Contributions to Geophysics and Geodesy Vol. 47/1, 2017 (23–38)

The resistivity image of the Upper Cretaceous Horné Belice Group: a case study from the Hranty section (Považský Inovec Mts., Western Carpathians)

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Abstract: The Tatricum crystalline basement in the northern Považský Inovec Mts. contains several narrow tectonic slices with different rock composition. Some of them composed of the Upper Cretaceous mass flow deposits (the Horné Belice Group) are considered unique within the framework of the Internal Western Carpathians and particularly within the Tatricum. Tectonic interpretation of their structural position is longer a matter of debate. Contrasting resistivity properties of the Hercynian mica schists and the Upper Cretaceous sandstones and shales were confirmed by the parametric geophysical measurements. The Hranty section, the structurally highest and most internal Upper Cretaceous tectonic slice was investigated by the electric resistivity tomography. Two longitudinal and two transverse resistivity profiles were measured and combined into a 3D image which suggests that the low resistivity Upper Cretaceous rocks form relatively shallow and flat lying structures folded and deformed between the crystalline basement slices.

Key words: Applied geophysics, electrical resistivity tomography, Horné Belice Group, Upper Cretaceous sediments, Považský Inovec Mts., Western Carpathians

1. Introduction

The Považský Inovec Mts. (PI) is one of the horsts in the area of the northwestern Internal Western Carpathians (*sensu Hók et al., 2014, Fig. 1A*). It

doi: 10.1515/congeo-2017-0002

is composed of the Tatricum crystalline basement and its Late Palaeozoic-Mesozoic sedimentary cover, which is overlain by two thin-skinned Mesozoic nappes, Fatricum (lower) and Hronicum (upper) (Fig. 1B).

The investigated northern Považský Inovec Mts. is mostly composed of the Tatricum (Figs. 1B and C) with widely distributed mica schist and gneiss basement mostly occurring in the eastern part of the region (*Ivanička et al., 2007*). The crystalline basement is overlaid by the Upper Palaeozoic sequence (Kálnica Group, *Olšavský, 2008*) distributed mainly in the continuous NNE-SSW trending belt in the central part of the region and as erosional remnants, synclines and tectonic lenses in the east. The Mesozoic sequence is reduced and tectonized. The Upper Palaeozoic rocks are often overlaid by the Lower Triassic quartzites and locally also by the Middle and Upper Triassic limestones and shales which prevail in the northwest.

One of the particularities of the Považský Inovec Mts. is the presence of the Upper Cretaceous sedimentary succession closely linked to the crystalline basement consisting of syn-orogenic mass flow deposits ("flysch") with olistoliths otherwise uncommon for the Tatricum, and with no comparable equivalent south of the Pieniny Klippen Belt in the nearby Tatra-Fatra Belt (*Lexa et al., 2000; Bezák et al., 2008*). The only exception is the borehole SBM-1 Soblahov in the western part of the Strážovské vrchy Mts. (*Kullmanová, 1978; Mahel', 1985*). The Upper Cretaceous sedimentary formations in the investigated area in the northern portion of the Považský Inovec Mts. are located in 100–500 m thick bodies between the complexes of mica schist basement rocks. Such configuration is unique within the framework of the Internal Western Carpathians, because the Upper Cretaceous rocks are here usually post-tectonic and overlying the highest nappe structures (*Michalík and Činčura, 1992*).

The Upper Cretaceous sedimentary succession is most often referred to as the Belice Unit (*sensu Plašienka et al., 1994*) or the Horné Belice Group (*sensu Ivanička et al., 2011*). For the purpose of this paper we follow the lithostratigraphic subdivision proposed by Rakús (in *Ivanička et al., 2011;* cf. *Pelech et al., 2016a*), which divides the Horné Belice Group into Coniacian–Santonian grey sandstones, shales and conglomerates of the Rázová Formation and overlying red Campanian–Maastrichtian mass flow deposits of the Hranty Formation. Both formations often contain olistoliths of various rocks of different origin, including the Upper Jurassic radiolarites

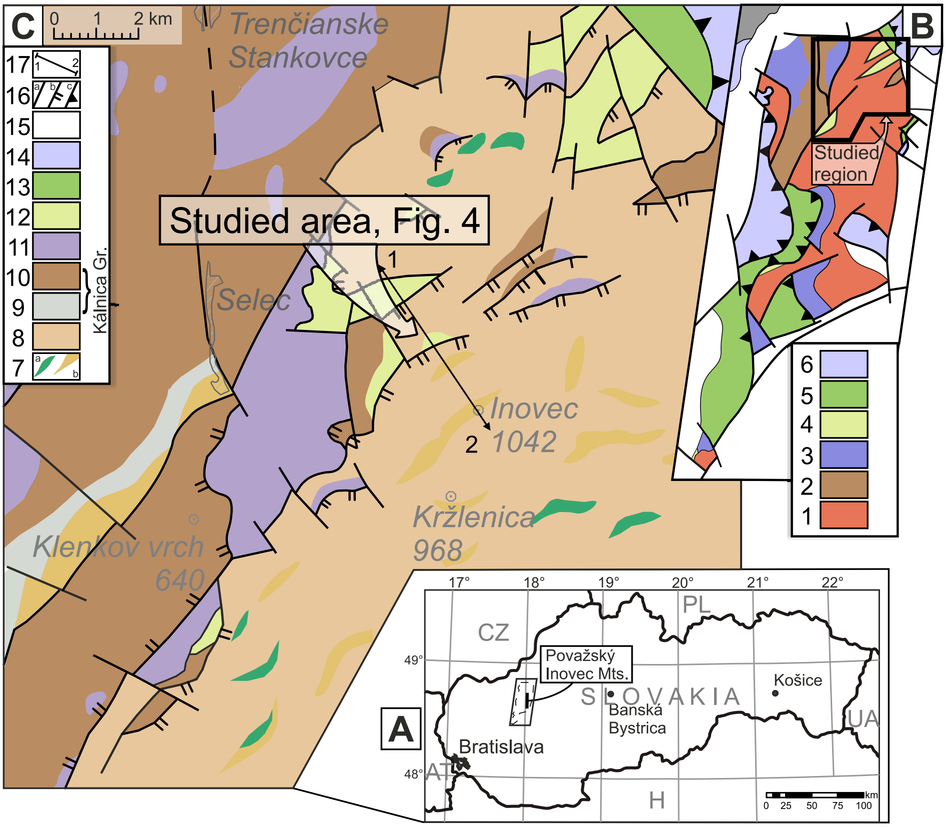

Fig. 1. Location of the studied region. **A**: Location of the Považský Inovec Mts. **B**: Tectonic map of the studied region in the northern Považský Inovec Mts. (after *Bezák et al., 2008*). Legend: **1**: Tatricum crystalline basement; **2**: Upper Palaeozoic of Tatricum; **3**: Mesozoic of Tatricum; **4**: Upper Cretaceous rocks; **5**: Fatricum; **6**: Hronicum. **C**: Geological map of the Hranty investigated area (map after *Bezák et al., 2008*). Legend: **7**: a) Amphibolite; b) Paragneiss; **8**: Mica schist; **9**: Carboniferous rocks (Novianska Formation); **10**: Permian rocks (Kálnica, Selec and Krivosúd) Fms11: Triassic rocks; **12**: Upper Cretaceous rocks; **13**: Fatricum; **14**: Hronicum; **15**: Cenozoic rocks; **16**: Faults – a) normal and strike-slip, b) reverse and thrust; c) nappe overthrust; **17**: Geological cross-section (Fig. 2).

(*Plašienka and Ožvoldová, 1996*), Jurassic crinoidal limestones, quartzites, mica schists, Calpionella limestones with mica schist clasts, metabasalts, as well as Upper Cretaceous limestones (*Rakús et al., 2006*). Some of these olistoliths are rather peculiar and exotic (*Méres and Plašienka, 2009*). The lithostratigraphic scheme used in this paper divides the Upper Cretaceous complex from the older Jurassic and Lower Cretaceous rocks (unlike *Plašienka et al., 1994* or *Putiš et al., 2008*) 1) because the normal sedimentary contact between the Rázová Formation and older formations was not observed (cf. *Pelech et al., 2016a*); 2) the Rázová Fm. usually overlies the crystalline basement or the Upper Palaeozoic sequences (*Ivanička et al., 2007*) and 3) the different metamorphic grade observed in Permian to Lower Cretaceous rocks on the one hand and Upper Cretaceous complexes on the other hand (*Putiš et al., 2016*).

Since its first discovery by *Kullmanová and Gašpariková (1982)* and *Havrila and Vaškovský (1983)* the structural position and tectonic affiliation of the Upper Cretaceous succession has been widely discussed by a number of authors (*Mahel', 1986; Leško et al., 1988; Plašienka et al., 1994; Plašienka, 1995; Pristaš et al., 2000; Rakús and Hók, 2005; Putiš et al., 2008; Ivanička et al. 2011; Pelech et al., 2016a; Putiš et al., 2016*). The original interpretations identified it as synclines (*Mahel', 1986*) or tectonic lenses (*Kullmanová and Gašpariková, 1982*) linked with the Tatricum crystalline basement; or tectonic windows of the Carpathian Penninicum (*Leško et al., 1988*) or the Infratatricum (structurally lower and more external Tatricum, *Putiš et al., 2006, 2008*). Further research brought the still persistent view that the Upper Cretaceous complexes represent thrust slices of the Penninicum/Vahicum brought from below the Tatricum unit by steep out of sequence thrusts (*Plašienka et al., 1994; Plašienka, 1995; Plašienka, 2012; Plašienka and Soták, 2015; Plašienka et al., 2017*). This interpretation was later challenged and a position in synclines and tectonic lenses within the Tatricum crystalline basement was supported by a number of authors (*Havrila in Pristaš et al., 2000; Rakús and Hók, 2005; Bezák et al., 2008; Ivanička et al., 2011* and *Pelech et al., 2016a; Pelech et al., 2017*).

Persisting problem of the contrasting interpretations regarding the structure and shape of the Upper Cretaceous rock bodies inspired us to use shallow geophysical methods to determine their subsurface continuation. Considering various locations with exposures of the Horné Belice Group, the Hranty section, between the Čierny vrch Hill (591 m a. s. l.) and the Inovec Hill (1042 m a. s. l.) was selected (Figs. 1 and 2). The main arguments are fairly good accessibility, relatively good exposures allowing cross-checking of geological and geophysical data, as well as its structural position. The Hranty section represents the structurally highest, and most internal representative of the Horné Belice Group in the northern ("Selec") block of the Považský Inovec Mts.

2. Material and methods

Geophysical resistivity methods were successfully used in the Považský Inovec Mts. for various purposes also in the past (*Polák and Kucharič, 1973; Šutora et al., 1985; Leško et al., 1988*).

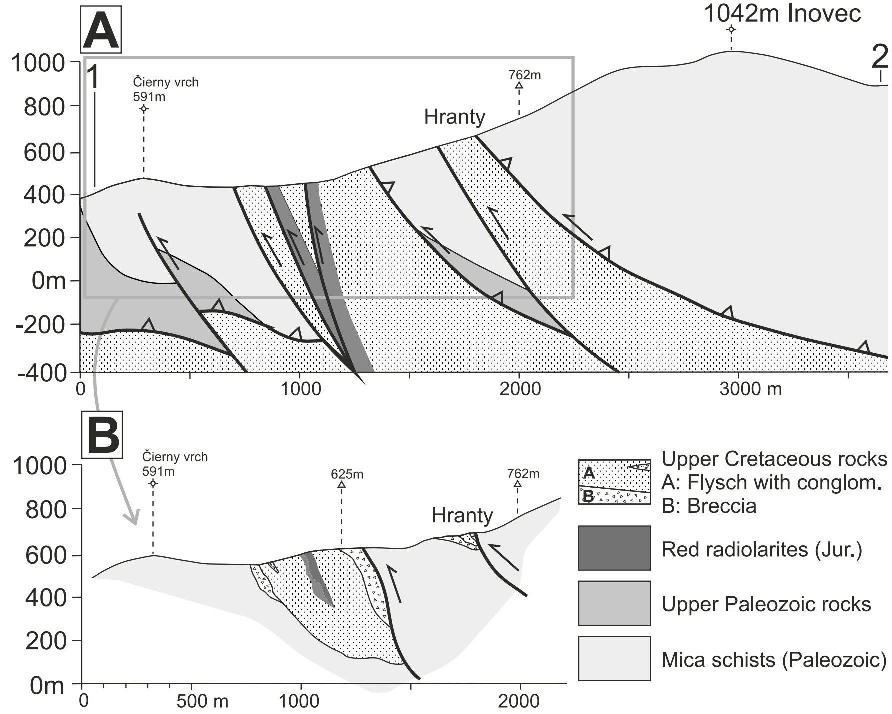

Fig. 2. Comparison of two different models of possible structural position of the Upper Cretaceous rocks in the Hranty section. A: Out of sequence thrusts of the Upper Cretaceous and Jurassic rocks "from below" the Tatricum proposed by *Plašienka et al. (1994)*. B: Synclines and tectonic lenses of the Upper Cretaceous complexes deformed between the Tatricum rocks (*Hók in Ivanička et al., 2011*). Location of the cross-sections in Fig. 1C.

The Upper Cretaceous sequence present in the Hranty section (48.78301° N; 18.03189° E) in the northern Považský Inovec Mts. is favourable for a shallow geophysical survey which could bring new insights into the structural position of the Upper Cretaceous rock bodies. The electric resistivity tomography method (ERT, *Milsom and Eriksen, 2011; Loke et al., 2013*) was applied.

In total four profiles (P1–P4) were oriented in cross-like arrangement, two transversely and two longitudinally across the investigated rock body. The distance between parallel profiles is approximately 100 m (Fig 4). The distribution of profiles was based on observation of surface geology. Major differences in resistivity properties between crystalline basement rocks and Upper Cretaceous sedimentary complexes rocks (Fig. 3) were assumed, based on earlier resistivity investigations in the northern Považský Inovec Mts. (*Šutora et al., 1985; Leško et al., 1988*) and therefore also two additional parametric profiles were done near the surface outcrops, in order to obtain reference values of the investigated rocks formations. The parametric profiles were 44 m long and the same instrument settings were used as for the profiles P1–P4.

Resistivity measurements were carried out using ARES equipment (GF Instruments), with 5.5 m electrode spacing with dipole-dipole electrode array. The dipole size (a) used for the survey was 5.5–82.5, and the spread

Fig. 3. Main lithological types of rocks in the investigated area of the Hranty section. A: Folded mica schist to gneiss (Early Carboniferous). B: Red sandstones and shales with sporadic beds of mica schist breccia of the Hranty Formation ("Red Flysch", Late Cretaceous).

factor for the electrode array (*n*) was 1–4. In order to increase data quality and density, all possible combinations of listed *a* and *n* factors were used. The obtained apparent resistivity datasets were processed into the 2D, topographically corrected, inverse resistivity models by means of RES2DINV inversion software package (*Loke and Barker, 1996*), applying inversion parameters listed in Table 1. The topographic data were collected in situ using a Trimble Pathfinder ProXH GNSS system.

Table 1. Main inversion parameters used for the calculation of all presented inverse models.

Inversion Parameter	**Value**
number of iterations	$3-7$
initial damping factor	0.5
increase of damping factor with depth	1.05
vertical to horizontal flatness filter ratio	1
thickness of first layer	0.5
factor to increase thickness layer with depth	1.01
model refinement	half-width cells
type of reference model	average resistivity
damping factor for reference model	0.01
forward modelling numerical approach	finite element method
type of Jacobian matrix calculation	Gauss-Newton
data constraint	L_1 norm (robust)

3. Results

Interpretation of the 2D inverse models was based on the contrast between the resistivity properties of the crystalline basement rocks and the Upper Cretaceous rocks of the Horné Belice Group. Simple statistical analysis of the parametric measurements are concluded in Table 2. For interpretation of the profiles P1–P4 the average resistivity of the inverse models were taken as the reference resistivity fingerprint of the investigated geological formations and afterwards the colourscale of the inverse resistivity models was updated in order to represent the crystalline basement by warm shades of the colourscale ($500-2000$ Ohm.m) while the cold shades represent the

Table 2. Statistical evaluation of the parametric resistivity measurements.

Geological formation	**Upper Cretaceous sedimentary complex**	**Crystalline basement rocks**
Apparent resistivity range	203 – 440 Ohm.m	680 – 2066 Ohm.m
Average apparent resistivity of the dataset	287 Ohm.m	1110 Ohm.m
Average resistivity of the inverse model	280 Ohm.m	1040 Ohm.m

Upper Cretaceous sedimentary complexes (10 – 500 Ohm.m) (Fig. 5). As additional information two nearly parallel NW-SE faults were identified on the transverse profiles P2 and P4 characterized by very low resistivity areas (1 – 100 Ohm.m). These faults were not previously identified from the surface geology. They partly correspond to the surface occurrence of the tectonic breccia with hematite matrix present in the north-eastern slope of the ridge at the Hranty.

Visualization of profiles P1–P4 as a 3D image (Fig. 6) helped to clarify the overall geometry and the structural position of the Horné Belice Group in this location. The resistivity values were substantially different so the determination between the lithologically distinct complexes appears to be reliable. The internal structure of the body cannot be defined on the basis of available information due to its substantial complexity.

Resistivity anisotropy of the studied layered rocks was initially expected (*Telford et al., 1990*), however, its effect can be considered negligible comparing the resistivity values on the perpendicular profiles which could be clearly visible on the profiles intersections (Figs. 5 and 6).

4. Discussion

The main discrepancy between the conflicting interpretations (Fig. 2) is whether the Upper Cretaceous complexes represent shallow or deep rooted structures. According to the first interpretation (Fig. 2A) the Upper Cretaceous rocks on the surface represent the frontal parts of steep thrusts which

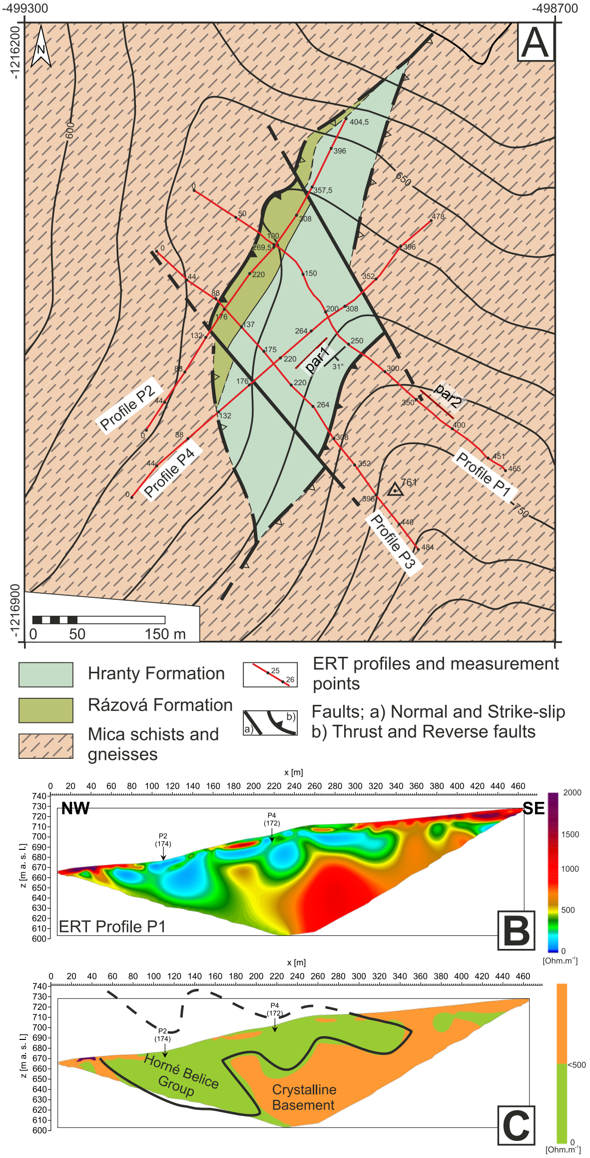

Fig. 4. **A**: Localization of the investigated profiles in the Hranty area. par1: parametric measurement in the Upper Cretaceous sequence. par2: parametric measurement in the crystalline basement rocks. **B**: Uninterpreted inverse resistivity section of profile 1. **C**: Interpreted Profile 1 with different scale, showing low resistivity Upper Cretaceous sedimentary rocks (green) and high resistivity mica schists (orange).

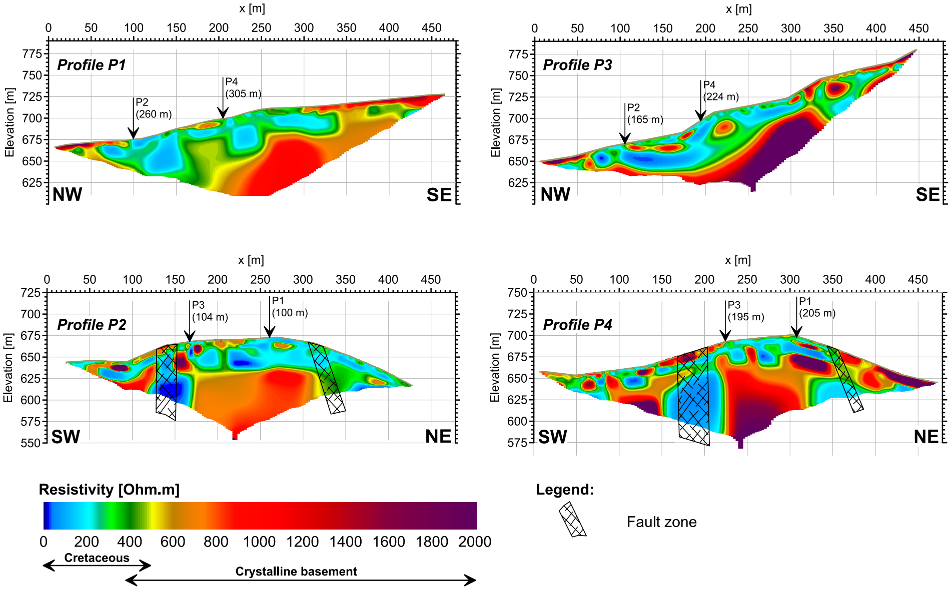

Fig. 5. Results of the electrical resistivity tomography measurements. Location of the profiles is in Fig. 4. The Upper Cretaceous rocks are generally characterized by the low resistivity (cold colours), while the crystalline basement has higher resistivity (warm colours).

increase their thickness with depth due to position below the Tatricum crystalline basement (*sensu Plašienka et al., 1994; Plašienka, 1995*). On contrary, according to the second interpretation (Fig. 2B) they represent relatively narrow lenses or synclines thinning with depth as a result of their position between the crystalline basement slices (*sensu Hók in Ivanička et al., 2011*).

Apart from data from the surface geology and geological map, the arguments for near-surface, hence a shallow crustal position of the Upper Cretaceous rocks are generally confirmed at the crossing of the geophysical profiles. According to the geophysical model, the low resistivity Upper Cretaceous bodies overlie the high resistivity crystalline rocks (Figs. 5 and 6). It should be noted, that the resistivity model in the marginal parts of the profiles could be generally considered less reliable compared to the central part, due to the lack of measurement points in the area. This aspect was,

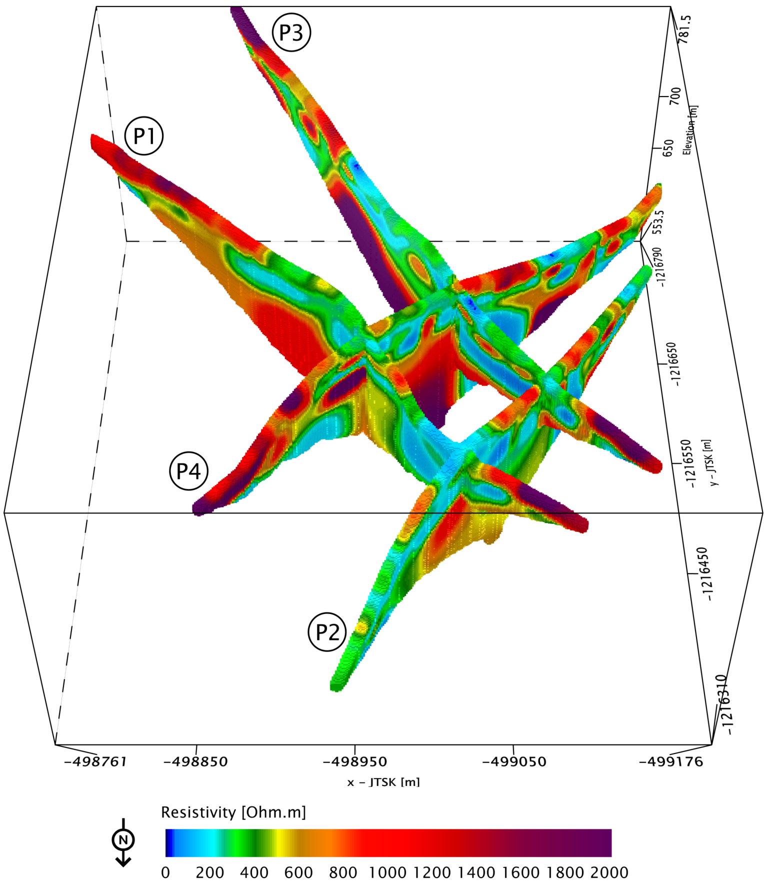

Fig. 6. 3D representation of measured profiles. Resistivity scale same as in Fig. 5.

however, taken into consideration and does not question the overall interpretation of the investigated structures. The shallow structural position generally corresponds to the older interpretation *sensu* Hók (in *Ivanička et al., 2011*, Fig. 2B). Further confirmation of the presented results could be supported in the future by additional geophysical works also involving different methods, such as seismics or gravity which could be applied to the Hranty section, but also to the other localities with Upper Cretaceous rocks (e.g. Rázová, Humienec, Hlohovec etc.). The geophysical survey is consistent with previous field investigation (*Ivanička et al., 2007; Pelech et al., 2016a*) as well as the results of borehole HPJ-1 near Hlohovec (*Pelech et al., 2016b*).

In relation to the deeper structure, the northern Považský Inovec Mts. and nearby areas are transected by several deep seismic reflection and refraction profiles (124, *Kadlecík et al., 1980*; 6HR, *Vozár et al., 1999; Pelech, 2015*; CEL15, *Hrubcová and Środa, 2015*; S04, *Hrubcová et al., 2010*) as well as one regional magnetoteluric profile (MT-15, *Bezák et al., 2014*). Regional profiles are usually not detailed enough to interpret the local structures known from the surface geology. They, however, display deeper crustal structure and properties of the crust in the investigated region. Masses with different geophysical properties that would be tectonically incorporated within the Tatricum or penetrate to the surface as steep out-of-sequence thrusts were not detected. Signs of heavy masses related to the relicts of subducted oceanic Penninicum/Vahicum (*sensu Plašienka et al., 1994*) are missing (*Szalaiová and Šantavý, 1996; Kucharič, 2013*).

5. Conclusion

Contrasting resistivity properties of the investigated crystalline basement, mostly mica schists and gneisses, and the Upper Cretaceous complexes composed mostly of mass flow sandstones and calcareous shales (Fig. 3, Table 2) are favourable for the application of the electric resistivity tomography method for the determination of shape and mutual relationship of the studied rock bodies.

Geophysical survey shows that the Upper Cretaceous sequence does not form a larger rock body that increases its volume with depth. This is confirmed by the combination of longitudinal and transverse ERT profiles. On the contrary, the sequence forms an approximately 90 m thick folded tectonic lens, bounded from the top and bottom by the crystalline basement complexes. Transverse profiles also suggest that the Upper Cretaceous sequence is dismembered by the NW-SE trending faults, which are not apparent from the surface geology. The internal structure of the Upper Cretaceous body cannot be defined on the basis of available information due to its substantial complexity.

Acknowledgements. We would like to thank two reviewers for their constructive comments and suggestions that have helped to improve our paper. This research was financially supported by the Scientific Grant Agency under the contracts Nos. VEGA 1/0587/11, VEGA 1/0141/15, VEGA 1/0559/17 and Slovak Research and Development Agency under the contracts Nos. APVV-0212-12, APVV-0129-12 and Grant of Comenius University for Young Scientists UK/532/2013.

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