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Microseismic identification of geological and tectonic structures in the Komjatice Depression (Western Carpathians)

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Abstract: The microseismic survey method was applied to the study of the geological structures in the region around the Mochovce nuclear power plant. The previous geological and geophysical investigations considered a contact between the Miocene volcanites and sediments as a neotectonic fault. The results of the microseismic investigations allow us to interpret the zone of a supposed neotectonic fault as a transgressive contact of the sediments and the volcanic rocks without a tectonic disruption.

Key words: Miocene, Western Carpathians, geological structure, microseismic survey, Rayleigh waves, microseisms.

Introduction

The Western Carpathians form a mountain range arc with dominant nappe structures with a significant zonal arrangement and orogen polarity processes migrating in time. It is one of the essential reasons dividing the Western Carpathians into the Outer Western Carpathians (OWC) and the Inner Western Carpathians (IWC). One of the typical morphotectonic features of the IWC are Neogene depressions and volcanites. The investigated area belongs to the Komjatice Depression which is a north-eastern part of the Danube Basin. Numerous studies focused on the geological and tectonic structures of the Komjatice Depression in the past (e.g. Gaža & Beihauerová 1976; Zbořil et al. 1987; Harčár & Priechodská 1988; Priechodská & Harčár 1988; Baráth & Kováč 1995; Nagy et al. 1998; Hók et al. 1999). Detailed geological and tectonic studies were realized in the vicinity of the Mochovce nuclear power plant (EMO) situated at the easternmost margin of the Komjatice Depression. In the EMO vicinity a conspicuous contact was described between the Miocene volcanics and sediments. This contact is situated on the eastern foothill of the Dobrica elevation (Fig. 1). From the point of view of the conservative solution approach the contact was interpreted as a neotectonic fault with potential Quaternary activity (Hók et al. 2003). The fault separates the Miocene volcanites from the Quaternary and Miocene sediments. The application of the microseismic survey method yielded new information, which helped to specify the geological and tectonic structures, as well as a supposed fault-like contact in the EMO vicinity, which is located in the NE part of Komjatice Depression.

Geological setting

Miocene sediments of the Komjatice Depression overlay an erosive divided pre-Tertiary substratum drilled in several boreholes (Biela 1978) and rising up in the Tribeč Mts (Fig. 1). The stratigraphic range of Neogene sediments is Middle Badenian (Middle Miocene) to Pliocene. The sedimentary fill of the Komjatice Depression during the Miocene megacycle was characterized by a gradual decrease of salinity of the depositional environment upward. There are three lower-order shallowing upward cycles in sedimentary record. The depositional environment changed from marine to brackish, caspibrackish and lacustrine-swamp with coal deposition. This succession is overlain by a Pliocene cycle, composed of deltaic and fluvial deposits (Hók et al. 1999). The occurrence of the Middle Badenian sediments (the Pozba Formation) is restricted to the central part of the depression. The Sarmatian sediments (Vráble Formation) are transgressively spread over the whole depression. The Vráble Formation comprises calcareous clays, sands and conglomerates with volcanic rocks at the bottom. The volcanic rocks form subaquaceous lava flows, which belong to the distal parts of the Štiavnica stratovolcano rock complexes (the Priesil Formation sensu Konečný et al. 1998). The paleocurrents of the lava flows were generally oriented in a NE–SW direction in the investigated area. Sediments of the Vráble Formation, biostratigraphically constrained to the Sarmatian period, were found in the parametric borehole ŠVM-1 drilled about 5 km SW from the investigated area (Sliva in Hók et al. 2003). The Lower Sarmatian sediments of the Vráble Formation are situated directly above the volcanic lava flows.

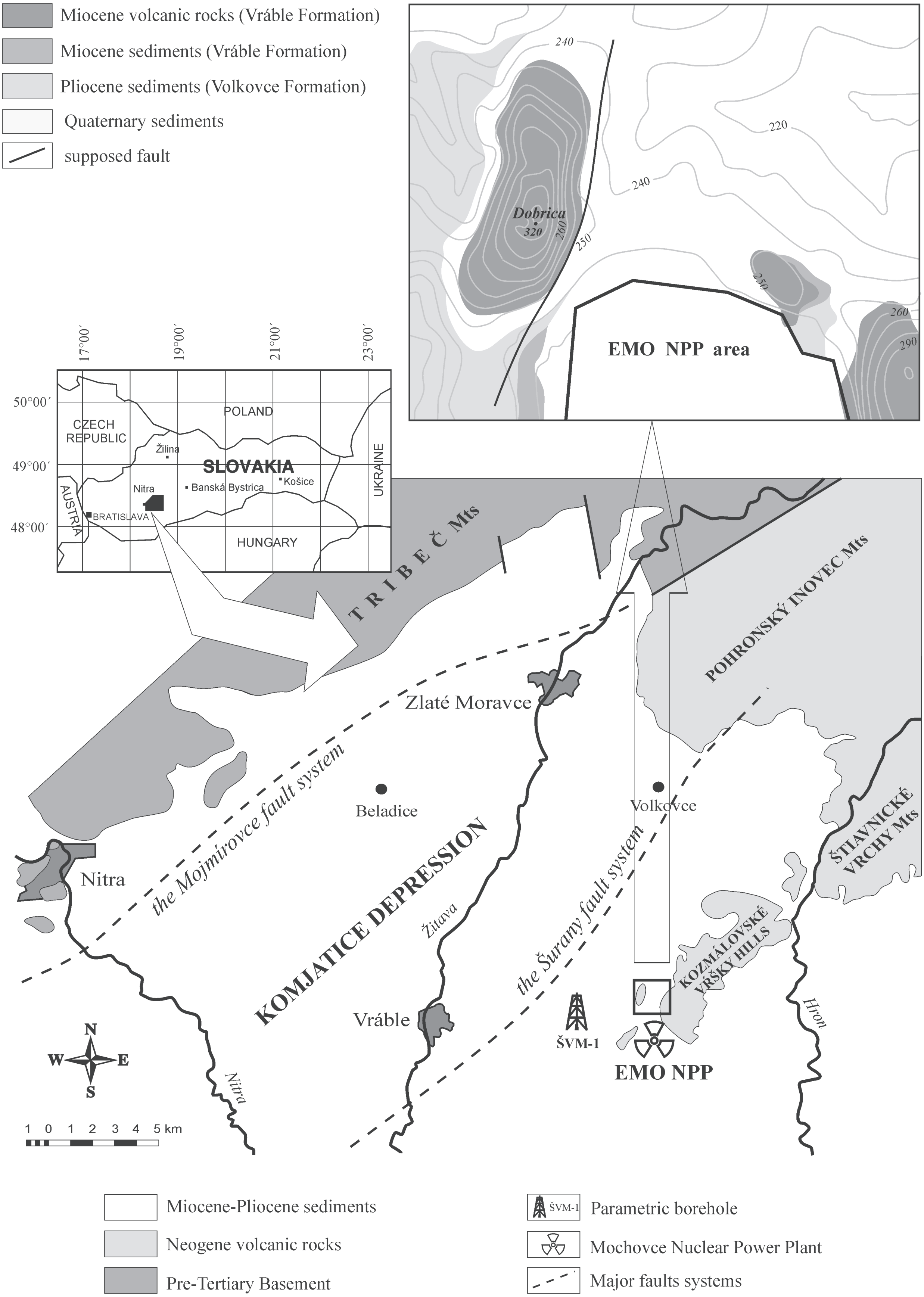

Fig. 1. Simplified geological map of the Komjatice Depression and the investigated area (according to Nagy in Hók et al. 2003).

The Pannonian sediments of the Ivánka Formation overlay the Vráble Formation. The angular unconformity is present between the Ivánka and the Vráble Formations. The Ivánka Formation sediments are predominantly represented by calcareous clays and claystones with admixture of sands representing fluvial influence in sedimentary basin. The Beladice Formation (Pontian) is the last member of the Miocene megacycle sedimentation. It was deposited in a shallow lacustrine to swamp environment. The variegated clays with coal intercalations are typical for the Beladice Formation. The Pliocene sediments (the Volkovce and Kolárovo Formations) are products of the deltaic sedimentation. The most typical sediments are coarse-grained gravels and sands with clay admixture.

The northeast trending faults are most remarkable in the tectonic structures of the Komjatice Depression. The brittle structures of the Mojmírovce and Šurany fault systems were the most important of the faults activated during the development of the Komjatice Depression (Hók et al. 1999). The Mojmírovce fault system bounds the Miocene deposits with the pre-Tertiary rocks of the Tribeč Mts. The Šurany fault system is a comparative, partly antithetic fault system relative to the Mojmírovce fault system. It restrains the southeast and east margin of the Komjatice Depression depositional area and also the horst-like structure of the neovolcanic rocks comprising the Kozmálovské vŕšky Hills. We assume that the Mojmírovce and Šurany fault was active during the initial rifting of the Komjatice Depression and the rifting was connected with the Pozba Formation, deposition (cf. Hók et al. 1999). The paleostress field with NW–SE oriented extension accompanying subsidence of the depression and deposition of the Vráble Formation, during the Sarmatian period. The transgressive characteristic of deposits and modelling suggest a moderate subsidence during this period (Lankreijer et al. 1995). The next phase of a wide rifting manifests the angular unconformity between the Sarmatian and Pannonian sediments (the Vráble and Ivánka Formations). The Late Miocene paleostress field, with a NE–SW to ENE–WSW compression and perpendicularly oriented extension resulting in following subsidence of the depression. Deposition during the Pannonian and Pontian suggests a rapid transition of the synrift stage evolution to final thermal subsidence (postrift stage) of the whole Danube Basin.

The Pliocene Volkovce Formation deposits, reaching up to 1000 m in thickness toward the Danube Basin centre (Baráth & Kováč 1995) points to a rejuvenation of the tectonic activity. However, the end of the Pliocene and the beginning of the Quaternary represents structural reworking of the Komjatice Depression during the period of tectonic inversion. The central part of the depression between the Tribeč Mts and the Kozmálovské vŕšky Hills is characterized by uplift resulting in erosion of older sediments (Priechodská & Harčár 1988).

The area southeast of the Kozmálovské vŕšky Hills has been subsiding since the Mindelian. This is shown by the age of the oldest preserved terrace of the Hron River (Halouzka 1968), as well as by the 40 m thick accumulations of Quaternary sediments (Tkáč et al. 1996). It was one of the reasons why the sharp contact between the volcanics and the Miocene sediments was interpreted as a fault structure with potential activity during the Quaternary.

Methodology

Seismic background oscillations (microseisms) have been studied for more than a hundred years. Recently many investigations were devoted to developing methods using microseisms as sounding signals. Microseismic signals are always present at every point on the Earth's surface eliminating the necessity of artificial sources of registered signals. A number of experiments demonstrate the relations between the amplitude-frequency characteristic of the microseisms and the elastic properties of the medium (Bard 1999).

The approaches utilizing microseisms for the study of the geological environment could be approximately divided into two groups. The first group studies the experimental dispersion dependencies between microseismic wave velocities and corresponding frequencies. The main purpose of these measurements consists of receiving the velocity section of the investigated area after the inverse problem solution on the basis of the experimental dispersion curves. This approach requires synchronous measurements with the help of seismic arrays of different configurations (Shapiro & Ritzwoller 2002). The second group studies the composition of the correlation of stable statistical properties of the microseismic field and the structure of geological heterogeneities (Asten 1978; Nakamura 1989). In that case, the measurements could be performed using a single seismic station. But in practice a number of assumptions regarding the nature of the microseisms sources, their spectral properties, and the proportion of the content of different types of waves are accepted based on previous experimental investigations, both in the study area and in other regions. This group is characterized by the simplicity of measurement procedures and good consistency of microseismic investigation results with other geological and geophysical methods despite the set of initial assumptions.

The microseismic signal looks like interference by different types of seismic waves, which propagate as separate wave trains of limited duration, and which present the deterministic signals within this duration. From the other side, the microseismic signal is a random signal, because the proportion of the content of waves of different type, initial phases, amplitudes, and duration of wave trains are unknown. As an illustration of the randomness of the process $X(t)$, the following example could be used:

$$X(t) = A\cos(\omega t + \varphi),$$

where A and ω are constants, and φ is a random value with defined probability distribution, so that for one realization the random value φ is equal for all values of t (for example for the time interval of observation). In that case the random variations take place only on the realization ensemble, but not on time intervals.

The method of microseismic survey, where the spatial properties of the spectral characteristics are used for the location of the geological heterogeneities (Gorbatikov et al. 2004; Ammosov et al. 2007), was applied. This method could be referred to as a statistical approach. The measurements above the investigated structures were performed using separate mobile station (one or several units). For proper interpretation of the received data we shall ensure that the resulting values are stationary and do not vary during the day, month, and do not depend on changing climatic conditions, etc. The estimation of the stationary interval of the signal dispersion in the increasing temporal window takes into account the known dependence between the spectrum and the dispersion of a random signal:

$$\sigma_x^2 = 2\int_0^\infty S_x(f)df$$

where σ_x^2 and $S_x(f)$ are dispersion, and spectral density correspondingly of the random microseismic process (Bendat & Piersol 1966). The experimental investigations of the stationarity of intervals of the microseisms for different localities and different conditions on the Earth's surface showed that the signal dispersion begins to stabilize after the signal accumulation during 15–20 minutes for the frequency range 10–12 Hz and during 40–60 minutes for the frequency range 0.1–1.0 Hz (Gorbatikov & Stepanova 2008). It is necessary to notice that the stationary interval is limited. Moreover the time is changing for different frequency ranges and for different observation conditions. To separate the global and local microseismic sources during the measurements, it is necessary to install one seismic station (reference station) for continuous recording of the microseismic signal in the vicinity of the investigated area.

Physical background of the microseismic survey method

The microseismic survey method is based on the analysis of the spatial distribution of the vertical component of the microseismic field for all frequencies of the spectra. The analytical solutions proved that in the Rayleigh fundamental mode the zone of maximum shear stresses is located at the depth equal to half of their wave length. The zones of maximum amplitudes are situated close to the surface. The local heterogeneities with different elastic modules lead to changes of the oscillation character of the microseism and their amplitudes. If seismic wave velocities in the heterogeneities are higher than in the surrounding rocks the amplitude of the microseismic waves above the heterogeneities decreases, and vice versa (Gorbatikov et al. 2004; Kalinina et al. 2008).

The observations were performed at different points with the step 100 m in the investigated area using mobile stations. During processing the field data were corrected using the reference station data records. The results of the analysis are maps of the distribution of microseismic amplitudes reflecting the fields of the relative velocity changes for different frequencies. The dependence of the Rayleigh wave amplitudes on the depth of the half-space is given in (Levshin et al. 1992). The maps of the distribution of microseismic amplitude for different frequencies give information about the velocity properties of the medium at different depths.

It was necessary to check the following circumstances during processing:

1. Type of waves dominated in registered signal;
2. Statistical stability of the registered parameters.

The main assumption of the microseismic survey method is the prevalence of the Rayleigh-type waves in the vertical component of the low frequency (lower than 1 Hz) microseismic field. However, our working frequency band also lies in the high frequency area, which contains a high percentage of body waves. The wave composition using the polarized analysis of the particle movement was studied, and it was necessary to preprocess the data to remove the high amplitude noises (mainly the noises caused by transportation).

The control of statistical stability was realized by the investigation of the behaviour of the signal dispersion in the increasing temporal window for each observation point. During processing the data were corrected using the reference station records, and the ratio of accumulated (stationary) power spectra was obtained. The pictorial representations of the resulting matrix are the horizontal and vertical slices at any chosen site.

Processing and results

The investigated area represented a rectangle with the size approximately 0.5 by 2.2 km (Fig. 2). The measurements were realized along six profiles 100 m apart. The average distance between points of registration along the profiles was 100 m. Close to the contact zone between volcanites and sediments near the Dobrica Hill the registration points were denser (25–50 m). For the continuous registration the reference station was installed in the center of the studied area. The registration time interval for mobile stations at each point was 45–50 min. The seismic station consisted of the three-component velocimeter KMV and a registration block UGRA (Marchenkov et al. 1997).

The main goal of the processing was the gathering and analysis of the power spectra. In Fig. 3 the observed smoothing power spectra of microseisms along profile 3 are shown. The results of the microseismic survey are presented as vertical profiles and horizontal layers (Figs. 4 and 5). The axes are given in meters. The XY projection is UTM Zone 34 Northern Hemisphere (WGS 84). The zero depth on the vertical axis corresponds to the level located at the absolute mark equal to 200 m. The colour spectrum reflects the intensity of the relative amplitude of the microseisms in decibels. The microseismic survey method allows us to distinguish rocks by velocity properties. It was meaningful to assume that at least two types of lithological rocks — the Miocene volcanites (intensity of the relative amplitude of the microseisms $\lg A < -2$ dB) and the Miocene and Pliocene sediments ($\lg A > 2$ dB) — could appear in the resulting maps.

The vertical profiles and horizontal layers presented in Figs. 4 and 5 exhibit the following characteristic features of the investigated area:

1. The zones of low amplitudes $\lg A < -2$ dB (blue colour) interpreted as volcanic rocks are well distinguished down to 600–650 m. The sediments $\lg A > 2$ dB (red colour) are located between them.
2. The bottom stratum, $-2 \text{ dB} < \lg A < 0$ dB, (green colour) has velocity properties, which are nearly average be-

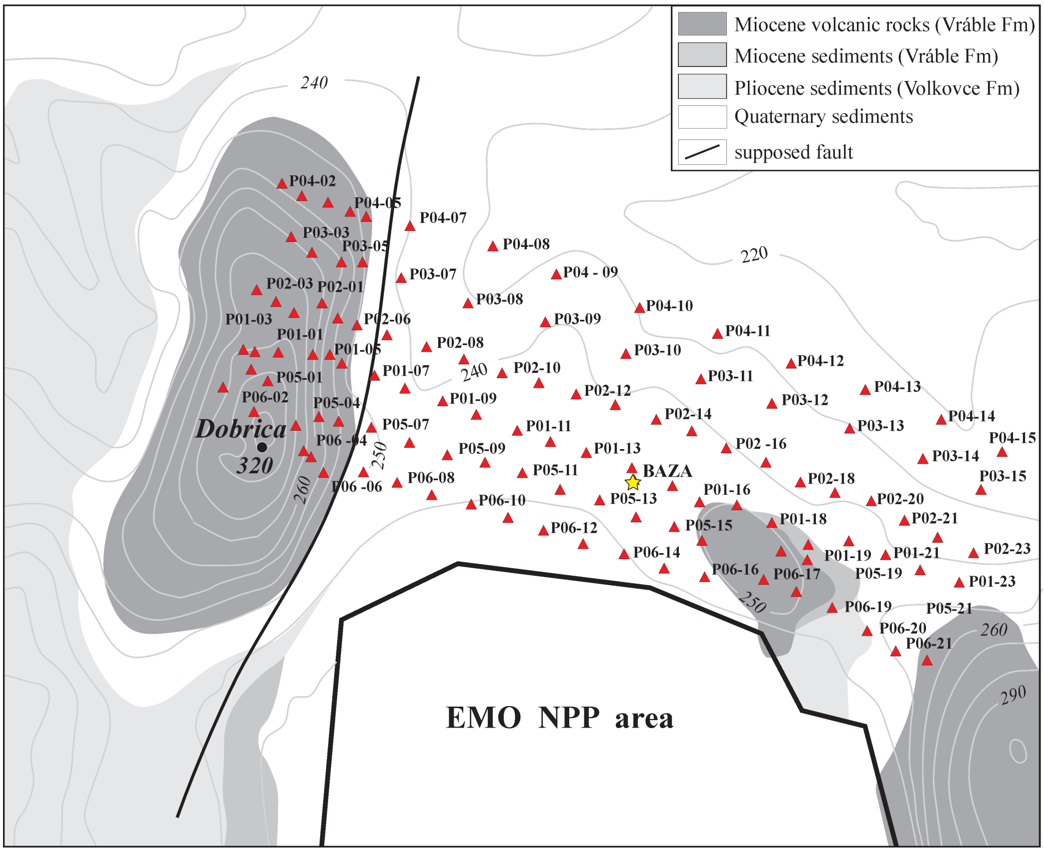

Fig. 2. The map of study area with points of observations (the positions of observation points indicated as red triangles, the position of base station — as a yellow star).

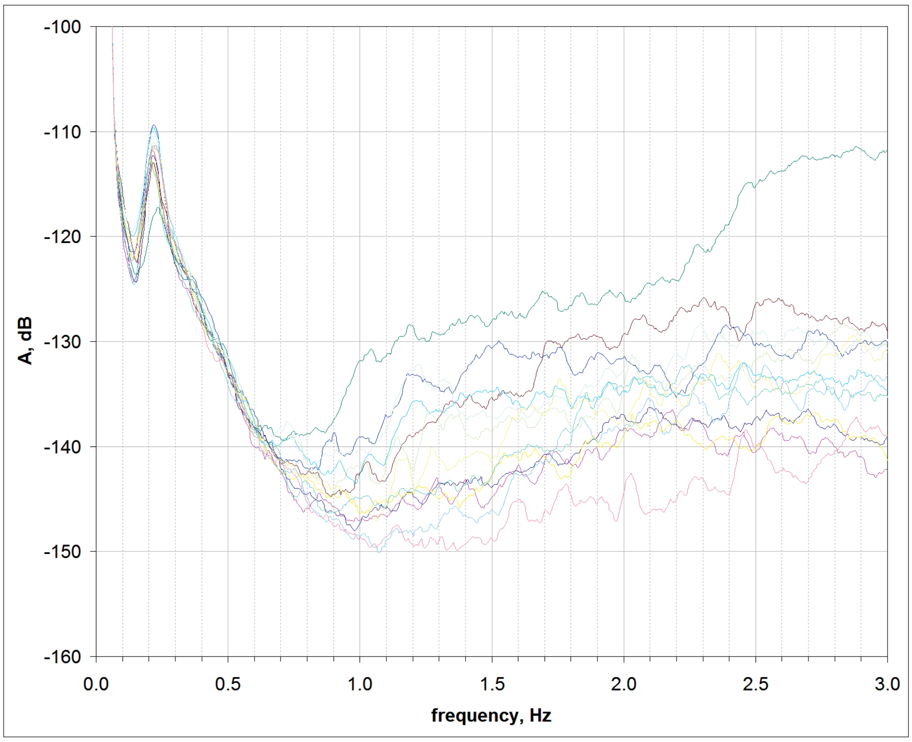

Fig. 3. The observed smoothing power spectra of microseisms along the profile 3.

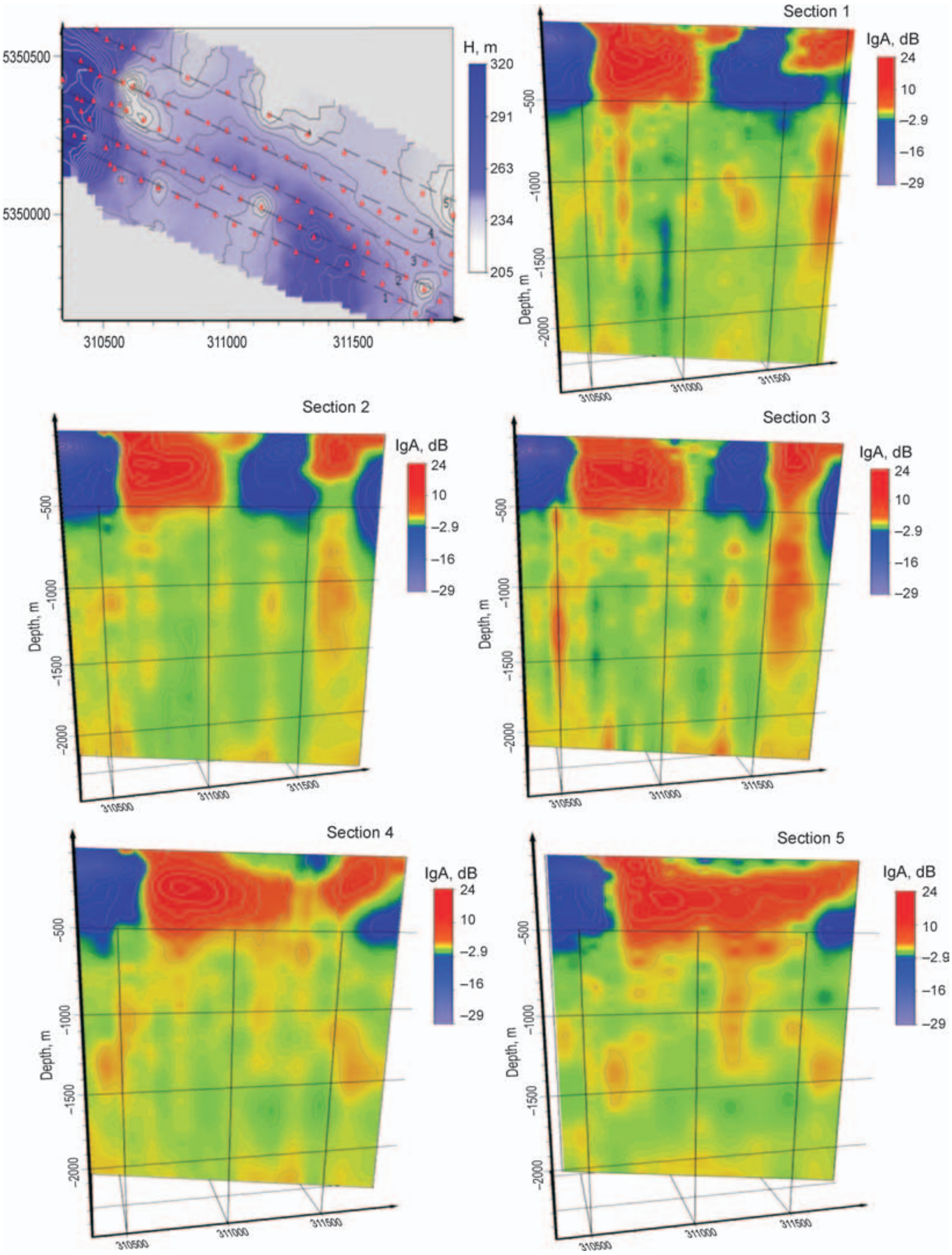

Fig. 4. The variations of spectral amplitudes of microseismic signals of investigated media volume; (**a**) the relief map with points of observations, the dashed lines show the positions of vertical sections presented on the maps (**b–f**).

tween volcanites and sediments; it looks homogeneous enough and this hinders the identification of any fault features there.

3. In the upper part of profiles 4 and 5 it is possible to distinguish the difference of sediment velocities, -2 dB < lg A < 0 dB and by A > 0, (the green colour above the red one).

The more contrasting zones are displayed separately in Fig. 6 as isosurfaces bounding the difference values of microseismic amplitudes. In Fig. 6a the isosurface bounds the high amplitudes area (A > 9 dB), which corresponds to a low velocities area (the sedimentary deposits). In Fig. 6b the volcanic rocks are presented, their velocity properties increase (amplitudes of microseisms decrease A < -2 dB). This figure allows us to investigate the range of the softening and weathering of the volcanics.

The interpretation of the geophysical data shows two different horizons in the geological structure in the EMO vicinity (Figs. 4, 5). The lower horizon could be interpreted as the pre-Tertiary basement rocks (green colour). The upper horizon represents the Miocene volcanites and sediments between them. The Miocene volcanic rocks (blue colour) are

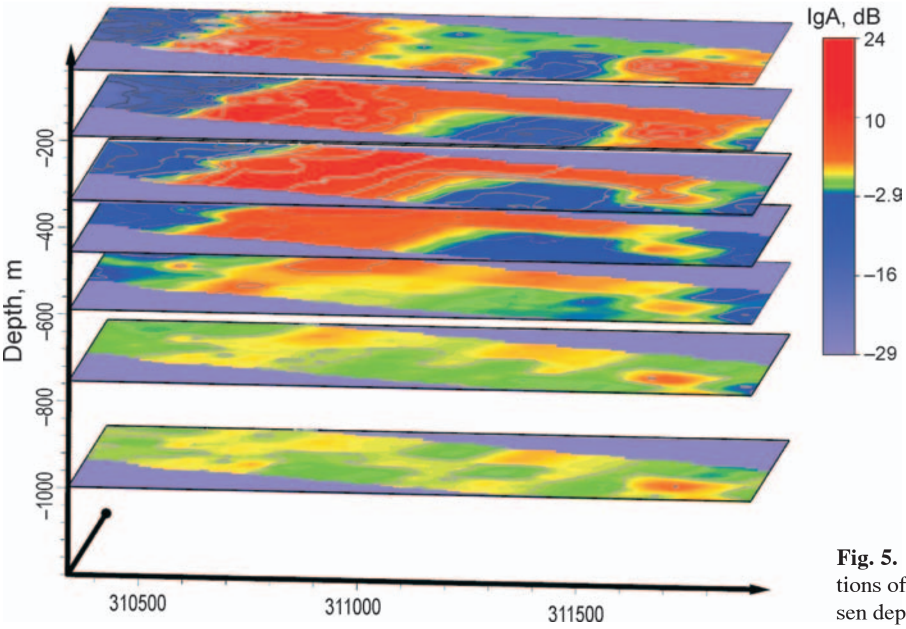

Fig. 5. The maps of spectral amplitude variations of microseismic signals for different chosen depths.

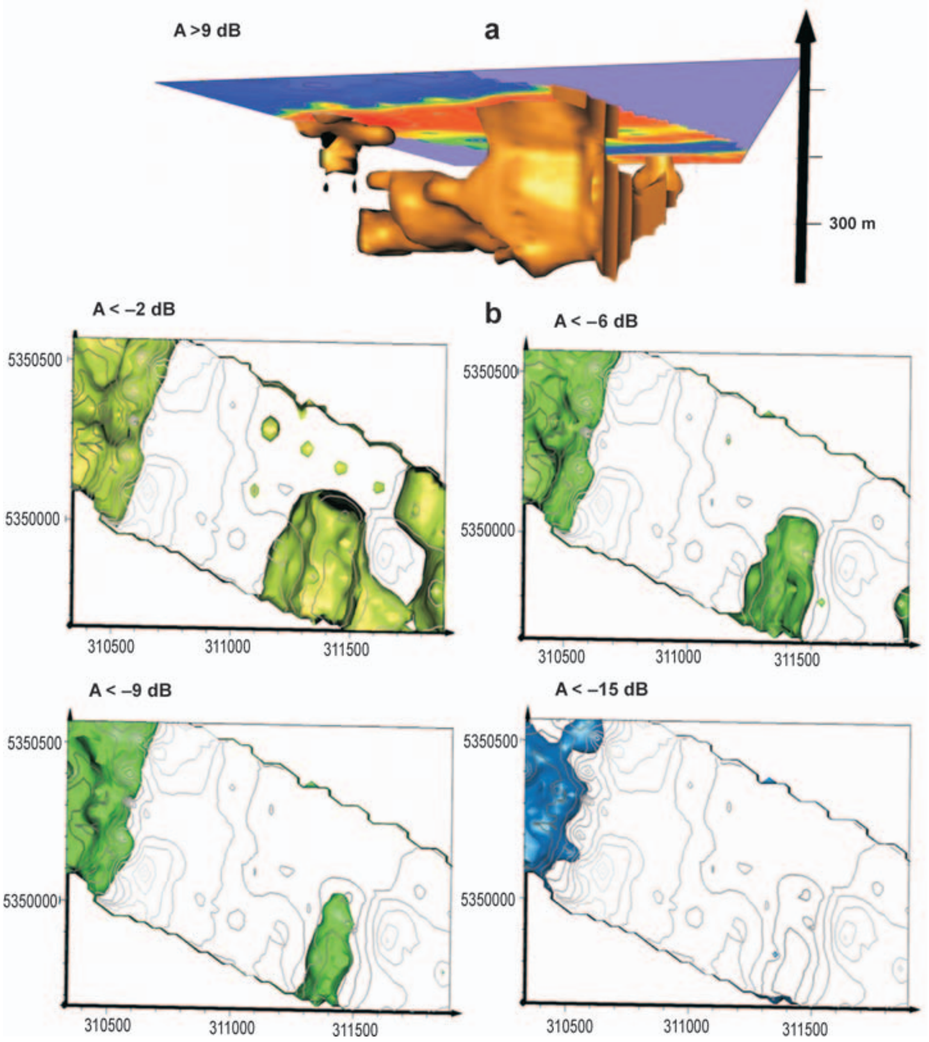

Fig. 6. The isosurfaces bounding the different values of amplitudes; **a** — the isosurface bounding the high amplitudes area of microseisms which correspond to the low velocities area (the sedimentary deposits); **b** — the isosurfaces bounding the different isovalues which correspond to the high velocities area (volcanic deposits).

remnants of lava flows. The lava flows are situated directly over the pre-Tertiary basement rocks. A similar situation is described at borehole GK-6 drilled about 10 km NE from the investigated area (Biela 1978). The Miocene and the Pliocene sediments (red colour) are placed partly on the pre-Tertiary basement rocks, partly on the volcanic lava flows. This arrangement is in good agreement with the lithological and sedimentological character of the Vráble Formation.

Between the Miocene volcanites and the sediments a normal fault (Fig. 2) was formerly supposed, separating the volcanites from the sediments at the east foothill of the Dobrica elevation (Hók et al. 1999). The interpretation of the microseismic investigation results did not prove a fault contact between the volcanites and the sediments. This result is also supported by no existence of adequate offset along the supposed fault in the pre-Tertiary basement (see Fig. 4).

Due to the above mentioned facts, it is possible to interpret this structure as the transgressive contact of the sediments overlaying the volcanic lava flows.

Conclusions

The interpretation of the geophysical investigation results allows us to recognize two floors in the geological structure in the EMO vicinity. The lower horizon contains the pre-Tertiary rock sequence. The upper horizon belongs to the transgressive formation of the Miocene volcano-sedimentary sequence. According to previous investigations (e.g. Priechodská & Harčár 1988; Hók et al. 1995) the upper horizon represents the Vráble Formation. The uppermost part of this horizon most probably belongs to the Volkovce Formation (e.g. Baráth & Kováč 1995). The results of the geophysical investigation show a transgressive contact without a tectonic disruption (fault) between the volcanic rocks and the sediments at the eastern foothill of the Dobrica elevation.

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