Geological mapping by geobotanical and geophysical means: a case study from the Bükk Mountains (NE Hungary)

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Received 7 November 2008; accepted 31 January 2009

Abstract: Geological mapping of an unexposed area can be supported by indirect methods. Among these, the use of mushrooms as geobotanical indicators and the shallow-penetration electromagnetic VLF method proved to be useful in the Bükk Mountains. Mushrooms have not been applied to geological mapping before. Common species like Boletus edulis and Leccinum aurantiacum are correlated with siliciclastic and magmatic formations while Calocybe gambosa is correlated with limestone. The validity of this correlation observed in the eastern part of the Bükk Mts. was controlled on a site where there was an indicated (by the mushrooms only) but unexposed occurrence of siliciclastic rocks not mapped before. The extent and structure of this occurrence were explored with the VLF survey and a trial-and-error method was applied for the interpretation. This case study presented here demonstrates the effectiveness of the combination of these relatively simple and inexpensive methods.

Keywords: Bükk Mts • geobotany • VLF • elongated structures • fungi

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1. Introduction

Geological mapping is often hindered by the a lack of exposure when the bedrock is covered by thick soil and detritus. Making artificial exposures (e.g., drillholes or trenches) on the unexposed area is an expensive and time-consuming process. Furthermore, it can cause environmental damage. To avoid this, there are indirect methods to gain information about the structural pattern of the area. By mapping the eastern part of the Bükk Moun-

tains two methods proved useful which were not used here before: the application of geobotanical indicators (mushrooms in particular) and resistivity measurements based on radio waves. This paper presents a case study where the joint use of these is demonstrated.

It is a known fact that vegetation is linked to the bedrock of its habitat through the soil cover. Therefore, we can draw some conclusions about the character of the rocks from observations of this vegetation. The science dealing with this, among other topics, is called geobotany. The method has been used for a long time (e.g. [1]), but the applied multidisciplinary knowledge can discourage researchers. On different bedrocks, or rather in the soils formed on them with different physical and chemical char-
acter, there will develop different typical associations even when geographic conditions (climate, exposure, etc.) are the same. The mapping of the natural distribution area of these species or, in the case of planted vegetation, mapping of patterns of vividness can substitute for the mapping of exposures of geological bodies. Therefore, it can be useful for the mapping geologist to collect floristical observations during their field work, because these could prove worthwhile in judging the poorly exposed parts of the area. These observations do not require supplemental investments and may spare expensive exploration projects. When one wants to know about the continuation of surface border traces at depth, the solution is a geophysical survey. The method applied by the geological mapping should be simple and quickly executable with a suitable resolution for the zone under the detritus cover. There is no need of deeper penetration than about a dozen metres. Different physical parameters of the rocks (like density, magnetic permeability, radioactivity, thermal conductivity, resistivity, elastic wave velocity) can be investigated by geophysical methods. Radioactive, magnetic and resistivity surveys are more easily undertaken than most other geophysical measurements. Radioactivity measurements cannot be applied to this case, because no information can usually be expected on the underlying formations below the detritus cover due to absorption. Magnetic survey can only be an efficient tool if the variation of ferromagnetic mineral content is significant. However, there is frequently no significant magnetic susceptibility contrast. If there are lateral small-scale near-surface variations, then electromagnetic methods with frequent spacings are preferred to geoelectric ones in general. These conditions are met by the VLF method. It only requires at least one operating radio transmitter, a portable selective receiver instrument and a single operator.

The combined use of geobotany and shallow-penetration geophysics seems to be promising for detailed mapping of covered geological structures. It is especially true in stratigraphically varied mountains or hill-country with a complicated structure where the lithologic boundaries can sometimes be sharply marked in the vegetation.

This is also the case in the Bükk Mountains. These mountains are situated in North Hungary, between the Great Hungarian Plain and the River Sajó (see Figure 1), and although their area is rather small, there are a lot of unsolved problems in its stratigraphy and structure. In the eastern part of the Bükk Mts. it can be observed that the spatial distribution of some mushroom species is correlated with certain rock types. This is true for every case where the rocks crop out. The aim of this study was to show that these species can be used as geobotanical indicators, by selecting a site without obvious outcrops, where the geobotany conflicts with previous geological mapping, and to demonstrate the use and efficiency of the VLF method in a geological environment with variously dipping lithological contacts.

Few shallow geophysical explorations have been made earlier in the Bükk Mountains. Long and medium frequency radio waves had already been used by Takács [2] for mapping covered near-surface limestone with changing topography in the Great Plateau. A seismic refraction survey was performed to determine the thickness of the surface clay filling a doline in the Bükk Mts. [3]. In both cases two media were assumed: conductive clay with low seismic velocity overlying a resistive limestone of high velocity.

This investigation was also prompted by the proximity of the study area to a spring swallowed back after a short surface runoff in a vulnerable karst area. As the water supply of the town Miskolc is based on the karst aquifers of these mountains, the opinion of the authors is that more knowledge of the geology of karst springs’ vicinity and their catchment area should be required in the future. This method can be a part of the solution.

2. Stratigraphy

In several areas of the Bükk Mts. the frequent alternation of carbonate and non-carbonate stratigraphic units is typical. In several areas, the individual rock types occur in a relatively small area: in a band or in a spot. In general, the differences in rock type can be seen in the topography: the more resistant limestone forms steep slopes and cliffs, while the more eroded strata between them form gentle slopes and local depressions covered by recent deluvium. The former provides well exposed areas; the latter have, in most cases, not even an artificial exposure, as on a gentle slope there is no need of a road-cut. However, the gentle slope alone is not a proof of the presence of a non-competent strata, as it also can develop over stand-
ing bedrock. Nevertheless, if this assumption is supported by the presence of certain plant species, we cannot avoid exploration of the spot’s rock type.

Figure 2 is extracted from the geological map of the western part of the Kis-fennsík (= Small Plateau) compiled by M. Forián–Szabó [4] and represents the vicinity of Köpüs spring. The stratigraphy of this area comprises an Upper Carboniferous to Lower Triassic succession, which is folded, faulted, thrusted by tectonic events and generally dips steeply. Clastic and carbonate sediments are both present. The Upper Carboniferous Mályinka Formation is an interbedded succession (laminated cherty limestone); *T₃*: Kisfennsík Limestone Formation (light-gray massive limestone); *T₄*: Szinva Metabasalt Formation (laminated metavolcanic). Crosses indicate habitats of aspen bolete (Lecinum aurantiacum), filled circles indicate habitats of king bolete (Boletus edulis).

### 3. Geobotany

Although most forests are planted and non-domestic coniferous monocultures are frequent, other species connected to the trees continue to form associations typical for the habitat. The connection between the forest types and the soil together with bedrock was investigated with the 1:50000 vegetation mapping made in the 1950s by Zölyomi and his co-workers [7]. More detailed observations were undertaken in the Southeastern Bükk Mts. and some other rock-association connections (mainly on dolomite and rough limestone) were discovered by N. Less [8]. His work was a part of the 1:10000 vegetation remapping of the whole Bükk Mts. [9], but unfortunately, it was not completed because of his early death. The soil types of the mountains and the vegetation typically formed on them will be presented according to these works.

The natural occurrence of the forest types and the species composition depends essentially on altitude or the steepness and exposure of the slopes, and the microclimate of the area. The dependence on the soil characteristics is best observed in the underwood, but sometimes the tree species of the association can also change with them. For example, the hornbeam is prolific over limestone and grows rapidly on clearings and former pastures, but over metavolcanic rocks it is significantly less prolific.

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The soil of the Bükk Mts. developed from the detritus of the bedrock and contain grains of their material. On deluvial slopes they can cover-up exposures of other rocks or mix with their detritus by creeping or slipping downwards. Different covering materials can rarely be found (remnants of an eroded Cenozoic sediment cover: extraneous pebbles, red clay and loess-type sediments), mainly in sediment-traps, for example in dolines [10], although the red clay is frequently distributed in the Southeastern
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Bükk Mts. and can form very thick layers above carbonates. There are two main soil types in the Bükk Mts. with several variations. The pure limestones are covered with rendzina with a transition to brown forest soil over red clay, while the typical cover of the clastic sediments and metavolcanic rocks is the non-podzolised brown forest soil with lessivage. The non-waterexigent species that need calcareous soil prefer the first soil type, the species demanding an acid soil with good water-bearing capacity prefer the second one. According to the observations of the authors in road cuts, on steep slopes the different soil types border on each other rather sharply, with a 1–2 m transition.

The beechwood with sweet woodruff (Asperula odorata) is the typical forest type of the calcareous soils on thick soil of good quality, on thin soil of poor quality the beechwood stands with wood melick (Melica uniflora). Towards the warmer zones the beech is substituted with hornbeam and oak. On slopes with rocks and boulder’s dog’s mercury (Mercurialis perennis) and bishop’s weed (Aegopodium podagraria) are the typical underwood members. The light acidity of the soil is indicated by the bulk appearance of beech sedge (Carex pilosa). The soil of carbonate bedrock is preferred by several spectacular flowers like (according to observations of the authors) martagon lily (Lilium martagon) and oregano (Oreganum vulgare).

As the higher parts of the Bükk Mts. are composed mainly from limestones, the percentage of metavolcanic rocks, radiolarites, shales or other silicate rocks is rather small, the beechwood types characteristic of acid soils are comparatively rare in the inner part of the mountains. Beyond the above-mentioned beech sedge, the main indicators are white wood-rush (Luzula albida), common speedwell (Veronica officinalis) and bilberry (Vaccinium myrtillus), which is infrequent in the Bükk Mts. The indicator of the water in local depressions and in clay soil is the bulk appearance of wood sorrel (Oxalis acetosella) and some ferns, mainly on soils of non-carbonate rocks or aluvium [7, 8].

On the explored site, at the Köpüs spring there is a meadow with aspen and birch groves on its southern and eastern border. On the vegetation map ([9], Figure 3) there is a meadow around the spring. The bulk of the forest is beechwood with underwood typical of soils formed on limestone. The vegetation on the western part consists of species characteristic of limestone, such as the forests in the neighbourhood and moisture lovers which live on the eastern part beside the brook. This vegetation pattern does not show the exposure of the rock differing from limestone. Still, there is a visible element indicating the non-calcareous, acid soil: the occurrence of some mushrooms, namely boletes.

4. Mushrooms used as geobotanical indicators

Mushrooms have not been the subject of vegetation mapping. The mushroom genera and species mentioned below are classified according to a specialized book on the fungi of Hungary [11], while the findings concerning their distribution and connection to rock types are based on decennial observations of the authors based on a much larger part of the mountains than presented here. Fungi usually live hidden in the soil or in the tissue of other living beings, so the only visible parts that can...
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Figure 4. Young individuals of orange-cap or aspen bolete (*Leccinum aurantiacum*) from Szentlélek.

be used for mapping are the sporophores. Accordingly, mapping of their distribution is only possible during the time interval of abundant growth. There are many edible species among them growing in huge numbers during favourable weather, which are gathered preferentially by connoisseurs. Certain fungi are saprophytes, others are symbions or parasites of living trees linked to certain tree species. For example, the death cap (*Amanita phalloides*) is a micorrhizal mushroom of oaks, while milky agaric (*Lactarius deliciosus*) grows only in coniferous woods. Most of them are moisture lovers and some of them need light. Some fungi live in meadows and pastures only. From a geological point of view the most interesting species are the ones sensitive to soil characteristics (e.g., water-retaining capacity, acidity, Ca-content). On the Kis-fennsík the species listed below proved to be indicators of certain soil and rock types.

In the Bükk Mts, St. George’s mushroom (*Calocybe gambosa*) lives only in rendzina soils developed on pure, non-clayey limestone. Here it is an indicator of the Kisfennsík Limestone Formation and Gerennavár Limestone Formation eastwards and southwestwards from the area on Figure 2.

King bolete (*Boletus edulis*) prefers acid soils and avoids calcareous soils, therefore it is an indicator of strata containing no carbonates, mainly of sandstones and metavolcanic rocks.

Orange-cap or aspen bolete, (*Leccinum aurantiacum*) (Figure 4) is a micorrhizal mushroom of aspens as well as other *Leccinum* species of birches and/or hornbeams. The aspen-birch groves generally grow on non-carbonate rocks, but the appearance of aspen boletes (like king boletes) always suggests eluvium of non-carbonate rocks or non-calcareous covering sediment.

In addition to these, the bulk appearance of some other mushroom species can indicate rock types, although (because they do not grow exclusively in this soil) they ought to be assessed carefully. Clayey, acid soil is generally indicated by the chanterelle (*Cantharellus cibarius*), *Russula* and *Amanita* genera or *Lactarius* *piperatus*. As the appearance of mushrooms is also linked to factors other than soil (for example, the aspen bolete to the aspen trees) they are not necessarily distributed over the whole area of a certain rock type so the lack of the mushrooms cannot be interpreted as the lack of the rock under consideration.

The habitats of the boletes around the Köpüs spring appear to be the forests above sandstone, siltstone and shale (Figure 2). Boletes occur in the vicinity of the area on Figure 2 not only on soils above the Szentlélek Formation, but also over other stratigraphic units comprising non-calcareous acid rocks. Mainly the ones that include sandstone, for example on shales and sandstones of the Málgyinka Formation, on siltstones and sandstones of the Ablakoskővölgy Sandstone Member and on metavolcanic rocks of the “Kisfennsík nappe” at Barátság-kert. The exposures of these formations are indicated with well-defined outlines in some places by the habitat of the boletes.

However, there was an occurrence at the Köpüs spring where the geological map indicated limestone only, although both king bolete and aspen bolete live there. But the small terrace formed on the slope and the spring arising there and swallowed up below it suggested an outcrop of the non-competent, watertight strata of the Szentlélek Formation in a core of an anticline or along a thrust fault over which the water falls. Without exposed rocks, based on the scant debris on the surface, this was impossible to prove, because all perceptible grains came from limestone (not counting quartzite pebbles dragged in during construction of the spring). So, for the mapping of the indicated occurrence, it was necessary to find an exploration method which enables us to trace the detritus-covered formation boundaries without exposures.

5. Features of the VLF method

The VLF (very low frequency) method is an electromagnetic geophysical method for detecting conductive and/or resistive zones located at depths of about a dozen metres, (e.g. [12, 13]) and therefore it can be applied for geological mapping. This method utilizes the carrier waves of some very powerful VLF stations located at several points around the globe. They broadcast at frequencies between 15 and 30 kHz for communicating with submarines. The antenna is usually a grounded vertical electric monopole with high power broadcast. At distances considerably
greater than one wavelength the combination of ground wave (travelling along the Earth’s surface) and sky wave (propagating in the space between the Earth’s surface and the first ionized layers of the upper atmosphere by reflections) can be utilized. At large distances (more than about 800 km from the transmitter) the second mode is the dominant one. For the purpose of a survey, the incident EM field can be considered to be uniform within a small area. The incident magnetic field only has a horizontal component (H₀), which is perpendicular to the transmitter bearing. The incident electric field has both vertical and horizontal components, where the latter is in the direction of the transmitter bearing. Due to the almost infinite conductivity of the ground compared to air, the refraction of the VLF wave is irrespective of its angle of incidence and results in a vertically downwards propagating wave with unchanged horizontal magnetic field component and a radial electric field component (Eᵣ). The skin depth, which is the distance in which the amplitude of the surface EM field is reduced by 1/e, is, to 37% of the surface value, expresses the attenuation of the EM field. This depth (p) depends on frequency (f) and on conductivity (σ) as follows [14]:

\[ p = \frac{1}{2\pi} \sqrt{\frac{10^7}{1/\sigma}}. \]  

(1)
The skin depth can also be correlated with the penetration of EM waves, however, it cannot be stated that the exploration depth is equivalent to the skin depth. The larger the resistivity contrast between the underlying layer is, the greater is the probability of the detection for the lower layer situated at the proximity of the skin depth. Apart from the difference between the EM source of magnetotellurics (MT) and VLF, the same physical phenomena can be observed, so the basic equation of MT [14] can be applied to determine the resistivity of the homogeneous half-space. From the VLF wave impedance – which is the ratio of the radial electric and the horizontal magnetic field component – the resistivity of the homogeneous half-space (ρ₀), or using the same relationship, the apparent resistivity of the inhomogeneous ground (ρₐ) can be defined as:

\[ \rho_a = \frac{1}{2\pi f T_{\text{VLF}}} \left| \frac{E_r}{H_0} \right|^2, \]  

(2)
where fᵥᵥL stands for the frequency and \( \mu_0 \) denotes the absolute permeability of vacuum. In the carrier wave transmitted into the homogeneous ground, the horizontal radial electric field component leads the horizontal magnetic field perpendicular to the transmitter bearing in phase by 45°. Practically, when the thickness of a homogeneous layer on the surface is more than two or three skin depths, the situation is identical to a homogeneous half-space. It means that phase difference between Eᵣ and H₀ can furnish information about changes of conductivity to a depth of some tens metres. The definition for phase [14]:

\[ \phi = \arctan \left( \frac{\text{Im} \left( \frac{E_r}{H_0} \right)}{\text{Re} \left( \frac{E_r}{H_0} \right)} \right). \]  

(3)
Assuming a horizontally stratified half-space consisting of two layers within the skin depth, with a lower layer to be more conductive compared to the upper one, one finds that the phase angle Φ(Eᵣ/H₀) is generally more than 45°, and it is less than 45° if the conductivity ratio is inverse. In these homogeneous situations the measured values are independent of the transmitter bearing. In case of inhomogeneity – when the geology is different from the homogeneous or horizontally stratified half-space – it does not hold: both the apparent resistivity and its phase depend on the mutual position of transmitter bearing and the direction of structural elements. Besides apparent resistivity and phase yielded by VLF R method parameters of the polarization ellipse of the resultant magnetic field are also provided in tilt angle mode by VLF instruments. This latter method can also help geological mapping, mainly in the case of significant near-surface inhomogeneity contrasts.

If the geologic structures are elongated, like a steeply dipping fault plane or a folded bed plane, and the formations on opposite sides of these planes can be characterized with different conductivities, then these structures can be approximated with 2D (two-dimensional) models. Restricted to 2D conductivity inhomogeneities, there are two modes based upon the angle between the transmitter bearing and the structural strike. If they are parallel to each other, the term of E polarization or TE mode is used. If the structural strike is perpendicular to the transmitter bearing, the case is named as H polarization or TM mode. In TE mode, current channelling in the conductive part can be detected. In TM mode, the galvanic effect can be observed. As a result, a secondary electric field from the oscillating electrical charge accumulation on the interfaces perpendicular to the primary electric field can be measured. For this reason TM mode is an effective tool to locate near-surface vertical or nearly vertical contacts.

6. Exploration of the Köpüs spring outcrop

6.1. Material types of the survey area

For the sake of proving the existence of the Szentlélek Formation rocks at the spring, we took samples from the clayey detritus below the humus with hand-driven auger
drilling (Figure 5). From the two samples on the right side of the brook near the habitat of the boletes (site 1 0.6–1.4 m; site 2 0.3–1.7 m) we collected greenish, flat grains typical of the Szentlélek Formation Garadnavölgy Evaporite Member. The clay was yellowish–greenish coloured and partly rust stained. After decanting and sieving the samples and examining them under a microscope, it became evident that the material comes from this member as it hardly contained any carbonate grains, while green mudstone and quartz fragments were apparent. In the 0.25–0.5 mm fraction it contained a few grains of hexahedric pyrite, which is typical of no other stratigraphic units in the vicinity. Rust stains of the clay may originate from the secondary iron-oxide minerals after oxidation of pyrite.

On sampling site 1 between 0.3–0.6 m there was a stratum of cream-coloured grains with lime accretion which proved to be the alluvium of the brook with travertine precipitation comprising mainly dark limestone grains. In the sample collected from the left side of the brook this material reaches a larger thickness (site 4 0.4–1.3 m) under the humus layer. This explains why boletes do not live here, despite the fact that the aspen grove is continued.

We also collected a sample in the meadow westward above the aspen grove (site 3) but the drilling broke down after only 80 cm at a limestone rock. At that point it went in reddish brown clay with small grains of bituminous limestone which can be accounted for as material of the debris cover formed above the Nagyvisnyő Limestone Formation.

6.2. VLF measurements in the surroundings of Köpüs spring

All measurements were made with a Geonics EM16R instrument. At the beginning of the geophysical survey there were two operating VLF transmitters: GBR (Great Britain, Rugby, f=16.0 kHz) and JXZ (Norway, Helgeland, f=16.4 kHz). From the first measurement lines (1, 2, 4 in Figure 4) laid along 110°–290°(which corresponds to the GBR bearing) sharp changes in the phase angle with a nearly NE-SW striking line were observed with both transmitter stations. So GBR was supposed to meet the TM mode condition better than JXZ in this survey because these changes predicted the strikes to be more nearly perpendicular to GBR than to JXZ bearing. Further measurement results strengthened this assumption and this transmitter was generally used. Moreover, GBR was active (with short intermissions) during all measurement sessions while other stations transmitted only episodically.
The surroundings of the spring were investigated along 6 lines parallel to the transmitter bearing (Figure 5). Effort was made to have continuous profiles, however, owing to some natural obstacles it was not always possible. VLF resistivity and phase measurements were made using a 10m station interval which was also equal to the interprobe (or electrode) spacing. Figure 6 shows the apparent resistivity contour map in ohmm, Figure 7 presents the areal distribution of the phase difference between \(E_z\) and \(H_x\) in degrees. The apparent resistivity and phase data show similarities for neighbouring profiles. This correlation is more pronounced in the case of the phase map, because apparent resistivity is sensitive to surface inhomogeneities, while the phase is hardly influenced by it. On the basis of the two contour maps it can be stated that the main structural strike is parallel to the NE-SW direction, and although the explored geologic structures cannot be considered as a pure 2D situation, it can be a good approximation.

### 6.3. Modelling and interpretation

In the course of geophysical EM data interpretation, the task is to determine the conductivity structure that has the same EM response as the measured one. For interpretation, different inversion algorithms are used and among those, robust methods are preferred nowadays (e.g. [15]). Taking into consideration the number of measured EM parameters and the number of the unknowns it is obvious that the problem of underestimation cannot be avoided. This is why the trial-and-error method was applied.

The essence of the trial and error method is to solve the forward problem several times in order to get an acceptable agreement between the measured and the model data. In the course of successive model modification our intention is to minimize the error, i.e. the difference between the model response and the measured data. In this case, for forward modelling, a finite difference two dimensional magnetotelurics (2DMT) code developed for H-polarization was applied. This forward modelling assumes that the vertical section perpendicular to the strike is divided to rectangular elements by a grid [16]. The sizes and conductivity values are defined for every single cell as input data. For each grid point numerical solutions are achieved by approximating the relevant differential equation (time independent Helmholtz equation for both polarizations) by a finite-difference equation taking into account the boundary conditions. The solution to the set of these equations is the strike-directional magnetic field component solution for each gridpoint and the output of modelling is the apparent resistivity and the phase between \(E_z\) and \(H_x\) in the surface gridpoints. The finite difference solution is preferable for simulating complex geology. In our case the applied grids had 39 columns and 49 rows.

For the sake of having the resistivities of the formations needed for the model determination, we made VLF-R measurements on known outcrops with sufficient thickness not far from our survey site. We distinguished three formations: bituminous limestone (Nagyvisnyó Limestone Formation) with a resistivity of 300 ohmm, mudstone (Garadnávölgy Evaporite Member) with a resistivity of 40 ohmm, and the covering detritus. This detritus is very inhomogeneous, so it was characterized with two resistivity values: 60 ohmm for the detritus consisting mainly of clay, and 120 ohmm for the other type with limestone boulders.

The aim of the interpretation was to determine the thicknesses of the two-to-four underlying formations, usually with dipping boundaries when only two data were measured for each station. This task can be considered as an underestimated inverse problem as was mentioned before, so the solution is not unique. However, not all solutions are equally probable as geological models. The way to get the solution was a classical trial-and-error method: the parameters of the model were changed as long as the best fit between the measuring data and computed data was reached along the profiles. The start model for the lines was constructed with horizontal and vertical boundaries only on the basis of the measured data and the predicted formations. On sections with \(\Phi < 45^\circ\) a more conductive layer was placed over a less conductive layer, and vice versa on sections with \(\Phi > 45^\circ\). Where there was limestone on the surface along the section, we put limestone layer on the top; where the habitat of the boletes was, mudstone was chosen as the uppermost layer. When changing the model it was transformed toward geologically possible situations, that is, to gradual changes in thickness and depth with continuous, dipping, but not sharply breaking boundaries. After some dozen trials we achieved an acceptable agreement between measured and computed data (see Figure 8).

Further modification was not made on the model because of limits of measurements and those of the modelling process. The measurement itself contains some measuring error, usually not more than 5%. Topographic effects can be an additional source of VLF survey error (e.g. [17]). From this point of view of the survey site, the horizontal magnetic field and the contours of topography were mainly parallel to each other and there was no significant topographical slope change. For limits of the computing, the question of dipping boundaries and the fixed values of formation conductivities should be mentioned. This program applies rectangular grid elements with fixed conductivity values as input data. If there are two cells with different
conductivity in contact, the linear change of conductivity between the centre of grid elements is assumed in the computation. In this way, by using sufficient number of fine grid elements, the gradual change of boundary slope can be approximated. However, even this resolution is not enough to model the very small-scale near-surface inhomogeneities (like rock blocks in the detritus or cavities in the weathered zone) which may influence the measured apparent resistivity data. The resistivity of bituminous limestone and that of mudstone were taken as constant, but actually they are average values, just like in the case of the covering detritus.

Figure 8. Measured (circles) and computed (crosses) apparent resistivity and phase data of line 6 and line 7-8 (see Figure 4) with the interpreted geological cross-sections.

The modelled and the measured $\rho_a$ and $\Phi$ data are presented for the two outermost lines in Figure 8. The data of the remaining lines form a transition between them. The interpreted cross-sections according to the final models (which are similar even for the outermost lines) show a syncline-anticline pair covered with an eluvium of changing thickness. The divergence from the 2D model arises partly from the differences of this thickness and partly from the lateral change of the fold geometry. The syncline of limestone seems to deepen towards line 6. As the deepest part of this modelled syncline is at 1.7 skin depth the measurement of this depth may not be accurate. The NE-SW striking axes of these folds (see map view, Figure 9) correspond to the typical fold axis direction stated by Forián-Szabó and Csontos [4] and their possible continuation is mapped by them NE from the Köpis spring area.

The mudstone in the core of the anticline is covered by limestone detritus except on the topographically lower side at the spring. The spring flows out from the detritus but comes from the limestone of the syncline dammed by the watertight layers in the anticline. The water is swallowed back where the runoff reaches the uncovered limestone of the relatively steep hillslope on the SE flank of the anticline.

7. Conclusions

Mushrooms have never been used as geobotanical indicators before in the Bükk Mountains, but the observations showed a clear correlation between the spatial distribution of the habitats of certain fungi and the soil-forming rocks. In this case, *Leccinum aurantiacum* and *Boletus edulis* were correlated with sandstone- and mudstone-dominated formations. The connection was valid in all observed cases in the eastern part of the Bükk Mountains. Moreover, it provided the opportunity of correcting
the geological map. The exploration of the exposure both demonstrates and gives reasons for using the mushrooms – in particular the boletes – as indicators for geological mapping. The information gained in this way was utilized in the interpretation of VLF measurements. Besides proving the existence of the indicated structure, some knowledge about the extent of it was gained by applying the relatively simple and inexpensive VLF method. Both the measurements and the interpretation were made while taking into consideration the geological data known so far. Before measurements are taken, an estimation of the strike of the structures being explored is required for choosing the transmitter bearing which is perpendicular to the strike. Before interpretation, the resistivities of the predicted formations are needed for the start model. This start model can be constructed on the basis of the measured apparent resistivities and their phases. The steps of the trial-and-error method should not be chosen at random, but in accordance with the possible geological model geometries in order to converge to a realistic solution. The 2D assumption has to be verified in the interpretation. In this case the combination of these methods proved to be an efficient tool for mapping shallow elongated structures with covered contacts, but with sufficient contrast in conductivity in both the lateral and vertical sense. The mapping results were utilized in compiling the new geological map of the Bükk Mts. [18].

Acknowledgements

The survey was supported by the projects T 042686 and T 37619 of the OTKA Hungarian Research Fund. Ferenc MÁDAI is acknowledged for his help at the collection and investigation of the soil samples.

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