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Kinematic Evolution of the Central-Carpathian Paleogene Basin in the Spišská Magura region (Slovakia)

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Abstract. The Subtatric – Ružbachy Fault System played a considerable role in the Cenozoic evolution of the northern part of the Central-Carpathian Paleogene Basin. The system, which represents a shear zone with NE – SW direction, restricts the eastern continuation of the Mesozoic rocks of the Tatra Mts., bounds the Mesozoic Ružbachy Island to the Paleogene deposits and it has governed the deposition in the area since the Paleogene. In the area neighbouring to the system we distinguished four deformation stages connected with 1) NNW-SSE compression resulting in NE-SW trending thrusts, 2) E-W compression resulting in strike-slip movements along the system, 3) NNE-SSW compression resulting in WNW-ESE overthrusts and 4) NW-SE extension associated with normal fault formation. Rock sequences record activity of the system from the Eocene and Oligocene up to the Recent.

Key words: Central-Carpathian Paleogene Basin, Subtatric-Ružbachy Fault System, structure, tectonics, sediments, basin evolution

Introduction

The striking Subtatric - Ružbachy Fault System (ST - R in the following) trending from the SW to the NE and bounding the Tatra Mts. to the deposits of the Central-Carpathian Paleogene Basin has been subject of geological investigations and discussions for many years. The system sharply bounds the Paleozoic and Mesozoic units of the Tatras Mts. to the Paleogene deposits in the south and uplifted Ružbachy Mesozoic Island in relation to the Paleogene deposits on its both sides. This system, which we call in this paper Subtatric - Ružbachy Fault System in order to emphasize its geographic position, has played a considerable role in the geologic evolution of the studied area. It governed uplift of the Tatra and Spišská Magura regions, accumulation of thick Quaternary deposits on the foothill of the Tatra Mts. and probably also evolution of the Paleogene turbidite system in the Central-Carpathian Paleogene Basin. Because the ST-R Fault System is still active, it is interesting not only from the viewpoint of basic geology, but also from the viewpoint of applied geological disciplines.

The aim of the presented paper is to analyse tectonic structures in the area of the Spišská Magura region and to interpret these structures in order to get kinematic evolution of the area. This should also provide new knowledge on character and chronological succession of brittle deformation along the ST - R Fault System.

Geological setting

The Spišská Magura Region is a part of the Central-Carpathian Paleogene basin (CCP Basin) and represents the northernmost part of the Central Western Carpathians (Fig. 1). It consists of the Paleogene deposits transgressively overlying Mesozoic rocks of the Krížna Nappe, and tectonically bounded in the north by the Pieniny Klippen Belt and in the east by the East-Slovakian Neogene Basin. The deposits have a wide stratigraphic span ranging from the Middle Eocene to the Late Oligocene (e.g. Gross et al. 1999, Janočko et al. 1998, Janočko & Jacko 1999) and they prevailigly consist of turbidites filling the CCP Basin. Only the lowermost part of the basin fill is composed of continental and shallow-marine deposits, mostly consisting of breccias, conglomerate and nummulitic sandstone and limestone (Borové Formation). The overlying deposits comprise Huty (Middle Eocene - Late Oligocene) and Zuberec (Late Eocene - Late Oligocene) Formations (Gross et al. 1984, Janočko & Jacko 1999). The Huty Formation prevailingly consists of dark shale sandwiching conglomerate representing a fill of a canyon incised into shales. The Zuberec Formation consists of alternating shale and sandstone representing channel and levee and interchannel deposits of turbidite systems (Janočko & Jacko 1999, Fig. 2). The CCP Basin is usually defined as a forearc basin (e.g. Soták et al. 1996), however, the unambiguous evidence proving the basin position is still missing. From this reason we define the CCP Basin in this paper as a basin with a complex, prevailingly extensional and subordinate compressional history.

The structure of sediments, their succession and kinematics imply a complex character of tectonic evolution in the eastern part of the CCP Basin (c.f. Hrušecký et al., 1995; Sperner & Ratschbacher, 1995). The complexity of structural evolution of the basin is most pronounce in the studied region where thrusts, normal faults and strike-slip faults occur.

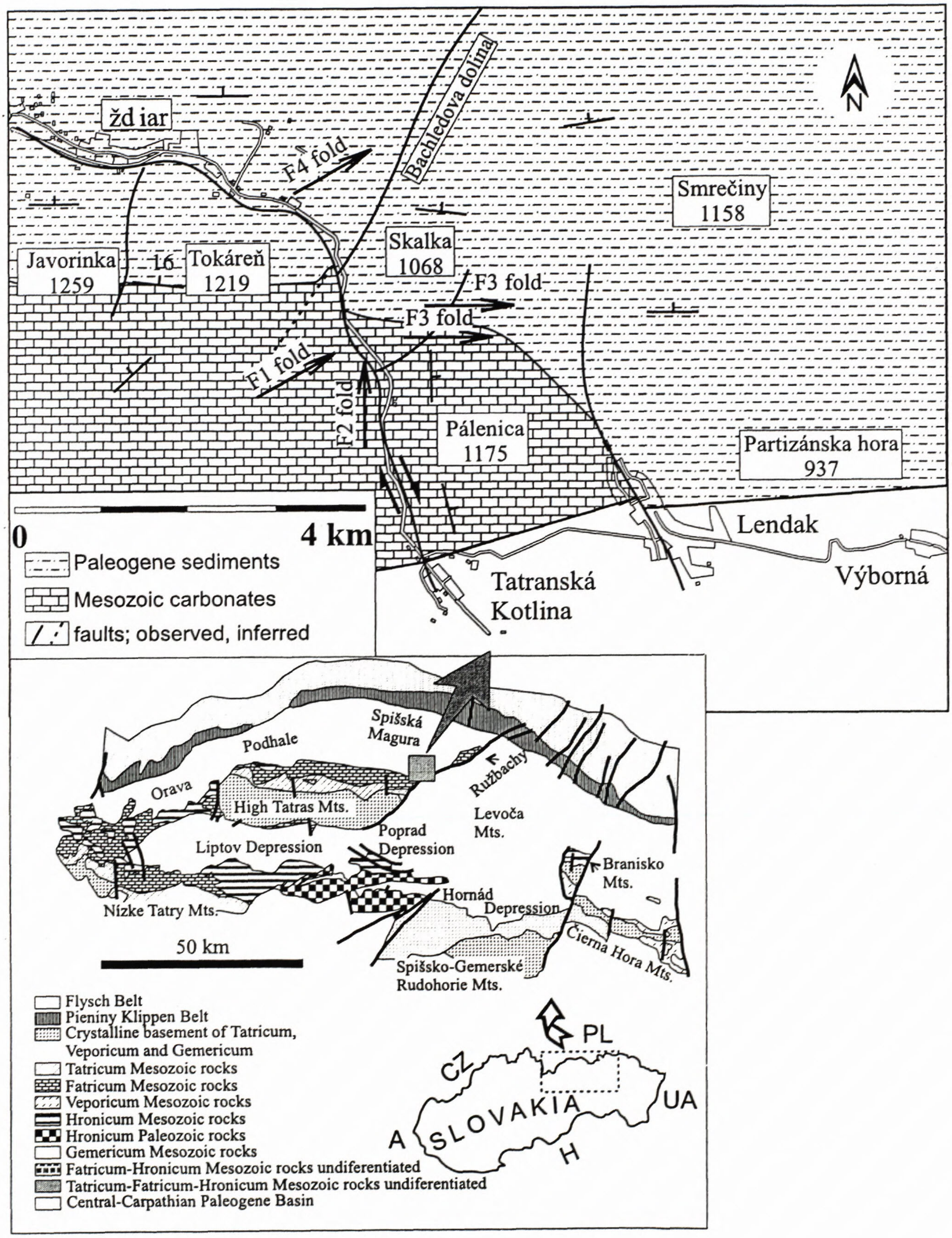


Fig. 1: Location of the studied area and schematic map with geological structures among Ždiar, Tatranská Kotlina and Lendak. Position of the Central-Carpathian Paleogene Basin is also shown.

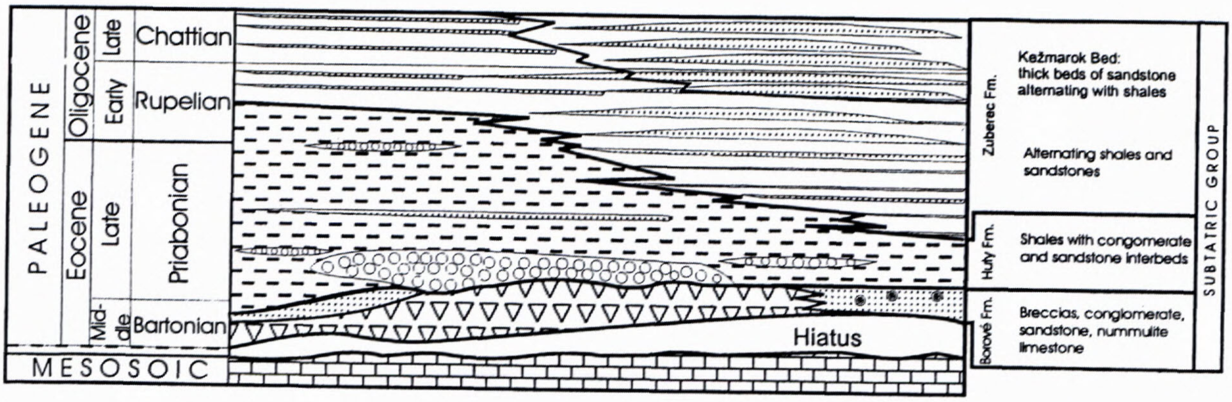


Fig. 2: Lithostratigraphic column of the Paleogene deposits in the studied area

The most expressive structure in the studied area is represented by ST - R Fault System (Fig. 1). It is a brittle shear zone having NE-SW strike and steep dip toward SE. It tectonically restricts the southern and eastern parts of the Tatra Mts. and probably passes to the Krynica Unit of the Outer Carpathian Flysch Zone in NE. In the area of Ružbachy the system restricts a horst of the underlying Mesozoic rocks belonging to the Krížna Nappe. Most of the authors up till now considered the ST - R Fault System as a reverse fault structure (Koutek, 1931, 1936; Matějka, 1935; Gorek, 1954; Andrusov, 1958, 1968; Chmelík et al., 1963; Fusán et al., 1963; Maheľ et al., 1967; Gross, 1973; Nemčok et al., 1993; Hrušecký et al., 1995).). Based on the description of the borehole CH – 1, located SE of the studied area, Gross et al. (1980) documented normal slip kinematics of at least a part of the system. Timing of the activity of the system is constrained by apatite fission track ages of the Tatra granitoids which yielded 15 Ma (Kráľ 1977) and 10 - 19 Ma (Kováč et al. 1994), respectivelly, suggesting Early to Middle Miocene. Assumed amplitude of the Neogene uplift of the Tatra Mts. is about 2 700 m and amplitude of the Quaternary uplift is assumed to be about 400 m (Nemčok et al., 1993). However, the recent results from the sedimentological analyses of the CCP Basin suggests occurrence of a submarine high located in the same direction and area like the ST-R Fault System suggesting possible older activity of the system. The occurrence of the high is proved during the deposition of the Zuberec Formation i.e. in the time span Late Eocene - Late Oligocene (Janočko & Jacko 1999). Strike-slip movements were recorded in several sections of the ST-R Fault System (Nemčok et al. 1993, Hrušecký et al. 1995, Sperner and Ratschbacher 1995, Sperner 1996) suggesting an even more complex kinematics.

Methods

The construction of the geologic map from the Spišská Magura region (Janočko et al. 2000, Janočko & Jacko 1998) required a detail structural analysis of the Paleogene deposits and their basement in order to understand the structural evolution of the area. Based on the analysed structures, we divided the whole region in three, generally NW-SE elongated domains (Fig. 6B). The first domain, consisting almost exclusively of carbonate belonging to the Krížna Napppe, occurs in the SE part of the region between Tatranská Kotlina and Lendak. The second domain, composed of carbonate of the Krížna Nappe and deposits of the Paleogene Borovo and Huty Forma-

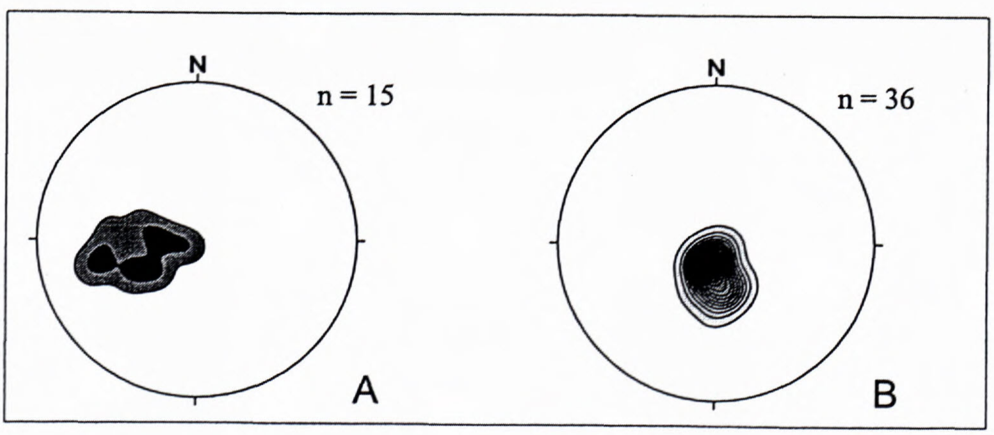


Fig. 3: Distribution of bedding poles: a – Mesozoic carbonates; b – Paleogene deposits
The figure represents non-folded data at lower hemisphere projection

tions, occurs in the central part of the region. The third domain, extending between Ždiar and Bachledová dolina, consists of the Central-Carpathian Paleogene deposits overlying carbonates of the Krížna Nappe. We studied synsedimentary depositional structures indicating the filling of the basin (Janočko & Jacko 1998), geometry of mesoscopic structures yielding primary data for structural analysis, bedding, fold structures, cleavage and brittle shear zones. Geometric classification of folds has been based on the Hudleston (1973) principle of visual analysis of fold structures. Statistic evaluation of the obtained structural data also provided a comprehensive information on succession and spatial - lithological relations of the individual measured sections and relations between the sections. The orientation of palaeostress axes was deduced by application of Angelier's „direct inversion method„ (Angelier 1990).

Description of structural domains

Southeastern, marginal domain

The pre-Paleogene structures, necessary for interpretation of kinematic evolution of the area in the Paleogene, were divided on the base of the structural analysis of the underlying Mesozoic rocks. The area SE of the CCP Basin consists of the Krížna Nappe. It extends among Tatranská Kotlina, Lendak and Toporec, its northern boundary occurs about 500 m south of the elevation point Skalka (1068 m. a. s. l., Fig. 1). The Krížna Nappe prevailingly consists of Ramsau Dolomite (Nemčok et al. 1993) with characteristic bedding parting and occurrence of intensively tectonized dark shales. The bedding of dolomite has N - S direction and dip about 50° toward W (Fig. 3A). The most conspicuous overthrust structures are penetrative, often conjugated and they have NE-SW strike and dip 30°- 50° toward NW and SE. The NE - SW trending dextral strike-slip structures steeply dip (75°-85°) toward NW. The succession of structures ends with extensional structures represented by normal faults of N - S and NE - SW strike dipping toward E and SE. They are often filled by calcite which forms 3 mm thick veins.

Central domain

The central domain occurs in the surroundings of Tokáreň and Skalka (1 068 m.a.s.l., Fig.1). It consists of the Triassic carbonates comprising Carpathian Keuper, Fatra Formation and Kopienec Bed belonging to the Krížna Nappe (Nemčok et al. 1993). These rocks are transgressively overlain by basal Paleogene deposits (Borové Formation, Gross et al. 1984, Janočko et al. 1999) and capped by deposits of Huty Formation.

The Mesozoic deposits have commonly N - S bedding dipping 5° - 30° toward W. The Paleogene deposits have general WNW - ESE bedding diping about 5°-25° toward NNE (Fig. 3B).

We find fault structures common for Mesozoic and Paleogene deposits of the studied area. They are represented by dextral strike-slips having E - W and ESE - WNW orientation and dip 45°- 80° toward S and SSE. The normal faults have E - W direction and they dip with 40°- 65° toward S. Conspicuous extensional fault system suggests NW - SE direction of $\sigma 3$. The extensional structures are filled by calcite which forms up to 3 mm thick veins of NE - SW direction dipping about 60°- 80° toward SE. Another conspicuous structure is sinistral strike - slip system having WNW - ESE orientation with 75°- 86° dip toward NNE and SSW.

F1 and F2 fold structures were identified in the Triassic carbonates of the Krížna Nappe in this domain. The axes of the F1 folds have 5^0 dip toward NE (Fig. 4A). The folds are typically developed in the Carpathian Keuper of the Krížna Nappe. They are larger than 1 m and represent parallel, slightly open folds of 1B class according to Ramsay (1967) or 1D folds according to Hudleston (1973). They only occur in the surroundings of Tokáreň.

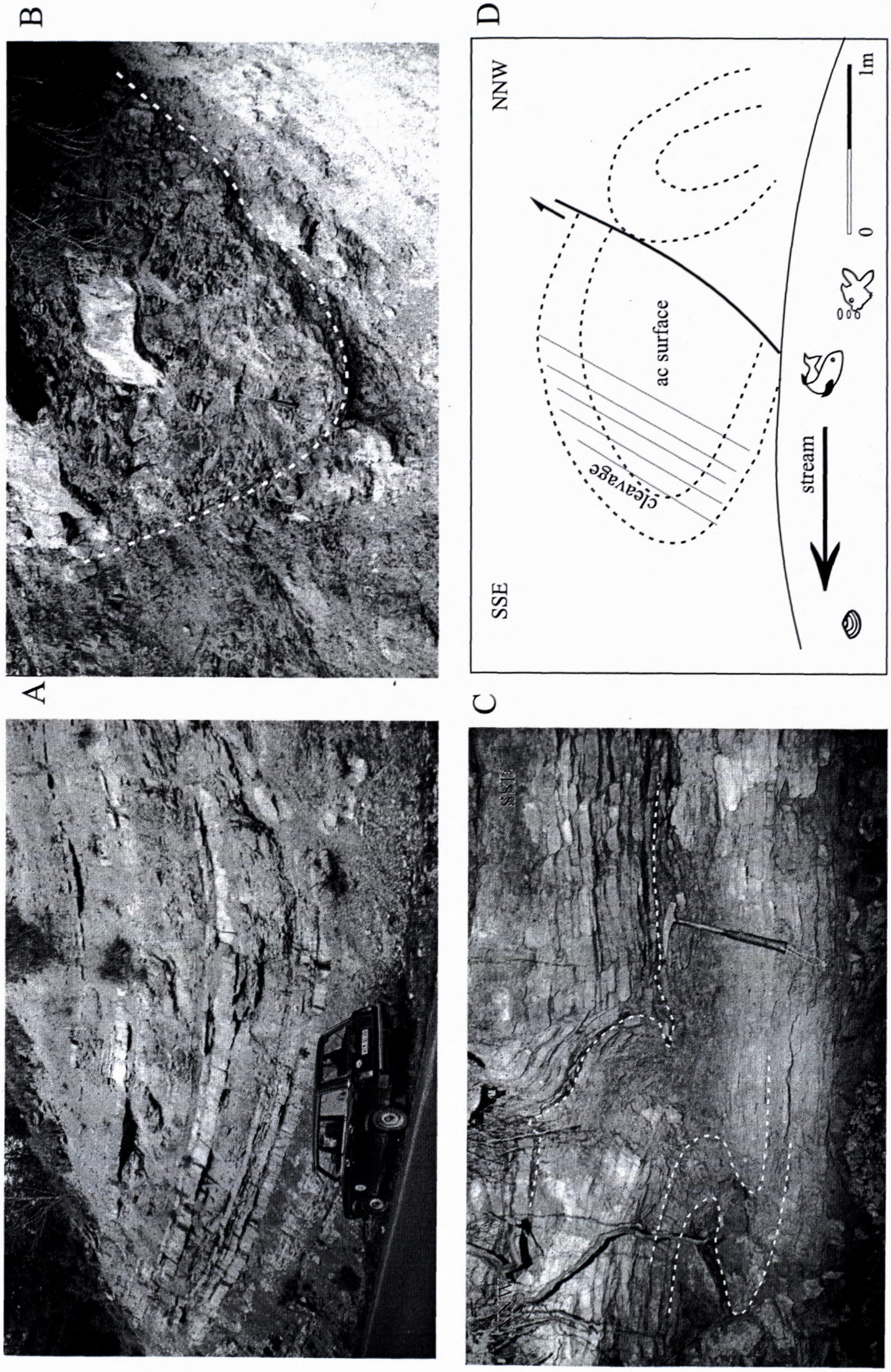
The subhorizontal dip of fold axes of the relatively older mesoscopic folds (F2, Fig. 4B) is15°- 45^0 toward the North. The folds are asymetric, often disharmonic, parallel, uprighted, inclined and they belong to the class 2D sensu Hudleston (1973).

The axes of the folds of F3 type (Figs. 4C and 4D) are oriented from N to S and they dip with 10^0 - 35^0 toward E. The folds are recumbent, parallel, compressed, isoclinal (Fleuty 1964) and according to Hudleston (1973) they represent fault propagation folds with south vergency of the 1C class. They are associated with dark mudstones with sandstone interlayers of the Huty Formation. They have also been observed in marginal parts of the Carpathian Keuper.

Northern marginal domain

The domain occurs between Ždiar and Bachledová dolina. It only consists of Huty Formation deposits dipping with 20°-30° toward N (Fig. 3B). The geologic structure of the area is strikingly influenced by normal fault tectonics. The movement occurred along NW - SE extensional faults dipping 65°- 80° toward NE and SW, occasionally it also originated along WSW - ENE faults dipping 70°- 80° toward NNW. Two systems of inverse fault structures are typical in the area: the first one is represented by NW - SE inverse faults dipping 80°- 85° toward SW and the second one is composed of ENE - SWS inverse faults dipping about 70^0 toward NNW. The last fault structures in this area are conjugated fault pair with NE - SW and E - W strike dipping 65° toward S and SE.

Fig. 4: Representation of fold structures around Ždiar area:
A - Alternation of dolomite and variegated shale of the Carpathian Keuper
B - Disharmonic folding of the Carpathian Keuper and distinct segmentations of dolomites
C - Plastic deformation in the Mesozoic shales belonging to the Carpathian Keuper and in the Paleogene deposits.
D – Sketch: isoclinal folding of Paleogene deposits


A
B
C
D
SSE
NNW
ac surface
cleavage
stream
0
1m

Slovak Geol. Mag., 6, 4(2000), 409–418

We found F4 folds in the area (Fig. 5A) with fold axis direction dipping 10° toward NE. The folds larger than 1 m range from overturned and recumbent to open and parallel 2D folds according to the classification Hudleston (1973).

Interpretation of structural domains

The results of structural analysis imply more deformation etapes in the studied region. They also confirm discordancy between Mesozoic basement and Paleogene deposits of the CCP Basin.

Generally, Mesozoic carbonates have N - S bedding diping toward W (Fig. 3A) and Paleogene deposits have WNW - SES direction of bedding diping toward N (Fig. 3B). The disjunctive structures have NW - SE and W - E directions corresponding to the orientation of the ST - R Fault System. The different kinematic activity of the structures reflects only regional geologic processes related to the postdepositional evolution of the basin. Different dynamics within the basin is also documented by entirely different disjunctive structures measured in the Paleogene deposits.

Southeastern, marginal domain

The oldest tectonic etape is probably related to the activation of the Subtatric - Ružbachy Fault System which is only developed in the southeastern marginal domain. The results of structural measurements suggest more deformation etapes directly connected to the tectonic activity in this extremely exponed tectonic zone. Based on the analyses we divided three deformation etapes here:

The first, probably oldest deformation etape is connected to the compressive palaeostress field with maximum compression σ1 of NW - SE direction (Fig. 6/Ia). In this palaeostress field NE - SW thrust faults, corresponding to the regional direction of the Subtatric - Ružbachy Fault System, developed. The maximal E - W extensional field σ3 resulted in origin of extensional tectonic structures of N - S and NE - SW directon, which have been filled by calcite.

The second palaeostress field (Fig. 6/Ib) is characterized by E - W compression resulting in dextral NW - SE strike-slip movements. The tensional axis σ3 has NNW - SSE direction.

During the third, youngest tectonic etape (Fig. 6/Ic), mainly the NW - SE extensional stress σ3 was active. It gave the rise to NE - SW normal faults with joints often filled by calcite.

The palaeostress measurements from a vicinity of the ST - R Fault System confirmed a polyphase tectonic activity of the system which started in the Middle and Late Miocene or even earlier, in the Paleogene. The activity of the system in the Paleogene is suggested by change of palaeoflow directions of the Paleogene turbidites along the fault course. This change was probably caused by existence of submarine high stretching from the Štrba area along the foothill of the Tatras Mts. to the Ružbachy Mesozoic Island (Janočko et al. 1999 in press) which determined evolution of two separated depositional systems on its both sides. The activity of the system since the Miocene is proved by evidence of the High Tatras Mts. uplift during this period (Kráľ 1977, Nemčok et al. 1993).

Based on structural analysis of the domain it is also possible to recognize a conspicuous cyclic succession where rotation of compressional σ1 field occurs. It is also confirmed by change of angle of maximum compressional stress σ1 in the marginal part of the studied area, which evolves from SE to E and NNE in anticlockwise direction. The maximal extensional stress σ3 rotated from NW to SE also in anticlockwise direction. Based on these results we think that in the studied region a gradual rotation took part which may be related to the transtensional movements in the High Tatras Mts. region.

Central and northern domain

The tectonic situation is different north of the ST - R Fault System, in the central and northern marginal domain, where tectonic deformation was not so intense. However, also here we can observe indications of polyphase tectonic deformations most probably related to the tectonic activity on the southern margin of the mountains. The structural analyses in this part of the region suggest four tectonic phases:

The first, probably the oldest phase, is related to the activity of extensional stress σ3 with NW - SE direction (Fig. 6/IIa). The structures are characteristic for both Mesozoic and Paleogene deposits. They consist of normal faults having NW - SE and E - W directions. Kinematic response of this paleostress field is also conjugated Fault System with hanging walls of NW - SE direction dipping 80^0 toward SE and footwalls of N - S direction with 40° dip toward W.

The second palaeostress field is characteristic by maximal compressional stress σ in ENE - WSW direction and maximal extensional stress σ3 in NNW - SSE direction. In this palaeostress field associated pair of dextral strike-slips of ENE - WSW direction and sinistral strike-slips of WNW-ESE direction originated. All these strike-slips have character of Riedel shears R and R` (Fig. 6/IIb). A dextral strike-slip in the main shear zone of NNW - SSE direction was formed during an increased deformation (Fig. 1). This zone is followed by creek Belá between Skalka and Tokáreň (Fig. 1). We also relate formation of F2 folds with fold axis diping toward north to the activity of this palaeostress field.

The third palaeostress field in the central part of the area is characterized by maximal compressional axis σ1 in NNE - SSW direction and maximal extensional component σ3 in WNW - ESE direction (Fig. 6/IIc). The products of this stress field are WNW - ESE overthrust structures diping toward NNE as well as extensional structures of ENE - WSW direction. On the overthrust structures F3 fold structures of fault propagation type and duplex structures were formed.

The fourth palaeostress field is characteristic for the northern marginal domain of the studied region, the Paleogene deposits crop out (Fig. 6/III). In this palaeostress field normal fault structures of ENE - WSW and WNW - ESE direction were formed which were determined by σ3. These structrures are expressed by folded beds (Fig. 5B). Along the normal faults, induced by σ1 compression of NNW - SSE direction, the Paleogene deposits were gradually uplifted and folding generating F4 folds (Fig. 5A).

The analysis of discussed palaeostress fields suggest, similarly to the southern part of the region, rotation of the maximal compressional stress σ1 counterclockwise from the W toward SSE. The extensional component σ3 is not evolved so regularly like in the surroundings of the Subtatric - Ružbachy Fault System because is was not originated at one tectonic line.

Based on the structural analysis, it is possible to suggest correlation of the second deformation phase between the southern and central part of the region (Fig. 7). The deformation phases in both regions are characteristic by strike-slip faults. Also the third deformation phase of the southeastern and central domain shows analogous relations. In this part extensional component prevails resulting in normal faults.

Discussion and conclusion

The Spišská Magura region between Ždiar, Tatranská Kotlina and Lendak, consists of Paleogene deposits (Middle Eocene - Oligocene) unconformably overlying carbonates of the Krížna Nappe. The main geologic evolution was influenced by the ST - R Fault System representing the most striking structure of the region. This shear zone with NE - SW direction and steep dip toward SE restricts the eastern continuation of the Tatras Mts. and continues toward NE. In our study we found that several deformational indicators in the entire studied area are closely related to the kinematics at this structure.

The oldest deformation phase, influencing the evolution of the region, is NNW - SSE compression occurring in the SE part of the studied area. The compression induced activity of the Subtatric - Ružbachy Fault System along which Paleogene deposits were uplifted. This resulted in the subsequent erosion of the Uppermost Oligocene deposits which were described in the Levoča Mts. south of the Subtatric - Ružbachy Fault System (Soták et al. 1996, Janočko et al. 1998). The effect of compression is most striking in the vicinity of the Subtatric - Ružbachy Fault System where the uplift amplitude was highest. In this area also NE - SW overthrust structures originated diping toward NW and SE. In the central part of the studied region smaller uplift amplitude was observed. The compression is manifested by NE verged F1 folds occurring in the Carpathian Keuper deposits. However, it is

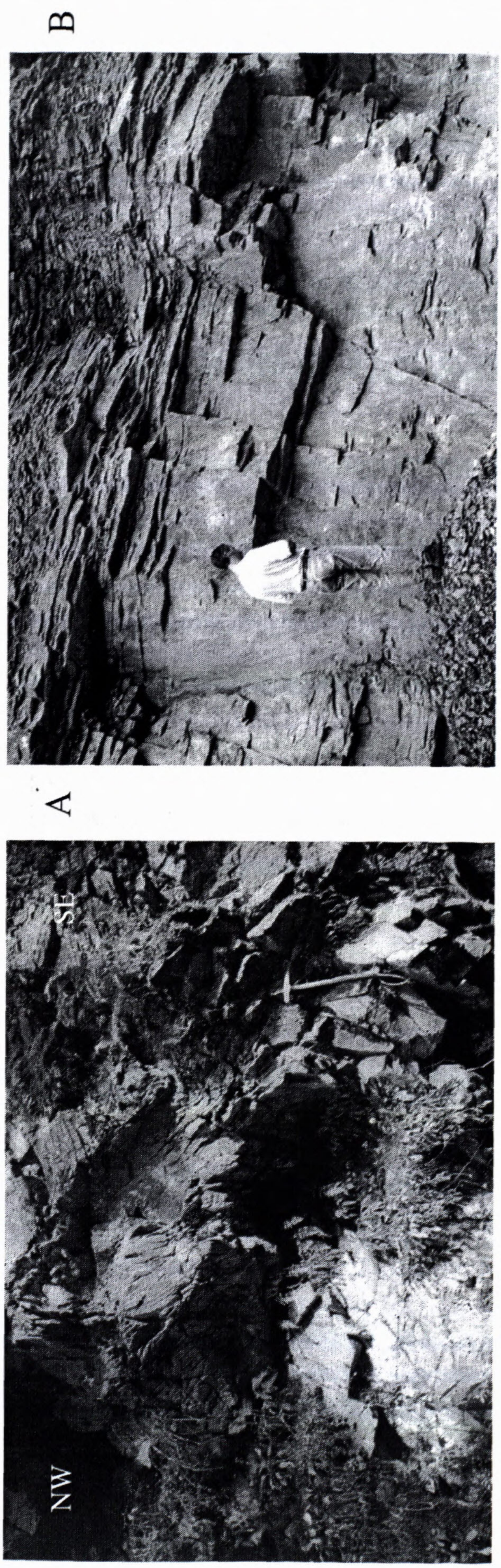


Fig. 5: Photo of A) fold structure in the Paleogene rocks with different competence in the Bachledova dolina, B) Conjugate pair of normal faults with little deflection in layers of thick sandstone beds (marker bed in the study area) in Bachledova dolina.

Slovak Geol. Mag., 6, 4(2000), 409–418

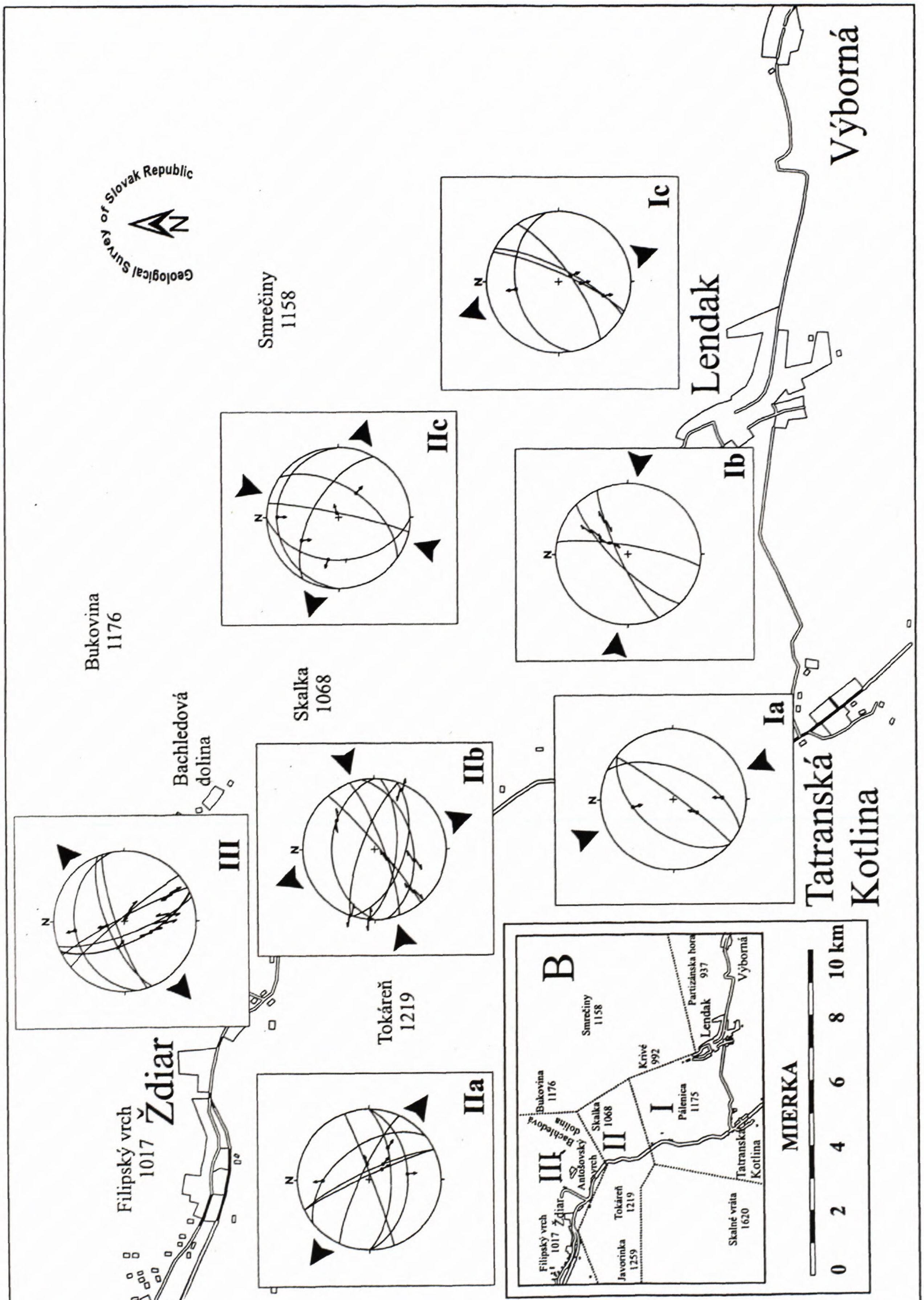
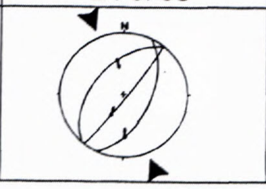
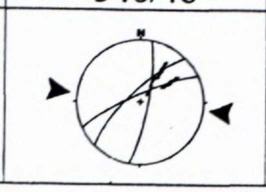
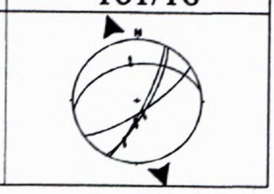


Fig. 6: Stress tensors and localization of structural domains

	Ia	Ib	Ic
σ1	157/12	97/18	13/72
σ2	61/24	201/36	254/9
σ3	270/63	346/48	161/16
Paleostress field			

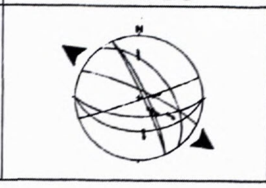
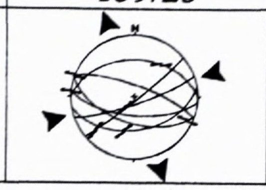
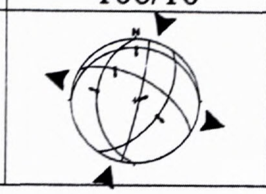
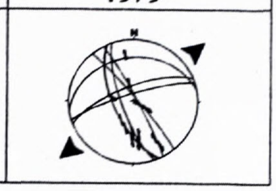
	IIa	IIb	IIc	III
σ1	263/67	253/10	200/25	160/66
σ2	29/14	5/65	356/63	316/23
σ3	124/18	159/23	106/10	49/9
Paleostress field				

Fig. 7: Summary table of calculation of paleostress poles and their values in the study area.

probable that initial compression in the central and northern part was replaced by extension inducing subsidence of the CCP Basin fill. This is proved by NW - SE normal fault structures oriented perpendicularly to the main compression direction and by well-preserved Late Triassic and Paleogene deposits. The age of the deformation may be is suggested by timing of the Tatras Mts. uplift (some 15 Ma, Kráľ 1977) and by existence of submarine high in the Oligocene which had the same course like the ST - R Fault System (Janočko et al. 1999 in press). The proved Quaternary uplift also suggests the recent activity of the Fault System. The Miocene uplift also determined exposure of the oldest Paleogene sequences in the Spišská Magura region due to subsequent erosion of overlying younger deposits and slight tilt of the Paleogene formation toward N.The second deformation stage in the SE part of the region is related to the E - W compressional stress σ1. It resulted in NE - SW strike-slip faults of the Subtatric - Ružbachy system with dextral movement. Their activity induced NW – SE conjugate fault structures. These structures are well observable in the SE marginal part, where they often segment the ST - R Fault System.

The activity of this fault system probably also induced maximal compressional stress σ1 of ENE - WSW direction and maximal extensional stress σ3 of NNW - SSE direction in the central part of the studied region. In this area, associated pair of ENE – WSW dextral strike-slips and WNW – ESE sinistral strike-slips originated, which have character of Riedel shears R and R´. The formation of mesoscopic shear folds of F2 type is also related to the activity of these pair translations. With increasing deformation dextral strike-slip movement originated in the main NNW - SSE shear zone between Tokáreň and Skalka. The origin of the NW - SE and NNW - SSE structures in the whole Spišská Magura region is probably related to the transpressional movements in the area of Tatra Mts. described by Hrušecký et al. (1995). Our geological-structural analysis showed that the dislocations have frequently strike-slip character with local, small normal fault occurrences. They are often associated with subparallel systems of subvertical joints filled by carbonates. The occurrence of travertine along the structures suggests their recent activity continuing from the Neogene.

The third deformation stage in the central part of the studied region is related to the maximal compresional stress component σ1 in NNE - SSW direction and to the maximal extensional stress component σ3 in WNW - SES direction. The existence of these stresses resulted in WNW - ESE overthrusting structures with NNE vergency and ENE - WSW extensional structures. On the overthrusting structures flexures, duplex structures and fold structures of F3 type originated. The fold axis, diping with 10°, is oriented toward E. There are characterized like fault propagation folds. This deformation stage which is probably of local character, is closely related to the formation of NNW - SSE dextral shear zone between Tokáreň and Skalka which we describe in the second deformation stage. Intensive tectonic activity at the shear zone induced local overthrusts consistent with dextral movements in the area. The compressional σ1 and extensional σ3 stress of this deformation etape only partly rotated from the main compressional and extensional stress field found in the second deformation etape of the central part of the studied region. We assume almost synchronous development with the NNW - SSE shear zone.

The youngest deformation stage on the SE margin of the studied area is characteristic by prevailing extensional stress component σ3 with NW - SE direction. This etape of the evolution of the Subtatric - Ružbachy Fault System is associated with normal faults of NE - SW direction. The normal fault was convincingly manifested by the borehole CH – 1 (Gross 1973). Similarly, in the central part of the studied region we recorded activity of maximal extensional stress component σ3 resulting in formation of NW - SE and WSW - ENE normal faults.

The system of NE - SW faults belongs to the youngest dislocation structures strikingly segmenting lithologically different deposits of the CCP Basin and deforming NW - SE faults. This infers the Late Miocene and/or Pliocene age of the faults.

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