

## INVESTIGATION OF DEPRESSION SYSTEMS ON A CARBONATE TERRAIN NEAR SOPRON, HUNGARY

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**Abstract:** Detailed geomorphological mapping on the carbonate terrain between Sopron and Lake Fertő found unusual, active depression systems. The landforms such as complex systems of nearly cylindrical structures, collapse dolinas and small caves remind to karstic forms. Near-surface geology was also reviewed in connection with these landforms and the detailed geological map of the area was compiled. The physical and geochemical properties of the near surface Badenian and Sarmathian Lajta limestone made the assumption of the karstic origin questionable. The main aim of this paper is to prove the origin and assess the future evolution of the landforms. In lack of evidences of karstic or non-karstic origin underground cavity (voids) and fracture systems – possibly connected to these landforms – were investigated on the basis of electromagnetic properties of the subsurface. The applied geoelectric and electromagnetic methods indicated the cavity but no connections were found with the fracture zones. According to the geoelectric tomography image of the test area the cavity is probably anthropogenic rather than natural in origin. Results of geophysical exploration were checked and evaluated by partial excavation of the subsurface formations and structure of the study site. Resolution power and proper scaling of different methods were also discussed. Finally, industrial archeology documents were taken into account. Number of medieval archeological records also supports the artificial origin assumption. Importance of holistic approach is emphasised in such complex cases.

**Keywords:** carbonate terrain, Lajta limestone, dolina, underground cavity, bedrock, geoelectric properties, GPR, resistivity sounding, industrial archeology, holistic approach

### 1. INTRODUCTION

Caves and karstic landforms have many natural values but at the same time both artificial (e.g. mine related) and natural (mainly karstic) underground cavity represent hazard source in a civil engineering (Parise & Gunn, 2005). Besides geological and geomorphological informations geophysical methods are widely used to locate and characterise karst zones and individual caves (e.g. McCann et al., 1987, Kruse et al., 2006, Radulescu et al., 2007).

The study area is located at the transition zone between the Alps and Carpathian basin. Structurally it is a foothill of the Eastern Alps where the crystalline rocks are covered by Badenian and Sarmathian limestone. The plateau-like carbonate terrain called Balf block is composed of Lajta limestone. The territory actually belongs to the World Heritage for its specially protected natural values as the flora of Szárhalmi forest and for such

historical memories as Fertőrákos quarry or Mithras cave. The Balf block (see Fig. 1) is a hardly dissected derasion-erosion hill between Lake Fertő and the Sopron basin.

Great number of landforms were found and analyzed during the detailed geomorphological mapping in 2007 (Prodán & Veress, 2007). The characteristic curved edge depressions are grouped in several depression systems. The origin of these landforms could not be clarified purely on the basis of the morphological features. Karstic, anthropogenic and mixed origin can be assumed; therefore relations between geological structure and the location of depression systems were searched for. Subsurface conditions were also investigated by different geophysical methods. Considering the physical properties of the limestone geoelectric, electromagnetic and geomagnetic methods were applied. In lack of final geological and geophysical evidences industrial archeology records were considered. Great number of historical documents

describe intense medieval quarrying and lime burning activity on the territory, which also makes the artificial origin more likely.

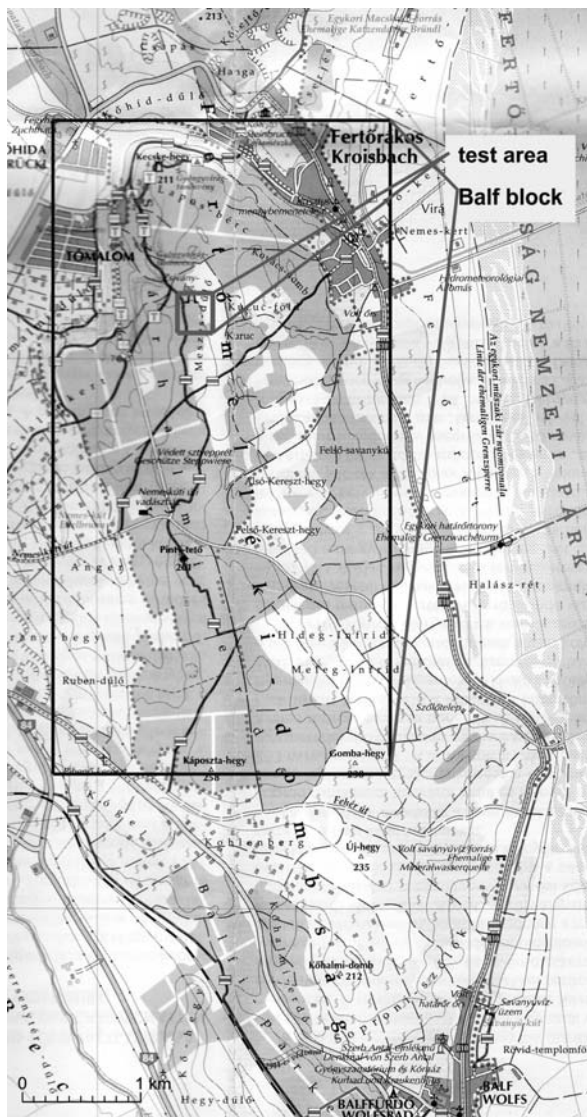


Figure 1. Map of the study site and its environs (based on Faragó, I., Szarvas, A., 2007. Environs of Sopron / Ödenburger Gebirge (1:40000). Szarvas András Cartographic Agency, www.map.hu).

Beyond the clarification of the origin and expected future development of morphological forms the further aim of this study is to provide methodological aspects for characterisation of landforms, detection of underground cavities and buried objects in similar environment.

## 2. GEOPHYSICAL METHODS APPLIED IN SUBSURFACE INVESTIGATIONS

Due to the topography, the geological structure (the high horizontal and vertical

segmentation of the rock physics parameters), the diverse positions and geometry of the karstic formations (sinkholes, cavities) the research of the karstic areas represents a real challenge for geophysics. Application of near-surface geophysical methods in exploration of buried subsurface objects and complex structures have been discussed by several authors but general recommendations are very rare and their effectiveness varies site by site. Very Low Frequency (VLF) electromagnetic method is generally used in primary exploration e.g. in detecting lateral changes of the resistivity along fracture zones. Geomagnetic mapping may also indicate lateral inhomogeneities. Ground Penetrating Radar (GPR) and multielectrode geoelectric methods play important role in imaging subsurface objects.

VLF electromagnetic method is based on large distance, low frequency (10-30 kHz) radiowave propagation. The ratio of the electric and magnetic field depends on the near-surface (upper 30 m) resistivity. VLF-EM version shows the resistivity distribution along the profile. The more comfortable VLF-Hz version detects sudden changes of underground resistivity. Such 2D lateral inhomogeneities (often caused by geological strikes) are sources of secondary electromagnetic field. In this version the linear relation between horizontal and vertical magnetic components is computed. The vertical component originates purely from secondary sources while horizontal component is composed from primary and secondary sources. Significant anomalies appear when crossing a conductive fracture zone, strike.

The GPR is a widely used efficient method to detect vertical changes of resistivity and dielectric constant near the surface. The high-frequency (50-500 MHz) electromagnetic wave generated on the surface penetrates into the soil and it is reflected from the surfaces where the dielectric constant changes. The depth of the penetration depends on the electric properties of the sediment and on the frequency. High conductivity cause high absorption but it may attain even 20 m in dry soil without clay on 100 MHz. The travel time of the reflected wave is measured on the surface. On the GPR profile horizontal and quasi-horizontal layering is generally easy to follow but the indication of 2D and 3D structures is much more complicated. Diffractions, multiple reflections occur depending on the electromagnetic properties and geometry of the object and on the wavelength applied.

The theory and methodology of geoelectrical methods are relatively simple. Each of them are based on the vertical and horizontal changes of subsurface resistivity.

# Geological map of Sopron-Fertő area

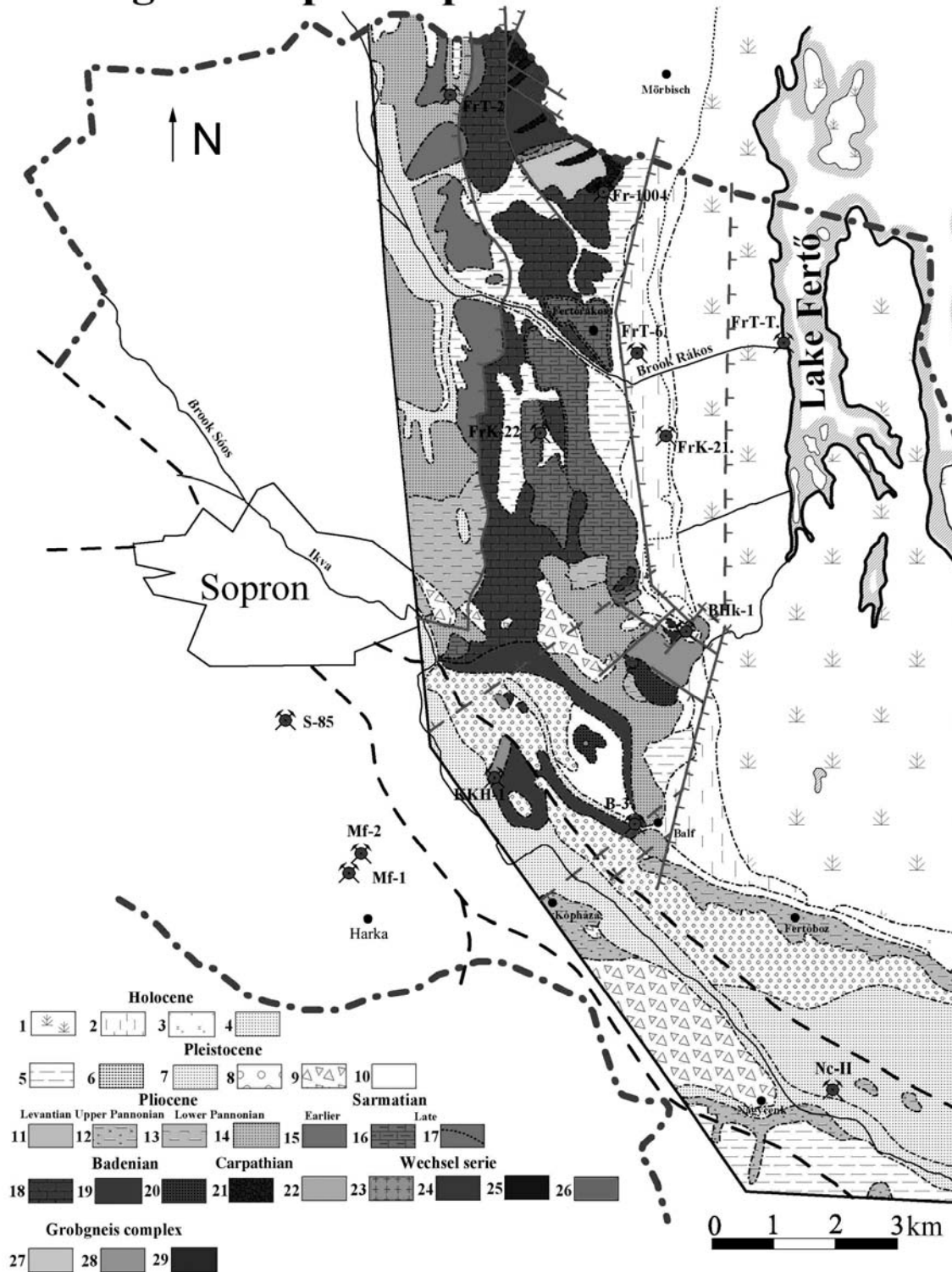


Figure 2. Geological map of the study site and its environs.

1. Reed 2. Muskeg, mull soil 3. Gravel, sand, silt 4. Holocene generally 5. Sandy loess 6. Fluvial gravel 7. Fluvial debris 8. Fluvial gravel (Fertőboz) 9. Terrace gravel 10. Pleistocene generally 11. Fluvial sand 12. Clay, marl, sand 13. Clay, sandy clay, ferrous clay 14. Sand and gravel with small amount conglomerate 15. Sand, sandstone, gravel, conglomerate 16. Limestone, sandy limestone 17. Conglomerate bedrock 18. Coarse limestone, lime-sand 19. Clay, silty clay 20. Conglomerate bedrock 21. Rust gravel 22. Mica-schist with phyllite 23. Muscovite gneiss 24. Feldspathic mica-schist 25. Amphibolite, amphibolite slate 26. Leuco-phyllite 27. Disthen-quarzit 28. Muscovite-biotite gneiss 29. Mica-schist

The response of the earth (surface potential difference) to quasi DC electric current is measured. In the simple conventional cases two current electrodes and two potential electrodes are applied in different colinear spatial arrangements. The investigation depth i.e. the thickness the current passes depends on the distance of current electrodes for Schlumberger and Wenner configurations. In case of dipole-dipole configuration the investigation depth depends on the offset of transmitter-receiver electrode pairs. Successively greater distance results in a series of apparent resistivities from which the vertical distribution of subsurface resistivity is obtained by different numerical inversions.

Geoelectric tomography techniques apply great number of electrodes in regular grid at the same time, which makes the measurement more effective and helps to minimize the external noise. The great number of electrodes and all available coupling between them provide high number of apparent resistivity data. Inversion techniques provide resistivity versus depth image of the subsurface. Besides the conventional applications (Kruse et al. 2006, El-Qady et al., 2005) special arrangements are known, e.g. from Szalai et al. (2002).

Geomagnetic methods detect the spatial variation of the Earth's magnetic field, better to say its scalar value. The local field is a superimposition of the main field and the local induced and remanent magnetisation. Reference measurement is applied to remove the time variation of the geomagnetic field. Scalar value or gradient is measured by high resolution Overhauser-effect proton magnetometer.

### 3. GEOLOGICAL STRUCTURE

The investigated area is structurally a foothill of the Eastern Alps, where the crystalline schists of the Sopron Mountains are overlaid with several hundred meters thick sediment. The older Paleozoic crystalline rocks appear on the surface only in a few places in this area. The Neogene sediment sequence is unconformable on the Paleozoic basement, so the Mesozoic and Paleogene formations are absent. The sedimentation started in the Miocene. At the beginning of the Badenian Lajta limestone was formed on the shallow coastal parts of the sea.

As a result of the regression between Badenian and Sarmathian the Badenian limestone is overlaid by sand and conglomerates. (This indicates that the nearshore facies became real littoral facies – the crystalline rock lifted a little.) During the next transgression in Sarmathian practically the earlier facies returned.

The carbonate terrain is strongly fragmented by faults and fractures. Presumably, a part of faults has many times renewed. Renewing of the faults formed around the early Miocene has affected also the later sediments. The major fault lines have N-S direction (their age is at least Badenian), the transcurrent faults are secondary, but there may be plenty irregular inferior faults apart from these. The detailed geological map of the area (Fig. 2) was compiled on the basis of a former manuscript (additional geological mapping and personal communications (Ivancsics, 2009).

### 4. GEOMORPHOLOGICAL MAPPING

The morphological mapping found varied surface forms grouped in three major areas (Fig. 3). These are mostly curved edge forms reminding of collapse dolines. Smaller parts of them are holes and caverns opening up in the side wall of depressions. A typical depression system (B-12) is shown in details on figure 4.

#### 4.1. Surface forms

Basically three versions of surface forms could be distinguished.

- The small-sized simple depressions are generally shallow with uneven bottom. Semi-detached twin depressions also occur. Inside these forms the limestone outcrops very seldom.

- The small-sized complex depressions with horizontal dimension of 50-100 m and uneven bottom are composed from more than two fragment-depressions. Deposition related elevations, heaps can be observed in their interior.

- The large-sized complex depressions or depression systems. All the four systems are several hundred meters wide and slightly elongate in E-W direction. Since numerous fragment depressions interlock into each other a significant number of their marginal slopes are archedly joined. The edge of the depression system is formed typically by the succession of semicircular asymmetrical depressions (asymmetrical collapse dolines). These forms either do not have side slope towards the interior of depression system, or if so, that has small inclination. Their steep side slopes form the edge slope of depression system. The limestone typically appears at these places. In their interior small mounds (up to 1-2 m in diameter) may rarely occur. The 1-2 m wide debris- and weathering product heaps at the rocky and steep lateral slopes are more frequent.

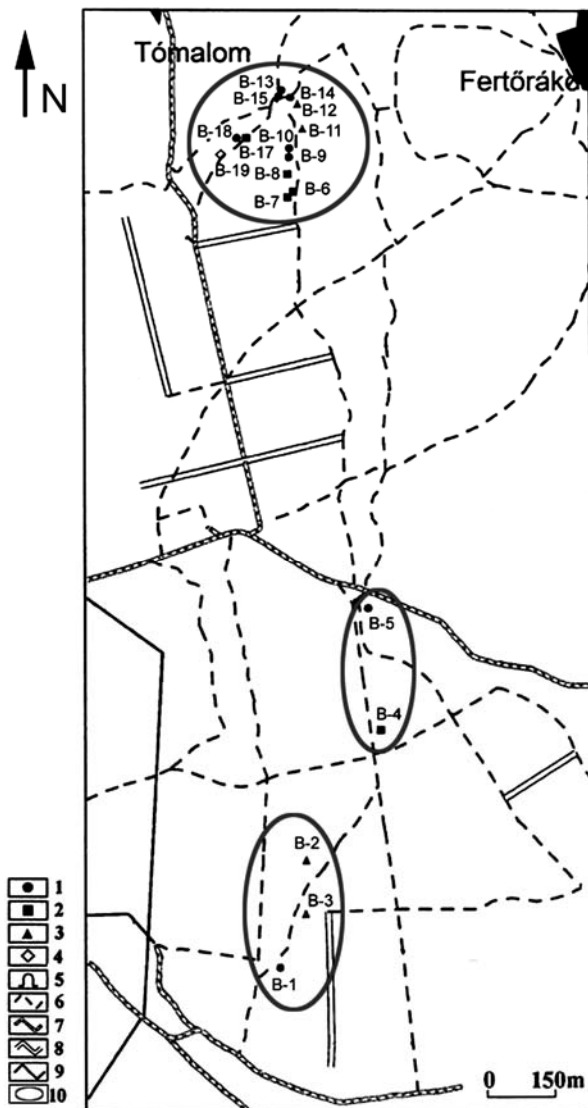


Figure 3. Occurrences of karst-like forms of the Balf block.

1. Small-sized simple depression
2. Small-sized complex depression
3. Large-sized complex depression
4. Group of small-sized complex depression
5. Cave
6. Dirt road
7. High road
8. Path
9. Power line
10. Main occurrences of landforms.

At the side walls of dolines small caves, caverns take place. The entrances of some caves are partly blocked up by the collapsing material. The threaded lined up dolines are separated from each other by thresholds, semithresholds. The thresholds are narrow forms between two dolines, which are the remains of the original terrain.

#### 4.2. Caves, voids

On the basis of relative position of caves depression system related and independent caves can be distinguished.

Two small caverns and the cave of Szárhalmi-quarry are independent of the depression systems.

These cavities were discovered and opened during mining activity. The cave of Szárhalmi quarry is about 20 m long (4.0-4.5 m high, 7 m wide) in the fault direction. There is no indication of karst processes in the lower part of the cave, solution forms occur only at the upper part.

An example for depression system related cave is the so called Zsivány cave. The cave is located in dip direction. Its height is 1-2 m, the horizontal size is approximately 20 m x 50 m. The room is partly separated by eleven pillars. The present entrances were formed by the breakdown of the ceiling. The number of entrances was changing quite quickly during the last 60 years. See e.g. Kotsis (1940). New connections are opened by the breakdown of the ceiling while others become blocked in the side wall of collapse depressions. The lack of any karst signatures and the pillars suggest that the cave was formed in the course of mining, however any proper entrance through which the quarried stone could be easily transported out is not known.

Smaller caves, holes opening from the slope walls of the depression systems are present in each of the major depression systems, moreover they can be found in some of the smaller-sized complex depressions, too. Two versions of this cave type can be distinguished: sack-like and bridge-like caves.

The sack-like caves appear at the edges of depression systems in the continuation of the collapse dolinas. The bridge-like caves are in connection with thresholds, semi thresholds and form passes between the neighbouring collapse dolines. Their typical height is 1-2 m.

By comparison of the geological map with the morphological map it was found that the morphological formations always coincide with the appearance of limestone at the surface. In terms of our examinations it is indifferent whether the age of limestone is Badenian or Sarmathian because both share the same physical-chemical properties. This spatial correlation may, but need not, reinforce karstic origin assumption. It must be also taken into account that this rock is less susceptible to karstification because it has coarse grained porous structure and the compaction is rather poor. The depression systems can not be connected to the tectonic lines known from geological mapping and former geophysical measurements. Since the karstification can be stronger along the fracture structures, additional inferior structural lines and associated cracks were also searched for by means of electromagnetic geophysical measurements.

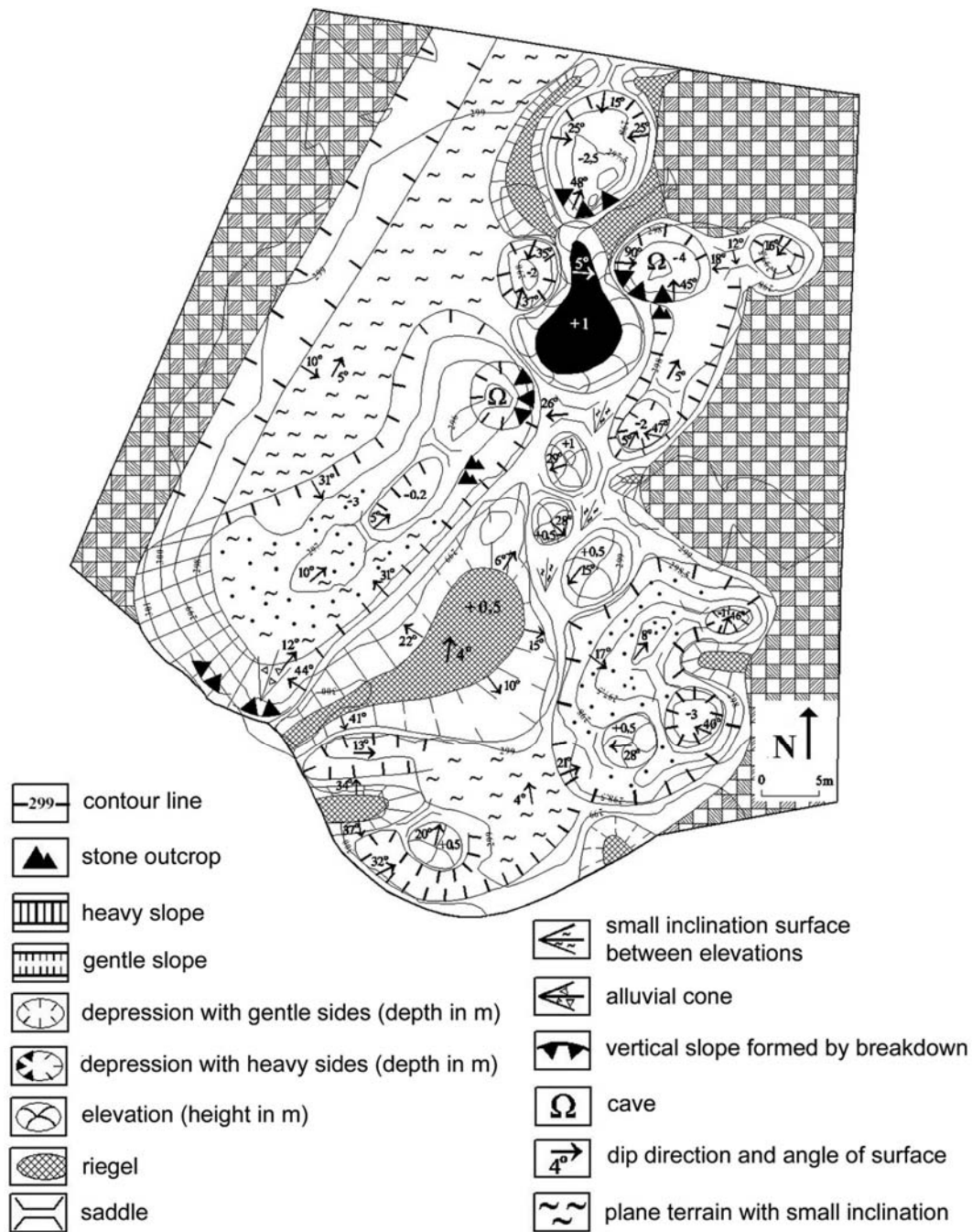


Figure 4. Geomorphological map of depression system B-12

## 5. RESULTS OF GEOPHYSICAL MEASUREMENTS

The more suitable geophysical methods had been selected on the basis of geomorphological mapping, geological data and rock physics parameters. Noise level was also taken into account. To examine the possible spatial correlation between depression systems and tectonic lines VLF profiling was made. Detailed GPR, geomagnetic mapping, respectively 2D and 3D geoelectric tomography

were performed over subsurface formation on a suitably selected test area

### 5.1. Lateral changes of the electromagnetic properties – primary geophysical exploration by VLF method

A VLF-Hz profile in approximately N-S direction crossing the whole carbonate terrain was made. The measurement point spacing was 10 m apart along the 4 km profile (Fig. 5). Four additional profiles were measured with much higher resolution

(2 m spacing). The sudden changes indicate major lateral inhomogeneities.

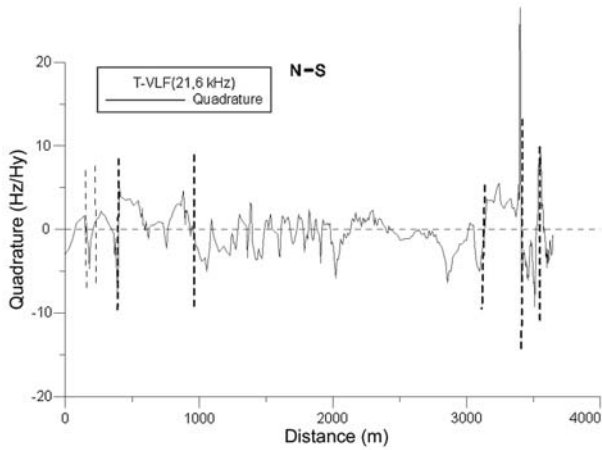


Figure 5. The VLF profile.

These VLF measurements identified several new fractures beside of the previously known tectonic lines but no spatial relationship was found between them and the examined morphological formations.

## 5.2. Detailed geophysical mapping

Of course application of laborous, high resolution methods is impossible on the whole area. A test area (Figs 1 and 6) was chosen where each typical surface forms and presumable caves and voids also occur. Further requirements were the low electromagnetic noise level, flat surface, and sparse vegetation. The test area is located on the edge of depression system marked B-11. There is a double dolina separated by a bridge-like cave in the vicinity. An almost fully blocked narrow entrance of a presumably sack-like cave can be observed on the neighbouring side wall.

### 5.2.1. GPR measurement

Four GPR profiles were measured parallel to the road at the edge of collapse depression (S1-S4) and perpendicularly six additional ones (S5-S10). The length of the radar profiles were 21 m each. Figure 7 depicts S5 GPR profile.

On the GPR profile the diffraction hyperbola and the multiple reflections slightly indicate the cave. The applied 250 MHz provides high vertical resolution but the penetration depth proved to be shallow mainly due to the clay and water content of the soil. Slight indication of the cave also appears at 100 MHz, but the wavelength (approximately 2 m) seems to be large in comparison with the vertical size of the cave. It can be deduced from this experiment that the georadar profiles give a fast, qualitative information about the subsurface cavity but its application is very limited. Proper imaging is available on the basis of a priory information about the local electromagnetic properties and the expected depth and size of the object.

### 5.2.2. Geomagnetic measurement

On the test area in a 0.25 m x 0.25 m regular network high-resolution magnetic measurement was performed. Scalar value of the geomagnetic field was measured by an Overhauser-effect proton magnetometer. Reference field values were taken from the nearby (NCK) geomagnetic observatory.

The anomalous magnetic field is caused by remanent magnetisation or lateral changes of magnetic susceptibility (induced magnetisation). Temperature of lime burning exceeds the so called Curie temperature which means that remanent magnetisation can not be excluded at certain places.



Figure 6. Photos of the test area.

This type of magnetic anomaly would provide final evidence for human activity. There is no indication of remanent magnetisation on the anomaly map but the cave clearly appears in form of an elongated anomaly. The weak (cca. 5nT) positive anomaly indicates that this subsurface cave is partly filled by higher susceptibility material (Fig. 8). Weathering, erosion of the sidewalls and accumulation of organic material tends to fill the depression. When its level exceeds the entrance of the cave (opening from the sidewall) transportation of the material occurs. Cave animals may also contribute to the deposition. This material (not speleothem) at the bottom of the cave may cause several nT induced magnetic anomaly on the surface.

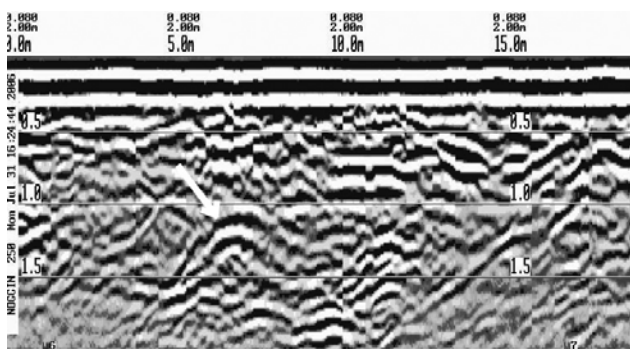


Figure 7. Radar profile marked S5 (250 MHz).

### 5.2.3. Geoelectric measurements

On test area geoelectric tomography was conducted with 168 electrodes in a regular 26 m x 27.5 m network from which 8000 apparent resistivity values were obtained. The resistivity of the embedding rock was also determined from a couple of 1D Schlumberger soundings. Its value (100-300 ohmm) can be regarded typical for the whole carbonate terrain. Sudden resistivity increases of several thousands ohmm can be interpreted as voids and caves filled (at least partly) by air.

Figure 9 depicts the image obtained by supposing that the resistivity of the embedding rock is 100 ohmm while that of the cave is 2000 ohmm. The resistivity contrast is remarkable at the boundary of the cave. There are no indications of underground drainage and passages. High conductivity infilling material (clay, water) does not appear. To confirm the 3D image additional 2D profiles were measured applying two different configurations. From the inversion of 2D profile the same shape and size was obtained. On the 2D profiles the thickness (1.5-2 m) of weathered limestone is clearly seen. The cave lies fully beneath the level of weathered material. Visual

observation of the size and shape of the blocked entrance of the cave also confirm that the 3D image is realistic.

The image on figure 9 shows an elongated, finite size, isolated sack-like cave. There is no signature of cracks connected to the cave except the depression. Its shape and connection with the dolina-like depression appear to support the hypothesis of artificial origin rather than karst processes. According to the 3D image several small sized objects are associated to the main cave, but their existence could not be confirmed by the 2D profiles. Such uncertainties are often caused by measurement errors and by the inversion process.

## 6. INDUSTRIAL ARCHEOLOGY

An attempt has been made to support our assumption concerning the anthropogenic origin of the examined formations with historical data and archival documents.

The architectural significance of Lajta limestone used since the Roman times is known from a number of sources.

It is known to be transported on the 80 km continuous waterway to the construction of the abbey church built in 1208 of Lébény and later it was also a popular building stone in Vienna and Sopron. The abundant archival material was published by several authors, for example Nováki (1962), Mollay (1992), Gömöri (1981).

This relatively small area supplied a very big district with building stone and caustic lime according to their works. According to the evidence of a map presenting the market district of the caustic lime of Sopron the entire former county of Sopron was supplied with slack lime. Nováki (1962) presents data and map about the 17-19 century's lime-burning on the area on the basis of the documents found in the State Archives of Sopron. The lime-kilns of the city during the 15-16th century worked on the investigated area (Okl. II/5. 94. 1499, Okl. II/5. 89. 1498 of Sopron Archives). The caustic lime was transported to the city on the Kalkweg (Chalcweg). The medieval small-scale lime-burning was replaced by large-scale technologies in the 18th century.

In the course of our several years' work the erosion and degradation processes were also monitored. From recent quickness of these processes the age of the landforms can also be estimated. In all probability the erosion and degradation of the former quarrying sites, the lime-kilns and associated stores began not earlier than 500-1000 years ago.



Figure 8. Anomalous magnetic field (field values are given in nT).

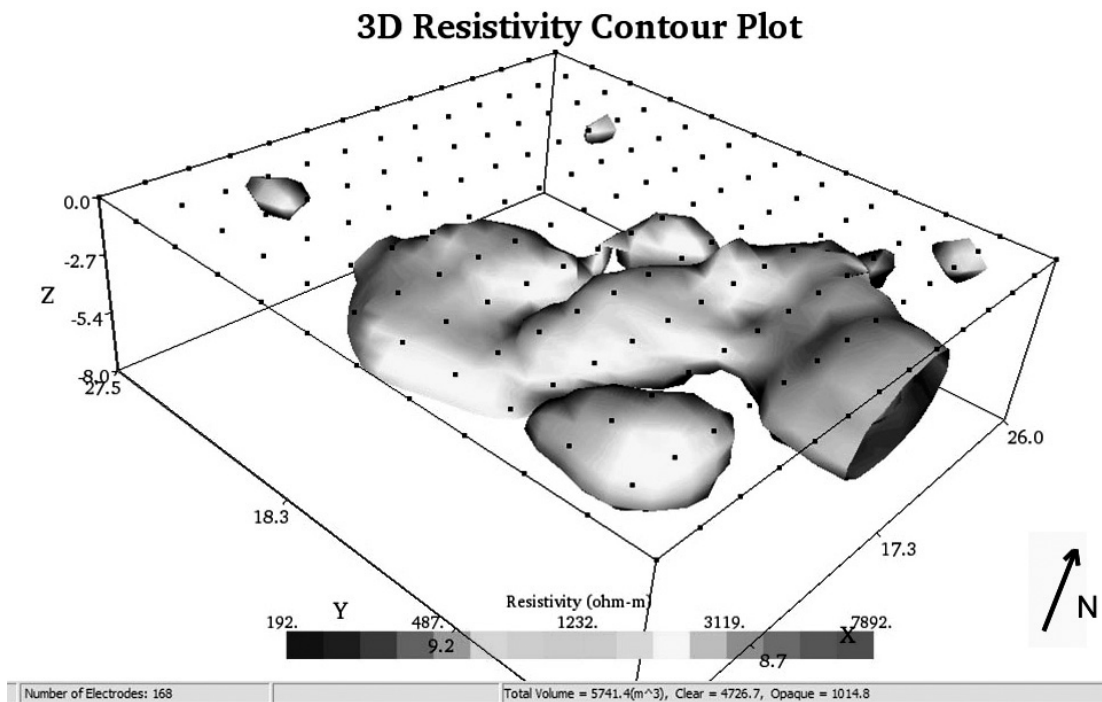


Figure 9. 3D geoelectric image of the investigated cave.

## 7. CONCLUDING REMARKS

The geomorphological mapping found landforms with unknown origin reminding mainly of collapse depressions and dolines.

Based on the uncovered geological map it was established that the depression system everywhere coincide with the surface appearance of the limestone. However, the coarse-grained structure of Lajta limestone, its high porosity and permeability and the geological structure makes the assumption of the karstic origin questionable.

Relation between the investigated formations and the tectonical structures was searched for by VLF method. The VLF profiles detected several young tectonic faults besides the known ones but no spatial connection could be established between the tectonics and the location of depression systems.

For detailed geophysical investigation a proper test area was chosen where all the typical surface and subsurface formations occur. Above a cavity opening from one of the collapse depression GPR profiling, geomagnetic mapping and geoelectric tomography were carried out. Although the investigated cavity is indicated by GPR measurement, its detailed mapping

was not possible due to the high absorption and due to the depth and size of the cavity. Apart from the indication GPR did not yield new information. The geomagnetic anomaly map provides information about the position of the cavity. It can be also concluded, that the cavity is partially filled with weathered/organic material which has higher susceptibility compared to its environment. The vertical electric soundings proved to be very efficient. The weathered material near the surface, the big resistivity differences between the limestone and the air filling the subsurface cavity made the reliable imaging possible.

The geophysical measurements appear to support the hypothesis of artificial origin rather than karst processes.

This assumption was supported by archival industrial historical documents about the intensive medieval quarrying and lime burning activity. The quick erosion process (collapse, denudation of formations) monitored for several year suggests also the medieval artificial origin.

The artificial origin assumption seems to be very probable but many questions and uncertainties has remained. Appearance and behaviour of the whole complex system is somewhat different from simple superimposition of individual parameters, one way approaches.

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