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CASMI—A visualization tool for the World Stress Map database[*]

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Abstract

The World Stress Map (WSM) project has compiled a global database of quality-ranked data records on the contemporary tectonic stresses in the Earth's crust. The WSM 2005 database release contains approximately 16 000 data records from different types of stress indicators such as earthquake focal mechanisms solutions, well bore breakouts, hydraulic fracturing and overcoring measurements, as well as quaternary fault-slip data and volcanic alignments. To provide a software tool for database visualization, analysis and interpretation of stress data as well its integration with other data records, we developed the program CASMI. This public domain software tool for Unix-like operating systems enables the selection of stress data records from the WSM database according to location, data quality, type of stress indicator, and depth. Each selected data record is visualized by a symbol that represents the type of stress indicator and the orientation of the maximum horizontal compressive stress. Symbol size is proportional to the quality of the data record, and the colour indicates different tectonic regimes. Stress maps can be produced in different geographical projections and high-quality output formats. CASMI also allows the integration of user-defined stress data sets and a wide range of other data such as topography, Harvard centroid moment tensors, polygons, text data, and plate motion trajectories. CASMI, including the WSM 2005 database release, can be requested free of charge from the project's website at http://www.world-stress-map.org/casmi. We present two stress map examples generated with CASMI ranging from plate-wide to regional scale: (1) A stress map of central Europe, that reveals the correlation of stress field orientation and relative plate motion. (2) The fan-shape stress pattern in North Germany.

Keywords: Tectonic stress; Stress indicators; Database; Stress map

1. Introduction

Knowledge of the stress field in the Earth's crust is a key issue for the understanding of geodynamic processes, seismic hazard assessment, and stability of underground openings such as waste disposals, tunnels, mines or wells, and reservoir management (*Fuchs and Müller*, 2001). The principal idea of the World Stress Map (WSM) project is to provide a global compilation of quality-ranked data about the contemporary tectonic stresses in the Earth's crust (Fig. 1).

The WSM project was initiated in 1986 under the auspices of the International Lithosphere Program as a global cooperative effort. It is a collaborative project of academia, industry, and governmental organizations, which aims to understand the states and sources of tectonic stresses in the Earth's

[*] Code available at http://www.world-stress-map.org/casmi.

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crust. In 1992 the first release of the WSM database together with major results was published (*Zoback*, 1992). The WSM data come from a wide range of stress measurement techniques. They are provided in a database of standardized format and are quality ranked in order to be comparable on a global scale (*Heidbach et al.*, 2007a; *Reinecker et al.*, 2005; *Sperner et al.*, 2003; *Zoback*, 1992; *Zoback et al.*, 1989; *Zoback and Zoback*, 1991). The first public WSM database release in 1992 with ~7300 data records provided fundamental insights into the nature and impact of forces that drive the tectonic plates and control the large-scale crustal deformation over hundreds to thousands of kilometres. Major findings were that plate-wide stress provinces with prevailing compressive tectonic regime exist in intraplate regions and that the orientation of the maximum horizontal compressive stress S_H is subparallel to the plate motion in North America, South America, and Europe (*Müller et al.*, 1992; *Zoback*, 1992; *Zoback et al.*, 1989). Thus, plate boundary forces are the major controls on the first-order pattern of S_H orientation in the plate interiors (*Richardson*, 1992).

Since 1996, the WSM has been a research project of the Heidelberg Academy of Sciences and Humanities with the project being located at the Geophysical Institute of Karlsruhe University in Germany. Besides the compilation and maintenance of the WSM database, the project also provides tools for the visualization of the database. The latter is a key issue for data analysis, interpretation, and integration with other geodata. From 1999 onwards the database could be visualized in terms of the so-called stress maps via CASMO (Create A Stress Map Online), a web-based database interface located at http://www.world-stress-map.org/casmo (*Heidbach et al.*, 2004). With CASMO, users can select the area of interest and data sets according to data quality, stress indicator type, and depth. The stress map will be generated within a minute and sent via e-mail to the user.

The increasing number of requests from the WSM user community on a stand-alone visualisation tool with an increased functionality and capabilities to combine the stress data with other data sets encouraged us to develop CASMI (Create A Stress Map Interactively). CASMI has a graphical user interface for choosing a wide range of appropriate parameters for the visualization of the WSM database in terms of stress maps. It also allows the combination with user stress data and other geodata.

In this paper, we present the general concept of the WSM project, the content of the WSM 2005

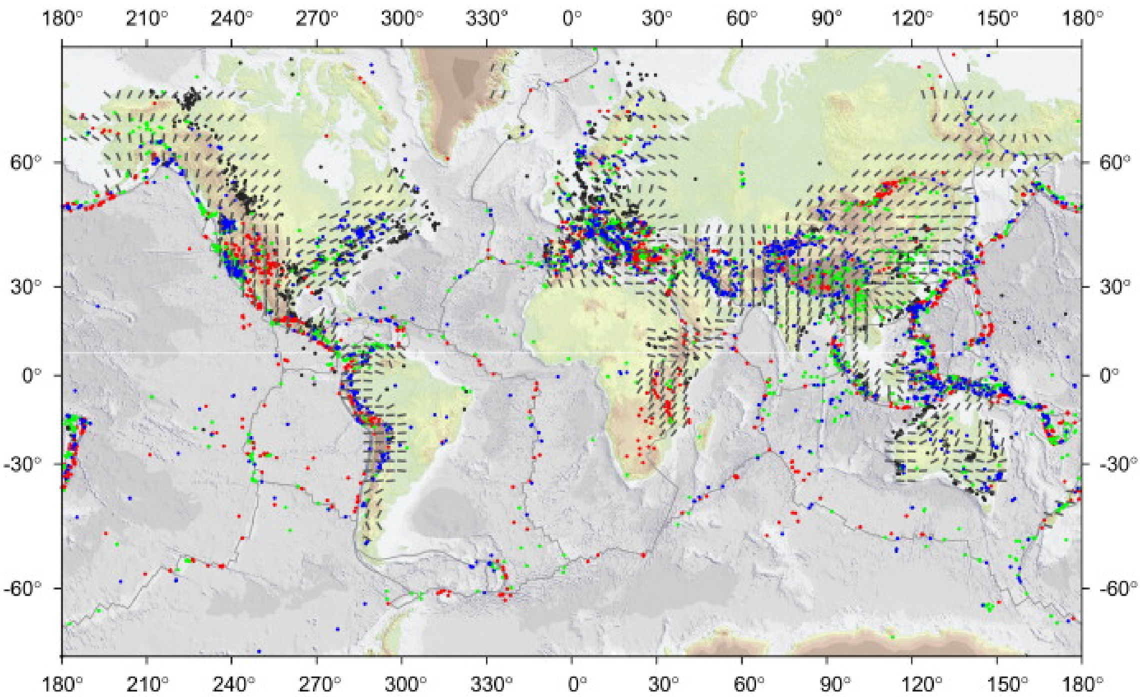

Figure 1. World Stress Map from WSM 2005 database release. Points give location of A–C quality data records from 0 to 40 km depth. Colour indicates stress regime: red = normal faulting (NF), green = strike-slip faulting (SS), blue = thrust faulting (TF), black-unknown regime (U). Short grey lines represent mean S_H orientations on a regular grid on continents calculated with smoothing algorithm of *Müller et al.* (2003). Search radius for smoothing algorithm is 750 km, data quality is weighted in smoothing procedure, and a minimum of 10 data points must be detected within this search radius for calculation of a grid value. Thin grey lines give plate boundaries from global model PB2002 of *Bird* (2003). Topography is from ETOPO2 data (National Geophysical Data Center, NGDC; http://www.ngdc.noaa.gov/), bathymetry is from *Smith and Sandwell* (1997).

database release, as well as the structure and functions of CASMI. We also present two stress map examples: (1) a plate-wide scale example from central Europe where the plate motion trajectories are combined with the S_H orientations, and (2) a regional example showing the changes of S_H orientation in North Germany.

2. The WSM database

2.1. Data types

The orientation of the present-day stresses in the Earth's crust is estimated primarily from earthquake focal mechanism solutions, well bore breakouts and drilling-induced fractures (from borehole images or caliper log data), in-situ stress measurements (overcoring, hydraulic fracturing), and quaternary geological indicators (fault slip, volcanic vent alignment). The stress information from these different stress measurement techniques represent various rock volumes ranging from 10^{-3} to 10^9 m^3 (*Ljunggren et al.*, 2003) and depths ranging from near surface down to 40 km.

2.2. Quality-ranking scheme

One of the key aspects of the WSM is on making information from different stress indicators globally comparable following a standardized quality-ranking scheme for all stress indicators. The quality-ranking scheme was introduced by *Zoback* (1991) and *Zoback and Zoback* (1989), and was refined and extended by *Sperner et al.* (2003). It guarantees reliability and global comparability of the stress data. Each data record is assigned a quality between A and E, with A being the highest quality and E the lowest. A-quality indicates that the S_H orientation is accurate to within ±15°, B-quality to within ±20°, C-quality to within ±25°, and D-quality to within ±40°. E-quality marks data records with insufficient or widely scattered (>40°) stress information. In general, A, B, and C quality data records are considered reliable, e.g. for the use in regional stress analysis and the interpretation of geodynamic processes.

2.3. Stress information and database access

All information in the WSM database is provided in a standardized format and is available in three different file formats on the website (http://www.world-stress-map.org): ACSII, Excel spread-sheet, and dBase. The minimum information for each stress data record contains the S_H orientation, the data quality assignment, the type of stress indicator, the location, the average depth of the measurements, the tectonic stress regime, and the reference where the data are published. Additional information is compiled according to the different types of stress indicators such as stress magnitudes, number of measurements, standard deviation, rock properties, and rock age. Within the upper ~6km of the Earth's crust the stress field is mapped by a wide range of methods with borehole breakouts being a major contributor. Below ~6 km depth, earthquakes are the only source of stress infor-

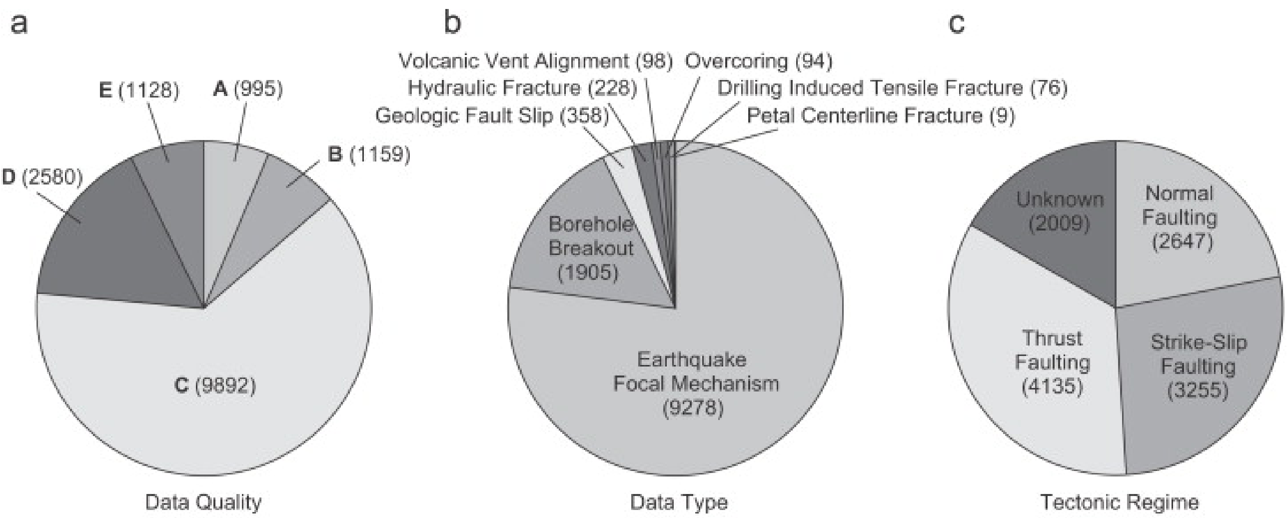

Figure 2. Statistics of WSM 2005 database release. In brackets: number of data for each subset. (a) Quality distribution of 15 976 stress data records. More than 75% have A–C quality, i.e. S_H orientation is reliable to within ±25°; (b) distribution of stress indicator type of 12 046 A–C quality stress data; (c) tectonic regime for 12 046 A–C quality stress data.

mation except a few deep scientific boreholes.

2.4. WSM 2005 database release

The current WSM 2005 database was released in December 2005 and published as a Map in 2007 (*Heidbach et al.*, 2007b). It contains 15 969 data records with more than 12 000 having A–C quality (Fig. 2), i.e. they are considered to show the S_H orientation reliably to within ±25°. Most of the stress information result from earthquake focal mechanism solutions (77%) and well bore breakouts (16%) (Fig. 2). The stress regime is unknown in 17% of the A–C quality data, since this information has not be determined or provided for most of the well bore breakouts and drilling-induced fracture data records.

3. Database visualization with CASMI

3.1. CASMI development environment

A widely used tool for plotting geodata is the Generic Mapping Tools (GMT) (*Wessel and Smith*, 1998). It is an open source collection of ~60 scripts for manipulating and plotting of geographical and Cartesian data sets as maps in encapsulated postscript format. GMT supports a wide range of map projections and transformations and comes with geographical data such as coastlines, rivers, and political boundaries. However, in order to visualize the WSM database, some additional functions are needed. The major ones are a database interface that allows to define selection criteria for the data records, a number of specific symbols for the different stress indicators and tectonic regimes, and a legend explaining the selected types and qualities of the selected stress data records.

These additional functions are provided by ~50 Unix shell and awk scripts. The scripts also execute a number of procedures needed for the automated calculation of the stress map size on the chosen plot format as well as the plate motion trajectories. In order to control both, these additional ~50 scripts as well as the options of the incorporated GMT commands for the stress map production, a so-called master script was developed. It controls all settings for the user-defined stress map production incorporating the WSM 2005 database release in combination with other data such as user stress data, plate motion trajectories, and Harvard centroid moment tensor (CMT) solutions.

For easier application of the master script, we implemented a graphical user interface based on the scripting language Perl/Tk, and gave the software tool the name CASMI (Fig. 3). It provides easy control of (a) the data record selection criteria, (b) the options of all incorporated GMT commands, and (c) the combination with a wide range of other geodata sets. CASMI contains the most recent WSM database release, the plate boundaries of the global plate model PB2002 of *Bird* (2003), the master script and all scripts necessary to control the input and output of the used GMT commands. It is a public domain program for Unix-like operating systems. CASMI is provided free of charge via e-mail after registration on our website under http://www.world-stress-map.org/casmi. Alternatively, user-defined stress maps can be generated with the web-based database interface CASMO. The response time via e-mail is less than a minute (*Heidbach et al.*, 2004). However, compared with CASMI, its functionality is significantly lower.

3.2. Installation of CASMI

CASMI has so far been successfully tested and installed on Linux systems (SuSE, Free BSD). Since the core library is written in C and the graphical user interface in Perl/Tk, it can be installed on a wide range of Unix-like operating systems. To install and run CASMI successfully, installations of GMT (version 3.4.1 or higher), Perl (version 5.6.1 or higher), and Perl/Tk (version 800.023 or higher) must be provided.

3.3. Graphical user interface of CASMI

The graphical user interface provides control via drop down menus (Fig. 3). Each of them has a number of submenus with dialog boxes where the user can define details for the stress map production. Since GMT is the background software tool used for the stress map production, the logic for the control of the options in all dialog boxes is according to the GMT commands and options. The latter are briefly introduced in the help file of CASMI and in great detail in the GMT cookbook and the GMT manual, which are available on the GMT website (http://gmt.soest.hawaii.edu/).

The four drop down menus for the control of CASMI are

1) The File menu: it controls the page setting and provides the option to produce an ASCII file of the selected stress data records, to choose the output format of the stress map (postscript, pdf, gif) and to reset, load, or save the settings for CASMI.
2) The Data Parameter menu: it provides the dialog boxes for the selection criteria for the user data. It also allows the control of the symbol size and

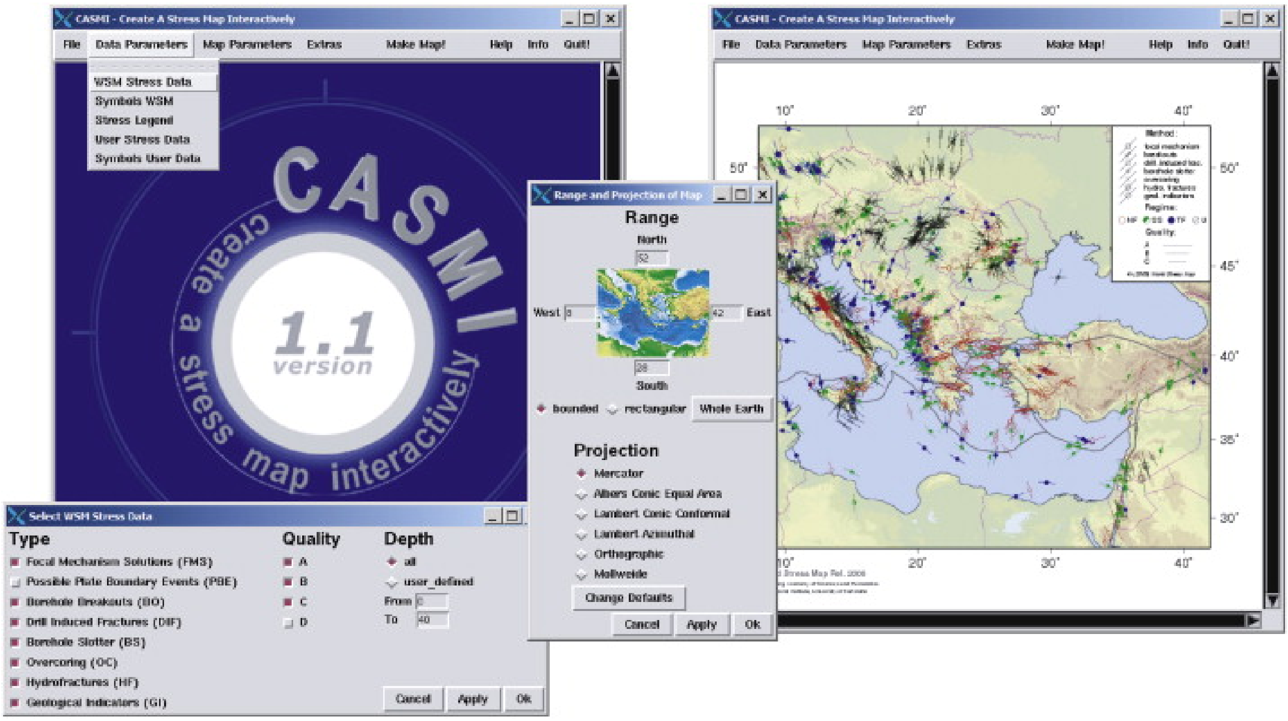

Figure 3. Graphical user interface of CASMI. Left-hand side shows starting display of CASMI and two control dialog boxes, one for stress data selection and other for range and type of projection of stress map. Right-hand side shows created stress map as a preview; it can be saved with higher resolution in postscript, pdf or gif file format.

colour as well as the size and location of the stress map legend.

3) The Map Parameter menu: here the setting of map attributes such as map range, projection, gridlines, topography are controlled. Topography from grid files are not included in CASMI, but can be linked in the Extras menu. The format of the grid file must be according to the definition given in the GMT manual.
4) The Extras menu: in this drop down menu additional data can be added to the stress map such as topography, relative or absolute plate motion trajectories, text, polygons, symbols, and CMT solutions from Harvard (http://www.seismology.harvard.edu).

When all selections are made and confirmed in the dialog boxes, the button Make Map! generates the stress map and displays a gif-preview within the CASMI window (Fig. 3). Once the user is satisfied with the stress map, it can be saved in pdf, gif, or postscript format.

More details on the handling of CASMI and the internal structure of the program can be found in the help.pdf file. This file and the info.pdf file, which contains the GNU licence agreement, can be accessed via mouse click according to the buttons in the main menu.

4. Stress map examples

In the following sections, we present two stress maps at plate-wide and regional entirely created with CASMI. Even though the smoothed stress field on a grid was calculated externally, its visualization has been made with CASMI importing the values on the grid as user data in the Data Parameter menu. Such stress maps enable us to analyse the stress information compiled in the WSM database.

4.1. Plate-scale stress field: central Europe

For central Europe the WSM 2005 database release provides ~2700 data records with more than 1850 having A–C quality (Fig. 4). According to the principal findings of *Müller et al.*, (1992) the first-order pattern of the S_H orientation in central Europe show a NW to NNW orientation of S_H. *Müller et al.* (1992) hypothesize that this observed prevailing orientation is controlled by the plate boundary forces, i.e. by the ridge push of the Northern Atlantic and the collision of the African with the Eurasian plate. This was confirmed by several large-scale finite element models (e.g. *Jarosinski et al.*, 2006; *Gölke and Coblentz*, 1996; *Grünthal and Stromeyer*, 1992, 1994). Even though the number of data records have almost doubled since 1992 this first-order pattern can still clearly be identified in the smoothed stress field (Fig. 4). The general S_H orientation is in agreement with the convergence direction of the African plate and the Eurasian plate. Large-scale deviations from this trend occur in the Aegean and West-Anatolian region, where the slab roll-back at the Hellenic arc subduction zone produces N-S-oriented extension, and thus E-W-oriented S_H, in the back-arc (e.g. *Heidbach and Drewes*, 2003), and in the Pannonian Basin where NE-SW S_H orientation is probably due to collision in the Dinarides (*Bada et al.*, 1998). The deviations of the S_H orientation from the plate motion trajectories in the North Germany are presented in more detail in the following example.

4.2. Regional stress field changes: North Germany

In central Europe the mean S_H orientation of 144° is almost parallel to the trajectories of relative plate motion of 1371 (Fig. 4). However, *Grünthal and Stromeyer* (1992) noted for the first time that there is a swing in the stress pattern towards east taking place in the North German Basin and Poland, resulting in a fan-shaped pattern of the S_H orientation (Fig. 5). Initially this observation was based on a very small data set, but more stress data provided by *Grünthal and Stromeyer* (1994) and *Roth and Fleckenstein* (2001) supported this interpretation. These data sets and 42 additional A–C quality stress data records are now compiled in the WSM 2005 database release. They confirm the fan-shaped pattern of S_H orientation changing from NW orientation in the west over N to NE orientation in the east as seen in the smoothed stress field (Fig. 5).

Roth and Fleckenstein (2001) discuss three possible reasons for this pattern: (1) the influence of an active trans-European suture zone that separates the East European platform from the West European part of the Eurasian plate, (2) the local dominance of stresses due to postglacial rebound, and (3) that the northern boundary of the Central European Basin System has a higher lithospheric strength that acts as a mechanical barrier. Whereas the latter argument is favoured by the results of a 2D finite element model of *Marotta et al.* (2002), *Kaiser*

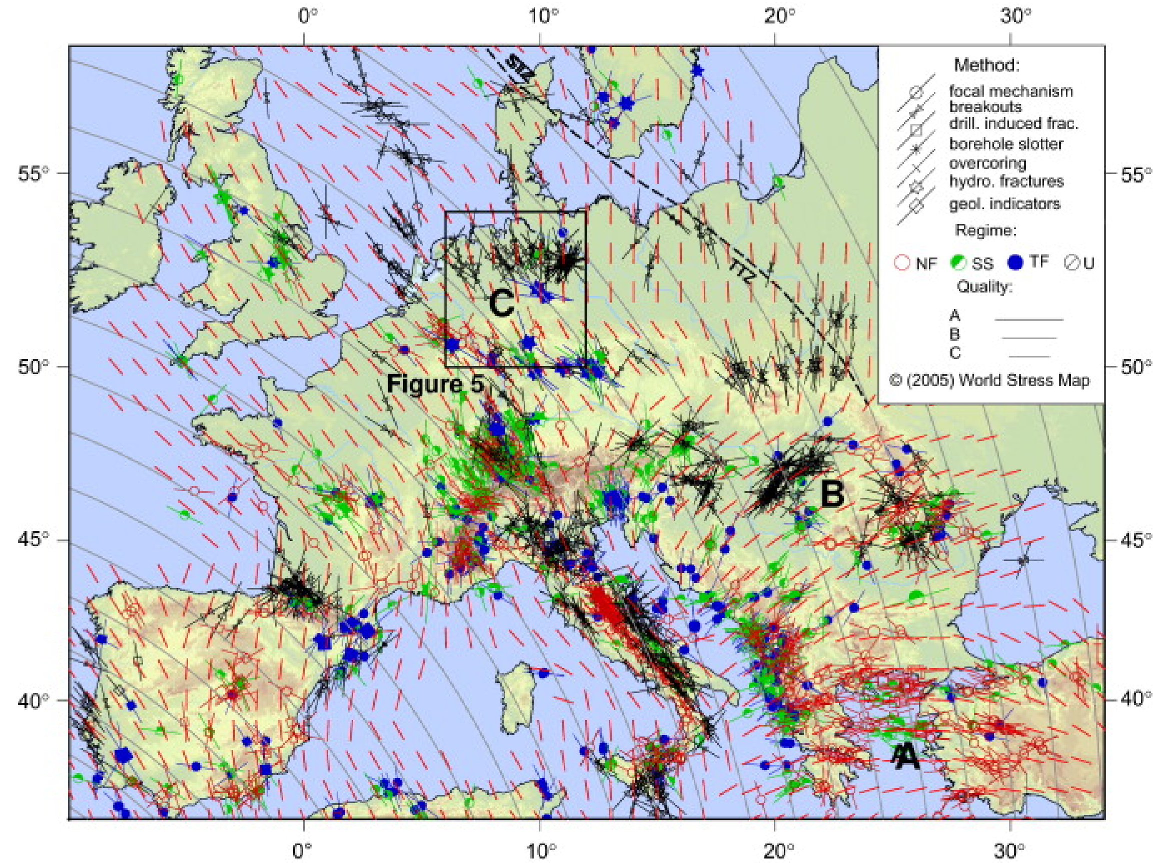

Figure 4. Stress map of central Europe. Thin grey lines show relative plate motion of Africa with respect to Eurasian plate using rotation pole from NUVEL-1A (*DeMets et al.*, 1990, 1994). Short red lines are mean S_H orientations on a regular grid calculated with smoothing algorithm of *Müller et al.* (2003). Search radius for smoothing is 300 km, data quality is weighted in smoothing procedure and a minimum of five data points must be detected within this search radius for calculation of a grid value. Regions A, B, and C are Aegean and Western Anatolian region, Pannonian basin, and North Germany where regional stress field orientation deviates from NW–SE orientation of plate-wide scale stress field. Details of region C are shown in Fig. 5. Dotted black line indicates Sorgenfrei-Teisseyre zone (STZ) and Tornquist-Teisseyre zone (TTZ), where Moho steps from about 35 to up to 50 km thickness (*Thybo*, 2001).

et al. (2005) conclude from their numerical model results a combination of (1) and (2). However, the disadvantage of both models is that the eastern model boundary is close to the area of interest, and thus the rotation towards east could be to a certain extent a boundary effect of the model geometry.

A fourth source of the stress field rotation are probably the lateral density and strength contrasts across the Sorgenfrei-Teisseyre and Tornquist-Teisseyre zone where crustal thickness increases sharply from about 35 km in the west towards 50 km of the East European platform (*Thybo*, 2001). *Gölke and Coblentz* (1996) investigated in a large-scale 2D finite element model of western Europe the impact of the lateral density contrast due to topography and found that this has an impact on the stress magnitudes, but to a lesser extent on the stress orientations. *Jarosinski et al.* (2006) included in their 2D finite element model of western Europe also the effect of the varying lithospheric strength as well as the effect of the topography and received a swing of the stress field orientation towards east roughly in agreement with the stress observations. They also implemented the NW-SE striking Hamburg-Elbe fault zone as the southern boundary of the eastern section of the North German Basin. However, the faults display in their model results an unrealistic high displacement of 200–300 m in a predominantly aseismic area. Such a strike-slip motion releases stresses parallel to the fault, i.e. in return the remaining stresses perpendicular to the fault have a larger, but probably artificial influence on the stress orientation.

In summary, the various processes contributing to the fan-shaped stress field pattern now fully revealed in the WSM 2005 database release are still controversially discussed. So far, the existing models only reveal that strength and density contrasts, boundary conditions and geometry, as well as post-glacial rebound contribute to a certain extent to the

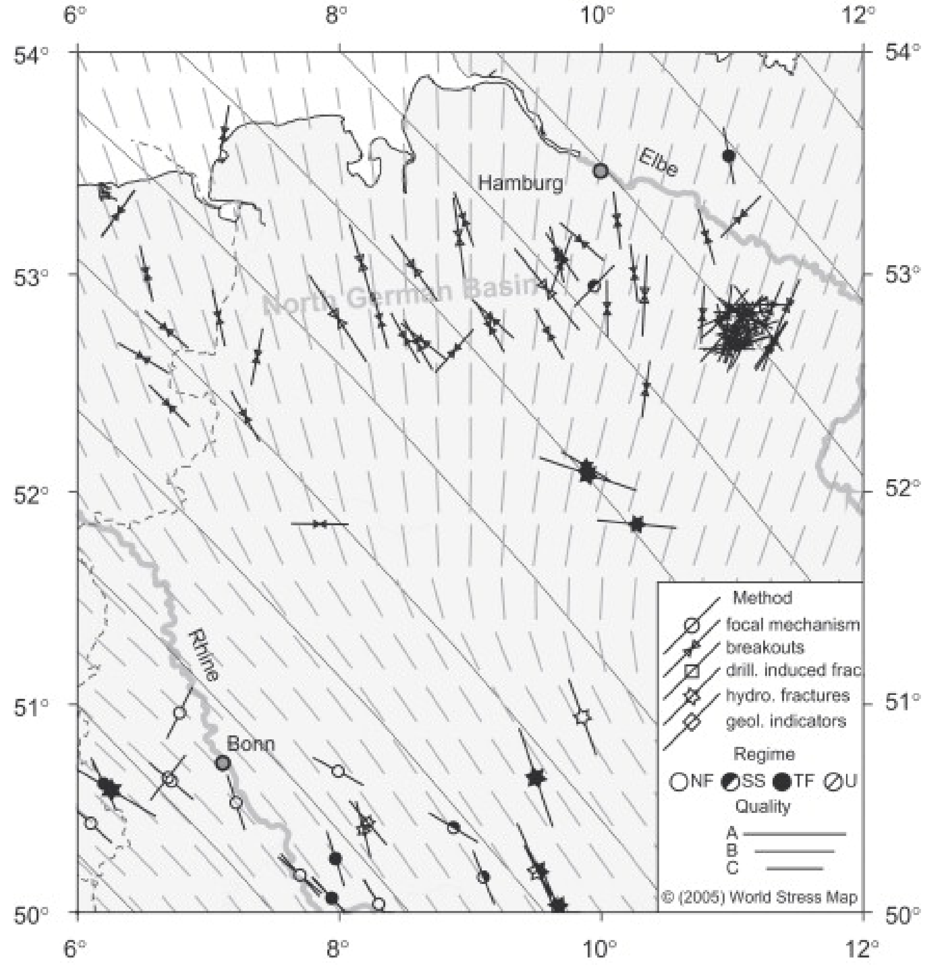

Figure 5. Stress map of northern Germany. Thin grey continuous lines mark relative plate motion of African plate relative to Eurasian plate from global plate model NUVEL-1A (*DeMets et al.*, 1990, 1994), black dotted lines are political boundaries. Short grey lines are mean S_H orientations on a regular grid calculated with smoothing algorithm of *Müller et al.* (2003). Note increase of deviation between smoothed stress field orientation to plate motion trajectories from Rhine River to Elbe River. Search radius for smoothing is 100 km, data quality is weighted in smoothing procedure and a minimum of three data points must be detected within this search radius for calculation of a grid value.

stress field re-orientations, but their relative importance is still an open question.

5. Outlook

Since data influx from the hydrocarbon industry and academia into the WSM is increasing, we will update the WSM database regularly. The new release will be announced via both the WSM and the CASMI newsletter. In the latter, we will provide the CASMI users with the new database file including a short description of how to replace the old by the new database file. A new WSM database release and a new CASMI version is planned for mid 2008. Both will be presented at the 3rd international World Stress Map conference, 15–17 October 2008 in Heidelberg, Germany (http://www.world-stress-map.org/conference).

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