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Present-day stress field and tectonic inversion in the Pannonian basin

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Abstract

This paper presents a latest compilation of data on the present-day stress pattern in the Pannonian basin, and its tectonic environment, the Alpine–Dinaric orogens. Extensional formation of the basin system commenced in the early Miocene, whereas its structural reactivation, in the form of gradual basin inversion, has been taking place since Pliocene to recent times. Reconstructed compression and associated horizontal contraction are mainly governed by the convergence between Adria and its buffer, the Alpine belt of orogens. The resulting contemporaneous stress field exhibits important lateral variation resulting in a complex pattern of ongoing tectonic activity. In the Friuli zone of the Southern Alps, where thrust faulting prevails, compression is orthogonal to the strike of the mountain belt. More to the southeast, intense contraction is combined with active strike–slip faulting constituting the dextral Dinaric transpressional corridor. Stresses are transferred far from Adria into the Pannonian basin, and the dominant style of deformation gradually changes from pure contraction through transpression to strike–slip faulting. The importance of late-stage inversion in the Pannonian basin is interpreted in a more general context of structural reactivation of back-arc basins where the sources of compression driving basin inversion are also identified and discussed. The state of recent stress and deformation in the Pannonian basin, particularly in its western and southern part, is governed by the complex interaction of plate boundary and intra-plate forces. The counterclockwise rotation and north-northeast-directed indentation of the Adriatic microplate appears to be of key importance as the dominant source of compression ("Adria-push"). Intra-plate stress sources, such as buoyancy forces associated with an elevated topography, and crustal as well as lithospheric inhomogeneities can also play essential, yet rather local role.

Keywords: stress field; basin inversion; neotectonics; Pannonian basin

1. Introduction

The World Stress Map Project (WSMP) has been running for two decades, providing excellent service for both the academic and industrial community. As present-day stress field governs ongoing deformation in the lithosphere, the reconstruction of the stress pattern helps the understanding and quantification of active tectonic processes. First, the concept of regionally uniform stress orientations and magnitudes was established, and the first-order stress provinces were defined on a global (c.f. Zoback, 1992) as well as European (c.f. Müller et al., 1992) scale. Parallel with the significant

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increase in the number of stress indicators, the spatial resolution of the European stress map has improved considerably. It allowed the recognition of short-scale lateral changes of stress regimes and the vertical variation of stress directions (e.g. Rebaï et al., 1992; Müller et al., 1997; Jarosiński, 1998; Mariucci et al., 2002; Sperner et al., 2003; Kastrup et al., 2004; Jarosiński, 2005). To explain the profound changes in the recent stress field, a link had to be found between forces acting at plate boundaries or arising in intra-plate setting, and the resulting deformation pattern. Efforts resulted in a number of modelling studies (e.g. Gölke and Coblentz, 1996; Meijer and Wortel, 1997; Muñoz Martin et al., 1998; Ragg et al., 1999; Bada et al., 2001; Heidbach and Drewes, 2003; Heidbach, 2005; Jarosiński et al., 2006) establishing a reliable neotectonic framework for interpreting the available stress data.

The WSMP data base (see latest data release in Reinecker et al., 2005) has clearly shown that Europe represents a region of complicated contemporaneous stress pattern (Fig. 1). Particular complexities exist in the broad bend of Europe–Africa collision. The Mediterranean system of subduction and collision zones, and related back-arc basins within the convergence zone between the African (Nubian) and Eurasian plates represent a good example of short-scale stress perturbations. The changes of stress directions occur over a distance that is comparable to or even smaller than the thickness of the lithosphere. In the central Mediterranean, where the Adriatic microplate is indenting the Alpine–Dinaric orogen, active compression or, where convergence is oblique, transpression takes place at the edges of Adria. On the other hand, behind subduction zones lithospheric extension occurs in the

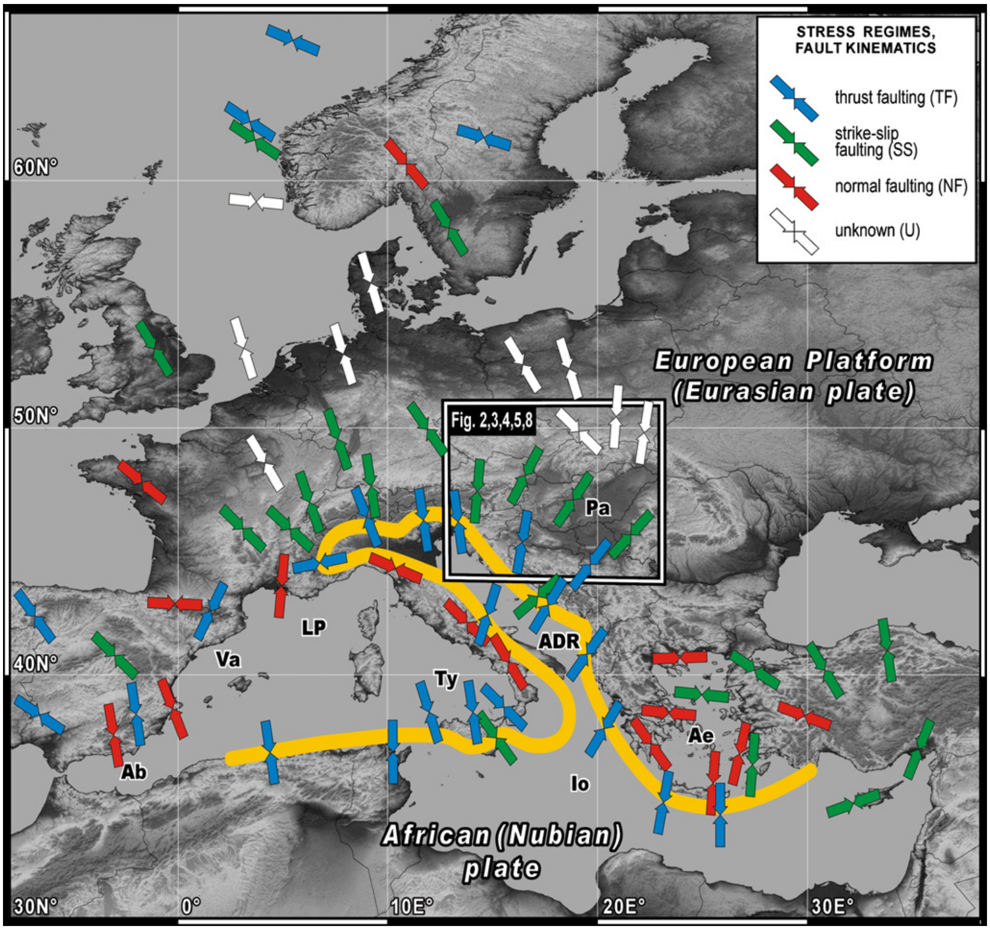

Fig. 1. Simplified pattern of the present-day maximum horizontal stress directions and tectonic regimes in Europe, generalised from the World Stress Map Project database (after Reinecker et al., 2005). Thick yellow line indicates the approximate boundary of the Adriatic microplate or promontory (ADR). Insert box shows the location of the study area in the Pannonian region. Key to abbreviations: Ab — Alboran Sea, Ae — Aegean Sea, Io — Ionian Sea, LP — Liguro–Provençal basin, Pa — Pannonian basin, Ty — Tyrrhenian basin, Va — Valencia trough.

Tyrrhenian, Aegean and Alboran back-arc domains (Fig. 1).

Due to the availability of good quality stress data, the Pannonian basin system is an area suitable to study the short-scale variation of the modern stress field, which is manifested in the changes of both the orientation of the stress axis and the tectonic regimes. Unlike other Mediterranean back-arc basins, the Intra-Carpathian area is characterised mainly by strike–slip and thrust faulting stress regimes (Fig. 1). The Pannonian basin has reached an advanced stage of evolution, and its structural inversion has been taking place for the last few million years. A major change in the paleostress fields from extension, governing Miocene basin formation, to compression, controlling Pliocene to Quaternary neotectonic deformation, was recognised (c.f. Horváth and Cloetingh, 1996; Fodor et al., 1999; Bada et al., 2001, 2007; Fodor et al., 2005; Horváth et al., 2006). The concept of ongoing basin inversion was confirmed already by the first regional compilation of stress indicators for the area of the Pannonian basin and surrounding orogens (Gerner et al., 1999).

The last few years has witnessed a substantial increase in the number of stress data for the Pannonian region. A high-sensitivity seismic monitoring network, installed in the central part of the basin system in 1995 (Tóth et al., 2002a, 2005a), provides about a dozen of new focal mechanisms yearly. The network has been operating for more than a decade that permits the reconstruction of stress regimes at an unprecedented spatial resolution allowing the definition of different stress provinces. In addition, data exchange between academia and industry led to new borehole breakout analyses providing further insights in the inhomogeneities of horizontal stress directions. These data represent powerful means to constrain inversion dynamics of sedimentary basins, and to better understand active tectonic processes in the Pannonian region.

Having a stress database with ca. 450 data entries and a novel model of basin inversion developed for the Pannonian basin system (Bada et al., 2007; Cloetingh et al., 2006; Horváth et al., 2006), the purpose of this contribution is twofold. Firstly, the latest edition of the Pannonian stress database is presented showing important lateral variation of both the maximum horizontal stress directions and the reconstructed stress regimes. Secondly, the present-day stress field is discussed in the light of the neotectonics of the region, whereas basin inversion is analysed in the context of stress propagation in the upper, elasto-brittle part of the Pannonian lithosphere. The focus of the study is on the Pannonian basin and its vicinity in the west and south, which are the Eastern and Southern Alps and the Dinarides, respectively (see insert box in Fig. 1). This region includes tectonic units with several common or strongly interrelated elements in their Miocene to present-day structural evolution. Thus, it seems useful first to overview the neotectonic habitat of the study area. This is followed by the presentation of the stress data. The paper concludes with a discussion on the principal features of basin inversion and active tectonics in the Pannonian basin, and the origin of the reconstructed present-day stress field.

2. Structural setting and neotectonic habitat

The neotectonic period in the Pannonian basin is characterised by a Late Pliocene through Quaternary phase of inversion. The build-up of lithospheric compression is considered responsible for horizontal shortening, an anomalous uplift and subsidence history, and repeated fault reactivation manifested in the intraplate seismicity of the region. Data indicate a strong spatial and temporal variation of the stress and strain fields during late-stage basin evolution. Accordingly, the related structural styles of basin inversion vary both in time and space. Inferences on the neotectonic habitat of the Pannonian domain provided a key to develop a conceptual model for the structural reactivation of back-arc basins in an overall compressional settings (Cloetingh et al., 2006; Horváth et al., 2006).

Basin formation (rifting) in the Intra-Carpathian area started in the early Miocene, whereas its deformation has been taking place in the form of structural inversion since latest Miocene–early Pliocene times. In this context, the Pannonian basin has reached a more advanced stage of development with respect to other Mediterranean back-arc basins. Inversion is related to changes in the regional stress field, from tension controlling basin formation and lithospheric extension, to compression resulting in fault reactivation, an increased level of active faulting and seismicity, and the overall contraction leading to folding of the lithosphere (c.f. Horváth and Cloetingh, 1996). Earthquake data indicate that brittle deformation is mainly concentrated near the contact zone between rigid Adria and its more deformable buffer, the Alpine–Dinarides orogen (Tóth et al., 2002a). Stresses and deformation are, however, transferred deep into the interior of the Pannonian basin resulting in a complex pattern of active tectonic processes.

Basin formation led to significant weakening of the Pannonian lithosphere, allowing subsequent deformation localised at crustal discontinuities and weakness zones originated from previous tectonic phases. This emphasises the significance of lithospheric memory, controlling the style and degree of subsequent deformation (Cloetingh and Lankreijer, 2001). The extended and hot lithosphere underlying sedimentary basins is prone to reactivation under relatively low differential stresses. Due to its low rigidity and the intra-plate compression concentrated in the thin elastic core of the crust, the region exhibits large-scale bending associated with Quaternary subsidence and uplift anomalies. Consequently, the area was interpreted as an example of irregular lithosphere folding with a wide spectrum of wavelengths (Cloetingh et al., 1999). Multi-scale folding of the Pannonian lithosphere is often manifested as short-wavelength vertical motions defining the overall morphology and landscape development (Horváth and Cloetingh, 1996; Fodor et al., 2005; Ruszkiczay-Rüdiger et al., 2005).

The sources of compression resulting in basin inversion were investigated by means of numerical modelling (Bada et al., 1998, 2001). The state of present-day stress in the Pannonian–Carpathian system, particularly in its western and southern part, is governed by various forces. The counterclockwise rotation and northward indentation of the Adriatic microplate ("Adria-push") is of fundamental importance. Superimposed intra-plate forces associated with the density variation in the lithosphere, such as changes in topography and Moho depth, can also significantly influence the stress pattern and, thus, the style of deformation. Extension in the Pannonian basin ended as a result of the complete consumption of subductable lithosphere of the European foreland and, hence, vanishing of forces driving or at least allowing stretching of the lithosphere (Horváth, 1993). The basin became completely landlocked and constrained on all sides, while continuous N-NE-directed indentation of Adria built up significant intra-plate stresses within the Pannonian lithosphere. Consequently, the stress field has been changing from extension to compression, causing positive structural inversion since Pliocene times on. A most direct evidence for ongoing contraction comes from the results

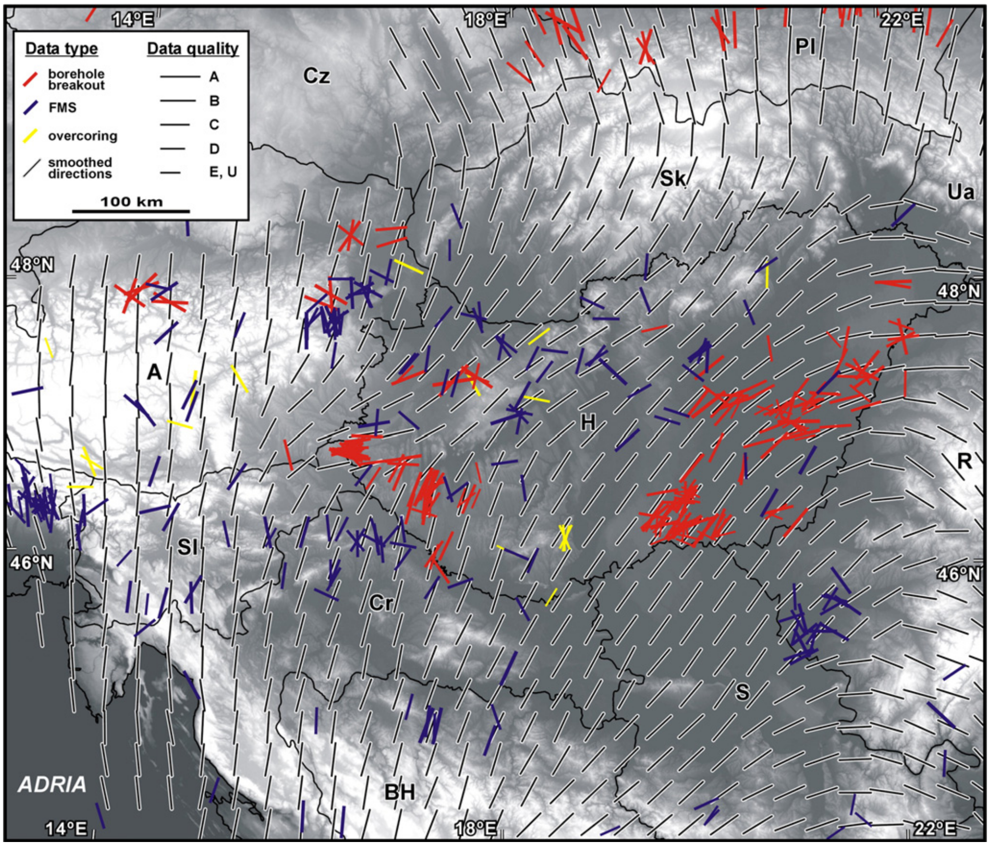

Fig. 2. Orientation of the maximum horizontal stress axis (S_{Hmax}) in the Pannonian basin and its vicinity. Data originate from earthquake focal mechanisms, borehole breakout analyses and *in situ* stress measurements. The smoothed stress pattern, indicated by a regular grid of tick marks, was obtained by applying the algorithm of Hansen and Mount (1990) on the displayed data set. FMS: focal mechanism solution. Country abbreviations: A — Austria, BH — Bosnia–Herzegovina, Cr: Croatia, Cz — Czech Republic, H — Hungary, Pl — Poland, R — Romania, S — Serbia, Sk — Slovakia, Sl — Slovenia, Ua— Ukraine.

of repeated GPS measurements (Grenerczy et al., 2005; Grenerczy and Bada, 2005). Data indicate an overall horizontal shortening around 4 ppb/yr over the entire Pannonian basin, concentrated mainly in the most actively deforming southwestern peripheries.

3. Horizontal stress directions and tectonic regimes

In this section we present the latest database of the contemporaneous stress field for the area of the Pannonian basin and its vicinity, the Alps, Dinarides and Western Carpathians orogens. The regularly updated stress database, compiled according to the conventions of the World Stress Map Project (Zoback, 1992) since the late 80's, comprises nearly 500 entries, including published (Gerner et al., 1999; Windhoffer et al., 2001) and new data from borehole breakout analysis (252 data), earthquake focal mechanism solutions (220 data), and *in situ* stress measurements (19 data). The direction of maximum horizontal stress axis (S_{Hmax}) is first investigated (Fig. 2), followed by the analysis of the stress regimes by means of earthquake focal mechanism solutions (Fig. 3). Considering the size of the study area (see Fig. 1), the amount of available data provides a coverage appropriate for high-resolution tectonic studies. The database is considered adequate for statistical analysis to determine mean horizontal stress directions and stress regimes. It is to be underlined that different data types give information from various depth ranges. The density of data is, however, inadequate to resolve the regional pattern of vertical stress deviations.

3.1. Direction of maximum horizontal stress axis

The Pannonian basin and the neighbouring orogens exhibit marked lateral variations in the maximum horizontal stress orientations (S_{Hmax}) (Fig. 2). The present-day stress pattern in this region is considerably more

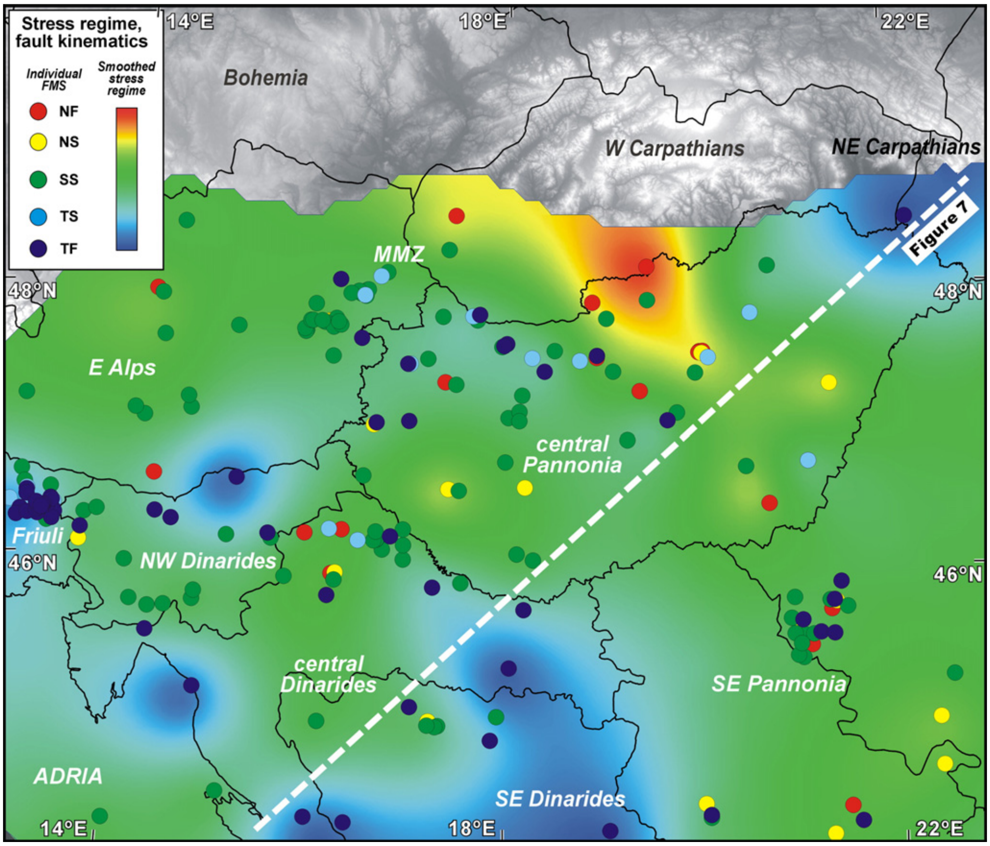

Fig. 3. Stress regimes and style of faulting in the Pannonian basin and its neighbourhood derived from earthquake focal mechanisms. Reconstructed focal mechanism solutions (FMS) are classified as normal faulting (NF), transtension (NS), strike–slip faulting (SS), transpression (TS) or reverse faulting (TF), and plotted as coloured circles. Main trends of the dominant tectonic style, calculated via the kriging interpolation of the FMS data, are shown by corresponding colouring. Dashed line indicates the location of transect in Fig. 7. MMZ — Mur–Mürz–Žilina fault zone.

heterogeneous than in the stable continental areas of the European Platform. This complexity is typical for mobile areas in orogenic belts, such as the whole Mediterranean region (Müller et al., 1992; Rebaï et al., 1992).

A most characteristic feature of the contemporaneous stress field is the gradual clockwise rotation of S_{Hmax} directions from west to east along the margins of Adria, illustrated by the smoothed stress directions (Fig. 2). The alignment of compression in the Southern Alps is NNW–SSE, becoming N–S further north in the central part of the Eastern Alps, and to the east in the Alps–Dinarides junction zone in Slovenia. At the Alps–Carpathians transition, the dominant direction of S_{Hmax} is NNE–SSW to NE–SW. Further to the south, the radial pattern of maximum horizontal stress can be traced along the Dinaric belt as S_{Hmax} orientations gradually change from NNE–SSW in Croatia, to NE–SW in Bosnia and Serbia, and then to E–W and WNW–ESE towards the Southern Carpathians in Romania.

The regional fan-like alignment of compression is also measurable in the interior of the Pannonian basin. Stress indicators, mainly borehole breakout data (Fig. 2), suggest that S_{Hmax} orientation changes from N–S to NNE–SSW in the southwestern parts to NE–SW in the east. Whereas a rather uniform stress direction prevails in the eastern Pannonian basin, the western areas show rapid lateral changes (Gerner et al., 1999; Windhoffer et al., 2001). In western Hungary, maximum horizontal stress becomes nearly E–W oriented, close to areas with NNE–SSW stress directions more to the south. This short-wavelength stress deviation is likely to be related to the lateral motion of crustal blocks squeezed out from the Eastern Alps (Bada et al., 2001), also evidenced by GPS data (Grenerczy et al., 2005). In most parts of the study area, the alignment of maximum horizontal stress closely matches the direction of ongoing crustal motions with respect to stable Europe. Differences appear only in the Southern Alps, where the NNW–SSE alignment of S_{Hmax} deviates about 20–30° from crustal motion directions derived from GPS measurements (Bada et al., 2007).

3.2. Stress regimes and style of deformation

The stress regimes and the dominant style of deformation were investigated using earthquake focal mechanisms (Gerner et al., 1999; Marović et al., 2002; Tóth et al., 2000, 2001, 2002a,b, 2003, 2004, 2005b, 2006 and references therein). Fault plane solutions yield the pressure (P) and tension (T) axes of maximum shortening and extension, respectively, and the intermediate B axis perpendicular to both P and T axes. According to Anderson (1951), the stress regime determines the dominant style of faulting through the orientation of the principal stress axes with respect to the horizontal plane. Three main stress regimes are defined: normal faulting (NF) when $P(\sigma_1)$ is vertical and $T(\sigma_3)$ is horizontal; strike–slip (SS) when both $P(\sigma_1)$ and $T(\sigma_3)$ are horizontal; and thrust faulting (TF) when $P(\sigma_1)$ is horizontal and $T(\sigma_3)$ is vertical. The World Stress Map Project also uses the intermediate cases transtension (NS) and transpression (TS) for the combination of strike–slip faulting with normal and thrust faulting, respectively. A similar classification scheme has been applied here by adopting cut-off values for plunges of the P, T and B axes (Zoback, 1992). To each focal mechanism solution (FMS) one of these five stress regime categories was assigned and plotted by colour circles (Fig. 3). The lateral variation of the stress regimes was estimated by interpolation to areas with few or no data, using the kriging method on the available FMS data, considered here as a rather robust averaging and interpolation technique routinely used for data sets with heterogeneous spatial distribution. For calculation, the quality of the stress data, according to the WSMP quality ranking scheme (Zoback and Zoback, 1989) was taken into account, and the regime assignments were converted to numerical values. Each FMS data entry was assigned by a number: NF — 1, NS — 2, SS — 3, TS — 4, TF — 5 (after Müller et al., 1997).

Tectonic regimes in the Pannonian region show significant lateral variations (Fig. 3). Small-scale changes in the stress regime, over distances of a few tens to hundreds of kilometres, indicate complex tectonic processes. The style of deformation at the margins of Adria is mostly thrusting, often in combination with strike–slip faulting, reflecting convergence between Adria and the Alps–Dinarides. Variations within the Dinarides may be due to the angular difference between the mean direction of tectonic compression resulting from Adria motion and the main structural trends and, perhaps, for the rather irregular shape of the Adriatic microplate. In other words, oblique convergence in the central Dinarides leads to dextral transpression along inherited NW–SE-trending fault zones associated with lateral motion and related rotation of crustal blocks. On the other hand, compression in the Friuli–northwestern Dinarides and the southeastern Dinarides is perpendicular to the main structural trends, resulting mainly in reverse faulting with only minor role of strike–slip faulting. In the Eastern Alps and, particularly, along the Mur–Mürz–Žilina shear zone, pure strike–slip faulting prevails confirming that most shortening between Adria and stable Europe is absorbed south of the Periadriatic lineament within the Southern Alps (D'Agostino et al., 2005; Grenerczy et al., 2005).

Profound changes in the stress regime occur from the edges of Adria towards the interior of the Pannonian basin. The dominant style of deformation gradually shifts from transpression in the south and southwest to strike–slip faulting in the central and southeastern areas. Due to partial stress release *en route*, this effect is less pronounced farther away from Adria. GPS data show that the degree of shortening is decreasing towards the northeast, in the direction of the Pannonian basin centre (Grenerczy et al., 2005). Therefore, it is proposed that inversion in the Pannonian basin system is in a more advanced stage in its western and southern parts. Fault plane solutions in the northeastern Carpathians (some outside the area in Fig. 3) make this simple pattern more complicated. This implies that inversion may be somewhat hampered in the eastern Pannonian basin perhaps due to sub-crustal processes and thermal effects resulting from an asthenospheric dome and associated thermal and density perturbations (Becker, 1993; Huismans et al., 2001). Nevertheless, compression may be transmitted across the Pannonian lithosphere resulting in shortening as far as in the Western and Northeastern Carpathians, representing the outermost edge of the Mediterranean mobile belt.

3.3. Inversion of earthquake fault plane and slip data

The stress directions and regimes have been investigated by the inversion of earthquake mechanisms. Fault plane solutions give the orientation of the nodal (fault and auxiliary) planes, and the slip vector on the fault plane. When fault slip is assumed to be in the direction of maximum resolved shear stress during an earthquake (Bott, 1959), a best fitting stress tensor responsible for the slip along the fault can be determined (Gephart and Forsyth, 1984). Because first motion focal mechanisms cannot distinguish between the fault and auxiliary planes, both planes were utilised. For the inversion the TENSOR program by Delvaux (1993) was used that yields four parameters: the orientation of three principal stress axes ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) and their relative magnitude, expressed by the stress ratio factor $R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$. This method, elaborated originally by Angelier and Mechler (1977) and adopted by Delvaux (1993), is especially suitable for the inversion of focal mechanisms because orthogonal planes – corresponding to the fault and nodal planes – are used to identify the compressional and extensional quadrants. The separation of FMS data into subsets and a first estimation of the stress tensor were performed by this method. Subsequently, a more accurate calculation was carried out for each regional group of mechanisms by applying the rotational optimization method (Delvaux and Sperner, 2003). It minimises the slip deviation α that is the angular misfit between the theoretical and actual slip directions on the fault plane.

Inversion of fault plane solutions resulted in the definition of seven regional data sub-sets (Fig. 4). Uniform stress orientations (directions of $\sigma_1 \geq \sigma_2 \geq \sigma_3$) and regimes ($R$ values), and the corresponding style of active deformation (Fig. 5), characterise these stress provinces in the Pannonian basin and its vicinity:

(A) The Friuli zone in northern Italy (Fig. 4a) is characterised by predominantly ENE–WSW-trending reverse faults and thrusts, and a pure thrust faulting stress regime (Fig. 5). Azimuth of σ_1 is N165°, $R=0.25$–0.35.

(B) The central Dinarides (Fig. 4b) are dominated by NW–SE- and NE–SW-directed dextral and sinistral faults, respectively, often in combination with thrusting, arguing for NNE–SSW-directed compression (Fig. 5). The low value of R indicates that σ_2 and σ_3 are close in magnitude, typical for transpression. Azimuth of σ_1 is N195°, $R=0.05$.

(C) The result of stress inversion in the southeastern Dinarides was statistically rather unreliable due to the low number of available FMS data (Fig. 4c). The region is characterised by pure contraction with NW–SE-striking reverse faults (Fig. 5). Azimuth of σ_1 is N045°, $R=0.55$.

(D) In the Eastern Alps NW–SE- and NE–SW-trending strike–slip faults are activated in dextral and sinistral sense, respectively, defining a strike–slip faulting stress regime (Fig. 5). Maximum horizontal compression, coinciding with σ_1, is N–S-directed (Fig. 4d). Azimuth of σ_1 is N005°, $R=0.2$–0.3.

(E) Stress direction near the seismoactive Mur–Mürz–Žilina shear zone exhibits a 35° clockwise deviation from the rest of the Eastern Alps, while both areas show mainly strike–slip motions (Fig. 5). Orientation of σ_1 is close to NE–SW, also reactivating a set of E–W-striking sinistral and N–S-trending dextral faults constituting the principal displacement zone (Fig. 4e). Azimuth of σ_1 is N220°, $R=0.3$–0.5.

(F) Most of central Pannonia is characterised by strike–slip faulting stress regime with NE–SW-directed maximum principal stress axis (Fig. 4f). Although R value indicates a stable stress field, the diverse focal mechanisms reflect a somewhat heterogeneous stress regime with a deformation style varying systematically from southwest to northeast (Fig. 5). Orientation of σ_1, however,

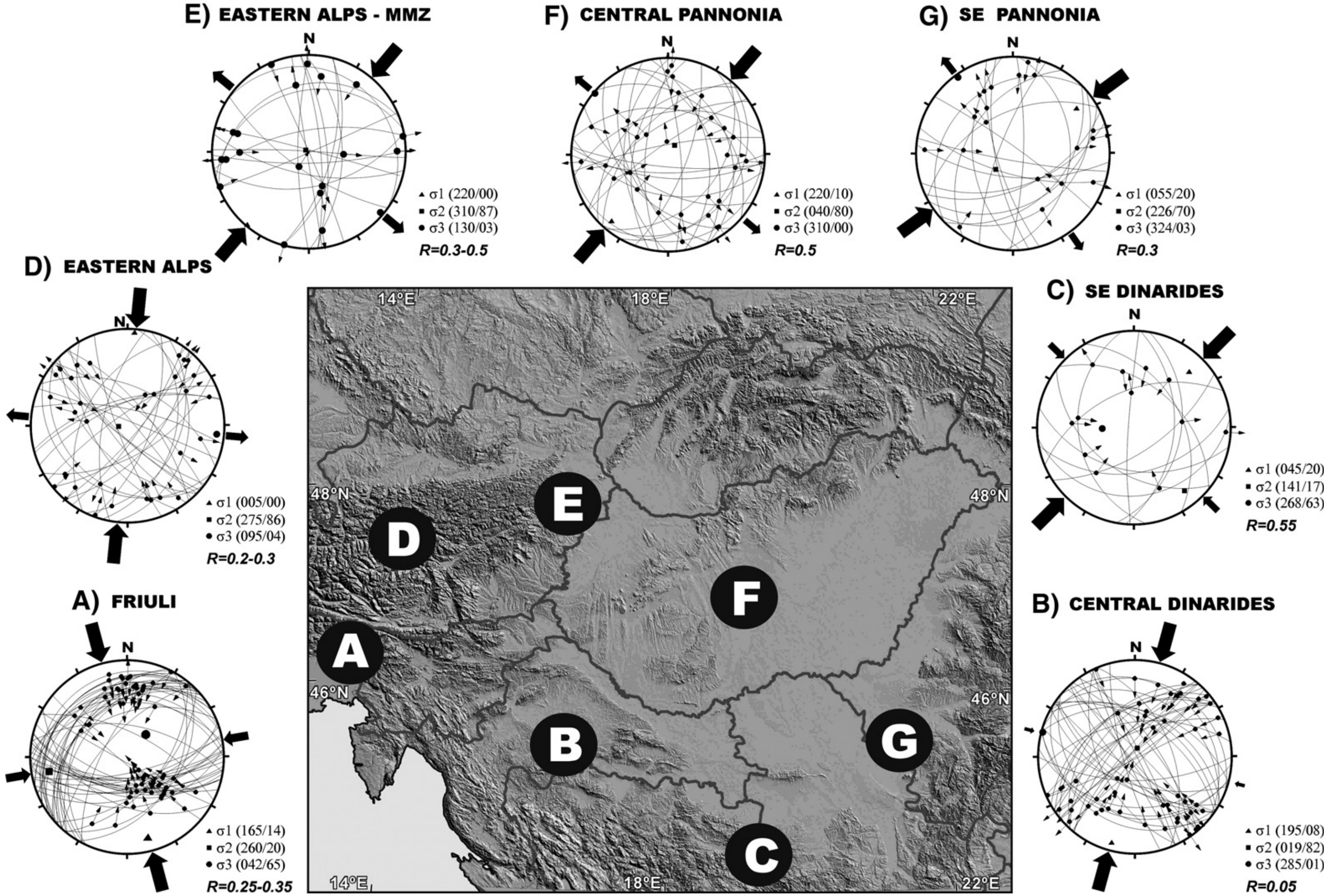

Fig. 4. Results of stress inversion of earthquake focal mechanisms in the Pannonian basin and neighbouring orogens. Consistent stress directions and regimes were obtained for seven sub-regions, or stress provinces. Stereograms show fault and slip orientation from focal mechanisms, and the direction of the principal stress axes $\sigma_1 \geq \sigma_2 \geq \sigma_3$. The shape of the obtained stress ellipsoids is described by the ratio of the principal stress magnitudes, expressed by $R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$. MMZ — Mur–Mürz–Žilina fault zone.

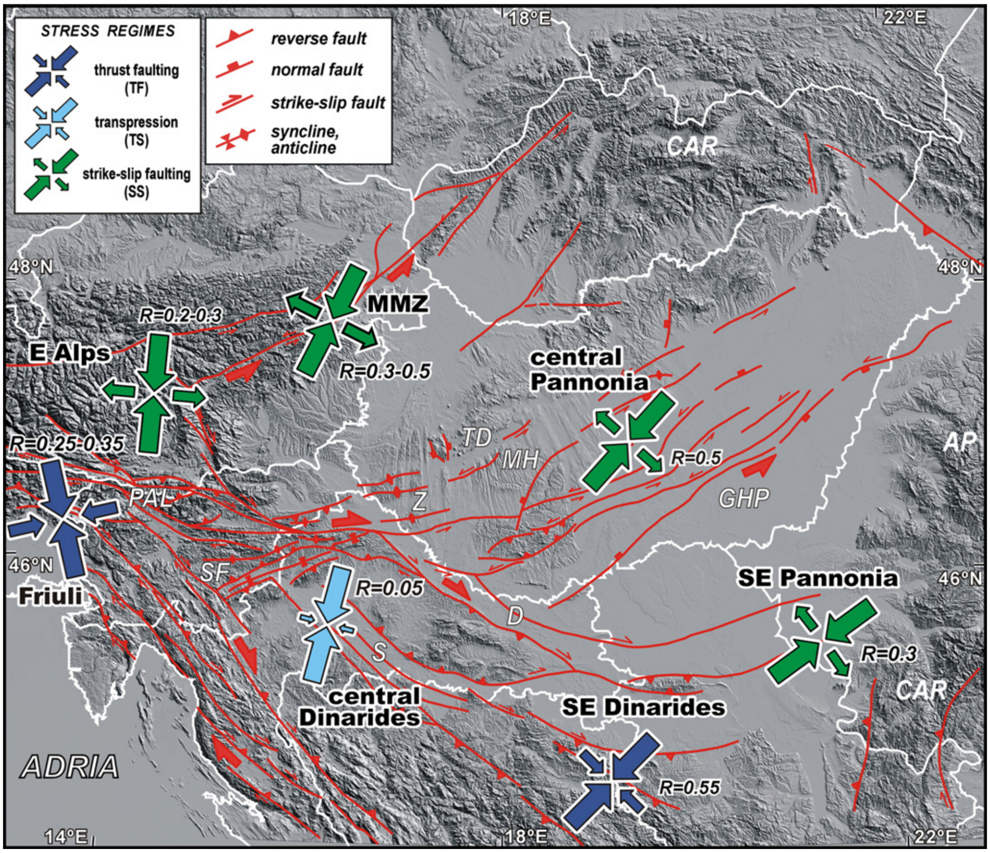

Fig. 5. Reconstructed stress provinces, and the location and kinematics of neotectonic (Pliocene to recent) structures in and around the Pannonian basin. Generalised horizontal stress directions are shown by arrows, whereas stress regimes are indicated by colouring, relative size of stress arrows, and the *R* value. Structural elements were compiled partly after Horváth and Tari (1988), Pogácsás et al. (1989), Prelogović et al. (1997), Tomljenović and Csontos (2001), Bada et al. (2003), Wórum and Hámori (2004), Decker et al. (2005), Fodor et al. (2005), Vrabec and Fodor (2005). Key to abbreviations: AP — Apuseni Mts., CAR — Carpathians, D — Drava trough, GHP — Great Hungarian Plain, MH — Mid-Hungarian fault system, MMZ — Mur–Mürz–Žilina fault zone, PAL — Periadriatic lineament, S — Sava trough, SF— Sava folds, TD— Transdanubia, Z— Zala basin.

appears to be rather stable across the basin interior with azimuth around N220°. $R=0.5$.

(G) The Timişoara seismogenic zone in the southeast Pannonian basin is dominated by ENE–WSW-oriented sinistral and roughly N–S-directed dextral faulting (Fig. 5), suggesting the dominance of a strike–slip faulting stress regime (Fig. 4g). Azimuth of σ_1 is N055°, $R=0.3$.

The reduced stress tensors for the Mur–Mürz–Žilina lineament, and the central and southeastern parts of the Pannonian basin are quite similar. One may therefore argue for a single stress province in these areas, at a distance from Adria's margins. Separation of fault plane solutions, however, seems reasonable due to the geographical clustering of earthquake epicentres.

From the calculated principal stress ratios defining the shape of the stress ellipsoid, the spatial distribution of tectonic regimes can be described by the stress regime index *R*', simply derived from the obtained *R* values. As defined by Delvaux et al. (1997), *R*' values are taken as $R'=R$ when σ_1 is vertical (extensional stress regime), $R'=2-R$ when σ_2 is vertical (strike–slip stress regime), and $R'=2+R$ when σ_3 is vertical (thrust faulting stress regime). Because *R* is always between 0 and 1, *R*' varies from 0 (radial extension) through 1 (transpression) and 2 (transtension) to 3 (radial compression), making a linear progression between the two stress regimes extremes. Fig. 6 shows the stress provinces reconstructed in the Pannonian basin and surrounding areas, plotted as a function of the stress regime index *R*' and the orientation of the principal stress axes with respect to the horizontal (modified after Philip, 1987). A striking feature of the diagram is the lack of extension in the Pannonian lithosphere, consistent with the model of an actively inverting basin system. This is supported by the

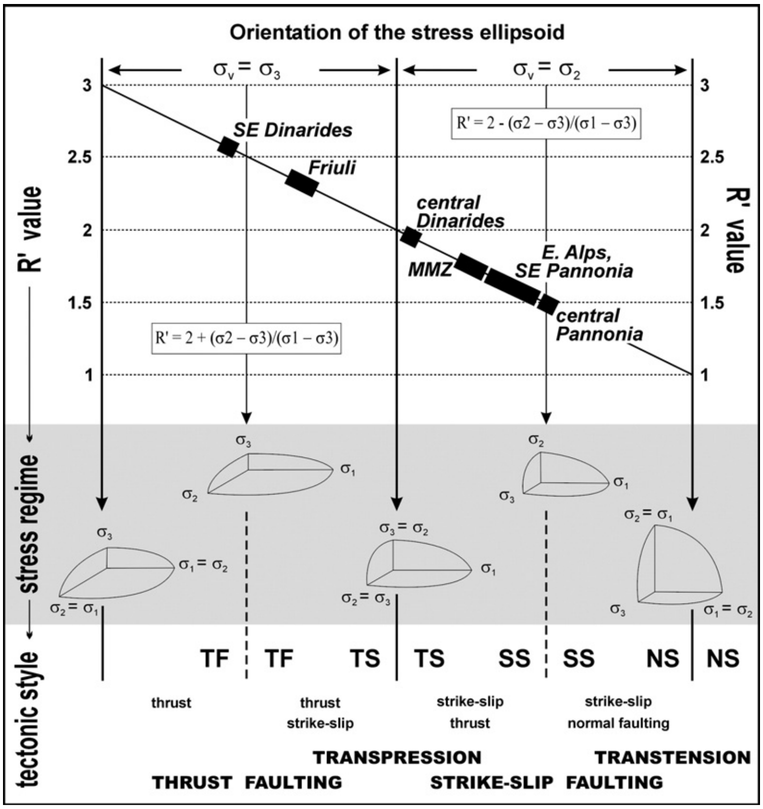

Fig. 6. Stress regimes and style of faulting in the Pannonian region. Stress provinces are plotted as a function of the stress regime index R' and the orientation of the stress ellipsoid (Philip, 1987, modified by Delvaux et al., 1997). $R'=R$ when σ_1 is vertical (extensional stress regime), $R'=2-R$ when σ_2 is vertical (strike–slip stress regime), and $R'=2+R$ when σ_3 is vertical (thrust faulting stress regime). Only values of $R' \geq 1$ are shown as no normal faulting was observed in the Pannonian region. MMZ — Mur–Mürz–Žilina fault zone.

minimum of $R'=1.5$ in the central part of the Pannonian basin, corresponding to pure strike–slip faulting. Closer to Adria convergence, the Eastern Alps, the area of the Mur–Mürz–Žilina transform fault and the southeastern part of the Pannonian basin are all characterised by the dominance of strike–slip faulting, with the largest and

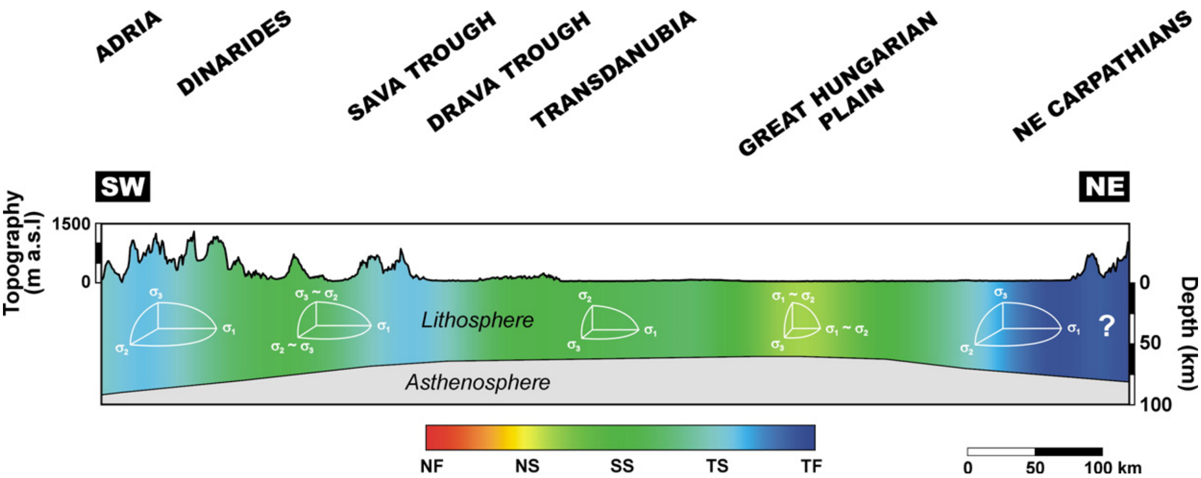

Fig. 7. Changes of the stress regime along a transect across the centre of the Pannonian basin from the Adriatic microplate in the southwest to the Carpathians in the northeast, as determined from earthquake focal mechanisms. Vertical variation of the tectonic style is not considered. Thickness of the lithosphere is from Horváth et al. (2006). Location of transect is in Fig. 3.

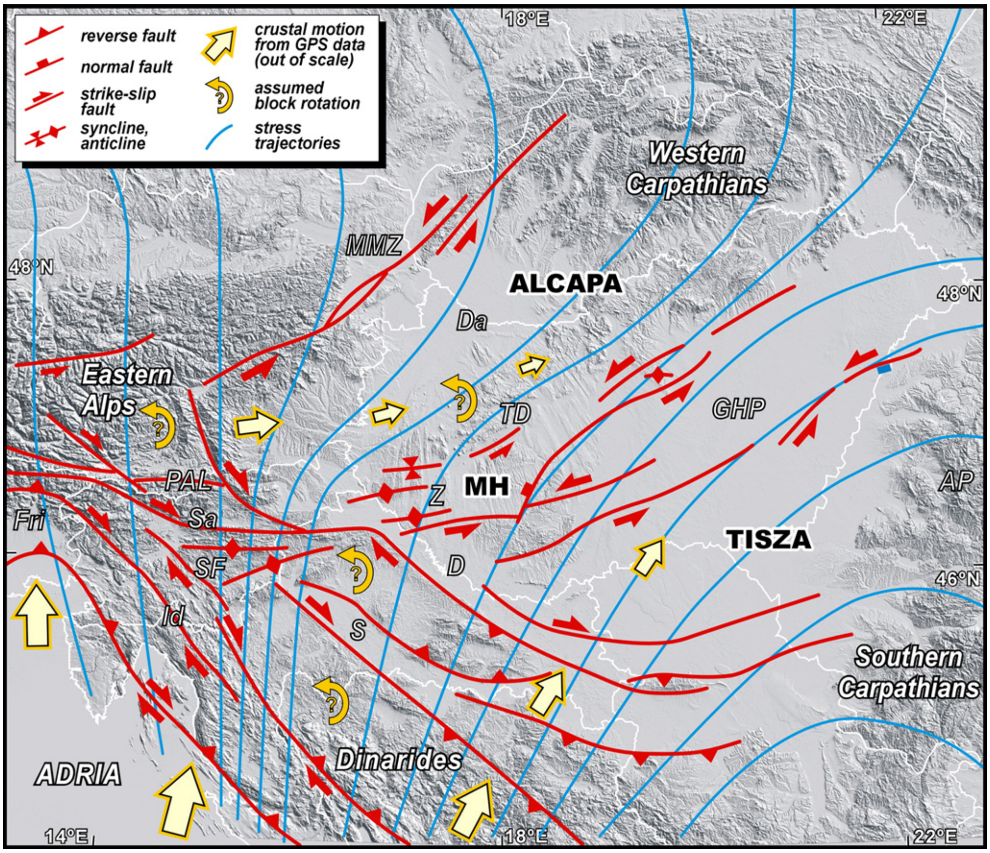

Fig. 8. Generalised stress and strain pattern in the Pannonian basin and its tectonic environment. The structural model shows the location and kinematics of major active fault zones, and the trajectories of maximum horizontal stress directions. Assumed Pliocene through Quaternary counterclockwise block rotations are after Márton et al. (2000, 2002, 2006) and Márton and Fodor (2003). Horizontal surface motions determined from GPS measurements are simplified after Grenerczy et al. (2005). Two major tectonic terranes, the ALCAPA and Tisza blocks, constitute the basement of the Pannonian basin and are separated by the broad zone of the Mid-Hungarian fault system (MH). Key to abbreviations: AP — Apuseni Mts., D — Drava trough, Da — Danube basin, FRI — Friuli zone, GHP — Great Hungarian Plain, Id — Idrija fault, MMZ — Mur–Mürz–Žilina fault zone, PAL — Periadriatic lineament, S — Sava trough, Sa — Sava fault, SF — Sava folds, TD — Transdanubia, Z — Zala basin.

least principal stress axes being horizontal. The central Dinarides represent an area where strike–slip faulting often combines with thrusting and, thus, transpression prevails. The calculated *R*' index indicates a similar magnitude of σ_2 and σ_3 leading to an unstable stress field where the stress regime and the tectonic style may show significant local variations. In the Friuli zone and, in particular, the southeastern Dinarides, thrust faulting stress regime appears. The dominance of reverse faulting reflects the close proximity of these areas to active convergence at the margins of the Adria microplate.

4. Discussion

Presented data indicate a pronounced variation of the present-day stress field in the Pannonian region. This applies to both the direction of maximum horizontal stress axis (S_{Hmax}) and the stress regimes. Based on the analysis of stress indicators, GPS measurements (Grenerczy et al., 2005; Grenerczy and Bada, 2005) and neotectonic studies (Fodor et al., 2005), a general feature is the lack of signs of extension in nearly the entire study area (Fig. 7). Most intense deformation is taking place at the convergence zone near the margins of the Adriatic plate in the Alps and the Dinarides (D'Agostino et al., 2005; Grenerczy et al., 2005; Ilić and Neubauer, 2005; Tóth et al., 2005a,b; Vrabec and Fodor, 2005). Orthogonal convergence was reconstructed for the Friuli area in the Southern Alps and for the SE Dinarides. In the central Dinarides, convergence is oblique to the main structural trends, resulting in a combination of dextral strike–slip and reverse faulting, associated lateral motion and counterclockwise rotation of crustal blocks (Fig. 8). Much of Adria's convergence is taken up by this dextral transpressional corridor, which is sandwiched between Adria and the Pannonian basin. Inversion of focal mechanisms predicts here similar magnitudes of the two least principal stresses, σ_2 and σ_3, and, thus, short-wavelength variation of the tectonic regimes can occur.

The Eastern Alps are characterised by the dominance of strike–slip faulting with no major shortening north of the Periadriatic line that separates the Eastern and Southern Alps. Instead, GPS velocities (D'Agostino et al., 2005; Grenerczy et al., 2000, 2005) and reconstructed horizontal stress deviations indicate that tectonic units are squeezed out from the axial zone of the Alpine orogen to the E-NE exerting intra-plate compression on the Pannonian lithosphere from the west. Lateral extrusion of crustal flakes towards the basin interior occurs along the sinistral Mur–Mürz–Žilina fault zone in the north (Decker et al., 2005), and a more complex transpressional corridor adjoining the Mid-Hungarian fault system in the south (e.g., Tomljenović and Csontos, 2001; Wórum and Hámori, 2004; Bada et al., 2005; Fodor et al., 2005; Vrabec and Fodor, 2005; Vrabec et al., 2006). In contrast, stresses directly propagate from Adria through the Dinarides far into the Pannonian basin, as shown on an NE–SW-oriented transect of the stress regime distribution (Fig. 7). Although most of Adria's motion is taken up in the Dinarides, shortening is also detectable inside the Pannonian basin at an overall rate of about 1–2 mm/yr (Grenerczy et al., 2005). This rate is attenuated towards the northeast, in good agreement with the spatial change of the stress regimes. Interestingly, stress transfer may advance as far as the Outer Carpathians and the European Platform. Jarosiński (2005) suggested that the NNE motion and resulting push by the ALCAPA unit (Fig. 8) is responsible for the notable variation of the stress field in the Polish Outer Carpathians (see Fig. 2). Although present-day GPS velocities are below detection level in the northeastern part of ALCAPA (Grenerczy et al., 2000), stresses may well be transmitted through the elasto-brittle part of the lithosphere that is the uppermost 10–15 km part of the crust.

Rheology models indicate that due to its high heat flow and attenuated lithosphere, the Pannonian basin is one of the weakest parts of the European continent with important lateral strength heterogeneities (Cloetingh et al., 2006). Pronounced lithospheric weakness led to a high degree of strain concentration, mainly in the form of repeated fault reactivation. In addition, the thinner and warmer the lithosphere is, the more sensitive it becomes to the fluctuations of intra-plate stresses. Because the lithosphere of a basin is normally characterised by the highest temperatures at the end of or shortly after rifting, a stress increase at this time can easily result in structural inversion. The seismicity in the Pannonian basin implies that differential stress magnitudes are large enough to induce earthquakes on pre-existing faults and, to a lesser extent, failure of intact rocks. Seismicity pattern in the Pannonian basin, both in terms of epicentre distribution and the cumulative seismic energy release (Gerner et al., 1999; Tóth et al., 2002a,b), can be fairly well explained by the release of accumulated stress at local weakness zones properly oriented with respect to the stress field. Accordingly, distributed seismicity argues for the internal deformation of principal tectonic units constituting the basement of the Pannonian basin (Gerner et al., 1999), rather than motion along the boundaries of large-scale fully rigid blocks (Gutdeutsch and Aric, 1988). Tectonic modelling of fault behaviour in the prevailing stress field (Windhoffer et al., 2005) argues for the repeated reactivation of basement structures in the Pannonian lithosphere under a relatively stable stress field. The map of active neotectonic structures (Fig. 5) indicates that seismoactive faulting is mainly concentrated along internal shear zones and not at major tectonic boundaries such as the Mid-Hungarian fault system. However, the vague boundaries of former structural terranes can be also delineated at a fairly good confidence level (Fig. 8).

A systematic spatial and temporal change in the style of deformation, and the onset of basin inversion is supported by the results of micro- and neotectonic studies. Paleostress indicators (Bada, 1999; Fodor et al., 1999) suggest that inversion first started in the southwestern Pannonian basin at the end of the Miocene. The onset of inversion gradually migrated towards more internal parts of the system, first to main parts of Transdanubia and then the western parts of the Great Hungarian Plain. An earlier start of basin inversion closer to Adria is also manifested in a more pronounced structural expression, including significant vertical surface motions. For instance, structural cross sections suggest that fold amplitudes decrease from west to east from the Sava fold belt through the Zala basin to southern Transdanubia (Horváth, 1995; Placer, 1999; Márton et al., 2002; Bada et al., 2005), with earliest phase of folding occurring in the latest Miocene (Fig. 8). No such pronounced compressional structures are present in the Great Hungarian Plain. Active deformation is taking place along pre-existing faults and shear zones, with these structures reactivated mainly in a strike–slip sense. Accordingly, basin inversion seems less and less pronounced towards the eastern part of the Pannonian basin where asthenosphere–lithosphere interaction may take over, resulting in limited ongoing lithospheric extension (Becker, 1993; Huismans et al., 2001). This pattern is confirmed by focal mechanisms showing that active deformation in the Pannonian region is primarily controlled by the reactivation of Miocene extensional faults (see also Gerner et al., 1999). In the western part of the basin, reverse faulting of basement faults leads to folding of the overlying Neogene to Quaternary strata. More to the east, the style of deformation becomes strike–slip faulting with transpressional (local shortening) and, in the northeastern part of the Great Hungarian Plain, transtensional (local extension) character (Figs. 7 and 8).

The complex interaction of plate boundary and intraplate forces at the Eastern Alps–Dinarides–Pannonian transition zone is fundamental in the present-day geodynamics of the system. In this context, the behaviour of the Adria microplate is of key importance governing the stress and strain pattern (Fig. 8). Space geodetic data (Ward, 1994; Oldow et al., 2002; Battaglia et al., 2004; Grenerczy and Kenyeres, 2005; Grenerczy et al., 2005) and seismotectonic studies (Anderson and Jackson, 1987; Console et al., 1993) indicate that today Adria moves independently from both the African (Nubian) and the Eurasian plates. However, its exact geometry and geographic extent, level of rigidity, mode of separation from Africa, and a possible internal segmentation are still a matter of debate (Pinter and Grenerczy, 2005; Stein and Sella, 2005). The role of Adria is, thus, somewhat dubious. In contrast to the rheology predictions by Cloetingh et al. (2005, 2006), Robl and Stüwe (2005) suggested that at present no pronounced strength contrast exists between the Adriatic indenter and the Eastern Alps–Pannonian realm. The different scenarios set up for Adria dynamics highlight inherent complexities in the tectonic evolution of this part of the Mediterranean region.

5. Conclusions

The state of recent stress and ongoing deformation in the Pannonian region is primarily controlled by the counterclockwise rotation and north-northeast drift of the Adriatic microplate (“Adria-push”). In addition, lateral extrusion of crustal flakes from the axis of the Alpine orogen has a significant role in the stress and strain pattern, particularly in the western Pannonian basin. Due to the convergence between Adria and its buffers, the Alps and the Dinarides, the lithosphere in the Pannonian basin and its vicinity is subjected to compressional tectonic stresses. As a result, the basin system has been inverting during Pliocene to Quaternary times. Stresses are transferred far from the edges of Adria towards the interior of the Pannonian basin. From the frontal zone of “Adria-push” near the Adriatic coastline towards the basin centre, the stress regime gradually changes from pure compression with σ_1 and σ_2 being horizontal, to a strike–slip type stress field when σ_1 and σ_3 are horizontal. Neotectonic structures in the Pannonian region are largely controlled by the reactivation of pre-existing shear zones. Accordingly, reverse faulting in the basement leads to folding of the overlying strata in the west. Towards the east, the style of deformation becomes strike–slip faulting with either transpressional (local shortening) or transtensional (local extension) component, depending on the interplay between 3D fault geometry and the local stress field.

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