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185 - 191

DEFORMATION SEQUENCE IN THE ORAVSKÁ LESNÁ AREA, FLYSCH BELT OF THE WESTERN CARPATHIANS

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Abstract: Palaeogene flysch deposits of the Oravská Lesná area, portion of the proximal zone of the Magura accretionary wedge formed in front of the West Carpathians, indicates the NW - SE shortening as the oldest tectonic event. This shortening of the Palaeocene - Late Badenian age, is responsible for the most dominant currently present structures of this area including: NE - SW striking folds and thrust planes, steep to overturned bedding planes of the same strike, slump bodies, and W - E and N - S striking strike-slip faults which accommodated inhomogeneous thrusting as lateral ramps. Younger tectonic event, N - S shortening of the Late Badenian age, reactivated pre-existing fault plane pattern, including the continuation of the roughly N - S striking Zázrivá sigmoide - large strike-slip fault zone which started to act as the dextral strike-slip fault for the first time. Pre-existing NE - SW striking dip-slip reverse faults were reactivated as oblique-slip reverse faults. The youngest, the Late Badenian - Late Sarmatian tectonic event, controlled by the stress field with the NE - SW oriented maximum principal stress axis, reactivated original reverse fault pattern as strike- and/or oblique-slip faults. This faulting accommodated the NE-ward lateral motion of the rock mass which occurs in outcrops of the Oravská Lesná area.

Key words: Western Carpathians, Flysch Belt, Oravská Lesná area, deformation history, paleostress configurations.

Introduction

The study area is situated in the Western Carpathians, at the contact of the Slovenské Beskydy Mts., the Oravská Magura Mts. and the Kysucké Vrchy Mts. Sediments present here belong to the Magura Nappe system of the Flysch Belt (Fig. 1a), to two of its units: the Bystrica and Oravská Magura Units (Fig. 1b). The Magura Nappe system was deposited as a flysch accretionary wedge, in the foredeep of the ancestral Western Carpathians during the Late Cretaceous - Palaeogene.

The goal of the presented work was to:

1 - Perform a mapping to the 1 : 25 000 scale map M-34-87-C-d Oravská Lesná;

2 - Collect data describing sedimentary transport;

3 - Collect structural data;

4 - Reconstruct a deformation history as based on evidences interpreted from available geophysical papers (Kadlečík et al. 1988; Speváková & Valušiaková 1986) and data mentioned above.

Methods

Discussed stress configurations have been computed by inversion stress techniques published by Carey & Brunier (1974), Aleksandrowski (1985), Hardcastle & Hills (1991). Reader is referred to original papers for the complete description and justification of these approaches. Each stress configuration, except ones determined by Aleksandrowski's graphic routine, provides orientations of principal stress axes and the ratio of their magnitudes in a form defined by Bott (1959). Data separation was based on misfit between computed and measured slip vector. Misfit equal to 15 - 20 degrees was set as a limit indicating that data which failed this test are not related to the computed stress configuration. These data have been used as database for another cycle of the stress computation. A relative age of computed stress configurations was determined as based on cross-cutting relationships of measured striations on fault planes. The geological timing was then made by taking into account the age of stratigraphic horizons affected by faults used for the computation of a related stress tensor.

The range of mapped stratigraphic horizons in the Oravská Lesná area does not include Neogene. For that reason, in order

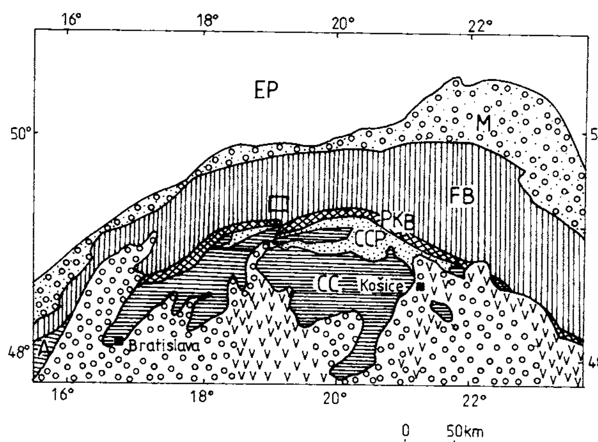

Fig. 1 a. - Map of the Western Carpathians with indication of the studied area. EP - European Platform; M - Neogene Molasse foredeep; FB - Flysch Belt; PKB - Pieniny Klippen Belt; CCP - Central Carpathian Paleogene Basin; CC -Central Carpathians; A - Austro-Alpine. Circles - Neogene sediments; V pattern - Neogene volcanic rocks.

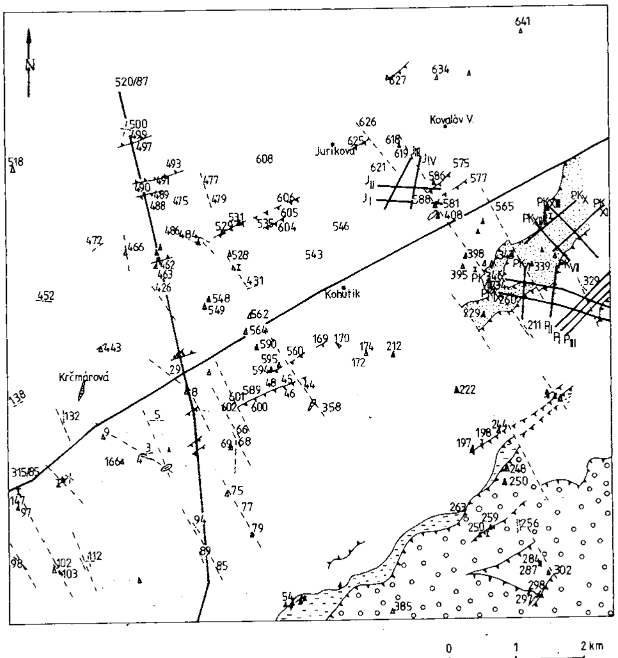

Fig. 1 b. - Map of the Oravská Lesná area with indication of cross sections. Bystrica Unit: blank - Middle - Upper Eocene Bystrica Formation (Zlín Formation); short line pattern - Lower - Middle Eocene Vychylovka Formation; dot pattern - Lower - Middle Eocene Beloveža Formation. Oravská Magura Unit: circle pattern - Paleocene sandstones, 520/87, 315/85 - deep reflection seismic profiles (Kadlečík et al. 1988); other profiles - vertical electric sounding profiles (Speváková & Valušiaková 1986); triangles - localities with a distinct amount of extensional veins filled by the calcite; I - sites of an intense deformation; thin discontinuous lines - strike-slip faults; thin continuous lines - geological boundaries other than faults; lines with a saw-teeth pattern - thrusts and numbers - localities with structural data.

to imply a geological timing, determined stress configurations have been compared with Tertiary regional stress fields published by Nemčok (1993). Justification for this approach is given in Turcotte & Schubert (1982) who describe a stress transmission over hundreds of kilometres.

In order to quantify the shortening which acted during and after the deposition of flysch sediments in the Oravská Lesná area, an extension parameter e=(l-l')/l (Ramsay & Huber 1983) was computed. Original and shortened bed lengths from the outcrop and interpreted geophysical profiles have been substituted for l and l', respectively. These values have been multiplied by +100 in order to get positive % values.

Data

Geological structure of the area is characterised in cross sections, which are interpreted along available reflection seismic and vertical electric sounding data (Kadlečík et al. 1988; Speváková & Valušiaková 1986) and compared with mesoscale data from 640 outcrops (Figs. 2, 3, 4). A basic picture of the structure is given by the contoured graph of bedding planes in Fig. 5. One can see rather steep dips of the layering showing bimodal distribution. Larger maximum (dip direction - 340, dip - 33) indicates foreland dipping bedding planes, while lesser maximum indicates hinterland dipping bedding planes. As indicated by evidences from the outcrops and interpreted profiles (Figs. 3, 4), foreland dipping bedding planes are formed by flats and originally overturned fold limbs of the thrust-fold system, while hinterland dipping bedding planes belong to remaining limbs of thrust propagation folds present in the area.

Sediments were brought into the basin by gravity flow mechanisms - turbidity currents. All present formations have in common products of high density, sandy turbidity currents and low density turbidity currents, sandstones and siltstones, respec-

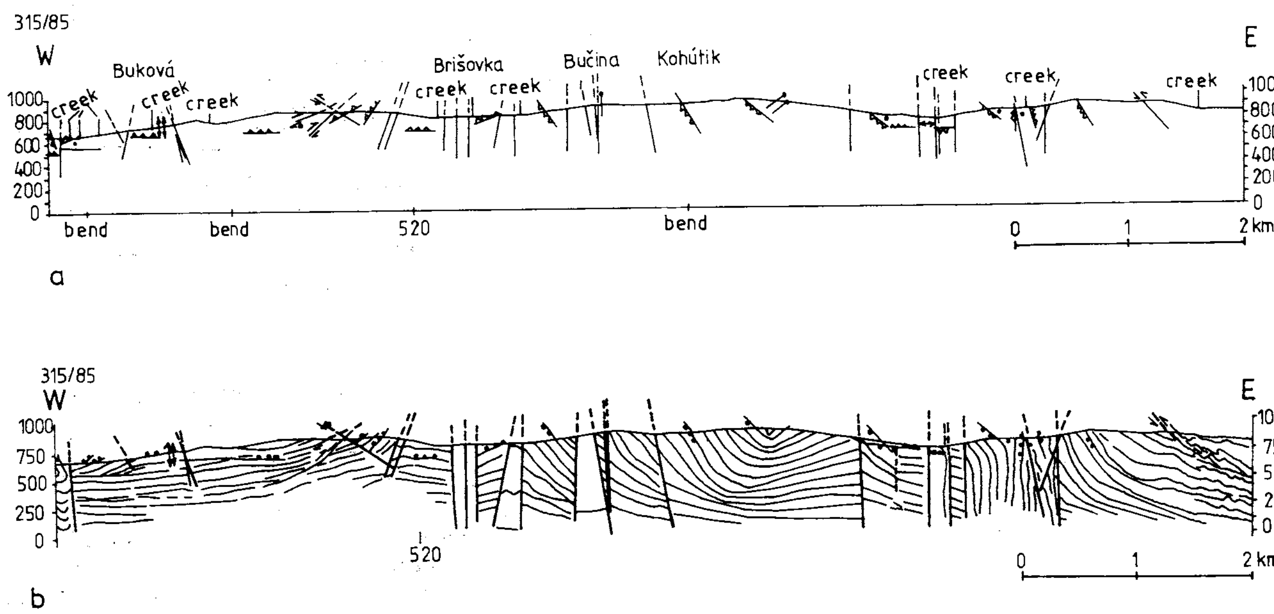

Fig. 2. Profile along the deep reflection seismic cross section 315/85 made by Kadlečík et al. (1988) through the Bystrica Formation, indicated in Fig. 1b. **a** - raw data: thin lines either with a dot at the one end or lines with triangle pattern - bedding planes and bedding planes with indicated position of turbidic sole structures, respectively, thin plain lines - faults, arrows - displacement along faults; **b** - interpretation: thin lines - bedding planes, dots-position of turbiditic sole structures, thick lines - faults, arrows - displacement along faults.

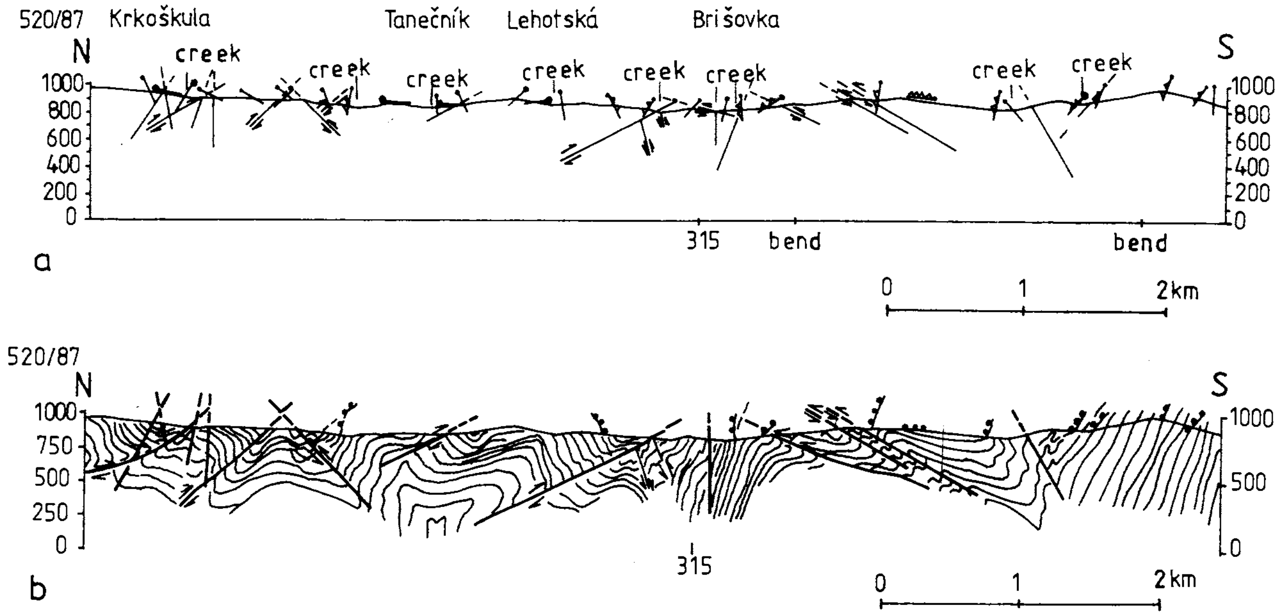

Fig. 3. Profile along the deep reflection seismic cross section 520/87 made by Kadlečík et al. (1988) through the Bystrica Formation, indicated in Fig. 1b. **a**, **b** - See Fig. 2 for an explanation.

tively. Following ages of sediments have been determined by Korábová (1990) and Raková (1990) as based on study of foraminifers and nanoplankton. Palaeocene sandstones of the Oravská Magura Unit (Fig. 1b) can be characterised as massive sandstones with scarce occurrence of thin layered siltstones. They can be described as top-absent classical turbidites of Bouma (1962). The lack of E horizon of the Bouma sequence (Bouma 1962) in this formation causes its age determination to be little bit dubious. The Lower - Middle Eocene Beloveža Formation can be characterised as having fine-grained turbidite sequences of Piper (1978) or Stow (1985). It provides the most complete turbidite sequence in a whole area, involving E_3 or T_8 (Piper 1978; Stow 1985) pelagic intervals for a proper age determination. The Middle - Upper Eocene Bystrica Formation has a medium grained, frequently thick bedded turbidite sequences. Presence of abundant E horizons (Bouma 1962) secure reliable age determinations. Sediment dispersion paths have been obtained from flutes. These unidirectional palaeocurrent data collected from sandy turbidites of the last two formations show a predominance of axial flow indicators whilst there is a little component of transverse flows. The NE - SW axial sedimentary transport directions from one of the outcrops corrected by "back tilting" is shown on Fig. 6.

Turbidite sequences characterising each of mentioned formations can be interpreted as a function of the flow velocity and carrying power decrease following Lowe (1982). That is why formations of the Bystrica Unit presented here indicate a deposition as medial to distal turbidites. The same fact is supported by the presence of axial flow indicators. Synsedimentary slumps present in some outcrops indicate record of the first stages of the accretionary wedge development described

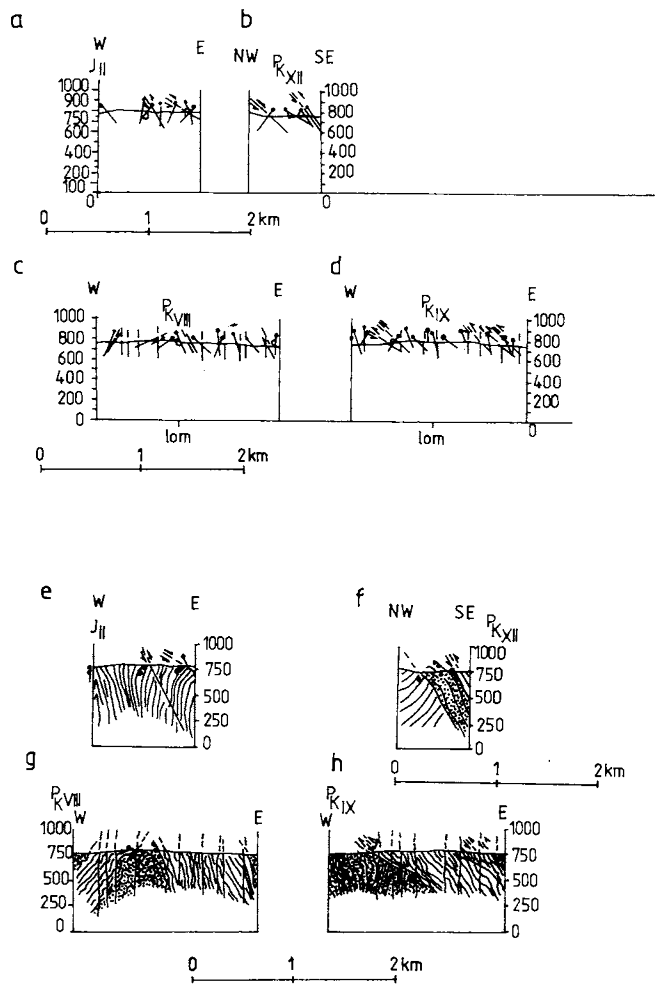

Fig. 4. Profiles along the vertical electric sounding cross sections J_{II}, P_{kVIII}, P_{kIX}, P_{kXII}, made by Speváková & Valušiaková (1986) through the Bystrica and Beloveža Formations, indicated in Fig. 1b. **a**, **b**, **c**, **d** - raw data; **e**, **f**, **g**, **h** - interpretation, blank - sediments of the Bystrica Formation, dot pattern - sediments of the Beloveža Formation. See Fig. 2 for an explanation.

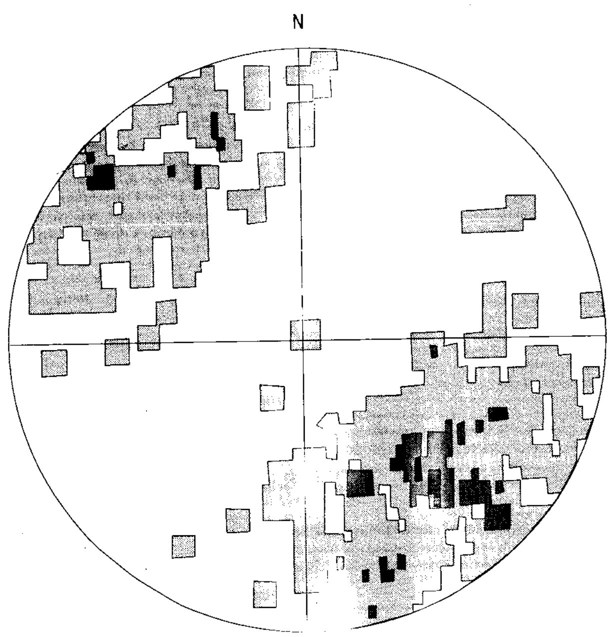

Fig. 5. Contoured graph of 300 bedding plane poles of the flysh sediments from the Oravská Lesná area. Contoured intervals include: 0 - 1.6 %, 1.6 - 3.3 % and more than 3.3 % of the whole data set.

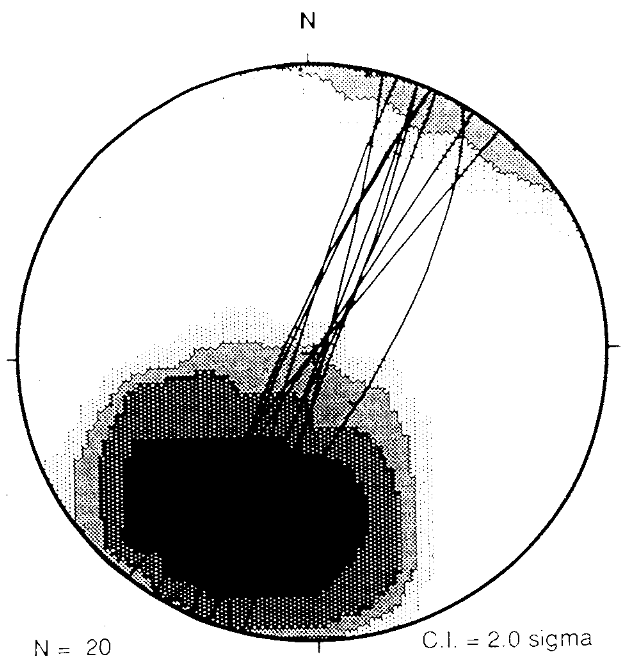

Fig. 6. Great circles of bedding planes and contoured 20 paleocurrent vectors on them plotted in a lower hemisphere stereonet, from the area to the east of locality 535, indicated in Fig. 1b. Step between contour levels is 2 %.

by Knipe & Needham (1986). The study of Korábová (1990) and Raková (1990) have indicated a redeposition of older flysch sediments as based on reworked older fauna present in younger rock in older clasts or as clasts. A huge shortening is indicated by a fact that medial to distal turbidites are present in slices

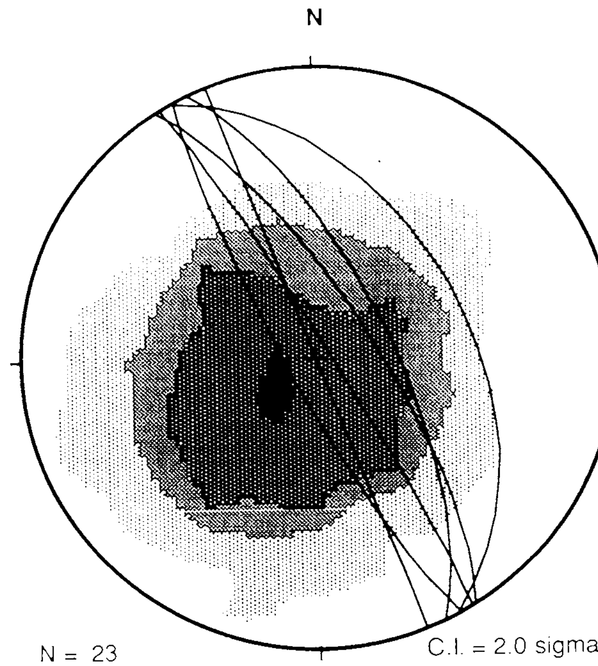

Fig. 7. Folds with subvertical axes related to the strike-slip faulting plotted in a lower hemisphere stereonet at locality 260, indicated in Fig. 1b. Strike-slip faults are indicated by great circles, 23 fold axes are contoured. Step between contour level is 2 %.

occupying proximal parts of the piggy-back thrust stack. They have now subvertical to overturned layering as shown in Fig. 5.

Among structural features, there are folds present in the outcrops, most frequently of the class 2 (sensu Ramsay 1967). They tend to have higher closure thickness/limb thickness ratio in the shales than in sandstones due to the rheological contrasts. Numerous folds have vertical axes (Fig. 7), made by strike-slip fault related folding of already steeply dipping thrust slices. Subhorizontal fold axes form two maximums: first with NNW - SSE oriented axes and second with NE - SW oriented axes. First of maximums is related to the dextral strike-slip faulting which is most clearly expressed by a dextral offset of the Pieniny Klippen Belt to the South of the Oravská Lesná area. Second of maximums is related to the thrust-propagation, sometimes to the thrust-bend folding. As based on a few occurrences of tension veins perpendicular to the fold axis, and bedding parallel striations perpendicular to the fold axis, σ_1 was assumed to act as roughly perpendicular to the fold axes. This approximation allowed to draw the σ_1 stress trajectory map (Fig. 8). In this case of thrusting and folding, these trajectories are the projection of the $\sigma_1\sigma_3$ plane to the surface, thus indicating movement trajectories of the flysch slices during the shortening. One can see on Fig. 8 the two distinct dextral strike-slip faults contemporaneous with the NW - SE thrusting, highlighted by σ_1 stress reorientation a long their strikes. Relatively younger N - S σ_1 stress trajectories are caused by younger displacements along the strike-slip faults. Youngest NE - SW σ_1 trajectories indicate how the development of the flysch accretionary wedge in this area led finally to the NE-ward motion.

Shortening computed on natural profiles from the structures made by the NW - SE oriented σ_1 varies from locality to locality, ranging from 65.4 %, through 42 %, 36 %, 34 % to 27 %. Computation of the shortening from the cross sections should be taken as minimal due to the fact that they are constructed up to certain depth levels and they lack marker horizons necessary for

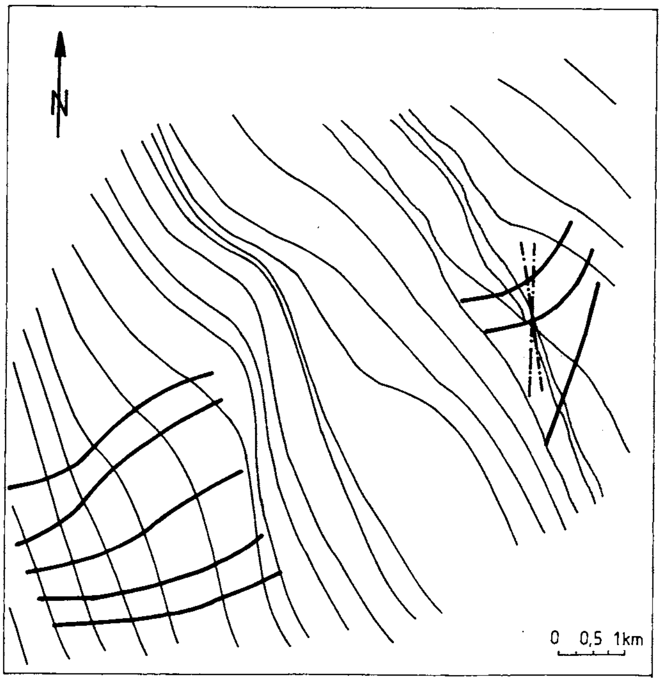

Fig. 8. σ_1 stress trajectory map based on the study of the folds. Maximum principal stress axis is pressumed to be perpendicular to fold axes of thrust-propagation and thrust-bend folds. Thin lines indicate σ_1 of oldest (Palaeocene - Late Badenian) event; thicker discontinous lines - middle (Late Badenian) event; and thicknest continuous lines - youngest (Late Badenian - Late Sarmatian) event. Note that a curvature of σ_1 stress trajectories for an oldest event exactly highlights zones of strike-slip faulting indicated in Fig. 1b.

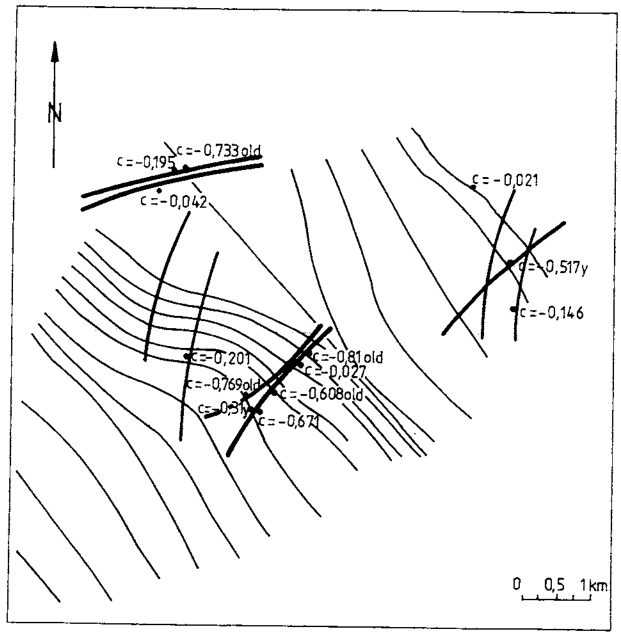

Fig. 9. σ_1 stress trajectory map based on the stress inversion study of the fault populations. Thin lines indicate σ_1 of oldest (Palaeocene - Late Badenian) event; thicker lines - middle (Late Badenian) event; and thickest lines - youngest (Late Badenian - Late Sarmatian) event. Numbers indicate values of the ratio of stress magnitudes.

the displacement determination. They provide values like 42 % (Fig. 4f), 40.3 % (Fig. 4e), or 32.5 % (Fig. 3b).

A more detailed view of the deformational sequence is provided by the fault population analyses. Stress tensors computed by inversion stress methods have been used for the stress trajectory map (Fig. 9). These trajectories make the image of the deformation history outlined by Fig. 8 more exact. Computed Bott's c parameters (Bott 1959) show the stress ratio of magnitudes of the three principal stresses.

Interpretation

The relative sequence of tectonic events characterised by stress trajectories which affected Palaeogene flysch sediments can be compared with regional stress fields computed by Nemčok (1993). Regional stress fields for Neogene were separated in parts of the Western Carpathians with the more-or-less complete stratigraphic sequence affected by them. Each of them was characterised by principal stress axes orientations and by the stress ratio that allowed the comparison with the relative sequence of the stress fields which affected Palaeogene sediments in the Oravská Lesná area. Thus the movement history of this area can be implied as follows.

During the Palaeocene - Late Badenian, the flysch sequences had been affected by the paleostress field with σ_1 and σ_3 oriented NW - SE and vertical, respectively (Fig. 9). This NW - SE shortening made thrust-fold structures which are the most dominant in the present structure of this area (Figs. 1b, 2, 3, 4). A majority of thrusts is foreland vergent. However, back-thrusts are also present. Numerous thrusts were formed from the pre-existing fault propagation folds, as they were later cut through their frontal syncline. That caused a frequent reverse stratigraphy in overturned limbs incorporated in the slices. A strong shortening is indicated by upright folds of 2nd class (sensu Ramsay 1967). An overall history of the fold-slice development records different stages of a piggy-back shortening in a thrust stack of accreted sediments as modelled for example by Mulugeta Koyi (1987). Initial structures were gently inclined ramps of thrust splays branching from the main decollement and thrust propagation folds above them, as it is visible in profiles published by Poprawa et al. (1989) or Steininger et al. (1984) from frontal parts of a piggy-back stack - i.e. most external parts of the Flysch Belt and/or most internal parts of the Neogene molasse foredeep. During the development of this piggy-back thrust stack, the same structures progressively occupied positions from distal parts of the stack towards its proximal parts. During this process, they rotated towards the steeper positions, underwent some amount of flattening due to the load of an overburden and were progressively uplifted due to increased shortening and erosion. Thrust slices of the Oravská Lesná area are now subvertical to overturned, as visible in profiles perpendicular to the strike of an accretionary wedge (Figs. 3, 4, 5), thus occupying the most proximal parts of the thrust slice stack. Their related thrusts were no more able to accommodate further shortening, thus a new system of back-thrusts was formed. Some foreland vergent thrusts were also created.

The deformational record is highly influenced by the flysch rheology. There are shear zones with an intensive deformation, while adjacent blocks frequently appear as undeformed. Shale horizons are frequently reactivated as decollements. In such cases the lack of distinct deformation features is somewhat misleading, 1 - because of the relatively high fluid pressure which decreased a magnitude of the shear stress required for thrusting, and **2** - because the ductile deformation inside shale horizons does not indicate a distinct mesoscale deformation markers. The intensity of the deformation seems to be larger when the thrust ramps are present. They acted as zones of the increased friction along the whole geometry of that particular thrust plane. In the case of shale/sandstone juxtaposition, well developed breccias with sandstone clasts inside shale matrix can be observed on the outcrop scale.

The thrusting was highly inhomogeneous. The displacement velocities along the thrust planes varied laterally. In the profile along the reflection seismic cross section 315/85 processed by Kadlečík et al. (1988), parallel to the strike of the flysch accretionary wedge, lateral ramps bounding thrust slices are interpreted (Fig. 2). They were created as tear faults accommodating the inhomogeneous thrusting. Apparent dips of the slices in Fig. 2 are subhorizontal. In reality, they are either true flats or projections of steeper ramps. These lateral ramps, strike-slip faults, are indicated on the surface by zones with distinct deformation and by slickensides with subhorizontal striations. Another evidences for varying values of the thrusting, arcuate shapes of the thrust plane strikes, are visible in both the map scale (see Fig. 1b) and outcrop scale.

Zones of an intensive deformation are present along the contacts of slices of the Bystrica Formation sediments with other slices including different formations with different rheological properties. While the slices with sediments of the Bystrica Formation, the thick rhythmic flysch, suffered distinct deformation along the contact with more competent massive sandstones of the Oravská Magura Unit, slices involving sediments of the Beloveža Formation of the Bystrica Unit, the distal thin rhythmic flysch, comprises highly deformed zones along the contact with slices involving more competent sediments of the Bystrica Formation.

Mentioned zones of an intensive deformation caused a migration of calcite to the fill of tension veins from the surrounding host rock. That caused serious problems for the paleontologic age determination from samples collected close to these deformation zones. It is, according to my opinion, indicated by the partially soluted calcite fauna pointed by Korábová (1990) and Raková (1990).

Inhomogeneous thrusting during the NW - SE shortening is also responsible for the origin of rather large-scale strike-slip faulting with prevalent NW - SE strikes in this area. The deep reflection seismic profile 315/85 processed by Kadlečík et al. (1988; Fig. 10) shows a presence of the distinct negative flower structure (sensu Gregory in Harding & Lowell 1979) interpreted for the first time by Kadlečík et al. (1988), indicative of the transtensional strike-slip fault zone. Various shears of the slightly reinterpreted flower structure found in the field show that the original displacements along them were sinistral. Dextral displacements, seemingly the only ones shown by passive markers in the area of the Zázrivá dextral offset of the Pieniny Klippen Belt to the South of the Oravská Lesná, are the result of the younger reactivation, as based on the shear sense indicators on the slickensides. It is clearly visible in the profile parallel to the strike of the accretionary wedge (Fig. 10) in the Oravská Lesná area that various shears of this large strike-slip fault zone branch from the principal displacement zone in the depth of about 10 km. From the maps available for southern regions and preliminary structural studies (Nemčok, Sperner & Lexa, unpubl. res.) it is obvious that this fault zone is the continuation of the dextral strike-slip fault which offsets the Pieniny Klippen Belt known as the Zázrivá sigmoide. Thus, this distinct strike-slip fault had a tear fault function - to accommodate an inhomogeneous thrusting of the flysch accretionary wedge on a large scale. During the initial time period, the Palaeocene - Late Badenian, this strike-slip fault acted as sinistral, and younger dextral striations on the slickensides as well as the dextral offset of the Pieniny Klippen Belt are obviously the result of the following younger tectonic events.

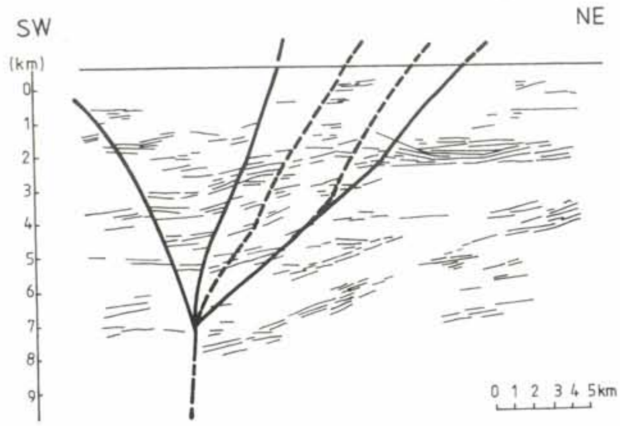

Fig. 10. Line drawing of the deep reflection profile 315/85 with interpreted negative flower structure (reinterpreted from Kadlečík et al. 1988). Note that horizontal scale is larger than vertical, that causes a tightening effect to interpreted flower structure. Real shear planes are dipping at shallower angles. Note that some of line-traced reflectors are downward convex that indicate a negative flower structure, i.e. transection along studied strike-slip fault zone.

First of them is the Late Badenian event, when σ_1 occupied roughly N - S position (Fig. 9), i.e. the distinct strike-slip fault zone indicated by the flower structure started to act as a dextral strike-slip fault. These displacements formed the folds with vertical fold axes in the pre-existing steeply dipping beds. Except this fault, also numerous smaller strike-slip faults had been active. Pre-existing thrust planes had been reactivated as having slightly oblique displacement vectors.

The next tectonic event, of the Late Badenian - Late Sarmatian age, was controlled by the stress field with the NE - SW oriented σ_1 (Fig. 9). The pattern of the pre-existing fault planes (prevalent NE - SW to W - E striking faults) was numerous enough to be reactivated, instead of the origin of new faults in the intact rock. Most of them had been reactivated as sinistral oblique-slip faults.

Discussion and summary

The described structural data collection is first of its kind in this area. However, the implied interpretation can be compared with pre-existing opinions based on mapping studies.

The dextral offset of the Pieniny Klippen Belt along the Zázrivá sigmoide have been discussed by numerous authors since the description of Andrusov (1926). However, no one of them was able to determine older sinistral displacements along this strike-slip fault zone because offsets of the passive line markers indicate only the final dextral deformation. Also the transtensional character of its kinematics during the last two tectonic events could be discovered only by structural methods or by a negative flower structure in the reflection seismic profile.

The same is valid for the thrust-fold structure of the whole area. The structure created by NW - SE shortening, already described by Matejka & Roth (1949), Roth & Matejka (1955), Roth (1959) and Roth et al. (1963), could be easily implied from the bedding planes and fold axes. Roth et al. (1963) pointed that the slice structures have progressively steeper positions coming from the foreland towards the hinterland, with the most proximal parts of the Magura Unit: back portion of the Bystrica Unit and the whole Oravská Magura Unit, having vertical or even overturned bedding planes.

As based on the evidences about the fault bend and fault propagation folding, frequent redeposition in the Magura Unit and mechanisms of faulting in more external units of the Western Carpathians, it is apparent that the Magura Unit underwent the piggy back thrusting during its deposition and after lithification. Uplifted shortened slices were sources for the continuing flysch deposition. The accretionary wedge piggy-back thrusting explains the fact that flysch slices become progressively steeper towards the hinterland. It also explains common occurrences of the features like: the fault bend, detachment and fault propagation folding, thrust faults, lateral ramps - i.e. strike-slip faults and synsedimentary slump bodies. However, some out-of-sequence thrusts cannot be ruled out, as indicated by preliminary studies from the other flysch areas, e.g. more to the SW.

Later N - S shortening determined by this work was discovered thanks to the structural techniques, because the only displacement markers on fault planes showed the younger movements oblique to the previous dip-slip reverse displacements. This tectonic event was the first one which started to form the Zázrivá sigmoide. Previous NW - SE shortening could not cause another displacement than sinistral along this fault zone.

Youngest NE-ward lateral motions of the flysch mass along the pre-existing thrust fault planes were distinguished only due to the slip-vector studies, because no marker horizons were available to infer this kind of the displacement.

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