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The recent crustal stress field in Central Europe sensu lato and its quantitative modelling

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Abstract

A detailed pattern of trajectories of the direction of maximum horizontal crustal stresses S_{Hmax} has been derived for Central Europe sensu lato according to actual data on fault plane solutions, in-situ stress measurements, geologic fault slip determinations and geodetic information. The generalization of this direction data on maximum compressive stress in the form of trajectories shows a bending from the well-established NW-SE direction in western parts of the study area to directions of NE-SW to E-W in the eastern part. In some regions there is evidence for a more complicated pattern, e.g. apparently differing S_{Hmax}-directions in different depth horizons, stress deflections at pronounced tectonic complexes, and radial directions around the Pannonian Basin. For studying the conditions in the brittle part of the crust steady-state elastic finite-element model calculations were carried out to explain the observed stress orientations. It is shown that the simulation according to a modern plate tectonic concept leads to a pattern of main principal stress directions that is compatible with the generalized observed stress directions. More regional features were modelled by reasonable variation of elastic parameters of different lithospheric blocks.

Introduction

The World Stress Map (WSM) project, initiated in 1986 under the auspices of the International Lithosphere Program, has brought a considerable increase of knowledge on the recent tectonic stress field in the Earth's lithosphere. According to the WSM data base the intraplate stress field of western Central Europe is characterized by a NW-SE orientation of maxi-mum compressive horizontal stress S_{Hmax}, which was described already by *Ahorner* (1975). Only relatively few data are available for the eastern part of Central Europe where the orientation of S_{Hmax} suggests a NE-SW direction. A finite-element modelling (*Grünthal & Stromeyer* 1992) shows that this first-order stress pattern can be explained by driving forces acting on the boundaries of the Eurasian plate, where locally stress variations are related to inhomogeneous lithospheric properties.

This paper presents an update of the *Grünthal & Stromeyer* (1992) data set and an actualized finite-element modelling of the recent crustal stress field of Central Europe sensu lato. The aim of this paper is to give a general consideration of newly derived data and especially to improve the presently limited know-ledge on the stress field of the eastern part of the study area. The new data include S_{Hmax}-directions derived from in-situ stress measurements in Thuringia (central Germany), in the north-eastern part of the Czech Republic, in south-eastern Hungary, and S_{Hmax}-data according to fault plane solutions or centroid moment tensors of several recent earthquakes; among them the Roermond earthquake of April 13, 1992 (*Braunmiller et al.* 1994). According to the additional data, the details of the pattern of S_{Hmax}-trajectories could be improved especially in the eastern part of the study area. The new model calculations consider extensional features within the Pannonian Basin as well as its northwestern margin and shear zones at the north-eastern margin of the Bohemian Massif.

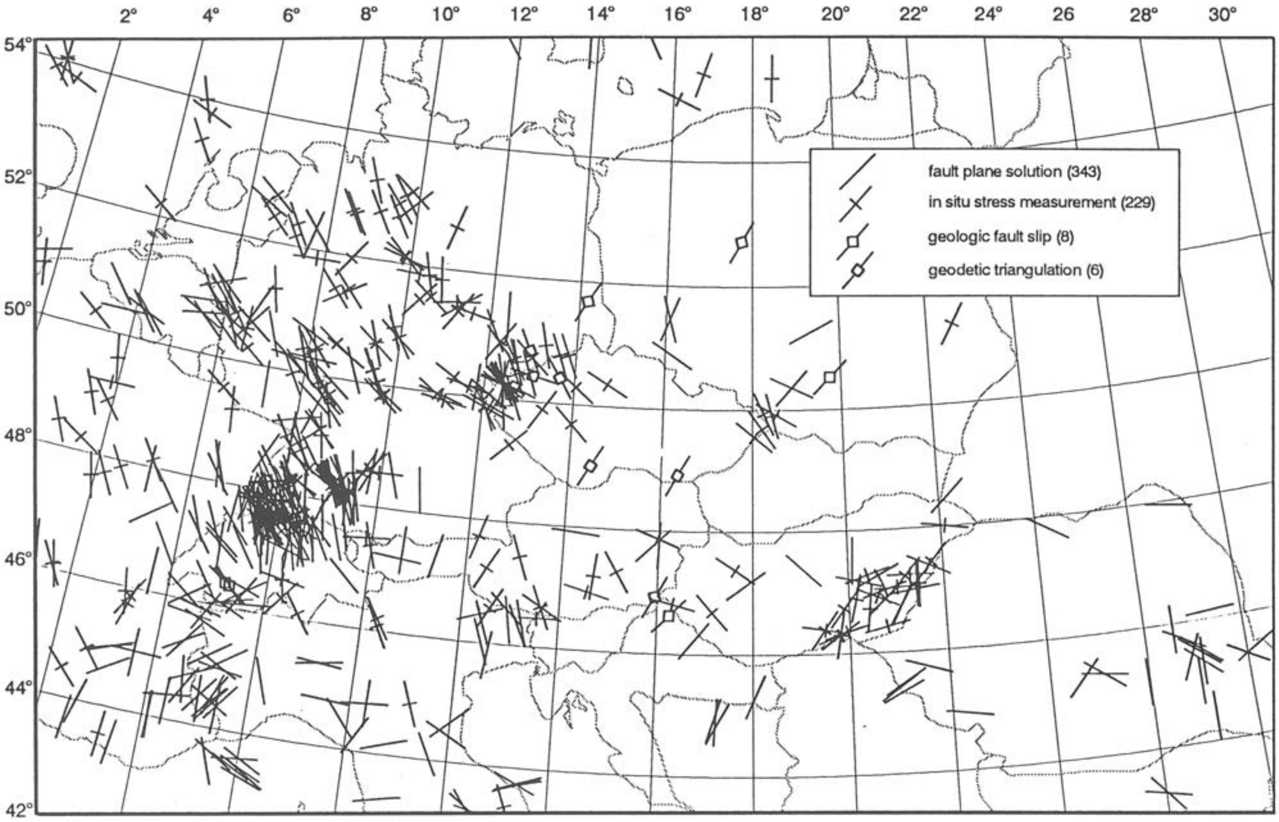

Figure 1. Direction of maximum horizontal compressive crustal stress, S_{Hmax}, in Central Europe sensu lato.

Data

The recent crustal stress field of Central Europe sensu lato (Fig. 1) is presented in terms of the direction of maximum horizontal stresses S_{Hmax}, the only stress parameter for the Earth's crust which is available with sufficient reliability and quantity. The compiled data are based on fault plane solutions, in-situ stress measurements, geologic fault slip determinations and repeated precise geodetic triangulations. The methods and constraints of the azimuth determination of S_{Hmax} have been summarized by *Zoback* (1992) for the different techniques mentioned. A detailed description of the data available up to 1990 has been given by *Müller et al.* (1992) for the western part of the study area, and by *Grünthal & Stromeyer* (1992) for the central and eastern part.

The generalization of all observations in the form of S_{Hmax}-trajectories, considering the quality of the data according to the quality ranking system of the WSM project, is shown in Fig. 2. This figure also contains some first-order tectonic information, as main first-order tectonic faults and indications for crustal extensional regimes. The generalized trajectories fit nearly all stress data. Their dominant features are (1) the NW-SE directed compression in western Central Europe, (2) the fan-like pattern perpendicular to the Western Alpine arc, (3) an obvious rotation of S_{Hmax} to NE-SW when approaching the eastern part of the study area, (4) additional rotation to E-W east of the Pannonian Basin, (5) a radial pattern around the Pannonian Basin, (6) stress deflections in and around the Bohemian Massif, and (7) apparently two different stress directions in at least the western and central parts of the North-German plain. There are evidences that the NW-SE direction represents a more shallow horizon, while the NE-SW pattern seems to prevail at greater depths. The trajectory pattern strongly suggests that the northwards directed compressive push of the African plate through the Adriatic promontory governs the stress conditions in Central Europe.

Four fault plane solutions in the Lower Rhine Embayment provide the most western indication for the deviating S_{Hmax}-direction, i.e. a change in orientation from the generally observed NW-SE S_{Hmax}-trend in western Central Europe to NE-SW in north-eastern and eastern Central Europe. Other evidence for this change in direction comes from the fault plane solution of the Ibbenbühren earthquake in 1981 (52.26N, 7.71E), the Soltau-Munster earthquake in 1977 (52.94N, 9.94E), and quality A stress measurements (best quality according to the WSM

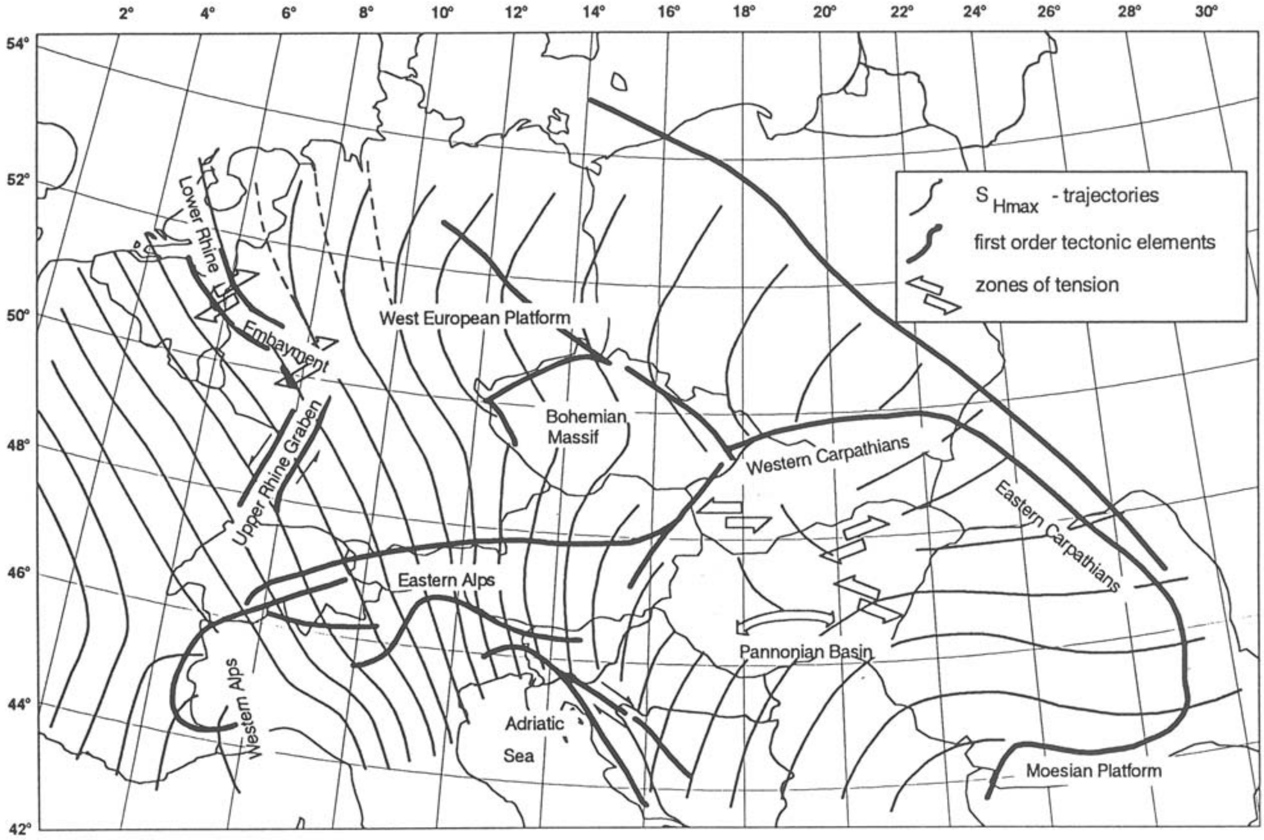

Figure 2. Pattern of S_{Hmax}-trajectories generalizing the stress directions (Fig. 1) in the study area. Hatched trajectories in the North-German plain represent an alternative interpretation of the direction (for explanation see text).

quality ranking system) from a deep borehole (3200 m) at 52.67N, 11.00E. Furthermore, four of the eight newly published in-situ data from Thuringia (*Bankwitz et al.* 1993) also show this NE-SW direction (two have an E-W orientation). These measurements were carried out at depths of 200-800 m, partly in different wells in close geographic proximity. In three of them two independent measurement techniques were applied with comparable results; their quality ranks are in no case worse than B.

All these NE-SW, and clearly deviating, direction data are presented in detail in Fig. 3. They correspond to the observed S_{Hmax}-orientation data in Poland (Fig. 1), and to those from high quality in-situ measurements in southern Sweden (*Müller et al.* 1992), as well as to those from newly well-constrained fault plane solutions for southernmost Sweden (Skåne) according to *Muir Wood* (1992). Further to the east and southeast, this NE-SW S_{Hmax}-trajectory pattern is confirmed by data in Slovakia, eastern Hungary, Serbia, the Dinarides, and the border region between Serbia and Romania (from well-constrained centroid moment tensors of a recent series of earthquakes with magnitudes M > 5.1; M.-C. Oncescu pers. comm.).

Finite-element modelling

Steady-state elastic finite-element model calculations were carried out for interpreting the observed S_{Hmax}-directions representative for the brittle part of the crust in the study area. The entire western Eurasian plate was taken into consideration for this modelling. The plate tectonic scheme of this larger area is shown in Fig. 4, while Fig. 5 presents the corresponding finite-element mesh. Moreover, Fig. 5 presents schematically also the plate tectonic forces acting on the boundaries of the western Eurasian plate for this larger area. The forces are: 1) ridge-push from the central and northern segments of the Mid-Atlantic ridge, 2) the northwards directed push of Africa with respect to Europe (which can be deduced from a northward directed motion of Africa with respect to Europe during the last 45 million years; *Biju-Duval et al.* 1977), and - as an innovation in comparison to our previous modelling - 3) the westward motion or push, respectively, of the Anatolian and Aegean microplates. The length of the arrows in Fig. 5 reflects the relative magnitude of the plate boundary forces. Absolute values of forces could be ignored, since the modelling is restricted to

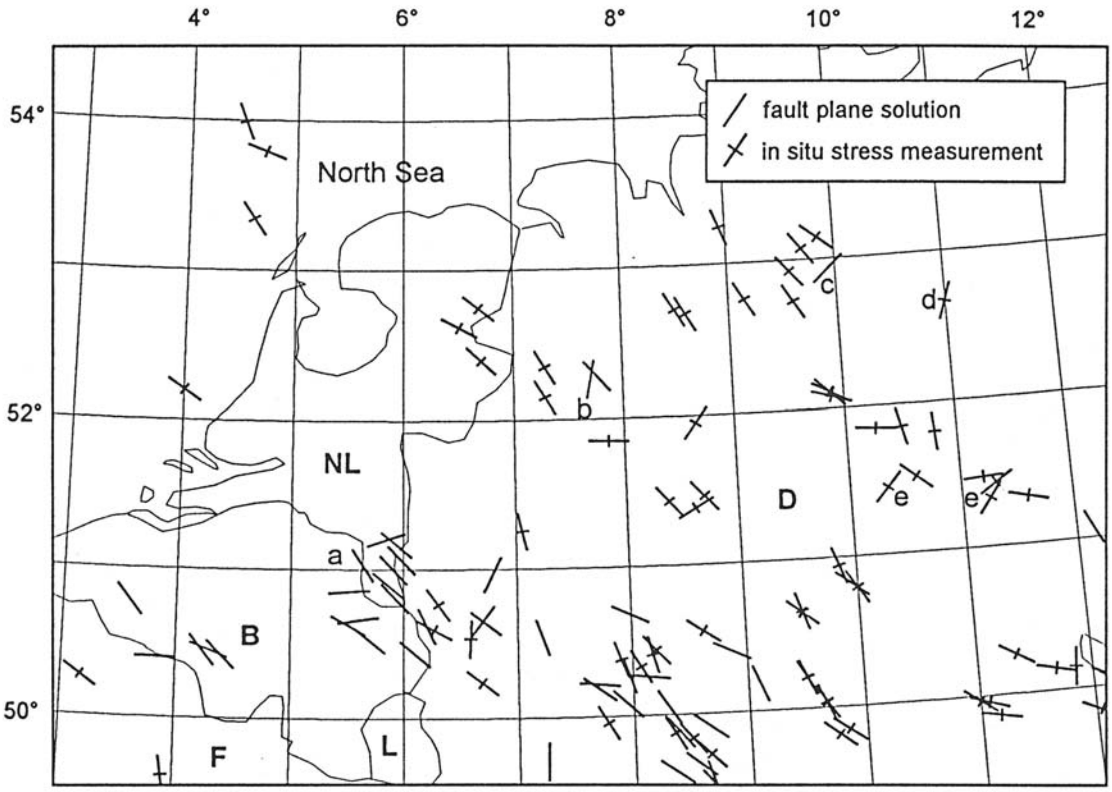

Figure 3. Details of S_{Hmax}-directions in the Benelux countries and in northern Germany. The indicated data present observed directions (a-c derived from fault plane solutions of earthquakes, d and e according to hydro-fracture data) deviating from the general NW-SE trend: a, Lower Rhine Embayment, b, Ibbenbüren, c, Soltau, d, Salzwedel, e, after *Bankwitz et al.* (1993).

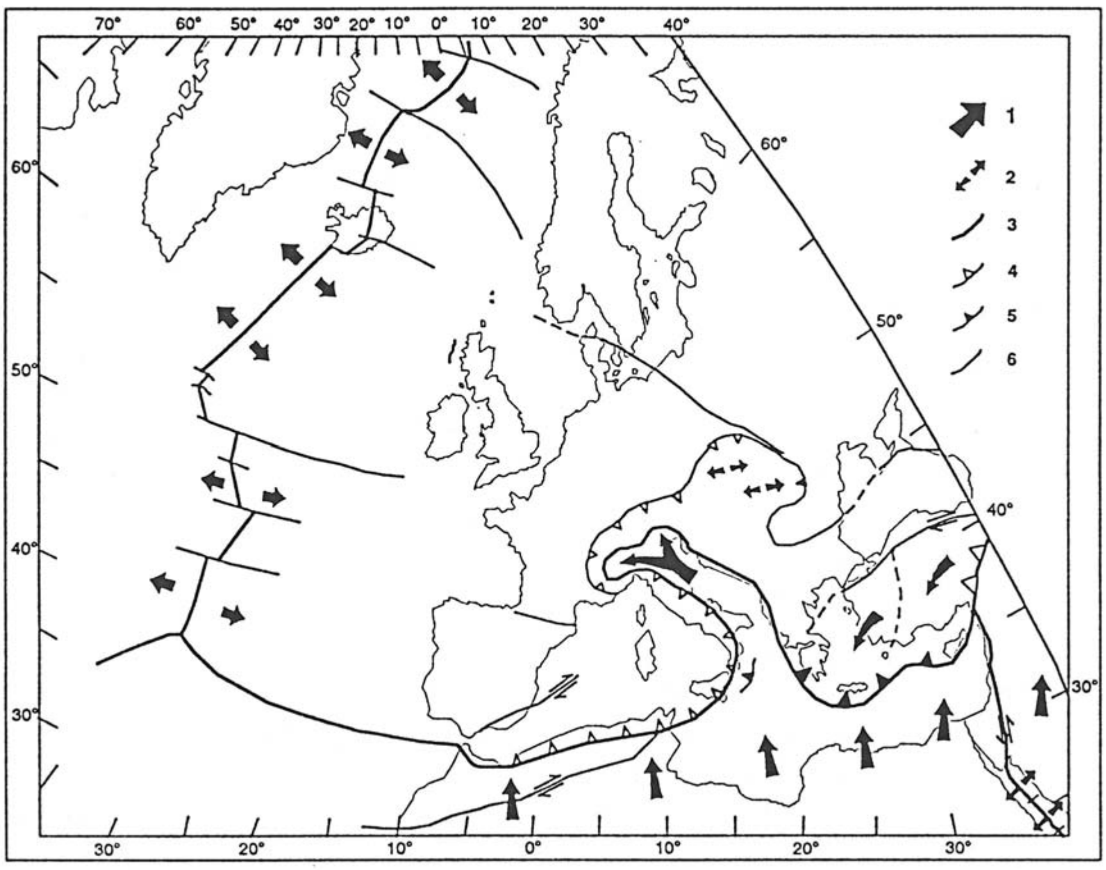

Figure 4. Plate tectonic scheme of the western part of the Eurasian plate. 1, direction of vector of motion relative to Europe and/or assumed main acting forces at the plate boundary; 2, extensional tectonic regime; 3, main plate boundaries; 4, subduction; 5, thrust and collision; 6, other first-order faults with sense of shear motion.

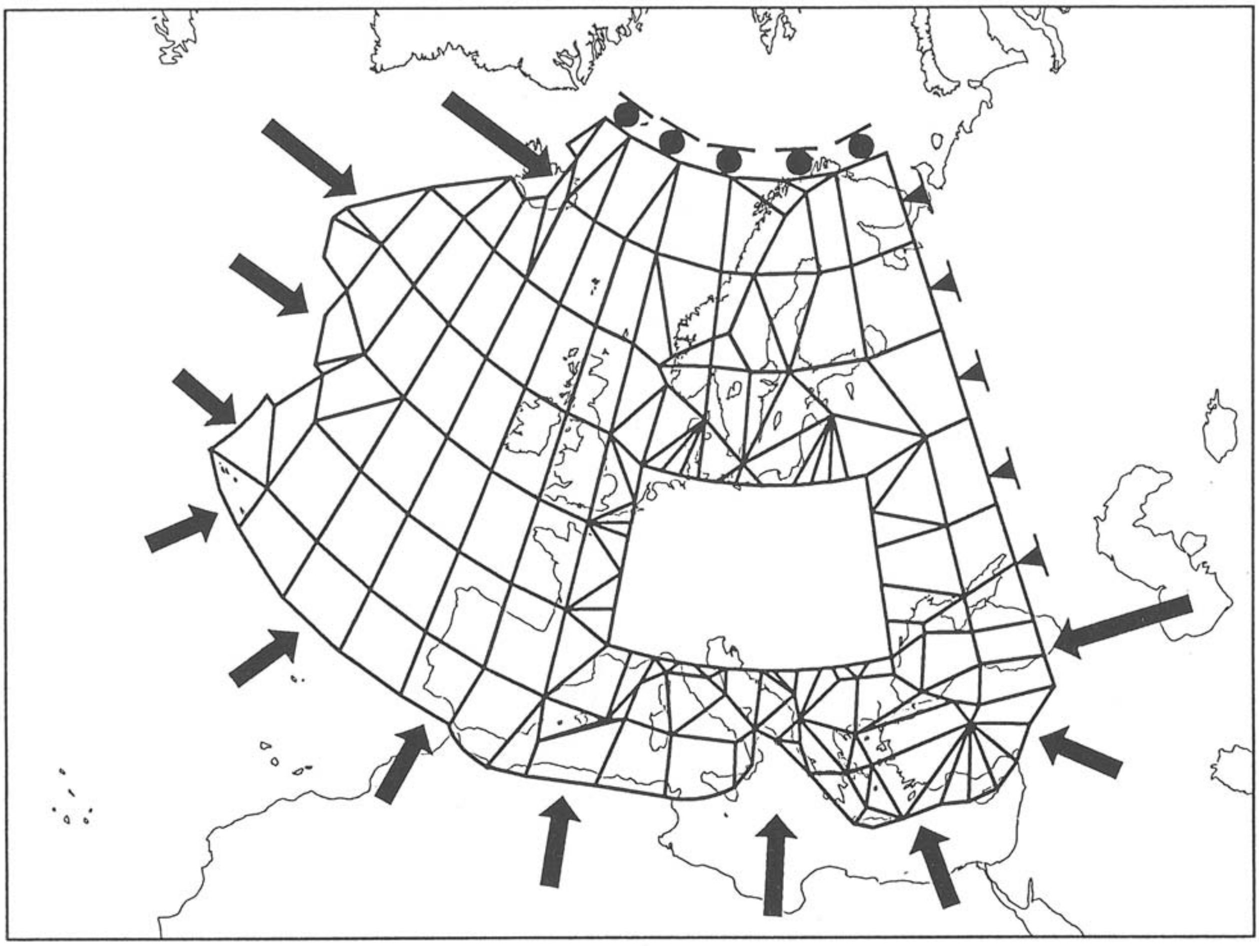

Figure 5. Finite-element mesh for western Eurasia and the distribution of net boundary forces. The study area in Fig. 6 appears as the central box. The schematically indicated boundary conditions are explained in the text.

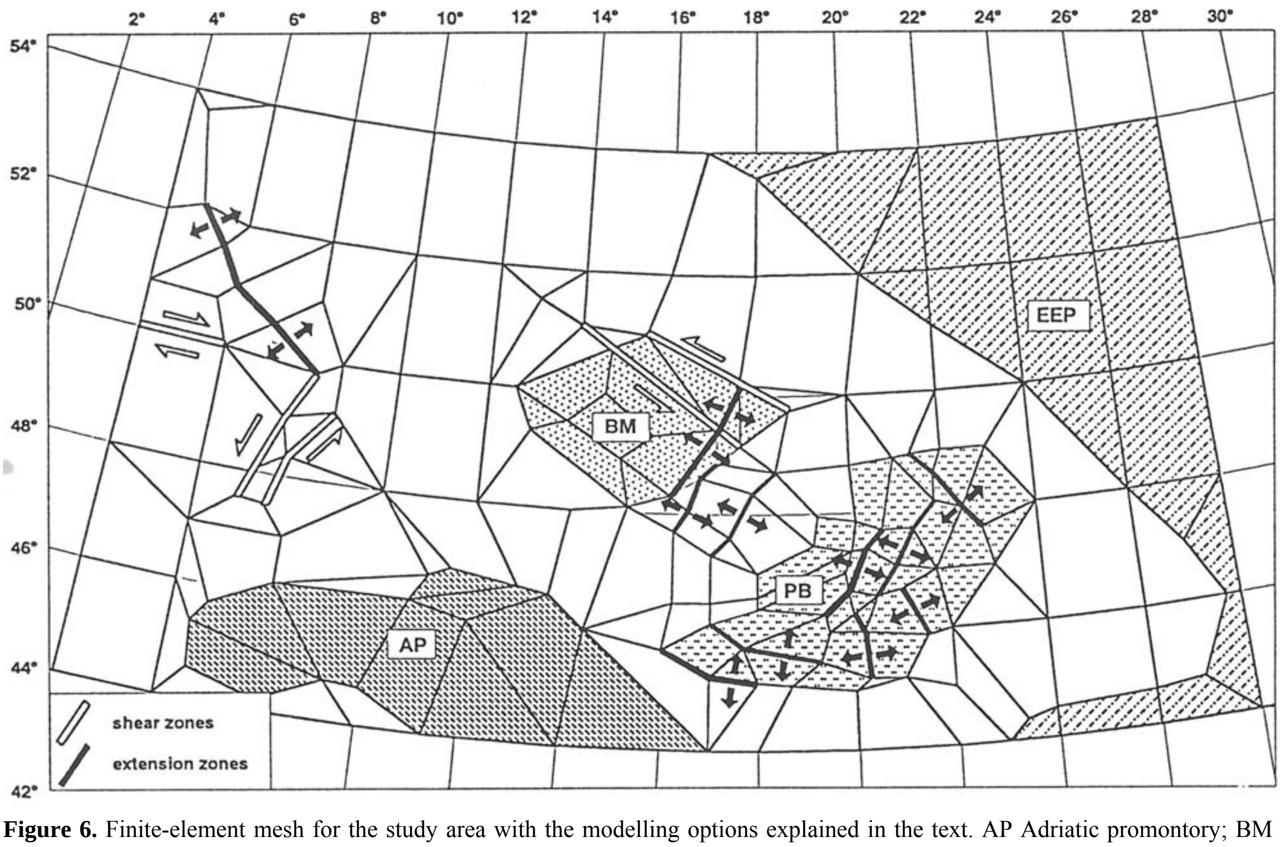

Figure 6. Finite-element mesh for the study area with the modelling options explained in the text. AP Adriatic promontory; BM - Bohemian Massif; PB - Pannonian Basin; EEP - East European Platform.

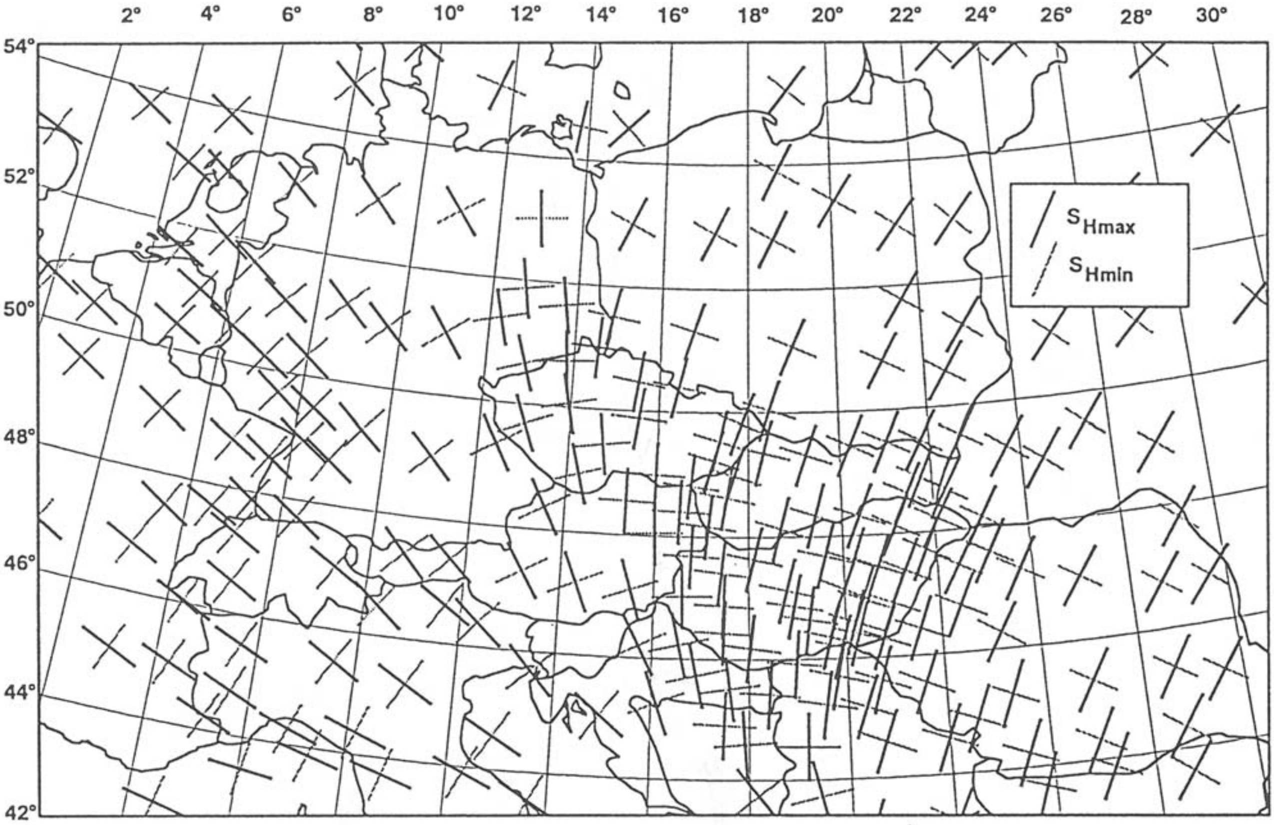

Figure 7. Calculated principal horizontal stresses S_{Hmin} and S_{Hmax} of a uniform elastic plate and boundary loads according to Fig. 5.

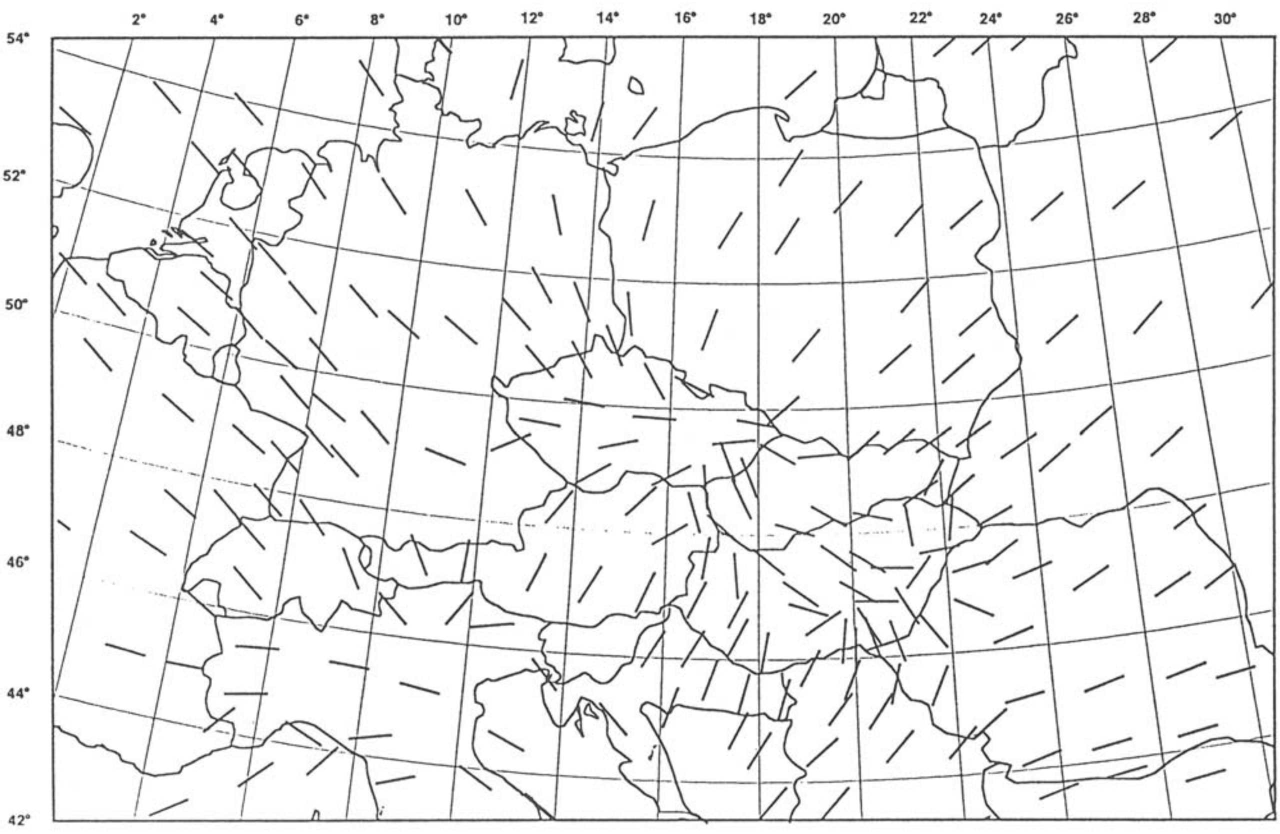

Figure 8. Calculated S_{Hmax}-directions of the final deformation model.

a regional interpretation of azimuths of S_{Hmax} only.

Sliding conditions have to be introduced at a sufficient distance from the study area itself at the northern margin and a fixed boundary in the east. This last assumption is consistent with the suggestion of decoupling between the western and the eastern part of the Eurasian plate (*Molnar et al.* 1973). The strongly simplified boundary conditions of the finite-element mesh do not prejudice the computation of the stress conditions in the study area, which is Central Europe. For modelling the regional features of the stress pattern, stiffness variations of the different lithospheric blocks, and extensional and shear zones were taken into account. Figure 6 shows the modelling options considered for the study area. These possibilities are different rigidities for the Adriatic promontory (AP), the Bohemian Massif (BM), the Pannonian Basin (PB), and the East European Platform (EEP), active extensional zones in the Lower Rhine Embayment and in the Pannonian Basin, as well as shear zones at the north-eastern margin of the Bohemian Massif, in the Upper Rhine Graben, and at the E-W directed Hainaut zone in Belgium. As will be shown below, not all these options are necessary for fitting the observed S_{Hmax}-trajectory pattern by model calculations.

The starting position for the modelling was a homogeneous elastic plate with a Young's modulus E = 50 GPa. The stress field of this simple model is only affected by the plate driving forces. As shown in Fig. 7 the calculated horizontal stress orientations can explain quite well the observed general broad-scale stress pattern, i.e. the NW-SE direction of S_{Hmax} in the western part of the study area and a bending of S_{Hmax} to NE-SW when approaching the east. The ratio of the absolute values of S_{Hmin} to S_{Hmax} is nowhere smaller than 0.6. The regions where the S_{Hmax}-orientation tends to bend are characterized by approximately the same absolute values of S_{Hmin} and S_{Hmax}. In the next step of the modelling the complexity of the model was gradually increased to match the data. Different modelling options were taken into account for the simulation of the subregional deviations from the general pattern of S_{Hmax}-directions. Figure 8 presents the calculated S_{Hmax}-directions for the deformation model described below. A sufficiently good fit between the calculated stress field and generalized trajectories was found for the following model parameters (the constraints on the introduction of the first four mentioned modelling options are described in detail by *Grünthal & Stromeyer* (1992)):

- an increased stiffness of the Adriatic promontory (E = 100 GPa), which leads to the fan-like pattern along the Western Alps, E-W directions in the Po plain, and the observed NE-SW direction in the Dinarides;
- an increased stiffness of the Bohemian Massif (E = 100 GPa), which explains the observed S_{Hmax}-deflections within the massif and its surroundings;
- no increased stiffness had to be introduced for the East European Platform;
- a slightly reduced E-value in parts of the Pannonian Basin (40 GPa);
- extensional features within the Pannonian Basin and its northwestern margin - the latter have been introduced according to *Tyráek & Zeman* (1984);
- shear zones at the north-eastern margin of the Bohemian Massif after *Schenk et al.* (1986).

The last two items represent innovations with respect to our previous modelling version which can explain the NW-SE S_{Hmax}-directions in the northernmost part of the Czech Republic. These data are located in a zone characterized by numerous pronounced NW-SE directed faults and fault zones. The fit between the generalized trajectories (Fig. 2) and the derived S_{Hmax}-directions shown in Fig. 8 seems to be remarkably good with respect to the quality of the measured stress directions.

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