Interpretation of deep seismic reflection profiles in the northern part of the Malé Karpaty Mountains

B. Kytková
Department of Applied and Environmental Geophysics, Faculty of Natural Sciences, Comenius University[1]

Č. Tomek
Institute for Geology and Paleontology, University of Salzburg[2]

M. Bielik
Department of Applied and Environmental Geophysics, Faculty of Natural Sciences, Comenius University[1]
Geophysical Institute of the Slovak Academy of Sciences[3]

M. Putiš
Department of Mineralogy and Petrology, Faculty of Natural Sciences, Comenius University[4]

A b s t r a c t : We present in this paper some results of the interpretation of deep seismic reflection profiling across the northern part of the Malé Karpaty Mountains. The goal was to recognize the tectonic character of western and eastern mountain range limitation in the area between Plavecký Mikuláš and Dolné Orešany, study the character of the Záhorský fault and the declination of inner structures. The result of the interpretation was the confirmation that the Vienna Basin is a pull-apart basin and that the western mountain range border is formed by an orthogonal strike slip connected with the mountain range uplift. On the eastern border (from the Danube Basin side) what was until now considered as fault, appears to be a fold. Hence, the Malé Karpaty Mountains represent at least in the northern part an anticline.

Key words: deep seismic reflection profiles, seismic interpretation, reflection event, the Malé Karpaty Mountains

[1] Mlynská dolina, 842 15 Bratislava, Slovak Republic; e-mail: bielik@fns.uniba.sk
[2] Kapitelgasse 4–6, A-5020 Salzburg, Austria; e-mail: Cestmir.Tomek@sbg.ac.at
[3] Dúbravská cesta 9, 845 28 Bratislava, Slovak Republic
[4] Mlynská dolina, 842 15 Bratislava, Slovak Republic

1. Introduction

This paper deals with geology of northern part of the Malé Karpaty Mountains and with its origin in the area between the Danube and Vienna Basins. The aim is to show the tectonic character of the west and east boundary of the Malé Karpaty Mountains in the zone between villages Plavecký Mikuláš and Dolné Orešany. We are particularly concerned with the east boundary, whether it is of a tectonic or an erosive character. We are interested also in the character of the Záhorský fault and the inclination of cover units, Fatricum and Hronicum and Upper Austroalpine nappes.

The study of geology leans on reinterpretation of deep seismic reflection lines (8CHR/86, 671/87, 671A/87, 689/87) which where measured for oil research. The Vibrosies was used as an energy source for lines 671/87, 671A/87, 689/87 and line 8CHR/89 was shot using dynamite. The recording times were 12 s (671/87, 671A/87, 689/87) and 14 s (8CHR/86). Measurements and processing of data were carried out by Geofyzika n. p. Brno in 1988.

Lines 8CHR/86, 671/87, 671A/87 cross transverse the mountain range of the Malé Karpaty Mountains. All of them are situated in the northern part of the mountain (Fig. 1). Line 8CHR/86 runs from north-west to south-east. It begins at root of the mountain, crosses the ridge and reaches the Danube Basin. Profiles 671/87 and 671A/87 are situated parallel with line 8CHR/86 in the same direction as that one. Line 671/87 leads from the Vienna Basin to the central part of the mountain ridge where it communicates with line 671A/87 which proceeds to the Danube Basin. At the 3.55 km it crosses the line 689/87.

Profile 689/87 is longitudinal to the Malé Karpaty Mountains. It runs from south-west to north-east and crosses lines 662/84 (3T) and 671A/87. Only a north-eastern part of line 698/87 (by 15 km) is interpreted.

Non-migrated versions of seismic sections are used for the interpretation. In the case of line 8CHR/86 also a migrated one is used.

2. Geology

The Malé Karpaty Mountains, the western core mountain range in the Western Carpathians, are very important for a correlation study of the East-

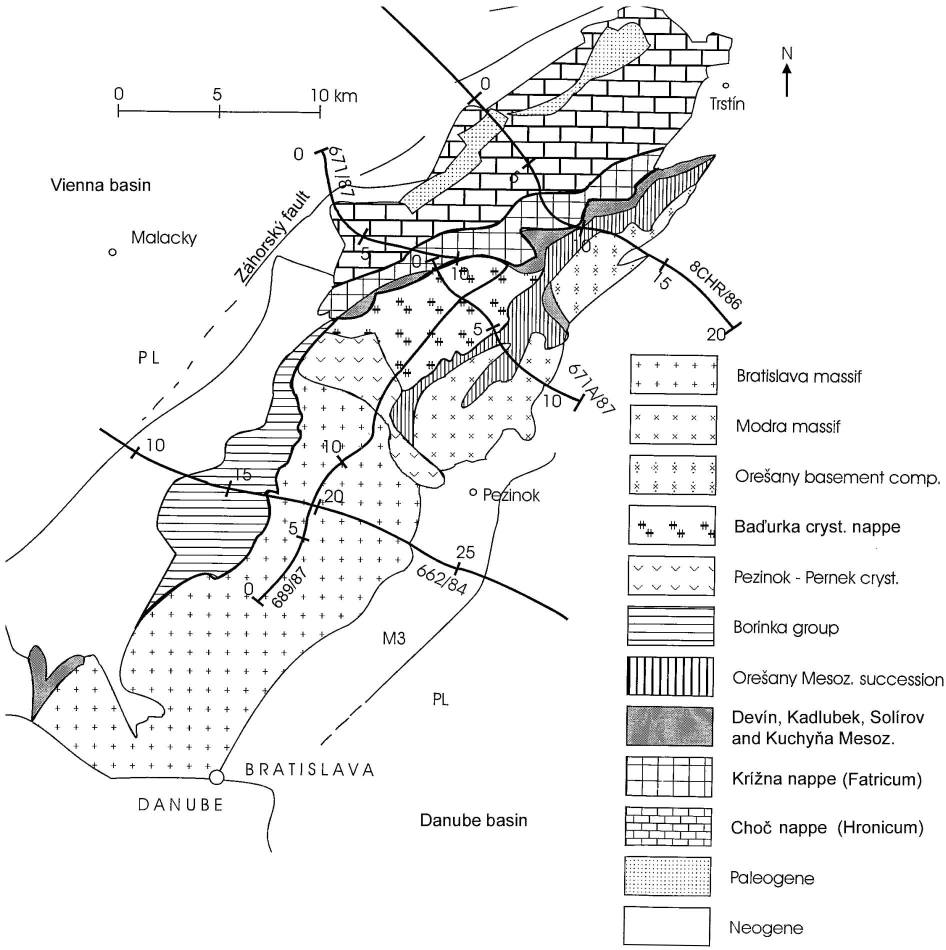

Fig. 1. Surface geological map of the Malé Karpaty Mountains with location of studied profiles (by Tomek, unpublished).

ern Alps and Western Carpathians. It is an uplifted horst incorporating pre-Mesozoic basement complexes and their sedimentary cover sequences, with the Mesozoic cover nappes on the top (*Plašienka et al., 1991, 1997*) Palaeogene sediments are a part of the horst in northwestern margin of the mountains. The horst, surrounded by the Tertiary Vienna and Danube Basins sedimentary deposits was uplifted in two main stages – in Oligocene and Miocene, according to apatite fission track study *(Danišík et al., 2004)* A Tertiary tectonic zone, separating the southwestern part of the Western Carpathians from the Eastern Alps disintegrated (rugged) basement-cover complexes, including the overstep Late Cretaceous-Palaeogene basin sediments. The Lower Miocene sedimentary infill of the basins appears to be associating the horst structure of the Malé Karpaty Mountains *(Plašienka et al., l991).*

2.1. Penninic unit

The Penninic unit is expected to be a part of underlying structural units in front of the Tatric unit. The southwestern and northeastern parts of the horst expose the Mesozoic Borinka and Orešany structural complexes *(Plašienka and Putiš, 1987; Plašienka, 1987; Putiš, 1987)* belonging to the Infratatric unit *(Putiš, 1992)*, the lowest tectonic unit of the Central Western Carpathians mega-unit, analogous to the Austroalpine mega-unit in the Eastern Alps *(Neubauer et al., 2000).* Only few remnants of the Infratatric unit are preserved in the Malé Karpaty and Považský Inovec Mountains after the Cretaceous and Early Tertiary orogenies. *Putiš et al. (2006)* and *Putiš (2006)* defined the Infratatric unit as former (southern) continental margin of the Penninic oceanic Realm. Consequently, the structural complexes with the Penninic affinity can be expected at the footwall of the Tatric unit.

2.2. Tatric unit

Plašienka et al. (1991) recognized four tectonic units in the Tatric structural complex of the Malé Karpaty Mountains: the Borinka and Orešany subautochthonous units, as well as the basement-cover Modra and Bratislava nappes.

Putiš (1992) and *Putiš et al. (2004)* included part of the basement-cover complexes into a Palaeo-Alpine Tatric Bratislava-Modra nappes, thrust over the Infratatric Orešany and Borinka structural complexes.

The Lower Palaeozoic basement complexes, incorporated into the Bratislava-Modra nappe and Orešany unit origined in distinctive palaeotectonic environments (from south to north): 1. the Pezinok Group formed on a passive-like continental margin crust (with the Limbach Formation), 2. the Marianka Group formed on a thinned passive subcontinental margin crust (with the Marianka and Lamač Formations), 3. the Pernek Group represents suboceanic to oceanic crust (with the Čertov kopec and Svätý Vrch Formations) of the central part of the Palaeotethyan (Late Devonian, *Putiš et al., 2006*) basin, 4. the Kuchyňa Group formed on a thinned active subcontinental margin crust (with the Harmónia and Dubová Formations). The four Groups build four pre-granitoid nappes as a result of Late Devonian subduction-collision evolution stages, connected with a general southward nappe thrusting. The Pernek nappe, however, represents an obducted oceanic crust fragment, backthrusted (with a northern vergency) over the Kuchyňa nappe. Only part of the oceanic or suboceanic crust (the Svätý Vrch Formation) was southvergently thrust over the Marianka and Pezinok nappes. Thus the area between Pezinok town and Pernek village represents a suture zone after obduction and a syn-collisional exhumation of the Pernek Group oceanic crust. The collisional stage caused metamorphism of continental crust sedimentary-magmatic formations in distinctive palaeotectonic environments separated by a suture zone. The collisionally thickened and metamorphosed passive-like continental margin crust was intruded by the S-type (Bratislava) granite. Tectonically attenuated active continental margin together with the main part of the oceanic crust was intruded by the I-type (Modra) granodiorite and tonalite (*Putiš, 2006; Putiš et al., 2004; Petrík et al., 1994*).

The six cover units were recognized in the Tatric structural complex (*Plašienka et al., 1991*): 1. Borinka succession with Prepadlé, Somár and Marianka Formations, 2. Orešany succession with Slepý and Solírov Formations, 3. Devín, 4. Kuchyňa, 5. Kadlubek and 6. Solírov successions. The differences between the successions occurred during the extension tectonic regime in the Tatric pre-Alpine basement.

2.3. Fatric nappe system

Large surface nappes formed by the tectonic detachment of the Mesozoic cover sequences from a compressed pre–Alpine basement in the Nort-Veporic area during late-Cretaceous times. This extensive Fatric nappe system with shallow to deep-water Triassic to Late Cretaceous sequences overlies the

Tatric unit. The Vysoká nappe of the Fatric unit is present also in northern part of the Malé Karpaty Mountains *(Plašienka et al., 1991).*

2.4. Hronic nappe system

These Mesozoic cover nappes, with thick Triassic sequences overlie the Fatric nappe system in the Tatric area *(Plašienka et al., 1991).*

3. Methodology

Line roving of chosen strong reflexes, considering of their factuality and distinguishing of real reflexes from noise or diffractions precedes the interpretation. The occurrence of strong reflexes is related to high reflection coefficients. Reflection coefficient expresses the amplitude and polarity of a wave reflected from the interface in the relation to a wave falling on the interface and depends on the impedance of both environments *(Lillie, 1999).*

Diffracted waves origin on discontinuities and thus are connected with the presence of faults. In crystalline rocks, they often reflect velocity anisotropies, that means shear zones. Similar origins have reflexes registered in nappes. Most likely it is an area with mylonites that means tectonically deformed rocks, on the other side there are basin areas, where the origin of reflexes is conditioned by the change of sandstones (sands) and claystones (clays).

After considering the factuality of reflexes the correlation of seismic profiles with surface geology follows and the determination of geological meaning of the marked interfaces and fault positions. For the correlation, the geological map of the Malé Karpaty Mountains 1:50 000 *(Mahel' et al., 1972)* has been used.

Originals of seismic profiles and respective lineations of reflexes were transformed into digital form, adjusted and refilled with interpretation signs and notes.

4. Results

Line 8CHR/86 (Figs. 2, 3)

At the surface this profile traverses units of Hronicum, Fatricum nappes,

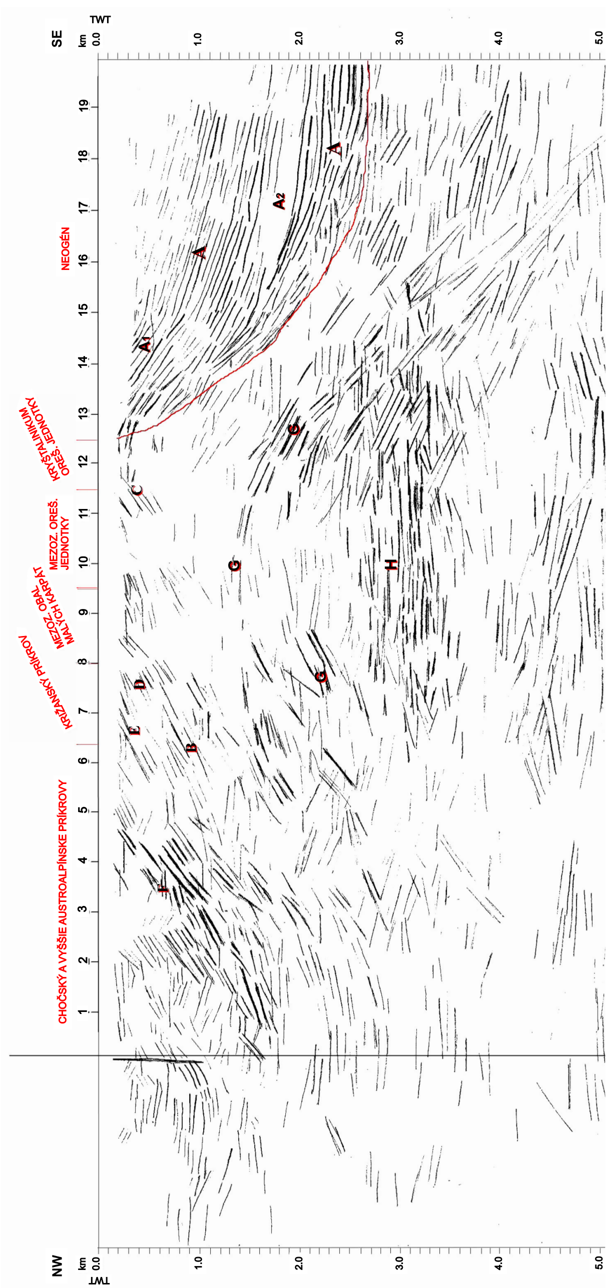

Fig. 2. Migrated time section 8CHR/86 refilled with interpretation signs. Letters are explained in the text. Vertical scale is two-way travel time; horizontal scale is in kilometers.

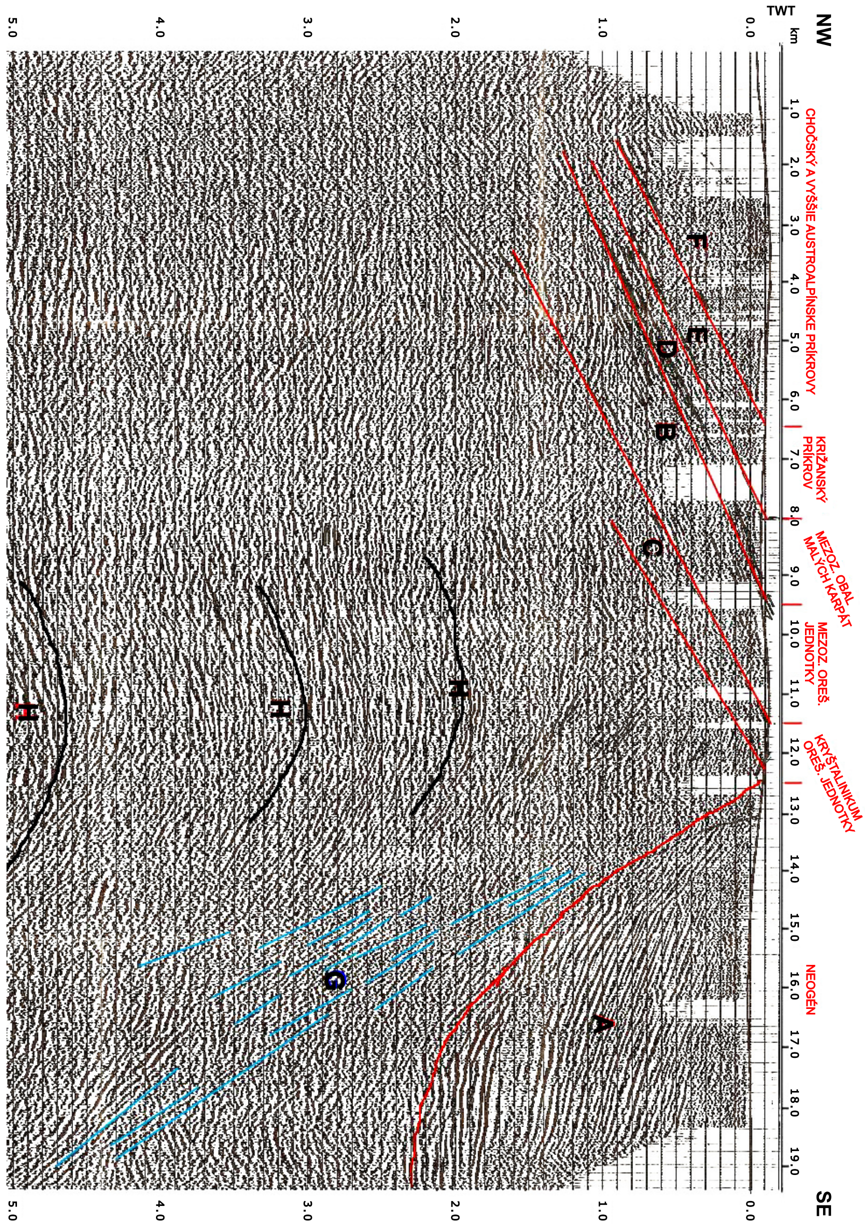

Fig. 3. Unmigrated time section 8CHR/86 refilled with interpretation signs. Letters are explained in the text. Vertical scale is two-way travel time; horizontal scale is in kilometers.

Tatricum and Neogene sediments of the Danube Basin. The Tatricum is represented by the Mesozoic cover of the Bratislava-Modra unit and Orešany unit (the Mesozoic succession and basement).

The line drawing of the migrated seismic section (Fig. 2) and also of the non-migrated one (Fig. 3) demonstrates clearly the boundary between the Malé Karpaty Mountains units (Orešany unit) and the Vienna Basin Neogene sediments. This interface represents a flexure (half fold). The package of bend and blooming out events A1 suggests that the folding became after the sedimentation in the basin and that a part of the fold erodes away.

Diffractions G at the non-migrated seismic record (Fig. 3) assigns to probable weak fault near the surface. After migration the diffractions mostly disappear.

Significant subhorizontal events A (Figs. 2, 3) represent sedimentary complexes of the Danube Basin. There is only one interruption at the section A2. The basis of the basin is at time level 2.6 s TWT.

Over the time level 3.0 s TWT the events G in the crystalline complex at migrated section (Fig. 2) have the character of a fold. The configuration of subhorizontal events H (Fig. 2) is related probably to the horizontal dislocation, where the fault propagating fold evolved. It could be the Penninic shear zone. Deeper events belong to Penninicum. Its nether restraint is not marked so it could continue downward to the appreciable depth.

We interpret the packages of northwest-dipping events B–F (Figs. 2, 3) as the Mesozoic succession (B) and basement (C) of Orešany unit, the Mesozoic cover succession (D), Fatricum nappe (E) and Hronicum and Upper Austroalpine nappes (F). The events C reach the surface and immerse down again so the fold upwarping can be noticed.

The event F is registrated by the time level of 1.7 s TWT at the migrated section (Fig. 2).

Line 671/87 (Fig. 4)
The line begins at the Neogene of the Vienna Basin and crosses units of the Fatricum and Hronicum.

The acquired reflections can be divided into two sections. There are significant subhorizontal events A in the northwest part of the profile representing the Neogen sediments of the Vienna Basin. Similar to the line 8CHR/86 (the Neogene of Danube Basin) there is also a belt without reflections A1. The basis of the basin A2 is very well marked. There are

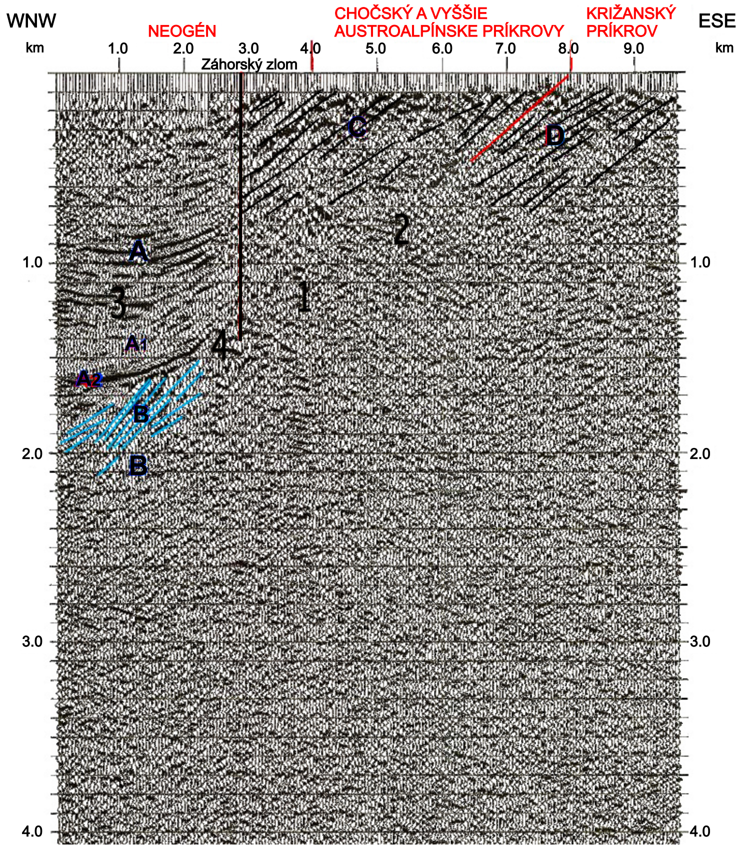

Fig. 4. Unmigrated time section 671/87 refilled with interpretation signs. Letters are explained in the text. Vertical scale is two-way travel time; horizontal scale is in kilometers.

no other evident reflection events beneath this interface. The package of steeply dipping events B are diffractions which have its origin at Záhorský fault. This sinistral strike-slip which is a part of the Mur – Mürz – Leitha line obviously separate the Malé Karpaty Mountains units from the Vienna Basin Neogene. The transpresion movements at the fault made the bending of events in basin (A).

The northwest-dipping event C is interpreted as the Hronicum and Upper Austroalpine nappes and D as the Fatricum. This one can be seen at 1.0 s TWT. The reflection which obtains surface at 8 km marks overthrust plane

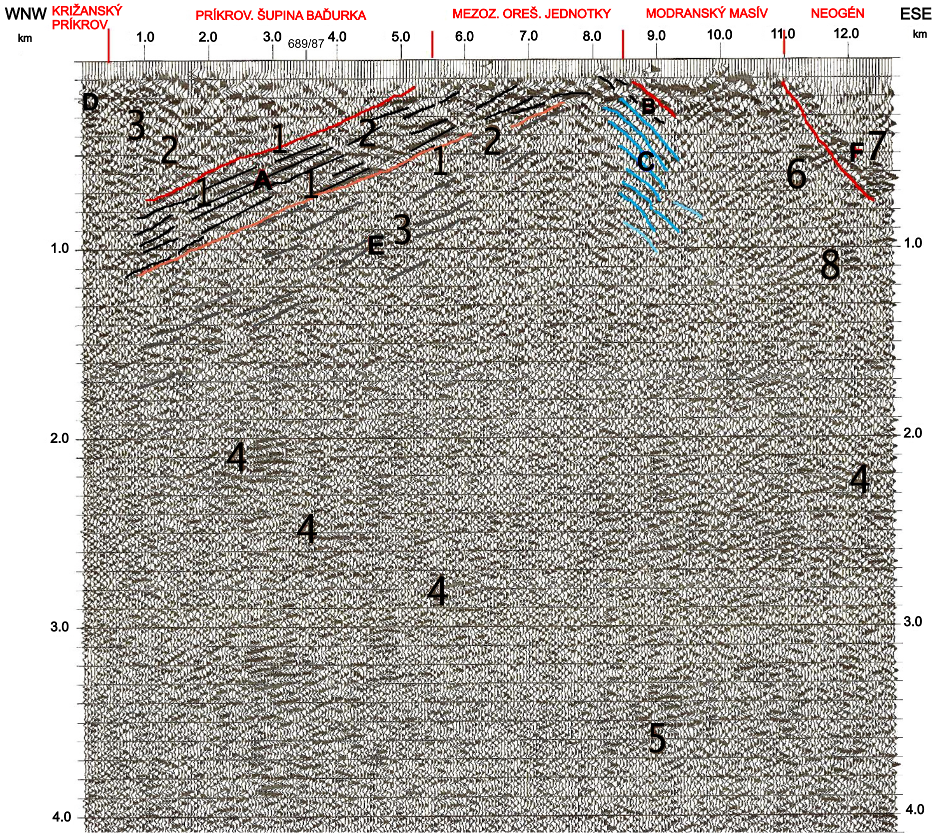

Fig. 5. Unmigrated time section 671A/87 refilled with interpretation signs. Letters are explained in the text. Vertical scale is two-way travel time; horizontal scale is in kilometers.

of the Hronicum over the Fatricum. The origin of lower events beneath Fatricum is in the cover units of the Malé Karpaty Mountains.

Line 671A/87 (Fig. 5)
This line passes the Tatricum represented at the surface by the nappe Baďurka, Modra massif and the mesozoic succession of Borinka unit. It ends in the Neogene of the Danube Basin.

There is a northwest-dipping event A reaching the surface at 5.5 km in the northwest part of this profile. It probably presents overthrust plane of nappe scale Baďurka to the Mesozoic of the Orešany unit. Not so significant south-east-dipping event B is interpreted as the boundary between the Orešany unit Mesozoic and the Modra crystalline massif. There are diffractions C at this interface. Probably it is tectonically battered. Among 5.5 km and 8.5 km the subautochthonous Orešany unit outcrops the alltochthonous Bratislava-Modra nappe (Modra massif and nappe scale Baďurka are part of this).

The interface between the Mesozoic and the basement of Orešany unit is marked as a change of reflection character at the seismic record. There are significant reflection events (A) in the Mesozoic. Beneath this the reflections are not so marked and continuous (E). It is typical for crystalline complex. The event is registrated at the 2.0 s TWT.

The events from northwest part of profile (A, E) reach the surface and immerse down again (B) so the fold upwarping can be notice. It is the same situation as at the line 8CHR/86.

At the begin of the line the small package of events D is observed. It probably belongs to the Fatricum nappe.

Approximately from 11 km to the end of line the contact of Modra masiff and the Neogene of the Danube Basin (F) can be marked. Only the end of the line hits the Danube Basin so the record of the contact is not so good as at line 8CHR/86.

There are no reflection events beneath the time level 2.0 s TWT in the interval among 5 km and 8 km. This transparent zone is a demonstration of low energy. It has no geological signification. The character of it is only technical because there were used lightweight vibrators as a source of energy. At the line 8CHR/86, which was shot by dynamit, there is no zone like this.

The band of parallel horizontal reflections occurs under the time level 2.0 s TWT on both sides of transparent zone. Their origin could be in deep upper crust units beneath the Tatricum. They are interpreted as sets of sedimentary complexes, translation planes or mylonite zones of the Penninicum. Its nether restraint is not marked.

Line 689/87 (Fig. 6)

The area crossed by the line is mostly formed by the Tatricum (the Bratislava-Modra massif) and its north-east part extends to the Fatricum. Eastward of crossing the line 671A/87 the Orešany unit comes out to surface.

Because of its orientation the line 689/87 is not suitable for interpretation

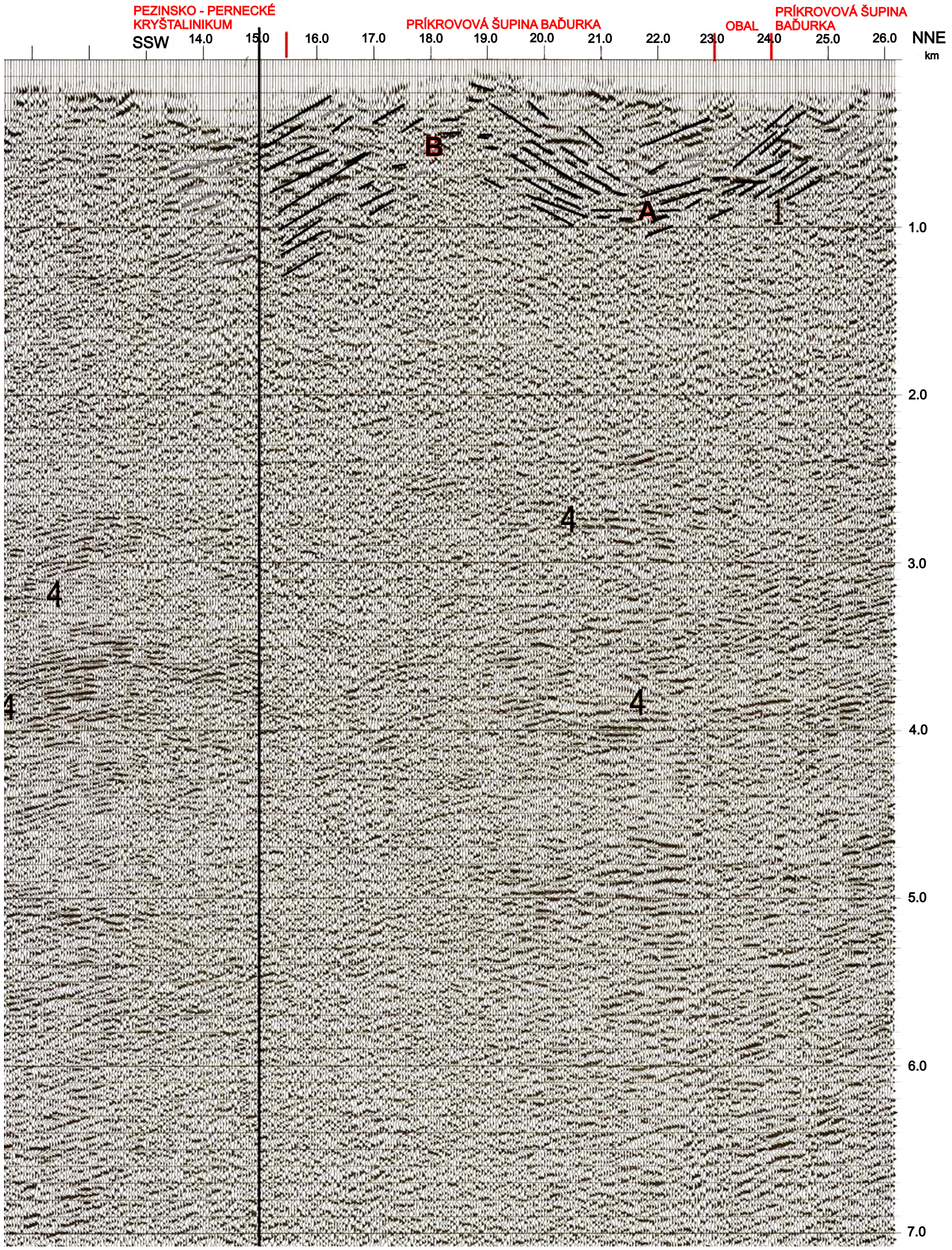

Fig. 6. Unmigrated time section 689/87 refilled with interpretation signs. Letters are explained in the text. Vertical scale is two-way travel time; horizontal scale is in kilometers.

of individual structures of the Malé Karpaty Mountains but it fills up the complex view of their constitution.

The whole upper crust is extremely reflective. Useful reflections appear at time level 7 s TWT. Considering to the velocity of seismic waves in the environment of the Malé Karpaty Mountains crystalline complex and Mesozoic it responds to 21.4 km depth.

The reflective sequences are mostly subhorizontal without fold upwarping observed at transversal lines. Only near the surface the synform (A) and antiform (B) occur. This structure demonstrates possible shortening of the mountain in the longitudinal direction.

At the part of the section between 15 km and 19 km beneath 2.5 s TWT the transparent zone is seen. Its character is the same as at line 671A/87. The same source of energy was used so the cause of this zone will be the same.

5. Conclusions

All interfaces on the chosen profiles are interpretable, including the change of Mesozoic of Orešany unit into its fundament.

Nappes and the Malé Karpaty Mountains unit interfaces decline to the north-west and are almost parallel to each other. The reflexes from Hronicum and Upper Austroalpine nappes are recorded after 1.7 s TWT.

Reflexes of the Malé Karpaty Mountains crystalline complex, especially at the migrated profile 8CHR/86, have up to the 3.0 s TWT a *fault propagating* character. Beneath it, a horizontal line (fault), probably Penninic shear zone is apparent. We assign deeper structures to Penninic but its lower boundary is not clear.

An indication of fold upwarping is apparent also in the Orešany unit (profile 671A/87, 8CHR/86).

The interface between the Danube Basin Neogene and Malé Karpaty units is represented by a half fold with marks of a plain descending fault at the surface in the northern part of the investigated area. It is not significant on the southern profile 671A/87.

A significant boundary of the Vienna Basin Neogene filling and Malé Karpaty units is the vertical Záhorský fault (recorded on the profile 671/87).

It is a sinistral displacement of a transpressional character, which is a part of the Mur - Mürz – Leitha line and also the line of the Malé Karpaty Mountains uplift.

The Vienna Basin is a pull-apart basin, the border from the Danube Basin side is folded and onlaps are formed.

The Malé Karpaty Mountains represent an anticline on the northern side (south from Smolenice). While the western border is formed by a significant orthogonal strike slip connected with the mountain range uplift, the eastern border has a fold character. In the area between villages Dolné Orešany and Doľany, the presence of diffractions indicates the possibility of a plain near-surface fault, but to the south its presence is not recorded anymore and the border character is erosional.

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References

Danišík M., Dunkl I., Putiš M., Frisch W., Kráľ J., 2004: Tertiary burial and exhumation history of basement highs along the NW margin of the Pannonian Basin – an apatite fission track study. Austrian J. Earth Sci., **95/96**, 60–70.

Lillie R. J., 1999: Whole Earth Geophysics. Prentice Hall. New Jersey.

Maheľ M., Cambel B., Buday T., Halouzka R., Matějka A., Peržel M., Sabol A., Vozár J., Hanáček J., Janáček J., Leško B., Lukniš M., Vass D., Žákovský R., 1972: Geologická mapa Malých Karpát 1:50 000. GÚDŠ, Bratislava.

Neubauer F., Genser J., Handler R., 2000: The Eastern Alps: Result of two-stage collision process. Mitt. Österr. Geol. Ges., **92**, 117–134.

Petrík I., Broska I., Uher P., 1994: Evolution of the Western Carpathian granite magmatism: Age, source rock, geotectonic setting and relation to the Variscan structure. Geol. Carpath. **45**, 283–291.

Plašienka D., 1987: Litologicko-sedimentologický a paleotektonický charakter borinskej jednotky v Malých Karpatoch. Miner. Slovaca, **19**, 217–230 (in Slovak).

Plašienka D., Putiš M., 1987: Geological structure of the Tatrikum in the Malé Karpaty Mts. In: Structural development of the Carphatian – Balkan orogenic belt – Guide to excursions. Bratislava, GÚDŠ, 47–82.

Plašienka D., Michalík J., Kováč M., Gross P., Putiš M., 1991: Paleotectonic evolution of the Malé Karpaty Mts.: An overview. Geol. Carpath., **42**, 4, 195–208.

Plašienka D., Grecula P., Putiš M., Kováč M., Hovorka D., 1997: Evolution and structure of the Western Carpathians: An overview. In: Grecula P., Hovorka D., Putiš M. (eds.): Geological Evolution of the Western Carpathians. Monograph. Miner. Slovaca, 1–24.

Putiš M., 1987: Geológia a tektonika juhozápadnej a severnej časti kryštalinika Malých Karpát. Miner. Slovaca, **19**, 2, 135–157 (in Slovak).

Putiš M., 1992: Variscan and Alpinic nappe structures of the Western Carpathian crystalline basement. Geol. Carpathica, **43**, 6, 369–380.

Putiš M., 2006: Litostratigrafia a predalpínsky geodynamický vývoj staropaleozoických komplexov Malých Karpát: prehľad poznatkov vs. nové členenia. Miner. Slovaca, **38**, 2, 181–186.

Putiš M., Hrdlička M., Uher P., 2004: Litológia a granitoidný magmatizmus staršieho paleozoika Malých Karpát. Miner. Slovaca, **23**, 183–194.

Putiš M., Sulák M., Gawlick H.-J., Bojar A.-V., 2006: Infratatricum of the Považský Inovec Mts. (Western Carpathians): Geodynamic evolution of continental margin in the vicinity of the oceanic Penninicum. Miner. Slovaca, **38**, 1, 7–28 (in Slovak).