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REVIEW ARTICLE

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World Stress Map of the Earth: a key to tectonic processes and technological applications

Abstract Modern civilisation explores and penetrates the interior of the Earth's crust, recovers from it and stores into it solids, fluids and gases to a hitherto unprecedented degree. Management of underground structures such as boreholes or reservoirs take into account the existing stress either to take advantage of it or at least to minimise the effects of man-made stress. This paper presents the World Map of Tectonic Stresses (in short: World Stress Map or WSM) as a fundamental geophysical data-base. The impact of the WSM is pointed out: in the context of global tectonics, in seismic hazard quantification and in a wide range of technological problems in industrial applications such as oil reservoir management and stability of underground openings (tunnels, boreholes and waste disposal sites).

Introduction: mobile surface of the Earth

Earth stress affects mankind not only during catastrophic earthquakes but also whenever engineers are reaching into the depth of the crust. Their underground constructions disturb the existing state of stress. Quarry workers and miners have experienced this for centuries and have taken advantage of the stress in rocks or have protected themselves against the collapse of tunnels and mines.

Despite its importance in many widespread fields of modern civilisation, a knowledge of Earth stress and its relationship to global tectonic processes has been lagging behind or has only been determined locally in an ad hoc manner. In this paper we describe how the notion of Earth stress evolved prior to and within the Global Plate Tectonics theory. This development culminated in the establishment of the World Stress Map (WSM) project first within the International Lithosphere Programme and subsequently at the Heidelberg Academy of Sciences. We demonstrate the role of the WSM as a fundamental geophysical data-base and in its industrial applications. The WSM project at the Heidelberg Academy of Science, in its endeavour to complete the global stress database, provides the opportunity to integrate and to rescue stress-relevant data which are widely dispersed in the data archives of various companies in the oil and gas industries.

This issue, WSM 2000 (Fig. 1), is the newest version of the WSM. It is an image of the largest data-base on globally measured tectonic stress. It contains data from more than 10,000 locations world-wide. The data-base is visualised by mapping the maximum horizontal compressional stress S_H as the best known component of the stress tensor. In addition it shows the tectonic regimes (i.e. relative magnitudes of the three principal stresses), the type of stress measurements and the quality ranking (Zoback and Zoback 1991; Zoback 1992) for each stress entry. The present status of the WSM is far from complete, it still contains vital gaps.

Nevertheless, even at a first glance the WSM already portrays some surprising features: the distribution of S_H stress orientations is not random but exposes patterns on continent-wide scales. The identification of global, regional and local patterns of stress distribution provides new insight into mountain building, the evolution of sedimentary basins and characterisation of active faults with earthquake potential.

Engineering of tunnels, and caverns for gas storage or waste disposal requires knowledge of contemporary stress to improve the stability of underground constructions on time-scales up to thousands of years. Accumulations of both water and hydrocarbons result from migration from a source rock to a suitable trap in a host rock. Optimised hydrocarbon recovery depends on the preferential fluid flow, and thus on how the actual in situ stresses drive hydrocarbons through a fracture network which itself may result from previous tectonic events. In this context the WSM provides fast and easy accessible first-hand information which can be used to constrain subsequent, more detailed, investigations rele-

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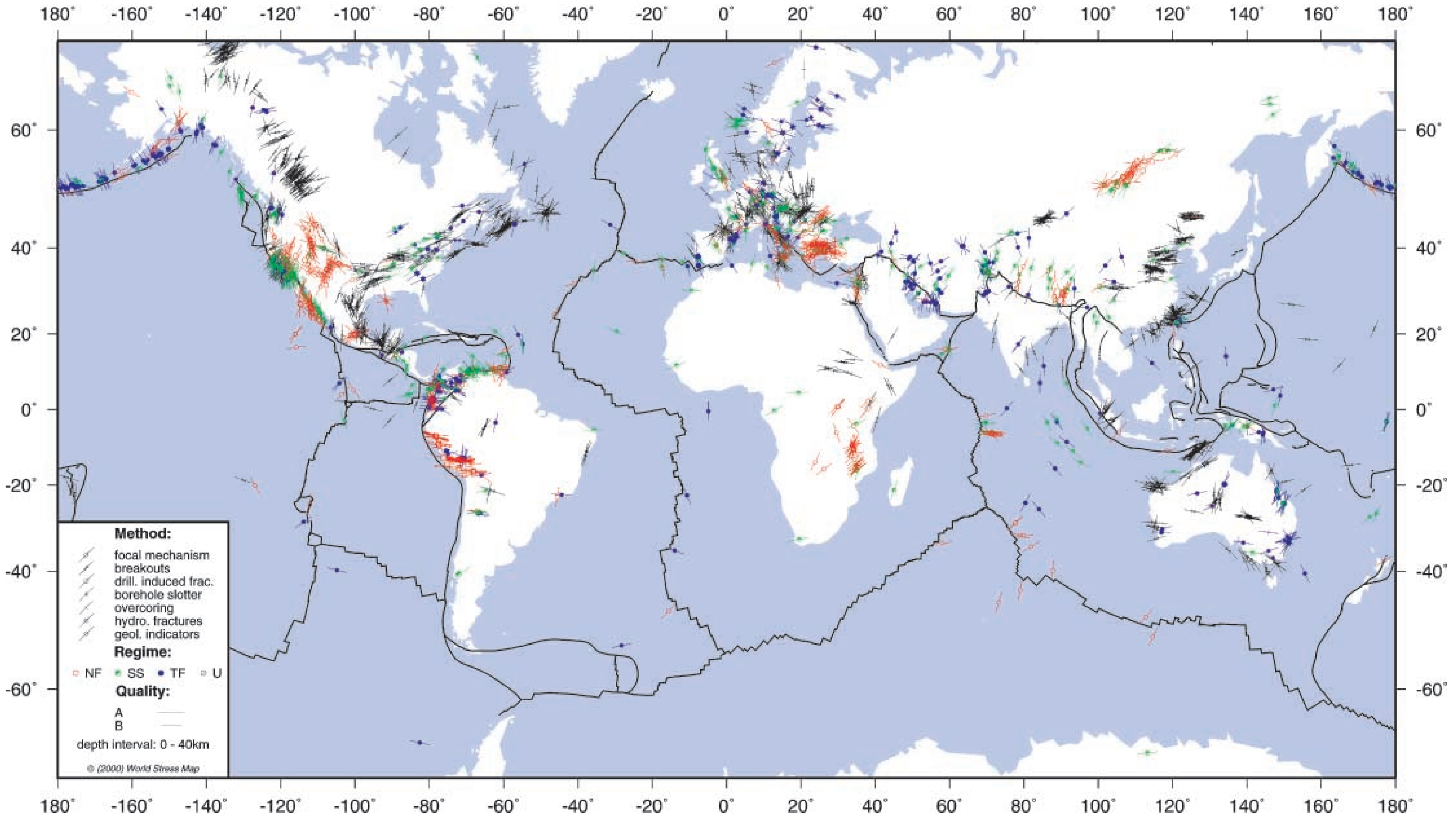
World Stress Map



vant to the hydrocarbon industry. From its very beginning the WSM has had a vital interaction with the hydrocarbon industry through the stress-relevant data obtained from routinely applied observations of stress-induced variations in borehole cross sections (so-called borehole breakouts).

WSM: a fundamental earthsciences data-base

Earthquakes mark the localities where the Earth crust is stressed beyond the limits of its mechanical strength. Together with volcanoes they are the most obvious expressions of a "living" planet with a surface deforming under stress. However, earthquakes are not uniformly distributed over the surface of our planet. Rather they are concentrated in relatively narrow seismic belts around the Pacific, along mid-ocean ridges and in the Himalayan–Alpine seismic zone of continental collision. The other larger "aseismic" parts of the Earth's surface are not free of stress and of earthquakes but the frequency of earthquake occurrence and their spatial density is much lower, though this does not necessarily apply to the intensity and magnitude of earthquakes.

The stress tensor which describes the state of stress is symmetrical with six independent components. The tensor can be rotated such that the shear components of stress vanish and that three normal stresses (S_1, S_2, S_3) remain. They are perpendicular to each other and are called principal stresses. The tectonic forces arising from plate interaction modify the stress pattern in magnitude and in orientation. Stress does not only vary in space due to the inhomogeneity of rock but also on various time-scales as a result of changes in plate motion and of stress release in creep and in earthquakes.

One of the principal in situ stresses is experienced as vertical (S_v) corresponding to the vertical load of the overburden. The others are therefore horizontal, the maximum and the minimum horizontal principal stress (S_H and S_h), respectively.

Anderson (1951) classified the tectonic regimes from the relation between the magnitudes of the principal stresses. In a normal faulting regime (NF) the vertical stress exceeds the horizontal stresses ($S_v > S_H > S_h$; remembering that S_H is per definition greater than or equal to S_h), in a strike slip regime (SS) the vertical stress is the intermediate stress ($S_H > S_v > S_h$), and in a thrust faulting regime (TF) the vertical stress is the smallest stress ($S_H > S_h > S_v$).

◀ **Fig. 1** World Stress Map issue 2000. The orientations of the symbols are in the direction of the maximum horizontal stress S_H. The *symbols* represent different kinds of stress indicators and their *length* is a measure for the data quality; only *A* and *B* quality data are shown for clarity. The *colour* of the symbol represents the tectonic regime (see legend). Plate boundaries are included as *solid lines*. *NF* Normal faulting regime, *SS* strike slip faulting regime, *TF* thrust faulting regime (see also Fig. 8)

Early stress observations: signposts towards WSM

Earth stress is mostly felt locally by workers in mines and quarries or during the drilling of boreholes. In the past there was already some understanding that these stresses are not just a local anomaly; stresses measured at neighbouring places correlate. But it was only after the establishment of the WSM that observed stress data could be confronted with global tectonic concepts.

Very early attempts were made to search for the causes of internal continental deformations and stresses by observations of the stress field through a variety of in situ stress measurements (e.g. overcoring and hydrofrac in boreholes, Hast-cell) and analysis of stress indicators, such as focal mechanism of earthquakes, displacement of geological faults, and alignment of volcanoes. Early investigations of stress conditions have been performed in quarries, mines and tunnels (e.g. Leeman 1964). The first regional stress maps then became available for Europe (Ahorner 1967, 1975; Illies and Greiner 1976, 1978; Greiner and Illies 1977; Stephansson et al. 1987) and North America (Sykes and Sbar 1973, 1974; Zoback and Zoback 1980). Hast (1967, 1969, 1974) discussed the state of stress in the upper part of the Earth's crust as a contribution to the discussions on the expanding or contracting Earth and continental drift. Richardson et al. (1979) was the first to link plate driving forces to sparsely observed stresses by numerical modelling on a global scale.

A major impetus enhancing the acquisition of tectonic stress data came from the progress in down-hole instrumentation for logging borehole geometry in sedimentary basins for the hydrocarbon industry. These basins are usually free of earthquakes and are represented by gaps in previous regional stress maps. It was already known that boreholes suffer stress-induced enlargements of the borehole cross-section, called sidewall fracturing by Leeman (1964). He suggested that the failure occurs perpendicular to the maximum principal stress. Numerous observations from industrial borehole logging showed zones with elongated cross-sections called breakouts. However, it was only during the 1970s that the tools to measure borehole deformation were equipped with a compass to determine the orientation of the breakouts and the orientation of S_H, which is perpendicular to that of the breakouts (Fig. 2a).

Breakout observations then became a tool for stress determination (Cox 1970; Bell and Gough 1979). From numerous loggings of boreholes it was verified that the azimuth of the breakouts in a hole is practically independent of depth and of rock type. It coincides also with the orientation of the stress tensor when compared with that determined from the focal mechanism of nearby earthquakes. This discovery was a milestone in the augmentation of stress observations. It required a strong link to the data-bases available in the hydrocarbon industry. In turn the hydrocarbon industry benefits from the release of their own data (see below).

Zoback and Zoback (1980) applied the new breakout tool extensively to the stress map of the conterminous

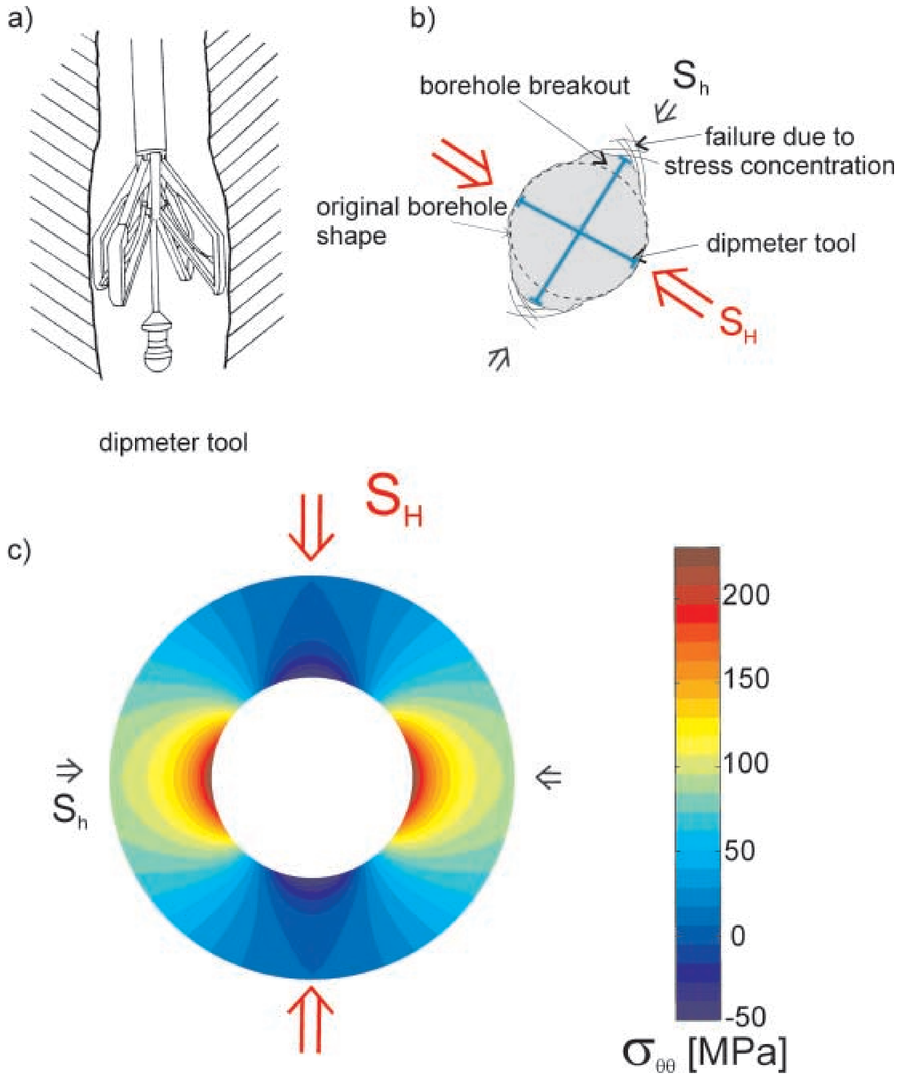


Fig. 2 **a** Oriented four-arm caliper tool (also used as dipmeter) to measure borehole elongation and the direction of breakouts, **b** borehole cross section with breakouts, **c** stress distribution around a circular hole under anisotropic horizontal stress conditions. *Red* indicates compressive stress, *blue* tensile stress. Borehole breakouts originate in segments of compressive stress parallel to S_h

United States. Zoback and Zoback (1991) developed the methodology of stress mapping with the emphasis of the data on the deeper – drillable – sections of the crust instead of the more likely to be biased measurements close to the surface. A crucial step was their foundation of a ranking system which forms the basis for a world-wide comparison of stress data from various sources.

In 1985 the International Lithosphere Programme formed a WSM task group with the mission of establishing a unified WSM on the basis of existing regional stress maps in Europe, Canada and the United States and with a drive to collect new data with strictly applied quality ranking (Zoback 1992). The WSM data-base is visualised by mapping the direction of the maximum horizontal stress S_H as the best known component of the stress tensor together with information on the stress regime wherever available. Since 1995 the WSM has been a project of the Heidelberg Academy of Sciences. The number of entries has increased from 7,000 to more than 10,000.

WSM: global phenomena of stress mapping

The global distribution of stress data is not homogeneous, even in the newest issue WSM 2000 (see Fig. 1) there remain essential gaps. Data coverage is relatively dense in North America and Europe, parts of Asia, the Indo–Australian plate and western South America. Other places such as Africa or Siberia are nearly as sparsely covered as the oceans. Dense data coverage does not mean that the region is highly stressed. Dense data are available in regions of intensive hydrocarbon exploration or mining and in seismically active regions.

Despite of gaps which exist, there are some features in the WSM which must surprise even the lay-person. The distribution of the direction of stress is not random but exposes astonishingly regular patterns (for a detailed description, see Zoback and Zoback 1989; Zoback et al. 1989; Zoback 1992):

1. Continents are characterised by large continent-wide stress domains of almost homogeneous orientation of

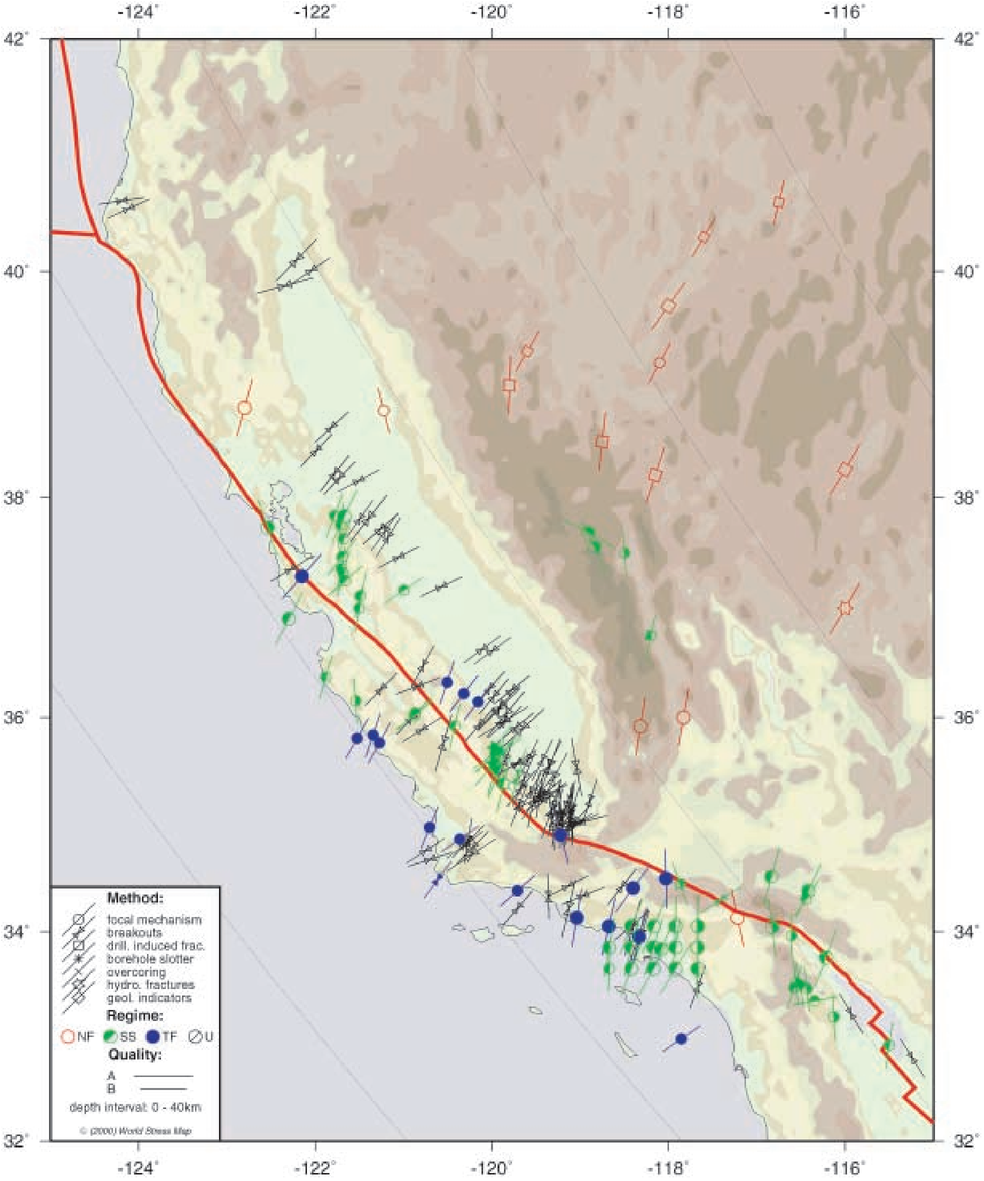


Fig. 3 Plate tectonic expression of S_H stress patterns: Rotation of S_H at the San Andreas Fault (*SAF*). Note that the far-field S_H tends to NNE and rotates to almost perpendicular to the strike of the SAF in its immediate vicinity, indicating low shear stress movement. Deep drilling into the SAF is aimed at understanding the physics of strong earthquakes on a low-shear stress fault

S_H. The S_H orientation is dominantly related to the movement of plates: forces at the plate boundaries are affecting large parts of the continental interiors and run subparallel to plate motion trajectories.

2. Midplates are under compression as derived from the relative stress magnitudes of the principal stresses (visible from the colour code of the symbols in the stress map). In the north-eastern United States the maximum principal stress S_1 is horizontal in the seismogenic part of the crust, thus it equals S_H, which is consistent with thrust faulting and strike slip tectonics.
3. Uplifted areas are under extension, for example the High Andes and the Basin and Range area in the western United States. Other properties of the stress data-base are not as obvious and were also unexpected, for example the direction of S_H is constant with depth and independent of rock type.

WSM and global tectonics

Earthquakes are the most obvious markers of plate boundaries and have played a decisive role in the development of the new global plate tectonic theory. This is the modern version of Alfred Wegener's concept of continental drift. To what extent are plate-tectonic driving forces reflected in the global stress distribution?

WSM: an expression of global tectonics

The continent-wide patterns of stress provinces with homogeneous orientation of S_H point towards global processes which are generating these distributions. Meanwhile it is accepted that the main driving mechanism of plate motion is the convective mass transport of heat en-

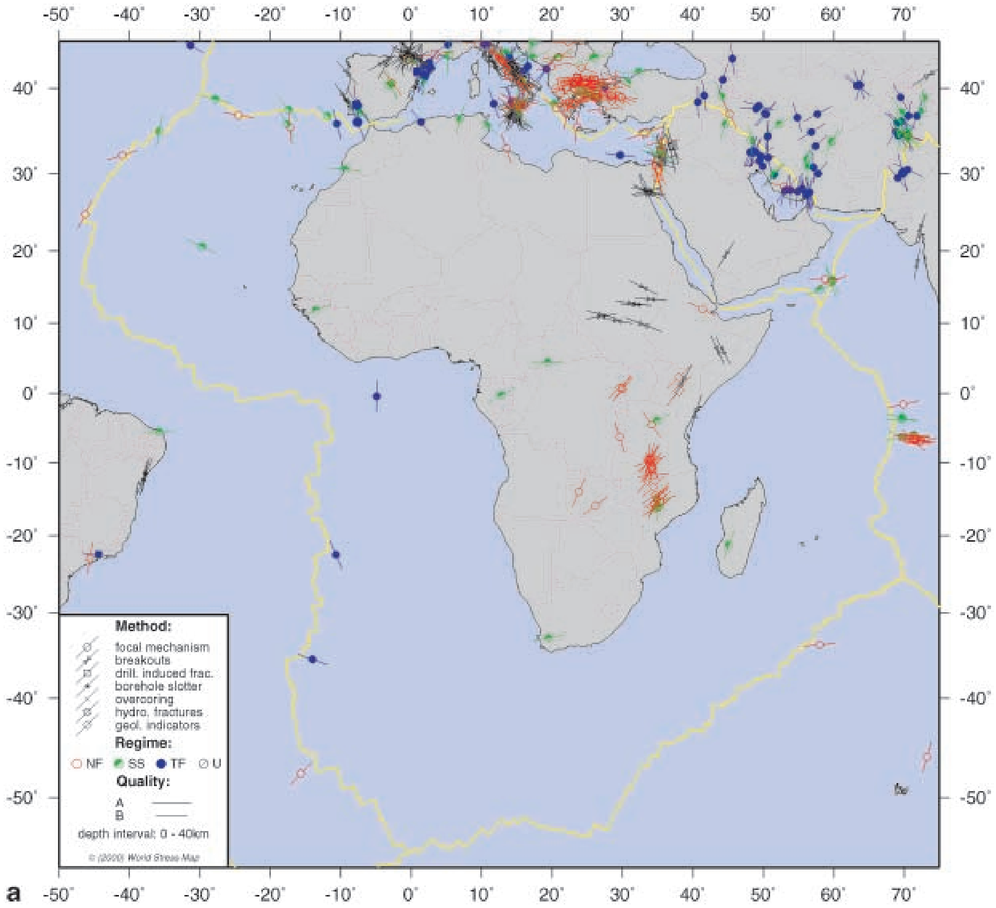


Fig. 4 Plate tectonic expression of S_H stress patterns. *Left* The African continent is set under E–W compression by surrounding plate boundaries. The 90° rotation of S_H along the East-African Rift is caused by upwelling of mantle material. *Right* The European stress pattern is characterised by a predominantly NW–SE orientation following the relative plate motion trajectories between Africa and Europe. Note the short-scale variation of the tectonic regimes, pointing to decoupled motion of individual blocks north of the Alps

ergy from the core–mantle boundary and its interaction with the “stony” outer shell, the lithosphere. The plates are kept in motion by the gravitational forces pushing them at uplifted mid-ocean ridges and pulling them at subduction zones.

Some of the features in the WSM are in agreement with the original “rigid plate” notion of global tectonics; other features witness that the continents are highly vulnerable to stresses and can deform (Gordon and Stein 1992; Stein 1993). Not only their borders but also their interiors are deformed on several scales in space and time. Continents break apart in mega-rifts at the beginning of a new plate tectonic cycle, they buckle, form sedimentary basins, plateau uplifts, recent crustal movements, and are subjected to large destructive earthquakes in their interior. All these features witness ongoing deformation processes incompatible with the notion of rigid plates. In the following sections we will point out regions where the stress patterns of the WSM are clear expressions of plate tectonics or of plate deformations.

Plate tectonic images in WSM: plate boundaries

In many cases the direction of S_H is concordant with the direction of plate motion. Very obvious cases of alignment of S_H with the direction of plate motion are subduction zones. The S_H orientations in the western part of South America where S_H points into the direction of the westerly drift of the South American plate (see Fig. 1) are among the best examples.

Other places show a clear discordance between plate motion trajectories and stress pattern. Continental transform faults form plate boundaries where neighbouring plates glide past each other. The largest transform faults are on continents near the ocean–continent contact (San Andreas Fault; Dead Sea–Aqaba/Eilat Transform Fault, North Anatolian Fault), and not in the oceanic lithosphere where they were discovered originally. This points to the reduced strength of the continental crust. Stress observations are very dense at the San Andreas Fault (SAF). It was an unexpected observation that approaching the fault the direction of S_H rotates from a NNE orientation at distance to an orientation almost perpendicular to the trace of the SAF in the vicinity of the SAF (Fig. 3; Zoback et al. 1987). This orientation of S_H is indicative of the reduction of shear stresses on the fault. The overall tectonic situation of a continental transform fault, with strike slip movement under fault normal compression, requires a comprehensive investigation of stress, strain and rock physics. The deep borehole planned to penetrate the SAF and the accompanying investigations should help to resolve the problem of low shear stress on a major continental transform fault under normal compression.

Fig. 4 (continued)

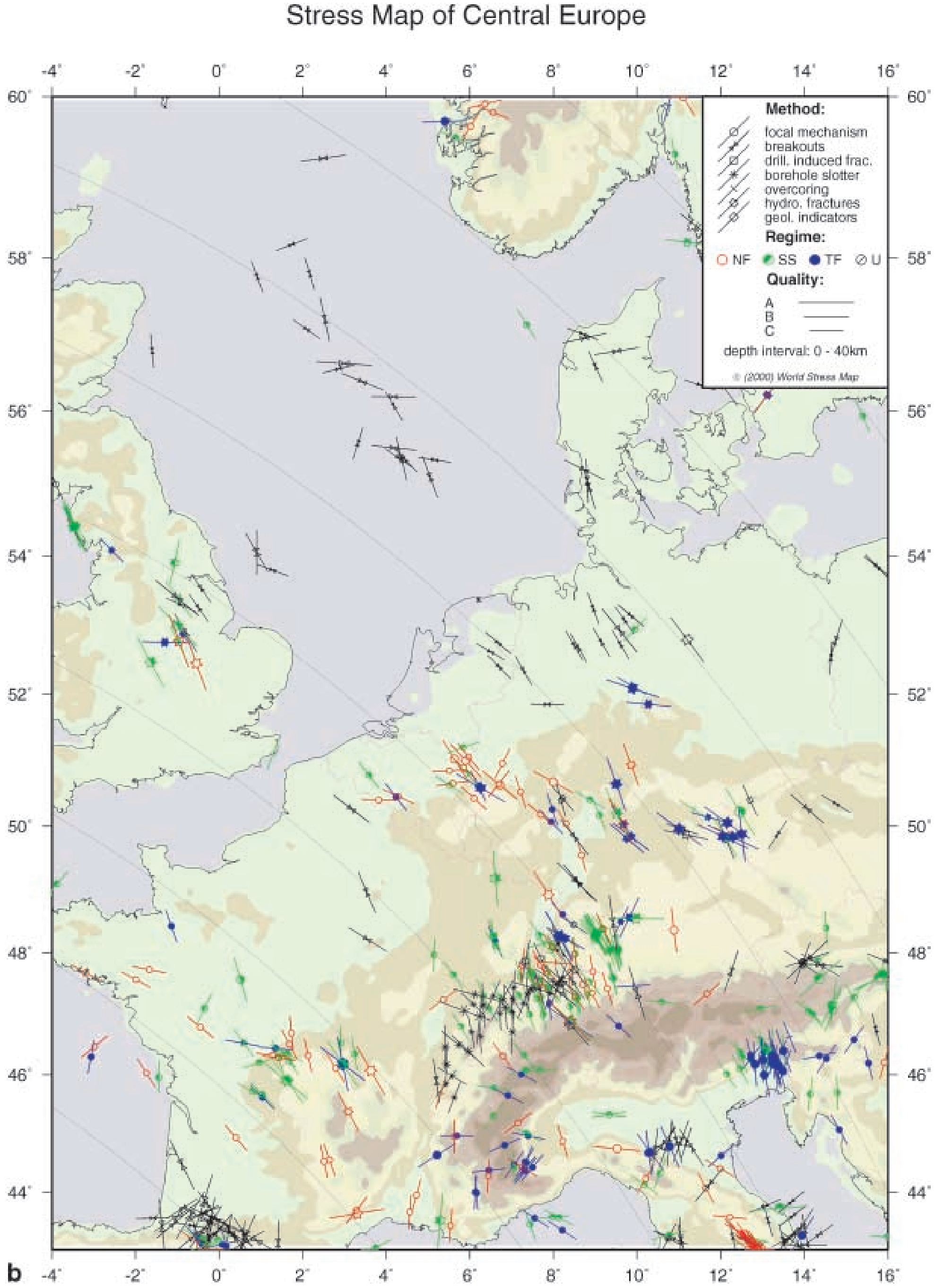


Plate tectonic images in the WSM: plate interior stresses

The African continent is surrounded by mid-ocean ridges in the west, south and east and a continental collision zone to the north, all of which should lead to mid-plate compression. This is in obvious contrast to the large-scale rifting in Eastern Africa. The prevailing E–W direction of S_H is conspicuously interrupted by an almost 90° rotation of S_H (Fig. 4a) within the East African rift. This rotation is very probably induced by the upwelling of diapiric material from the mantle below the rift (Zeyen et al. 1997).

The NW–SE trend of the S_H direction in western Europe north of the Alps is the interference of stresses induced by the North-Atlantic ridge in the west and north and the Alpine–African collision in the south (Müller et al. 1992). A specific feature of Western Europe (Fig. 4b) is the rapid change of the stress regime from thrust faulting, through strike slip to normal faulting on a small lateral scale of a few 100 km. This is understood as indicative of mobile crustal blocks decoupled at the crust–mantle boundary in a high temperature regime (Müller et al. 1997). This observation is in strong contrast to North America where thrust faulting is the prevailing re-

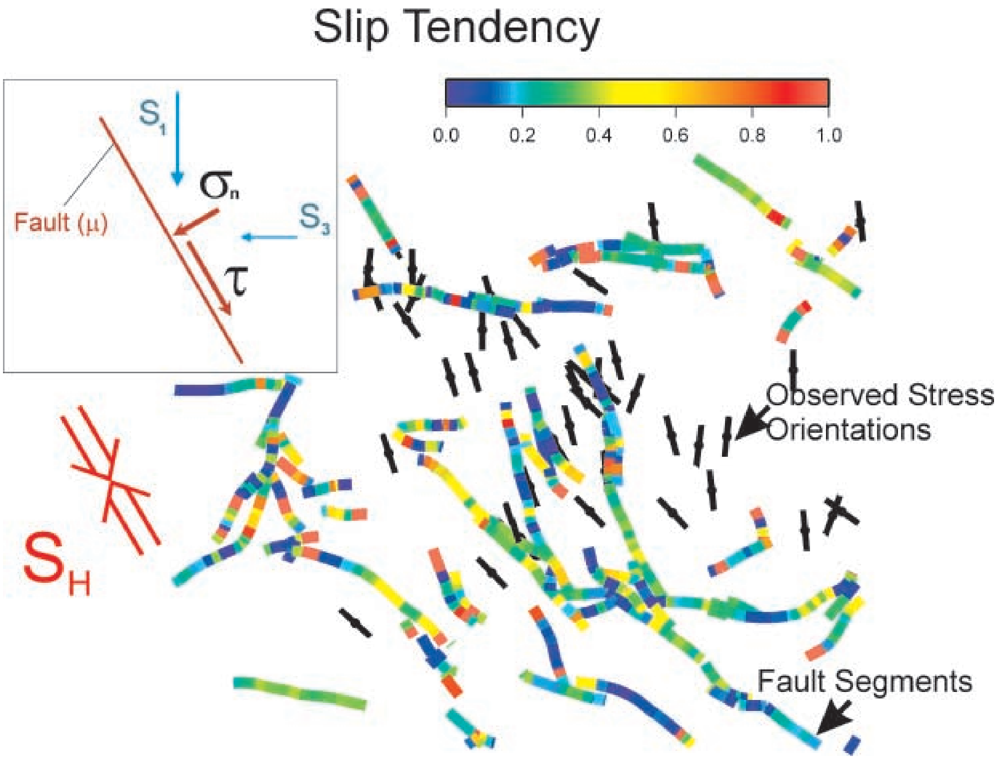


Fig. 5 Combination of regional anisotropic stresses (*black symbols*) with fault patterns leads to a slip tendency map based on the ratio of shear (τ) to normal stress (σ_n) on the individual faults segments (see inset). *Red colouring* indicates those segments which are most likely to slip

gime in a cold lithosphere without decoupling at the crust–mantle boundary.

Where stress affects civilization

Earth stress is a source of major hazards to our civilisation. We are encountering the effects of stress as natural and as man-made hazards. Natural hazards are experienced during earthquakes as stress release by rupture with increasing risk to our civilisation. Establishing and enforcing building codes is our response in an attempt to reduce seismic hazards. Moreover we become aware that all attempts of our modern civilisation to reach deeper levels of the subsurface for underground constructions become increasingly hazardous; safety and stability becomes a major concern. These underground constructions (mines, shafts, caverns for nuclear or toxic waste disposal, reservoirs for gas storage, tunnels, numerous exploration and production boreholes) suffer from the self-inflicted disturbance of the existing tectonic stresses. For both natural and man-made hazards, knowledge of the pre-existing stresses is essential for hazard reduction or mitigation.

Seismic hazard: stress and active fault patterns in a critically stressed crust

Seismic hazard estimation urgently requires refinement of current methods. Although the number and magnitude of earthquakes remain constant on the average, the seismic risk is increasing strongly. The main cause is the population explosion and the increasing concentration of people in megacities in seismically active regions (Fuchs and Wenzel 2000). What can the WSM contribute to the improvement of seismic hazard analysis? Present methods do not take into account the possible reactivation of faults in a critically stressed crust.

Critically stressed crust

Tectonic stress can only rise to the yield strength of the crust. In the ductile part of the crust below the depth where earthquakes are observed, the rock yields by creeping. In the upper brittle part (the upper 10–20 km of the crust) the material most probably ruptures by slip on pre-existing faults since their strength is far below that of intact rock.

Fault re-activation is a frictional process (Fig. 5, inset) and depends on the ratio of shear to normal stress, $r = \tau/\sigma_n$, sometimes referred to as slip tendency (Morris et al. 1996). If this ratio exceeds the frictional coefficient which ranges mostly between values of 0.6 and 1.0 (Byerlee 1978) the fault has an increased tendency to slip. According to Sibson (1974, 1990) the crust contains numerous faults in random spatial orientations. The crust is considered to be in frictional faulting equilibrium if the fault most favourably oriented for slip is just about to slip. A combination of a map of existing faults and the detailed distribution of stress directions results in a slip tendency map (Fig. 5) from which the fault segments that are most likely to slip can be identified.

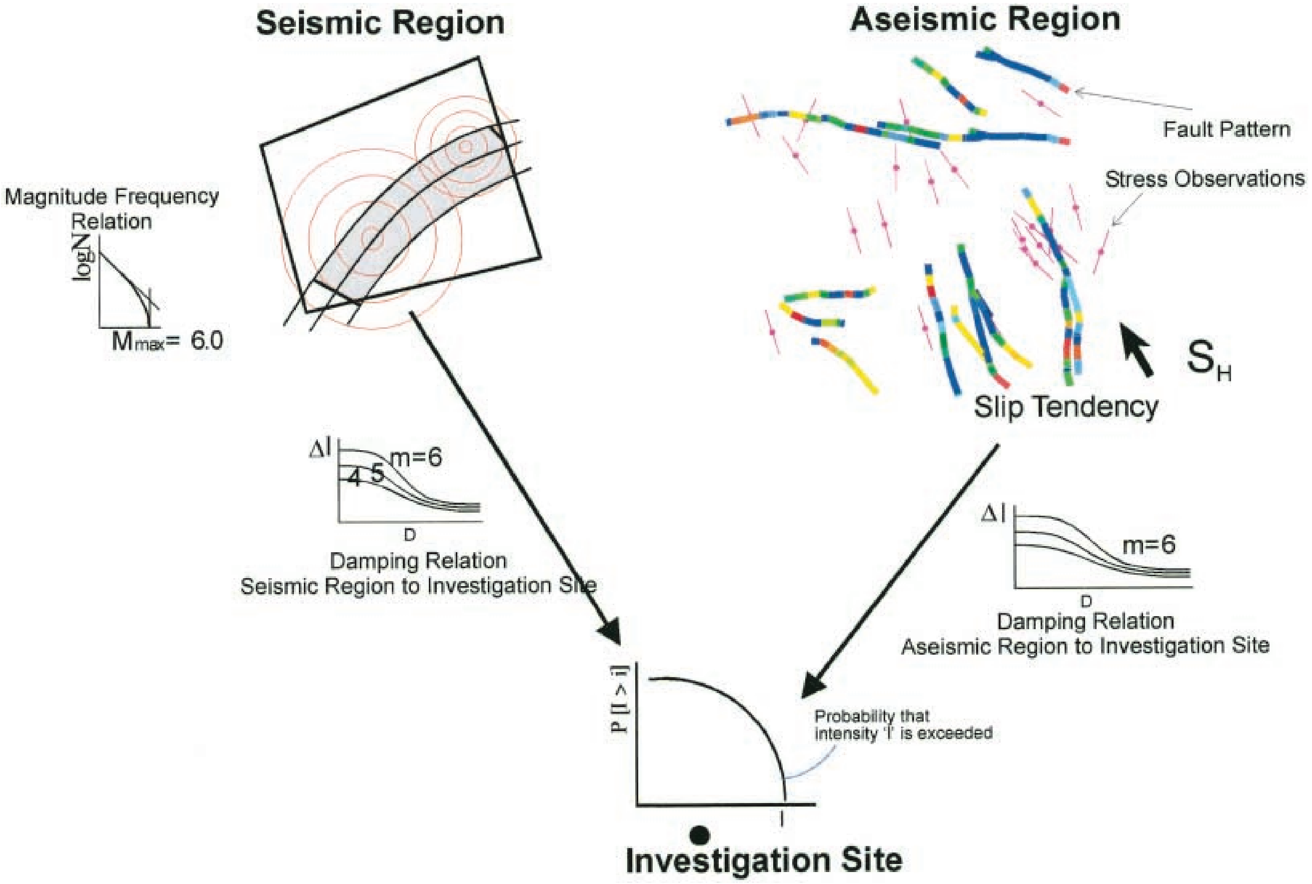


Fig. 6 The original method of seismic hazard assessment at a site following Cornell (1968) is based on magnitude history distribution of earthquakes and damping relations (*left*). Stress information, if combined with fault maps, offers the possibility to include slip tendency maps in the hazard assessment (*right*)

Seismic hazard: stress and active fault patterns

Classic seismic hazard assessment at a specific location is based on the likelihood that a certain ground acceleration will be exceeded within a given period, usually 50 years. These estimates use the magnitude–frequency relations which are derived from observed modern instrumental records or historic documents on damage or more recently by trenching the extent of buried geological faults (palaeo-seismology). Seismotectonic zonation and the damping of seismic waves along the path from possible locations of earthquakes to the site are taken into account (Fig. 6; Cornell 1968). Individual earthquakes are considered as independent and rare events. Regions without present earthquake activity, so-called aseismic regions, are not considered in this method.

Modern hazard assessment takes into account the instantaneous and temporal stress changes produced by previous earthquakes and how these stress changes bring pre-existing fault planes closer to rupture. The identification of those faults which are optimally oriented for reactivation by slip tendency analysis uses the computed stress changes and the far-field stress pattern and is an additional new component to be considered in seismic hazard estimations.

Aseismic regions form a special challenge in the development of hazard assessment. These regions are not free of stress. The question is whether the stress in these regions is far below the crustal strength. This can be achieved either by diminished stress magnitudes or by increased strength of the crustal material.

Modern concepts of crustal stress and the role of fluids

Deep drilling into the crust with stress measurements and related observations has resulted in new concepts on the state of crustal stress. The KTB (*Kontinentale Tiefbohrung in der Bundesrepublik Deutschland*) deep research borehole in the Upper Palatinate (*Oberpfalz*), Germany, with a final depth of 9,101 m, is the deepest hole in the world with stress measurements. Stress magnitude determinations by various methods to a depth of 7.7 km at KTB (Brudy et al. 1997) showed that the crust is in frictional equilibrium at all depth levels when normal stresses are reduced by hydrostatic fluid pressure. Three unexpected accompanying fundamental observations shed new light on the state of stress in the crust at the KTB site: (1) the presence of fluids at hydrostatic pressure to its final depth; (2) high permeability of the rock mass larger by two orders of magnitude than that of intact rocks (Huenges et al. 1997), and (3) a slight increase of fluid pressure (less than 1 MPa) during injection tests triggered micro-earthquakes or slip on pre-existing cracks (Shapiro et al. 1997; Zoback and Harjes 1997). The abundance of fluids at hydrostatic pressure signalled the presence of a network of open pathways connected to the free surface throughout a major section of the continental crust. What keeps these pathways open on time-scales in which chemical depositions would close them?

In the face of the three observations in deep drill holes, Townend and Zoback (2000) propose a new concept for the brittle part of the crust: in a crust close to frictional equilibrium it is the process of micro-cracking which continuously maintains the high permeability network of pathways with hydrostatic fluid pressure down to the final depth of the borehole.

This leads to the paradoxical scenario that continuous micro-cracking strengthens the crust. In its absence the open pathways would be chemically sealed, allowing the formation of large volumes of over-pressured fluids. These in turn would drastically weaken the strength of the crust by reducing the normal pressure on the cracks and thus increasing their slip tendency (see Fig. 5, inset). These are challenging questions for future research: What is the mechanism which determines the rate of micro-cracking and does this rate change with time? How does the rate of micro-cracking relate to the magnitude history relations derived in the macro scale from earthquake observations?

Mining, tunnels, drillholes: stability aspects in underground engineering

Ever since men began to dig deep into the ground to mine for minerals and to excavate rocks they had to learn to cope with Earth stresses. In a quarry the direction of stress can be used by the skilled miner to facilitate rock production. At deeper levels in a mine, the load of the overburden rock becomes a major concern; it has to be balanced by pillars and walls. However, it is well known from the many accidents in mines that this protection was not always successful (Fig. 7).

Today our civilisation is entering the subsurface for exploration, production, storage and traffic to an unprecedented degree. Modern underground openings are related to power plants, dams, road and train tunnels, caverns for gas storage or underground waste disposal and arrays of on- and off-shore drillholes for hydrocarbon or geothermal energy production. The following typical causes of stress-related hazards arise:

1. Severe redistribution of the initial stress is caused by the creation of new free surfaces in all underground openings, by increasing or diminishing mass loads. This redistribution may lead to stresses in excess of rock strength and thus to failure of the construction.
2. Penetration of fluids on faults crossing the underground construction may lead to activation of faults by increase of slip tendency. This eventually leads to shearing of the well or underground construction (Maury and Zurdo 1994) or leakage of reservoirs (Sibson 1990; Wiprut and Zoback 2000).

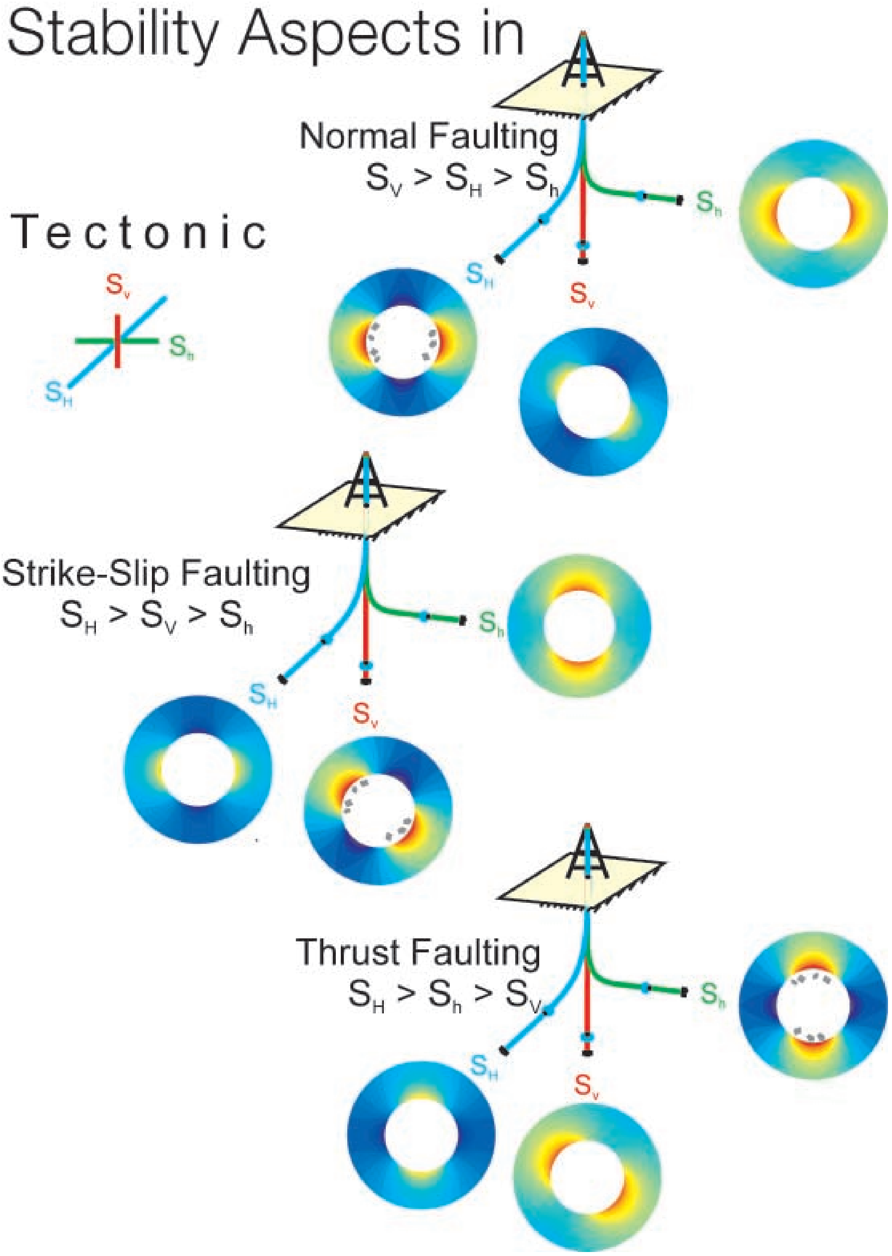
Fig. 7 View along strike of active thrusting exposed in a mine near Peissenberg in subalpine molasse, north of the Alps, triggered through mining at about 1,120 m below ground. Figure courtesy of Mrs H. Illies (Illies and Greiner 1976)

These hazards may arise both in classical mining and in modern underground construction. Knowledge of the prevailing tectonic stress and of fault locations, if available, is critical for the decision on the mining, drilling, construction or reinforcement method.

Today's underground constructions are also confronted with new constraints concerning their life-span. Whereas the stability considerations of ancient buildings ranged between 10^2 and 10^3 years, the wider application spectrum of modern underground openings requires a broader range of time-scales. The stability warranties of the underground openings range from tens of years for the drilling and production phase of reservoir drillholes to 10^4–10^5 years for deposits of dangerous materials. This requires that the evolving in situ stresses, those due to the excavation and the thermal stresses due to the heat release from radioactive waste, should not exceed the rock strength over time. Micro-fracturing of rock and mobilisation of waste in solution could not only alter the pathways of groundwater flow in the repository area but also pollute the biosphere in the vicinity of the repository.

In the following we will give an example of stress concentration which is important for the drilling industry. The stress modification around a circular hole in an anisotropically stressed rock mass is classically described by the Kirsch equations (Kirsch 1898). Numerical algorithms and detailed investigation of the stress pattern are required for more complicated designs. However, the principal failure conditions can be derived from the analytical Kirsch approach (Fig. 2b). Knowledge of the natural stress prior to the excavation is necessary to identify zones of stress concentration, either in tension or in compression, to decide about the appropriate means for stabilisation.

Fig. 8 Illustration of stress distribution around deviated boreholes located in different tectonic regimes with respect to the stress pattern. Despite the fact that the sketch is a simplistic visualisation, it shows the changes in stress distribution with dip and azimuth of the borehole. The *colour code* is the same as given in Fig. 2c. Possible failure is indicated. Note that failure occurs in different drilling directions in the three regimes



Tensile stress concentrations may lead to opening of pre-existing fractures or may even fracture the rock. This facilitates the penetration of fluids, increases the weathering and leads to further instability.

Compressive stresses: in view of the growing number of deviated (non-vertical or extended reach) boreholes, the relationship between stress orientation and regime and direction of drillholes increasingly gains in importance. Figure 8 visualises the possible compressive failure for boreholes (also valid for shafts, mines) in different drilling directions under different tectonic regime conditions. This simple illustration already implies that in normal faulting regimes, the boreholes are most likely to fail sideways when they are drilled parallel to the S_H direction. This topic is considered in numerous publications (Mastin 1988; Peska and Zoback 1995; Zajac and Stock 1997). This is in agreement with the observation that in normal faulting areas, problems occur in the sidewalls of mines (Amadei and Stephansson 1997). In thrust faulting regimes, boreholes will fail at the top and bottom when drilled into S_h, again in agreement with mining observation where problems in roofs and floor occur for areas of high horizontal stress. Under strike slip conditions, vertical boreholes and shafts are most endangered for failure because they experience high stress concentrations in the direction parallel to S_h.

Reservoir management in hydrocarbon and geothermal energy development

For exploration and production companies, in situ stress is a key element of reservoir management. Integrated basin modelling of development, migration and accumulation of hydrocarbons is one technique for estimating the economic significance of the individual reservoirs. The contemporary tectonic stress in combination with the actual natural fracture network constrains hydrocarbon migration, accumulation and production because it controls the fluid flow pattern (Connolly and Cosgrove 1999) through (1) the present anisotropy of permeability and (2) potential natural or induced leakage of reservoirs (Sibson 1990; Lorenz et al. 1988). The fluid flow is essential for the successful recovery of hydrocarbons as well as geothermal energy. Numerous examples of a strong correlation between the preferential direction of fluid flow in a reservoir and the orientation of horizontal stress are described by Heffer et al. (1997).

Fracturing of formations is the main technique to stimulate production by the creation of new pathways and thus to enhance oil and gas recovery, especially when fields are near the end of their life or when reservoir permeabilities are too small (Hickman and Dunham 1992) such as in so-called tight reservoirs. Fracturing is a process where a fracture away from the borehole is developed by pumping water or gels into the target area. The fractures propagate perpendicular to the least stress. The successful fracturing is dependent on the anisotropy (thus magnitudes) and orientation of in situ stress as well as on rock properties such as strength, permeability, natural fracture network, porosity and fluid saturation.

WSM: future developments

The WSM project does not stand alone but develops its power in connection with other observations related to the deformation of the Earth's surface. In the future there are a number of exciting challenges for the WSM project.

WSM and active faults

The link between the WSM and maps of active faults is a primary target for an improved seismic hazard analysis (see above). The establishment of local and regional maps of active faults is essential, especially in aseismic regions where seismic reflection surveys may be used to identify faults, and even to estimate their age. This could become another new link between the WSM project, the hydrocarbon industries, seismologists and earthquake civil engineers.

The estimate of fault reactivation potential must be considered as a valuable new asset in hazard estimates, especially where magnitude–frequency data are either not at hand or are only documented by sparse observations as in aseismic regions. Modelling of fault behaviour in a given stress field requires calibration with existing seismic data in order to gain information on fault properties, such as friction coefficients and fluid pressure. Furthermore, it will not be sufficient to model single faults as isolated entities. The next step will be to model the non-linear network dynamics of earthquake faults (Rundle et al. 2001).

If continual small-scale slip occurs due to the fact that the actual stress is close to the limiting crustal strength, the question arises why some regions react by continual slip, whereas others react by macro-slip as earthquakes. In other words: what controls the amount of micro-fracturing and of slip? In this context, one has to be aware that micro-slips are not directly observable.

WSM and strain rate maps

Strain rate is the amount of deformation in time for a given structural unit. The correlation of the distributions of stress and strain rate is an important tool to obtain information about the properties of the Earth's crust fractured on various scales, decoupled internally and also from its base (e.g. from the ductile lower crust). In a homogeneous isotropic medium, the principal axes of the stress tensor coincide with those of the strain and strain rate tensor. This is not the case in fractured media. This correlation of stress and strain rate distributions is influenced by the properties of the fault network. One opportunity for this kind of studies will be the comparison of stress orientations with data from the global compilation of strain rates (http://www.unavco.ucar.edu/science_tech/globalvelstrn/globalstrn1.html) within the 'Global Strain Rate Map' project of the International Lithosphere Programme.

WSM, seismic anisotropy of the upper mantle and absolute plate velocities

Seismic anisotropy of the upper mantle has been deduced from observations of various kinds of seismic waves. A number of researches attempt to correlate the direction of the fastest compressional velocity in the upper mantle with the direction of the largest horizontal tectonic stress S_H in the WSM (Fuchs 1983; Polet and Kanamori 1997; Polet 1998; Schulte-Pelkum et al. 2000) and also with the direction of absolute plate motions. From a regional and a world-wide comparison, it appears that a positive correlation between stress and anisotropy direction is observed in tectonically active regions where mantle flow is closely coupled with the deformation of the lithosphere. Correlation of absolute plate velocity and stress direction is observed in old plates such as North America and Siberia where the lithosphere is likely to move passively on the mantle convection flow. This is certainly a very important new field for the WSM, with direct application to tectonic modelling.

The WSM project: a unified repository for industrial data on tectonic stress – an appeal to the industry

The WSM is a research project of the Heidelberg Academy of Sciences. The release of the industrial borehole geometry data to the WSM did help to create a global view of a new fundamental data-set for the earth sciences. It proved to be an unexpected benefit for the industry itself: previously “fragmented” company data have now become united pieces of the global, regional or even local stress puzzle; and the WSM data bank has turned out to be a safe independent archive for stress data which would, at least in part, have been lost otherwise. Thus, the entry of industrial stress data into the WSM enhanced, in an essential way, the value of these data for the donors and the scientific community at large.

Apart from academic users, the industry itself has become a regular client of the WSM web-page on the Internet. The industry applies the WSM in exploration, borehole stability problems especially for the growing number of extended reach wells, reservoir management such as optimal positioning of injection and production holes, fracture measures to enhance productivity in low-permeability reservoirs, tectonic modelling, especially of basins, and correlation with other data-sets such as 3D structural information, e.g. faults.

The release of borehole deformation data is not only timely but urgent because of the pending danger of physical loss of memory of data carriers or organisational data loss. Companies have spent considerable time and money on collecting the data. A loss of the existing industrial data would in practice mean that this information became irretrievable because drilling costs prohibit a repetition of the holes in the same region and because the sites might no longer be accessible due to urbanisation or environmental protection.

We appeal to all companies in the hydrocarbon industry to participate in the rescue of stress-relevant data which ultimately are at risk of being lost permanently. The release of stress-relevant data from industry archives would be an important and crucial contribution to the WSM.

Summary and conclusions

Earth stresses range from continent-wide regional scales related to tectonic processes, such as the evolution of sedimentary basins and earthquakes, to local scales of reservoirs and construction sites in the order of kilometres, metres or even decimetres. The WSM has been established as a fundamental global data-base of the solid earth sciences and as a framework and guide for more detailed and local investigations of the contemporary tectonic stress field.

The global integration of all available data on present-day tectonic stress revealed a number of unexpected phenomena, such as: continent-wide provinces of homogeneous orientation of S_H, relation to large-scale tectonic features such as subduction zones, transform faults, continental collision zones and anisotropy of seismic waves in the upper mantle. Plate interior stresses are demonstrated in the East-African rift, in western Europe and especially in combination with stress measurements in deep continental drillholes. Here the continental Earth crust is revealed as permanently in frictional failure equilibrium. The crust is strengthened by the process of continually generated micro-fracturing, allowing high permeability and hydrostatic fluid pressure to the deepest sampled depth.

The WSM project serves as a long-term independent archive for data on tectonic stress with free access via the Internet. Further co-operation with the hydrocarbon industry is necessary to rescue the existing data from loss.

Earth stress affects our civilisation during earthquakes as natural hazards and as man-made hazards in underground construction. The WSM in combination with maps of active faults opens a new dimension for hazard estimates in calculating slip tendencies of segments of the fault networks. Moreover it opens up a new way to refine the mitigation of stress-induced hazards. An improvement of seismic hazard measurement is urgently required for a better calculation of seismic risk in view of the fast-growing population and its tendency to concentrate in megacities.

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All stress maps are plotted with GMT provided by Wessel and Smith (1991, 1998; http://www.soest.hawaii.edu/gmt/); plate boundaries come from the PLATES project (http://www.ig.utexas.edu/research/projects/plates/plates.html).

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