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Recent tectonic stress field investigations in Poland: a state of the art

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The paper summarizes up-to-date knowledge of the contemporary tectonic stress field in Poland and compares the results of geophysical measurements with mathematical models. The extensive set of data provided by borehole breakout analyses is supplemented by hydraulic fracturing tests, earthquake focal mechanism solutions and preliminary resolution of regional intraplate motions from GPS measurements. Frequent breakout presence shows that tectonically driven anisotropy of horizontal stress is a common feature in the study area. Roughly N–S direction of maximum horizontal stress (S_{Hmax}) in Eastern Poland differs significantly from Western European stress domain. This difference is produced by tectonic push of Alcapa, which is successively compensated within the Teisseyre-Tornquist Zone (TTZ) and in the Upper Silesian segment of the Outer Carpathians. In the western part of Poland stress directions are ambiguous due to interplay of several additional tectonic factors. Most of hydraulic fracturing data and earthquake focal mechanism solutions indicate strike-slip stress regime in Eastern Poland where stresses are in equilibrium with preferentially oriented faults of low friction (0.16). Limited data from Western Poland suggest normal fault stress regime. Good conformity between directions of S_{Hmax} and intraplate motions occurs from comparison of breakout and GPS data. Finite element modelling shows that the most important factor shaping the stress field in Eastern and Central Poland is the Adria push transmitted through the Pannonian region. Secondary, but still notable factors are differentiation of loads along the Mediterranean collision zone and changes in magnitude of the ridge push force along the NW continental passive margin of Europe. Results of rheological modelling indicate that the crust is entirely decoupled from the mantle in the Fore-Sudetic Platform, partial uncoupling in the base of the upper crust is possible in the TTZ while in the East European Craton (EEC) the whole lithosphere is coupled. The comparison of different set of data and models presented here provides a comprehensive geodynamic scenario for Poland, however, a number of unresolved questions still remains to be addressed.

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INTRODUCTION

The area of Poland provides a typical case of intracontinental lithosphere characterized by low recent tectonic activity, as can be judged from the limited number of neotectonic indicators and low seismic energy release (Wiejacz, 1994; Zuchiewicz, 1995; Guterch and Lewandowska-Marciniak, 2002). This part of the lithosphere has a complex tectonic structure and pronounced lateral contrast in the recent heat flow which results in a high mechanical heterogeneity. The primary far-field forces controlling the intraplate stress field in Central Europe are the North Atlantic ridge push and African push, which is strongly differentiated within the Mediterranean-Caucasus Collision Zone (Müller *et al.*, 1992; Gölke and Coblentz, 1996). Ridge push dominates in Western Europe and Scandinavia while the forces related to collision with Africa are crucial for stress distribution in the hinterland of the Alps and Carpathians. The area of Poland is located in the middle of the continental plate where these two far-field factors interact (Jarosiński, 2005*a*). Deflection of far-field stresses is expected in the interior of a heterogeneous continental plate due to fault reactivation, mechanical diversity between tectonic blocks and other local effects e.g. topographic forces. The aim of this paper is to summarize the current state of our knowledge about the recent stress field and try to decipher the puzzling interaction between several factors controlling present geodynamics of Poland.

The specific points addressed in this paper are:

— present-day tectonic stress orientation in Poland,

— structurally controlled stress rotation and partitioning between large scale geodynamic units,

— stress regime and stress magnitude in the upper crust,

— comparison between directions of the S_{Hmax} and the intraplate motions,

— the far-field forces, which may influence the recent stress field in Poland,

— vertical strength profiles, representing approximated limits on tectonic stresses within the rheologically stratified lithosphere.

In this paper I summarize the results of stress field investigations, which I have been carried out for over ten years. The development of new methods of measurements and their application have been a necessary step in furthering understanding of the recent geodynamics of Poland. Nevertheless, in many cases, due to the shortage of data or simplified modelling approach, presented results should be treated as preliminary.

GENERAL TECTONIC SETTING AND DEFINITION OF GEODYNAMIC DOMAINS

This section describes the largest tectonic structures, which are essential for understanding of the recent geodynamics of Poland. Their characteristics are limited to the features, which are important from a point of view of geomechanics. The study area covers complex tectonic junction comprises the East European Craton (EEC) separated by the Teisseyre-Tornquist Zone (TTZ) from the Palaeozoic Platform (PP) (Fig. 1). At its southern end the PP is covered with the Outer Carpathian orogen.

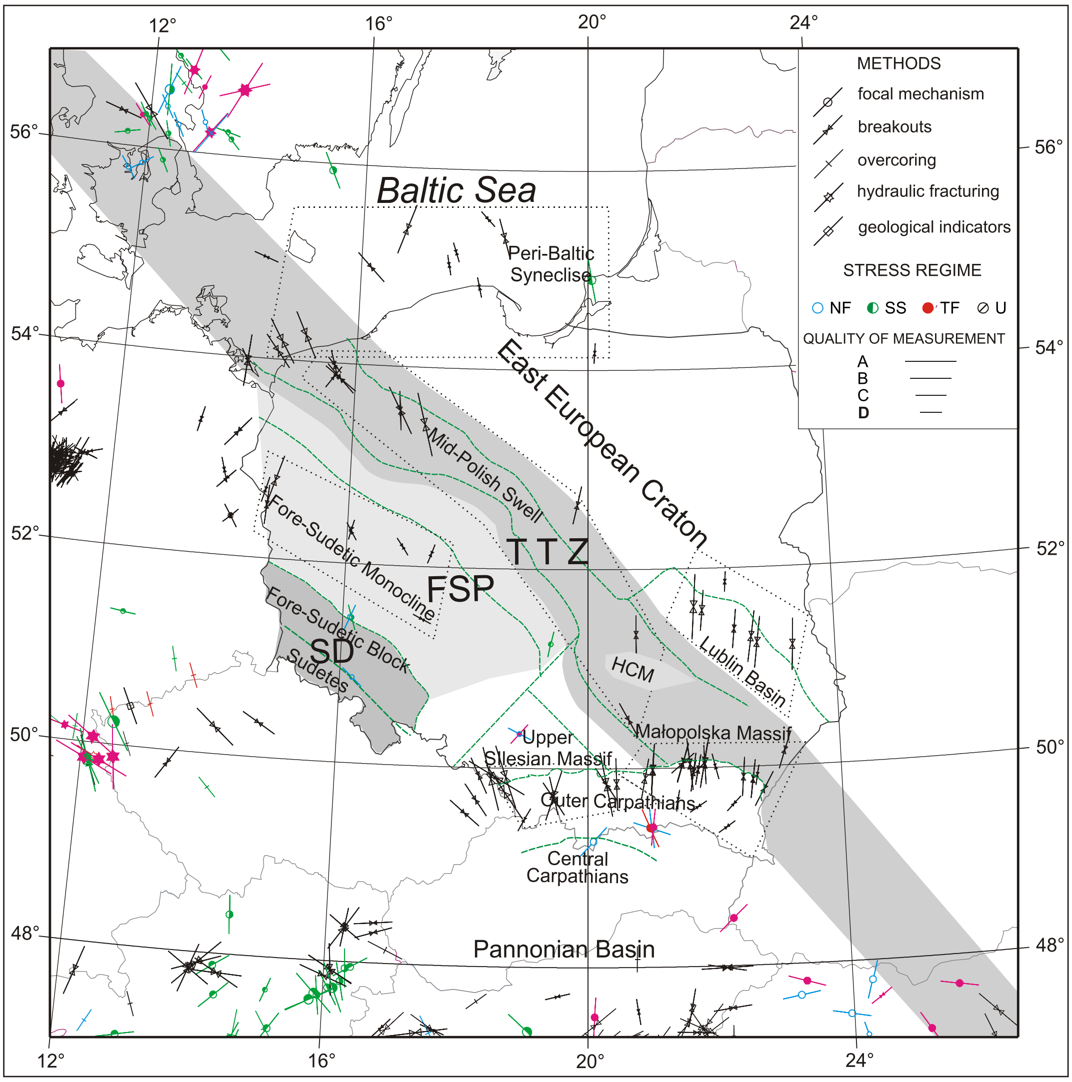

Fig. 1. Intraplate stress indicators showing the maximum horizontal stress (S_{Hmax}) directions for Poland and adjacent areas from the World Stress Map Database (Reinecker *et al.*, 2005), supplemented with data provided by Wiejacz (1994, 2004), Dębski *et al.* (1997), Roth and Fleckenstein (2001), Jarosiński (2005*a*)

Stress regimes: NF — normal faulting, SS — strike-slip faulting, TF — thrust faulting, U — unknown; the main structural units of Poland are drawn in green (after Dadlez *et al.*, 2000); in grey: SD — extent of the Sudetic Domain, FSP — Fore-Sudetic Platform, TTZ — Teisseyre-Tornquist Zone, HCM — Holy Cross Mountains; dotted frames delimitate sets of breakout data, which are attributed to distinguished geodynamical units (compare with Table 1); in this scheme the Palaeozoic Platform (mentioned in the text but not indicated in the figure) consists of TTZ + FSP + SD + Upper Silesian Massif + Małopolska Massif

Presently, the EEC is a mechanically strong and tectonically stable unit (Jarosiński *et al*., 2002*a*) characterized by thick lithosphere (Panza, 1985) and crust (Guterch *et al*., 1999; Grad *et al*., 1999), which reveals relatively low surface heat flow density (Majorowicz *et al*., 2003). From the SW the EEC is bounded by the lithospheric-scale fracture of the TTZ extending from the North Sea to the Black Sea. The Polish segment of the TTZ comprises several tectonic blocks hidden below the thick cover of the Mid-Polish Trough (Dadlez, 1989) or elevated near to the surface in the Holy Cross Mts. and the Małopolska Massif. The TTZ is heavily damaged fault zone, which has undergone several reactivation phases since Early Palaeozoic (Brochwicz-Lewiński *et al*., 1981). The lithospheric thickness and heat flow in the TTZ are transitional between the EEC and the PP (Grad *et al*., 1999; Jarosiński *et al*., 2002*b*; Jarosiński and Dąbrowski, in press).

Amalgamation of the PP took place in two stages: the Caledonian accretion of the Avalonia-type terranes and the Variscan accretion of the Armorica-type terranes (Pharaoh, 1999; Nawrocki and Poprawa, 2006). The Caledonian part of this platform (Mazur and Jarosiński, in press) is characterized by a notably higher surface heat flow (Hurtig *et al*., 1992) and thinner lithosphere then the Variscan part (Jarosiński and Dąbrowski, in press). As a consequence, this part of the PP is probably the rheologically weakest portion of Poland (Jarosiński *et al*., 2002*a*). The crystalline basement of the Variscan part of the PP is outcropping to the surface in the Sudetes, which together with Fore-Sudetic Block comprise relatively rheologically stronger Armorican part of the PP (Jarosiński and Dąbrowski, in press). A block-like structure of this area has been intensively remobilized in the Neogene time (Dyjor, 1993).

In direct foreland of the Carpathians the PP consists of the Upper Silesian and Małopolska Massifs, partially covered by the Carpathian Foredeep sediments (Oszczypko, 1998). Further to the south, these massifs sink below the Neogene accretionary wedge of the Outer Carpathians. Both massifs are characterized by moderate heat flow and intermediate rheological strength (Majorowicz *et al*., 2002). The Outer Carpathians and the North European part of the Eurasian Plate terminate at the suture of the Pieniny Klippen Belt. The Central Carpathians, located south to this suture, belong to the South European Plate. They consist of a pile of thrusts created during the Late Cretaceous collision in the Alpine realm (Plasienka, 1997). During the Miocene, the Central Carpathians become a part of the Alcapa microplate, which was extruded from the Alps and docked in their present-day position (Ratschbacher, 1986; Peresson and Decker, 1997).

For the purpose of geodynamic characterization of Poland in this study I used the simplified partitioning of structural units (Fig. 1):

— the East European Craton (EEC) includes the Lublin Basin;

— the TTZ corresponds to the centre of subsidence of the Permian-Mesozoic Polish Basin (the Mid-Polish Trough) that is slightly broader than the Mid-Polish Swell;

— the Fore-Sudetic Platform (FSP), being a part of the Paleozoic Platform lying between the TTZ and the Fore-Sudetic Block (slightly broader than the Fore Sudetic Monocline);

— the Sudetic domain (SD) comprising the Fore-Sudetic Block and the Sudetes;

— the Carpathian domain includes the Central and Outer Carpathians and the proximal part of the Carpathian Foredeep. The Outer Carpathian domain is divided into the Upper Silesian and Małopolska segments, depending on the affinity of their autochthonous basement. The boundary between these segments below the thick cover of the Magura Unit (near the Carpathian suture) is hypothetical.

METHODS

Prior to this effort none of the methods which I used has been applied in order to investigate recent tectonic stress in Poland. Their application required adaptation of standard methods to specific local types and quality of data and also needed development of new analytical approaches and computer programs, like: *SPIDER*, *TENSOR*, *SIGMAC* and *GEOSLIP* (Jarosiński, 1998, 1999) and *RHEOL* (Jarosiński *et al*., 2002*a*). A particular advance has been done in the methodology of breakout analyses from six-armed caliper tool (Jarosiński, 1998, 1999). Also some progress was made in higher level of numerical models' integration (Jarosiński *et al*., 2006). In this contribution presentation of developed methods is reduced to a necessary minimum, thus for a more complete explanation the reader is referred to the papers by the author (Jarosiński, 1994, 1998, 1999, 2005*b*) and literature cited therein. In general, four approaches were used:

— analysis of borehole breakout,

— interpretation of hydraulic fracturing from borehole tests,

— numerical modelling of stress field,

— analytical modelling of lithospheric strength.

In the World Stress Map Database focal mechanism solutions are the most important indicators of the recent stress field (Zoback, 1992; Jarosiński, 1994). In the aseismic area of Poland several other methods have to be applied in order to reconstruct the tectonic stresses. The most useful is the processing of dipmeter logs for the borehole breakout interpretation (Bell and Gough, 1979; Jarosiński, 1994). Breakouts are failures of borehole wall, triggered by differential stress excess, perpendicular to the maximum horizontal stress (= S_{Hmax} = horizontal compression) (Fig. 2A). Development of the breakout-type failure in the borehole wall is the function of several natural and technological factors (Zoback *et al*., 1985), however, the principal necessary condition is a sufficient value of the horizontal differential stress (S_{HD}). In Poland the greatest amount of data was acquired with a 6-armed dipmeter tool supplemented in some cases with information from a 4-armed dipmeter and borehole televiewer. For the purpose of automatic identification of breakouts from technological borehole failures the computer program *SPIDER* was developed (Jarosiński, 1998, 1999; Jarosiński and Zoback, 1998). This method of data processing, tested by comparison with borehole televiewer logs (Jarosiński and Zoback, 1998), appears to be efficient in precise determination of breakout orientation, however, results in reduction by half of combined breakout length (in comparison to televiewer record). This is

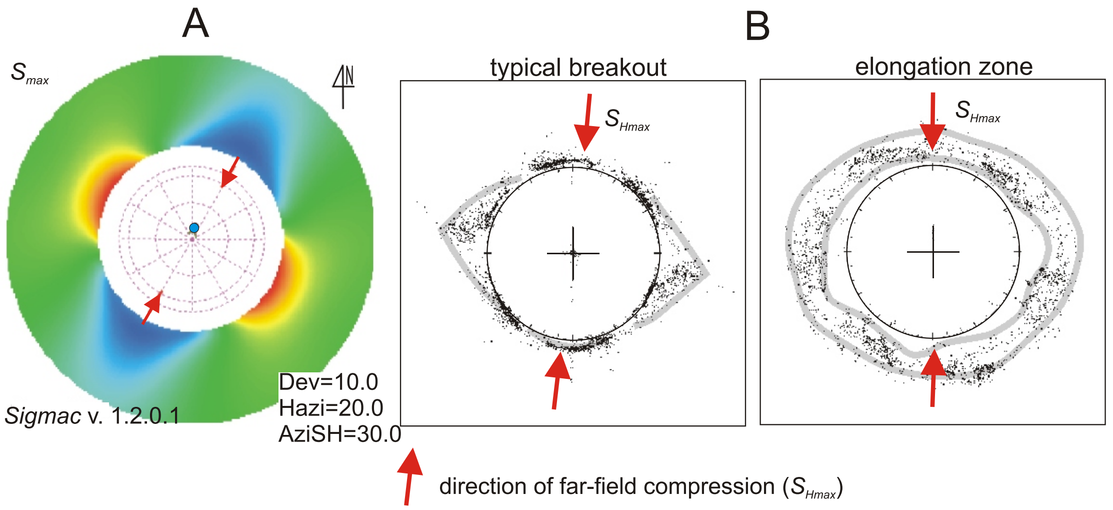

Fig. 2. A — stress disturbance around borehole in the plane perpendicular to the well axis obtained with *SIGMAC* computer program; the maximum effective principal stress (S_{max}) values are shown (high in red, low in blue, far-field stress value in green); B — approximate borehole cross-sections represented by caliper pad projections in the *SPIDER* program processing. Typical breakouts, being the best indicator of the S_{Hmax} direction, develop when only part of the borehole fails. Elongation zones, also regarded as tectonic stress indicators, develop when the whole circumference of the borehole fails. Usually in this case the azimuth of S_{Hmax} is determined with less precision

caused by imperfect dipmeter position within breakout and too small breakout size in respect to the caliper pad. The criteria of identification of breakouts from 4- and 6-armed dipmeter data were presented by Plumb and Hickman (1985) and by Jarosiński (1998, 1999), respectively.

Stress magnitudes were estimated from hydro-fracturing tests performed in hydrocarbon production wells (Jarosiński, 2005*b*). Although these tests where not originally designed for stress examination, regularly shaped pressure curves provide a significant information about the stress regimes. The results of borehole data analyses for determination of stress regime and orientation are compared with a scarce seismic and space geodesy data taken from literature (e.g. Gibowicz, 1984, 1989; Wiejacz, 1994; Hefty, 1998). It is worth mentioning that none of the borehole logs or tests were collected specifically for the purpose of studying geodynamics but the industrial data were reprocessed in order to resolve newly raised problems.

More general questions concerning the sources of the recent intraplate stress field of Poland and influence of far-field tectonic loads have been addressed using a finite element modelling method (FEM) and *ANSYS* commercial code. This approach provides a way to combine several factors responsible for the redistribution and modification of the far-field sources of the intraplate stress, facilitates an evaluation of the fit between observation and prediction, thereby resulting in a better assessment of the present-day geodynamic conditions.

Finally, thermo-mechanical models of the lithosphere were developed to provide a first order approximation of possible tectonic stress distribution in vertical profiles limited by strength envelopes (Ranalli, 1995). These 1D models provide a way to identify which layers are prone to ductile and brittle deformations and at what depth mechanical detachments have possibly developed. The modelling was performed using *RHEOLOGY 1.1* computer program written for this purpose (Jarosiński *et al*., 2002*b*).

TECTONIC STRESS INFORMATION FROM BOREHOLE BREAKOUTS

FREQUENCY AND CHARACTERISTICS OF BREAKOUT PROFILES

Breakouts are relatively frequent features in deep boreholes in Poland (Jarosiński, 1998, 1999, 2005*a*), what points to widespread anisotropy of horizontal stress field (= horizontal differential stress S_{HD}) in the upper 1–4 km thick layer of sedimentary cover. They are particularly plentiful:

— in the autochthonous basement of the Outer Carpathians and below the Carpathian Foredeep complex,

— in the sedimentary fill of the Lublin Basin,

— in the Palaeozoic and Mesozoic complexes along the TTZ. This high frequency of breakout occurrence implies relatively high value of the S_{HD}.

However, there are four complexes where breakouts are rare or absent, implying low S_{HD} conditions:

— the Carpathian Foredeep complex consisting of clays and mudstones is probably too soft to transmit regional stresses at long distances;

— the sedimentary cover of the EEC interior where stresses are probably dissipated in thick lithosphere;

— Zechstein evaporates where stresses are relaxed by viscous flow of the rock salt;

— the Palaeozoic complex of the Fore-Sudetic Platform (below evaporates) where boreholes are shallow and the pressure of mud-fluid is high what prevent development of breakouts.

In some places breakout directions rotate systematically in wellbore profiles. Three range-scales of rotations are identified (Jarosiński, 2005*a*):

— first-order rotations characterized by general change of breakout directions along a thousand metres of borehole section are connected with regional trends in stress field changes;

— second-order rotations embrace usually more than a hundred metres of depth section and may result from mobilization of large fault zones or salt structures;

— third-order breakout rotations limited to several metres of borehole profiles are linked to discrete motion along fault planes. In some cases it was possible to point out the specific fault planes responsible for this kind of rotations (Jarosiński, 1998, 2001).

Present-day maximum horizontal stress directions were successfully determined from breakouts and less frequently from elongation zones (Fig. 2B) for 62 wells in Poland. Whereas detailed results of this stress analyses have been published (Jarosiński, 1998, 1999, 2005*a*) and included in the World Stress Map Database (Reinecker *et al.*, 2005), geodynamic interpretation is presented below. For the stress field in each district unit is documented by significant amount of data, expressed by combined length of breakouts in the range of 1050–1550 m (Table 1) except for the Fore-Sudetic Platform where only 310 m of breakouts were found.

STRESS DIRECTIONS IN THE CARPATHIAN DOMAIN

In the western, Upper Silesian segment of the Outer Carpathians characteristic stress partitioning between structural levels is interpreted from several borehole profiles, giving consistent variation in the stress direction (Jarosiński, 1998) (Fig. 3). Herein, the NNE–SSW oriented S_{Hmax} in the accretionary wedge differs significantly from NNW–SSE S_{Hmax} in the autochthonous basement. The deepest boreholes show further NW–SE rotation of the S_{Hmax} near their bottoms. The maximum gradient of stress rotation appears across the bottom thrust of the Carpathian Nappe complex. Large angular discrepancy between stress directions in the nappes and their basement suggests that the nappes alone are tectonically pushed by Alcapa towards NNE with compensation of the thin-skinned push located in the top of the autochthonous basement. In the deeper basement the regional NW–SE S_{Hmax} transmitted through the North European Plate probably interferes with extension due to accommodation of sinistral strike-slip motion along the Mur-Žilina Fault Zone (Aric, 1981; Tomek, 1988) (Fig. 3), a suture between the Central Carpathians and the Eastern Alps.

In the accretionary wedge of the eastern Małopolska segment, the S_{Hmax} directions are nearly NE–SW thus perpendicular to the strikes of the nappes. However, in the flysch nappes of the eastern segment the quality of stress determination is poor owing to short breakout profiles. Shortage of breakouts in the nappes may result from high degree of the borehole destruction caused by natural tectonic failures as well as from low values of the S_{HD}. In the vicinity of the frontal thrust of the Outer Carpathians the S_{Hmax} direction is roughly NNE–SSW. Here, in some boreholes it was possible to compare stress directions in the nappes and their basement. With only one exception, small differences within the range of standard deviation of measurements are detected. A mean S_{Hmax} direction in the Małopolska segment of the Outer Carpathians is similar to this in the nappes of the Upper Silesian segment (Jarosiński, 2005*a*). This suggests that in the eastern segment the Alcapa push is efficiently transmitted to the basement but in the western segment it results only in thin-skinned compression.

STRESS DIRECTIONS WITHIN THE FORELAND OF THE CARPATHIANS

In sedimentary fill of the Carpathian Foredeep the S_{Hmax} is roughly perpendicular to the adjacent front of the orogen, suggesting the influence of topography-related stresses. The Alcapa push is transmitted into the foreland plate through the basement of the Małopolska Massif that results in N–S or NNE–SSW oriented compression in the edge of the EEC. In the Palaeozoic fill of the Lublin Basin unusually stable S_{Hmax} in the range of azimuths 2–9° is determined from very good qual-

Table 1

Statistical synthesis of breakout data for distinct geodynamic units based on data presented by Jarosiński (2005*a*)

Geodynamic unit	Mean S_{Hmax} azimuth	Standard deviation	Combined breakout length [m]	Mean breakout depth [m]	Comments
Carpathians, Upper Silesian segment	167°	19°	1552	2960	stress decoupling between nappes and basement; best data from the basement
Carpathians, Małopolska segment	13°	23°	1329	2490	small S_{Hmax} rotation between nappes and basement; best data from the basement
EEC, Lublin Basin segment	5°	11°	1304	2768	notably stable S_{Hmax} orientation with small standard deviation
Baltic EEC+ offshore TTZ	156°	17°	1048	2963	systematic S_{Hmax} rotation towards the trend of the TTZ
Onshore TTZ	161°	19°	1541	2368	common S_{Hmax} rotation in the range between NW–SE and N–S
Fore-Sudetic Platform	6°	25°	310	1759	plausible stress decoupling at salt layer; best data from Mesozoic complex
POLAND	**173°**	**26°**	**7086**	**2655**	**average results from breakouts**

For location of data included to each of these units see Figure 1

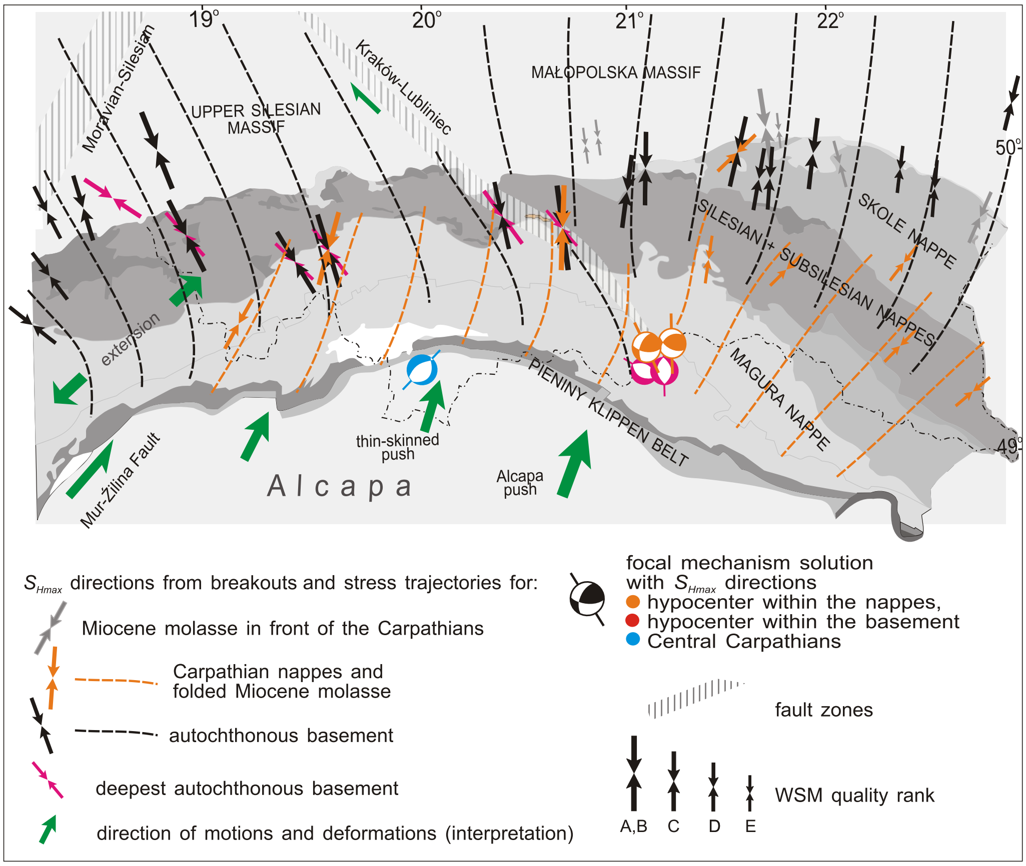

Fig. 3. Geodynamic sketch of the Polish Outer Carpathians showing S_{Hmax} distribution constrained by breakout measurements (after Jarosiński, 2005*b*, modified) and focal mechanism solution after Wiejacz (1994) and Wiejacz and Guterch (pers. comm.)

Dashed lines show extrapolated S_{Hmax} trajectories. Systematic stress rotation in the Upper Silesian segment of the Carpathians is interpreted as stress partitioning between the flysch nappe and autochthonous complexes. In the Małopolska segment only minor stress partitioning between the nappes and their basement might be expected. Green arrows indicate kinematics of tectonic blocks

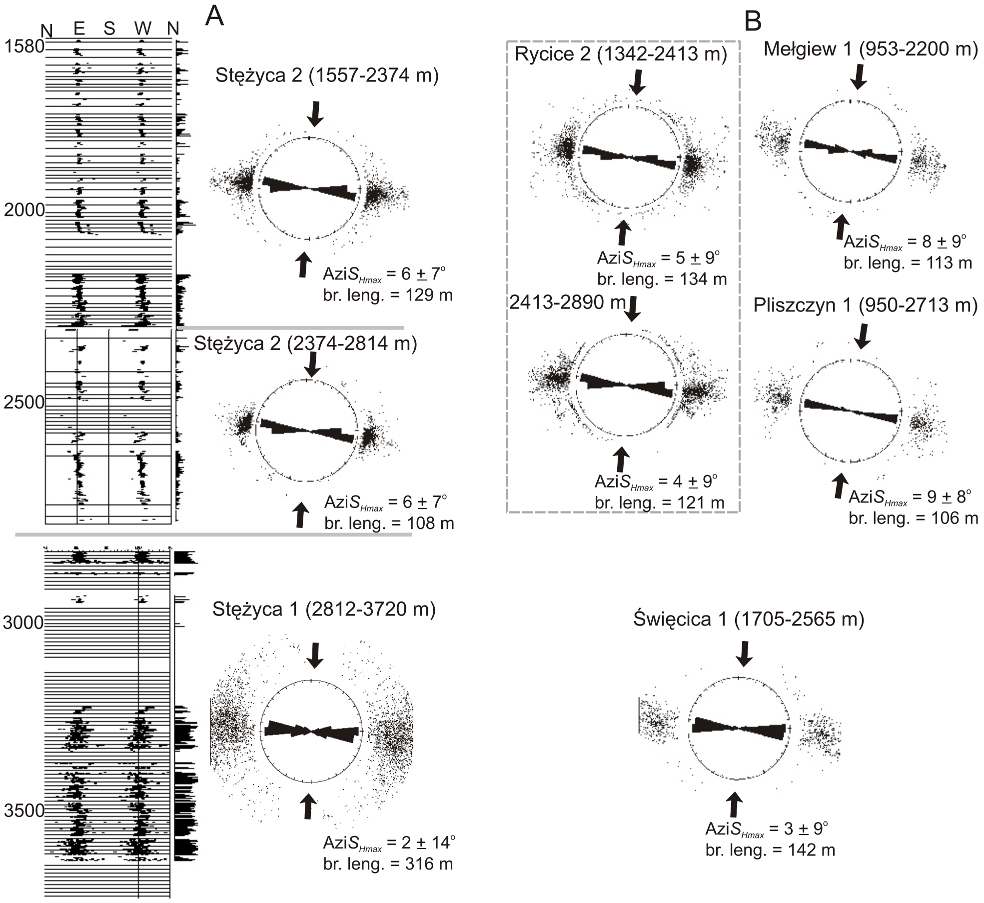

Fig. 4. Representative examples of breakout data from the Lublin Basin computed with *SPIDER* program (after Jarosiński, 2005*a*, modified) showing exceptionally stable S_{Hmax} directions; A — in vertical borehole profiles (points indicate breakout directions, bars on the right-hand side of the diagram show relative depth of breakouts); B — between the wells

Rose diagrams show breakout directions, points outside the rose diagrams indicate pad position within the breakouts. S_{Hmax} azimuth is perpendicular to the mean breakout direction for each analysed depth interval, br. leng. — combined length of breakouts in a given depth interval; for location of boreholes see Jarosiński (2005*a*) ity data (Fig. 4). Constant direction of breakouts, expressed also by a small standard deviation for the entire Lublin Basin (Table 1), indicates coaxial stress without horizontal simple shear component. Further to the NW, in the sedimentary fill of the Peri-Baltic Syneclise S_{Hmax} direction changes gradually to NNW–SSE. In most of the wells breakouts developed only in direct vicinity of faults, where stresses are amplified. Conformity between stress directions from several poor quality breakout profiles suggests that determined stress direction is a regional one. This stress direction is a mean between the Alcapa push and the Mid-Atlantic Ridge push that implies that these two factors are in equilibrium in the Baltic part of the EEC.

Within the offshore, Baltic portion of the TTZ, very good quality data from the Upper Palaeozoic complex indicates a well-defined S_{Hmax} orientation parallel to the NW–SE structural trend of this zone. Stress orientations are stable in vertical well sections. Minor amount of breakouts in the Permian sequence indicates that the exaggeration of S_{DH} is restricted to the tectonically disturbed Variscan structural complex. In contrast to the offshore part of the TTZ, the onshore wells exhibit common first- and second-order S_{Hmax} rotations (Fig. 5). In both the Mesozoic complex above the Zechstein salt and in the Upper Palaeozoic complex S_{Hmax} direction changes in the range from NW–SE to N–S, with some NE–SW exceptions. Irregularity in stress rotations makes the determination of a consistent geodynamic layers problematic. The large variation in direction and quality of stress indicators is evidence of high heterogeneity of the stress field within the TTZ, suggesting strike-slip mode of deformation, probably due to structurally controlled accommodation of the Alcapa push (Jarosiński, 2005*a*).

The stress field in the Fore-Sudetic Platform in Western Poland seems to be partitioned along the Zechstein salt layer. However, this notion is poorly constrained by limited available data. The best quality breakout profiles show that in the north-

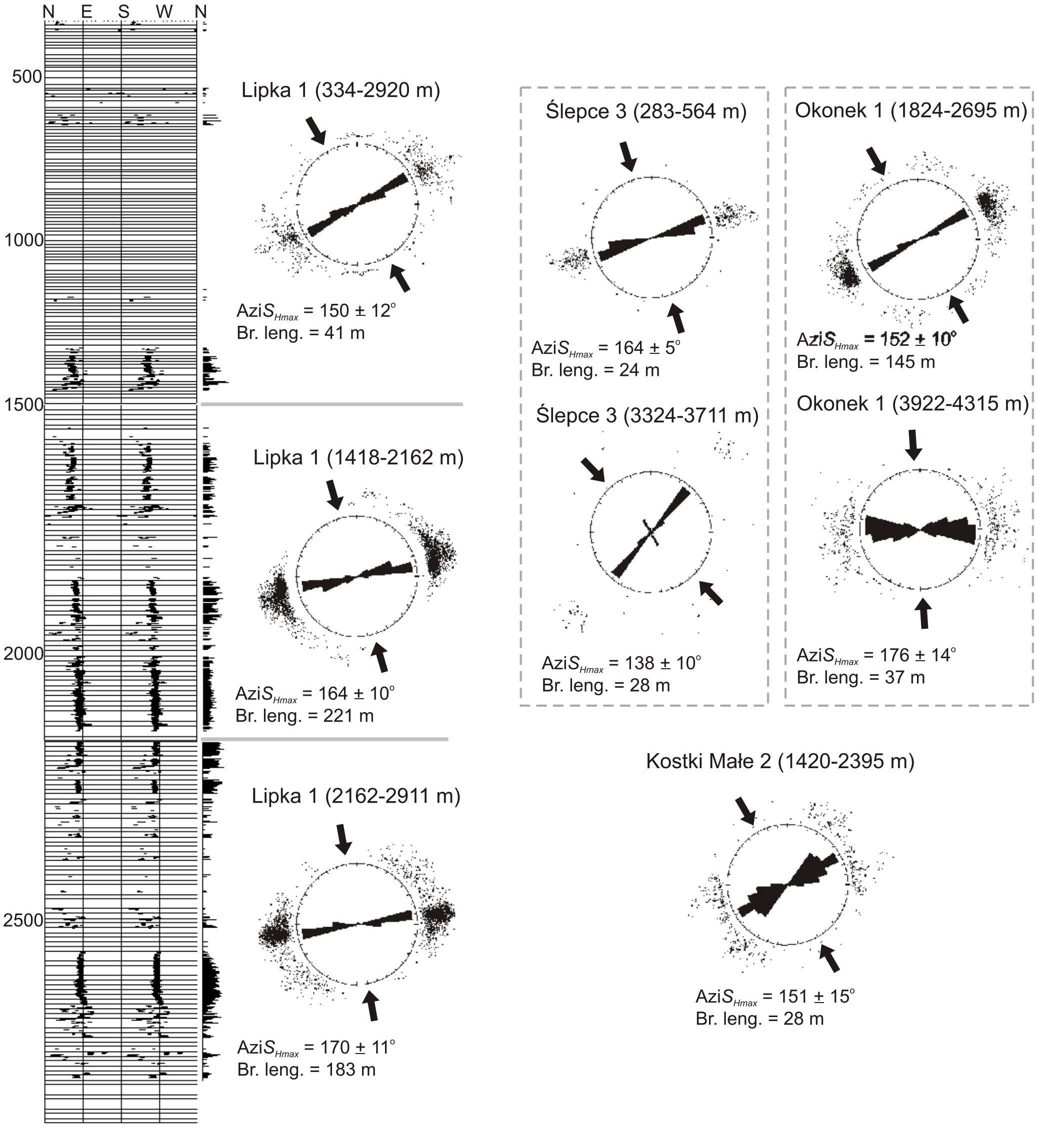

Fig. 5. Representative examples of breakout data from the TTZ indicating S_{Hmax} rotations with depth within individual wells (after Jarosiński, 2005*a*, modified)

In the well Kostki Małe 2, points outside the rose diagram indicate bimodal breakout distribution; there is no systematic trend of S_{Hmax} direction changes with increasing depth; see Figure 4 for explanation of the diagrams; for location of boreholes see Jarosiński (2005*a*) ern part of the Fore-Sudetic Platform, the Mesozoic complex is compressed in NNE–SSW or N–S direction. A significantly different, the NW–SE direction of S_{Hmax} was inferred from low quality data for the Variscan accretionary wedge complex located in the centre of this platform. In this case, stress directions are close to the main structural trend that may produce mechanical anisotropy in heavily tectonized complex. The scarcity of breakouts in borehole profiles suggests minor differential stress, at least in the examined top part of the Variscan structural complex. One of the possible explanation of the stress partitioning along the Zechstein ductile salt layer is the presence of gravitational sliding of the Mesozoic complex downwards of the homocline, which layers are inclined by *ca.* 2° towards NNE. The NW–SE compression in the basement can be produced by the Atlantic ridge push.

In general, the breakout data from Poland (Table 1) shows common deviation of stress directions from the NW–SE trend typical for Western Europe. The reason for that is suspected Alcapa push, which causes compressive reactivation of the Carpathians and influences the S_{Hmax} direction in the foreland plate at a distance of at least 700 km from the Carpathian suture. Due to this effect, the Fore-Carpathian stress domain can be discriminated within the North European stress province (Jarosiński, 2005*a*). This domain comprises the Małopolska Massif and at least the Polish part of the EEC. In this arrangement the TTZ and the Upper Silesian Massif, with specific stress rotations, comprise a transition zone between the Fore-Carpathian and West European stress domains.

STRESS REGIMES FROM HYDRAULIC FRACTURING TESTS AND SEISMICITY

Magnitudes of the recent tectonic stresses in Poland were estimated based on data from hydraulic fracturing tests (Jarosiński, 2005*b*). These tests were designed in order to prepare the industrial injections for enhancement of hydrocarbon production, therefore they do not fulfill requirements of high quality tests performed for geodynamic purposes. The volume of fluids used and the fracture interval lengths are typical for the largest mini-fracturing tests (Engelder, 1993). In spite of the drawbacks of these data, regular shapes of the pressure curves enable recognition of critical pressures for stress interpretation (Fig. 6A). Magnitudes of fracture opening pressure and instantaneous shut-in pressure (ISIP) from the tests where supplemented by fracture reopening pressures from commercial injections. Given set of data allows identification of minimum horizontal stresses (S_{hmin}) from ISIP with accuracy *ca.* 1 MPa and calculation of the S_{Hmax} (Hickman and Zoback, 1983) with accuracy of *ca.* ±5 MPa. This resolution permits inferences about stress regime in the vicinity of examined boreholes.

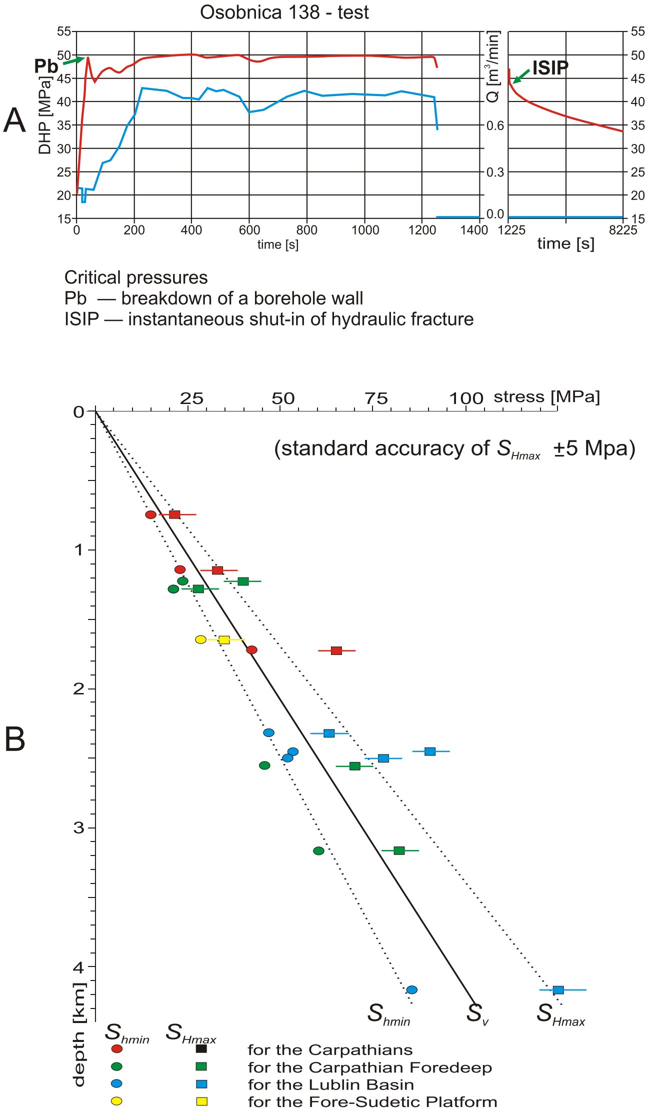

Fig. 6. Stress regime determination by means of hydraulic fracturing tests (after Jarosiński 2005*b*); A — typical curves of down-hole pressure DHP (red line) and pumping rate Q (blue line) in function of time; B — minimum (S_h) and maximum (S_H) horizontal stress magnitudes estimated from hydraulic fracturing tests

Dotted lines indicate trends of S_h and S_H increase with depth (without data from the Fore-Sudetic Platform), solid line shows linear trend of overburden pressure (Sv). In the most cases $S_h < S_v < S_H$, which is indicative of strike-slip stress regime

Most of investigated wells are located in southeastern Poland (Fig. 7). For three hydraulic fracturing tests performed in the Carpathian Nappe complex strike-slip stress regime with a singular deviation towards the thrust fault regime were determined (Figs. 6B and 7). Tests performed in four wells located in front of the Carpathians within the foredeep complex, and exceptionally in its basement, reveal strike-slip stress regime with local deviation towards normal fault regime. Stable, strike-slip stress regime is determined for four wells located in the Lublin Basin. It was also observed that in each of these regions the highest values of the S_{Hmax}/S_V ratio was attained in the hanging walls of reverse faults (S_V — vertical stress component). This suggests that heterogeneity of the stress field is controlled by inherited, Variscan and Alpine tectonic structures. In SE Poland linear increase of stress magnitude with depth can be estimated at 29 MPa for S_{Hmax}, and 19 MPa for S_{hmin} per 1 km of depth (Fig. 6). From this, the horizontal differential stress increase can be estimated at 10 MPa per 1 km depth and a ratio of S_{Hmax}/S_{hmin} at 1.47. While the strike-slip stress regime domi-

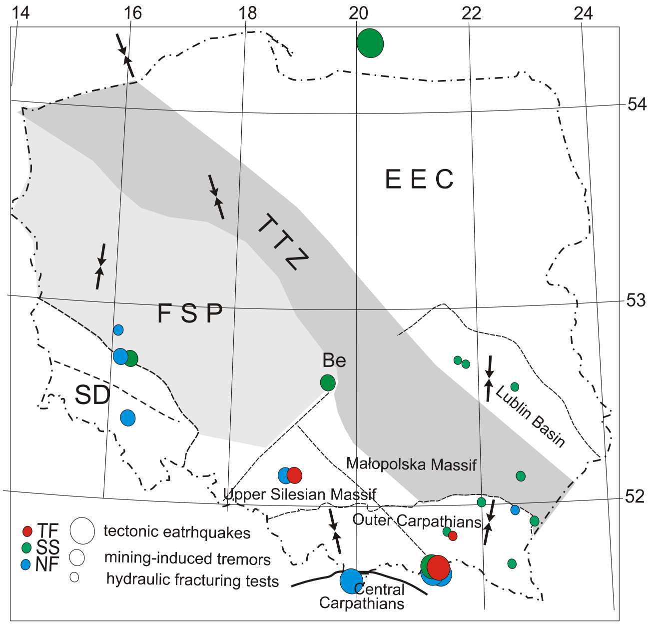

Fig. 7. Distribution of stress regime data from hydro-fracturing tests (small circles) and from natural earthquake focal mechanism (greatest circles) and mining-induced tremors (intermediate size of circles)

Stress regimes: TF — thrust faulting, SS — strike-slip faulting, NF — normal faulting; arrows indicate mean directions of S_{Hmax} for individual geodynamic units, according to the Table 1; Be — Bełchatów Mine; see Figure 1 for explanation of tectonic units abbreviations

nates in the uppermost crust in SE Poland, one test performed in the Fore-Sudetic Platform indicates normal fault stress regime in the Rotliegend complex.

The set of stress regime indicators is supplemented with earthquake focal mechanism data (Fig. 7). However, due to the low seismicity of Poland, good quality seismological data are very scarce. Focal mechanism was resolved for only a few natural earthquakes in Poland and adjacent areas. In the interior of the EEC, the Kalinigrad earthquakes from September 2004, points out clearly to the strike-slip stress regime at the depth of 10–15 km (Wiejacz, 2004; Wiejacz and Dębski, 2005). In the Outer Carpathians focal mechanism solutions for the Krynica earthquakes (Wiejacz, 1994) indicate transitional stress regime from strike-slip to thrust fault at the depth *ca.* 6 km, comparable to the bottom of the Magura Nappe and normal fault stress regime at the depth 18 km that may correspond to the basement beneath the accretionary wedge complex (Golonka *et al.*, 2005). The focal mechanism of the Podhale earthquake (November 30, 2004) with the epicenter located to the south of the Pieniny Klippen Belt suture indicates normal fault stress regime (Swiss Seismological Service *ETHZ*) at a depth of 7 km (Wiejacz and Guterch, pers. comm.).

In the World Stress Map database six records from Poland, described as mining induced tremors, have low quality (Figs. 1 and 7) and therefore their significance for tectonic stress determination is limited. However, an estimation of the tectonic component, particularly in the case of compressive regime indicated by focal mechanisms, is possible. For the Sudetic domain and adjacent part of the Fore-Sudetic Platform (copper mining district) two shallow tremors indicate normal fault stress regime (Gibowicz, 1984, 1986). From the same location at the platform also strike-slip event was reported (Gibowicz, 1989). The moment tensor solutions for almost a hundred tremors from Lubin cooper mine district (Wiejacz and Gibowicz, 1997) shows that all sources are located at a depth of mining level or above. Although no regularity was recognized in the pattern of focal mechanisms it can be inferred that the strongest events of strike-slip focal mechanisms indicate S_{Hmax} in the range between NNW–SSE and NNE–SSW. From one spot in the Upper Silesia Coal Basin contrasting stress regimes, namely normal and thrust faults are reported. The strike-slip stress regime resolved for the Bełchatów open-cast mine (Fig. 7; Gibowicz *et al.*, 1982) is coherent with observations of neotectonic strike-slip motions in this area (Gotowała and Hałuszczak, 2002). Directions and regimes of stresses inferred from mining induced tremors should be treated with caution because they are often incoherent when more than one events are registered from one location, which suggests a significant influence of technological component.

Full set of stress regime data suggests that in the eastern portion of Poland stress regime is generally strike-slip, with possible deviation towards thrust-fault or normal fault regimes (Fig. 7). In the western part of Poland a few indicators suggest normal fault stress regime with possible deviation towards strike-slip.

TECTONIC STRESSES VS. INTRA-PLATE MOTIONS

A deeper insight into the recent geodynamics of the lithosphere can be achieved by comparison between the principal stress orientations and deformations. Although within isotropic continuum directions of maximum stresses and deformations should be identical, due to mechanical heterogeneity and discontinuities within lithosphere, discrepancy between axes of stresses and deformations is common. Detailed information about the strain deformation field in Poland is not available due to a shortage of good quality space geodesy measurements, precise enough to determine low-rate strains. Instead, in this chapter the intraplate motions are considered, that are obtained from site coordinates changes after subtraction of the Eurasia drift (Hefty, 1998). Velocity vectors were calculated for the CERGOP (Central Europe Regional Geodynamics Project) stations and referred to the CETRF96 (Central European Terrestrial Reference Frame).

For a comparison between stresses and motions I consider only geodetic sites with velocity vectors exceed one sigma error ellipse (Fig. 8). For the central Carpathians the intra-plate velocity vector of 7 mm/year points towards NNE. This direction is in agreement with expected tectonic push of the Alcapa against the North European Plate that was inferred from breakouts for the Carpathian Nappes. Three other sites located in the eastern portion of Poland reveal small but systematic change in directions of the intra-plate motions from NNE in the Outer Carpathians to northward in the onshore part of the Peri-Baltic Syneclise. Velocities of these motions are sta-

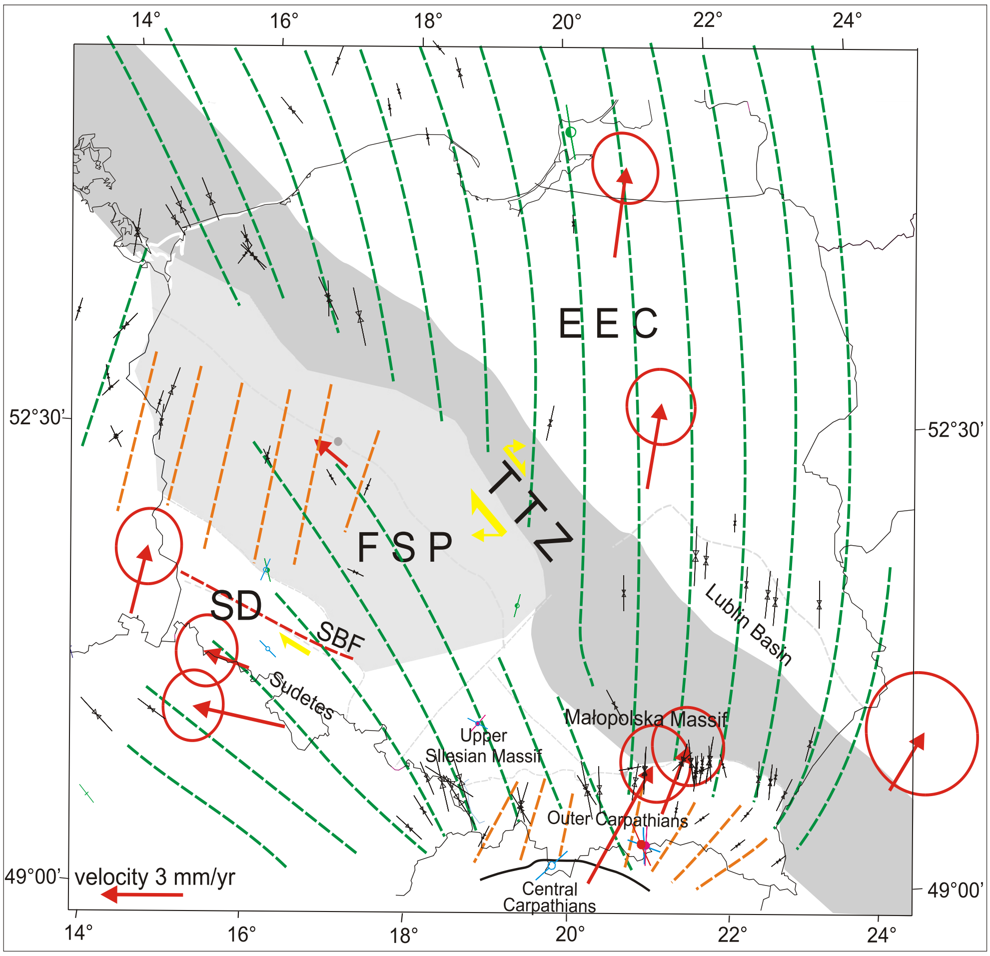

Fig. 8. Comparison of the S_{Hmax} directions with intraplate motion vectors

The green trajectories indicate general stress directions for the areas lacking stress partitioning or for the deeper level in the case of stress partitioning. In the latter case orange trajectories are added, showing S_{Hmax} directions for the upper level. For comparison the World Stress Map data are shown in the background (for explanation of symbols see Fig. 1). Red arrows show directions of the intraplate motions (after Hefty, 1998); length of each arrow is proportional to the velocity; one-sigma error ellipse is attached to each arrow. Yellow arrows show hypothetical strike-slip motions along the TTZ and the Sudetic Boundary Fault (SBF) that might be responsible for discrepancy between directions of S_{Hmax} and the intraplate motions. See Figure 1 for explanation of tectonic units abbreviations

ble and close to 3 mm/year. A gradual shift of the motion directions resembles distortion of S_{Hmax} trajectories in the same area (Fig. 8). The velocity vectors deviate systematically from S_{Hmax} trajectories by *ca*. 10° clockwise. For three stations in the Fore-Sudetic Platform and the Bohemian Massif the velocity vectors point towards NW and WNW motion at the rate 2–4 mm/year. In this case, directions of motions deviate from S_{Hmax} trajectories counterclockwise by 20–30°. The single measurement from Germany shows site motion towards NNE that is comparable to the nearby S_{Hmax} direction in the Mesozoic complex of the Fore-Sudetic Platform. However, this similarity is not straightforward as this geodetic station is situated within the Sudetic domain, and because of this, its motion should be closer to that of the Bohemian Massif.

From this comparison it can be seen that directions of intra-plate horizontal movements measured on the earth surface are in general agreement with S_{Hmax} directions in the uppermost crust. This supports a concept that the recent tectonic stress is generated by plate-scale tectonic factors responsible for horizontal motions of tectonic blocks within the plate interior. Second-order deviations between stresses and motions, character of which changes from Western to Eastern Poland, may result from simple shear along the TTZ. Its right lateral strike-slip should produce additional stretching component in W–E direction (Fig. 8). Due to a modest amount and large error bars of the space geodetic data these conclusions should be regarded as preliminary.

SOURCES OF RECENT TECTONIC STRESS IN POLAND INFERRED FROM FEM MODELLING

2D elastic finite element model was designed to explore the recent geodynamics of Central Europe (Jarosiński *et al*., 2006; Jarosiński, 2006). The modelled area extends from the northwestern continental passive margin to the southern Mediterranean collisional boundary (Fig. 9). The southwestern boundary follows the suture of Apennines and crosses France and Great Britain in the same NW direction. The model is fixed in the EEC interior, in the Ural's foreland. It is comprised of a relatively complex ensemble of 24 tectonic blocks, 16 fault zones and 12 boundary segments. Such detailed segmentation provides a way to fine-tune the calculated S_{Hmax} directions and stress regimes in an attempt to match the complex pattern of intraplate stress revealed by data (Reinecker *et al*., 2005). Calibration of the magnitude of tectonic loads at the model's boundary was possible using a correction for the gravitational potential energy load (Coblentz *et al*., 1994). This correction, applied to elevated or depressed areas, is related to a reference lithosphere without topography and assumes an isostatically-balanced lithosphere. In the high mountain ridges this so-called topographic stress is subtracted from the stresses generated by external tectonic forces (Bada *et al*., 2001). For instance the Alps, which are exposed to high-magnitude of tectonic push, are recently in slight tension due to topographic ex-

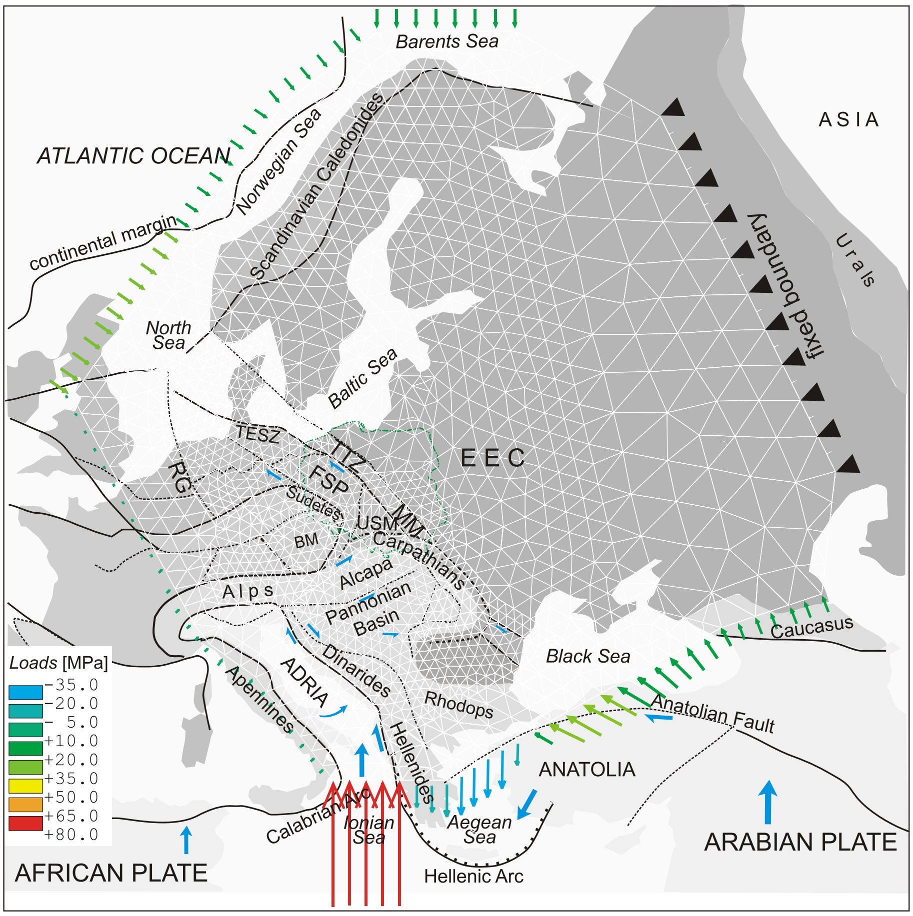

Fig. 9. Mesh of the FEM model (after Jarosiński *et al.*, 2006) overlying the tectonic sketch of Europe (after Berthelsen, 1992, changed)

Arrows are modelling results showing the configuration of forces, for which the calculated stress distribution fits best to the WSM data. These loads represent set of external forces governing the stress field in Central Europe. Inward and outward directed arrows designate compression and tension, respectively. Sizes of arrows are proportional to the loads; arrow color represents the absolute load magnitude averaged over 100 km thick lithosphere; BM — Bohemian Massif, EEC — East European Craton, FSP — Fore-Sudetic Platform, MM — Małopolska Massif, RG — Rhine Graben, TTZ — Teisseyre-Tornquist Zone, USM — Upper Silesian Massif, TESZ — Trans-European Suture Zone

tension (Selverstone, 2005). The lithospheric thickness and Young's modulus between tectonic blocks were varied to evaluate the maximum stiffness contrast, for which one may arrive at a satisfactory model solution. To examine the significance of single factor like active faults, topography or stiffness contrast on the predicted stress, the complexity of the model was successively increased, from the simplest without any of these factors to the most complex, combining all of them. After hundreds of "trial and error" computation rounds, satisfactory model solution was obtained that is characterized by a unique balance of external tectonic forces. For the purposes of this modelling study the absolute values of these forces are of secondary importance to the differences between forces acting on the various boundary segments of the model.

Results of modelling show that the kinematics of the Adria indenter exerts a fundamental influence on the predicted stress field in Central Europe. An observation is in agreement with the results obtained by Bada *et al.* (1998). The advancing African Plate pushes Adria northward with the force of 9×10^{12} Nm^{-1} (Fig. 9), resulting in dextral translation along the Dinaride suture (Jarosiński, 2004; Jarosiński *et al.*, 2006). The eccentricity between the Ionian Sea push relative to the buttress of the Alps, results in counterclockwise rotation of Adria. This rotation is responsible for additional compression propagating across the Pannonian Basin and the Carpathians to the distant foreland of the North European Plate. The modelling results indicate that the Apennine boundary of the Adriatic Block provides only a minor contribution to this compression, as much as the tectonic loads associated with this segment are less than 0.5 x 10^{12} Nm^{-1}. Significant tension in the Greece-Aegean segment (2.5 x 10^{12} Nm^{-1}) implies that active pull is produced within the Hellenic subduction zone. This Aegean extension opens additional space ahead of the Adria indenter, enhancing tectonic escape of the Alcapa and Tisa blocks. Tectonic pressure exerted to the Black Sea segment is four times weaker than this exerted to the short Ionian Sea segment. The fast northward advance of Arabia causing escape of Anatolia has only a secondary influence on the stress field in Central Europe, what can be explained by an effective compensation of this push within the Caucasus and Pontides.

Variability in the tectonic loads acting along the NW passive margin system is also constrained by our modelling results. We find compression in the range of 1.4–1.2 x 10^{12} Nm^{-1} acting across the North Sea segment which is significantly higher than the load of 0.8 x 10^{12} Nm^{-1} acting on the Norwegian Sea segment. This rapid modification of ridge push at the passive margin appears to be important factor controlling gentle bend of stress trajectories in the Polish part of the EEC. This northeastward decrease of ridge push, predicted by the modelling, is consistent with theoretical considerations, which postulate that younger oceanic plates produce a reduced ridge push force (Turcotte and Schubert, 1982; Andeweg, 2002). An opposite trend is predicted for the Barents Sea segment, suggesting that the push of the Arctic Ocean is greater than the northernmost Atlantic. The best results were achieved with the intracontinental French-British segment represented as a free boundary, implying that only insignificant tectonic stresses are transmitted from Western Europe to Poland in direction of S_{hmin}.

The absolute values of forces and stresses given below should be treated as the first-order approximation. The calculated tectonic forces in direction of the S_{Hmax} for Poland are relatively stable and close to 1.0 x 10^{12} Nm^{-1}. Averaging these forces over the variable lithospheric thickness, used in this numerical model, gives the mean tectonic component of S_{Hmax} in the range of 15–30 MPa. The general rule is that the magnitude of S_{Hmax} decreases eastwards from the Fore-Sudetic Platform to the EEC. The modelling results show that except for the limited part of the Carpathians in the rest of Poland the S_{hmin} is compressive (Fig. 10). It implies that magnitudes of the horizontal differential stresses are weaker than S_{Hmax} and range from 5 MPa to 20 MPa. Modelling results give also some predictions, as to which tectonic zones are prone to reactivation. For Poland, weak tendency for reactivation is obtained for the Sudetic Boundary Fault, the Pieniny Klippen Belt suture and the southern marginal fault of the TTZ. Moderate friction coefficients in the range of 0.4–0.5 where assumed for slightly active faults. These coefficients are higher than obtained for the Pannonian region where active strike-slip faults should have friction lower than 1.5–2.5 (Jarosiński *et al*., 2006).

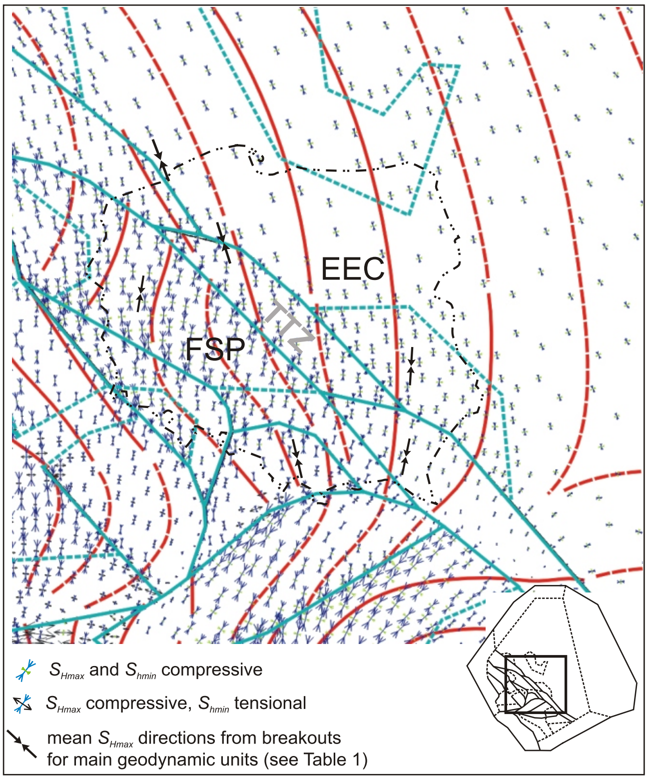

Fig. 10. Stress distribution in Poland and adjacent areas computed by finite element method (after Jarosiński, 2006)

Location of this detailed view within the whole model is shown in the lower right corner of this figure. In the case of stress partitioning within the lithosphere average direction are indicated. Arrows show horizontal tectonic stress components S_{Hmax} and S_{hmin}, averaged over the lithospheric thickness. Arrow lengths reflect relative stress magnitudes. Blue solid lines represent fault zones, blue dashed lines indicate boundaries without dislocations of tectonic blocks, defined using mechanical and thermal criteria. Red lines represents S_{Hmax} trajectories based on the World Stress Map data; red dashed — hypothetical trajectories

MECHANICAL LAYERING OF THE LITHOSPHERE AND LIMITS ON TECTONIC STRESSES OBTAINED FROM RHEOLOGICAL MODELLING

Rheological modelling was performed for the northern and western part of Poland in order to predict the plausible strength profiles, which can be used to place limits on the maximum magnitude of differential stresses in the lithosphere (Jarosiński and Dąbrowski, in press). Forty 1D rheological models were developed along the POLONAISE and LT deep seismic sections (Guterch *et al*., 1994; Guterch *et al*., 1999), which provided constraints on the structure of the crust and upper mantle (Fig. 11A). The investigated area is characterized by strong thermal and structural contrast across the TTZ. The first modelling step is the reconstruction of temperature profiles, which are essential for strength envelopes calculation. Temperature modelling was based on a steady thermal state assumption and Fourier's equations supplemented by heat production formula. Several other assumptions and boundary conditions for computing of rheological profiles were presented by Jarosiński *et al*. (2002*a*) and Jarosiński and Dąbrowski (in press). The main set of thermal data including surface heat flow was taken after Hurtig *et al*. (1992) and Karwasiecka and Bruszewska (1997). One of the most important findings of thermal modelling is that the radiogenic heat production in the upper crust of the EEC and TTZ is significantly smaller than in the Fore-Sudetic Platform. This result allows identification of the probable boundary between the Baltica-derived terranes and the Avalonian terranes, which is hidden deeply below the post-Silurian sedimentary cover (Jarosiński and Dąbrowski, in press). The large horizontal gradient of heat flow and structural contrast across this boundary should cause pronounced weakening of the lithosphere.

Strength envelopes were modeled for constant strain rate across the lithosphere, assuming brittle and viscous deformation, depending on temperature and pressure (Ranalli, 1995). The strength of the brittle layers is expressed by frictional Coulomb-Navier criteria (Sibson, 1974; Byerlee, 1978) while resistance against ductile deformation is given by the power law creep function (Kirby, 1977). Material parameters for this function were averaged for each layer as a geometrical or arithmetical mean of lithological components (Ji and Xia, 2002). The paucity of measured strain rates in Poland necessitates the use of a range of plausible values. Therefore strength envelopes were calculated for reliable options of the bulk strain rate: $10^{-17}s^{-1}$ and 10^{-16} s^{-1} which may be designated to the old craton (EEC) and young Palaeozoic Platform, respectively.The overall modelling results are remarkably consistent within large-scale tectonic units like the EEC, TTZ and the Fore-Sudetic Platform (some examples in Table 2). The EEC is characterized by a high integrated strength of the lithosphere, which is characterized by a strong crust and weak mantle lithosphere. The whole EEC profile is coupled. The TTZ has transitional lithospheric thickness and intermediate heat flux from the mantle, slightly exceeding heat production in the crust. Moderate strength of the lithosphere is shared more or less equally between the crust and the mantle. The mechanical decoupling systematically occurs in the base of each crustal layer, beginning from the upper crust. The Fore-Sudetic Platform has the

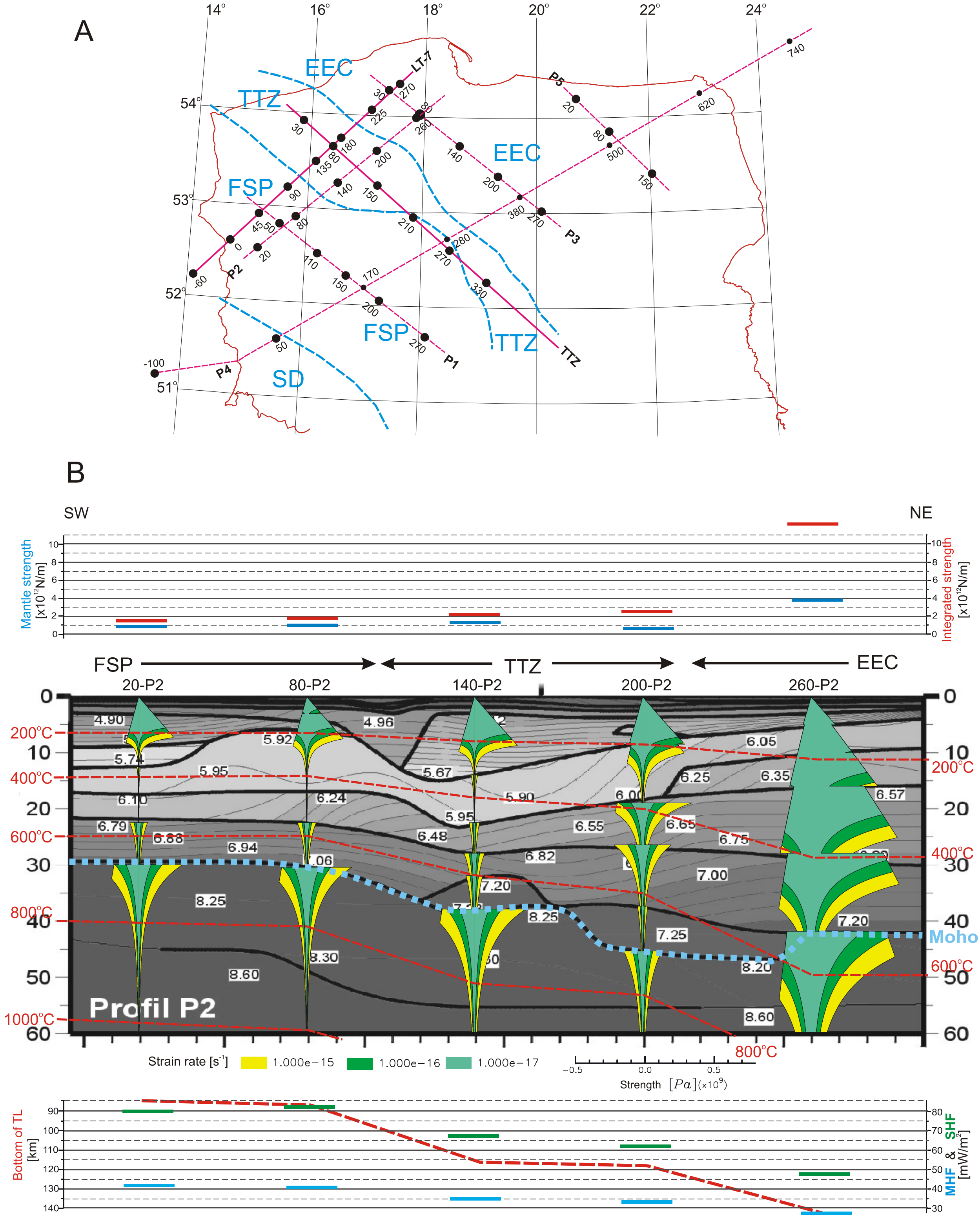

Fig. 11. A — location of the POLONAISE deep seismic sounding profiles and the 1D rheological models calculated by Jarosiński and Dąbrowski (in press), using the *RHEOL* computer program; B — rheological and thermal models along the P2 profile shown against modelled distribution of P-wave velocity in km x s^{-1} (for location see Fig. 11A)

Lithospheric strength profiles are shown for three alternative strain rates. The diagram above the profile shows integrated strength of the lithosphere and the mantle. Below the profile thermal regime of the lithosphere is characterized; TL — thermal lithosphere, MHF — mantle heat flow, SHF — surface heat flow. See Figure 1 for explanation of tectonic units abbreviations

Table 2

Mechanical properties of the lithosphere derived from thermal, rheological and FEM modelling after Jarosiński *et al*. (2006) and Jarosiński and Dąbrowski (in press)

Units	TTL* [km]	Sf** 10^9[mMPa]	ISL*** 10^{12}[Nm^{-1}]	ISC vs. ISM ****	Comments
EEC	140–170	9	8–20	0.8–1.3 (>) 1.0–3.2	coupling of the lithosphere, gentle changes of S_{Hmax} directions
TTZ	105–120	3.6	2.2–6.5	1.8–2.6 (≈) 1.3–3.9	possible decoupling of upper crust, common S_{Hmax} rotations
FSP	85–110	1.5	1.5–4.0	5.6–8.4 (<) 3.2–6.7	effective decoupling of the upper crust from the mantle, tectonic stress relaxation

* — thickness of thermal lithosphere (bottom temperature 1300°C); ** — stiffness assumed for elastic FEM model; *** — integrated strength of the lithosphere from rheological modelling; **** — relation between the crustal and mantle strength from rheological modelling

thinnest lithosphere in the range of 85–110 km. The highest mantle heat flux is in the range of heat production within the crust. Very low lithospheric strength is maintained by relatively stronger mantle lithosphere. The entire middle and lower crust seems to be mechanically weak.

Presented models are not the only possible solutions for the lithosphere in Poland. For example, taking into account climatic changes after last glaciation (Majorowicz *et al*., 2003) estimation of the surface heat flow may raise by 10–30%. It can be crucial for the EEC where increase of heat flow by 20% may decrease the integrated strength by *ca*. 50%. It clearly shows that areas of positive surface heat flow anomalies within the craton are especially prone to deformations. Another alternative that should also be considered is dry rheology of the mantle instead of the mixed dry/wet used in the models. Applying dry rheology for the weakest lithosphere of the Fore-Sudetic Platform can raise the integrated strength by *ca*. 60% and make it strong enough to sustain expected tectonic loads. This solution seems to be more reliable for this part of the lithosphere, which bears no sign of deeply rooted deformations due to the Laramide inversion of the Mid-Polish Trough (Jarosiński *et al*., 2002*b*). It should be stressed that present models show only potential mechanical property of the lithosphere under a number of assumptions, which, at the time being, are not constrained by good quality data.

CONSISTENCY BETWEEN DIFFERENT TYPES OF DATA AND MODELS

Broad range of stress analysing methods presented here can be used to evaluate the consistency between results of different measurements and models. It appears that collected sets of results are rather complementary than overlapping. For example, stress directions were provided by borehole breakout data while the hydraulic fracturing tests (without registration of fracture orientation) aimed solely at assessment of stress regimes. In turn, the 2D plane modelling gives the average stress distribution over elastic part of the lithosphere (assuming its vertical homogeneity), which is independent on time and temperature, while 1D rheological models examine viscous and plastic rock behaviour in vertical lithospheric profiles including temperature, pressure and strain rates. FEM model was designed to reproduce the stress measured around the boreholes, however, one should emphasise the scale gap between the model's element (several tens of kilometres) and the borehole diameter (several inches). Focal mechanism and intraplate motion data provide additional element to this geodynamic puzzle, however, their usefulness is limited by paucity of records or frequent incoherence between data. For instance, multiple earthquakes from one location reveal different stress directions or stress regimes. Because of these differences between datasets consistency of measurements should be judged first of all by comparison with the wider geodynamic context.

CONSISTENCY BETWEEN RESULTS OF MEASUREMENTS

The S_{Hmax} directions acquired from breakout analyses in Poland bridge the gap between the Scandinavian and Pannonian stress domains (Stephansson *et al*., 1991; Gerner *et al*., 1999), although stress data in the Central Carpathians are still not available. Stress directions for Eastern Poland follow the arc-shaped distortion of the S_{Hmax} trajectories from the North Sea to the southern part of the Pannonian Basin (Figs. 1 and 6). A similarly consistent trend of the S_{Hmax} directions can be observed in the Western Carpathians across the Czech-Polish border (Peška, 1992). More ambiguous is the stress transition from the Fore-Sudetic Platform in Poland to the North German Basin. Although in both areas stress partitioning across the Zechstein salt layer is postulated (Roth and Fleckenstein, 2001; Jarosiński, 2005*a*), S_{Hmax} directions vary substantially between structural levels. The NNE–SSW S_{Hmax} direction in the Mesozoic cover in Poland is very much like those in the Palaeozoic basement in Germany. Likewise, the NW–SE S_{Hmax} direction in Palaeozoic basement in Poland is similar to this determined for the Mesozoic cover in Germany. This reverse juxtaposition of stress directions between structural levels needs to be explained in the future, however modest stress dataset from beneath the salt layer in Poland should be expanded first.

It should be emphasised that focal mechanism data for the natural earthquakes confirm the results of hydraulic fracturing analysis from adjacent boreholes. Both sets of data from Central and Eastern Poland (and adjacent Kaliningrad area) reveal strike-slip stress regime transitional to a thrust fault regime in the Outer Carpathians. For Outer Carpathians S_{Hmax} directions from focal mechanisms of shallow earthquakes match well with stress directions inferred from breakout data for the Upper

Silesian and Małopolska segments. However, two extensional focal mechanisms from the deeper basement show inconsistent, almost perpendicular S_{Hmax} directions. This apparent contradiction can be explained by two coexisting mechanisms of deformation in the basement, namely bending-related extension, which might come along with extension transversal to compression. These results suggest that in the central part of the orogen Alcapa exerts compression directly to the nappes, while the basement undergoes extension. It evokes mechanical decoupling between the nappes and the basement and significant component of bending-related extension in the basement. Also in the case of mining-induced tremors in the Fore-Sudetic Platform two-fold S_{Hmax} directions resemble these determined from breakouts for the central part of this platform.

Coincidence between stress directions and intra-plate motions is remarkable, when taking into account significant error bars of geodetic measurements (Fig. 8). The angular discrepancy between S_{Hmax} directions and velocity vectors in the range of 10° for eastern and 30° for Western Poland (and adjacent areas) fit well to the concept of dextral strike-slip along the TTZ. Such conclusion is also supported by breakout rotation and clustering of historical earthquakes along the TTZ (Guterch and Lewandowska-Marciniak, 2002).

It is often claimed that friction on preexisting faults controls the state of tectonic stress in the upper crust (Zoback and Healy, 1992; Scholz, 2004). Taking into account stress profiles from hydraulic fracturing tests (Fig. 6B) and following approach by Sibson (1974) and Ranalli (1995) it is possible to estimate the friction coefficient on preexisting faults that can be reactivated in a recent stress field:

$$\sigma_1 - \sigma_3 = \alpha \rho g z (1 - \lambda);$$

where: $\lambda = 0$ for hydrostatic pore pressure; $\alpha = (R-1)/[1+\beta(R-1)]$ for strike-slip stress regime; $R = [(1+\mu^2)^{1/2} - \mu]^{-2}$ and $\beta = (S_V - S_{hmin})/(S_{Hmax} - S_{hmin})$; σ_1, σ_3 — maximum and minimum principal stress, respectively

Using these formulas for SE Poland, where stress ratios in the upper 4 km are estimated at $S_{Hmax}/S_{hmin} = 1.48$ and $S_V/S_{hmin} = 1.21$ and pore pressure is nearly hydrostatic, gives following values of coefficients: $\alpha = 0.39$, $\beta = 0.42$, $R = 1.46$ and the friction coefficient $\mu = 0.16$. It is extremely low value of μ in comparison with e.g. 0.6–0.75 postulated by Byerlee (1978) from laboratory tests and 0.65 calculated for the KTB scientific borehole (Brudy *et al*., 1997). But on the other hand, this value seems reasonable in comparison with e.g. $\mu < 0.1$ estimated for the San Andreas Fault (Lachenbruch and Sass, 1992). If the stress field in SE Poland and the slip on favourably oriented faults are mutually dependent, than fault friction needs to be low or the pore pressure in fault zones high. However, due to lack of seismicity in discussed area the stress may be controlled by faults reactivation elsewhere (e.g. in the Pannonian Basin) or by aseismic creep.

MODELLING RESULTS VERSUS MEASUREMENTS

The stress predicted by the finite element analysis is in good agreement with the measured S_{Hmax} orientation in Central Europe (Jarosiński *et al*., 2006). This agreement is also present at the regional scale of Poland particularly when the mean directions for geodynamic units are taken into account (Table 1; Fig. 10). In the Carpathians, model properly predicts changes of the S_{Hmax} trends from NE–SW in the Central Carpathians to NNE–SSW in the Małopolska segment of the Outer Carpathians. For the Upper Silesian segment of the Outer Carpathians, where breakout data indicates splitting of stress directions between the basement and nappes, results of 2D modelling show the mean trend of S_{Hmax} for these two structural levels (Fig. 10). Likewise, in the Fore-Sudetic Platform the predicted S_{Hmax} orientation ranges between two directions indicated by both breakout and seismological data (Fig. 10). Stress directions in the Sudetic domain have not yet been confirmed by borehole data, and therefore it is not clear whether NW–SE S_{Hmax} direction from Western Europe is transmitted through the Sudetes to the autochthonous basement of the Western Carpathians (Jarosiński, 1998). This possibility is at odds with the numerical modelling predictions, which indicate N–S oriented compression in this region and also in the Bohemian Massif. NNW–SSE stress directions in the basement of the Western Carpathians can be explained alternatively by accommodation of the sinistral strike-slip between Alcapa and the Eastern Alps (Jarosiński *et al*., 2006) (Fig. 3). Resolution of this ambiguity will be possible with the collection of a significant set of breakout data from the Sudetic domain and the adjacent Bohemian Massif. It is worth emphasizing that S_{Hmax} directions predicted by the model in the central Carpathians are in excellent agreement with these from focal mechanism solution of the Kaliningrad and Podhale earthquakes (Wiejacz and Guterch, pers. comm.), which took place after the modelling study was completed. Taking into account this prediction, and considering also the compressive (strike-slip) stress regime, it is argued that Kaliningrad earthquake was triggered by far-field tectonic forces (Jarosiński, 2006). In general, low seismicity of Poland is in agreement with low intraplate stress magnitudes obtained in numerical modelling.

Hydraulic fracturing tests and the focal mechanism data indicate predominance of the strike-slip stress regime in Poland; a stress field also predicted by the numerical analysis. The existence of an extensional stress regime determined by focal mechanism solution in the central Carpathians has been shown by the modelling results to be due to topographic forces. As it was pointed out in the previous chapter, stress profile in SE Poland (Fig. 6) may be controlled by preferentially oriented strike-slip faults of low friction ($\mu = 0.16$). This is consistent with the results of the numerical modelling, which indicate low friction (μ in the range 0.15–0.25) at the major strike-slip faults in the Pannonian-Carpathian region (Jarosiński *et al*., 2006). Because the stress field in SE Poland is dominated by compression exerted from the south, it can be hypothesised that low friction at faults in the Pannonian-Carpathian region may subdue tectonic stresses also in the considered part of Poland.

The most significant result of 1D rheological modelling indicates places of mechanical decoupling in the crust. Parts of the lithosphere which are strongly coupled are characterized by a more homogeneous stress distribution than in the case of uncoupled lithosphere, where various factors may affect the stress field within the detached layers. Indeed, a strong and coupled lithosphere of the EEC is characterized by gentle variations in S_{Hmax} direction and stable strike-slip stress regime. Dominant stress directions are easily seen in the TTZ, where the whole crust is decoupled from the mantle. However, in the TTZ stresses are probably disturbed due to slight strike-slip activation of this mega shear zone. An extremely weak lithosphere with clear decoupling between layers in the Fore-Sudetic Platform has poor quality stress indicators and highly variable S_{Hmax} orientations. Scarce data suggests extensional stress regime in this region. Such results suggest that weak and mechanically uncoupled lithosphere is not effective in propagating tectonic stresses. This notion contradicts the common expectation that within thinner lithosphere tectonic stresses should be amplified, which is apparently not the case in the nearly relaxed sedimentary cover of the Fore-Sudetic Platform. For this region additional factors might exert a dominant influence on the character of the present-day stress field. Given the available data and information, a plausible hypothesis is that dry and strong upper mantle of this platform sustains tectonic forces and mitigates the crustal stress field. Also the equilibrium between the Alpine push, ridge push and attenuated Alcapa push may result in minor differential stress. The reason for extensional stress regime in this area is still an open question.

COMPARISON BETWEEN LITHOSPHERE RHEOLOGY AND STRESS MODELLING

Comparison of lithospheric strength calculated using rheological modelling with the predicted tectonic forces from numerical study, provide a way to evaluate the consistency between the two models. However, it should be noted that forces incorporated into finite element analysis are responsible for the elastic strain alone. By comparison of lithospheric strength predictions with the level of loading one should know the real strain rates and stress regimes. Because strain rates are still unknown in Poland, only typical values for seismically calm areas, in the range of $10^{-16}s^{-1}$ to $10^{-17}s^{-1}$ can be taken for present considerations (Ranalli, 1995). When the strike-slip stress regime is assumed for the EEC, integrated strength is in the range of 1–2 x 10^{13} Nm^{-1}, what is an order of magnitude grater than the predicted horizontal tectonic forces obtained from FEM modelling. This observation agrees with the fact that the EEC has recently been a stable unit. Results of rheological modelling indicate that tectonic deformation of the craton may occur only when significant thermal weakening and decoupling of the lithosphere is present (Jarosiński and Dąbrowski, in press). In my opinion this is the case of the Kaliningrad earthquake, which was located within the centre of a positive thermal anomaly (Hurtig *et al*., 1992).

Similarly, integrated strength of the lithosphere within the TTZ seems to be several times greater than the predicted tectonic forces. Some present-day instability of this zone can result from stress amplification within uncoupled crustal layers. Only in the weakest part of the Fore-Sudetic Platform the lithospheric strengths (for reliable strain rates) are close to predicted tectonic forces. In such a state, the lithosphere is sensitive to any heterogeneity in mechanical strength and stress amplification due to e.g. partitioning of deformation. Considering tectonic weakening and lithological composition of the lithosphere, the boundary between Avalonia and the TTZ seems to be predestined place of failure (Jarosiński and Dąbrowski, in press). Indeed, along this zone neotectonic fault reactivation and mobilization of salt structures are clustered (Jarosiński and Krzywiec, 2001; Kurzawa 2003; Hałuszczak, 2004). It is also worth mentioning that preferred contrast of lithospheric stiffness between the Fore-Sudetic Platform and the EEC predicted by FEM model is comparable to the contrast in integrated lithospheric strength between these units obtained from rheological modelling (see Table 1).

SUMMARY

During the last ten years application of new methodology to investigate the present-day geodynamics of Poland has resulted in significant progress towards understanding the character of tectonic stress field. The analysis of borehole breakout and hydraulic fracturing data supplemented by modelling results, allow for discrimination of several areas of different but comprehensive stress field characteristics.

Stress pattern in the Małopolska segment of the Outer Carpathians and their basement points to co-axial NNE-directed tectonic push from the central Carpathians. This push is transmitted towards the sedimentary cover and to the top of the crystalline basement of the craton, causing constant stress direction in the Lublin Basin. Due to mechanical coupling of the EEC's lithosphere the S_{Hmax} directions change gradually towards interior of craton. Recent tectonic stresses can exceed the strength of the lithosphere only where the EEC is overheated, as shown by the Kaliningrad earthquake triggered by far-field forces within the centre of positive heat flow anomaly. Northeastward increase of the Mid-Atlantic ridge push component of stress field is responsible for smooth distortion of the S_{Hmax} in NNW–SSE direction in the Baltic part of the EEC. For the entire Eastern Poland, being under influence of the Alcapa push, strike-slip stress regime is inferred with possible secondary deviation towards trust-fault within the Outer Carpathian Nappes.

The TTZ is characterized by frequent S_{Hmax} rotations in the range between N–S and NW–SE. This stress pattern together with the clustering of historical earthquakes along the TTZ borders is interpreted as the result of strike-slip accommodation of the Carpathian push at the edge of craton. Stress perturbation and seismic activity are possibly enhanced by mechanical uncoupling between the upper and the middle crust. Stress direction is relatively stable only in the offshore part of the TTZ implying that strike-slip compensation of tectonic push is taken over by another fault zone. Vectors of the intraplate motions support the idea of dextral strike-slip along the TTZ. In the Upper Silesian segment of the Outer Carpathians tectonic push is accommodated in thin-skinned style, what is expressed by stress partitioning between the nappes and their basement. Autochthonous basement reveals the S_{Hmax} directions characteristic for the West European stress domain. The area influenced by the Alcapa push, including the EEC and the Małopolska Massif, is incorporated into the Fore-Carpathian stress domain (Jarosiński, 2005*a*).

Within the Fore-Sudetic Platform scarce data reveals an inhomogeneous stress field. Best quality data points to NNE–SSW directed compression above Zechstein salts while poor quality data suggests NW–SE S_{Hmax} direction below the salts. An extensional stress regime with deviation towards strike-slip is suggested for Western Poland from single hydraulic fracturing test and majority of mining-induced tremors. Heterogeneity of the stress field and probably low horizontal differential stress may result from the interplay between three factors, namely Alpine push, attenuated Carpathian push and the Atlantic ridge push. Due to mechanical decoupling within hot lithosphere in the Fore-Sudetic Platform different factors may dominate stresses in different crustal layers.

Based on cumulative stress profile from hydraulic fracturing tests in SE Poland, it was assessed that the state of stress is in equilibrium with preferentially oriented faults of low friction coefficient $\mu = 1.6$.

Although preliminary results of measurements of the intraplate horizontal motions suffer from substantial errors, the directions of velocity vectors generally follow S_{Hmax} trajectories, revealing systematic deviations at local scale. This suggests that stresses are controlled by the first order tectonic forces, which control also tectonic block movements.

Development of modelling techniques allows numerical testing of hypothesis and quantification of tectonic forces and stresses. The use of a finite element stress analysis for Central Europe provided the means to evaluate the influence of far-field tectonic forces on the stress field of Poland. Tectonic push of Africa transmitted through the narrow corridor of the Ionian Sea and the Adria indenter towards Central Europe is identified as the most important stress-controlling factor in Eastern and Central Poland. In Northern Poland, influence of the Atlantic ridge push transmitted across the European passive margin is more significant. Also variations of tectonic forces between separate segments of collision zone and passive margin influence stress pattern in Poland. Rheological modelling across the TTZ demonstrates potential mechanical contrasts between lithospheric layers. Lithospheric strength from rheological profiles compared to calculated levels of tectonic forces in numerical modelling indicates that the Fore-Sudetic Platform and its border with the TTZ is recently the most unstable part of Poland.

Although results of presented analyses can be integrated into a coherent theory of present-day geodynamics of Poland, they also raise questions, which will become the topic of future research efforts. The most problematic is the Sudetic domain, where lack of borehole data and incoherent results of repeated GPS measurements (Cacoń *et al*., 2004) preclude determination of both the stress directions and stress regimes. The situation is not much better in the Fore-Sudetic Platform. However, breakout analyse perspectives look promising as a good deal of new 6-armed caliper data is acquired by oil industry every year. Combination of breakout data with analyses of rock strength should enable constraining stress regimes in many boreholes. This point is vital because new hydraulic fracturing tests have not been performed for several years. Stress propagation within rheologicaly layered lithosphere should be reproduced satisfactorily in 3D thermo-mechanical model, however, its construction in the future requires more experience in 1D and 2D modelling and more complete constraints on structure, lithological composition and thermal state of the lithosphere.

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