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Pliocene to Quaternary tectonics in the Horná Nitra Depression (Western Carpathians)

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Abstract: The Horná Nitra Depression is an Upper Miocene–Quaternary intramontane sedimentary basin. This N–S elongated half-graben structure is rimmed from the west by the marginal Malá Magura fault which is the most distinctive fault in the Horná Nitra Depression, traditionally considered as an active fault during the neotectonic phase. This dislocation is attended by contrasting landforms and their parameters. The low *S-index* of about 1.10, at least two generations of well-preserved faceted slopes along this fault, and longitudinal river valley profiles point to the presence of a low-destructed actual mountain front line, which is typical for the Quaternary active fault systems. Comparison with known normal fault slip rates in the world makes it possible to set an approximate vertical slip rate between 0.3–1.1 $m \cdot kyr^{-1}$. The present-day fault activity is considered to be normal, steeply dipping towards the east according to structural and geophysical data. The NNW–SSE present-day tectonic maximum horizontal compressional stress S_H and perpendicular minimum horizontal compressional stress S_h was estimated in the Horná Nitra region. The Quaternary activity of the Malá Magura fault is characterized by irregular movement. Two stages of important tectonic activity along the fault were distinguished. The first stage was dated to the Early Pleistocene. The second stage of tectonic activity can by dated to the Late Pleistocene and Holocene. The Malá Magura fault is permeable for gases because the soil atmosphere above the ca. 150 meters wide fault zone contains increased contents of methane and radon.

Key words: Western Carpathians, Malá Magura fault, neotectonics, morphotectonics, intramontane depression.

Introduction

The Horná Nitra Depression (HND) is situated in the western part of the Central Western Carpathians. This depression is bounded by the Strážovské vrchy Mts on the west, the Žiar Mts on the north and east, the Tribeč and Vtáčnik Mts on the south (Fig. 1). The HND belongs to a group of small, intramontane back-arc basins in the Central Western Carpathians (Kováč 2000). The depression has a polygenetic structure; sedimentary filling was formed mostly in continental conditions and prevalence of fault tectonics produced a simple block of asymmetrical structure. This paper focuses on neotectonic investigation of the major fault structures. These faults were analysed by the methods of tectonic geomorphology, structural geology, remote sensing data analysis, and geophysics.

In the Western Carpathians, the neotectonics (*sensu* Stewart & Hancock 1994) has been the subject of up to date studies from the 1980's to the present day. The onset of neotectonic processes was considered to be the Sarmatian, after soft collision of the Alpine-Carpathian-Pannonian (ALCAPA) block with the European Platform (Pospíšil et al. 1992). This perspective was not very successful because of diachronism of the collision front and

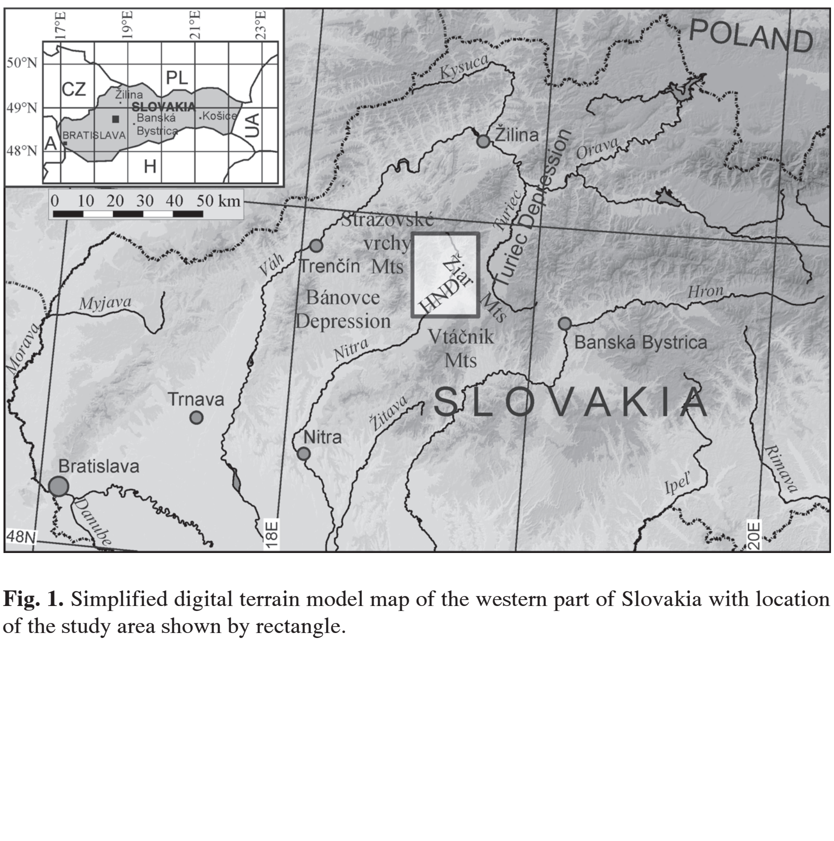

Fig. 1. Simplified digital terrain model map of the western part of Slovakia with location of the study area shown by rectangle.

not exact timing of neotectonic processes. The evolution of the ALCAPA area and current position of its tectonic units is considered to be connected with collision of the Eastern Alps and Bohemian Massif and the lateral escape of crustal fragments from the collision zone (e.g. Ratschbacher et al. 1991; Kováč 2000). These tectonic processes were accompanied by compression and the evolution of diachronous nappe systems at the front of the orogen (Jiříček 1979; Kováč 2000), segment rotation (Csontos 1995), transpressional, transtensional, and extensional tectonic regimes during the Neogene (Fodor 1995; Kováč & Baráth 1996; Fodor et al. 1999; Pešková et al. 2009; Vojtko et al. 2010), and volcanic activity of the back-arc type (e.g. Lexa et al. 1993; Lexa & Konečný 1998). The basic neotectonic research was finalized in the neotectonic map of Slovakia (Maglay et al. 1999; Hók et al. 2000).

In the tectonic evolution of the ALCAPA region, it is possible to distinguish several tectono-sedimentary megacycles, from which the last cycle started at the Miocene/Pliocene boundary (Kováč & Baráth 1996; Kováč et al. 1997). At the same time the tectonic regime changed to extensional and continued up to recent times (Bada 1999). From the point of view of Quaternary geology of the Western Carpathians and Pannonian Basin (Baňacký et al. 1993; Maglay et al. 1993), the neotectonic processes are younger than in previous definition and include tectonic events which have occurred from the Pliocene/Pleistocene boundary (2.558 Ma; Gradstein et al. 2004) up to recent. However, the Pliocene dynamics was important for the Quaternary evolution (Vojtko et al. 2008).

Finally, we define the term 'neotectonics' for the Western Carpathian area as tectonic events and processes which occurred during the Pliocene and Quaternary; from 5.4 Ma to the present-day (Hók et al. 2000; Vojtko et al. 2008). In this paper we present a multidisciplinary approach for neotectonic research.

The aim of the paper is to test and verify the neotectonic activity along the Malá Magura fault zone in the HND using the methods of structural, paleostress, geomorphological and remote sensing data analysis, and geophysical profiling, which are comprehensively presented in chapter "Methods of neotectonic investigation".

Geological setting

The pre-Cenozoic basement of the HND is composed of the Late Paleozoic basement and the Mesozoic cover sequences which belong to the Tatric Unit. The nappe structure of the Fatric and Hronic Mesozoic Units is superimposed over the Tatric Unit (e.g. Mahe 1985). They form elevated structures of the Žiar, Strážovské vrchy and Tribeč Mts and submerge below the Paleogene and Neogene volcano-sedimentary deposits of the HND (Fig. 2).

The lowermost part of the sedimentary fill of the HND consists of a Paleogene sedimentary succession, which represents a mixed facies of the Central Carpathian Paleogene and the Buda Basins provenance (Gross et al. 1970).

This sedimentary succession is discordantly covered by the Neogene deposits, which contain intercalations of products of Neogene volcanism. The Neogene sediments were deposited during two main sedimentary megacycles. The older megacycle is represented by Eggenburgian marine deposition. During the Middle and partly Late Miocene second sedimentary megacycle, typical basin and range structures (Nemčok & Lexa 1990) were formed. Volcanic activity was located predominantly in the south-eastern part (Vtáčnik Mts). The Lelovce Formation (Pontian to Pliocene) represents the youngest Neogene sediments (gravels, sands, and clays) of the HND which cover denuded relief and represent an infill of paleovalleys.

The Pleistocene sediments belong to the highest parts of the HND sedimentary fill. They are deposited at the foothills of the Strážovské vrchy Mts as huge alluvial fans. The remnants of the Lower Pleistocene terraces are located 120–150 and 90–110 meters above the Nitra River floodplain. The Middle Pleistocene sediments are spread out in the morphologically lower positions and they are developed in 3–4 levels, alternately on the right and left side of the Nitra River. The sedimentary bodies of the Middle Pleistocene are situated at the levels 45–90 and 20–40 meters above the Nitra floodplain. The Upper Pleistocene sediments consist of two typical accumulations of sandy gravels. The youngest morphological level (approximately 3–16 meters above the Nitra River) is formed by the flat lying Würmian alluvial fans. The maximum thickness of the fans varies from 4 to 10 meters (Šimon et al. 1997a,b). The Holocene was mainly characterized by fluvial deposition along the rivers. The thickness of fluvial deposits of the Nitra River is generally 2–5.5 meters.

The Pleistocene and Holocene travertines were formed along activated faults (Šimon et al. 1997a,b; Kernátsová in Gajdoš et al. 2005). Holocene travertines are predominantly situated near Bojnice Spa and form individual mounds which often cover Pleistocene travertine (Fig. 2).

Methods of neotectonic investigation

Neotectonic activity of faults was tested by various methods of structural geology, geophysics, and morphotectonics supplemented with remote sensing data interpretation. The most eligible used methods, which were partly modified, are described below.

Investigation was focused on testing neotectonic activity of regionally important faults. The most important structure in the area is the Malá Magura fault, which was analysed in detail and the results are presented here. The same methods of research were also used for other important faults affecting the basin such as the Pravno, Šútovce, Hájske, Necpaly and Brezany faults.

Structural and paleostress analysis

Structural research was focused on brittle structures related to the Neogene–Quaternary paleostress field, including travitonics (*sensu* Hancock et al. 1999). It included field structural research, which involved measurement and collection of field structural data, kinematic analysis of slickensides and processing of structural data including orientation and paleostress analysis. Combination of field meso-scale observations with

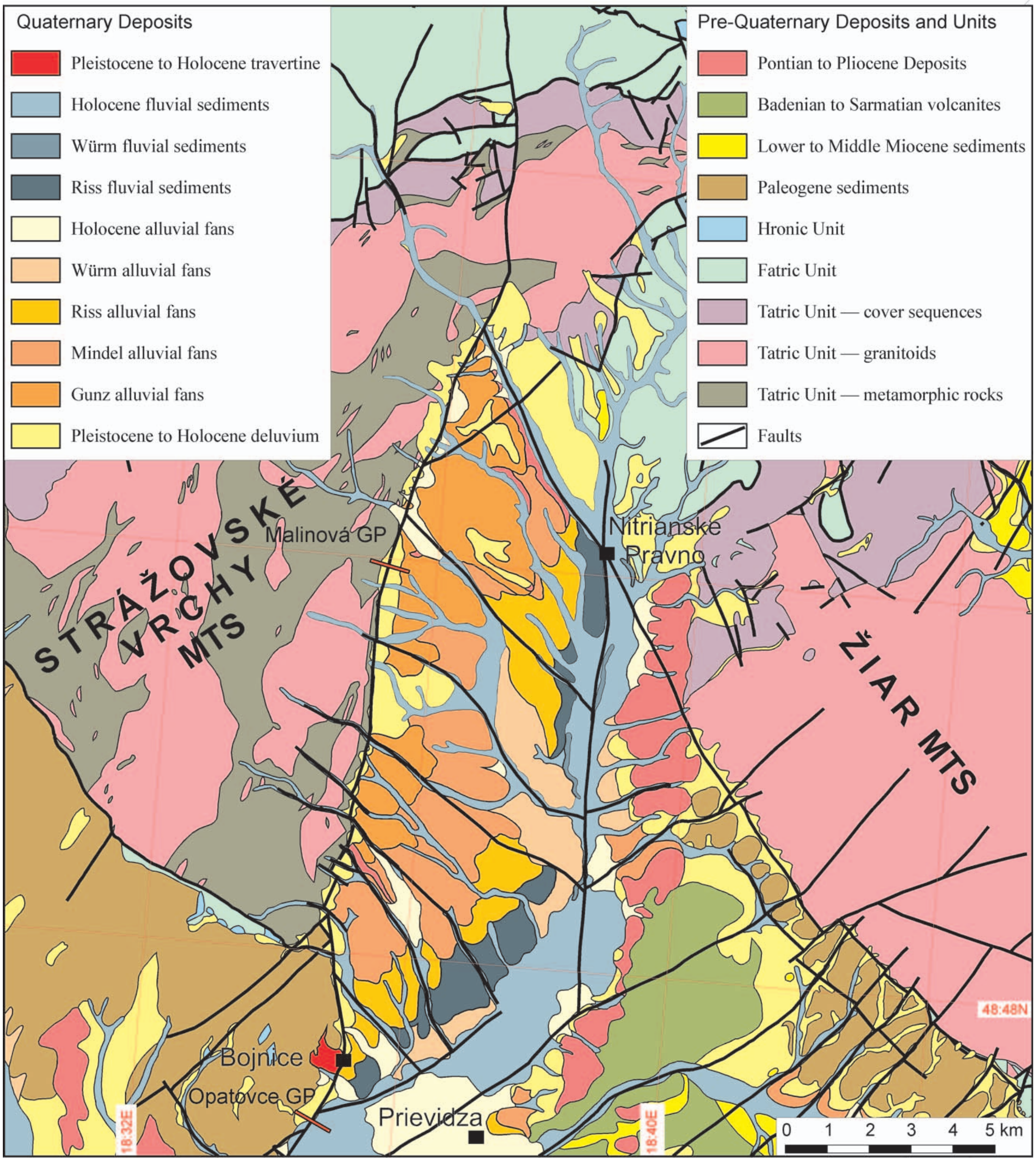

Fig. 2. Simplified geological map of the Horná Nitra Depression with main fault structures (according to Šimon et al. 1997a, modified). Note: thick red lines indicate position of geophysical profiles.

map-scale structures analysis has been applied. It has been accepted, that small-scale structures can be related to large regional structures and that both scales reflect the same dynamics and kinematics (Angelier 1994). The inversion method based on the Wallace (1951) and Bott (1959) assumption that the slip on a plane occurs in the direction of the maximum resolved shear stress was used for paleostress analysis.

Geomorphological analysis

According to Urbánek (1999), geomorphological analysis is a method covering a wide range of particular steps. In the first step, the identification of the tectonically-controlled landforms was done. The topographic data, precise Digital Terrain Model (DTM), other DTM-derived data and satellite imagery data were used during the identification process. The DTM used in this study was derived from vectorized contours of 1 : 10,000 topographic maps with cell size of 5 m in the S-JTSK (Datum of Uniform Trigonometric Cadastral Network) coordinate system. Longitudinal valley profiles were constructed on vectorized contours at a scale of 1 : 10,000.

Morphotectonic pattern

Many models describe the specific landforms of tectonically active relief, their spatial distribution, possible origin and further evolution (Thornbury 1956; Costa & Fleisher 1984;

Stewart & Hancock 1994; Burbank & Anderson 2001; Minár 2003). The spatial distribution of the identified landforms helps us to identify important features: lineaments and morphotectonic pattern. Particular lines may be categorized according to their sums of segment lengths and the robustness of the landforms, which are cut or limited by a line. It appears that analyses of DTM underlain with shaded relief (illuminated from different azimuths) are very suitable tools for identification of the morphotectonic pattern. On the other hand, the important geomorphic markers are preserved sometimes in relief details. The morphotectonic pattern can help to reveal or append some important information about the complex regional fault system. The following step identification, spatial distribution and characteristics of facets, denudational remnants of flat surfaces, and their interrelationships were crucial points in geomorphological analysis.

Linearity of mountain front

The linearity of the mountain front was quantified by the slightly reinterpreted *S-index*, introduced by Bull & McFadden (1977) using the formula:

$$S = L_{mf}/L_s$$

where L_{mf} is the total length of the considered segment of the mountain front, and L_s is the length of abscissa, which connects the end points of the considered segment of the mountain front. The L_s value should reflect the real course of the fault system, on which the mountain front was developed.

The *S-values* close to 1 indicate the mountain front predisposition by young tectonic processes. The higher resulting value indicates the degraded mountain front, which implies possible tectonic inactivity (interconnected with weathering conditions) or extremely fast weathering processes. However, the authors of the *S-index* were considering especially the straight mountain fronts. In the Western Carpathians, tilted and rotated blocks of various volumes are common. This produces complex fault systems, not only straight but often curved patterns. In this case the use of the L_s value in the traditional way might produce faulty results. Therefore, we experimented with tuning the L_s value. The considered mountain front has rather the shape of the 2^{nd} quadrant of the ellipse elongated according to the *Y* axis. The length of this segment was used to evaluate the value of *S*.

Thirdly, it is likely, that the fault system limit well-preserved facets and underlying flat base surfaces. Therefore in this case, the idealized mountain front defined by the flow-line which delimits the lower facets' *L* edges was used.

Geomorphological profiling

Profiling is still one of the important tools of tectonic geomorphology. The profile ridge lines usually preserve the most of the significant landforms on the slopes. If some remnants of the planated or structural surface are presented, their occurrence is often preserved on ridges. They preserve the oldest micro- and meso-forms on the local slope, while the forms inside are usually denuded by later slope degradation (e.g. sliding and young valley propagation). The longitudinal profiles of valley floors belong to the second important group. There are plenty of methods, which help us to requantify the length and height values (e.g. computation of equilibrium, profiles, and various indices). However, our experience shows that, because of data quality, in the large-scale morphotectonic research the visual analysis and expert intervention of each particular profile plays the most important role.

Another method of evaluating longitudinal profiles is the analysis of *K-index* diagrams, which show the rate of concavity of the valley profile (Zuchiewicz 1980, 1995) using the formula:

$$l_k = K\text{-}strech/H_h$$

where *K-stretch* is the longest perpendicular distance from the triangle's hypotenuse, H_h is the length of the height of the triangle, whose hypotenuse is the diameter of the triangle.

The *K-stretch* might be measured on a graph, the mathematical computation of which was introduced by Novotný (2006). According to Zuchiewicz (1980), the rate of valley concavity grows with the lowering of the vertical tectonic activity. The position of *K-stretch* divides the valley with prevailing bottom erosion in the upper part and prevailing lateral erosion in the lower part.

Geophysical methods

Geophysics was used for testing and characterization of fault zones on the basis of physical behaviour. Electrical methods [vertical electric sounding (VES), low frequency method (dipole electromagnetic profiling (DEMP), very low frequency (VLF)), spontaneous polarization (SP) and pulse electromagnetic emission (PEE)], soil radon and methane measurement were used to obtain this information.

Results and interpretation of neotectonic investigation

Upper Neogene to Quaternary stress field evolution

In the northern part of the HND, only a few outcrops were suitable for structural analysis because unconsolidated Quaternary alluvial fans almost completely cover older strata. Fault-slip analysis was also carried out at outcrops in the neighbouring Bánovce and Turiec Depressions. For the young tectonic evolution of the HND relief and adjacent mountains, the Late Miocene to Holocene tectonic regimes and deformation played the crucial role. This young tectonic evolution was controlled by three deformational subphases characterized by the NW–SE compression, NNW–SSE extension, and WSW–ENE extension. Compression oriented NW–SE is considered to be Late Miocene (Late Pannonian to Pontian) in age because it is younger than the NE–SW compression prevailing in the Upper Sarmatian to Lower Pannonian strata (Hók et al. 1995). These compressional tectonic regimes were followed by normal faulting during the neotectonic phase. The extensional tectonic regime with the NW-SE-oriented principal axis σ_3 played an essential role during the Pliocene (Vojtko et al. 2008; Králiková et al. 2010). The NE–SW tension

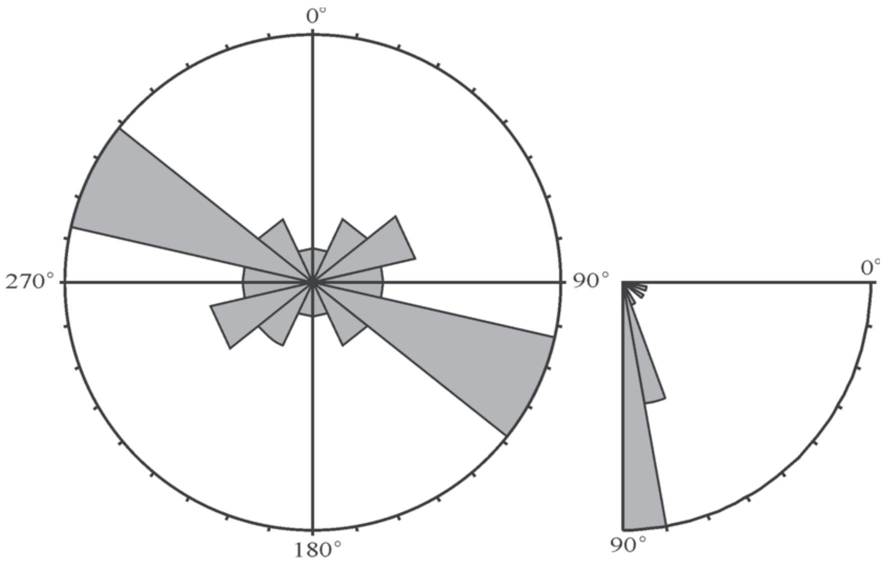

Fig. 3. Rose tectonogram of joints measured in the Bojnice Spa travertine mounds. Note: azimuth interval 26°, maximum of azimuth data (39 %); interval of dip 10°, maximum of dip data (56 %).

is the youngest deformation event described from the HND and Nitrianska pahorkatina Lowland. This deformation phase was precisely dated to the Late Pliocene to Holocene timespan (Vojtko et al. 2008).

Near the town of Bojnice, deformation of travertine mounds was also studied but no fault slip data were obtained. However, a systematic joint pattern (37 joints) was identified and it indicates that the travertine mounds were deformed in the condition of the NE–SW oriented tension in general (Fig. 3). Unfortunately, using the obtained data, we were not able to responsibly determine a tectonic regime.

Geomorphological analysis

Geomorphological parameters

The lineaments, depicted as the boundaries or interconnections of the landforms control the morphotectonic pattern of the study area (Fig. 4). The lines are subdivided into four hierarchical orders (from continuous to dotted lines) reflecting the robustness and properties of the potentially tectonic landforms, which delimit the particular line and length of the lineament in the specified direction.

The resulting morphotectonic pattern is complicated as well as the tectonic preconditions of the study area. It is possible to distinguish a few inner sub-patterns. The most sensible are the lines, which divide the mountain ranges and the basin. Their course is obvious on satellite images in visible and infrared as well as radar wavelength spectrum. In most cases they copy the identified mountain fronts. They delimit contrasting forms (such as faceted slope and flat surface), interconnected along the same line (alternatively the same system composed of more particular lines). Within the broader view of the study area, three such systems were identified. Two of them have the NW–SE direction (SW delimitation of the Strážovské vrchy Mts and the HND; the SW delimitation of the Žiar Mts

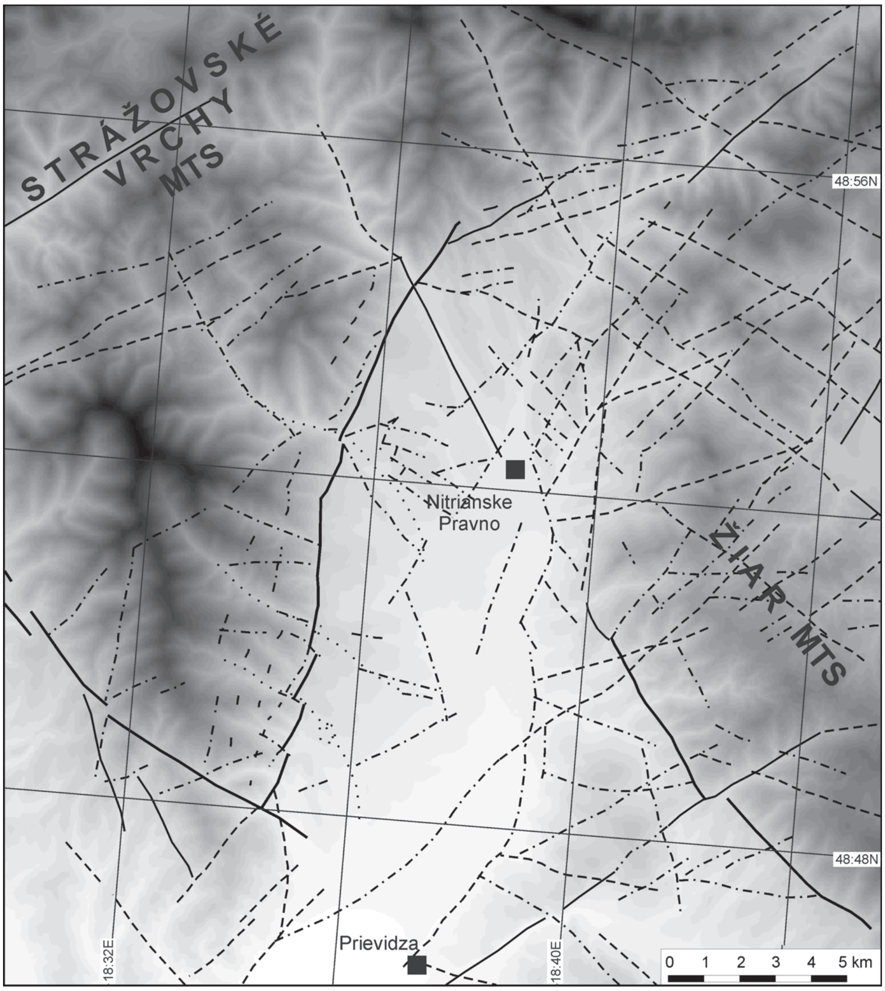

Fig. 4. Morphotectonic pattern in the studied area.

and the HND). Both of them have a rather linear shape. The third system is a non-linear delimitation of the SE part of the Strážovské vrchy Mts and the HND. In general, this is the N-S striking system, which in its northern part slightly turns to the north-east (Malá Magura fault).

The northern margin of the focused area is quite complicated. A few parallel ENE–WSW lines, which in the WSW part run further into the Strážovské vrchy Mts and delimit its core massif in the north, were identified. The morphotectonic pattern within the Žiar Mts is rather regular, mostly formed by the NW–SE lines (parallel to its mountain front) and NE–SW cross-lines (Fig. 4).

The landforms in the basinal area are usually less robust than the morphostructures in the mountain area and connections with potential tectonic activity are usually less preserved in the landforms. Therefore, the lines have lower tectonic significance. However, the spatial distribution of the identified landforms in the basinal area reveals the possible block structure. Most of the lines in the eastern and northern parts of the basin are the continuation of particular lines in the mountainous area. The morphotectonic pattern in the western (the core of study area) part is hard to build just from relief features and it is quite unique (Fig. 4). We will pay attention to this in a more detailed analysis.

Mountain front sinusoity (S-index)

The Malá Magura fault occurs in the context of the morphotectonic pattern. In the relief, it is represented especially by contrasting landforms (faceted slopes vs. flat surfaces), which can also be associated with the eastern mountain front of the Strážovské vrchy Mts (Fig. 5). The *S-index*, according to the computation introduced by Bull & McFadden (1977), reaches the value of 1.17 within the study area (Fig. 6). This is not far from value 1.0, which expresses the identity with the non-destructed mountain front line. However, our experimental method gives even lower values (S_{ideal} = 1.09; $S_{ellipse}$ = 1.10; for further information see Fig. 6). These low values indicate tectonic processes, which often create such linear features in the relief. We take into consideration, that weathering processes in the neotectonic period in the Western Carpathians were highly active, in general. The fact, that the mountain front is not very destructed by exogenic processes yet, supports the hypothesis about Quaternary tectonics, which have played a considerable role in the shaping of such contrasting landforms.

Fig. 5. Slope angle map of the Horná Nitra Depression and adjacent mountains. The grey colour indicates inclination of slopes in degrees. Solid lines represent faults.

Mountain front faceting

Along the entire mountain front we can distinguish three groups of landforms. The first are the faceted slopes situated to the west of the studied fault system; flat surfaces are situated to the east. Both groups of landforms fringe the mountain front on either side. The third group includes the valleys, which cross and disintegrate this system of landforms.

The system of facets fringing the studied fault system is composed of more subsystems (Fig. 7). The Malinovský stream divides the facets into two groups. The southern group contains composite facets. The younger generation is situated above the mountain front line. These facets are still well-preserved, gradually dissected by incipient headward erosion of recently seated valleys. They are incorporated into a larger system, whose facets are strongly degraded by long-term bottom valley erosion. The remnants of their genuine shape have been only identified. The existence of composite facets points to multi-stage tectonic development of the studied slope. In the northern group, only front facets were identified. However, there are some geomorphic markers which indicate also the older generation, but this system is in a higher stage of degradation.

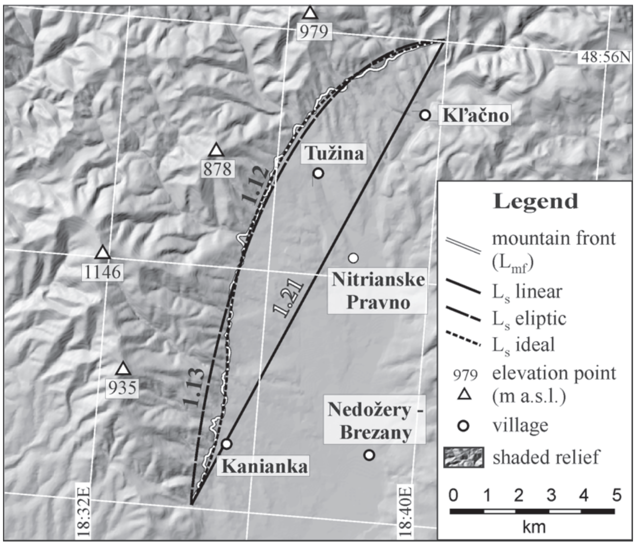

Fig. 6. Three alternatives of the *S-index* calculation.

The front facets are the most interesting landforms for active tectonic assessment. (Fig. 7). A few dependencies were noticed. First of all, robustness and the vertical range gradually increase from the south to the north. The southern facets achieve relative heights below 200 m, the northern rise up to 400 m. In the scale of long-term development, this feature is typical of the scissor-like effect in the normal fault system.

Secondly, a few remnants of flattened surfaces were identified inside the facets. Some of them are situated randomly (which can be caused, for example, by deep-seated block creeping), others, however, relate among each other on the basis of average altitude. Their absolute altitudes vary from 500 m a.s.l. in the south up to 630 m a.s.l. in the northern part on all studied facets (in case of facets 1 and 2 these flattened surfaces create the tops of the facets). Expressing this in relative values, the flattened surfaces occur at 120–150 m above the mountain front line, which clearly appears in the plots of selected ridge profiles (Fig. 7). This indicates that the vertical effect of tectonic process on the Malá Magura fault could have been interrupted and for a short time the passive processes took over the dominant role in the relief shaping and built the pediment. However, this stage did not last for a long time, because the pediment spread only very locally, presently witnessed by the analysed denudational remnants.

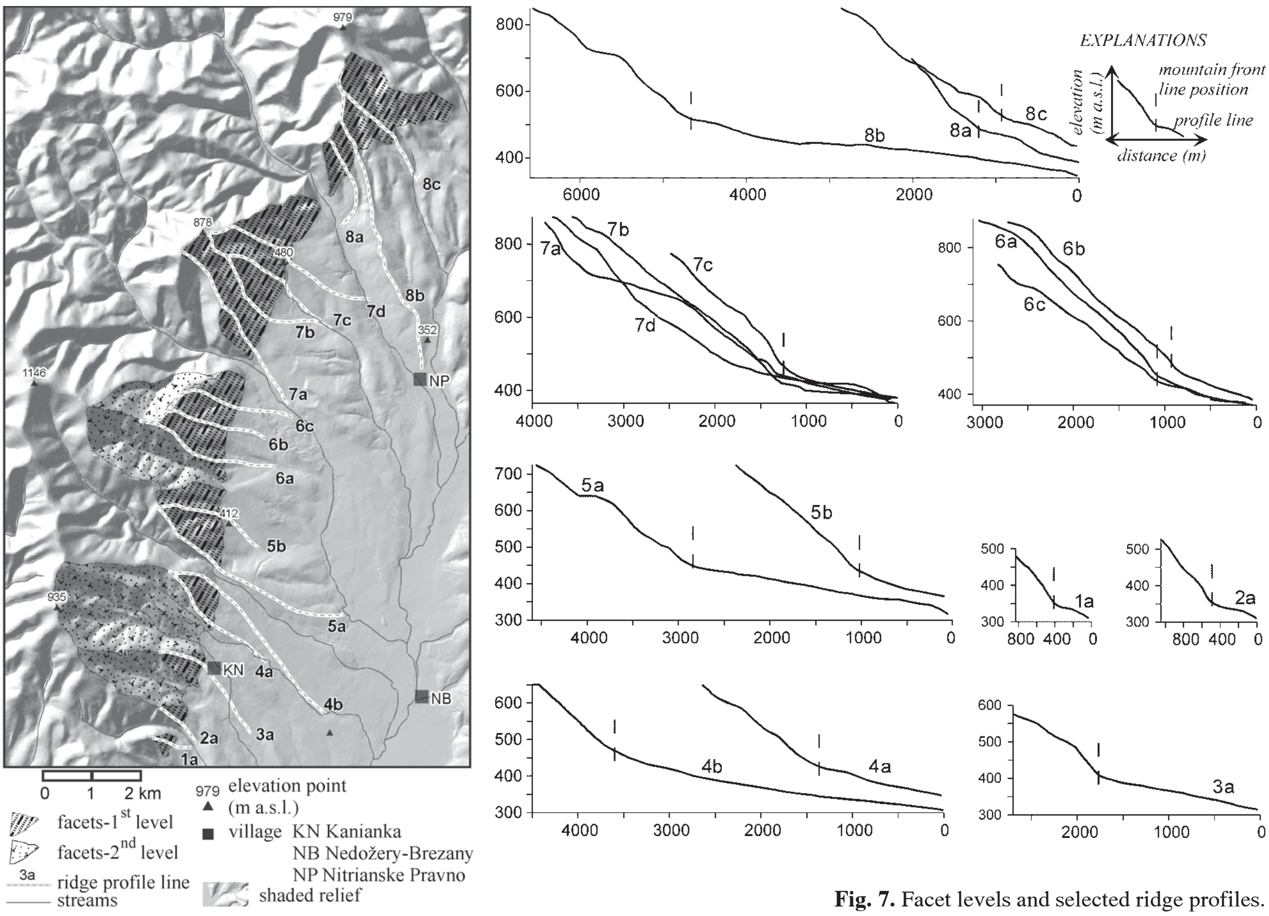

Fig. 7. Facet levels and selected ridge profiles.

The inclination of the faceted slopes computed on topographic data reflects the trend of inclination of the facets and ignores the meso- and micro-forms on the slope. The computation of the average value of inclination on DTM produces rather higher values, while it also involves the detailed modelling, such as small valleys with steep slopes. The difference between these two values is evident especially in case of facets 3, 7, and 8, which are at the same time the most dissected ones from the group of studied facets. The facets 5 and 6 are less dissected, the smallest ones (facets 1 and 2) reflect only the initial stages of the slope erosion (Fig. 7). Compared to other faceted slopes in the surrounding mountain ranges of the HND, the facets above the Malá Magura fault are almost "fresh".

Characteristics of alluvial fans

An interesting mosaic of landforms is found on the opposite site of the faceted slopes, in the basinal part of the study area. Plenty of alluvial fans of different volume, shape and age were described. East of the mountain front line (in relation to sudden change of slope inclination), the numerous small Upper Pleistocene to Holocene alluvial fans or in some cases debris flow accumulations were identified (Fig. 2). They are composed of sandy-gravel material, redeposited from small valleys cut into the faceted slopes on the eastern flank of the Malá Magura Mts.

The medium size streams cut through their own Lower and Middle Pleistocene depositions, transport the material and develop their alluvial fans in the central basin. The largest volumes of transported and deposited sediments naturally occur around the dominant streams, which have developed catchments also inside the mountain range (the alluvial fan of Poruba, Chvojnica, and Tužina streams). In general, all alluvial fans occur on the eastern side of the mountain front line (toward the basin), which supports the assumption of the recent activity of the Malá Magura fault.

In the case of the Chvojnica valley, the Upper Pleistocene to Holocene alluvial fans cap the older sediments just on the contact of the mountain and basin zone (Fig. 2). This is known as alluvial fan superposition and clearly points to tectonic uplift of the mountains or tectonic subsidence of the catchment. However, the probable interpretation of formation of the Upper Pleistocene to Holocene Chvojnica stream alluvial fan could be rooted in a more complex process involving deep-seated block creeping and massive landsliding. This is indicated by three translated and rotated blocks (approximately 0.5 km^2 each) localized on the left bank of the present Chvojnica stream. On the right bank forms of recent landsliding are evident. Active tectonics often influences such a pattern of landforms.

Longitudinal valley profiles

Information about tectonic activity of the mountain front system is also found in the longitudinal profiles of selected valleys (Fig. 8). Unlike the young valleys embedded into facets with simple concave longitudinal profile (cases 2, 3), the developed valleys have more complex longitudinal profiles. They are composed of two dominant parts: the upper part with a concave profile and the lower part with an almost linear (e.g. cases 1, 4, 5, and 8) or even slightly convex longitudinal profile (case 9). The two levels of longitudinal profiles do not reflect their equilibrium. The knickpoints occur around the absolute elevations between 400–500 m a.s.l., which is the space where the mountain front line fluctuates. The regimes beneath and above these points are different. The linear (or even convex) profile lines indicate that the potential uplift of Strážovské vrchy Mts has been faster than headward erosion of the streams. The valley gradient in the basin area is in some cases higher than the gradient in the lower mountain part. The convex bending of the largest Tužina stream also indicates possible subsidence of the central part of the basin (Fig. 8).

Geophysical measurements

Geophysical methods have been used to test the neotectonic activity of the Malá Magura fault (VES, SP, VLF, PEE and some others). The measurements were carried out on two profiles perpendicular to the faults system. These profiles (near Malinová and Opatovce villages) were located on the Malá Magura fault (Fig. 2).

Malinová geophysical profile

Geophysical measurements by VES, SP, VLF, PEE, magnetometry, radon and methane content measurements in soil air were carried out on this profile (Fig. 9). The results of the VES measurements indicate that the Malá Magura fault is a normal one with a faulted zone about 120 meters wide. In this zone the radon emanation has a higher content and changeable rate in the mountain part of the profile that is consonant with the characters of radon production in that environment. Increased methane concentrations in gas above the fault zone implies a permeable zone for gas emanations. Similarly, the negative anomaly of SP indicates a water drainage process in the fault zone. The curve of PEE shows a local maximum above the fault zone, that indicates mechanic stress in the local part of the fault system which is the source of the measured electromagnetic field. The resistivity curves measured by VLF (deeper range) and DEMP (shallower range) specify the location of the contact zone between the Tatric crystalline rock of the Stražovské vrchy Mts (Fig. 9 — block A) and the Cenozoic deposition of the HND.

Opatovce geophysical profile

The results obtained on this profile demonstrate very similar geophysical characteristics to the previous profile (Malinová). The fault zone divides the Pontian/Pliocene Lelovce Formation from the Upper Pleistocene to Holocene alluvial deposition. Increased intensity of the PEE fields is found at the foot of the mountains and also approximately 50 m from Holocene alluvial plane. The first peak is interpreted as a gravity mass flow towards the alluvial plane; the second one is a real discrete boundary of the Malá Magura fault. The shape of the VLF and DEMP curves document the sharp change between the rock mass of the mountain front and the depression. Radon

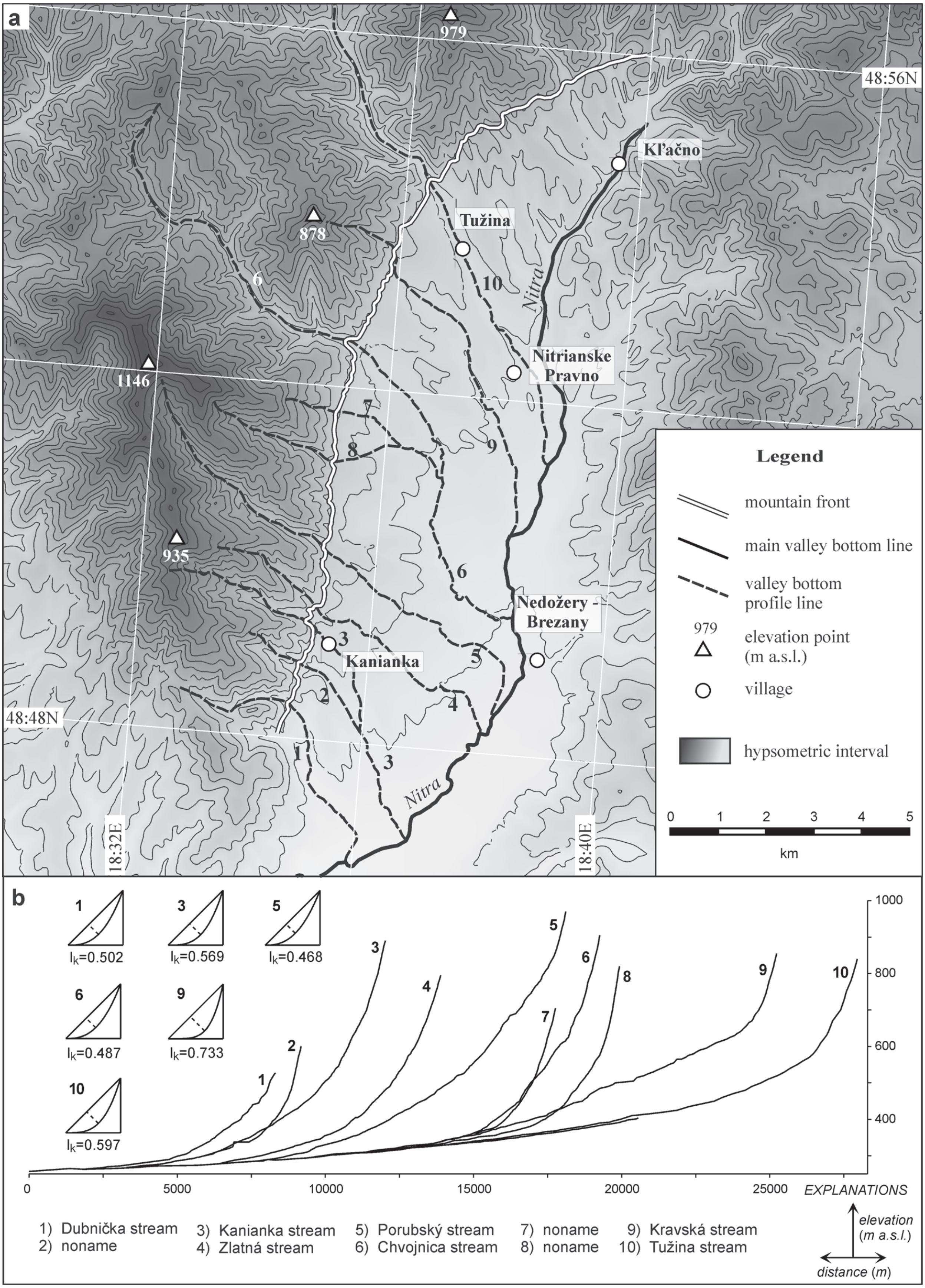

Fig. 8. Analysed streams in the studied area (**a**) and their longitudinal valley profiles (**b**).

measurement carried out in this profile shows that the mountain front has a lower radon content in the soil atmosphere than the alluvial plane. The maximum of the radon emanation is located above the Malá Magura fault zone, it is considered to be of tectonic origin. The shape of the SP curve is characterized by lower values in the mountain front and higher values in the depression (Fig. 10).

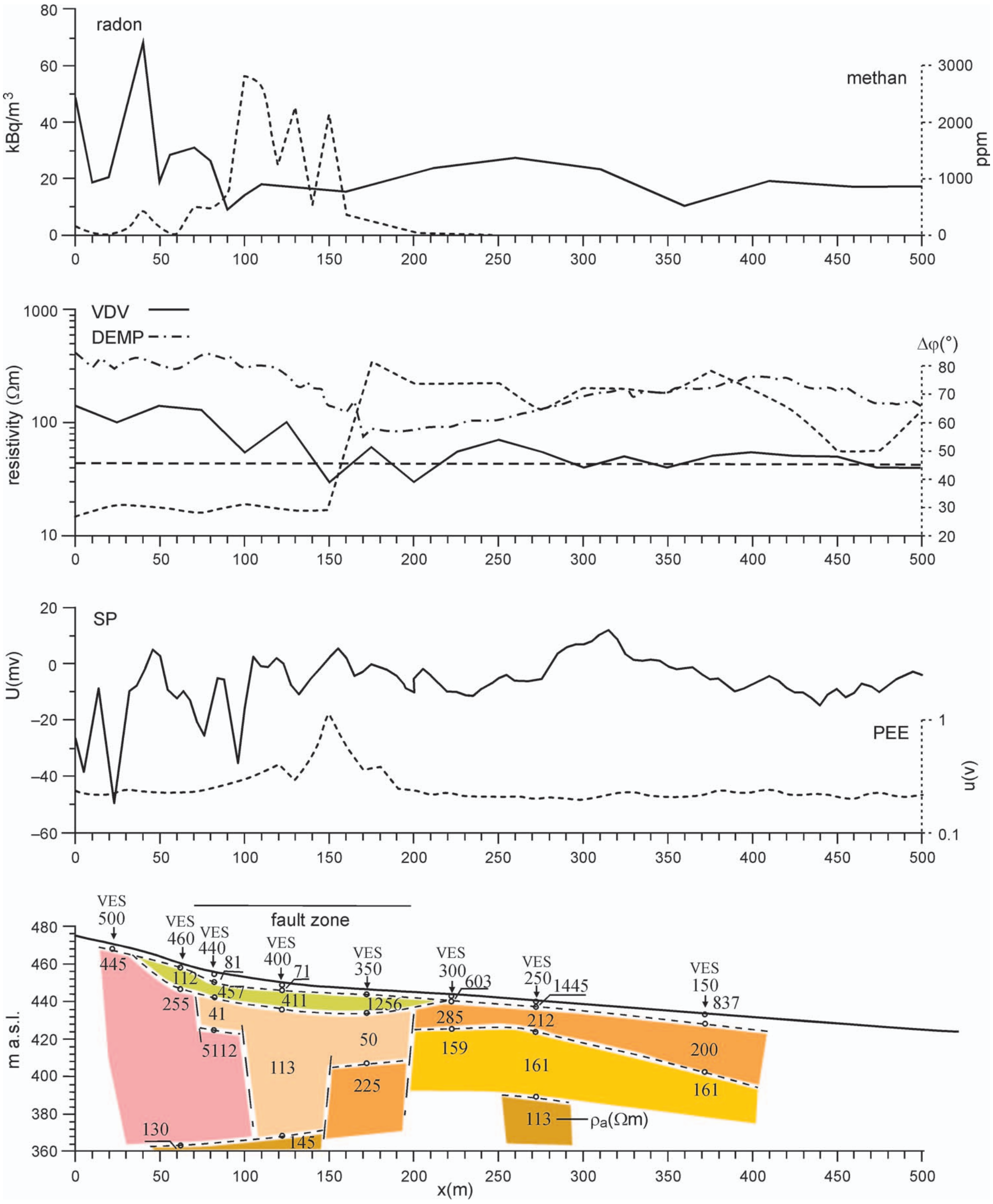

Fig. 9. The Malinová geophysical profile. Shape of the curves of Rn and CH_4 concentration in soil air; resistivity (deeper) and phase shift curves from VLF and resistivity (lower) curve from DEMP; SP and PEE curves and interpreted vertical cross-section along the profile constructed by the VES method. Contact between crystalline basement of the Strážovské vrchy Mts and the Horná Nitra Depression have the form of a fault zone with unconsolidated tectonic breccia.

Discussion

Ruptures in the zone of an active normal fault can be characterized as a series of linear fault segments separated by transfer zones with more complex geometries. The linear trend results from the fact that most normal faults intersect the surface at high angles; the dip is generally 60° and more. It means that the map trace of the fault is only slightly affected by surface topography. In many cases, normal faults also approximately define a boundary between an erosional domain in the uplifted footwall and a depositional, nearly horizontal domain above the downthrown hangingwall. This is also the case of the Malá Magura fault, which creates a linear tectonic boundary between two different domains.

Heights and stages of dissection of triangular facets are indicative of relative tectonic activity (Bull & McFadden 1977). Basal sections of triangular facets may resemble degraded fault planes (Ellis et al. 1999; dePolo & Anderson 2000; Bull 2008). Heights of basal triangular facets originating on the western side along the Malá Magura Mts are between 180–400 m above the alluvial plain of the HND. Comparison of these data with known normal fault slip rates (dePolo & Anderson 2000), it is possible to set approximately vertical slip rate between 0.3–1.1 m·kyr^{-1} (from the south toward the north).

Currently, horizontal movements along dislocation cannot be excluded, although no reliable data confirming their existence has been discovered. An indirect argument for the strike-slip movement tendencies emerges from orientation of the fault within the recent stress field. The movement along the Malá Magura fault can be characterized by oblique slip movement (combination of left-lateral and normal slip components) which was the result of the ENE–WSW relative tension and minor NNW–SSE relative subhorizontal compression. However, geophysical characteristics of the fault zone identified at two transversal profiles indicate a recent extensional regime of the Malá Magura fault zone (Figs. 9, 10). Taking into account

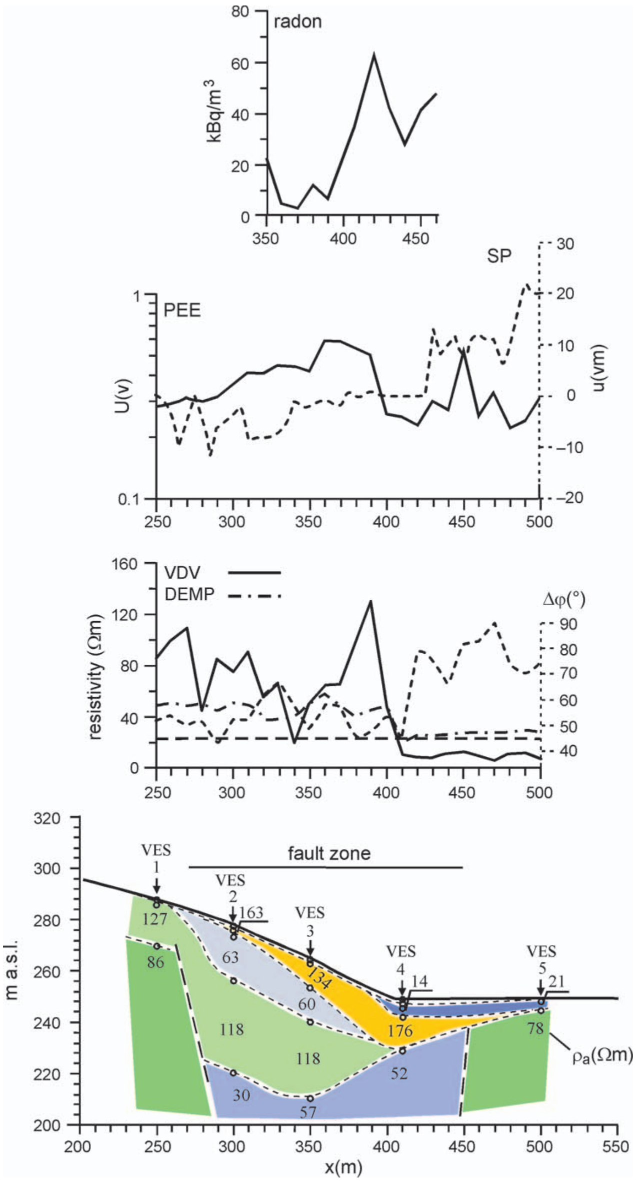

Fig. 10. The Opatovce geophysical profile. Shape of the curve of Ra concentration in soil air; PEE and SP curves; resistivity (deeper) and phase shift curves from VLF and resistivity (lower) curve from DEMP and interpreted vertical cross-section along the profile constructed by the VES method. The fault zone is also extensional as on the Fig. 9 and is filled by blocky breccia.

the described changes of the Cenozoic tectonic stress field in the Horná Nitra area (Hók et al. 1995), as well as in the wider region of the Western Carpathians (e.g. Marko et al. 1995, 2005; Fodor et al. 1999; Pešková et al. 2009; Vojtko et al. 2010) a multi-stage evolution of the Malá Magura dislocation is considered. The recent fault is a reactivated Neogene dislocation, an inherited fault, acting mostly as a basin opening dislocation, but also as an accommodation structure of neotectonic deformations.

Young tectonic movements can be observed from the Pontian to the Late Pleistocene times. The age of the Quaternary alluvial fan deposits is based upon their superposition, the age of travertine mounds is based upon biostratigraphical data (Kernátsová in Gajdoš et al. 2005). However, more precise dating of alluvial fans and the Lelovce Formation for more exact timing of the HND neotectonics is needed. For example, application of cosmogenic nuclides to date alluvial fans is highly recommended for the future. The Lelovce Formation (Pontian–Pliocene?) is the youngest widespread formation in the HND and was used for neotectonic studies, because the faults which disrupted this formation were considered to be neotectonic faults.

Conclusions

The morphotectonic, geological, sedimentological, structural, and geophysical pieces of evidence of the Malá Magura fault Quaternary activity have been summarized herein. The fault is a typical mountain front dislocation, which separates the Strážovské vrchy Mts and the HND. This distinct dislocation is attended by contrasting landforms and their parameters. The low *S-index* about 1.10 (Fig. 6), well-preserved, at least two generations of faceted slopes along this fault (Fig. 7), and convex-linear longitudinal river valley profiles (Fig. 8), the presence of low-destructed mountain front line are typical features for the Quaternary active fault systems.

The results of geophysical methods specified the location of the Malá Magura fault and brought additional information concerning the character of the fault zone. The present-day fault is considered to be a normal fault, steeply dipping towards the east. The Malá Magura fault is permeable for gases because the soil atmosphere, above the fault zone, contains increased contents of methane and radon.

The present-day tectonic stress in the Horná Nitra region was reconstructed by paleostress analysis and determined by analysis of geomorphological phenomena. The maximum principal horizontal compressional stress S_H was computed to be in a NNW–SSE direction, the minimum principal horizontal compressional stress S_h is perpendicular to this direction. This stress-field generates predominantly normal, oblique-slip movement along the Malá Magura fault (Figs. 9, 10) and the north-west segment of the Pravno fault, respectively.

The Quaternary tectonic activity of the Malá Magura fault is characterized by irregular movement. At least two stages of important tectonic activity along the fault can be distinguished. The first stage was tentatively dated to the Early Pleistocene by alluvial fans distribution, travertine production (Fig. 2) and morphometric criteria (Figs. 7, 8). The relatively small Lower Pleistocene alluvial fans were deposited at the foot of the mountain front during increasing fault movement (Burbank & Anderson 2001). However, the denudation of these alluvial fans is not excluded. The second stage of tectonic activity can by dated to the end of the Würmian and the earliest Holocene, based on the alluvial fans which are arranged at the foot of the mountain front (Fig. 2).

All the above mentioned attributes of the Malá Magura fault and knowledge of the current tectonic regime play an essential role in natural hazard assessment, especially in the risk assessment of fault activity. It should be important for local developments because it was a paleoseismologically active fault zone which may be active in the present and future and generate small to medium-magnitude earthquakes. Due to detected radon emanations and possible electromagnetic wave generation by hydrodynamic processes within the permeable Malá Magura fault zone, the monitoring of the about 150 m wide zone following the surface fault trace can be important.

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