst (Bezuidenhout & Enslin, 1970; Brink, 1984) or if the level of the piezometric surface falls (Jennings, 1966). The cause of the compaction can also be a chemical process, which affects the cover rocks (Williams, 2003); in this case the pore space of the precipitated material is less than before dissolution (Veress, 1995). According to Waltham and Fookes (2003) re-activated buried dolines occur on tropical karst, but in reality reactivated buried dolines may also occur on other karst types as well. On covered karsts closed and undrained forms, so called “depressions of the superficial cover” may also occur (Veress, 2000, 2009). They are found in the superficial deposits (for example loess). Their diameter is relatively large, reaching more than 50 metres, whereas their depth is only a few metres. Many smaller karst forms, such as dropout dolines, suffosion dolines and buried dolines, also occur within the floor of such large, shallow depressions.

According to Waltham and Fookes (2003), different types of dolines develop at different stages of karstification. Thus, for example, in the initial phase minor and sparse suffosion and dropout dolines emerge, which become more and more numerous during the mature karst phase. Buried dolines, on the other hand, develop on complex karsts. All doline types formed in the cover deposits occur on extreme karst, which stage is typical of the tropical karst (of course, extreme karstification may also occur on other karst types).

The characteristics of the concealed karst are the following:

● Permeable cover rocks are present over various areas of the karst. Solution dolines may occur, and they are covered partly or totally by cover material.

● Dropout dolines, suffosion dolines, depressions of the cover and buried dolines are present, and filled depressions containing small pools of water are also common. The side walls of dropout dolines and suffosion dolines were created in the cover, but limestone can crop out in the doline floors. Passages (in the cover rocks) or shafts (in the limestone) commonly appear in their floors. In some cases gullies lead to dropout dolines and suffosion dolines. Small pools of water may develop in the dolines during heavy rainfall, even if they are not filled completely.

● Small, immature depressions are numerous on concealed karst. They develop during breakdown of the cover materials of the floor and their size is about 1-2 metres. These forms are dolines that are at the first stage of their development.

3. Development of the Dolines in Covered Karst

Covered karst surfaces occur on temperate karsts in high and low mountains, on Mediterranean karsts, and on tropical karsts. They develop where sediment accumulates across areas of these karst types (for details see below). Covered karsts can develop in older karst forms in high and low mountains (e.g. palaeo-dolines, palaeo-uvalas and blind valleys) or within various dolines in tropical karst (fengcong or peak cluster). They also occur in epigenetic valleys (low mountains) or in rock basins (high mountains). They can develop in tectonic depressions, for instance in grabens, tectonic basins, synclines or syneclises (as in the Ukraine), in the poljes of the Mediterranean karst, and in the intermountain plains of fenglin karst (peak forest).

The depressions of the above mentioned temperate or high mountain karsts may be overlain by non-karstic rocks. Sediment that is transported onto the karst surface accumulates primarily in the karst depressions. During accumulation these pre-existing forms are filled up and buried. At the beginning of the process some residual high points stand above their covered surroundings as mounds or ridges, separating the depressions. Eventually, however, such residual highs are all buried under the sediment. Covered karsts may develop by sedimentation on tropical or Mediterranean karst surfaces. In such cases the karst forms are larger in size (poljes, intermountain plains of the fenglin type or peak forest karst) and surfaces dissected by karstification (uvalas, polygonal karst) develop. Karst areas that originally do not include dissolution forms (i.e. originally non-dissected) may also become covered (e.g. State of Kentucky, USA).

In the Central European low mountains (e.g. the Bakony, Mecsek and Bükk mountain ranges in Hungary), the sedimentary cover is loess and its various redeposited derivatives, clay, or alluvial deposits originating from non-karstic rocks (as on the Padis Plateau, Romania). In high mountains the cover can be glacial till, debris resulting from freeze-and-thaw or breakdown material. In the dolines of tropical karsts, in intermountain plains, and in poljes the sedimentary cover originates either as a weathering residue (or redeposited weathering residue) or as alluvial deposits derived from nearby non-karstic rocks.

Dropout dolines and suffosion dolines can emerge along the borders of areas of impermeable sedimentary cover (comprised of non-indurated superficial clay). Groundwater moves over the surface of the impermeable beds, and reaches the karst along their margins (Figure 1a). Such karst features occur, for instance, in the Mecsek Mountains. In other cases dropout dolines and suffosion dolines develop where the cover is locally thinner (Figure 1b, 2a). We define the outer sedimentary thickness as the thickness of the cover material at the margin of the doline, as measured from the geoelectrical-geological cross-section. This outer sedimentary thickness was found to be equal to the local sedimentary thickness, defined as the average thickness of the cover in a zone (a few metres to a few tens of metres in diameter) around the dolines. In the Bakony Mountains (Veress, 2005, 2006a, 2008) we observed that dropout dolines and suffosion dolines develop if the outer sedimentary thickness is less than 3.5 metres.

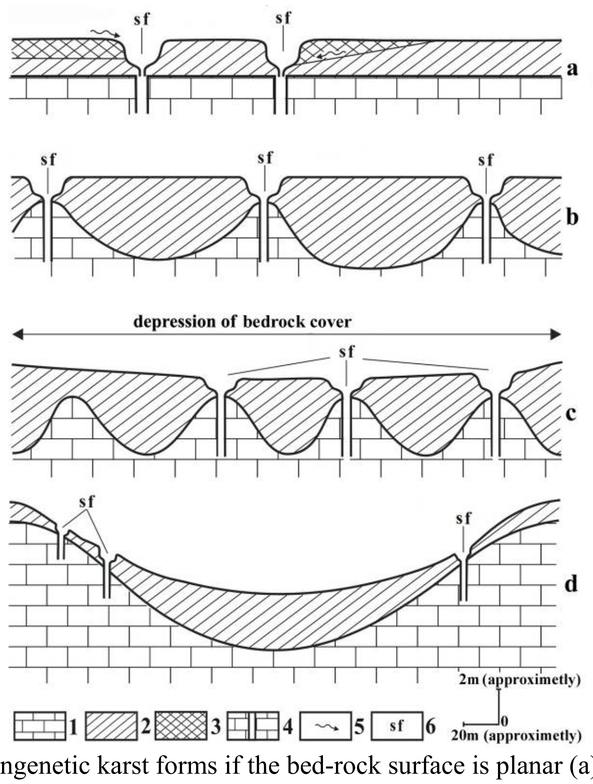

Figure 1. Development of syngenetic karst forms if the bed-rock surface is planar (a) and if it is dissected (b, c, d)

Legend: 1. limestone, 2. cover deposits, 3. mud, 4. shaft, 5. water inflow, 6. syngenetic doline.

Dropout dolines and suffosion dolines develop in the following way. A blind shaft (void without opening) develops in the bedrock and later caves-in (Veress, 2000, 2009); this in turn induces caving-in of any superficial cover materials. The shaft and the depression are effectively of the same age (syngenetic karstification). Embryonic conduits develop in the superficial cover if its thickness is between 3.5-6 metres or if it is very thick (more than 6 metres). The cause of such embryonic void development can be the local increase of the porosity of the superficial cover (Figure 3), which is triggered by dissolution in the underlying bedrock (Veress, 2009). In general superficial deposits contain various amount of clay; if the clay content is high then the superficial cover is drawn towards points where dissolution of the karstic rock allows downward drainage to focus.

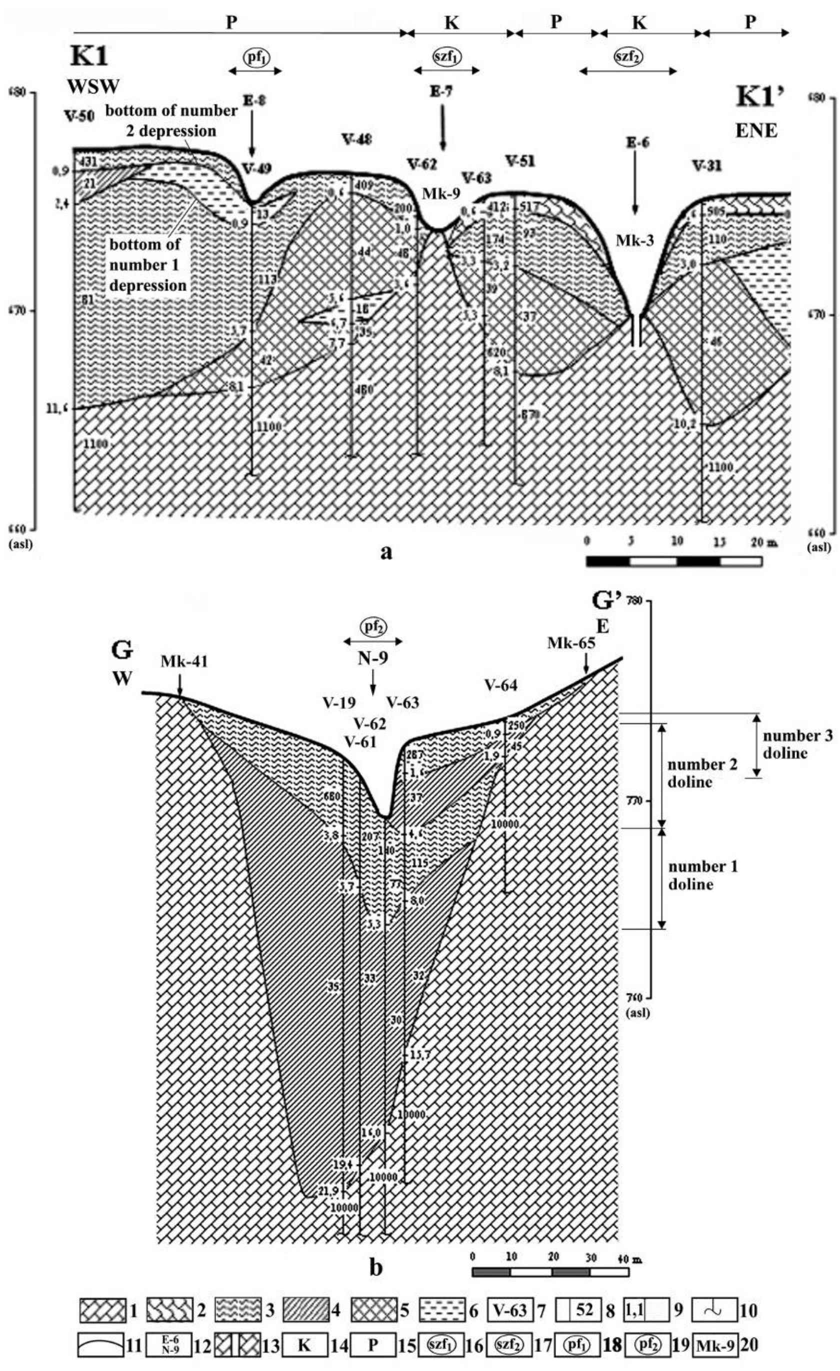

Figure 2. Lenticular intercalation structure from the Bakony Mountains (a), and from Nagy Mező (geoelectrical-geological profile shown in Figure 7) in the Bükk Mountains (b)

Legend: 1. limestone, 2. limestone detritus, 3. limestone detritus (with clay), 4. loess (with clay-mud), or clay with limestone detritus, 5. clay (with loess and limestone detritus), 6. clay, 7. number of VES measurements, 8.

the geoelectrical resistivity of the beds (in Ohms), 9. depth of the base of the geoelectrical beds (m), 10. the approximate penetration of the VES measurement, 11. the margin of the geoelectrical beds, 12. the extent of the doline, 13. shaft, 14. elevation on the bedrock, 15. palaeokarst depression on the bedrock, 16. syngenetic doline, which developed above an elevation of the bedrock (external cover deposits are thin), 17. syngenetic doline, which developed above an elevation of the bedrock (external cover deposits are of medium thickness, internal cover deposits are thin, because sediment from the base of the doline was transported into the karst), 18. postgenetic doline developed above a palaeokarst depression, the thickness of the internal cover is great (because it developed in the sediment that filled a palaeokarst form in the bedrock), 19. postgenetic doline, which developed above a former sinkhole, 20. rock outcrop.

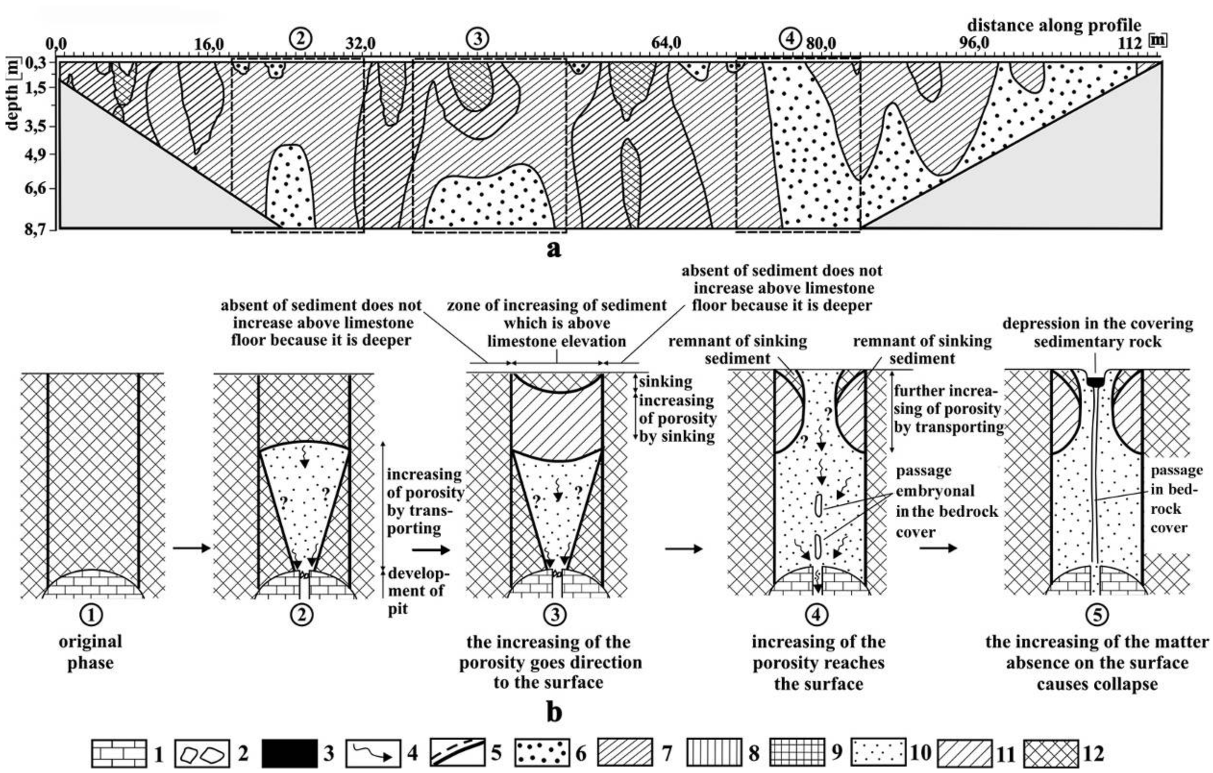

Figure 3. Phases of passage development in the cover deposits (Veress, 2009)

Legend: 1. limestone, 2. breakdown that consists of limestone, 3. breakdown that consists of cover material, 4. water infiltration and suffosion in the sedimentary cover, 5. boundary of cover deposits with different porosity; a. measured specific resistivity: 6. 1-5 Ωm, 7. 5-50 Ωm, 8. 50-120 Ωm, 9. 120-400 Ωm, b. theoretical porosity derived by using specific conductivity: 10. porosity of the cover material is high, 11. Porosity of the cover material is medium, 12. porosity of the cover material is low; subfigures 2, 3, 4 were constructed using parts of figure (a) indicated with broken lines.

Karstification in the bedrock is generally more moderate if the cover thickness is greater. We investigated dropout dolines and suffosion dolines in the Bakony Mountains (Hungary). Out of 21 syngenetic dolines investigated, in 33% the outer cover thickness was less than 3.5 metres, in 48% it was between 3.5 and 6 metres, and it was more than 6 metres in only 19% of the cases. Therefore, we concluded that the likelihood of syngenetic karstification decreases with increasing cover thickness.

In the case of thick sediment cover, the development of dropout dolines and suffosion dolines is aided by the presence of an older shaft in the bedrock if this shaft is deprived of any contained sediments (postgenetic karstification). If any sediment originally in the shaft is transported into deeper caves in the karst, whether through caving-in or carried by percolating water, then the shaft in the bedrock is older than the voids in the cover or the depression on the surface. Out of 16 postgenetic dropout dolines (dolines formed during postgenetic karstification) and suffosion dolines investigated in the Bakony Mountains, the outer sedimentary thickness was more than 6 metres in 56% of cases, between 3.5 and 6.0 metres in 37% of cases and less than 3.5 metres in 6%

of cases. The structure of the cover material indicates whether or not a depression is a postgenetic doline. Lenticular intercalations are fills of former depressions. Within the cover multiple lenticular intercalations can occur on top of each other (Figure 2b). A new lenticular intercalation develops if, due to alluviation, a higher surface is created and a new covered karst form that is subsequently filled in develops on this new surface. If a new karst form develops in the newly created covered karst feature, then the upper surface of this lenticular intercalation will be arched.

In the case of syngenetic karstification, shafts develop gradually in the bedrock; therefore the material deficit builds up relatively slowly. During postgenetic karstification a shaft that developed earlier in the bedrock quickly loses its infilling sediment, thereby facilitating the creation of a material deficit in the cover rocks. Consequently, in situations with similar sediment properties and thicknesses, postgenetic forms evolve more rapidly than syngenetic forms. Most postgenetic forms develop by collapse related to their relatively rapid development (dropout dolines).

Depressions of the superficial cover develop where sediment is transported into voids and caves in the underlying karst through dropout dolines and suffosion dolines (Veress, 2009). Because the sediment is not transported on the surface a closed feature develops within the cover sediments.

4. Methods

Investigations were carried out on covered and partly covered karst areas in Hungary (the Bakony Mountains, Mecsek Mountains, Bükk Mountains and Aggtelek Mountains; Figure 4) and in Romania (Padis Plateau). Additional observations were made in other relatively low mountains (Padis, Romania), in high mountains (Dachstein, Totes Gebirge, Julian Alps, Durmitor Mountain) and in poljes (Cerkniško Polje), as well as in the intermontane plains of tropical karsts (South China).

Karsts can be investigated by applying various geophysical surveys such as seismic, electrical resistivity, ground penetrating radar (Hoover, 2003), electromagnetic, and gravity methods. We constructed detailed topographical maps of the study areas; we measured the depth to the bedrock and the thickness of the materials (cover) above the karstic beds at different places using vertical electrical sounding (VES). The theoretical background of the widely used method is described in the speciality literature (Loke, 2010), especially an application can be found in Pethő & Vass article (2012). The method for our acreage has been described in details in the following article Veress, 2009. We also provided detailed lithological descriptions of the beds comprising the cover.

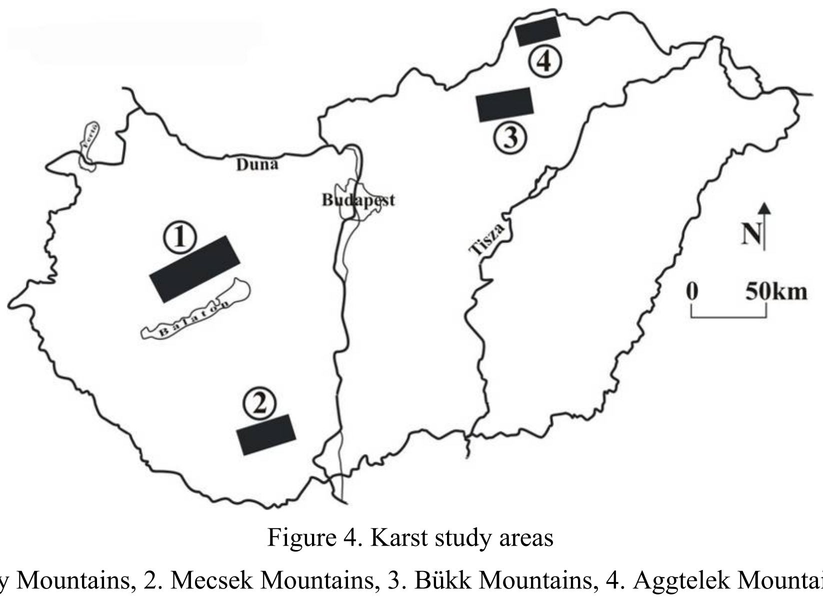

Figure 4. Karst study areas

Legend: 1. Bakony Mountains, 2. Mecsek Mountains, 3. Bükk Mountains, 4. Aggtelek Mountains

Table 1. The specific resistivity of various rock types

The name of the rock	Specific resistivity (Ohm m)
Bentonite	1-8
Clay	5-20
sand (wet-dry)	50-1000
gravel (wet-dry)	100-10000
limestone-dolomite (crumbly-compact-dry)	200-500-10000

VES measurements are done by passing electric current into the rock through two grounded (zero potential) electrodes. Another two electrodes are used to measure the electric potential created by the current dispersion. We can calculate the apparent resistivity of the rocks if we know the current (I) and the voltage (V) at given distances between the two grounded electrodes. Resistivity is the direct current resistivity measured over the unit length of a conductor with unit cross section. Resistivity depends on the structure of the material and it is independent of its geometry. The inverse of the apparent resistivity is the apparent conductivity. Because the dispersion of the current depends on the resistivity and the thickness of the beds, as well as the type of the rock, measuring the electric potential provides information about the geological structure of the survey area (Table 1). The sound curves present the results of our measurements; they show how resistivity changes with increasing 'research' depth (distance between the two grounded electrodes). There are several methods to evaluate sound curves. The fundamental idea of the analytical method is to calculate thousands of theoretical curves using potential theory on various rock types, and to choose the ones that best agree with the measured curves. From the theoretical results we determine the resistivity (ρ) and the thickness (h) of the beds.

It is well-known that the resistivity of various sedimentary rocks (for example clay, mud, sand, limestone, and dolomite) depends primarily on their water content, and the concentration of ions within the water. In the case of non-indurated rocks (e.g. clay mud, sand) the resistivity depends on the pore space and the specific area of the grains in addition to the above mentioned factors. In the case of indurated rocks (e.g. limestone) there is a strong correlation between the resistivity and the degree of fracturing of the rock, as well as the properties of materials filling any cavities in the rock. However, the exact form of the relationships changes between different areas.

We constructed the profiles (geoelectrical-geological cross-sections, Figure 2) by interpolating the results obtained for the beds at the individual measurement sites. The profiles show the surface with covered karst depressions, the bedrock, the boundaries of the beds, the cover rocks, the structure of the cover and the computed resistivity of the various rock types. A more complete and exact profile of the surface of the bedrock can be reconstructed where the limestone crops out. Using elevation data, a topographical map of the bedrock can be constructed.

We applied a multi-electrode measuring technique in one of the study areas of the Bakony Mountains. Based on these results we can present the variations in the resistivity of the cover deposits continuously from the surface to a few metres depth. Changes in the porosity of the superficial cover can be deduced from the resistivity variations, because these changes are related to the water content of the voids. Porosity is represented along a section in Figure 3.

5. Description of the Hungarian Research Areas

In the investigated areas the limestone is covered by unconsolidated superficial cover.

The Bakony Mountain range is part of the Transdanubian Mountains. Its area is 2400 km^2, its height is between 200 and 700 metres. The mountain range is built mainly from Triassic Dachstein limestone, but Triassic dolomite, Jurassic limestone, Cretaceous limestone and Eocene limestone also occur. The range is made up of horsts of various altitudes. The surfaces of the horsts are remnants of the Late Cretaceous peneplain, and they are covered by a gravel blanket (cryptokarst) or loess (concealed karst).

The height of the Mecsek Mountain range is between 250 and 680 metres; its area is 350 km^2, and it comprises Mesozoic rocks. Its structure is folded and the range as a whole is divided into horsts; its peneplains are at different altitudes. The western part of the Northern Mecsek range is karstified (concealed karst); its surface is covered with clay, loess and sand.

The area of the Bükk Mountain range (or Central Bükk) is 550 km^2; its height is between 275 and 959 metres. The range is built mainly of Ordovician, Devonian, Carboniferous and Permian clay shales, sandstones, limestones (Upponyi Mountain), Triassic limestone (Bükk Plateau) and Jurassic limestone (Southern Bükk). Some parts of the range are folded (Upponyi Mountain), some have a nappe structure, other parts display an imbricate structure that is related to reverse faulting (Pelikán, 2002).

Some of the dolines, uvalas (the uniting of several adjacent dolines produces the more complex uvala) and former blind valleys are accrued or covered with loess, loess with clay, red clay, aleurit with clay-sand (Jámbor, 1959; Pelikán, 1992), with in situ or reworked and transported weathering residue. These surfaces represent the concealed karst of the mountain.

The area of the Aggtelek Mountain range is about 185 km^2; its height is between 150 and 600 metres. The Triassic rocks of the mountains have been deformed to produce a nappe system. Folds of the Szilice nappe have developed into secondary nappes (Less, 1998). Karst plateaus within the mountain range are the synclinal areas of the secondary nappes (Less, 1998). The southern part of the mountain range became covered in the Upper Miocene sediments (Sásdi, 1990). This area includes cryptokarst. Permeable sediments are found in the solution dolines and dry valleys. These surfaces represent the concealed karsts of the mountain range.

The Padis Plateau has an extension of 24 km^2, with 1100-1300m elevation highs. It is built up mostly by Triassic limestone and marginally by sandstones. The plateau has an upper and a lower level (Veress, 1992). The upper lever is characterised by 50-100m relative elevation differences. The lower level is also divided in several minor parts, embraced by the higher, elevated parts. The lower surfaces of the paleokarsts were covered by sandstone debris from the marginal sandstones (Magura-Albastra). The covered karsts of Padis Plateau were generated on these covered surfaces by young sediments over the sandstone debris.

6. Discussion

6.1 Development of Karst Forms under Thin Sediment

Sediment deposits are locally thin if relatively small amounts of material are distributed across an uneven bedrock surface (Figure 1). They can also be thin if an originally thicker cover is locally partly denuded. In both cases the sediment thickness tends to be least above the more upstanding parts of the bedrock surface. Higher parts of the limestone may rise as ridges or mounds, some of which might be remnant landforms from earlier karstification. Covered karst formation is not favoured if the thickness of the sedimentary cover is small and the upper surface of the limestone is flat and unbroken. In this case there is a greater chance that water percolating through the cover deposits will dissolve the limestone relatively uniformly across its upper surface.

The thinning of the cover can happen in two different ways: denudation of the sediment across the land surface or by sediment transport into the karst through open voids and passages. Naturally, both processes can operate at the same time. Sediment transport on the surface provides the conditions that could allow covered karst formation on the side slopes of older dolines in high mountains, because the superficial deposits on the side slopes can become thinner as a result of rainwater sheet wash. Stream erosion might affect intermittently or constantly wet poljes and areas of intermountain plain within low mountain karsts. Covered karsts may form on valley floors and in the beds of intermittent watercourses. Karstification occurs mostly over valley floors where the bedrock includes mounds (Figure 5).

We can distinguish the following types of covered karst formation in the case of thin superficial cover:

● In the case of smooth rockhead with shafts covered karstification may occur beneath thin deposits at the boundaries of the impermeable cover (Figure 1a) or where shafts in the bedrock have developed earlier. The karstification is syngenetic in the first case, but postgenetic in the second. Covered karst formation of this type can occur in poljes and intermountain plains.

● Uneven bedrock surface and thin cover. It is possible that shafts developed under an older cover of superficial deposits on the karst. Later the superficial material was denuded and a new cover accumulated, in which dolines developed. In such cases former sedimentary fill of the shafts and passages is indicated by the presence of forms such as ceiling channels or pendants (indicating paragenetic conduit growth). These forms develop when the sediment from the older superficial deposits are transported into cave passages, thereby pushing up the water level to the passage ceilings (Bretz, 1956; Renault, 1968; Slabe, 1995). Therefore, regardless of a thin superficial cover, postgenetic karstification is possible in the case of dolines where shafts and passages show the above-mentioned diagnostic paragenetic features.

● If the average distance between neighbouring covered mounds is great then the average distance between neighbouring dolines is equally great (Figure 1b) and the density of the dolines is low. Such dolines are syngenetic and they occur on the surfaces of low mountains where the sedimentary cover is thin, in dry poljes, in fengcong or peak cluster type karst (e.g. as ‘cockpit’ dolines).

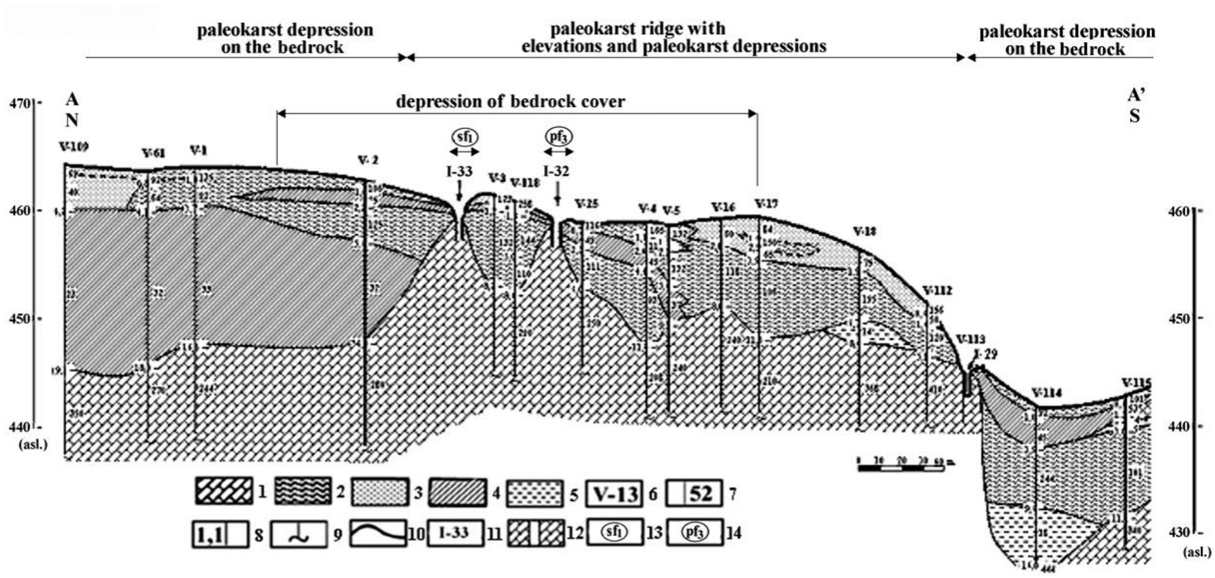

Figure 5. Dolines, with breakdown sediment structure (along geoelectrical-geological profile marked A-A' from the foot of the Tábla Valley in the Bakony Mountains)

Legend: 1. limestone, 2. limestone detritus (with clay), 3. loess (with sand or with limestone detritus), 4. loess (with clay-mud), or clay with limestone detritus, 5. clay, 6. number and site of VES measurements, 7. the geoelectrical resistivity of the beds (Ohm), 8. depth of the base of the geoelectrical beds (m), 9. the approximate penetration of the VES measurement, 10. the margin of the geoelectrical beds, 11. the extent of the doline, 12. shaft, 13. syngenetic doline, which developed above an elevation of the bedrock surface (the thickness of the external cover deposits is small), 14. postgenetic doline, which developed above an elevation of the bedrock surface (the thickness of the external cover deposits is small); there are forms that developed when the shaft was filled, suggesting that it was created by postgenetic karstification.

● If the average distance between neighbouring covered mounds is small then the average distance between neighbouring dolines is equally small. In such cases a depression may develop in the cover deposits. This happens because large quantities of the unconsolidated sediment may be transported into the dolines or through them into the karst and, as a result, a depression is formed in the overlying deposits (Figure 1c, 5).

● It can happen that the fill within an older karst depression is transported into the karst. Dolines develop where the unconsolidated superficial deposit becomes sufficiently thin. Such dropout dolines and suffosion dolines occur, for example, on the Padis and probably along the floors of some constantly wet poljes in the Dinaric Mountains (e.g. Cerkniško Polje). But they can also develop in the cover of palaeo-dolines in high mountain environments (Figure 1d).

● It can also happen that older dolines (such as solution dolines) are lined or filled in by (impermeable) superficial deposits. In both cases karst forms develop along the margins of the impermeable beds.

6.2 Development of Karst Forms under Increasing Sediment Thickness

Dolines mostly develop during postgenetic karstification if the cover is thick (i.e. greater than 6 metres).

Cover deposits can increase their thickness over even or uneven bedrock. Postgenetic dolines develop above the shafts or passages which developed during older karstification. Due to sedimentation dolines can fill up and if the process continues they can get buried. In the now thick unconsolidated superficial cover over the buried older doline a new doline can form, which in turn can get filled up and buried as well. This process results in a structure where younger dolines are stacked up above older dolines.

If the bedrock has many mounds, then sedimentation is concentrated between the mounds. Syngenetic dolines develop between the mounds during the first stage of the infilling process as the cover thickens due to deposition processes. Postgenetic karstification replaces the syngenetic process between the mounds, while syngenetic karstification continues over the mounds.

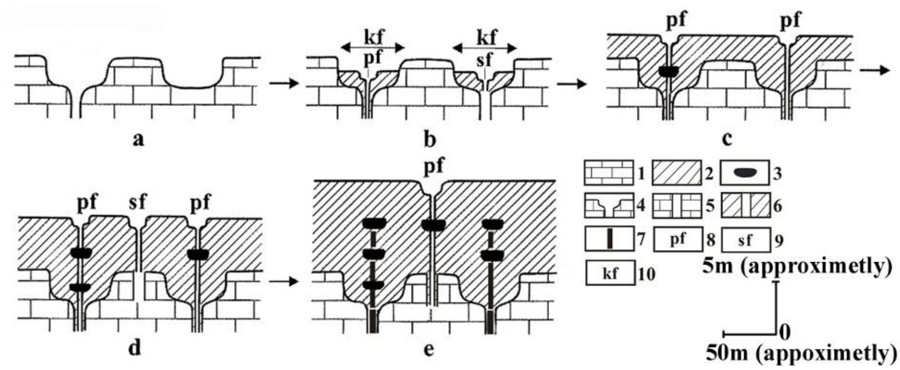

Figure 6. Covered karstification during alluviation above a limestone area that is dissected by depressions

Legend: 1. limestone, 2. cover deposits, 3. lenticular sediment structure, 4. depression (for example a doline) on the limestone, 5. shaft, 6. passage, 7. infilling of the shaft and passage, 8. postgenetic doline, 9. syngenetic dolines, 10. uncovered depression that is partly filled, a. depressions develop on the uncovered karst, which may have or may not have shafts, b. postgenetic or syngenetic covered depressions develop in the partly filled doline, c. the depressions (dolines) are filled and covered, postgenetic karstification occurs above the depression, d. the cover material thickens, new postgenetic covered karstification takes place above the depressions, syngenetic karstification happens above the ridges between the depressions, e. the cover thickens to such a degree that covered karstification does not happen above the depression, postgenetic karstification follows the syngenetic karstification above the ridges.

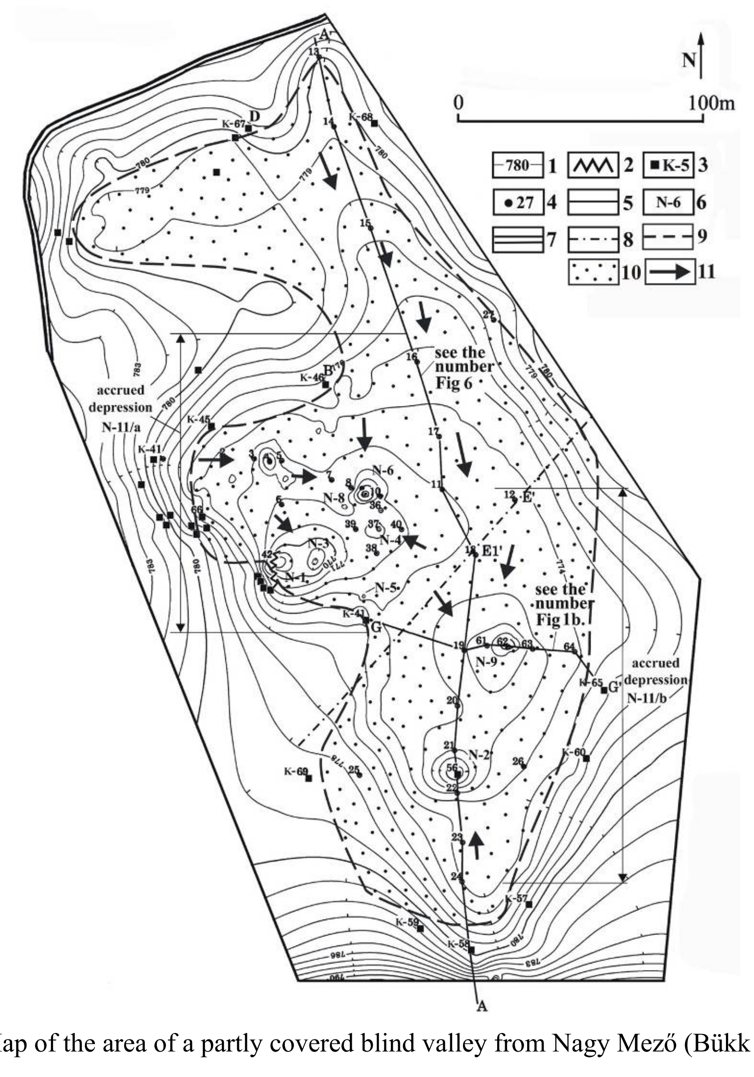

Figure 7. Map of the area of a partly covered blind valley from Nagy Mező (Bükk Mountains)

Legend: 1. contour line, 2. rock wall, 3. limestone outcrop and its number, 4. the number and the location of the VES measurements, 5. the line of profile, 6. extent of karst form, 7. road, 8. fence, 9. boundary of cover deposits, 10. cover deposits, 11. water flow.

The location and the characteristics of the covered karstification may change if the thickness of the cover deposits increases where depressions are present in the bedrock. First the depressions are partly filled (Figures 6b, 7, 8); such surfaces develop during accumulation and their shapes are adjusted to the accumulating karst forms (Figure 7, 8). Postgenetic karst forms emerge on surfaces with previously developed shafts (former sinkholes) in the depressions. They receive water from the accumulating surfaces. Covered karst formation of this type occurs in the Bükk Mountains (Figure 2b, 7) and in the Apuseni Mountains.

Syngenetic karstification can take place over the ridges and mounds if alluviation is ongoing (Figure 8) and postgenetic karstification progresses over the depression fill (Figure 2b, 6d). If accumulation continues further the thickness of the cover increases and postgenetic karstification effects are also observed above the higher parts of the bedrock (Figure 6e). We can cite examples from the Bakony Mountains. The thickness of the cover deposits is probably so great in these depressions that even postgenetic dolines cannot develop. Our observations indicate that covered karst formation does not happen if the superficial cover is clay or contains clay and its thickness is about 10 metres. Dolines do not occur if the thickness of the sedimentary cover is more than 20 metres, even if the cover material is permeable (Figure 5, area between the sites marked V-61 and V-2). Finally, the thickness of the cover can be so great that postgenetic karstification cannot proceed even on the ridges. Such surfaces occur in intermountain plains, but also in some parts of the Bakony Mountains.

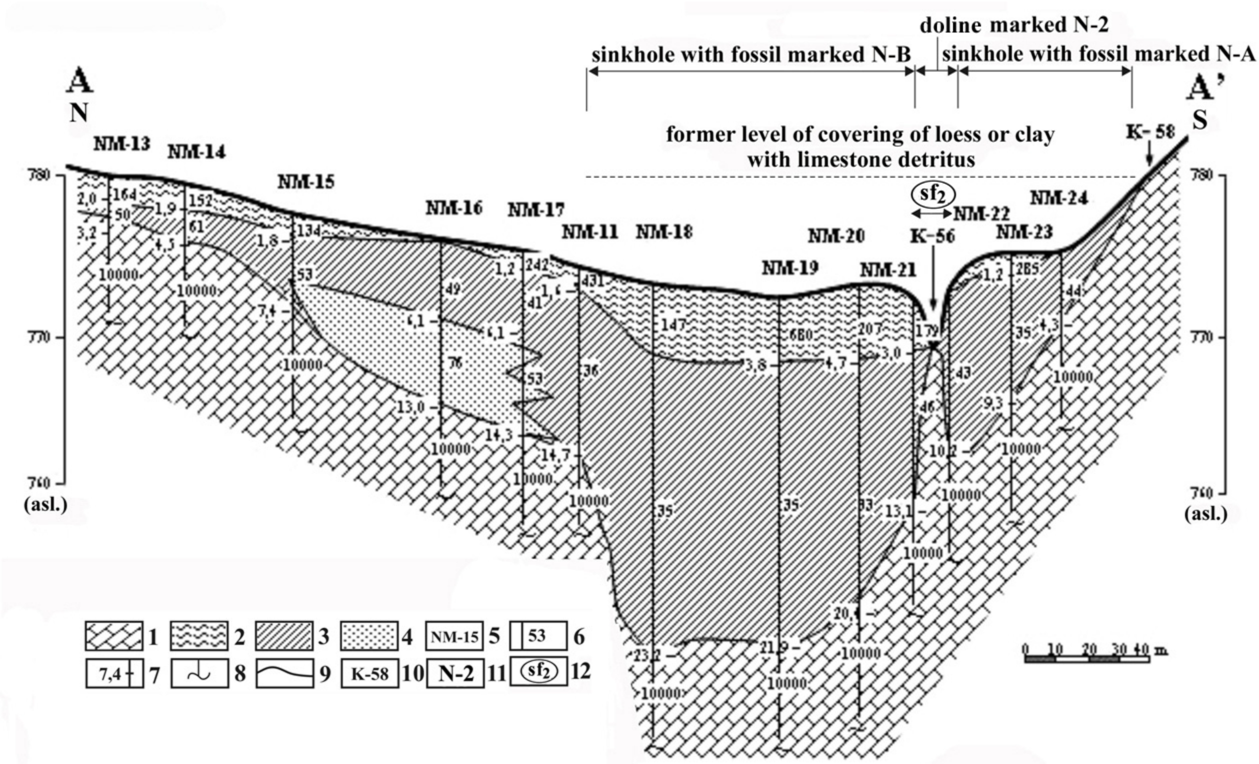

Figure 8. The geoelectrical-geological profile marked A-A' from the Bükk Mountains (Nagy Mező)

Legend: 1. limestone, 2. limestone detritus (with clay), 3. loess (with clay-mud) or clay with limestone detritus, 4. loess (with sand or with limestone detritus), 5. number and the location of VES measurements, 6. geoelectrical resistivity of the beds (Ohm), 7. depth of the base of the geoelectrical beds (m), 8. the approximate penetration of the VES measurement, 9. margin of the geoelectrical beds, 10. outcrop of the limestone and its number, 11. the extent of a doline, 12. syngenetic doline that developed above an elevation of the bedrock surface (the thickness of the exterior sedimentary rock cover is medium).

The depressions in the superficial cover can initially be filled in and then, after the sediment is transported into the karst, in a few thousand years they can reappear. Depressions in the bedrock are filled in if more sediment is transported from the surrounding environment into the depression than from the depression into the karst. But if less new sediment arrives than is being transported into the karst, depression modification is renewed through postgenetic karstification. Such karstification can happen if the cover deposit thickness is great in the area surrounding the depression. Such covered karst formation may take place in low mountains with thick bedrock cover (e.g. the Bakony Mountains, Aggtelek Karst), in intermittently wet poljes, in permanently wet poljes and in intermountain plains.

6.3 Recognition of Syngenetic and Postgenetic Karstification

The main characteristics of syngenetic karstification are as follows:

● Dolines (dropout dolines, and suffosion dolines) occur mostly along the floors of eroding channels, dry valleys and depressions within the superficial cover.

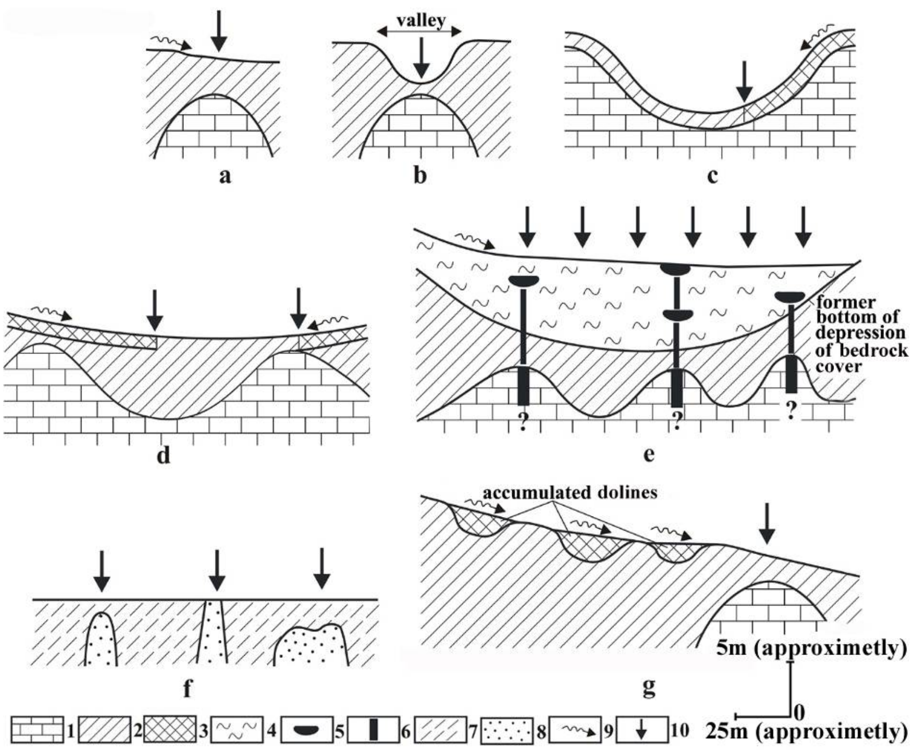

Figure 9. Areas susceptible to covered karstification

Legend: 1. limestone, 2. cover deposits in general, 3. clay, 4. filling of the depression in the cover deposits, 5. lenticular sediment structure, 6. filling of the shafts and passages, 7. zone of cover deposits with low porosity, 8. zone of cover deposits with high porosity in which a passage developed, 9. flow of water on the surface, 10. area susceptible to covered karstification: where the accumulation is small above the elevation of the bedrock surface (a), local denudation happens (b), at the margins of the impermeable beds (c, d), in a filled depression, where there are many shafts and passages (e), above places with high porosity (f) or near such places, where there are many depressions that are filled with impermeable sediments on the surface (g).

● These karst forms occur above the high points of the bedrock surface where the cover is locally thinner (Figures 2a, 5, 9a-b), as well as along the edges of adjacent impermeable beds (Figures 9c-d). Above the high points of the bedrock surface dolines will form. Through the dolines the unconsolidated cover material gets transported into the karst causing material deficit, which results in the formation of a large scale depression of the unconsolidated superficial cover.

● The lack of lenticular sediment structure in the cover deposits beneath these surface forms indicates that there were no previously developed dolines.

Postgenetic karstification is indicated by the following factors:

● Dolines (dropout dolines and suffosion dolines) occur on surfaces where the thickness of the overlying sediment is increasing (in accumulating valleys, older accumulating karst depressions and intermontane plains).

● Where a buried doline or a filled solution doline occurs on the covered karst.

● Syngenetic suffosion dolines cannot form in thick covers, thus dolines formed in thick covers are postgenetic dolines.

● Forms develop in lenticular intercalations of which upper surface is curved, or places where there are lenticular intercalations above each other under the karst forms.

● Smaller lenticular beds can also occur within larger sized thin lenticular beds. The thin lenticular bed indicates that an earlier depression was filled up. Smaller lenticular intercalations wedging out indicate that dolines developed in former depressions within the superficial cover (Figure 9e).

● Forms within the shafts and voids beneath dolines indicate that the features were previously filled with sediment.

6.4 Predicting Karstification

Dolines may develop at any time on potential sites of karstification. Constructions created on potential sites of karstification will potentially be damaged; therefore, identifying such sites is extremely important. Predicting karstification can be done using quantitative or qualitative analysis. Predicting qualitative features of karstification one can draw conclusions about the type of the covered karst feature (its characteristics) and the number of the forms that might appear. During this analysis the nature of cover deposits and the morphology of the bedrock are determined. Knowing the composition of the cover we can predict the type of doline that will develop. Dropout dolines develop in the cover if it is indurated (Figure 10.Ia). During postgenetic karstification the probability of dropout doline development is greater (Figure 10.Ib, see above). If the cover is thicker and non-indurated, then suffosion dolines develop (Figure 10.II). Knowing the morphology of the bedrock we can predict approximately how many dolines per unit area will develop in the near future. If the number of bedrock mounds per unit area is great, than the number of the dolines per unit area will also be great, and this will aid the development of depressions within the cover (Figure 10.III). Covered karstification is also influenced by the type of materials making up the bedrock. So if the bedrock is gypsum or salt, there is a greater probability that dropout dolines will develop in the cover (Figure 10.IV).

During quantitative analysis of karstification we make predictions about the type, the size and the location of the dolines. The data necessary for quantitative analysis may come from borehole or geophysical measurements. If cover deposits are thin or if shafts in the bedrock are greater in number than in the case of postgenetic karstification it is probable that dropout dolines will develop (Figure 10.Ib-c). If the cover thickness is greater or if the size of the shafts and passages is greater, then dolines developing in the cover deposits will also be bigger (Figure 10.Ib).

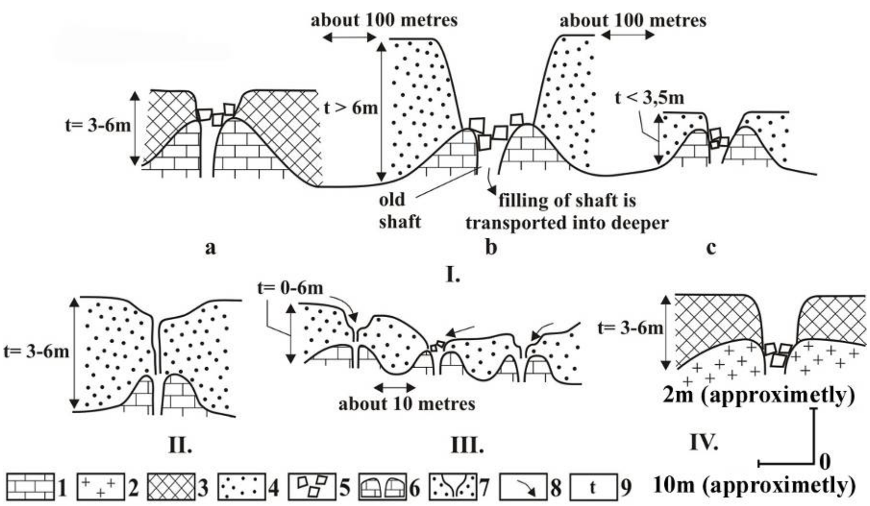

Figure 10. Predicting the characteristics of karstification based on the factors influencing covered karstification

I. dropout dolines develop if the cover deposits are indurated and relatively thick (the thickness is between 3-6 metres, a), if the diameter of the shaft is large, and the thickness of the cover is greater than 6 metres, b), if the cover is thin (it is thinner than 3.5 metres, c), II. suffosion doline develops if the cover is non-indurated, and it is thicker (between 3.5-6 metres, III. depression develops in the cover if the distance between mounds on the bedrock surface is small, IV. mainly dropout dolines develop if the bedrock is gypsum or salt.

Legend: 1. limestone, 2. gypsum, salt 3. indurated cover deposits, 4. non-indurated cover deposits, 5. collapse of the cover, 6. shaft, 7. passage, 8. sediment transport, 9. the thickness of the cover.

We can predict future sites of doline development if we can identify potential sites of karstification. The following characteristics indicate potential sites of karstification: thinning of the cover deposits (Figure 9a-b), points in the cover where the porosity exceeds the porosity in the surrounding environment (Figure 9f, Veress 2009), shafts and cave passages in the bedrock (Figure 10.Ib), lenticular intercalations (Figure 9e) and sites at the edges of adjacent impermeable beds. Smaller diameters of lenticular intercalations indicate former dropout and suffosion dolines, larger diameters indicate former depressions in the cover deposits (Figure 9e). Covered karstification is aided by buried dolines, impeded drainage areas, valleys, gullies (if cover deposits are thin under their floors), older dolines that are filled with clay, because water flow starts from the clay patches (Figure 9g).

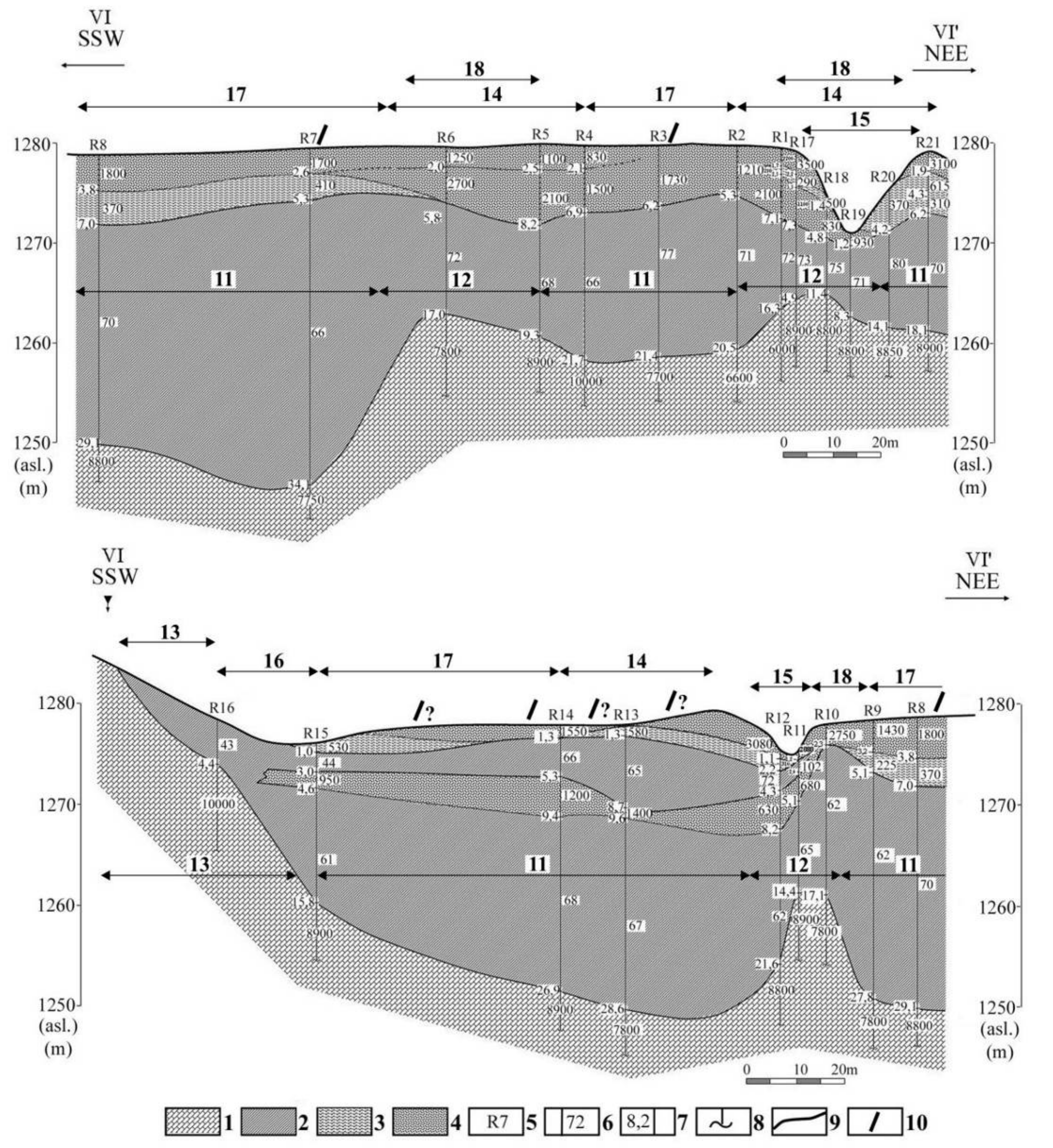

Figure 11. Geoelectrical-geological profile from Răchițele (Rekettyés) region, Padiş plateau, (Apuseni Mountain-Romania)

Legend: 1. limestone, 2. clay, argillaceous deposits, 3. clay with debris elements (the debris components are limestone and siliceous sandstone), 4. argillaceous debris (the debris components are limestone and siliceous sandstone), 5. location and number of the VES measurement, 6. apparent resistivity value of the package (Ohmm), 7. bottom depth of the geoelectrical sequence (m), 8. estimated penetration depth of the geoelectrical profile, 9. interpreted geoelectrical sequence limit, 10. position of a (i.e. road) structure (perpendicular on our profile), 11. the dolines fragment of an uvala, 12. ridges between the dolines fragments, 13. the slope of the high delimiting Răchițele-region, 14. buried suffosion paleodolines, 15. postgenetic suffosion dolines, 16. syngenetic suffosion dolines, 17. area free of possible karstic events, 18. area with possible karstic processes.

Indicating the above-mentioned factors on a local map we create a map of karstification potential for the area. Using such a map sites of constructions can be carefully planned; i.e. based on the geophysical measurements we marked the potential areas of covered and hidden karst processes on a depression of superficial deposits in a karstic area of Răchițele (Rekettyés) from Padis Plateou (Figure 11)

Based on the above mentioned we propose a posible structure (i.e. road) alignment on the Răchițele (Rekettyés) acrage (Figure 12).

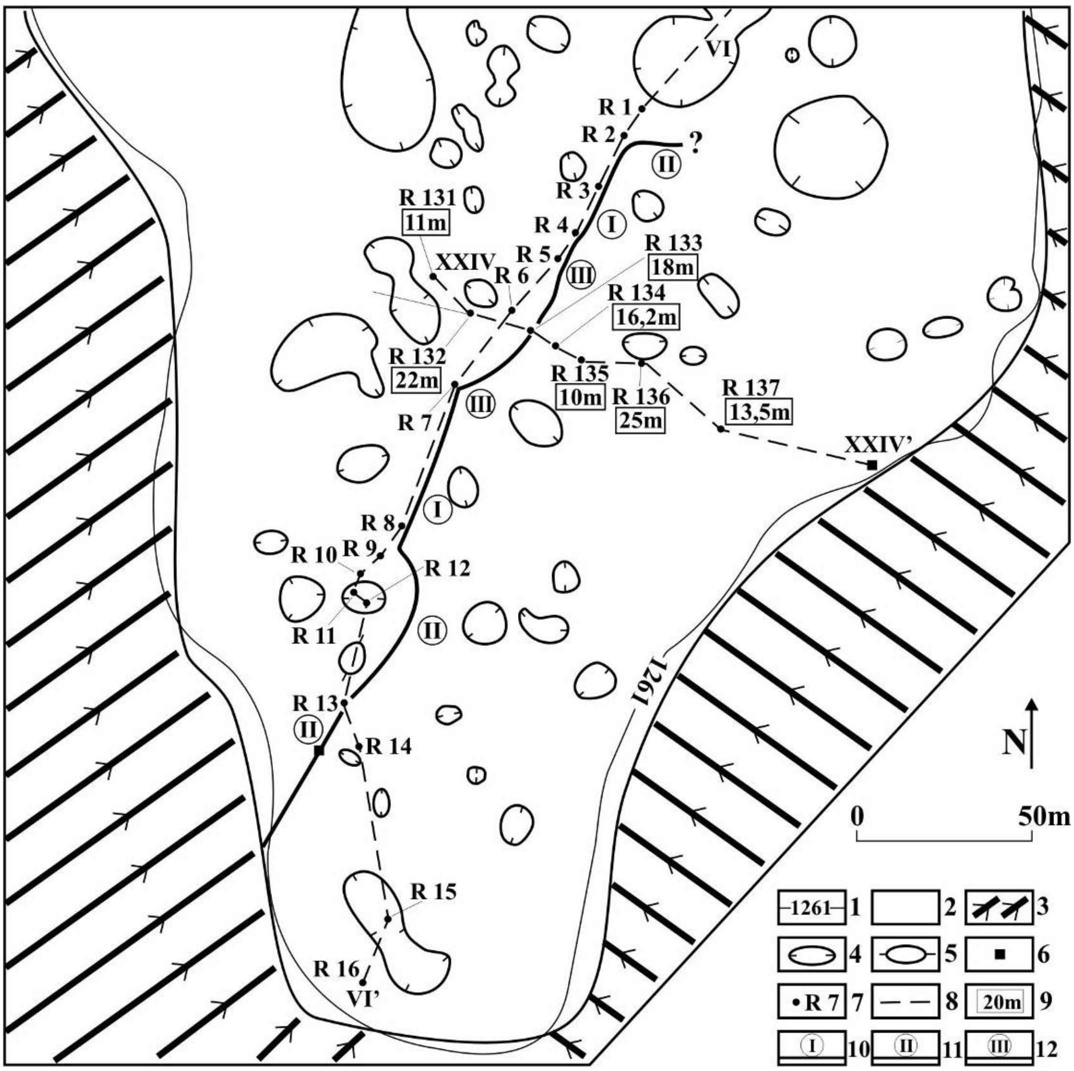

Figure 12. An eventually designed (i.e. road) structure position through Răchițele-region

Legend: 1. contour line, 2. bottom of the depression of superficial deposit, 3. the slope of the depression of superficial deposit, 4. dolines, 5. small mound, 6. limestone outcrop, 7. location and the number of the VES measurement, 8. location of the geoelectrical-geological profile, 9. the superficial deposit thickness along the measured profile, 10. the location of the structure along the profile regarding the superficial deposit thickness (see Figure 11), 11. the proposed position of the structure regarding the actual karstic features, 12. the proposed position of the structure regarding the interpreted results of the XXIV-XXIV' geoelectrical-geologicsal profile (this mentioned profile is not edited in this article).

Principles of construction site planning are demonstrated on an example karstification potential map (Figure 13).

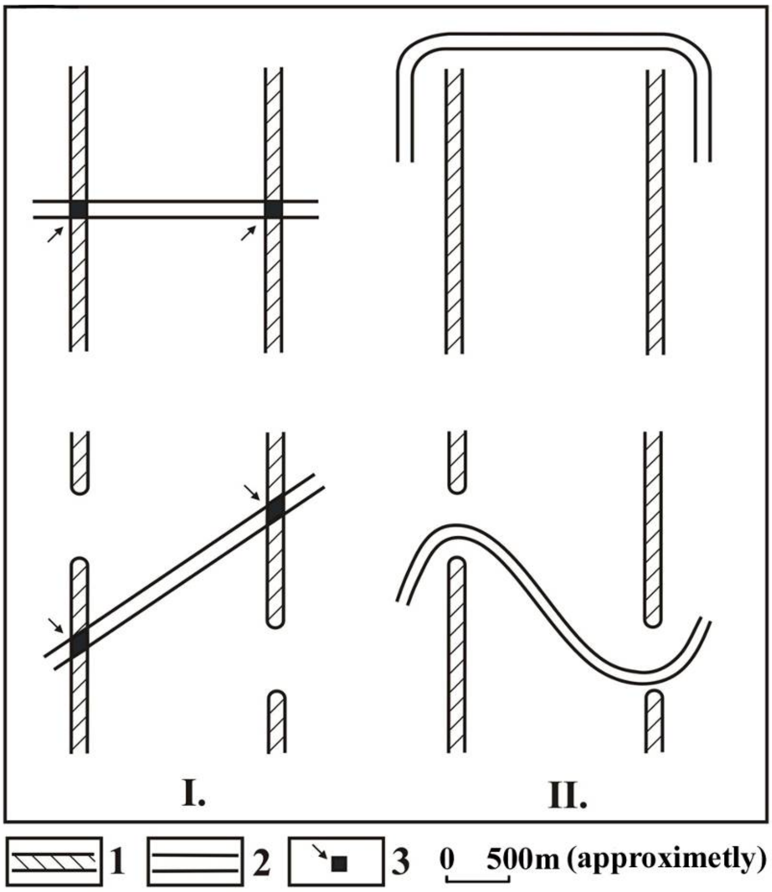

Figure 13. Planning of a road using the potential covered karstification map

Legend: 1. potential karstification zone, or karstification patch, 2. road, 3. the crossing where precautions against covered karstification are needed I. the inappropriate planning of a road, II. appropriate planning of a road.

Using such a map, the subsidence or collapse of the sedimentary cover and any resulting depression can be avoided to allow roads or railways to traverse the karstification zones safely. We can reduce the hazard of karstification if we identify these sites of potential karstification and if, for example, we restrict water inflow to such areas. The map must be more detailed if the planned density of man-made structures is high. The greater the covered karst area, the greater is the chance that construction will be affected. So in such areas the need for a map of karstification potential is great. In major karst areas the length of man-made structures can be considerable. Therefore, mapping sites of karstification potential in areas where poljes and intermountain plains are common is highly advisable. If in a karst area the density of man-made structures increases (e.g. in Asia where these covered karst areas are large and densely populated) then the creation of such a map is necessary, because the probability of accidents related to karstification also increases.

7. Conclusion

By investigating the bedrock and overlying beds in covered karst areas we can identify potential sites of karstification. Such sites are indicated by: the thinning of the cover deposits, sites where the porosity of the cover material is locally greater, lenticular intercalations within the cover, the edges of adjacent impermeable beds, clay patches on the surface, buried dolines, impeded drainage areas, valleys, gullies, shafts and cave passages in the bedrock. The probability of covered karstification in a given area is greater if several of the above-mentioned factors are locally present.

Covered karstification is not observed where the sedimentary cover is dominantly clay and its thickness is greater than 10 metres or if the cover is permeable (e.g. loess) and its thickness is greater than 20 metres.

The sites of potential covered karstification can be represented on a map (map of karstification potential). Lines of roads, railways, gas pipelines, etc. should be planned carefully in the light of knowledge of the potential zones of covered karstification.

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