Morphological Analyses of the Central Slovakia on Base of the DEM

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Abstract Satellite images revealed an extensive deformation on the southern slopes of the Nízké Tatry Mts. Range. This deformation can be ascribed to group of gravity nappes. Geologic survey, however, neither confirmed nor negated its existence. Therefore a detailed analysis of DEM and aerial images was carried out on the scale 1:35,000. Analytical interpretation led to the construction of a special morphotectonic and geodynamic scheme of the area, supported by the various geophysical data. The purpose of contemporary studies on the southern and south-western slopes of Nízke Tatry Mts. and marginal parts of the Velká Fatra Mts. were to verify the important tectonic boundaries and deformation structures interpreted on satellite images by the geophysical, geomorphological and GPS data.

Keywords DEM · Geologic survey · Aerial images · Morphotectonic and geodynamic scheme · Analytical interpretation

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1 Introduction

The complex analysis showed that during the Tertiary the south-western part of the Nízke Tatry Mts., presumably had the character of a horst whose relative fast uplifts had been caused by active deformations within the fundament (Fusán et al. 1979). Complicated faults or fracture systems of great diversity were found, many of them have strike-slip character. Also the expressive dissection of the relief, the chaotic arrangement of planation surfaces and numerous geodynamic features outline the intricate geologic environment and complicated late Alpine development of the whole structure. Interpretation and detailed geological analysis has been previously carried out by Klinec et al. (1985). Most of the anomalous morphologic phenomena detected has been found on base of DEM, satellite and aerial image interpretation. The reason is the vastness and extent of the structure mentioned, which goes beyond the possibilities of field verification. New GNSS measurements at permanent stations, and results of several epoch campaigns that were uniformly processed and evaluated (Hefty et al. 2010) made it possible, in relation to the existing tectonic plan in region of the Western Carpathians, to create the kinematic model of this area (Pospíšil et al. 2012). Overview of the block division of the Western Carpathians territory revealed that the area concerned maintains uniform character from the point of view of velocity vectors orientation, while in its surroundings the vectors are changing in relation to the single active fault systems, mostly of transcurrent character (Pospíšil et al. 2012). Review of all existing data and their interpretation shows that such structure type is closely related to the distinct Hron tectonic system (Pospíšil et al. 1985; Doktór and Graniczny 1983—Fig. 1).

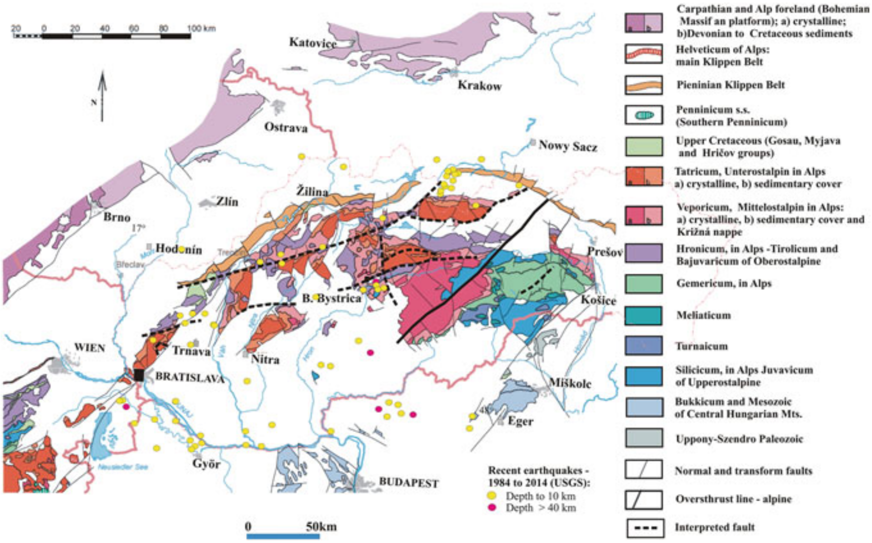

Fig. 1 Simplified geological map of the Western Carpathians supplied by interpreted seismoactive faults and analysed structure of the Nízke Tatry Mts. (NT)

The extent and scale of deformations can be compared with structures of the "foreberg" type, described in detail in Bayasgalan et al. (1999), which appear nearby the reverse faults of the strike slip character type (e.g. the Gurvan Bogd fault system in Mongolia). Unlike the structure mentioned, the interpreted gravitation nappe is not of recent character, but it is an older considerably broken and destroyed structure above an active fault system. The structure was clearly indicated by magnetotelluric (MT) measurement (Varga and Lada 1988), and is continually "resuscitated" by the underlying fault.

2 Methodology

In the interpretation of DEM we proceeded in the following methodological steps:

- evaluation of the tectonics of the area, with regard to orders of faults, fault zones, fracture zones, etc. and to the analysis of the drainage system,
- analysis of the morphological features, reflecting the particularities of the geo-tectonic development of the area (the relief forms, planation surfaces, etc.),
- distinction of geodynamic processes and other geodynamic phenomena—re-evaluation of the previous and recent findings concerning the geologic-tectonic development,
- evaluation of the latest geophysical and structural—geologic data, correlation of data yielded by the individual research methods applied—compilation of data, construction of maps and cross-sections.

3 Geological Characteristic

The Nízké Tatry Mts. are part of the Central Western Carpathians and belong to the Tatra-Fatra Belt of core mountains, which create Late Tertiary asymmetric horst structures, comprises from bottom to top (Plašienka et al. 1997—Fig. 1):

- the Penninic-Vahic oceanic rock complexes (it is supposed, only);
- the Tatric pre-Alpine crystalline basement and its Late Paleozoic-Mesozoic;
- sedimentary cover;
- the Fatric (Križna) Mesozoic cover nappe system;
- the Hronic (Choč) cover nappe system;
- the Veporicum unit at south;
- the overstepping Late Cretaceous (uncommon) and Tertiary (abundant) post-nappe;
- sedimentary and volcanic cover.

The structure mentioned is located at dividing line of Tatricum and Veporicum. The Tatricum is a crustal sheet present in the Western Carpathians only, but the

Infratatric units may be well correlated with the Lower Austroalpine units (Plašienka et al. 1997); the Veporicum, a large crustal-scale basement wedge best corresponds to the Middle Austroalpine basement units with the typical Cretaceous metamorphic overprint.

4 Active Faults in Tertiary

The basement exceptional activity was noticed in Tertiary, mainly on EW fault systems (Figs. 2 and 3). Primarily it was the Hron fault and its deep tectonic equivalent system. It fits into the system, according to which the southern part of the nappe is subject of progressive stepwise sinking. This principle (sinking) does not involve the part of the nappe that represents piling up of masses in form of bank (Ľubietová anticlinorium Fig. 2).

The Nízke Tatry Mts. fault system had been active during all the Tertiary period. The area of the gravitational nappe is divided by system of primary and secondary faults (Figs. 2 and 3).

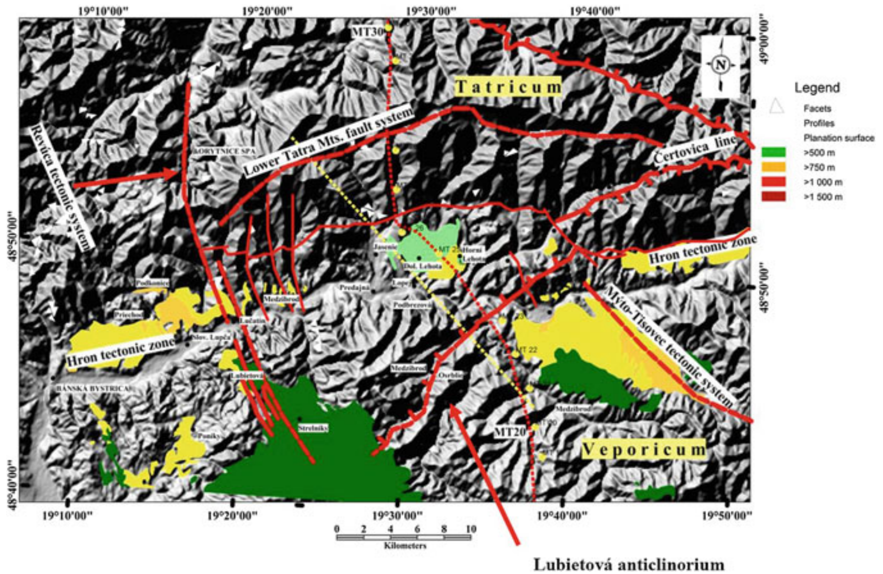

Fig. 2 Explanations to the paleogeographical scheme. (1) the Revúca fault system, (2) the Mýto Tisovec fault system, (3) the Nízke Tatry Mts. fault system, (4) the Hron river fault system, (5) the Čertovica fault system, (6) the Vajsková conglomerates, (7) sediments of motley series (the Polhora development of Paleogene, the Pre-Lutetian age), (8) dolomitic conglomerate facies, (9) sediments of the Podkonice syncline, (10) sandstone—conglomerate facies, (11) claystone lithofacies, (12) regressive facies of the Oligocene (the Upper Hron valley development of Paleogene, Lutetian—Oligocene), (13) gravel (Pliocene)

From overall directing and structural conditioning of relief over the nappe area it is possible to conclude that the movement was in SE direction (roughly perpendicularly to the Čertovica fault system), but there the sliding rock masses collided with NW margin of the Veporic structures. The compress zone, represented in the Čertovica fault system by development of antiform rock composition, is proof of the movement mentioned. Lengthwise the movement was reoriented to S, so the nappe front reached farthest to the south at the Strelník area.

Satellite image of the area of interest indicates possible movement of masses which have in their interior structure style employed in landslides. Its location in bedrock of the fault system mentioned and precondition for development of such phenomena—rapid pulsewise uplift of the area are the bases for analysis of wider area. The analysis is also possible from the point of view of Tertiary sediments development in the area (Fig. 2).

5 Analysis of Morphological Features

Geomorphological research in the area showed the heterogeneous nature of the relief leading to expressive difference in elevations of levelled surfaces in mid mountainous and riverine systems (Fig. 3). The morphological analysis realized on the stereoscopic model confirmed this relief destruction into various individualized blocks and strips, in their heights extraordinarily differentiated. As it is indicated by contemporary investigations are these results of various, not yet strictly

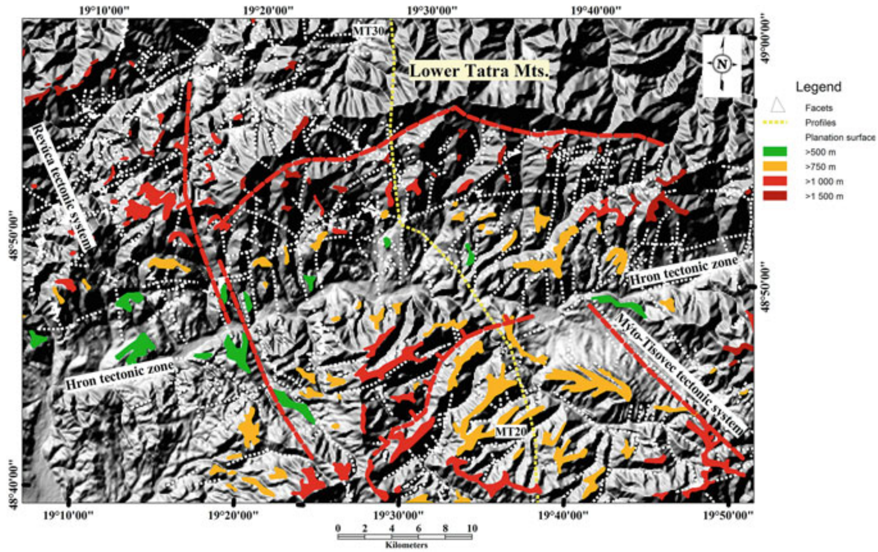

Fig. 3 Map of interpretated linear boundaries and planation surfaces interpreted from DEM and air photos

distinguished movements and of the selective exogenetic destruction of rocks. Neither the extensive gravity movement on the southern slopes of the Nízké Tatry Mts. can be excluded. This assumption is supported by the height differentiation of the mid-mountainous levelled surfaces (in absolute values from 850 to 1400 m a.s.l.) and of the riverine terrace system (100–300 m relatively above the Hron River valley —Fig. 3). Due to the extreme morphological conditions it was possible only to range following groups of levelled surfaces: (1) less than 700 m a.s.l., (2) 700–1000 m a.s. l., (3) 1000–1300 m a.s.1., (4) More than 1300 m a.s.l.

6 Analysis of Geodynamic Processes

Important secondary factors demonstrating the dynamics of the geologic environment, and of all exogenetic processes are geodynamic phenomena.

The following were in the focus of the interest (Fig. 4): (1) Slope deformations (creep, slide and fall gravity deformations, taluses, block disintegration and block fields), (2) Erosion elements (gully and sheet erosion, erosion edges), (3) Surface karst phenomena (sinkholes, areal and linear surface karst elements, (4) Forming of

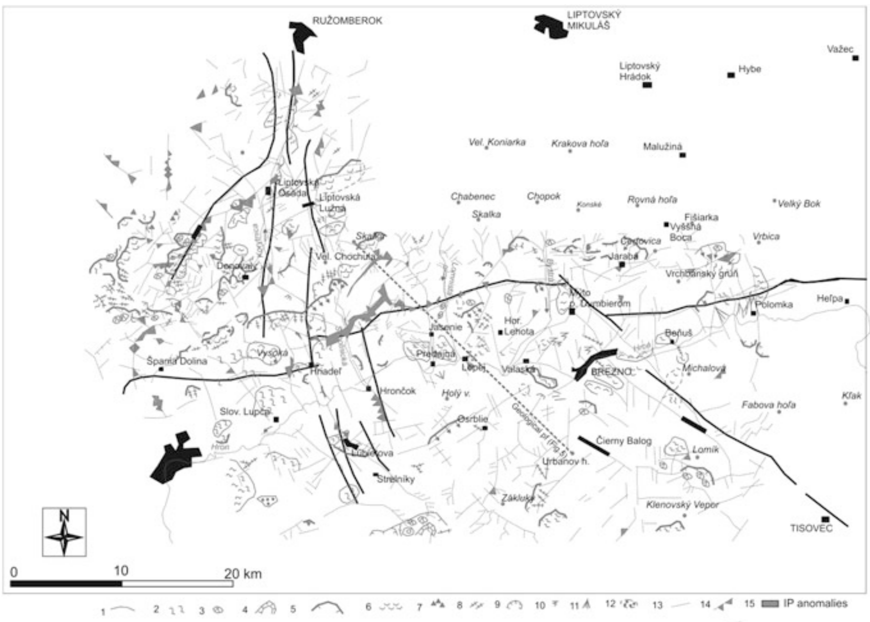

Fig. 4 Analysis of geodynamical phenomena. *Legend 1* slope deformations general, *2* talus creep, *3* block rifts, block fields, *4* individualized blocks, *5* scarps, *6* landslides, *7* alluvial fan, *8* gully erosion, *9* erosion edge, *10* sheet erosion, *11* proluvial cones, *12* sinkholes, karst valleys, *13* linear boundaries (after remote sensing), *14* facets, *15* zone with height IP (induced polarization) anomalies

proluvia (young alluvial cones), (5) Weathering. Slope deformations. The relatively new results of tectonics, engineering-geologic and geophysical investigations show that numerous structure at the Earth's surface so far related to the dynamics and mechanism of tectonic (plicative and disjunctive) movements are actually, connected with gravitational tectonics. In the Velká Fatra Mts. such deformations are represented on top ridges in the vicinity of elevation points Zvolen Mt. (1402 m a.s.l.), Chabenec Mt. (1955 m a.s.l.), Krížna Mt. (1574 m a.s.l.), etc. (Nemčok 1982).

Along the mountain ridges they form a linear succession and may represent a boundary of the active root area of an extensive gravity deformation. The slides could be well identified on Velká Fatra Mts., slopes (Turecká valley), on the Nízké Tatry Mts. slopes (S of the village Dolná Lehota, Prašivá Mt., Kozí chrbát Mt. etc.), but namely on the slopes of intra-mountainous basins, e.g. near Lubietová village (Fig. 4). It cannot be excluded their direct connection with the significant tectonic Revúca zone.

Erosion phenomena. Two types of erosion can be encountered in the area of interest: gully erosion and sheet erosion. Due to a large uplift of the mountain, an intensive down cutting of water flows took place and created a variable erosion relief with various types of the water system. At the present time the size of the erosion down cutting and its extension depend on the gradual disintegration of the rocks and on climatic changes. In places of tectonic or lithological weakening mainly on the steep slopes a considerable progress of back erosion can be observed (Fig. 4). Scours, deep ravines and gorges, and also flat closures of mountain valleys in the top parts of the ridges are formed. In the greater part of the area, back erosion has modelled the top parts into sharply-cut shapes and thus has disintegrated ancient structural planes.

Karst phenomena. Karstification is scarce in the area of interest due to the relatively rare occurrence of soluble karst carbonate rocks. Its surface elements can be encountered only in the south-western part near the village Poníky and Nemecká where the sinkholes form small groups of greater or smaller depressions. Linear arrangement indication occurrences and systems of tectonic lines cannot be observed (Fig. 4).

Other phenomena. Among the best identified phenomena belong proluvial cones. On images they are clearly visible by the tributaries of the Hron River.

The most product of weathering in the diversified relief, remodelled by erosion and denudation activity were transported away.

7 Correlation of Morphological, Regional Geological and Geophysical Data

The position of fault zones, fault lines and other structural features by means of remote sensing, regional geologic and geophysical data in the study area are in a good agreement. First of all the stereoscopic interpretation of various images produces much more continuous picture and complex results) than geologic or other maps on different scales. Evidently, the interpretation criteria make possible an identification of faults also in places where they have not been confirmed by field mapping.

It was impossible to find out on the satellite images which linear elements belong to older evolution stages and which to the Late Alpine development stage. According to the development and diversity of the geomorphological features it can be assumed that, the majority of fault and structural-tectonic features are from the latest evolution stage or are results of several stages. For instance, the linear Hron River valley is presumably based on one ancient fault in partial segments documented by linear, steep and sporadically facetted slopes. The facets in valleys were taken as a criterion for interpretation of faults (e.g. numerous facets along the northern part of the Korytnica River valley indicating the Revúca fault line—Fig. 4).

The fault and fracture zones are best characterized by the configuration of the drainage system. It can be assumed that the river follows the lines or zones of tectonic or lithological "weakening". In this way the principal directions of prevailingly linear tectonic zones, dislocations and shorter fault-fracture elements were distinguished (Figs. 2, 3 and 4):

1. NE-SW, ENE-WSW systems (western branch of the Revúca fault zone, the Hron River valley and the system of lines in the east of the area). In this direction runs the Hron lineament (Pospíšil et al. 1985) interpreted as a transcurrent fault with a large dextral strike-slip.
2. NW-SE, NNW-SSE (the eastern branch of the Revúca fault zone and transverse faults between Lučatín and Brusno, in the east the Rohozná and Čierny Hron River fault).
3. N-S faults forming important valleys in this direction on southern slopes of the Nízké Tatry Mts. as well as the Northern part of Revúca fault system.

All the tectono-structural features are indicated by the forms of valleys abrupt changes of drainage system, spring lines, erosional features, morphological structures, etc. (Fig. 4).

All the identified faults are mostly wide zones of the highest inhomogeneity rate in terms of secondary lithological changes, fragmentation or blockiness. They are all very expressive in the morphology. In this connection of greatest significance is the confirmation of extraordinarily manifested tectonic zone, corresponding partly to the Revúca fault system. First of all the interpreted branching into the two separate systems was of significance. One of them N-S or NNE-SSW system progresses along the Revúca River valley and indicates the continuation of important regional tectonic boundary—so-called Považany-Ihráč fault system. The second branch in direction NNW-SSW could mark the indication of the west border of the Nízké Tatry Mts. gravity deformation. The analysis of satellite, aerial and radar images confirmed a great relief diversity, frequent changes in its morphological forms, development of gravity elements on slopes, etc. within the entire Revúca system.

The vertical density boundary was based on the gravity data which demonstrate the diversity and frequent tectonic delimitation of structural blocks (Fig. 3).

The interpreted tectonic line often coincide with density boundaries or with places of disrupted correlation. The loss of correlation can be observed along the entire length of the Revúca fault zone, Hron lineament etc. Geophysical data focused our interest to the disruption of the NW-SE branch of the Revúca system. This not exactly limited wide zone is de-formed there and along about 5 km it is bending to the WNW-ESE direction. It may be the crossing point of several tectonic faults with variable orientations.

The tectonic predisposition of the Hron River between Banská Bystrica and Brezno where two distinct NW-SE and NE-SW striking faults have been interpreted, can be supported by an intensive gravity gradient. Many of interpreted structural and tectonic boundaries, e.g. Mýto-Tisovec fault zone or Čertovica line have been confirmed by geo-electric, magnetometric and gravity data.

The broader surroundings of the south slopes in the middle-west part of the mountain has been the focus of investigations for are prospecting. Geophysical measurements and aerial photographs yielded a detail picture of the tectonics of the area. Mapping of the so-called “productive zone” showed equal values of resistivity and polarization to those of the immediate surroundings of the existing deposit (Vybíral et al. 1986). The zone of the anomalous induced polarization values strikes from NE to SW and it is evidently bounded by fault zones. Tectonic lines interpreted on the images disturb this zone in form of shifts and disruptions so that it proves the particular interest from the viewpoint of tectonics, geological structure and mineralization in this area.

Obtained geophysical data from various methodological stages cannot be fully illustrated in the simplified geologic cross-sections, but only in the schematic section (Fig. 5). It is because of an in clarity in the geologic interpretation of the Nízké Tatry Mts. structure itself.

8 Discussion

Interpretation of multispectral space image LANDSAT and aerial B/W images combined with DEM was based on evaluation of the relief and its main elements—hollows and ridges. On base of their structuring the tectonic predispositions were considered. It is therefore possible to state that the evaluation of relief texture in the image of interest It can therefore be concluded that the appreciation of the relief texture to the image significantly contributed to support the geologic and geophysical indices, and also to analysis of the paleo-horst and its supposed gravitational deformation (structurally conditioned relief in Veporicum area, i.e. in supposed accumulation part of the gravitational nappe, cannot be decidedly taken as proof of its existence).

After Tertiary period the SE part of the Nízke Tatry Mts. territory had character of a horst. Its rapid pulsewise movements had been conditioned by bedrock active faults that formed its exterior limitations. From W-SE side it was the Čertovica fault system in section of the Čertovica saddle—Ľubietová crystalline—Strelníky.

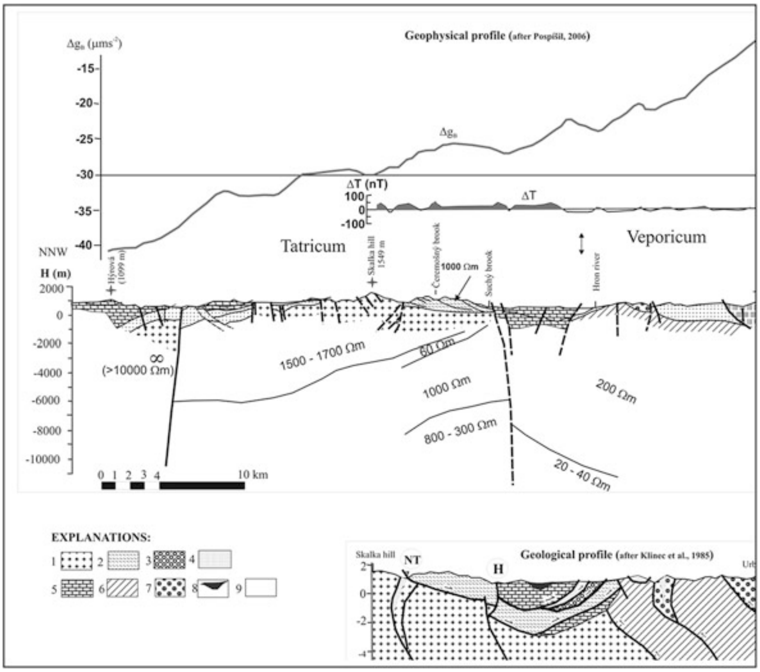

Fig. 5 Geological (*bottom*—Klinec et al. 1985) and geophysical profiles located in area where is interpreted "gravity nappe". *Area of Tatrides 1* granitoids, *2* crystalline schist, *3* sandstones, conglomerates, rhyolites (Permian), *4* quartzites and carbonates of lower tectonic unit, *5* carbonates and melaphyres of the upper tectonic unit. *Area of Veporides 6* mica schists, amphibolites, *7* gneisses, migmatites, *8* the Vajsková conglomerates, *9a* basement of the gravity nappe, *9b* dislocations of higher order, *9c* dislocations of lower order, *NT* the Nízke Tatry Mts. fault system, *H* the Hron river fault system, *Č* the Čertovica line (thrust of the Veporides on the Tatrides). The geophysical profile (Pospíšil 2006) clearly demonstrate different resistivity image of the contact area between Tatrides and the Veporides

From W-SW side it was the Revuca fault system in section Korytnica-kúpele over Medzibrod to Strelníky, and from N the section of Nízke Tatry Mts. fault (E-W) from Sopotnice springs to Čertovica.

If the concept of gravitational nappe is accepted, then it must be of pre-Pannonian era. Reason for such opinion is the existence of considerably reshaped planation levels of pre-Pannonian age (Pospíšil et al. 2006). Indices for this are flat parts of the Nízke Tatry Mts. crevasses of elevations 1200–1400 m (Vanko and Wyrzykowski 1981). In case of the Pannonian gravitational nappe of supposed extent the planation surfaces would be completely destructed.

It is necessary to emphasize that it is altogether impossible to explain the identified gravitational nappe structure in complete space-time development only on base of remote sensing. It is possible to point at some influences which had to exist during formation of such structure. Paleogeographical analysis of the development in Tertiary showed that until Oligocene the whole area had tendency to rise against its surroundings. That movement, even if pulsewise, should have enormously rapid course in final phase. The horizontal motions of Carpathian blocks along the ENE-WSW oriented faults could play the deciding role, how it was pointed out before on base of the satellite image analysis and the detection of linear divides of this type by (Janků et al. 1984—Fig. 6).

One of these divides (the Hron tectonic zone) runs in direction of line Banská Bystrica–Brezno towns and reaches out as far as the area concerned. Early Miocene age of these movements corresponds to dynamic conditions which existed at that time. The gravitational nappe rapid uplift and tearing away may be attributed to the collision of two (or more) blocks moving in different directions with different velocities (Figs. 2 and 6). It cannot be excluded that also other linear divides (clearly observable in satellite images and in illuminated relief)—the Muráň fault, along with its northern parallel—the Divín fault (the Muráň-Malcov system—Pospíšil et al. 1985), controlled similar movements in vicinity of more to the south (Veporic) blocks.

Contributing in some way to understanding and explanation of this mechanism are also some geophysical findings. In the gravity map (Ibrmajer 1964; Pospíšil et al. 1985; Pospíšilová et al. 2012) the both linear ENE-WSW oriented divides

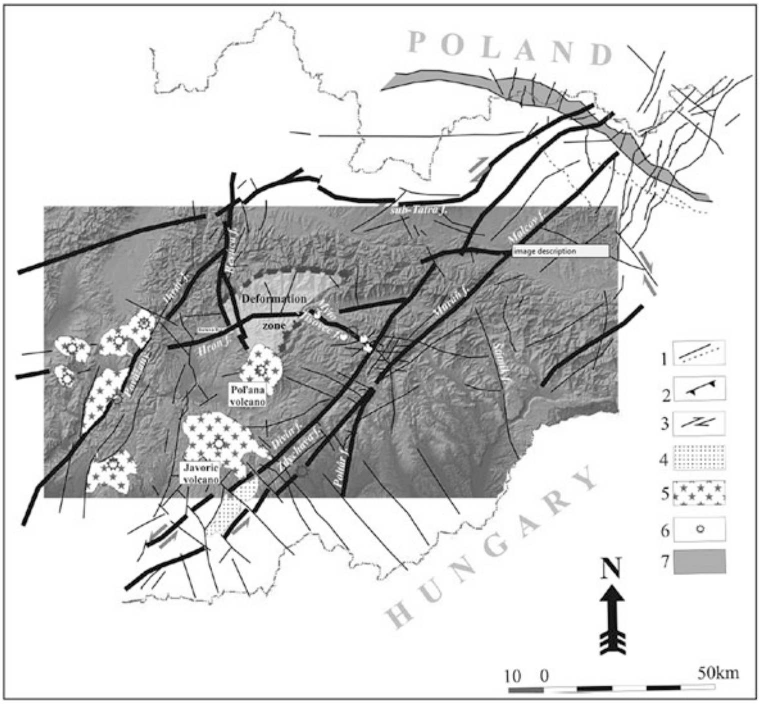

Fig. 6 Regional relationship among the main tectonic zones surrounding of the Nízke Tatry Mts. *Explanations 1* known and supposed faults, *2* thrust, *3* strike slip character, *4* graben structure, *5* Pannonian volcanic, *6* central volcanic zone, *7* Klippen Belt

appear as border lines separating the individual blocks, that are arranged asymmetrically in relation to these lines, but are maintaining constant mutual distance.

In space between the divides mentioned there are preserved the sediments of the Central Carpathians paleogene, partly also of Early Miocene (Fusán et al. 1979; Nemčok 1978—Figs. 1 and 2). If the fault systems (e.g. in areas of intra-mountain hollows) and the timing of sedimentation cycles are accepted, it is possible to assume that the mentioned system of divides plays the role also in opening, resp. in founding of the molasse basins.

It is reasonable that during the horizontal movements there were initiated the extended transversal crevices, resp. faults, which could be of a deep reach. The Revúca fault and the Mýto-Tisovec fault can be considered as such fault types, which controlled not only the formation and extending of the gravitational nappe, but also the ascending of the neogene intermediate magma to the surface.

To proving of the gravitational nappe existence in the area concerned, but also in other areas of Carpathians where the anomalies in stratigraphic sequencing and the zonality destructions are discovered, must be paid increased attention because part of these anomalies could originate from the same genesis. Contemporary means for tracing the subtle Earth surface deformations with help of GNSS monitoring could particularize some lack of clarities of relation to surrounding blocks. Considering the increased seismic hazard in the area it could be utilized for risk studies in the territory concerned.

Because the interior arrangement of the gravitational nappe structure shows the landslide body features, it is possible to apply this distinction also by exploration of accumulations of utility minerals. Inside the gravitational nappe body the W-Au ore is contained, which in the past times was corroborated by exploratory works. Their spacing is, with regard to their character (mobility of elements), originally deformed in relation to the environment, and they have to adapt to the plan of the developing deformation. In accordance with this is the contemporary asymmetric distribution of ores without distinctive zonality in space (section of the gravitational nappe). It is notable that most of Pb, Cu, Sb, W, Au ores in region of the Nízke Tatry Mts. is localised within the gravitational nappe area.

9 Conclusions

The purpose of contemporary studies on the southern and south-western slopes of Nízke Tatry Mts. and marginal parts of the Velká Fatra Mts. were to verify the important tectonic boundaries and deformation structures interpreted on satellite images by the geophysical, geomorphological and GPS data.

This analysis showed their great heterogeneity rate in the area of interest. The relief diversity, existing deep founded and at the same time hidden transcurrent tectonic zones offer clear indications about presence of a seismo-tectonic active risk zone. Supposition about existence of a gravitation nappe are also offered by the secondary influences accompanying alike structures (relicts sediment, exogene dynamics elements, distribution of isolated neovolcanic bodies etc.). The interpreted gravitation nappe structure very closely resembles structures accompanied by numerous thrust-related folds, thrust faults, and elongated low ridges (‘forebergs’), sub-parallel to the mountain range, all of which result from the shortening component on the fault zone (Bayasgalann et al. 1999).

Evidence from geomorphology and surface ruptures suggests that they may all serve a common function, which is to broaden the deforming zone by creating new structures that are able to accommodate both the strike-slip and the shortening components of motion.

The migration of faulting away from the main range is likely to be driven by stresses associated with topography, which in turn is a consequence of the shortening component.

Development of such structure in Nízke Tatry Mts. region may be ascribed to the present Hron strike-slip fault system, which has reverse component and which can produce more elements of the “flower structures” that are often described in such oblique-shortening zones (Pospíšil et al. 1989). Particularly yet neglected results of MT measurements along the 2T profile (Varga and Lada 1988) provide conclusive information about significant deformation in the area. While the results of seismic measurements along the same profile are ambiguous (Tomek et al. 1989), the unambiguously different resistance distribution in the area north of the Hron tectonic zone allows to explain also the other yet neglected interpretations—presence of light granitoid masses (with “infinite resistances”) under the Nízke Tatry Mts. mountain range (Pospíšil and Filo 1980). This could explain the cause of uplift and instability of the mountain range during Tertiary and up to the recent. The presented results and interpretations show that even at contemporary level of exploration and research of the Western Carpathians it is possible to encounter the essential problems of regional dynamics, which from the recent point of view can lead to some risks in connection with subsequent unexpected earthquake occurrences. From that reason it would be suitable to supplement such areas by a number of additional permanent GNSS stations which could contribute to monitoring of eventual changes and movements of single blocks (Gašinec et al. 2012; Staňková and Černota 2013).

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