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NEOGENE HISTORY OF INTRAMONTANE BASINS IN THE WESTERN PART OF THE CARPATHIANS

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Key-words: Intramontane basins, Neogene, Western Carpathians.

Riassunto. La collisione neogenica dei Carpazi con la piattaforma europea ha portato alla sovrapposizione delle falde di flysch nella parte frontale dell'orogene. L'attivazione tettonica dell'edificio paleoalpino dei Carpazi centro-occidentali ha determinato modificazioni del loro assetto strutturale. L'asse di compressione principale ha ruotato da NW-SE a NE-SW. Faglie inverse e faglie trascorrenti destre ENE-WSW erano dominanti nel Miocene inferiore. Il movimento dei Carpazi occidentali verso NE durante il Miocene medio e superiore causò l'attivazione di faglie trascorrenti sinistre ENE-WSW e faglie normali NE-SW. L'estensione regionale pliocenica è manifestata soprattutto da faglie normali NE-SW, che controllavano la sedimentazione e la forma dei bacini.

Abstract. Neogene collision of the Carpathians with the European Platform resulted in flysch nappes overthrust in frontal part of the orogene. Tectonic activation of the Paleoalpine-consolidated Central Western Carpathians led to modification of their structural pattern. Axis of the main compression rotated from NW-SE to NE-SW. Thrust-reverse faults and ENE-WSW dextral strike- slips were dominant in the Lower Miocene. Movement of the Western Carpathians north-eastward during the Middle and Upper Miocene caused activation of ENE-WSW sinistral strike-slips and NE-SW normal faults. Pliocene regional extension was manifested mainly by NE-SW normal faults which controlled the sedimentation and form of the basins.

Introduction.

The Neogene development of the Western Carpathian intramontane basins was predominantly controlled by the subduction of the North European Platform below the overriding Carpathian-Pannonian block system changing in this period into a collision of continent - continent type, and by the formation of the Pannonian asthenolith in the hinterland area. The present configuration of the Carpathian suture zone suggests that the relative movement of the colliding plates was oblique (Vass et al., 1988). This resulted in the opening of different types of basins and had a notable effect on the bending of the Carpathians (Fig. 1).

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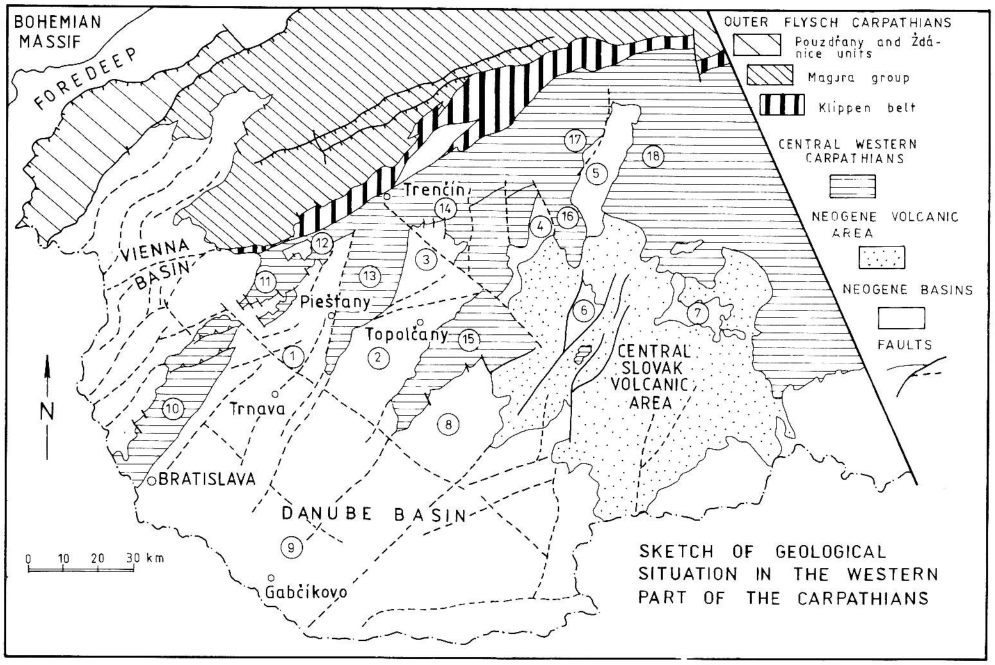


Fig. 1 - Sketch of geological situation in the western part of the Carpathians. 1) Piest'any-Trnava depression of the Danube Basin; 2) Topol'cany depression of the Danube Basin; 3) Bánovská kotlina basin; 4) Upper Nitra Basin; 5) Turcianska kotlina basin; 6) Ziarska kotlina basin; 7) Zvolenská kotlina basin; 8) Komjatice depression of the Danube Basin; 9) Central-Gabcíkovo depression of the Danube Basin; 10) Malé Karpaty Mts.; 11) Brezovské Karpaty Mts.; 12) Cachtické Karpaty Mts.; 13) Povazsky Inovec Mts.; 14) Strázovské vrchy Mts.; 15) Tribec Mts.; 16) Ziar Mts.; 17) Malá Fatra Mts.; 18) Vel'ka Fatra Mts.

Paleomagnetically determined rotation of the western part of the Carpathians, whose maximum was dated at the end of the Karpatian-Lower Badenian, was associated with the bending of the Western Carpathian arc in the Lower Miocene. In the Paleoalpine-consolidated part of the Central Western Carpathians (in the Malé and Brezovské Karpaty Mts.), an anti-clockwise rotation of 37°-43° northwestward was documented, while in the flysch of the outer Western Carpathians (in the Moravian-Silesian Beskids) this is of 40° northwestward (Túnyi & Kovác, 1989; Krs et al., 1977).

Paleostress field changes which controlled the fault activity affecting the formation and development of the basins during the Neogene played an important role. In the western part of the Carpathians, the determined maximal compression axis σ_1 rotated from the Lower to Upper Miocene from the NW-SE to NE-SW and caused the fluctuation of activity on the main tectonic zones which is manifested by their different kinematic-dynamic regime. Paleostress field changes, as well as the rotation of the region, corresponded well with the ending of the overthrust movements in front of the orogene, from the west to the east during the Neogene (Buday et al., 1965; Jirícek, 1979; Steininger et al., 1984; etc.).

Lower Miocene intramontane basins.

After the collision of the Eastern Alps with the Bohemian massif, the movement of the Western Carpathian orogene northwards during the Lower Miocene is well documented by a dominant paleostress field, whose maximal compression axis σ_1 was oriented to the N (the present day determined NW direction of σ_1 is caused by post-Lower Miocene rotation of the western part of the Carpathians). The effects of the paleostress field in time and space changed owing to the distance from the collision suture zone and the established anti-clockwise rotation of the orogene movement trajectory. Thrust-reverse fault tectonics acting in marginal part of the overriding system of the Carpathian segment was dominant during basins opening in the Eggenburgian.

With advancement of the orogene towards the platform and its shortening, lithostatic pressure raised rapidly. During the Karpatian it caused a change of the tectonic regime in which mainly strike-slip and normal faults predominated (Fig. 2, 3).

The Eggenburgian transgression of the sea spread from the West, from the Mediterranean region through the Alpine foredeep and the sedimentary area of Pouzdrany, Waschberg and Zdánice units. Crossing the fronts of the flysch nappes of the Magura Group the sea penetrated to the Paleoalpine-consolidated part of the orogene in the SW part of the Western Carpathians, on the boundary with the Eastern Alps.

The formation of the Lower Miocene sedimentary basins in the area of the flysch nappes and the Klippen Belt was controlled by tectonic activity characterized by the Biele Karpaty unit structure (analyses in Vlára river valley; Nemcok et al., 1988). Large thrust and overthrust movements are considered as the oldest tectonic events, prevailingly of pre-Neogene age. Besides striation, the vergency of the thrusts to the northwest is documented by analyses of the folds generated by them, as well as by the formed stylolites. Strike-slip faults, formed as compensation structures of thrust movements, were reactivated and rotated around the horizontal axis, perpendicular to their direction.

In front of the nappes, individual depressions of W-E to WSW-ENE orientation were formed during the Eggenburgian. Besides the western and northern parts of the Vienna Basin, the transgression of the sea proceeded to the ENE where sedimentation took place on the both sides of the Klippen Belt. The thickness of the Eggenburgian sediments of the Vienna Basin gradually decreases from the West to the East and from the North to the South. In the Mistelbach depression it ranges from 300 to 500 m, in Luzica depression it reaches 700 m, in Stefanov depression it is 200 m and in Koválov depression, on the inner side of the Klippen Belt, it is only 150 m (Jirícek & Tomek, 1981). Depressions, as well as elevations separating them, were formed in the Lower Miocene, documented by the fact that a gradual transgression of the Eggenburgian, Ottnangian or Lower Karpatian strata is present on the elevations.

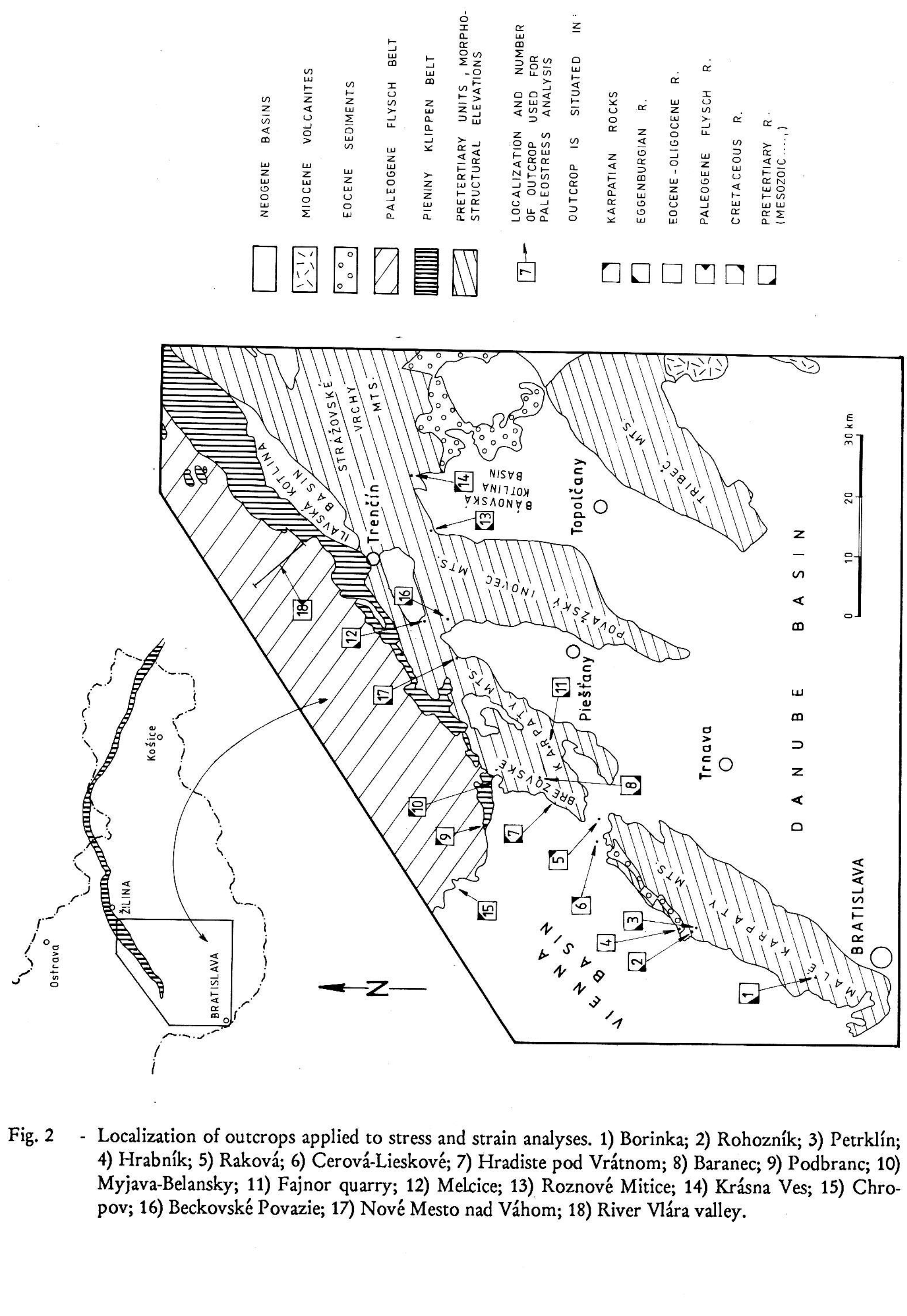


Fig. 2 - Localization of outcrops applied to stress and strain analyses. 1) Borinka; 2) Rohozník; 3) Petrklín; 4) Hrabník; 5) Raková; 6) Cerová-Lieskové; 7) Hradiste pod Vrátnom; 8) Baranec; 9) Podbranc; 10) Myjava-Belansky; 11) Fajnor quarry; 12) Melcice; 13) Roznové Mitice; 14) Krásna Ves; 15) Chropov; 16) Beckovské Povazie; 17) Nové Mesto nad Váhom; 18) River Vlára valley.

Owing to the advancing collision, a system of thrusts and reverse faults with opposite vergency was formed in the Biele Karpaty unit. The movements of SE vergency continued in spatial shortening of the thrust slices. The formed reverse faults of NW vergency rotated around the horizontal axis parallel with their direction. In such way high-angle reverse faults were formed. In addition to older reverse faults, new low-angle reverse faults and faults of SE vergency originated.

Ottnangian uplift of the territory NE of the present Vienna Basin resulted in partial retreat of the sea from the region of the flysch nappes and Klippen Belt. Depocentres migrated to the SE, to the Vienna Basin and Bánovská kotlina depression. Shallowing of the sea in the present Vienna Basin is reflected in the formation of sandstone horizons (Lednice, Hodonín, Stefanov sands) dividing the Luzica Formation "schlier" sediments into the Eggenburgian with *Cyclammina-Bathysiphon* microfauna and the Ottnangian with *Cibicides-Elphidium* and remnants of fishes. Maximum thickness of the Ottnangian sediments is in the Lower Miocene depressions: Luzica, 500-600 m, Stefanov, 700 m and Koválov only 60 m (Jirícek & Tomek, 1981).

The western boundary of the Luzica depression is formed by the margin of Raca nappe (Schratenberg fault; Spicka, 1967). The Lower Miocene is preserved only in its inner part. Eggenburgian and Ottnangian deposits were eroded from the front of Raca nappe during the overthrust of Raca flysch on the folded Eggenburgian and Ottnangian sediments of Waschberg and the southern part of Zdánice units during the Karpatian. This resulted in the uplift of the western margin of Luzica sedimentary area. Karpatian and Badenian sediments cover the Eggenburgian and Ottnangian beds with angular unconformity.

During the further shortening of the region, from the Karpatian, spatial exchange of σ_2 and σ_3 took place causing preferential formation of strike-slip faults in the region of the flysch nappes. Younger phases described from Vlára river valley profile were well documented mainly in the Paleoalpine-consolidated part of the orogene, in the Central Western Carpathians. There was, in fact, a phase with σ_1 having N-S direction during which fold structures were no longer formed (Karpatian-Lower Badenian) and a phase with σ_1 having NE-SW direction characterized by the formation of strike-slip faults (Badenian-Sarmatian).

The tectonic structure of the outer flysch Carpathians is supported by the results of the tectonic analysis of a reflection-seismic profile (Kadlecík, 1979). A flexure of the platform (Bohemian massif) and two apparent dislocations in gravimetric minimum regions are markedly recorded in the profile. Thrust slice structures of the Magura Group nappes with NW vergency and reverse thrusts and faults with opposite vergency in the Klippen Belt area are also observable.

In the western part of the Central Western Carpathians, Lower Miocene sediments form a part of various geological structures. They form denudation remnants on young horst structures of the core mountains or they are incorporated in the filling of young basin structures. The origin of these basins, as well as of the main part of their sedimentary filling is dated at the Middle to Upper Miocene, sporadically Pliocene. The

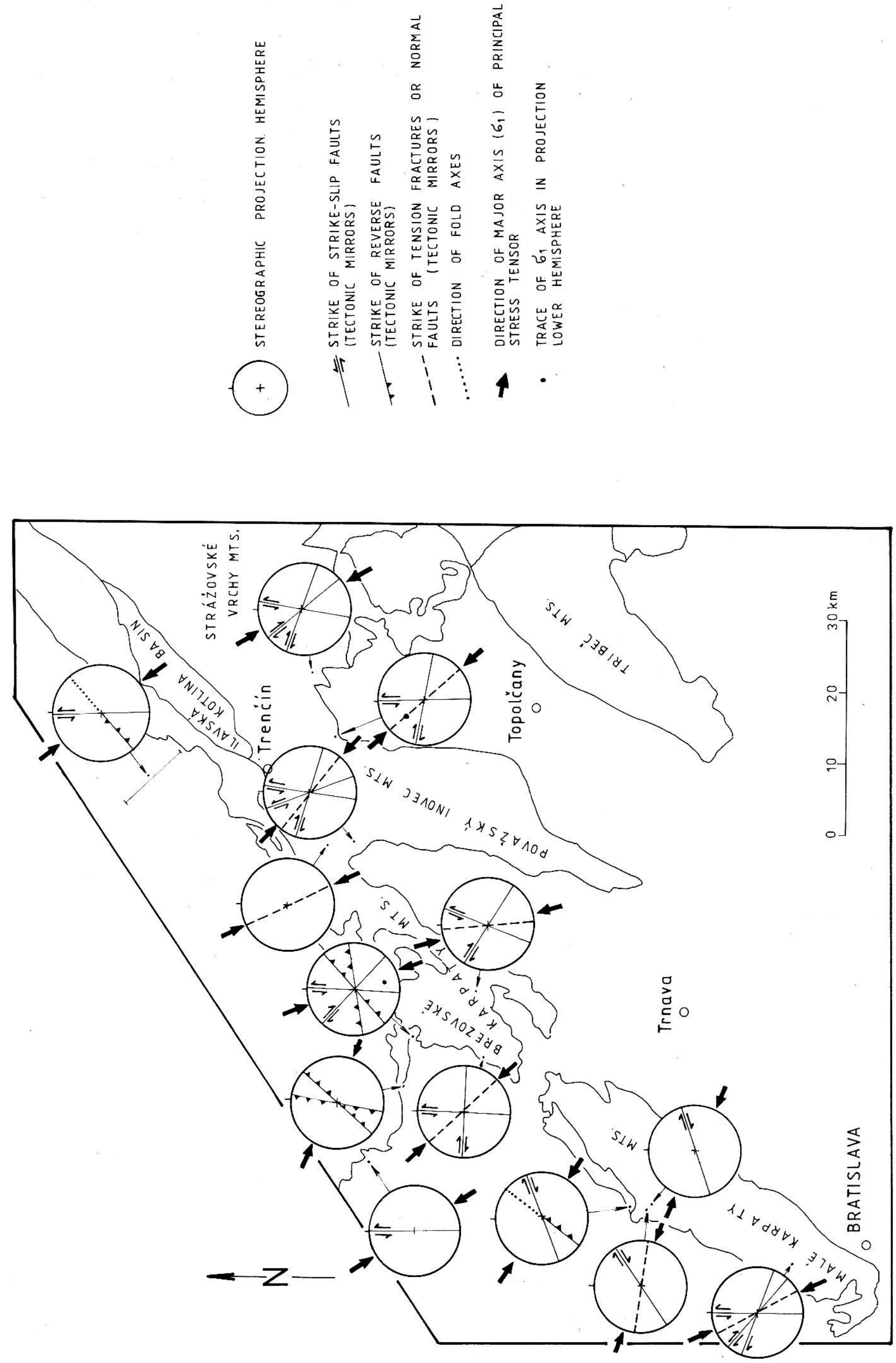


Fig. 3 - Stress and strain during the Lower Miocene.

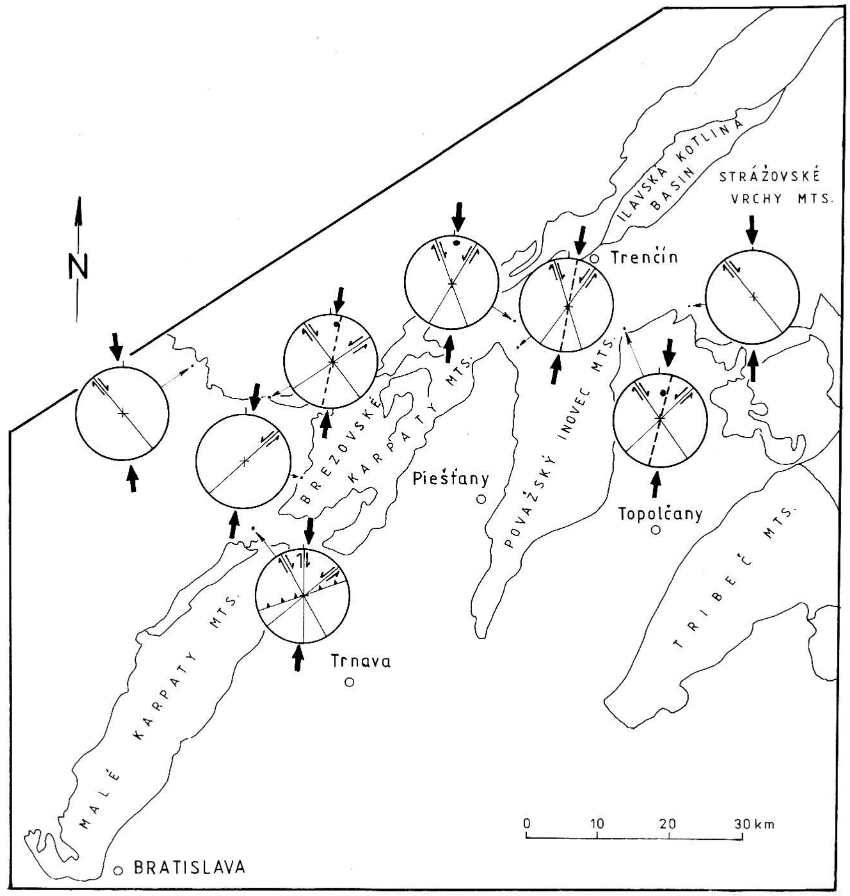


Fig. 4 - Stress and strain during the end of the Karpatian and the Lower Badenian.

tectonic regime of the Central Western Carpathians is documented by analyses from the NE part of the Vienna Basin, Váh river valley, northern margin of the Danube Basin - regions of Piest'any and Topol'cany depressions and from the Bánovská kotlina basin (Marko in Kovác et al., 1989; Nemcok et al., 1989) (Fig. 2, 3).

The movement of the Western Carpathian segment to the N was characterized by a paleostress field with maximal compression axis oriented to the N. However, the results of tectonic analysis suggest that in the Lower Miocene the axis of maximal compression was of NW-SE direction, what is in good agreement with the determined rotation of the region. Paleogeographic situation in this period was controlled by right-lateral strike-slip faults of ENE-WSW, WNW-ESE direction, by reverse thrusts and reverse faults of NE-SW direction with vergency inside the Carpathians (south-eastward), lateral strike-slip faults of N-S direction and normal NW-SE faults (Fig. 6).

The Lower Miocene sedimentary area in the western part of the Carpathian orogene was formed in a right-lateral strike-slip mobile zone. An intramontane basin (or system of depressions) between the Eastern Alps and the Western Carpathians followed the southern margin of the Klippen Belt, spreading from there to the Central Western Carpathians. The general direction of individual depressions separated by basement elevations was E-W to ENE-WSW (Jirícek, 1979).

The Eggenburgian deposition started with basal conglomerates forming separate fans on the margin of the sedimentary area which had a character of shallow sea with several island archipelagos. The sources of clastic material were local. Detrital material in the NE part of the Vienna Basin was transported formerly from the S and SE to the N and NW, but a transport parallel with the axis of depressions, from the ENE to the WSW, prevailed later on (Kovác et al., 1989). The formation of reverse faults with vergency inside the Carpathians, oriented NE-SW in the Malé and Brezovské Karpaty Mts., is associated with the deposition of talus and alluvial fans in a belt stretching from Rozbehy through Dobrá Voda to Cachtice where alteration of poorly sorted conglomerate and breccia beds with well-rounded conglomerate and sandstone beds is present.

Reverse thrusts of NE-SW direction were preferentially formed on the Mesozoic thrust planes of the nappes. The proceeding compression caused the rotation of these planes around the horizontal axis, whereby high-angle reverse faults were formed. Right-lateral strike-slip faults of ENE-WSW direction were formed as compensation structures in the northern part of the Malé Karpaty Mts. Strike-slip faults generated en échelon folds of NNE-SSW direction in the Paleogene sediments from the vicinity of Solosnica (Hrabník).

Gradual deepening of the Eggenburgian sedimentary area is documented by the transition of basal conglomerates and sandstones to pelitic sediments (schlier). The maximum preserved thickness of sediments in the contemporaneous intramontane basins is in the Bánovská kotlina basin (250 m). Thicknesses are decreasing west- and eastward. Eggenburgian sediments form only erosion relics in the Malé Karpaty Mts. The thickness of the Eggenburgian sediments in the Upper Nitra depression, where freshwater and brackish sediments of sea-shore lagoons are present at the base of the sequence, is 120-130 m.

Continuous Eggenburgian-Ottnangian sedimentation is known from the region of Piest'any bay (Krupá borehole) and the Bánovská kotlina basin. Increased supply of sandy material is due to the shallowing of the sedimentary area during the Ottnangian. Change in the source areas of the clastic material from the Mesozoic to Mesozoic-Paleogene (Marková in Brestenská, 1980) indicates an uplift of the territory northeastward and its denudation. The thickness of the Ottnangian sediments in the Bánovská kotlina basin reaches 300 m.

The activity of left-lateral strike-slip faults of N-S direction (oriented NE-SW in the Lower Miocene) seems to be an important event of the Lower Miocene tectonics in the Central Western Carpathians. The offset of rock bodies of the Malé Karpaty Mts. along the N-S faults (Marko, 1986) indicates that displacements reach quite high ampli-

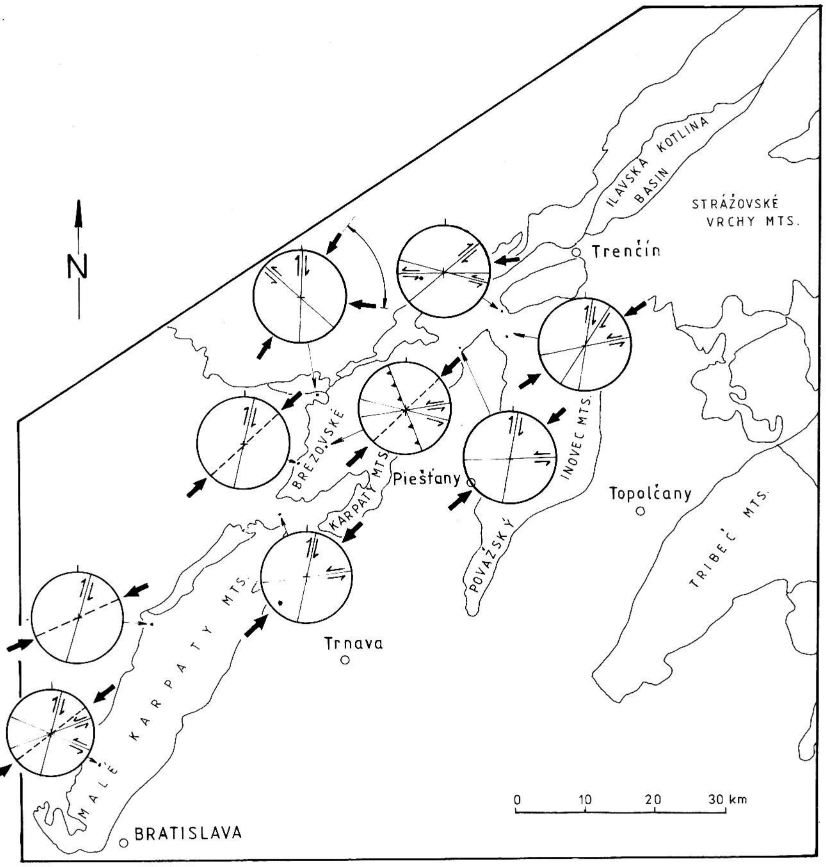


Fig. 5 - Stress and strain during the Middle Miocene.

tudes. One of the most dominant dislocations of N-S to NNE-SSW direction is a fault zone nowadays following the western margin of the Povazsky Inovec Mts. (Fig. 7). The Povazie fault, indicated by the occurrence of the Pliocene travertines, mineral springs (Piest'any), as well as by the difference between the units on the opposite sides of the fault (Mahel', 1950), is well documented by satellite images. The neotectonic importance of dislocation is documented by the localization of earthquakes along the boundary of the blocks, with differential vertical movements (Kvitkovic & Plancár, 1975). The eastern margin of the Povazsky Inovec Mts. - Závada-Dubodiel fault (J. Kamenicky, 1956), and other faults of N-S direction in the western part of the Carpathians have probably a similar behaviour.

The Lower Miocene orogenic movements (Savian) caused the interruption of the marine connections with the Mediterranean area through the Alpine foredeep at the end of the Ottnangian. This resulted in a gradual decrease of salinity in the sedimentary areas of the Western Carpathians (Rzehakia beds). In the Karpatian, a new marine transgression advanced from the Mediterranean through NE Yugoslavia to the Styrian Basin in Austria and NW Hungary. The subsidence of the eastern Alpine margin at the end of the Ottnangian and in the Karpatian is documented by terrestrial and fluvial-limnic, coarse-clastic strata following the western margin of the Karpatian marine sediments (Rögl & Steininger, 1983).

The Lower Miocene sedimentary area was deepened in the Paleoalpine-consolidated western part of the Carpathians because of declination movements from the horizontal axis along strike-slip faults of N-S direction and also along normal faults of NW-SE direction. Jastrabie fault (Mahel', 1969; Fusán et al., 1971) and Dobrá Voda fault system were the most important NW-SE dislocations (N-S direction in the Lower Miocene). Both faults are deep-seated (Fusán, 1985). Jastrabie fault or fault zone separates the Mesozoic of the Strázovské vrchy Mts. from the Povazsky Inovec crystalline complex. Jablonica fault caused the formation of the depression situated between the Brezovské and Pezinské Karpaty Mts.

The sedimentary record of the Early Karpatian in the Bánovská kotlina basin indicates the deepening of the sedimentary area, coinciding with changes of microfauna assemblages (K. Sutovská, pers. comm.). Alternations of sandy and pelitic beds are observed near the base of a 500 m thick sequence; the pelites become totally dominant upwards. Brestenská (1980) considers the Karpatian sediments from the Bánovská kotlina basin as equivalent of the marine Laksáry Fm. in the Vienna Basin (in the sense of Spicka & Zapletalová, 1965).

On the NE margin of the Vienna Basin and N margin of the Danube Basin (Piest'any-Trnava depression), alluvial-delta fans of Jablonica conglomerates and sandstones, bound to the normal faults of NW-SE direction (parallel with Jablonica fault system), occur at the base of Karpatian strata. The polymictic pebble material was transported predominantly from the S, SW- the present Malé Karpaty Mts., and the pre-Neogene basement of the Danube lowlands (Danube Basin) which represented an elevated area in this time. The conglomerates and sandstones pass here laterally and vertically into pelitic marine sediments (Laksáry Fm.; Spicka, 1966). The maximum thickness of the Karpatian marine sediments is bound to the Lower Miocene depressions in the northern and western parts of the Vienna Basin, sedimentation centres, however, migrate to the Central Carpathian pre-Neogene basement. In Mistelbach depression thicknesses range from 500 to 700 m (Laa Fm.), in Stefanov and Koválov depressions from 600 to 900 m (Jirícek & Tomek, 1981).

During the Late Karpatian, the depocentres migrated southeastward. Sedimentation in brackish environment in the N (Závod Fm.; Spicka, 1966) started with Sastín sands, locally up to 400 m in thickness, passing upwards to calcareous clays alternated with sandy beds. In the southern part of the Vienna Basin, the freshwater sequence of Láb ostracode beds (Aderklaa Group) having 1000- 1500 m in thickness, was deposited during the Karpatian (Jirícek & Tomek, 1981). Paleogeographic distribution of sedimentary environments confirms the importance of transversal structures in the Vienna

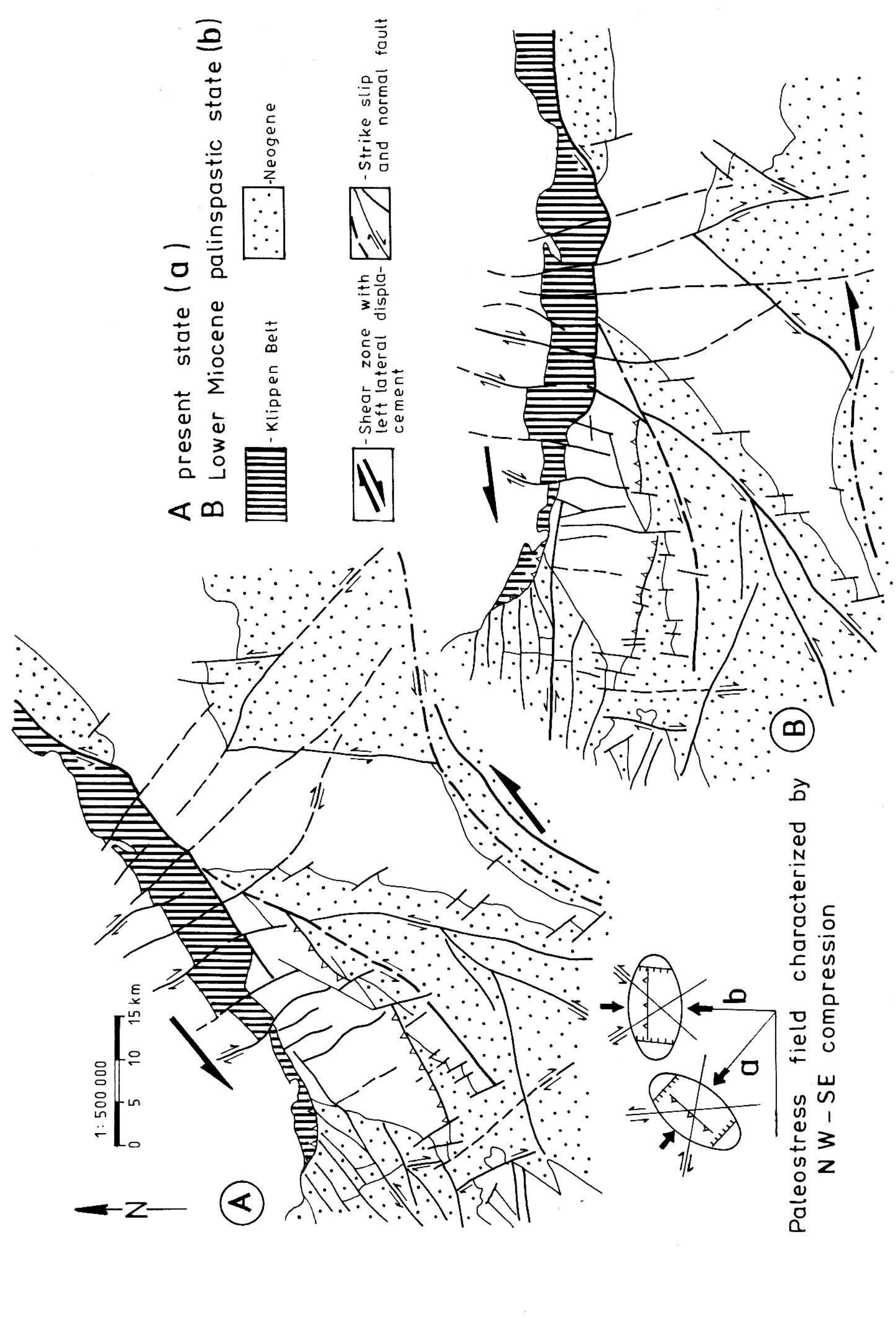


Fig. 6 - Sketch of kinematic regime in SW part of the Central Western Carpathians (Lower Miocene).

Basin. Freshwater sedimentation took place south of Lozorno high, while Karpatian marine beds are present in the north.

Karpatian sedimentation in the Czechoslovak part of the Vienna Basin is marked by the greatest rate during the Neogene (Vass & Cech, 1983). The northern margin of the present day occurrence of sediments in the Vienna and Danube Basins is erosive. Because of the absence of Karpatian marginal deposits, only their substantially larger areal distribution north- and northeastward is considered. The dynamics of the sedimentary environment is documented by the frequent presence of angular unconformity, rapid changes in facies and thickness, synsedimentary activity of faults, presence of slump bodies, increase of terrigenous material input, as well as by the migration of basin depocentres from the N, NW to the S, SE.

Formation of a new structural model (Upper Karpatian-Lower Badenian).

Paleostresses with maximal compression axis of N-S direction played an important role in the western part of the Carpathians during the Upper Karpatian-Lower Badenian. In front of the Carpathians, this period is characterized by the final overthrusting of nappes on the foredeep. In southern and central Moravia (the Czechoslovak territory) this took place at the end of the Karpatian, while in northern Moravia and Poland, in the vicinity of Krakow, it took place in the Lower Badenian. The paleostress field with N-S compression was manifested in the paleotectonic regime of the intramontane basins mainly by the formation of strike-slip and normal faults. Reverse faults occur only as compensation structures of strike-slip faults (Fig. 2, 4).

From the paleogeographic point of view, the Lower Badenian sedimentary areas show greater affinity with the Karpatian ones than with the sedimentary areas in the Middle and Upper Badenian. Remnants of marine sediments from the contemporaneous intramontane basins are preserved today in the Vienna Basin and on the northern margin of the Danube Basin (Piest'any depression). The Lower Badenian represents a separate sedimentary cycle displaying an angular unconformity in the marginal parts with the Karpatian strata ("Lanzendorf series", in the sense of Spicka & Zapletalová, 1965).

The conglomerates with pelitic intercalations occurring along the eastern slopes of the Malé Karpaty Mts., at the base of Devínska Nová Ves Mb., are considered as marginal, basal facies in the Vienna Basin. They contain calcareous nannoflora of NN-5 Zone (Vass et al., 1988). Mesozoic carbonates are prevailing in their pebble material, granites occur sporadically. In the north, Cupy gravels are regarded as marginal facies (Buday, 1956). Their pebble material is composed particularly of flysch rocks. Marginal facies pass basinward and upward to pelitic facies of marine clays, the "tegel". Their thickness in the Vienna Basin varies from 500 to 800 m (Jirícek & Tomek, 1981).

On the northern margin of the Danube Basin, the Lower Badenian sediments are known from Piest'any-Trnava depression. They are represented by conglomerates and sandy-clayey sediments on the NE margin of the Malé Karpaty Mts. (K. Sutovská, pers. comm.) and on the SW slopes of the Povazsky Inovec Mts. In a borehole in the vicinity

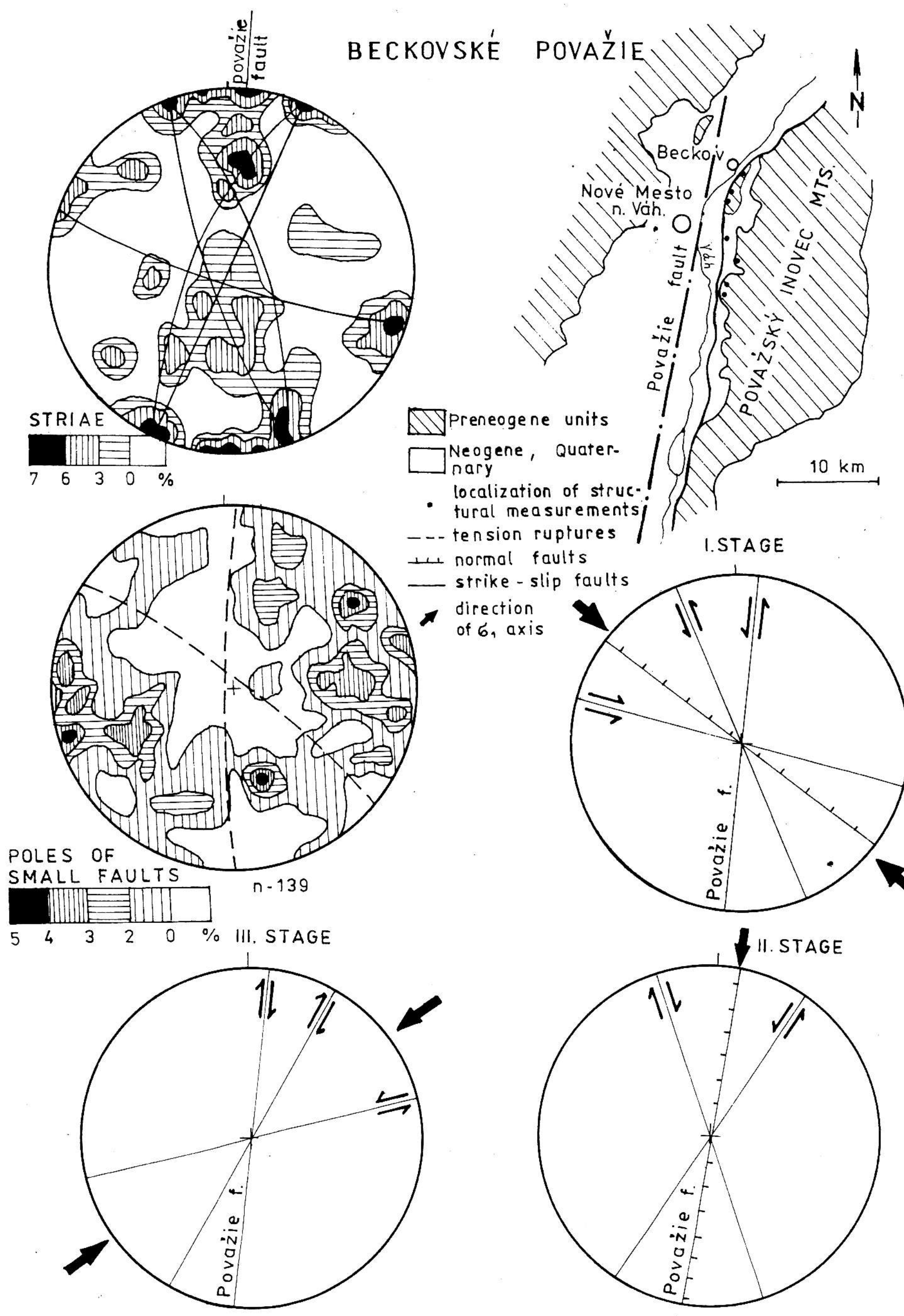


Fig. 7 - Kinematic-dynamic regime in the Povazie fault zone.

of Trakovice they attain a thickness of 560 m. In the central part of the strata there is a 50 m thick tuffitic intercalation (Gaza, 1983). The occurrence of tuffites is associated with the Lower Badenian volcanism buried by the sedimentary filling of the Danube Basin. Volcanism probably followed a deep-seated transtension zone bordering the Danube block in the SE (Fusán, 1985). The thickness of volcanites varies from 1000 to 1500 m.

A paleostress field with maximal compression axis of N-S direction is documented in the western part of the Carpathians by right-lateral strike-slip faults of NW-SE direction, accompanying a rotation of blocks to the NW. Left-lateral strike-slip faults of NE-SW direction, opening the Middle to Upper Miocene sedimentary area, and normal faults of N-S direction, were dominant in the Lower Badenian.

Lower Miocene sediments, as a part of the Neogene filling of the Middle to Upper Miocene basin structures were lowered down along the N-S normal faults and were not eroded. Povazie fault and N-S faults in the Bánovská kotlina basin, where total thickness of the Lower Miocene deposits exceeds 1100 m, were active as normal faults in this period (Fig. 7).

Middle Miocene intramontane basins.

The end of the Lower and the beginning of the Middle Miocene were characterized by orogenic movements of the Styrian phase in the Alpine-Carpathian region, followed by the opening of the basins according to a new structural model. The formation and development of pull-apart basins s.l. and grabens were controlled in the western part of the Carpathians by strike-slip and normal faults.

In the Lower Badenian, a large marine transgression spreads from the Mediterranean region to the Western Carpathians. Subtropic fauna, characterized by great diversity of assemblages, is present even in the northern parts of the foredeep in Poland (Rögl & Steininger, 1983). In the Middle Badenian, orogenic movements caused a salinity crisis (particularly in the foredeep region) and led to a gradual interruption of the marine connections with the Mediterranean area through northern Yugoslavia. From the Upper Badenian, the Western Carpathian intramontane basins were connected with the Eastern Paratethys only through the Pannonian region. The gradual isolation from the world oceans led, during the Sarmatian, to the change of the marine environment. The sediments of intramontane basins were deposited mainly in brackish environment and some basins were filled only with fluvial-limnic and terrestrial sediments.

From the Middle Badenian, the paleostress field changed in the western part of the Western Carpathians. The maximal compression axis was of NE-SW direction (Fig. 2, 5), what is in good agreement with the activity of the nappe front overthrust on the foredeep in the eastern part of the Western Carpathians in Poland (Oszczypko & Slaczka, 1989). The results of tectonic analysis of the NE part of the Vienna Basin (Nemcok et al., 1989) show that strike-slip faults form transtension zones with small displacement. During this period a system of left-lateral strike-slip faults of ENE-WSW direction, accompanied by normal faults with NNE-SSW to NE-SW direction, with high amplitude of throw, was dominant. N-S dislocations (e.g. Povazie fault system) were activated as right-lateral strike-slip faults, but the amplitude of displacement was far from the extent of the Lower Miocene left-lateral strike-slip faults (Marko in Kovác et al., 1989). The margins of the NE-SW directed Malé Karpaty horst became more distinct. The sedimentation in the Vienna Basin and on the NW margin of the present Danube Basin took place in pull-apart basins s.l. The sedimentary areas in the NE part of the Danube Basin and in the Central Slovakian Volcanic Area had a graben character.

The tectonic activity and stressing of relief differences in the NE part of the Vienna Basin are supported by the occurrence of coarse clastics on the slopes of the Malé Karpaty Mts. The Middle Badenian in the region between Lozorno and Devínska Nová Ves (Vass et al., 1988) shows a character of debris flow and debris apron composed mostly of poorly rounded granite material. These are considered as marginal equivalents of the sandstone bodies of Jakubov beds (Middle Badenian), what is proved also by the presence of poorly rounded to angular rock fragments from the Malé Karpaty Mts. in them (Dlabac, 1972). Another typical feature of the Middle Badenian sedimentation is the formation of *Lithothamnium* bioherms, known from the region between Láb and Malacky and from the vicinity of Stupava and Rohozník. We suppose that they were formed on tectonically uplifted blocks of the eastern margin of the Vienna Basin, which subsided in the Middle Badenian, and were covered by monotonous sedimentation of *Spiroplectammina* Zone. The Middle Badenian sedimentation in the deeper parts of the basin passes with continuity to the Upper Badenian. Sand-rich Studienka beds of *Bulimina-Bolivina* Zone are deposited (Spicka, 1966); in the NW part of the basin they have a brackish character. In contrast to the Lower Badenian sediments, the Middle and Upper Badenian sediments contain often shallow and freshwater intercalations. Their thickness ranges from 400 to 700 m (Middle Badenian) and from 400 to 600 m (Upper Badenian) (Jirícek & Tomek, 1981).

In the NW part of the present Danube Basin (Trnava depression) (Gaza, 1983), the Middle Badenian sedimentation started with a marked angular discordance. Conglomerates and sandstones at the base have a thickness of several 100 m. The clastic material was derived from the Mesozoic and crystalline complex of the surrounding mountain ranges of the Western Carpathians. Upwards, the predominant lithologic type of the Middle and Upper Badenian rocks is represented by calcareous clays with sandy intercalations. The thickness of the sequence ranges from 2700 to 3000 m (Gaza, 1983), what represents the culmination of sedimentation rates in this region (Fig. 2, 5).

In the NE part of the present Danube Basin (Komjatice depression; Gaza, 1983), marine sediments of the Middle and Upper Badenian reach a thickness of 800 m. The presence of conglomerates and sandstones composed of volcanic material, from a source in the Central Slovakian Volcanic Area, increases eastward. The Komjatice depression has a graben structure and stretches in NE-SW direction. Its tectonic regime recalls the basins of the Central Slovakian Volcanic Area. Its SE continuation is represented by the central depression of the Danube Basin, belonging by its development to the hinterland basins, and with inferred thicknesses of the Middle and Upper Badenian sediments up to 1000 m (Gaza, 1983). Occurrences of *Lithothamnium* bioherms (Pozba elevation) of the

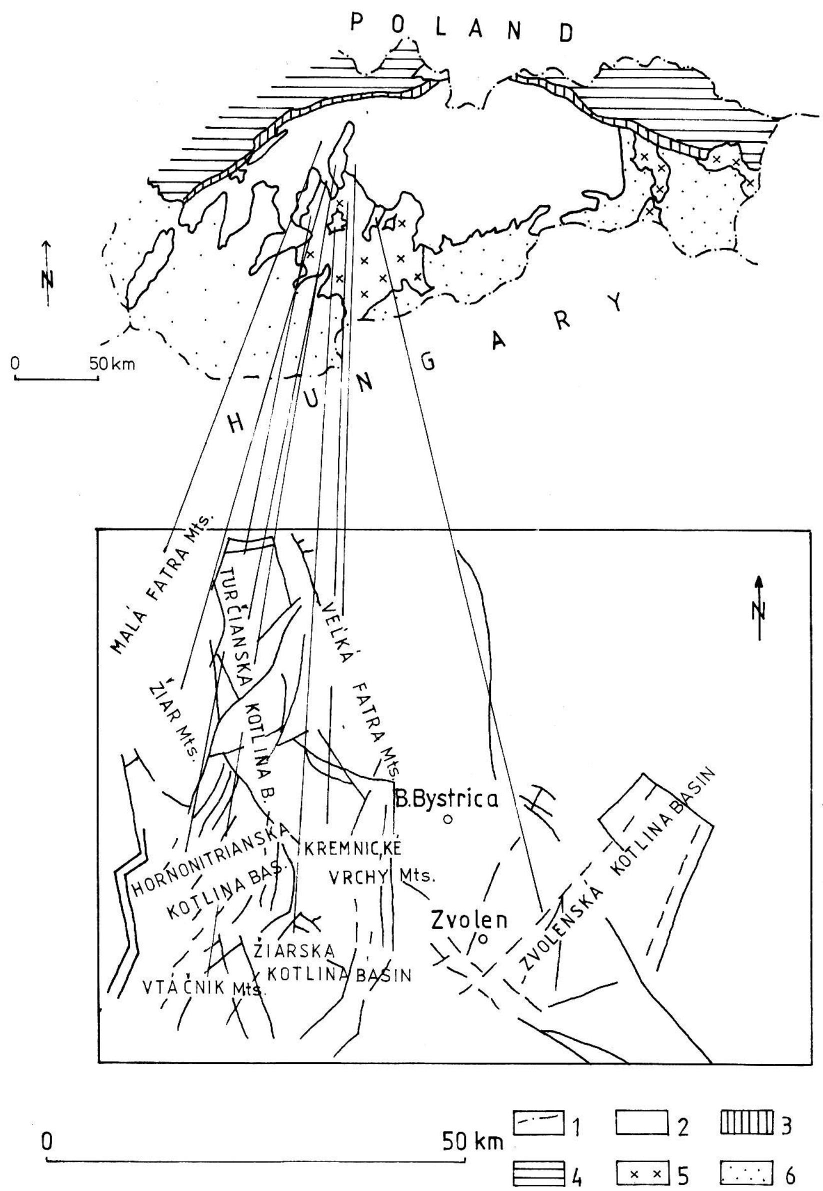


Fig. 8 - Central Slovakian Volcanic Area. 1) State border; 2) Central Western Carpathians; 3) Klippen Belt; 4) outer flysch Carpathians; 5) neovolcanites; 6) Neogene basins.

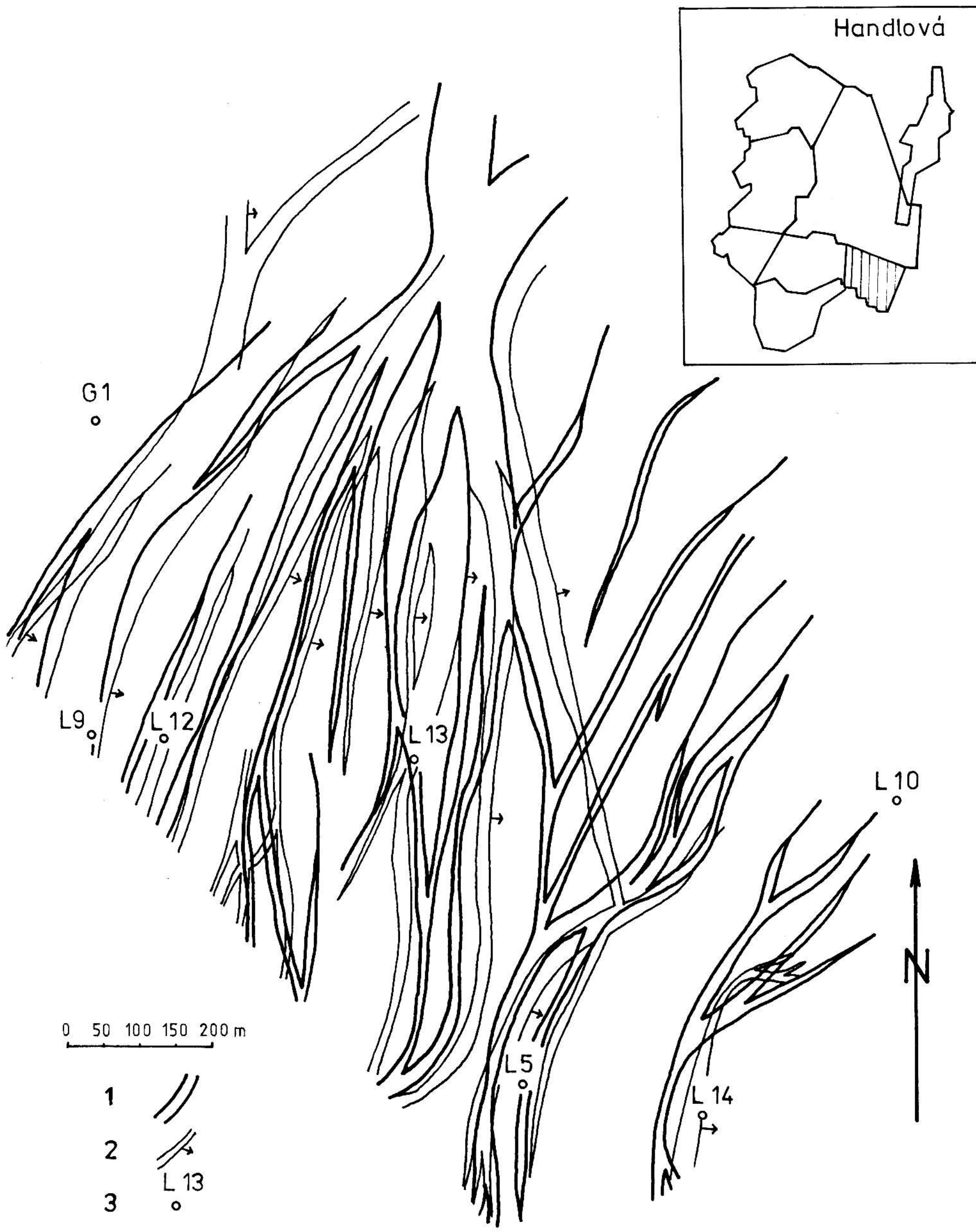
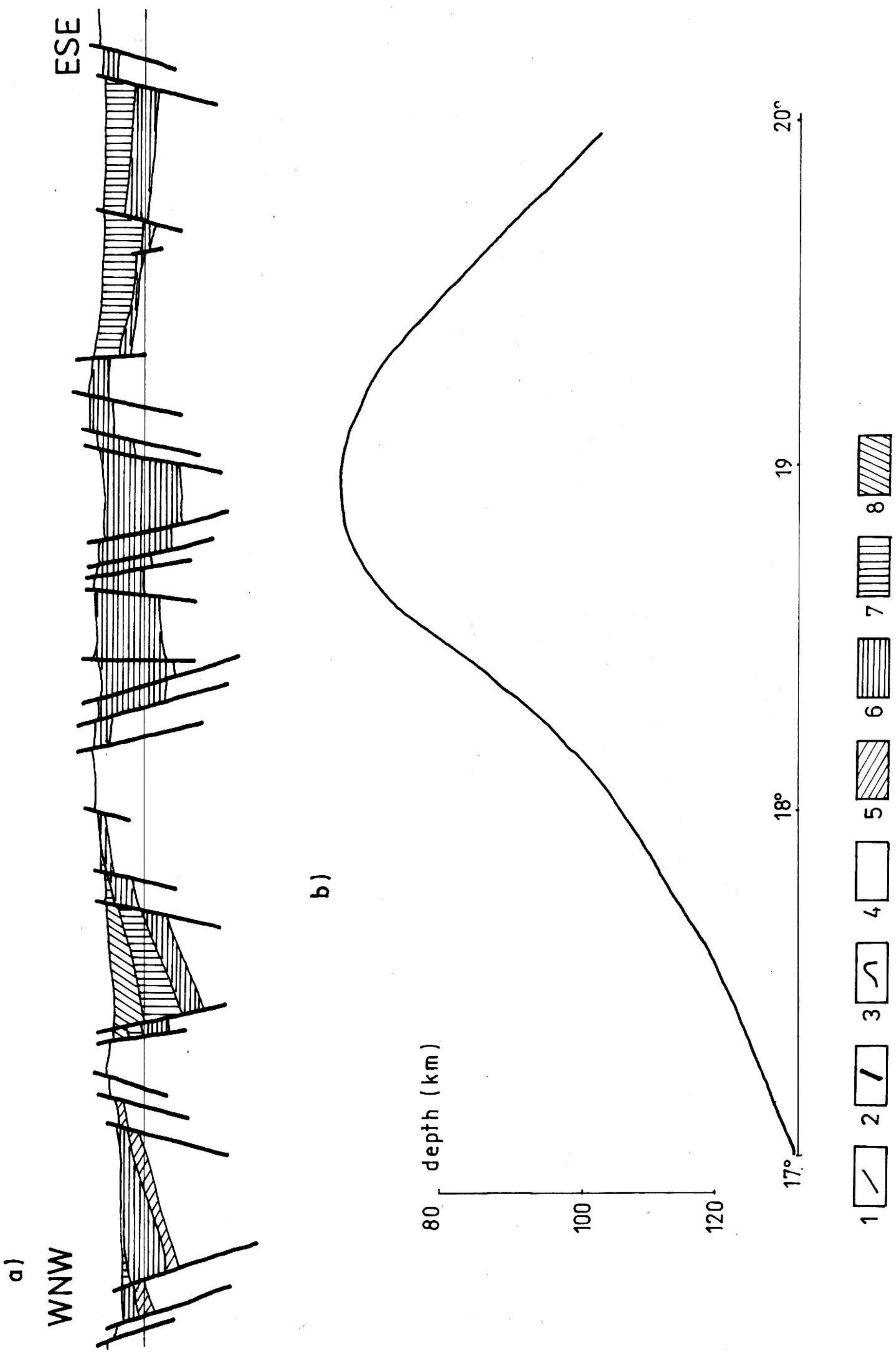


Fig. 9 - Fault system in the Upper Nitra Basin coal seams. 1) Faults in the base of 1st coal seam; 2) faults in the base of 2nd coal seam; 3) boreholes.


a)
WNW
ESE
b)
depth (km)
80
100
120
17°
18°
19
20°
1
2
3
4
5
6
7
8

Middle Badenian age are known from the eastern margin of the Danube Basin, as well as from the Vienna Basin.

A decrease in subsidence rates during the Sarmatian is observed upwards in the section. The sedimentary area of the Vienna Basin was controlled particularly by normal faults of SSW-NNE to SW-NE direction. Thicknesses of sediments in the basin vary from 300 to 600 m. The Sarmatian depocentres in the Danube Basin coincide with the Badenian ones. The greatest thickness (about 600 m) is in the NW part of the Danube Basin, in Trnava depression (Gaza, 1983).

In the northern bays of the sedimentary area in the western part of the Carpathians, freshwater environment was frequent in the Sarmatian, and brackish sedimentation was prevailing in the basins. The sandy marginal facies are rich in macrofauna remnants, sporadically forming lumachelle beds. Clays with different calcium content represent basinal facies, with sandy intercalations and beds increasing upwards.

A structural rearrangement of the Central Slovakian Volcanic Area began during the Middle Miocene. The formation of intramontane basins together with Ca-alkali volcanism in this region were controlled by mantle diapir updoming (Fig. 8).

Andesite volcanism in Central Slovakia became active in the Lower Badenian and continued in the Sarmatian and Pannonian. The volcanic activity was accompanied by the fragmentation of the territory into a system of horst-graben structures with vertical movements of great amplitudes, predominantly asymmetric (partial rotation of blocks) and corresponding to extensional conditions. NE-SW trending faults, accompanied by the NW-SE trending system dominated in the eastern part, whereas a NNE-SSW to meridional fault system, which became active mainly in the period from the Sarmatian to Pontian, prevailed in the western part of the region. This system of faults was related also to younger occurrences of acid sialic volcanism in the Central Slovakian Volcanic Area between the Upper Sarmatian and Pannonian. This system of faults was associated with block movements of considerable vertical amplitudes (1500-2000 m) (Lexa & Konecny in Vass et al., 1988).

The first signs of blocks faulting in the Central Slovakian Volcanic Area with σ_1 of NW-SE orientation appeared during the Lower Badenian. Strike-slip and normal faults, as well as intermediate types were formed at first. The NW-SE orientation of Ziar Mts. and a short section between Turcianska kotlina depression and Kremnica graben may document also extension of NE-SW direction (Nemcok & Lexa, 1988).

Fig. 10 - Schematic cross-section of the graben and horst structure in the Central Slovakian Volcanic Area with sketch of astenosphere-lithosphere boundary (according to Babuska et al., 1986). 1) Geological boundaries; 2) faults; 3) astenosphere-lithosphere boundary; 4) pre-Neogene basement; 5) Eggenburgian sediments; 6) Upper Badenian-Lower Sarmatian sediments; 7) Sarmatian sediments; 8) Pannonian sediments.
Idealized cross-section (WNW-ESE) of graben structures from left to right: Upper Nitra Basin, Turcianska kotlina basin, Kremnica graben, Zvolenská kotlina basin.

The change of paleostress orientation with maximal compression axis oriented to N-S caused the preferential formation of left-lateral strike-slip faults of NE-SW orientation. This phase was short, it did not extend later than the Upper Badenian and formed an anisotropy system favouring the Upper Badenian volcanism.

Though regionally significant faults did not display large horizontal movements, left-lateral strike-slip faults of NE-SW direction were observed in the NW part of the region. The NW-SE striking Pravno fault, which divides Ziar Mts. from the subsiding Upper Nitra Basin, is offset by numerous small-scale left-lateral strike-slip faults having NE-SW orientation. The horizontal displacement of one of the faults is over 800 m and the sinistral character is documented by slickenside lineations. Faults of the same orientation in Nováky and Handlová coal basins are accompanied by horse tail en-échelon structures in the underlying clays (Nemcok & Lexa, 1988) (Fig. 9).

The most intense evolution of graben and horst structures took place during the Upper Badenian and Lower Sarmatian. It was less intense during the Middle and Upper Sarmatian and continued even during the Pannonian in Turcianska and Ziarska kotlina basins. The orientation of extension vector during the formation of graben-horst structures varies around the E-W direction (Nemcok & Lexa, 1988).

Significant vertical amplitudes of movement, dislocation dips within an interval of 40-70°, several bendings and arrangements of graben marginal faults indicate priority of normal extensional faults. The active role of extension results also from the presence of listric faults, rotation of blocks around the horizontal axes and opened fractures. Some of the main faults were used also as feeding channels of surface volcanic activity. Listric faults with fault planes reaching depths of about 10 km, as interpreted from deep seismics in the Pannonian Basin (Horváth & Tomek, 1987), enable to explain crustal thinning by the mechanism proposed by Hamilton (1987) for the Great Basin region, i.e. by stretching above astenosphere elevations. The overheated lower part of the crust was deformed plastically while the upper part by movements along the listric faults.

In addition to meridional and NNE-SSW oriented faults, also NE-SW faults (Ziarska kotlina basin) markedly participate in the basin structure. These latter faults controlled the sedimentation in Turcianska and Ziarska kotlina basins till the Pannonian. These faults were caused by extension in NW-SE direction.

Middle to Upper Miocene sedimentation (sporadically also Pliocene) took place in the Central Slovakian Volcanic Area in a fluvial-limnic environment. The isolation of intramontane basins was caused by a general updoming of the region, whereby the subsidence of grabens was accompanied by the uplift of the surrounding mountains by 1000 to 2000 m. The thickness of the volcanosedimentary filling in the basins exceeded 1500 m (Konecny et al., 1983). The grabens are bordered by the N-S to NE-SW directed faults. The faults on the western side of the grabens have greater amplitude of movement, varying from 1200 to 3000 m. The Zvolenská kotlina basin having a horizontal or slightly eastward inclined attitude of strata, is an exception. The rotation of the pre-Neogene basin basement blocks around the horizontal axis is considered as a result of regional updoming above an elevation of a mantle diapir with axis of N-S direction, situated along the eastern margin of Kremnica graben (Fig. 10).

Upper Miocene-Pliocene intramontane basins.

After the Lower Sarmatian, the last nappes front overthrust on the foredeep in eastern Poland took place (Oszczypko & Slaczka, 1989). The western part of the Carpathians became an extension area controlled, on the one hand, by the retreat of the active collision to the Eastern Carpathians and, on the other hand, by the thermal history of the mantle diapir, as early as in the Pannonian (approx. 8 MA) (Horváth, 1987). In the Upper Miocene and Pliocene, rapid subsidence with high sedimentation rates took place in the Pannonian Basin. Widening of the backdeep is observed.

During the Pannonian, the largest intramontane basins of the Western Carpathians became bays of strongly brackish sea of the Pannonian Basin, which then became freshwater in the Pontian. In minor, more or less isolated, basins, fluviatile and lacustrine sediments were deposited. Gradual filling of the sedimentary area and subsidence decrease are supported by the formation of coal seams in the marginal parts of the basin. Deposition in the basin ceased at the end of the Pliocene. In the Vienna and Danube Basins, a complex of sands, clays and marls was deposited during the Pannonian. In the Pontian, limnic and fluviatile sedimentation took place. Pliocene sediments are represented mainly by fluviatile fans, whose clastic material was transported from the source areas bordering the basins.

In the NE part of the Vienna Basin and on the western margin of the Danube Basin, extension of NW-SE orientation was documented by tectonic analysis. Besides tension fractures, listric normal faults are often represented (Nemcok & Kovác, 1988). The activation of extension tectonics in the Pannonian is supported in the Vienna Basin by the transgressive character of the sediments and the deepening of the sedimentary area, especially in the SE part. In the Pontian, the sedimentation took place only in the central parts of depressions. Thicknesses of the Pannonian and Pontian sediments vary from 10 to 100 m on highs and reach 1500 m in depressions (in the Austrian part of the basin).

Pannonian sediments display discordance with the Sarmatian in the Danube Basin, excluding the central depression. The Upper Miocene and Pliocene depocentres migrate to the S, to Gabcíkovo depression. The maximum thickness of the Pannonian reaches here 1500 m. Pontian sediments cover the same extension as the Pannonian ones. Their thickness is several 100 m. The greatest thickness of the Pliocene sediments is observed in Gabcíkovo depression (and farther on Hungarian territory). The thickness of Dacian sediments reaches 1000 m, while the Rumanian are from 100 to 200 m. Sedimentation continues also in the present day. The Gabcíkovo depression, because of its development, belongs to a back-deep basin type.

In addition to NE-SW to NNE-SSW oriented faults, NW-SE faults were present in the western part of the Western Carpathians. These are represented by the Jastrabie fault (along which 1000 m thick marine Lower Miocene is justaposed to freshwater Upper Miocene), and also by the Ludince line, in continuation of Jablonica fault system, which borders the buried southern margin of the Povazsky Inovec Mts. and Tribec Mts.

and separates the Middle Miocene from the Upper Miocene and Pliocene depocentres in the Danube Basin. A gradual uplift of the region northeastward took place along these faults. This can be explained partly by isostatic upheaval of thick blocks of the crust in a suture zone and, partly, by the extension of the NE-SW direction.

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