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MESO-CENOZOIC TECTONIC STRESS FIELDS WITHIN THE ALPINE-CARPATHIAN TRANSITION ZONE: A REVIEW

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Abstract: The results of paleostress analysis based mainly on fault slip data realized in the Slovakian part of the Alpine-Carpathian junction area are briefly summarized. Some weak points of the general stress field reconstruction are discussed. Six periods of the Tertiary deformation have been characterized by homogeneous stress fields. The recent orientation of paleostress axes is explained as a result of interaction betweeen younger counterclockwise rotations of blocks bearing older stress record and primary clockwise rotation of stresses due to general geodynamic processes. Rigid body block rotation is responsible for the currently NW-SE trending Early Miocene compressional stress axes, originally roughly N-S oriented. The Middle-Late Miocene paleostress vectors are in their original position. Their changing directions are consequences of primary stress field reorganizations.

Key words: Alpine-Carpathian junction, Late Cretaceous, Tertiary, stress fields, transpression, transtension.

Introduction

Owing to the current progress of paleostress methods used in the tectonic analysis, a lot of microtectonic studies have also been performed in the Carpathian-Pannonian area of the Alpine-Carpathian transition zone during the last 5 years (Fig. 1). They brought a great deal of data concerning the tectonic stress fields and filled the gap in knowledge about the stress/strain relations in this area. However, the obtained stress determinations are scattered in numerous papers which are dealing more or less with local paleostress phenomena. The main objective of our contribution is to summarize all available published stress data from the area under question. We have done this in spite of the fact that several synthetic papers treating the Tertiary tectonic stress fields evolution have been published recently (Csontos et al. 1991, 1992; Nemčok et al. 1993). In these papers, the problem is dealt with generally in the scale of the whole Western Carpathian orogen, while we have focused our attention only on the Alpine-Carpathian transition zone. All the complex details related to the variations in the stress field of this region could not be described in the general papers, as we aspire to do in our contribution.

The Alpine-Carpathian junction area permanently attracts structural geologists as a key region for unravelling the neo-Alpine tectonic evolution of the entire orogenic belt. The Late Tertiary tectonosedimentary events, including paleostress fields, are recorded in the Neogene sediments of the Vienna and surrounding basins covering the Alpine-Carpathian contact zone. The observed stress fields can be well dated here, thanks to the precise dating of the Neogene sediments bearing the stress record.

The paper summarizes knowledge concerning the direction and distribution of paleostress axes determined from fault slip data, fault geometry and the relationships of mesostructures observed in the field. However, we are dealing neither with a detailed kinematic interpretation of the stress-induced deformation, nor with the magnitudes of the stress tensor parameters.

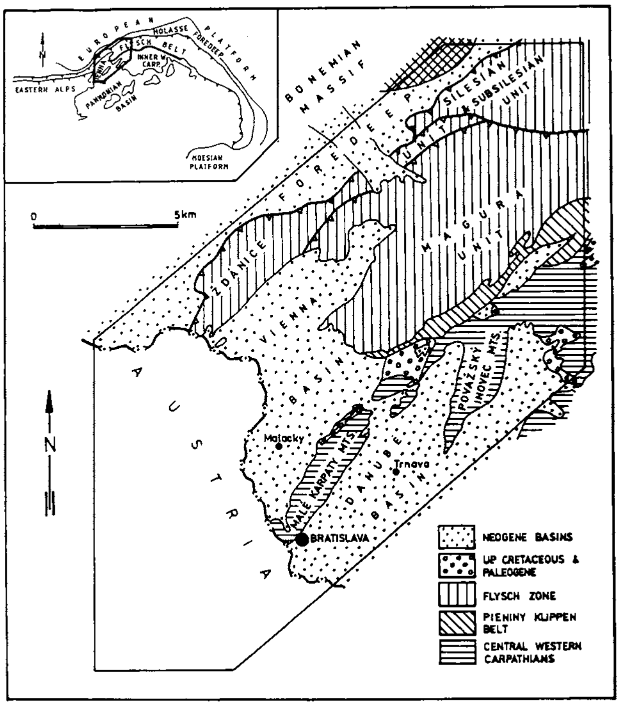

Fig. 1. The studied area of the Alpine-Carpathian transition zone in Western Slovakia and Southern Moravia.

Basic principles and methods

The observed structures are believed to reflect the pattern of the regional stress field and the determined paleostress fields are considered to be responsible for deformation on a regional scale (Angelier 1984). We have to take into account that the calculated paleostress directions need not to be in their original position. In this respect, we have to consider the possibility of paleostress direction changes due to the rigid body rotation within shear zones. As a matter of fact, the apparent block rotation in the area has been confirmed by paleomagnetic measurements (Túnyi & Kováč 1991; Márton et al. 1992; Kováč & Túnyi in press). Besides these secondary reorientations of paleostress directions, there were also primary modifications of the stress field directions in time due to some global geodynamic events (e.g. changing in the plate motion vector, lateral escape of the deformed domain etc.). The current orientation of the tectonic paleostresses should be considered as a combination of both rotational phenomena. The third one - the "en bloc" rotation of the entire Western Carpathian domain played an important role as well.

The orientation of the Tertiary tectonic stress tensors described in our paper is inferred from the observations of mesoscopic fault parametres (attitude and slip data) and subsequent computer or manual analysis. Most of the quoted authors used methods of the "French school" based on the Anderson's classical concept of fault dynamics (Anderson 1951). The manual separation of homogeneous, synchronously active fault population developed in an autonomous stress field is preferred in most papers.

The methods used in processing of field data have various levels of sophistication and sensitivity, but generally the results are compatible. The stress tensors constructed by simple and less precise right dihedra method and by other graphical methods are considered as equivalent to the stress tensors reconstructed by more sensitive computer methods. In the scale of our research, this simplification might be acceptable, or even advantageous in some aspects.

Due to the possible rotation of stress fields, we have decided to outline the paleostress patterns by single stress axes, located approximately at the sites of measurements. To avoid risk of mistakes caused by extrapolations among measurements, we are using paleostress trajectories only to describe the relations between the currently observed and supposed general directions of paleostress fields in the large scale views (see inserts in Figs. 3-7).

The nature and orientation of the Late Cretaceous stress field was also estimated, in the case of lacking fault-slip data, on the basis of changes of the incipient (predeformational) and final (postdeformational) geometry of regional-scale structures with respect to the mesoscopic structural elements.

To compile all available stress data into a synthetic form, a lot of obstacles have to be overcome. The principal problem is the heterogeneity of the published data and of used stress analysis methods. Even when the methods used by different authors are based on the same principles, the results may have different degree of reliability. For example this may apply to the fault slip data used for paleostress determination in the compiled papers.

A correct choice of conjugate pairs of faults also plays an important role, when single graphical methods are used for paleostress directions determination. First of all, results depend on the correct field determination of sense of movement along observed faults. Other constraints arise from the heterogeneous distribution of measureable exposures in the field. There is usually no evidence that the investigated outcrops are the proper representives of the general stress record we are searching for, and one has often to face the danger that only a local stress field is measured. Fortunately, all these difficulties can be overcome by comparison of measurements from different areas. Similar directions of stress axes determined in comparable rock complexes suggest that the general stress field of the same age was calculated.

We had also to bring into harmony the time constraints for the recognized stress field, which slightly vary in some cited publications. As a result, we suggest several deformation periods governed by distinct tectonic stress fields, which were distinguished on the basis of the quoted published age data.

Some uncertainties in the stress determinations may be seen in the controversial application of Anderson's pure shear concept in the current stress analysis methods, whilst the fault slip is believed to be a result of simple shearing. Nevertheless, simple shear versus pure shear concept remains a question of philosophy and we adopt the observed stress axes as real representations of the tectonic stress fields responsible for observed deformation.

Geological setting and sources of data

The Alpine-Carpathian junction area is an important region joining two independent, though mutually related orogenic systems. Most of the area is covered by the Cenozoic sediments of

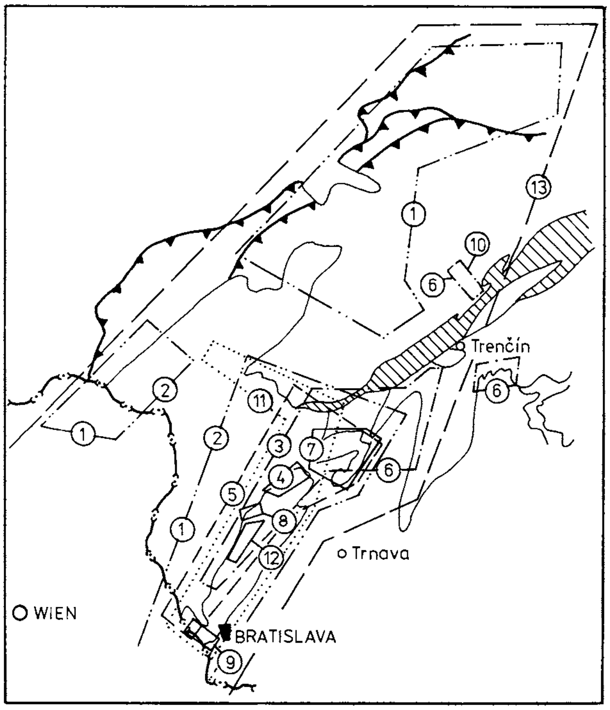

Fig. 2. Areas of applied paleostress analyses. The numbers refer to source publications (see below) which deal with paleostress analysis in areas indicated by polygons. **1** - Fodor (1991 - IM), **2** - Fodor et al. (1990 - IM), **3** - Kováč et al. (1989 - GM), **4** - Kováč et al. (1993a - GM), **5** - Kováč et al. (1993b - GM), **6** - Kováč et al. (1990 - GM), **7** - Marko et al. (1991 - IM), **8** - Marko et al. (1990 - GM), **9** - Marko & Uher (1992 - RD), **10** - Nemčok (1991 - RD, MP), **11** - Nemčok et al. (1989 - RD, MP), **12** - Plašienka (1990 - X), **13** - Fodor (1991, in press - IM). **IM** - inversion method (Angelier 1984), **RD** - right dihedra method (Angelier & Mechler 1977), **MP** - method based on movement planes analysis (Aleksandrowski 1986), **GM** - simple graphical methods based on the analysis of conjugate faults (Gzovskij 1975), **X** - other methods not using brittle fault slip data.

the Vienna and the Danube (Little Hungarian Plain) Basins, divided by the horst of the Malé Karpaty Mts. (Fig. 1). The pre-Neogene substratum of this horst consists of the Tatric Variscan crystalline basement and its Permomesozoic cover, the Fatric-Hronic Mesozoic cover nappe system (the Krížna-Vysoká, Choč and higher nappes) and some Senonian and Paleogene post-nappe deposits. To the NE, the focused area includes also the Brezovské Karpaty Mts., built mostly by Mesozoic décollement nappes and their Late Cretaceous (Gosau) and Tertiary post-nappe sedimentary cover and touches the westernmost part of the Pieniny Klippen Belt and the Považský Inovec horst. Units of the Outer Carpathian Flysch Belt in Southern Moravia are also included in the investigated areas (Figs. 1, 2). The outline of the structure and paleotectonic evolution of this region is given e.g. in papers of Mahel' (1983, 1987), Plašienka et al. (1991) and Kováč et al. (1991).

Development of exact knowledge on paleotectonic stress fields in the Western Carpathians commenced in the late 1980's, when the first paleostress axes determinations appeared. Areas of investigations of fundamental works reviewed in the present paper are outlined in Fig. 2. The Tertiary (Early Miocene) stress field from the focused area was described in the paper of Kováč et al. (1989). The fault slip data analysis has revealed the dominant role of strike-slip faulting and several stages of compressional stress fields with subhorizontally operating σ_1 in the NE part of the Vienna Basin during the Early Miocene. It was also for the first time pointed out that changing fault kinematics is a consequence of a clockwise rotation of the principal compression axis. The effect of a secondary rotation on the paleostress directions was interpreted as "en bloc" rotation of the whole Western Carpathians. Later on, Nemčok et al. (1989) and Kováč et al. (1990) confirmed the clockwise stress field rotation also during the Middle Miocene. Fodor et al. (1990) added paleostress data computed from the southern part of the Vienna Basin, where changing stress conditions were interpreted in terms of extrusion tectonics (e.g. Neubauer & Genser 1990, Ratschbacher et al. 1991). The extrusion model considers the eastward escape of the Carpathian domain during the Tertiary collision in the Alps. The studied area lies in the northwestern sector of the escaping domain, where the left-lateral wrench corridor would be expected during the Tertiary.

However, further detailed research in the northern part of the Malé Karpaty and Brezovské Karpaty Mts. brought surprising indications of important dextral shearing along a ENE-WSW trending shear zone (Marko et. al. 1990, 1991) during the Late Oligocene and Earliest Miocene. The dominant role of this dextral transpressional regime was also inferred in the Tatric cover units of the Malé Karpaty Mts. by Plašienka (1990) for the Late Cretaceous - Early Paleogene period. The observed Early Mio-

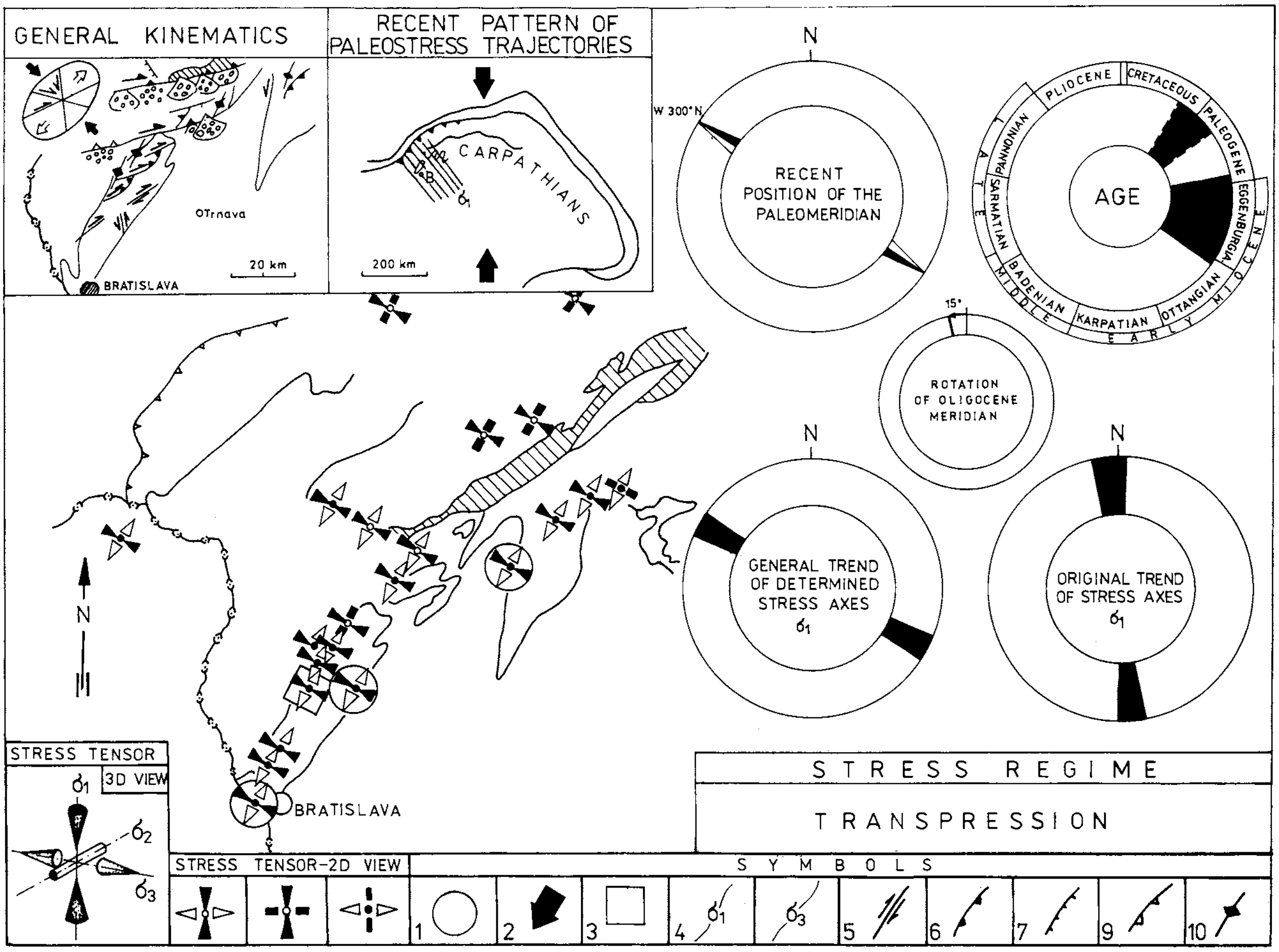

Fig. 3. Tectonic stresses and induced fault kinematics during the Cretaceous - Paleocene and Oligocene - Eggenburgian periods. σ_1 - maximum compressive stress axis, σ_2 - intermediate stress axis, σ_3 - minimum stress axis (rel. extension). 1 - stress tensor determined from fault-slip data gathered from several outcrops, 2 - general trend of compression (plate convergence) or extension (plate divergence), 3 - stress tensor estimated from the geometry of structural associations in the Mesozoic units, 4 - paleostress trajectories constructed by interpolations among localized stress tensors, 5 - strike-slip faults, 6 - reverse faults, 7 - normal faults, 9 - overthrusts, 10 - fold axes.

cene dextral shearing does not fit well the generally adopted idea of left-lateral separation of the Western Carpathian domain from the Alpine realm during the Tertiary tectonic evolution. The trend of compression connected with this dextral shearing also seems to contradict the overall N-S convergence of Africa and Europe during the Miocene (e.g. Philip 1987). The paleomagnetic data pointing to the Ottnangian-Badenian anticlockwise rotation of paleomagnetic vectors were very helpful in solving this puzzle (Kováč et al. 1989; Túnyi & Kováč 1991; Márton et al. 1992; Kováč & Túnyi in press). The late phase of rotation was explained as a result of block rotation due to the Middle Miocene sinistral shearing along the ENE-WSW trending zone (Marko et al. 1991). Another model (Fodor in press) reconciles the observed dextral shearing with the kinematically supposed left-lateral wrench zone and anticlockwise rotation. In each model, the trends of the Lower Miocene compression axes measured in outcrops are also allochthonous, anticlockwise rotated together with tectonic blocks, from the originally roughly N-S position to the NW-SE attitude. This idea is in accordance with the model of both rotating structures and stress fields which has been given in the area by Fodor (1991, in press). The Early Miocene transpressive and Middle to Late Miocene transtensive stress regimes (Kováč et al. 1993b) are described in detail in the quoted papers and supported by structural and sedimentological evidence.

Besides the above mentioned fundamental publications dealing with paleostresses, several local works have been published supporting the general results (Nemčok 1991; Marko & Uher 1992; Kováč et al. 1993a). All chosen areas, where the paleostress orientation has already been determined, are schematically contoured in Fig. 2.

Review of the Meso-Cenozoic tectonic stresses

Following the processing methods and principles explained above, the tectonic stress axes were determined (computed or graphically constructed) in many parts of the focused area. Stress data from publications quoted in the previous chapter have also been accepted and summarized in figures representing several conspicuous deformation episodes, characterized by the type and orientation of the general stress tensor. The precise stratigraphic age of Tertiary sediments bearing measured faults has been considered as the best time constraint for the determined stress field. However, the stress data derived from Mesozoic complexes have been also taken into account, on condition that came from the margins of Tertiary exposures and were compatible to those observed in the Tertiary sediments.

The clockwise rotation of actually determined paleostress directions from an older NW-SE orientation towards a younger NE-SW one was clearly recognized. However, there are some hints that, during the Pannonian (Late Miocene) period, the compression axis switched counterclockwise back to the N-S direction (Csontos et al. 1991). The Mesozoic to Early-Middle Miocene stresses recorded in rocks are regarded to be in an rotated possition due to several phases of superposed rigid body block rotation confirmed by paleomagnetic measurements (see above). These rotations rely to the progressive evolution of a sinistral shear zone separating the Western Carpathians from the Alpine block. The original position of the rotated stresses can be reconstructed by eliminating the known amount of the Early to Middle Miocene counterclockwise rotation of paleomagnetic meridians, as is shown in our diagrams (Figs. 3, 4, 5).

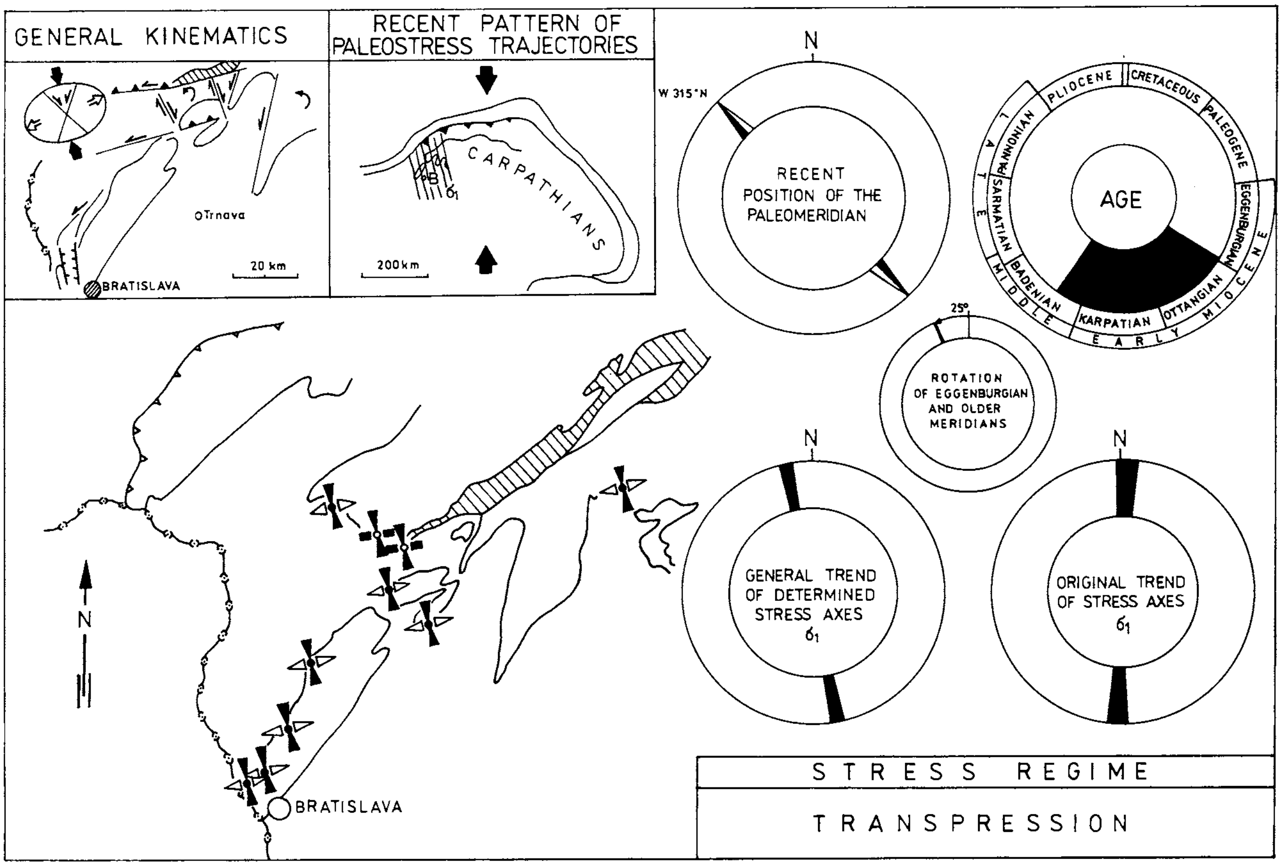

Fig. 4. Tectonic stresses and induced fault kinematics during the Ottnangian - Early Badenian period.

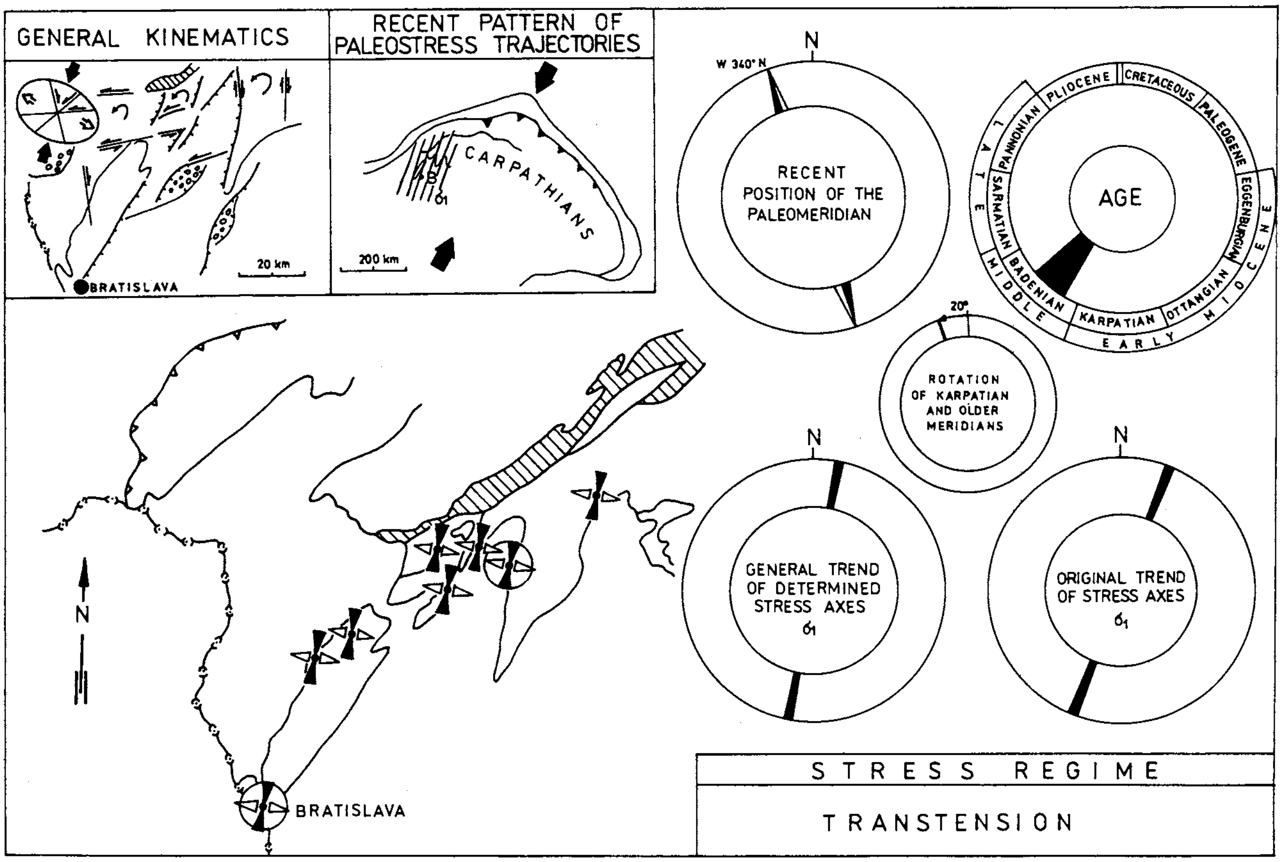

Fig. 5. Tectonic stresses and induced fault kinematics during the Middle Badenian period.

This may account for the misfitting NW-SE, or even WNW-ESE Early Miocene compressive stresses measured in a generally N-S converging area. These stresses were originally more or less N-S trending. Rotation of upper crustal blocks also explains varying stress directions of the same age. If we consider the general stress field to be homogeneous, the scattering of locally measured stress directions could be a result of block rotation during stress recording. In spite of the fact that the role and nature of block rotation in the recent distribution of paleostress axes has not been fully unravelled yet, the magnitudes and ages of these rotations have been already evaluated (Marko et al. 1991; Fodor 1991, in press).

Six periods of more or less homogeneous stress patterns characterized by a uniformly developing structural record are distinguished in our review. This separation is a little artificial, however, as the transition from one period to the next was obviously not sharp, but gradual. Nevertheless, the defined periods characterize the prevalent stress conditions in the given time brackets controlling the tectonic and paleogeographic evolution of the area.

The Late Cretaceous - Early Paleogene period

The stress conditions during this period were estimated from the orientation and mutual relationships of structures recorded in the Tatric crystalline basement, its Permomesozoic cover and the mostly Mesozoic sediments of the Krížna, Choč and higher cover nappes. The stacking of this nappe pile occurred during the Turonian. The Gosau sediments sealing the nappe edifice started already in the lowermost Senonian and are involved in the post-nappe structures.

The orientation of stretching lineation and shear sense criteria within ductile shear zones confined to the overthrust planes dividing the Tatric basement/cover nappes point to top-to-NW nappe stacking (Plašienka 1990; Putiš 1991; Plašienka et al. 1991). Post-nappe structures within the Tatric complexes include upright folding with axial-plane crenulation cleavages, ductile/brittle conjugate shear zones with en-echelon arrays of curved tension gashes, several sets of extensional veins with fibrous calcite fillings and kink bands. This structural association evolved in an uplifting domain with a gradually developing dextral transpresional, today NE-SW trending zone. The dextral movement is revealed by the rotation of older fold axes and axial cleavages into a near parallelism with the shear zone walls and general pattern of oblique-slip faults bounding the transpressional duplexes (Plašienka 1990).

The generalized principal horizontal stress orientation shows a slight rotation from a WNW-ESE to a NW-SE direction (Fig. 3). The lower time bracket of this stress regime is the time immediately after nappe thrusting, i.e. Early Senonian. It persisted probably until the Early Paleogene, because of the involvement of the Gosau sediments in transpressional structures in the northern part of the Malé Karpaty Mts. (Maheľ et al. 1987).

The Oligocene - Eggenburgian period

Fault-slip data from the Eggenburgian sediments point to the NW-SE, or even WNW-ESE direction of a horizontally operating maximum compressive stress axis during the Lower Miocene (Kováč et al. 1989, 1990; Nemčok et al. 1989; Fodor et al. 1990; Fodor 1991), similar to that one ascertained in the Late Cretaceous - Paleogene period (Fig. 3, cf. Plašienka 1990). Continuation of earlier stress conditions during this period is confirmed by deformation of the Kiscellian sediments in the northwestern rim of the Malé Karpaty Mts. The estimated NW-SE to WNW-ESE trending horizontal compressive stresses are believed to be responsible for en-echelon type folding of Kiscellian sediments in a long lived WSW-ENE trending dextral wrench corridor (Fig. 3, see also Marko et al. 1990).

The importance of ENE-WSW trending shear zone in the Oligocene - Early Miocene structural evolution was also pointed out in the area of the Brezovské Karpaty Mts. (Marko et al. 1991). Transpressional basins of the wrench furrow type were formed here during the Early Miocene dextral transpressional regime (Marko et al. 1991). The Oligocene-Eggenburgian stress axes determined from microfaults are twisted anticlockwise due to the Ottnangian-Karpatian block rotation. Their original position, after elimination of the block rotation, has been restored as approximately NNW-SSE to N-S trending.

Apart from block rotations inside the shear zones, there is also a possibility that even master faults bounding the shear zones are no longer in their original position and have also rotated. We can suppose that they rotated slightly anticlockwise during the translation of the Western Carpathian domain to the north. The regional rotation occurred west of the SE corner of the Bohemian Massif and caused the near parallelism of the older dextral transpressional and younger sinistral transtensional wrench zones in Western Slovakia, both now trending SW-NE. The former, however, should have originally trended WNW-ESE to NW-SE to be in accordance with the N-S principal compression direction. This would explain why the restored, originally N-S trending Oligocene-Early Miocene principal compression axis does not accord properly with the dextral shearing observed within the currently ENE-WSW trending shear zone.

The Ottnangian - Early Badenian period

The Ottnangian-Karpatian stress field determined from the microfaults suggests the NNW-SSE orientation of compressive stresses (Fig. 4). Due to the block rotation lasting until the Early Badenian, all determined, NNW-SSE trending compressional stress axes older than the Middle Badenian are allochthonous - rotated. Their original N-S position was reconstructed by eliminating the magnitude of the Middle Badenian anticlockwise block rotation (Marko et al. 1991; Fodor in press). This stress field induced sinistral shearing within the WSW-ENE and SW-NE trending shear zones.

The Middle Badenian period

This period of originally NNE-SSW trending compressional stress is characterized by the rigid body block rotation culminating during the Middle Badenian (Fig. 5). Rotation was a result of the sinistral shearing along the ENE-WSW and NE-SW wrench corridors developing as accomodation structures of NE-ward translation of the Western Carpathian megablock with respect to the Alpine domain. The anticlockwise block rotation during this time span is a result of an inversion from the older transpressional to the younger transtensional tectonic regime. The transtensional regime resulted, besides shear movements along wrench corridors, from an enlarging component of divergence movements. Consequently, block rotations were accommodated by secondary antithetic faults working inside the wrench zones.

The anticlockwise rotation affected the orientation of the already recorded stresses, which were rotated together with the rock blocks. This means that observed stresses older than Middle Badenian, are not in their original position. To estimate their original direction, we have to eliminate the degree of block rotations, which is recorded by rotation of magnetic paleomeridians.

The Sarmatian period

This period obviously postdates the rigid body block rotation. Approximately NE-SW trending stress trajectories are believed to be in an original, unrotated position (Fig. 6), similarly as the stresses of the next periods.

During the Sarmatian, the compressive stress axis turned slightly clockwise from the Badenian NNE-SSW to the ENE-WSW direction. Besides the strike-slip motions, transtensional conditions during this time span allowed the formation of normal faults suitably oriented to the applied stresses.

The Pannonian - Pliocene period

The lack of structural data makes period of the Pannonian deformation a little obscure. Several outcrops (Marko et al. 1990; Fodor et al. 1990) also display the existence of a strike-slip faults in the Pannonian sediments. Approximately N-S to NE-SW compression can be deduced. It suggests an anticlockwise rotation of the principal horizontal compressive stress from the earlier ENE-WSW (Sarmatian) to a roughly N-S (Pannonian?, Pannonian - Pliocene?) position. The jump of the compressional stress direction back from the general clockwise trend of the primary stress field rotation probably reflects some important geodynamic event. However, the opinion regarding these rare strike-slip indications in the Pannonian sediments as a result of local transtensional conditions in a general extensional regime seems to be more realistic.

During the Pliocene, the structurally also less supported deformation period is characterized by a regional NW-SE to NNW-SSE trending extension which triggered large scale normal faulting (Fig. 7). The faulting is obvious from the geological structure of the subrecent sedimentary basins and from the horst and graben system arrangement of the investigated area. It is structurally recorded in the youngest Tertiary sediments by distinctive population of roughly NE-SW trending small-scale normal faults (Nemčok et al. 1989).

Discussion and conclusions

The review of the paleostress evolution within the Carpathian-Pannonian part of Alpine-Carpathian junction zone has been compiled on the basis of structural investigation of this area in the late 1980's and early 1990's. The orientations of paleostress axes were deduced mainly from field structural observations of faults, rarely folds and from the geometry of map-

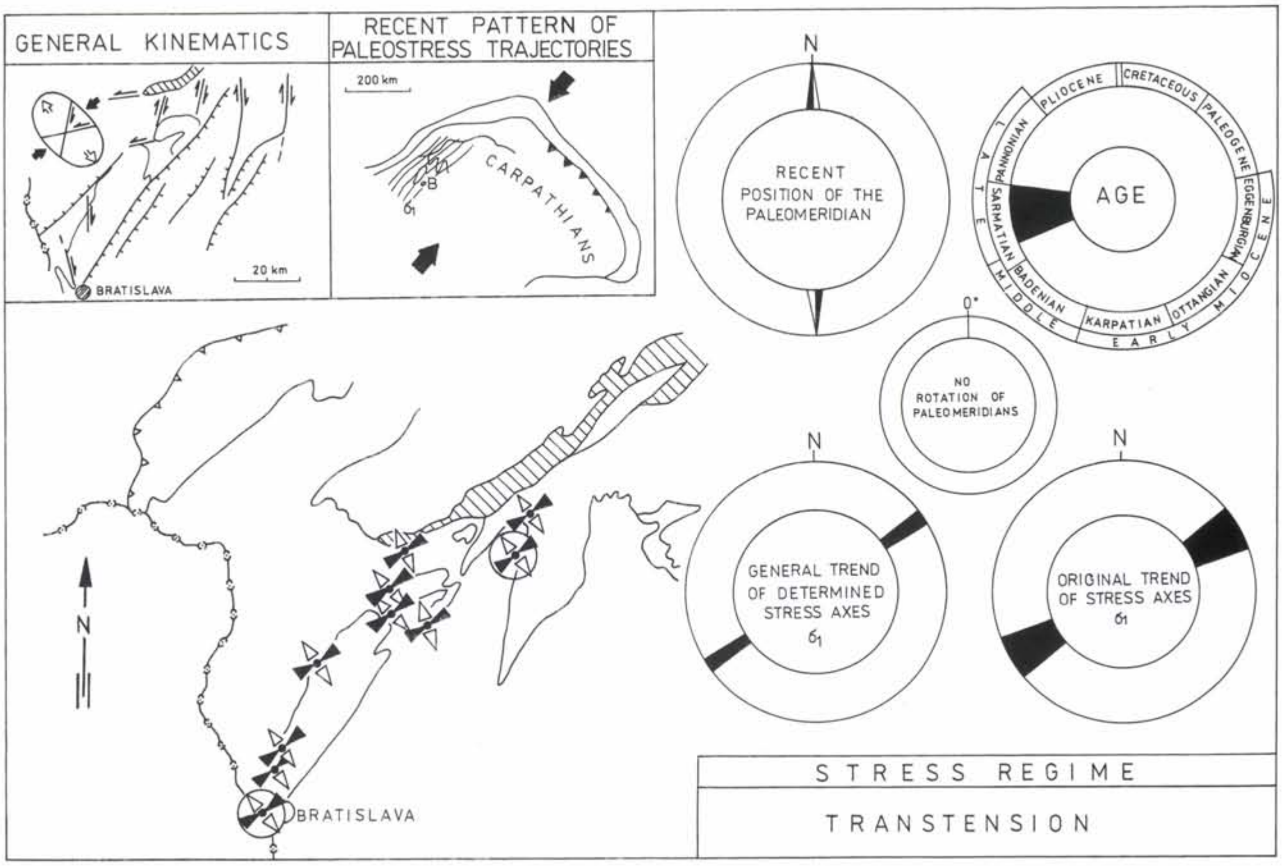

Fig. 6. Tectonic stresses and induced fault kinematics during the Sarmatian period.

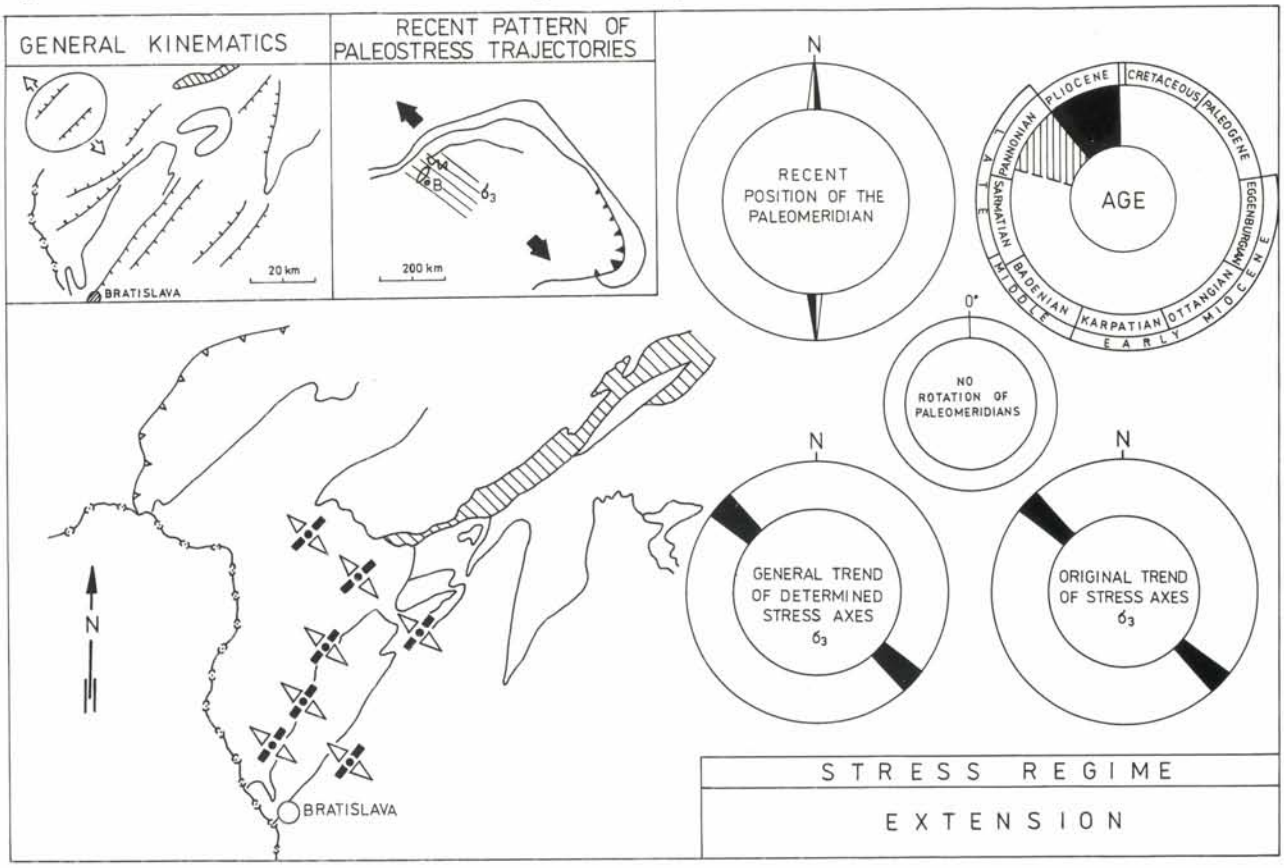

Fig. 7. Tectonic stresses and induced fault kinematics during the Pannonian-Pliocene period.

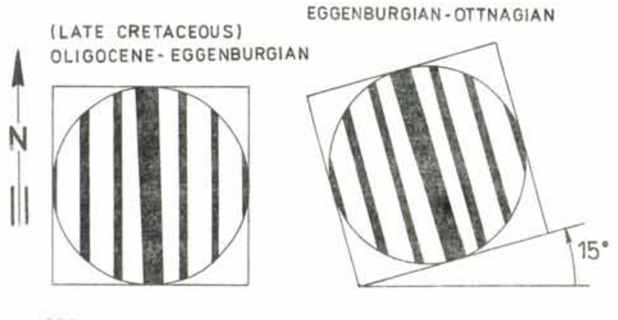

Fig. 8. A model of rotation history of paleomeridians and compressive paleostress axes recorded in the Alpine-Carpathian transitional zone of southwestern Slovakia. **1** - Oligocene-Eggenburgian meridians, **2** - Ottnangian-Karpatian meridians, **3** - Badenian meridians, **4** - Sarmatian meridians, **5** - directions of maximum compressive stress axes, **6** - brittle wrench zones within which the rigid body block rotation took place.

scale structures. The general stress fields for several deformation periods have been reconstructed from local observations.

Field observation indicates the dominant role of the strike-slip fault regime with accommodating normal and reverse faulting during most of the Tertiary structural evolution. The clockwise rotation of compressive stress trends from NW to NE is conspicuous. Considering the Early to Middle Miocene anticlockwise rigid body block rotation also confirmed paleomagnetically, it has to be realized that the recently measured Early to Middle Miocene stress axes are in an allochthonous position. Their original attitude was generally N-S. The block rotation inside the left-lateral wrench zone separating the Alpine and Carpathian domains is regarded as a dominant broad-scale deformation mechanism during the Early and Middle Miocene.

The real clockwise rotation of compressional stress axes occurred in the Middle Badenian, when NNE-SSW and ENE-WSW (Sarmatian) compression operated. Later the Pannonian compression switched back to the more N-S direction, as is supposed from several field observations. Regional NW-SE trending extension affected the Late Miocene and Pliocene tectonic evolution.

An attempt to interpret all these rotations synoptically is presented in Fig. 8. The scale-less model schematically simulates rotational history of both paleomeridian and paleostress records in several steps which also represent more or less independent tectono-sedimentary periods.

The block rotation is one of the most considerable phenomenon structurally recorded in the western part of the Carpathians. The role of complex rotational movements of crustal megablocks in formation of the arcuate shape of the Western Carpathians has been already pointed out by Krs & Roth (1979), Roth (1986) and Unrug (1984). A more sophisticated kinematic model of the Tertiary tectonic evolution of the Carpathian-Pannonian realm, exploiting exact data of paleomeridian rotations, has been developed by Balla (1984, 1987). According to this model, the up to 35° counter-clockwise rotation of the Western Carpathian crustal segment culminated during its Early and Middle Miocene escape from the Alpine collision to form the present orocline. The sense, amount and time of these rotations are compatible with the paleomagnetically confirmed rotations in our area. Nevertheless, the model of Balla (1984, 1987) considers rotation of large crustal segments only. Our present review and source papers reveal the importance of the rigid body rotations of smaller blocks inside wrench corridors, at least in areas of large translation movements, as is the Alpine-Carpathian transition zone. The compatibility of both views based on different scales of observation is obvious, however.

The interpretation of the Tertiary stress evolution in the Alpine - Carpathian junction area is in a good accordance with the global geodynamic processes characterized by N-S trending convergence of the North-European and African lithospheric plates. The neo-Alpine tectonic evolution of the area under consideration was directly controlled by a complex movement of smaller crustal blocks in a collisional zone between these two principal plates.

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