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Pliocene to Quaternary stress field change in the western part of the Central Western Carpathians (Slovakia)

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Knowledge of the current tectonic regime plays an essential role in natural hazard assessment, especially in the risk assessment of fault activity. Structural analysis of brittle deformations (using inversion techniques) was used to determine the stress field state occurring within Pliocene and Quaternary deposits in the western part of the Central Western Carpathians. The deformation pattern of the reduced stress tensor showed that all structural measurements could be separated into two groups. An older, Late Pliocene fault population was activated under NNW–SSE oriented extension. A younger, Quaternary fault population reflected origin in a NE–SW extensional tectonic regime and it distinctly showed a change the orientation of the S_3 of about 70°. The change in tectonic activity, as well as in the stress field orientation, is dated to the Pliocene–Pleistocene boundary. The Quaternary stress field developed during the post-collisional stage of the orogen. Our study shows that the Western Carpathian internal units document NE–SW to NNE–SSW extension in the broader region around of the northern Danube Basin.

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Key words: Western Carpathians, fault-slip data, Quaternary stress field, neotectonics, palaeostress analysis.

INTRODUCTION

The youngest tectonic history and changes in the structural evolution of the Alpine–Carpathian–Pannonian domain have been described in many papers (e.g. Csontos *et al*., 1991, 1992; Ratschbacher *et al*., 1991; Csontos, 1995; Fodor, 1995; Fodor *et al*., 1999, 2005; Kováč, 2000; Hók *et al*., 2000). Results of these investigations have provided information on the Miocene palaeostress field evolution. This evolution and the changes in the palaeostress field were affected by the counterclockwise rotation of the ALCAPA microplate (approximately 40–80°) that took place during this time (Márton *et al*., 1992; Márton and Fodor, 1995; Kováč and Márton, 1998; Márton *et al*., 1999; Kováč, 2000). The latest, Quaternary evolution of the stress field and of the associated tectonic regime have only been studied in part, due to the shortage of field data. Results of computer simulation and modelling of the recent stress field orientation (Zoback, 1992; Gerner *et al*., 1995, 1999; Bada *et al*., 1996, 2001; Horváth and Cloething, 1996; Bada, 1999; Fodor *et al*., 2005) at the Alpine–Carpathian–Pannonian junction contrasted with those from field measurements in the Danube Basin and Transdanubian Range in Hungary (Fodor *et al*., 2005), the Eastern Alps and Vienna Basin in Austria (Reinecker and Lenhardt, 1999; Decker *et al*., 2005), and also in the Outer Western Carpathians and the European Platform eastern margin in Poland and the Czech Republic (Peška, 1992; Jarosiński, 1998, 2005). The main goal of our investigation was to determine the Pliocene to Quaternary stress field and its evolution in the northernmost part of the Danube Basin in Slovakia (the Central Western Carpathians).

GEOLOGICAL SETTING

The Western Carpathians are the north-easternmost Alpine Orogen in Europe, where they are divided into three parts (Outer, Central and Inner Western Carpathians) according to

Plašienka (1999) and Kováč (2000) (see also references therein). The western part of the Central Western Carpathians comprises elevated mountain chains and inverted margins of the Neogene Pannonian Basin (Fig. 1). Depocentres of the northern part of the Danube Basin are situated among exhumed horst structures of the Tatra Core Mountains, from the west to the east: these include the Malé Karpaty, Považský Inovec and the Tribeč Mts. (Fig. 2). These mountains are composed of four pre-Tertiary tectonic units, from bottom to top: Infratatric, Tatric, Fatric and Hronic units. The present arrangement of the units was created during Cretaceous collision. The Považský Inovec Mts. comprises a horst-like mega-anticline structure. Its crystalline basement belongs to the latest exhumed pre-Tertiary basement unit in the Western Carpathians. Apatite fission track (FT) thermochronology has provided ages from 14.0 to 25.0 Ma (Kováč *et al*., 1994; Danišík *et al*., 2004; Kráľ in Hók *et al*., 2005). This suggests very recent uplift, as is also documented by the geomorphology of its western margin, where the N–S running Považie fault system divides the horst from the Blatné Depression. These fault disruptions are marked by morphological facets of the mountain front.

The Blatné, Rišňovce and Komjatice depressions have a finger-like configuration (Fig. 2) and are filled predominantly with Miocene marine sequences passing upwards into to Pliocene and Quaternary lacustrine, fluvial and alluvial deposits (Fig. 3). The central part of the Danube Basin is represented by the Gabčíkovo Depression, and it is filled predominantly with Quaternary fluvial deposits. The youngest sedimentary sequence of the Danube Basin consists of the Upper Miocene: Ivánka Formation (Fm.), the Hlavina Member (Mb.) and the Beladice Fm., the Lower Pliocene: Volkovce Fm. and Pieš any Mb., the Upper Pliocene: Kolárovo Fm. and the Syslie vŕšky Mb. (Vass, 2002). The Quaternary sequence is generally composed of the Lukáčovce Mb. and Rissian and Würmian loess deposits, alluvial fans and Nitra–Váh terraces (Joniak *et al*., 2001; Šarinová, 2002; Šarinová and Maglay, 2002).

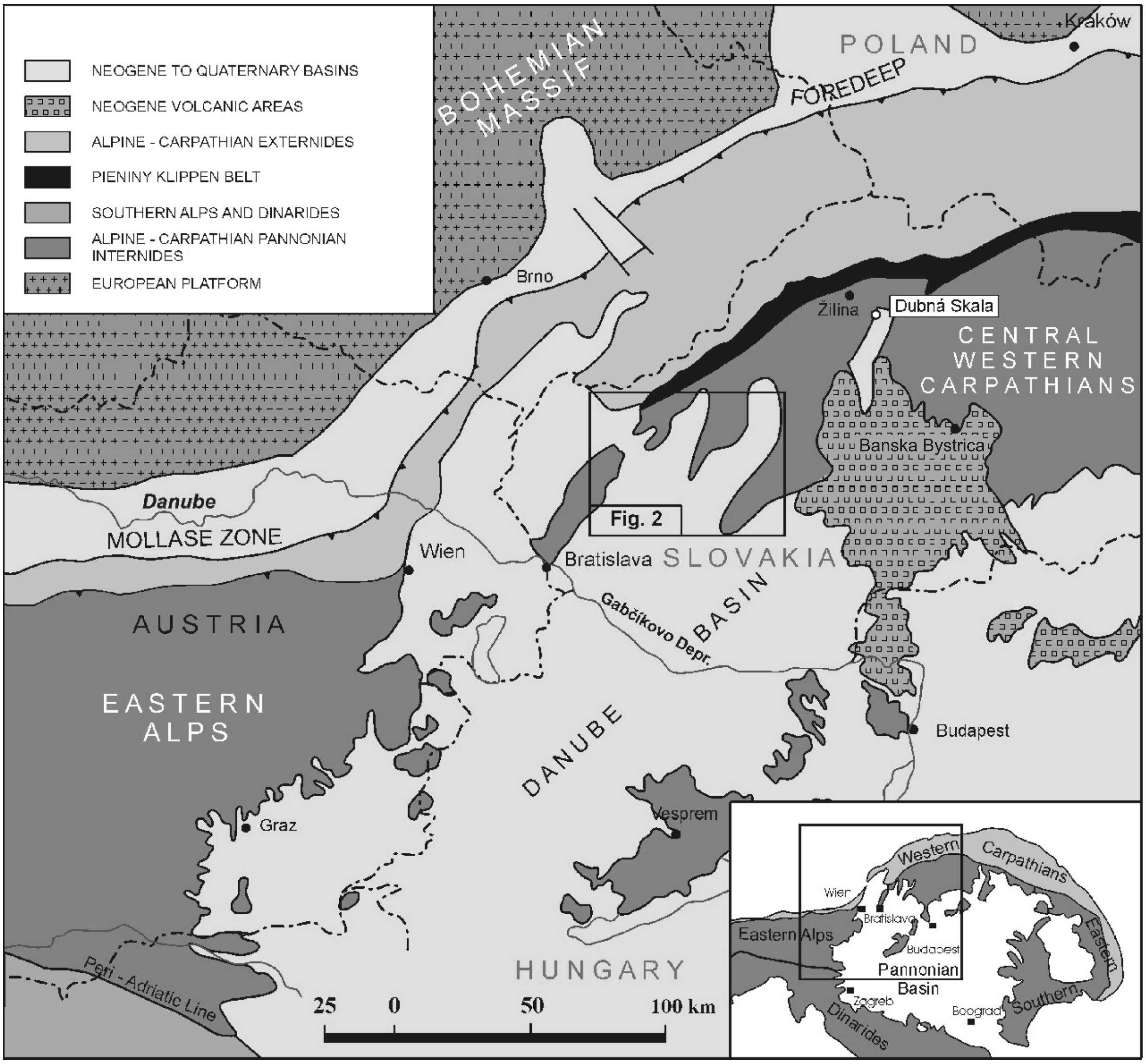


Fig. 1. Tectonic sketch of the Alpine–Carpathian–Pannonian junction area

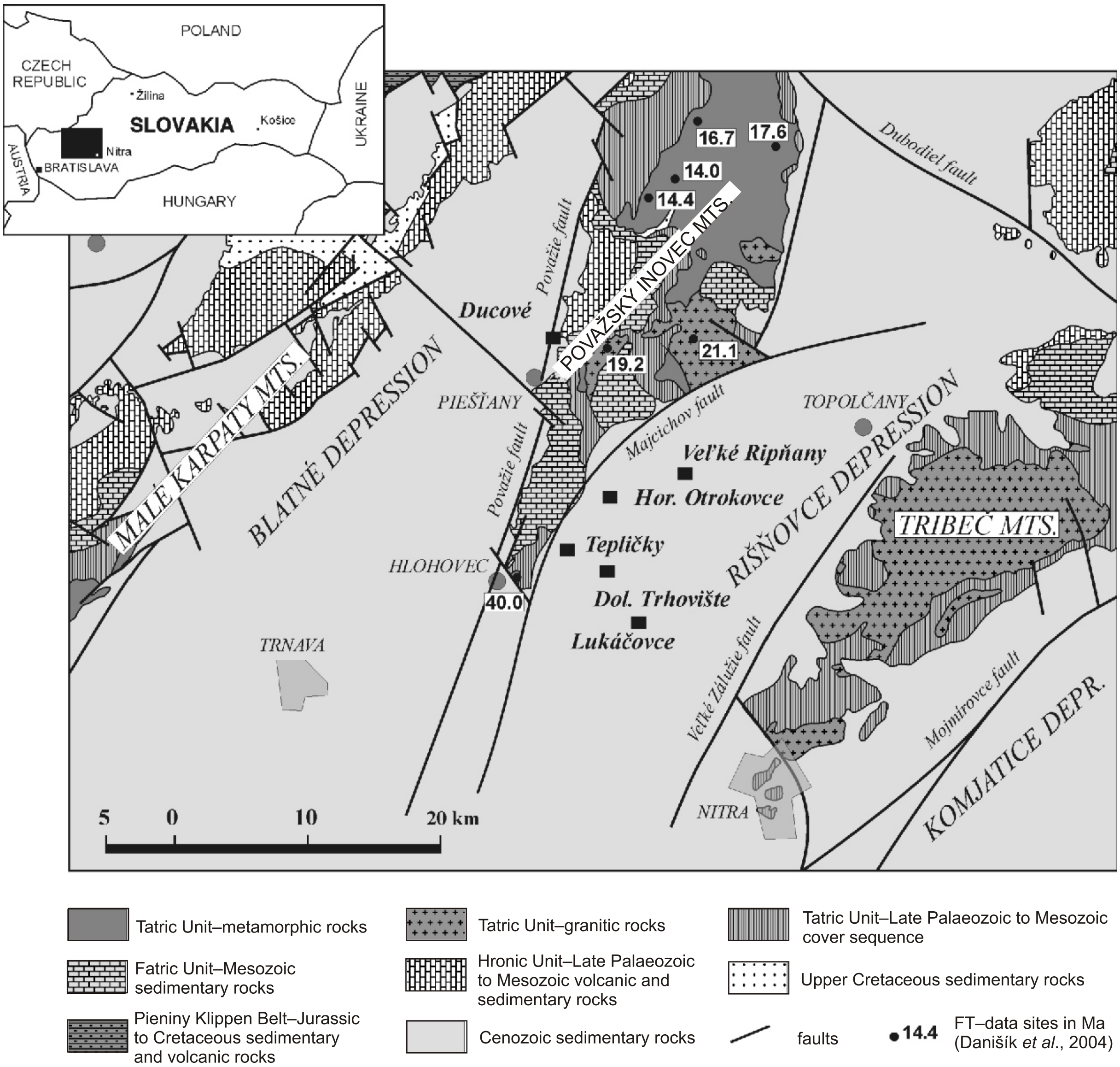


Fig. 2. Tectonic map of the northern part of the Danube Basin and adjacent mountains

The Upper Miocene sedimentary sequence begins with a Pannonian deltaic to shallow lake environment (the Ivánka Fm.). This Pannonian sequence is covered by the Upper Pannonian to Pontian freshwater environment of ephemeral lakes with lignite (the Beladice Fm.). In the lower part of this formation, the Hlavina Mb. occurs. It is characterized by carbonate deposition, of travertine type. Pliocene deposition starts with alluvial, fluvial and lacustrine environments (the Volkovce Fm., Kolárovo Fm. and Syslie vŕšky Mb.); a Mastodon fauna at MN15–MN17 constrains on age of Early to Mid Pliocene (Holec *et al*., 2002). Similar conclusions as to the age of this Mastodon fauna were published by Gasparik (2001) and by Tóth (2006). Above these formations, with a erosive contact, lies a red bed unit of Early Pleistocene age (the Lukáčovce Mb.).

These sedimentary sequences mainly represent tectonically inverted formations of the northern margin of the Danube Basin (the Volkovce and Kolárovo Fms.). The formations were deposited in alluvial and fluvial environments of meandering channel belts encased within overbank fines (Kováč *et al*., 2006). Palaeotransport direction and grain-size analysis suggest that the southern part of the Považský Inovec Mts. was buried at this time, and not elevated as today. At the Pliocene–Pleistocene boundary, the sedimentary environment of the northern Danube Basin changed and a distinct erosive surface developed. This event was closely related to an increase in tectonic activity and a change in the source of clastic material (Joniak *et al*., 2001). The southeastern slopes of the Považský Inovec Mts. were gradually elevated and the Lower Pleistocene alluvial fans of the Lukáčovce Mb. were deposited (Šarinová and Maglay, 2002; Kováč *et al*., 2006). The sedimentary record of the entire area studied is generally covered by Quaternary loessic deposits, predominantly of Würmian age.

The structural analysis was carried out in disturbed Pliocene, Pleistocene and Holocene strata (*cf*. Hók *et al*., 1998; Joniak *et al*., 2001; Kováč *et al*., 2006) within the basin, while field measurements were also carried out on deposits presently

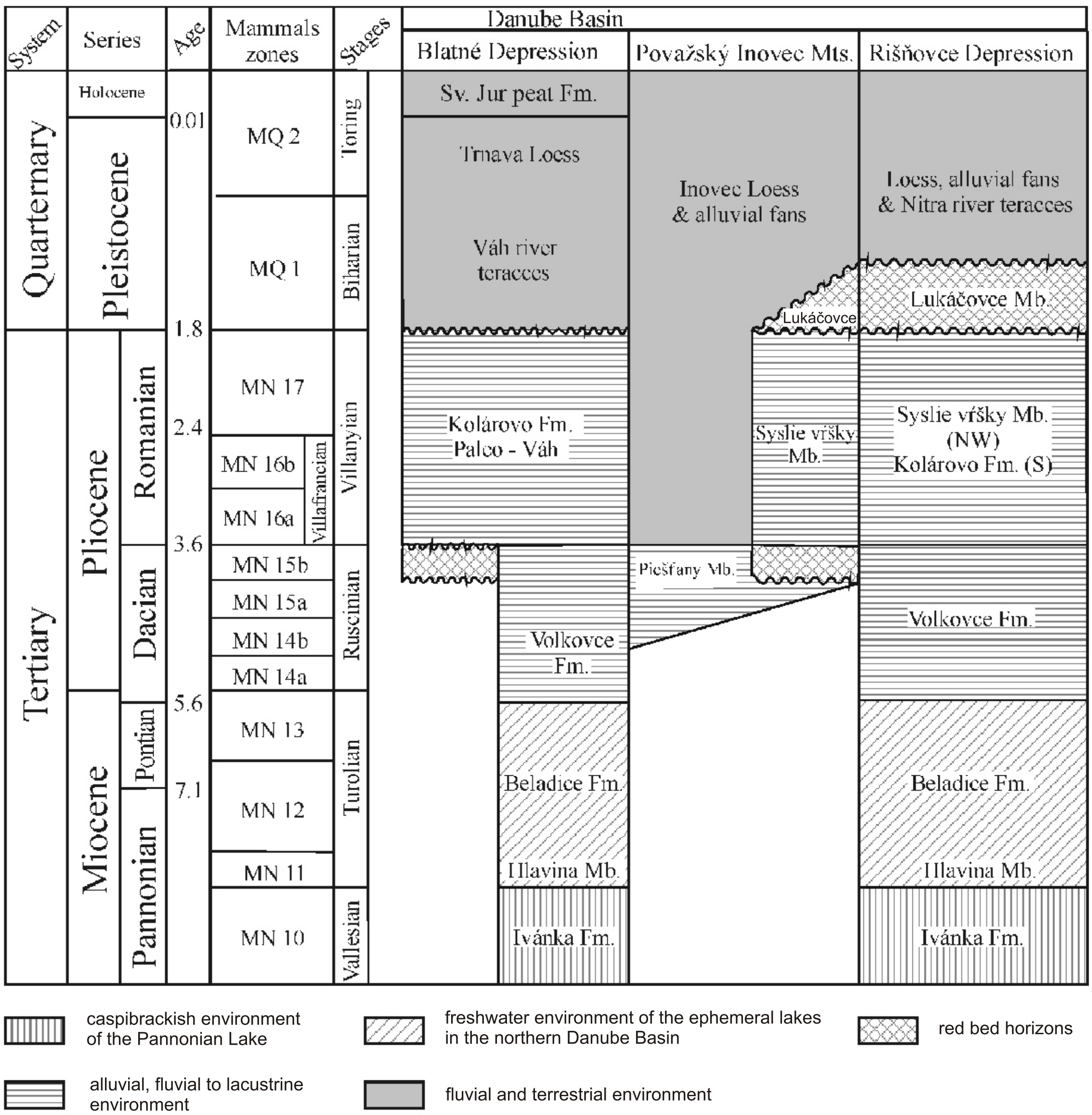


Fig. 3. The Pliocene and Pleistocene sedimentary formations of the northern part of the Danube Basin (according to Joniak *et al*., 2001; Holec *et al*., 2002; Kováč *et al*., 2006)

incorporated into the exhumed young horst structures, occurring mainly in the Považský Inovec Mts.

METHODS

The structural research was directed towards determining the palaeostress field orientation during the neotectonic interval. The standard procedures used for analysis of fault-slip data and palaeostress reconstruction are well-established (Angelier, 1979, 1989, 1990, 1994; Etchecopar *et al*., 1981; Michael, 1984; Célérier, 1995; Célérier and Séranne, 2001; Delvaux and Sperner, 2003). In this study, we used two methods of palaeostress tensor computation from fault slip data:

— the inversion method (Angelier *et al*., 1982; Angelier, 1984, 1994) which has the ability to separate heterogeneous fault populations;

— in the case of small sets of conjugate faults, the Dihedra method was applied (Angelier and Mechler, 1977).

The inversion method calculates the reduced tensor which shows palaeostress fields that are defined by the S_1 or σ_1 (principal maximum compression axis), S_2 or σ_2 (principal intermediate compressional axis) and S_3 or σ_3 (principal minimum compressional axis. The ratio between these axes defines the shape of the stress ellipsoid and is expressed by the R or Φ parameter (for further details see Angelier, 1984, 1994). Fault slip datasets are shown in stereograms of fault planes with observed slip striae and histograms of slip-shear angles (the Lambert equiplanar projection, lower hemisphere).

The results of the Dihedra method are derived from fault planes and slip lines and include histograms of counting deviations. The reduced stress tensors were computed by the *TENSOR* software package developed by Damien Delvaux (Delvaux, 1993; Delvaux and Sperner, 2003).

The results are arranged in figures according to the relative chronology of the stress stages and explained below in this text. Parameters of the reduced stress tensors are shown in Table 1. We discuss two aspects of the results obtained; a quality assessment, according to the World Stress Map standards (Sperner *et al*., 2003) and the numerical expression of the stress regime as the Stress Regime Index for regional comparisons and mapping (Delvaux and Sperner, 2003). In the World Stress Map, the quality ranges from A (best) to E (worst), and it is predominantly determined as a function of at least two criteria (number of fault slips with fluctuation of the whole dataset; *cf*. Sperner *et al*., 2003). Orientations of the stress axes (S_H — maximum horizontal compression axis, S_h — minimum horizontal compression axis, and S_v — vertical axis) and the stress regime ($R' = 0–1$ for extensional regime, 1–2 for strike-slip regime, and 2–3 for compressive regimes) are fully described by the S_H azimuth (as defined in the World Stress Map by Müller *et al*., 2000) and by the average stress regime index R' as defined by Delvaux *et al*. (1997).

RESULTS OF FAULT SLIP ANALYSIS AND STRESS INTERPRETATION

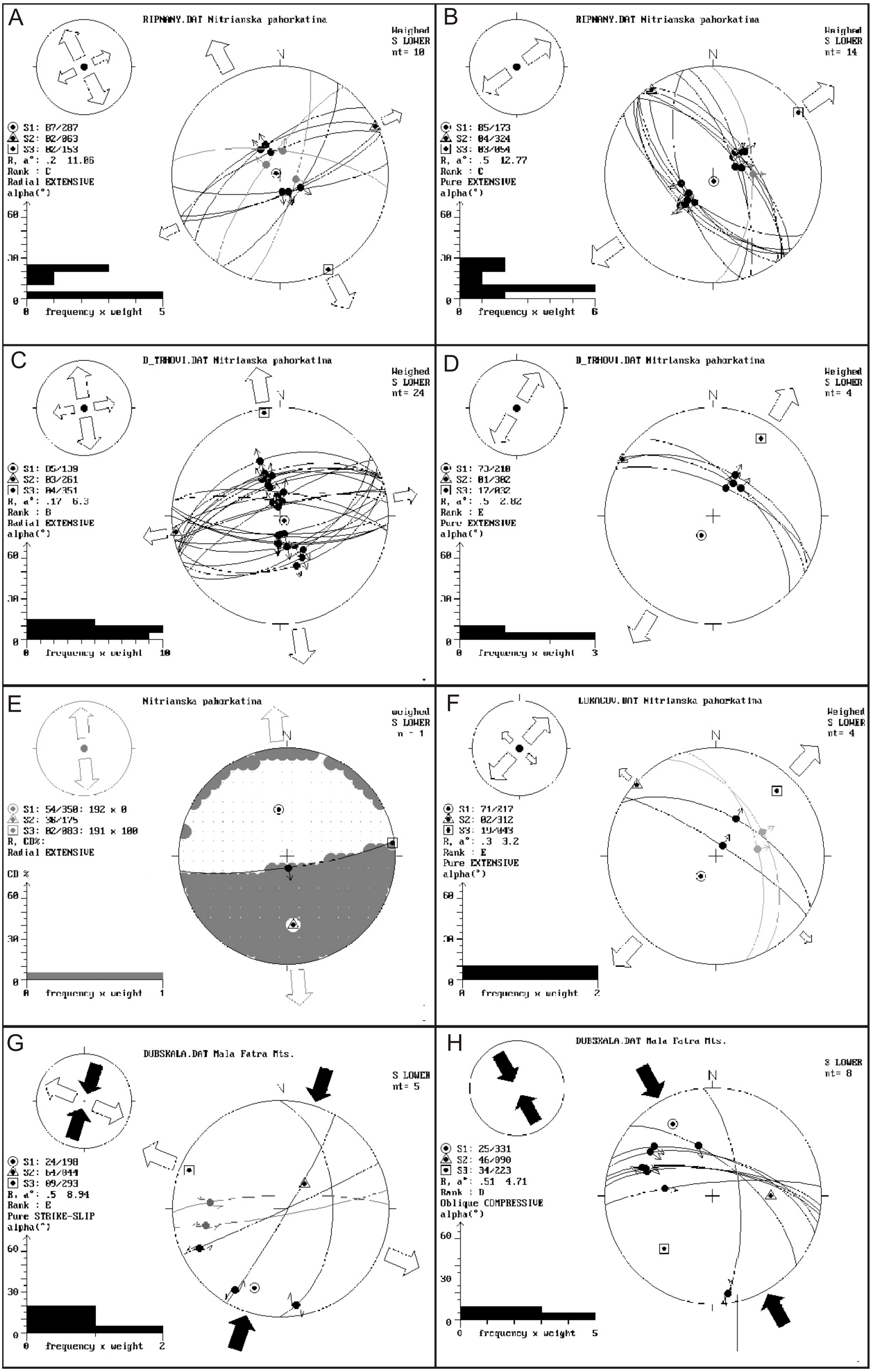
The research was carried out in the western part of the Tatric core mountain zone which has a basin and range structure. This structural pattern was formed during the Neogene, as constrained by apatite fission track data (Kováč *et al*., 1994; Danišík *et al*., 2004; Kráľ in Hók *et al*., 2005) and also by the sedimentation history of surrounding depressions (Kováč *et al*., 1994; Šarinová and Maglay, 2002; Kováč *et al*., 2006). Structural analysis of brittle deformation was carried out for reconstruction of the stress field that affected Pliocene and Quaternary deposits. We found only a few sites which were suitable for structural analysis (Figs. 1 and 2). In the unconsolidated Pliocene and Quaternary deposits slickenside lineations on fault planes are poorly preserved. In our study, we have taken into account well-preserved fault planes, though these are very rare in the Western Carpathians.

Table 1

Palaeostress tensors from fault slip data

Site	Latitude	Longitude	Description	n	n_T	S_1	S_2	S_3	R	α	Q	R'
Veľké Ripňany sandpit site												
PI-VR1	N48°30.085’	E017°57.05’	covered by the Lukáčovce Member	10	25	287/87	063/02	153/02	0.2	11.06	C	0.2
PI-VR2	N48°30.085’	E017°57.05’	cut Quaternary formations	14	25	173/85	324/04	054/03	0.5	12.77	C	0.5
Dolné Trhovište sandpit site												
PI-DT1	N48°26.078’	E017°55.386’	covered by the Würmian loess	24	28	139/85	261/03	351/04	0.17	6.3	B	0.17
PI-DT2	N48°26.078’	E017°55.386’	cut Quaternary formations	4	28	210/73	302/01	032/17	0.5	2.82	E	0.5
Lukáčovce sandpit site												
PI-LU1	N48°24.443’	E017°55.707’	covered by the Lukáčovce Member	1	5	350/54	175/36	083/02	–	–	E	–
PI-LU2	N48°24.443’	E017°55.707’	cut Quaternary formations	4	5	217/71	312/02	043/19	0.3	3.2	E	0.3
Horné Otrokovce quarry site												
PI-HO1	N48°29.642’	E017°52.482’	covered by the Würmian loess	2	2	355/78	252/03	161/12	–	–	E	–
Tepličky site												
PI-TE2	N48°28.383’	E17°50.800’	cut Quaternary formations	1	1	216/60	125/00	035/30	–	–	E	–
Ducové “Old quarry” site												
PI-DO1	N48°37.466’	E17°56.233’	covered by the Lukáčovce Member	8	13	301/85	082/03	172/04	0.5	11.23	D	0.5
PI-DO2	N48°37.466’	E17°56.233’	cut Quaternary formations	4	13	138/82	311/08	041/01	0.46	11.02	E	0.46
Dubná Skala site												
MF-DS1	N49°07.917’	E18°53.450’	cut Pliocene formations	5	13	198/24	044/64	293/09	0.5	8.94	E	0.5
MF-DS2	N49°07.917’	E18°53.450’	cut Pliocene formations and MF-DS1 faults	8	13	331/25	090/46	226/34	0.51	4.71	D	0.51

Site — code of locality; Description — additional important comment; n — number of faults used for stress tensor determination; n_T — total number of fault data measured; S_1, S_2 and S_3 — azimuth and plunge of principal stress axes; R — stress ratio ($S_2–S_3/S_1–S_3$); α — mean slip deviation (in °); Q — quality ranking scheme according to the World Stress Map Project (Sperner *et al*., 2003); R' — tensor type index as defined in the text


A
RIPNANY.DAT Nitrianska pahorkatina
Weighed
S LOWER
nt= 10
N
S1: 87/287
S2: 02/063
S3: 02/153
R, a°: .2 11.06
Rank : C
Radial EXTENSIVE
alpha(°)
60
30
0
0 frequency x weight 5
B
RIPNANY.DAT Nitrianska pahorkatina
Weighed
S LOWER
nt= 14
N
S1: 85/173
S2: 04/324
S3: 03/054
R, a°: .5 12.77
Rank : C
Pure EXTENSIVE
alpha(°)
60
30
0
0 frequency x weight 6
C
D_TRHOVI.DAT Nitrianska pahorkatina
Weighed
S LOWER
nt= 24
N
S1: 05/139
S2: 03/261
S3: 04/351
R, a°: .17 6.3
Rank : B
Radial EXTENSIVE
alpha(°)
60
30
0
0 frequency x weight 10
D
D_TRHOVI.DAT Nitrianska pahorkatina
Weighed
S LOWER
nt= 4
N
S1: 73/210
S2: 01/302
S3: 17/032
R, a°: .5 2.82
Rank : E
Pure EXTENSIVE
alpha(°)
60
30
0
0 frequency x weight 3
E
Nitrianska pahorkatina
weighed
S LOWER
n = 1
N
S1: 54/350: 192 x 0
S2: 36/175
S3: 02/083: 191 x 100
R, CD%:
Radial EXTENSIVE
CD %
60
30
0
0 frequency x weight 1
F
LUKACOV.DAT Nitrianska pahorkatina
Weighed
S LOWER
nt= 4
N
S1: 71/217
S2: 02/312
S3: 19/043
R, a°: .3 3.2
Rank : E
Pure EXTENSIVE
alpha(°)
60
30
0
0 frequency x weight 2
G
DUBSKALA.DAT Mala Fatra Mts.
S LOWER
nt= 5
N
S1: 24/198
S2: 64/044
S3: 09/293
R, a°: .5 8.94
Rank : E
Pure STRIKE-SLIP
alpha(°)
60
30
0
0 frequency x weight 2
H
DUBSKALA.DAT Mala Fatra Mts.
S LOWER
nt= 8
N
S1: 25/331
S2: 46/090
S3: 34/223
R, a°: .51 4.71
Rank : D
Oblique COMPRESSIVE
alpha(°)
60
30
0
0 frequency x weight 5

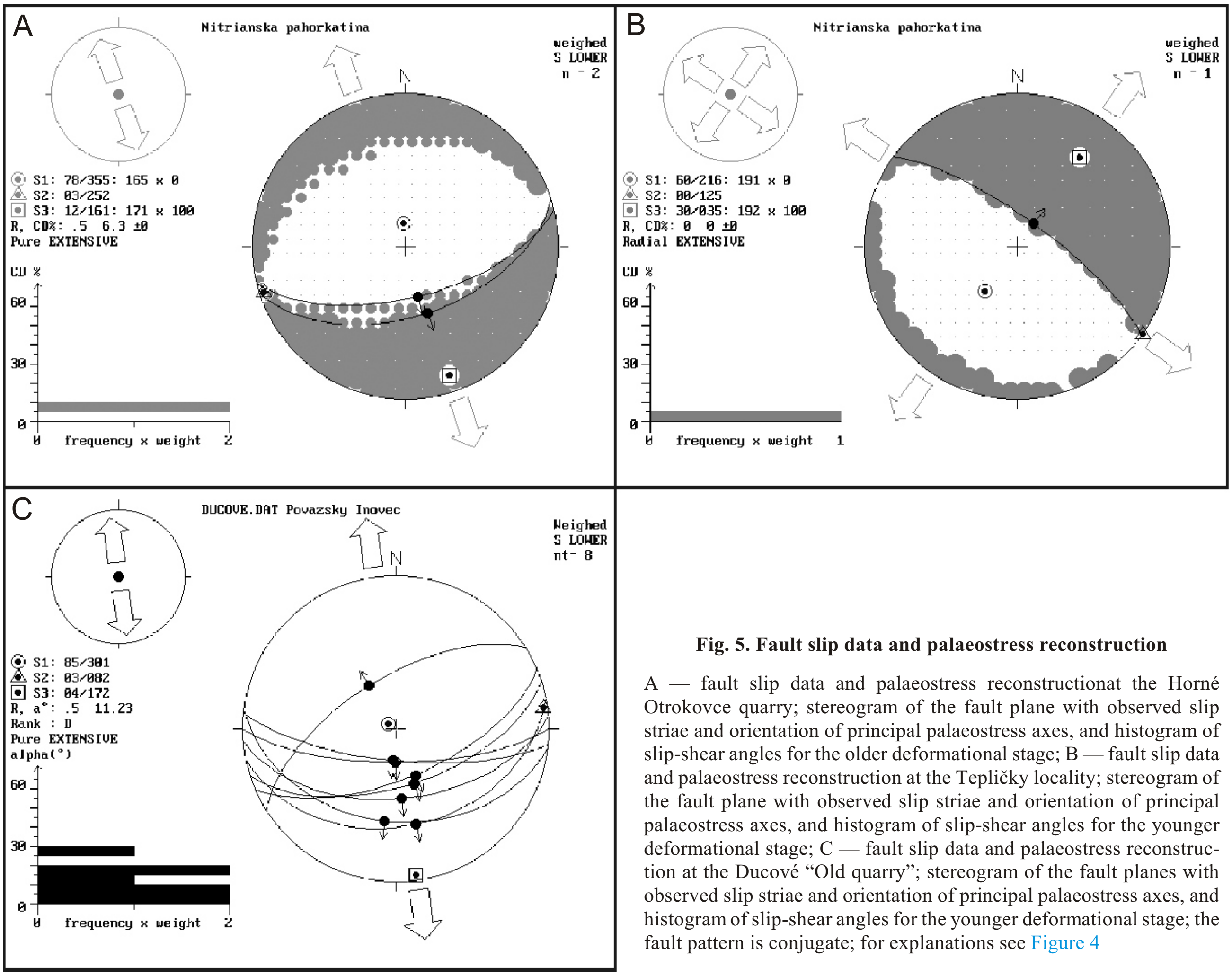


Fig. 5. Fault slip data and palaeostress reconstruction

A — fault slip data and palaeostress reconstructionat the Horné Otrokovce quarry; stereogram of the fault plane with observed slip striae and orientation of principal palaeostress axes, and histogram of slip-shear angles for the older deformational stage; B — fault slip data and palaeostress reconstruction at the Tepličky locality; stereogram of the fault plane with observed slip striae and orientation of principal palaeostress axes, and histogram of slip-shear angles for the younger deformational stage; C — fault slip data and palaeostress reconstruction at the Ducové "Old quarry"; stereogram of the fault planes with observed slip striae and orientation of principal palaeostress axes, and histogram of slip-shear angles for the younger deformational stage; the fault pattern is conjugate; for explanations see Figure 4

Twenty five fault planes were found at the **Veľké Ripňany** locality (Figs. 4A, B and 6A, B) which is situated 2.5 km north-west of Veľké Ripňany village (for more precise localisation see GPS information in Table 1). Sediments are faulted with offsets ranging from 2 to 130 cm. The faults strike almost perpendicular to the NE–SW running Majcichov fault which bounds the Považský Inovec Mts. to the south-east (Fig. 2). Two generations of faults were measured. Faults of the older generation cut the Pliocene Syslie vŕšky Mb. but do not continue into the younger strata consisting of the Lower Pleistocene Lukáčovce Member. The younger fault generation cuts both sedimentary sequences, and also the Würmian loess. The older, Upper Pliocene set of conjugate normal faults documents NNW–SSE pure tension (Fig. 4A). The younger, Quaternary set of faults shows tension in a NE–SW direction (Fig. 4B). The data gained support a change in the principal stress axes orientation at the Pliocene–Pleistocene boundary, of approximately 70°. The S_1 stress axis is nearly vertical.

In the next exposure, the **Dolné Trhovište sandpit** (1.75 km south-east of Dolné Trhovište village, Fig. 2) twenty seven faults with offsets from several cm to 50 cm were measured (Fig. 6C, D). Two genetic sets of normal faults can be distinguished. (1) Older faults, observed only in the Pliocene Volkovce Formation die out at the base of the Pleistocene. This set is represented by 23 conjugate faults creating a characteristic horst and graben pattern (Fig. 4C). The ENE–WSW striking normal faults indicate a vertical position of the S_1 stress axis and consequently point to NNW–SSE-directed extension.

Fig. 4. Fault slip data and palaeostress reconstruction

All stereograms have Lambert lower hemisphere projections. Tectonic regime is expressed by relative values of principal stress with R-ratio ($R = S_2–S_3/S_1–S_3$) and standard deviations characterized by the "a°" value are situated on the left side of the stereograms. Graph of slip deviations (a° = y axis) versus frequency of weight (x axis) of the fault slip data is located on the lower left side of the stereograms. **A** — stereogram of the fault planes with observed slip striae and orientation of principal palaeostress axes, and histogram of slip-shear angles for the older deformational stage at the Veľké Ripňany site; **B** — stereogram of the fault planes with observed slip striae and orientation of principal palaeostress axes, and histogram of slip-shear angles for the younger deformational stage at the Veľké Ripňany site; the fault pattern is conjugate; **C** — older deformational stage at the Dolné Trhovište site; **D** — younger deformational stage at the Dolné Trhovište site; **E** — older deformational stage at the Lukáčovce site; **F** — younger deformational stage at the Lukáčovce site; **G** — older deformational stage at the Dubná Skala site; **H** — younger deformational stage at the Dubná Skala site

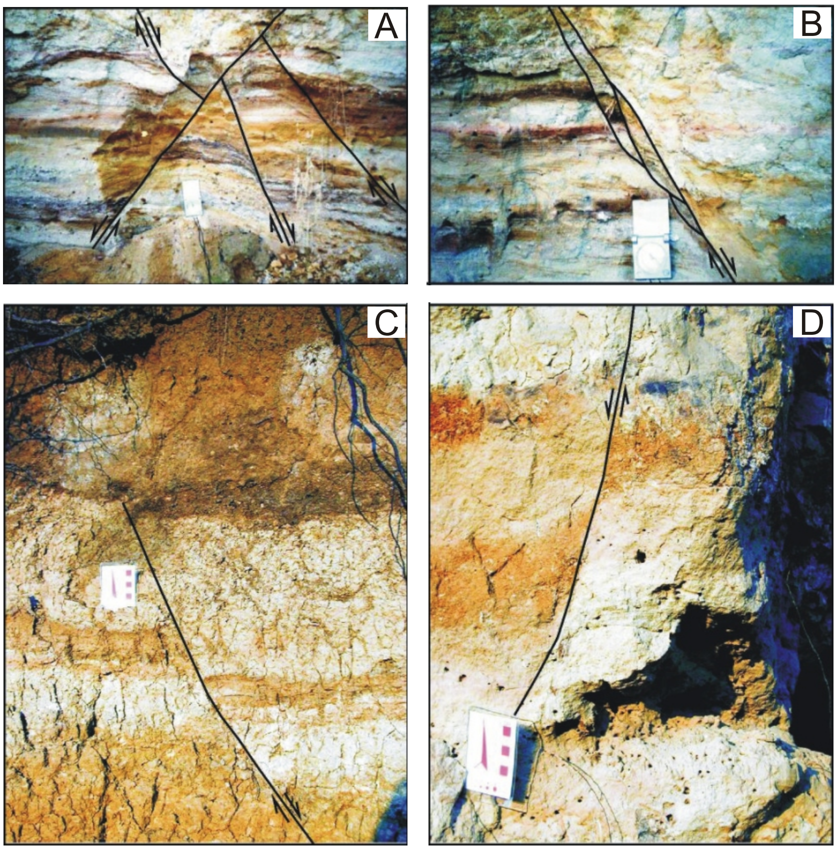


Fig. 6. Field photos of the fault structures measured

The Veľké Ripňany locality with observed conjugate normal fault system and drag folds (A) and a complex normal fault with extensional duplex structures (B); the Dolné Trhovište locality with normal faults in the loessic sediments (C and D)

(2) The subordinate set is represented by 4 normal faults dipping at less than ~60 degrees towards the NE, which indicates extension in a SW–NE direction. The faults are restricted to the Pleistocene (Lukáčovce Fm.) (Fig. 4D).

The next locality with faulted Pliocene and Quaternary deposits is situated 1 km north-west of Lukáčovce village. Five normal faults were measured. One fault cuts the older Pliocene strata composed of the Volkovce Fm. and does not continue into the younger Lukáčovce Fm. This fault indicates N–S-directed extension (Fig. 4E). The remaining four faults cut the entire sedimentary sequence below the Holocene colluvium. The NE-dipping faults indicates that is vertical and reflect NE–SW-directed extension (Fig. 4F).

The **Horné Otrokovce** abandoned quarry with dark dolomite of the Fatric Unit is situated 100 m north-west of Horné Otrokovce village. This dolomite is covered by tectonically unaffected Quaternary debris and by Würmian loessic deposits (Joniak *et al*., 2001). At this locality, two faults were observed which were probably activated during the Late Pliocene, as they have a similar pattern to the faults measured at the Veľké Ripňany and Dolné Trhovište quarries. The strike of the faults is ENE–WSW, with dips towards the south. These faults were activated in the NNW–SSE oriented extension (Fig. 5A).

The **Tepličky** locality is situated in a deep gully 1200 m north-west of Tepličky village. The lower part of this exposure is formed of sand and gravel. These deposits belong to the Syslie vŕšky Mb. The upper part contains authochtonous and redeposited Würmian loessic material, and overlies the Syslie vŕšky Mb. At this locality, one fault structure with a normal slip of 60 cm was observed. This fault strikes to the NW–SE, where the NE block subsided and the fault was most probably activated in an NE–SW extensional tectonic regime during the Upper Pleistocene to Holocene interval (Fig. 5B).

The **Ducové "Old quarry"** is situated south of the village of Ducové (Fig. 2). The Middle Triassic dolomite of the Hronicum nappe is exposed in this quarry. This dolomite is covered by poorly-sorted debris and a small Pleistocene alluvial fan. Thirteen faults were analysed at this locality (Fig. 5C) and five of these did not continue into the Quaternary deposits. The faults were generally observed to have two directions. The first fault generation is represented by those faults that do not continue into the Quaternary succession. Their age cannot be determined more exactly than "pre-Quaternary". These faults were generated during the imposition of pure NE–SW to E–W tension. Thus, these faults are not described in this paper. The second and neotectonically important fault generation was developed during the Upper Pleistocene to Holocene because these faults have disturbed Würmian loessic deposits. The Quaternary deformation is characterized by N–S tension which has a slightly different orientation to that seen at the previous localities (Fig. 5C).

The **Dubná skala** locality is an abandoned quarry which is situated approximately 5 km NW from Martin town on the left side of the Váh River (Fig. 1). Freshwater limestones, travertines and sandy clays to clays are present in the base of the quarry. According to biostratigraphical evidence, this rock sequence belongs to the Pliocene Dubná skala Formation (Hók *et al*., 1998; Rakús and Hók, 2002).

Thirteen faults were observed and measured at this locality (Fig. 4G, H). These faults were activated predominantly as transpressional strike-slips with a general E–W-strike. A polygenetic fault population was present, which can be divided into two generations. The older generation comprises five conjugate fault structures which are oriented towards the WSW–ENE and NNE–SSW (Fig. 4G). These strike-slip faults were developed during NNE–SSW compression and tension perpendicular to this. The next, younger, homogeneous fault population was activated under a strike-slip tectonic regime. The principal maximum stress axis S_1 was computed trend NW–SE, and the principal minimum stress axis S_3 to be NE–SW (Fig. 4H). The chronology of both fault sets was deduced on the basis of the cross-cutting relations (Table 1).

EVOLUTION OF STRESS FIELD SINCE THE PLIOCENE TO QUATERNARY — A DISCUSSION

The recent stress field is often deduced from earthquake focal mechanisms, borehole break-out analysis and modelling of crustal processes (Gerner, 1992; Jarosiński, 1998, 2005;

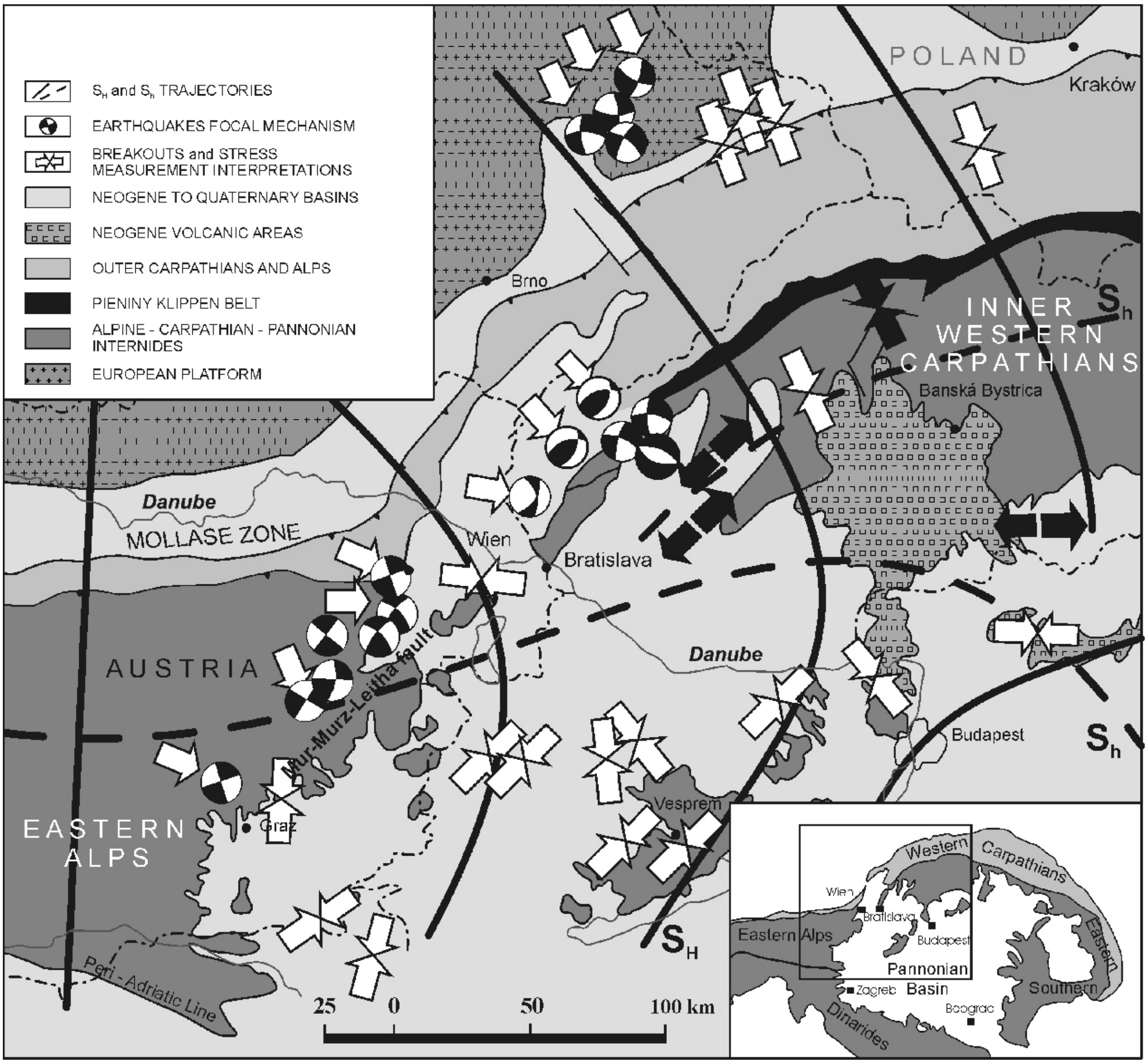


Fig. 7. Simplified map of the Alpine–Carpathian–Pannonian junction area with the interpreted trajectories of recent horizontal stress S_H and S_h

Compiled from structural measurements, interpretation of the focal mechanism solution and from borehole breakout analysis (according to Peška, 1992; Gerner, 1992; Pospíšil *et al*., 1992; Labák *et al*., 1997; Jarosiński, 1998, 2005; Reinecker and Lenhardt, 1999; Gerner *et al*., 1999; Hók *et al*., 2000; Havíř and Stráník, 2003; Havíř, 2004) and own dataset demonstrated by black arrows

Gerner *et al*., 1999; Bada *et al*., 2001). Structural measurements of fault slip data in Pliocene and Quaternary deposits have, by contrast, rarely been made.

Measurements on 87 faults in Pliocene and Quaternary strata permit reconstruction of the palaeostress field evolution in the western part of the Central Western Carpathians. The fault slip analysis and stress reconstruction allowed recognition of two stress phases during the Pliocene to Quaternary interval. The Pliocene stress field is characterized by NNW–SSE tension and a sub-vertical orientation of the principal maximum stress axis. The normal faults are predominantly oriented in an E–W or NE–SW direction forming conjugate sets (Figs. 4A, C, E, G and 5A, C). The Pliocene palaeostress field had a stable direction with small fluctuations seen at individual localities (standard deviation $\alpha < 20°$).

At the Pliocene–Quaternary boundary in the western part of the Western Carpathians the direction of extension changed from NNW–SSE to NE–SW. This change is documented by different relationship between faults observed in the Pliocene and Pleistocene sediments.

The Quaternary stress field of NE–SW tension (S_h) is oriented parallel to the Western Carpathian range. This tectonic stress field was observed at several localities (Figs. 4B, D, F, H and 5B). Standard deviation of the principal stress axis orientations is 15°. A similar Quaternary stress field was supposed by Marko *et al*. (1995) and Marko and Kováč (1996) in the Alpine–Carpathian transition zone and by (Hók *et al*., 1995) in the Horná Nitra Depression. The fault-slip data of these authors were collected from rocks older than Pliocene.

Borehole break-out and earthquake focal mechanism analysis indicate NW–SE oriented S_H compression in the Bohemian Massif and in the western part of the Outer Western Carpathians (e.g. Peška, 1992; Jarosiński, 1998, 2005; Havíř and Stráník, 2003; Havíř, 2004). The compression is generally perpendicular to the front of the Outer Western Carpathians (Fig. 7).

A compressive tectonic regime prevailed in the Outer Western Carpathians and in the adjacent Bohemian Massif. A strike-slip tectonic regime had been determined along the Pieniny Klippen Belt and the Mur–Murz–Leitha fault system (Labák *et al*., 1997; Reinecker and Lenhardt, 1999; Fig. 7).

The dominant extensional tectonic regime in the Central Western Carpathians can be explained as hinterland extension caused by continuing convergence of the ALCAPA with the European platform (*cf*. Csontos *et al*., 1991; Gerner, 1992; Peška, 1992; Pospíšil *et al*., 1992; Fodor *et al*., 1999; Hók *et al*., 2000).

A NE–SW orientation of S_H has been documented in the southern part of the Danube Basin (Fig. 7) and the Transdanubian Range (Gerner, 1992; Gerner *et al*., 1999; Fodor *et al*., 2005). It is most probably the result of interaction between the ALCAPA and the Adria microplate pushing to the NE (e.g. Bada *et al*., 1999; Gerner *et al*., 1999).

CONCLUSIONS

This study has further constrained the development of the stress fields and the shape of S_H and S_h trajectories in the Alpine–Carpathian–Pannonian junction area during the Pliocene and Quaternary. The analysis of fault slip data indicated extensional tectonic regimes in the western part of the Central Western Carpathians.

Two main extensional phases can be distinguished: the older, represented by a Pliocene fault population, was generated during NNW–SSE oriented extension, and consists predominantly of normal faults. The younger, Quaternary fault population indicates origin during NE–SW oriented extension. The result of palaeostress analysis clearly showed a 70° change of stress tensor orientation at the Pliocene–Pleistocene boundary.

This study has shown that the western part of the Central Western Carpathians and the broader region around the northern Danube Basin area have recently undergone NE–SW to NNE–SSW directed extension.

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