10. Stress and stress release in the lithosphere – Geothermics and borehole geophysics

for sustainable use of the underground and geodynamic understanding

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Abstract

Safe and environmentally compatible exploration and production of underground energy resources and the description of geodynamic processes such as earthquakes require a detailed quantitative understanding of the state of stress in the Earth´s crust. This needs a compilation of stress information in time and space by natural as well as anthropogenic processes. With responsible application of knowledge about the relations between fluid pressure and mechanical stress, hazard in mining can be reduced, the efficiency of underground utilization will be enhanced and the influence on the living environment is minimized. Tectonic stresses that form our planet are ultimately linked to volcanism, plate tectonics and earthquakes. The researcher Karl Fuchs at the Geophysical Institute of the University of Karlsruhe (now KIT) initiated numerous projects in that context on national and international scales which led to a new understanding of processes. This knowledge is today's basis for modern reservoir management and safely use of the underground for a reliable and economical future energy supply. Moreover, it contributes to systematic earthquake and tsunami risk reduction as has been foreseen in the essay of Karl Fuchs on the 1755 Lisbon and 2004 Aceh earthquakes.

1. Introduction

In a common sense *stress* is mostly understood as a feeling of strain. Thus, stress is perceived mostly in a negative way when man is under extreme pressure with panic exhaustion, high blood pressure or conflict and political tension. Moreover, the German translation of stress is "Spannung", which is used as equivalent to electrical voltages as well as human excitement, which can lead to misunderstandings. In a geological sense stress is related to strain of rocks, but even in scientific literature there is some confusion about some of the stress definitions. Terry Engelder has described that in 1994 in EOS in his essay "Deviatoric stressitis: A virus infecting the Earth science community" in a humorous style. Thus, stress is not an easy term. The geomechanical stresses in the Earth´s crust are of great relevance for geodynamic processes that generate our landscape such as plate tectonics, orogeny, volcanism and earthquakes or cause catastrophes such as the strong motion earthquakes generating tsunamis responsible for hundreds and thousands of casualties such as in Lisbon 1755 or Banda Aceh in 2004 (Fuchs, 2009). In that context geomechanical stresses have found broad acceptance.

The necessity to deal with stress in the framework of effective and safe energy exploitation is less known in the public, but also relevant. E.g., seismicity occurring as a consequence of hydraulic stimulation in the Basel geothermal project led to project abandonment. Seismicity in the gas fields of the Netherlands started after about 10 years of production (van Eck et al. 2006). Furthermore, there is an intense public concern about shale gas production using hydraulic fracturing that can also result in induced seismic events.

A wide spectrum of use of the underground for energy supply is under debate: efficient use of hydrocarbons in combination with a reduction of the CO_2 emissions into the atmosphere by underground storage of CO_2, Enhanced oil Recovery (EOR), Enhanced Gas Recovery (EGR) using hydraulic fracturing technology, shale gas and coal bed methane exploration . The further development of hydropower reservoirs is limited, but is an important contribution for base load supply. The underground storage of gas in caverns and abandoned gas reservoirs requires a good knowledge about geomechanical stresses and is an important contribution to stable energy supply. For the efficient use of geothermal energy and for EGS systems at depth geomechanics is an important issue in terms of safety and economics.

How stresses in the Earth´s crust influence modern life also indirectly was experienced by the strong earthquake at the Japanese coastline in April 2011 that led to political shut-down of power plants in Germany - located more or less on the other side of the globe. A number of system components of the Fukushima nuclear power plant could not withstand peak ground accelerations from the earthquake in combination with a tsunami wave which finally led to nuclear meltdown in several reactors. This strong earthquake is basically a consequence of the movement of tectonic plates where especially at convergent plate boundaries strain and stress build up, which will be released in form of seismicity when the crustal strength is exceeded. Aside from well-established probabilistic methods for seismic hazard assessment which are based on statistical analysis of (mostly incomplete) earthquake catalogues, there are geomechanical approaches to understand the earthquake process of strong motion earthquakes and to perform numerical simulations in advance. For this approach the mechanical stresses and their changes with time are required to quantify these processes.

A wide spectrum of research activities of the Geophysical Institute, initiated by Karl Fuchs dealt with the processes involved in reservoir exploitation. During about 20 years the scientific base for the understanding of the process has been founded by the creation of a fundamental stress database within the framework of the World Stress Map (WSM) project. The WSM project was initiated in 1985 as a task force under the leadership of Mary Lou Zoback during Karl Fuchs´ time as president of the International Lithosphere Program (ILP) of the IUGG and IUGS. Applying this stress database, important findings for the interpretation of geodynamic processes on a continental scale but also for the optimized and safe production of hydrocarbons on reservoir scale have been established. Karl Fuchs intensified research on strong motion earthquakes especially after the tsunami generating earthquake in December 2004 in Indonesia (Fuchs, 2009).

Here, we describe the activities of crustal stress research taking place in the last 40-50 years, without claim of completeness. We want to highlight the contribution of scientific investigation of reservoir geomechanics for the current discussion on safe energy supply and climate protection. We sketch the state of the art of research and give a future perspective on the potential of geomechanical-numerical 2D to 3D modeling especially for strong earthquake understanding and hazard assessment. We will first start with the definition of the stress terminology used in this essay and then focus on the research for reservoir geomechanics and geodynamic processes along with earthquake generation – a field of research for which Karl Fuchs motivated generations of geophysicists and settled a solid base in the Geophysical Institute of the University of Karlsruhe (now KIT).

2. Stress in the Earth´s crust

Stress is a field quantity which we cannot sense such as temperature or velocities. Whereas temperature at any location can be described by a scalar and velocity by a vector, the stress has to be described by a second-order tensor, thus a 3x3 matrix with nine components. Due to conservation of momentum, the stress tensor is symmetric, thus there are only six independent components of the stress tensor. For a symmetric tensor it is always possible to find a principal coordinate system, for which only the diagonal elements of the matrix remain and the stress state can be described by three eigenvectors. Those are the principal stresses, which can be visualized by a stress ellipsoid (Fig. 1). The difference between the magnitudes of the largest and the minimum principal stress is called differential stress.

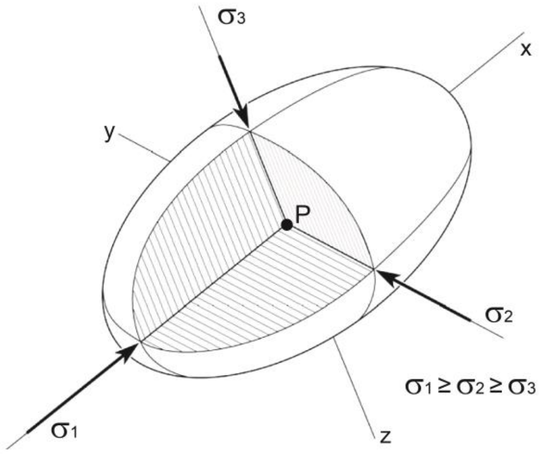


Fig. 1: Lamé stress ellipsoid. The three principal stresses (Eigenvectors) σ_1, σ_2 and σ_3 of the symmetrical stress tensor σ_{ij} describe the state of stress at a point P.

Under the assumption that in the Earth´s crust the vertical stress resulting from the gravitational load is one of the principal stresses – which is only valid directly at the surface under the assumption of the absence of shear stresses e.g. induced by winds – the state of stress can be described at first approximation by the vertical stress $S_v=\rho gz$ with g gravitational acceleration ρ the rock density and z the depth and the maximum and minimum horizontal stresses S_H and S_h.

Above we provided a rather general description of the state of stress, more popular is the following special case: When the three principal stresses are equal in magnitude ($S_v=S_H= S_h$), the stress ellipsoid is a sphere and the stress state is called lithostatic. Already in 1878 Heim postulated that this enables to describe the state of stress in the Earth´s crust. However, if the state of stress would be everywhere lithostatic only volumetric shape changes would occur but no other types of deformation such as distortion and strain which cause the shaping of our landscape *e.g.* by forming deep sea trenches and mountainous areas. In purely elastic media stresses and strains are related by Hooke´s law, named after the 17th century British physicist Robert Hooke. Terry Engelder (Engelder, 1992) defined the differences from a reference state of stress (*e.g.* lithostatic state of stress) as *tectonic stress.* In the following we use the term state of stress independent from its origin for the sum of all its components, natural or in situ stress or induced stresses by human activities, which is a disturbed in situ stress.

The three principal stresses S_v, S_H and S_h have been used by Anderson (1905) to define the three tectonic regimes, which describe the kinematic behavior of tectonic fault zones. In a normal faulting regime the vertical stress is the maximum principal stress, in a strike slip regime it is the intermediate principal stress and in a thrust faulting regime it is the least principal stress (Fig. 2).

Some confusion appears for the terms deviatoric stress and differential stress. The latter is the difference between the maximum and minimum principal stress, thus $\sigma_d=\sigma_1-\sigma_3$. The differential stress is causing the deformation of the Earth´s crust. The deviatoric stress σ'_{ij} is the total stress σ_{ij} minus the isotropic part of the stress tensor which is the trace of the stress tensor (the pressure, Jaeger et al., 2007):

$$\sigma'_{ij} = \sigma_{ij} - \delta ij\, (\sigma_{11} + {}_{22} + \sigma_{33})/3$$

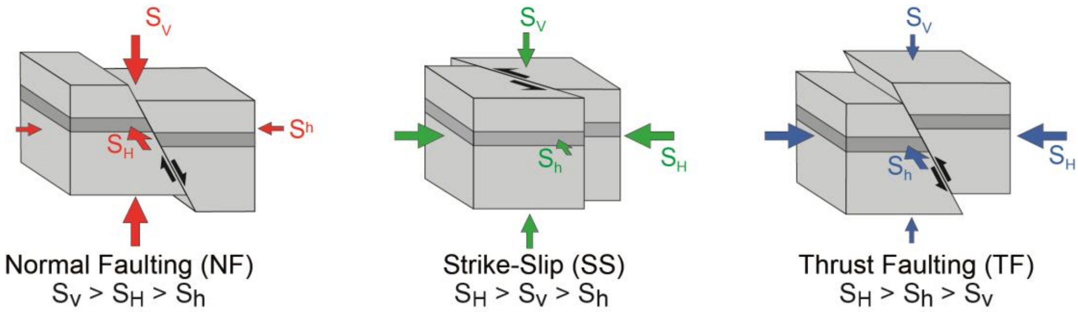


Fig. 2: Tectonic regimes and the role of the vertical stress which is the maximum principal stress in normal faulting regimes, the intermediate principal stress in a strike-slip regime and the least principal stress in a thrust faulting regime.

Furthermore, the state of stress is limited by so-called boundary conditions. For example at free surfaces shear stress cannot exist and stresses normal to the boundary have to be continuous (normal stresses of planes perpendicular to the free boundary are not necessarily continuous across the boundary). This results in vertical and horizontal orientations of the principal stresses at the Earth´s surface. Deviatoric stresses can be released in plastic (hot) material, thus the stresses have to be taken over by the more stiff material, which leads to stress concentrations in more competent layers. Especially in mining such stress concentrations can lead to dangerous situations.

3. The Why and Where of Stress Changes and Concentrations

3.1. Human activities

Any anthropogenic modification of the underground results in changes in stress of the Earth´s crust. Removal of material in wells, shafts or mines creates free surfaces with zero shear stress boundary conditions and normal stresses equivalent to the filling (gas or fluid) of the underground opening. As a consequence, the stresses in the crust have to readjust, which leads to changes in stress orientation and can lead to stress concentrations in the immediate vicinity of the underground opening (Fig. 3). If these stress concentrations exceed the strength of the rock, failure may occur, which can result in the so-called borehole breakouts (despite the name, borehole breakouts do not occur in wellbores only but also in tunnels etc.). Breakouts occur in the orientation of the minimum stress concentration (for isotropic rocks). In the orientation of the maximum stress, the tangential stresses at the borehole wall can result in tensile fractures. The latter process is the base for the so-called hydraulic fracturing, which is under intense current debate in relation with shale gas production.

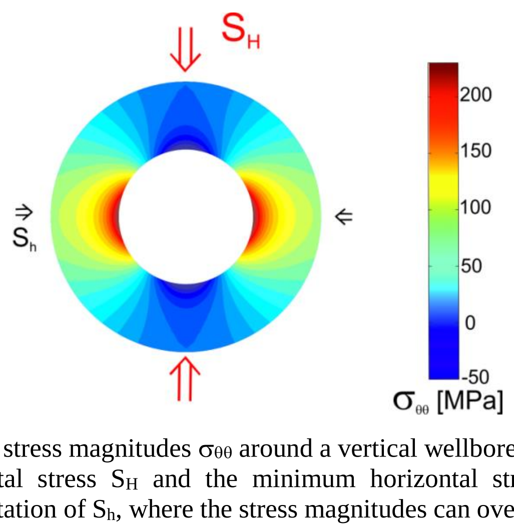


Fig. 3: Distribution of tangential stress magnitudes $\sigma_{\theta\theta}$ around a vertical wellbore situated in a far field stress with the maximum horizontal stress S_H and the minimum horizontal stress S_h. The stress magnitudes concentrate in the orientation of S_h, where the stress magnitudes can overcome the rock strength and lead to the evolution of wellbore failure: borehole breakouts.

In mines and tunnels those failures of the borehole wall can have dramatic consequences for activities and miners (Fig. 4). Despite the facts that a) the stress readjustment at free surfaces is well-known (Leeman, 1964; Cox, 1970) and that b) it was recognized that the stress orientation derived from the orientation of the breakouts is rather independent from depth, lithology and orientation of the tunnel or well (Babcock, 1978), the phenomenon of borehole breakouts has been explained at first by cross-cutting of pre-existing fault zones.

The interpretation could only change because new logging technology, namely the oriented 4-arm caliper tool, was invented to determine borehole cross section geometry. This tool was used in numerous wells and Bell and Gough (1979, 1981, 1982) as well as Gough and Bell (1981, 1982) could empirically relate the breakouts to independent observations of stress orientations. Furthermore, they developed the rock mechanical concept of breakout generation as result of stress concentration in anisotropically stressed rock. This convinced Karl Fuchs during a visit at Ian Gough in such a way that he promoted the breakout investigation as contribution to the Institute´s efforts to improve the knowledge of the state of stress in the Earth´s crust (Blümling et al., 1983).

Anthropogenic influence on the tectonic stress field is manifold, such as potash mining, copper mining or loading of parts of the crust during the impounding of water reservoirs. The 1989 earthquake of M_w=5.4 at Werra/Völkershausen as a consequence of potash mining and the seismicity due to copper mining in Legnica/Glogow in Poland with magnitudes up to 4.5 are examples with broad public perception. Large induced events in the German coal mining sites occurred in the Ruhrgebiet (M_w =4.1, 1888) and Peissenberg (M_w =3.6). An induced event of M_w = 3.8 in 2008 in the Saarland resulted in abandonment of coal mining in that area. However, there had been also economic reasons for that decision.

Fig. 4: Breakouts in tunnel walls can lead to loss of lives or require expensive safety measures. Left: fractures in a shaft wall in the Äspö rock mechanics laboratory in Sweden. Right: tunnel wall deformation in the Lignite Mine near Peissenberg, Germany.

3.2 Application of Stress Field Knowledge for the Use of the Underground

Apart from the unwanted phenomena such as breakouts occurring as a result of stress concentrations, tectonic stress can be used to improve the economic use of the underground significantly. The hydraulic fracturing (Fig. 5) has been invented in the 1940s of the last century to enhance the connection between wellbores to the reservoir in the underground. In this method directed fractures are initiated by pressurization of a wellbore depth section. The fractures develop in the orientation of S_h as soon as the tensile strength of the rock in the wellbore surrounding is exceeded. In normal faulting and strike slip faulting regimes the fractures are oriented vertically, in thrust faulting regimes horizontal fractures can develop.

The process of fracturing causes induced seismicity with small, normally imperceptible earthquakes. When in December 2006 the fracturing of crystalline rock from a geothermal well caused a magnitude M_w=3.2 earthquake at 5 km depth, intense public debate led to abandonment of the project. In the year of the 650th "anniversary" of the Basel M=6.6 earthquake people had been skeptical about larger damages to be triggered by geothermal activities. In 2013 in St. Gallen a magnitude 3.5 event was induced during measures to inhibit gas inflow into a geothermal well, in this case the city parliament decided to go ahead with the project.

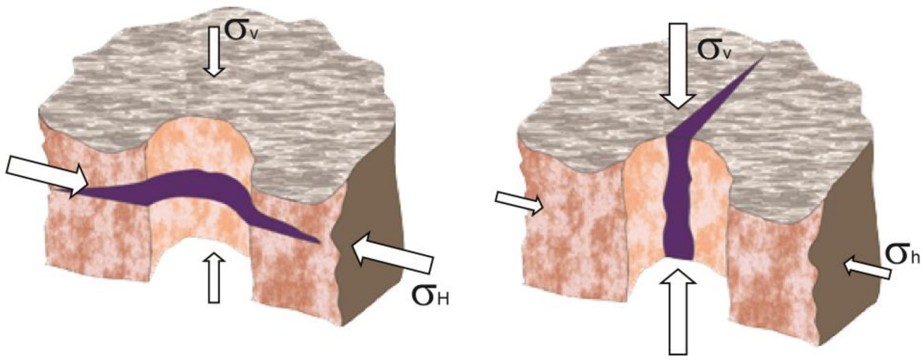


Fig. 5: Hydraulic fractures initiating at a wellbore. These develop when fluid-pressure in the wellbore creates tensile stresses at the borehole wall which exceed the tensile strength of rock mass. At greater distance to the wellbore the pressure necessary to keep fractures open corresponds to the least principal stress. The fractures open according to the principle of least resistance and close when the pressure reduces.

In the past few years hydraulic fracturing was intensified for shale gas production. Following news and films about burning taps in the US (Film "Gasland") the technology is criticized and under intense public discussion, especially since some of the chemicals used in the fracturing fluids are treated as industrial secrets. Residents are afraid that the fracturing fluid might contaminate drinking water if the fluids can migrate along fracture zones or leaky wells to drinking water producing horizons. In Germany, there is also a large resistance against hydraulic fracturing operations in the public because of water contamination issues and potential hazard to nature.

Natural leakage of gas reservoirs to the surface is known in numerous countries. However, only few systematic studies on the relationship between gas leakage in aquifers above producing reservoirs exist (Osborn, 2011). Osborn (2011) showed that the drinking water did not contain fracturing fluids or drill muds. It is difficult to investigate scientifically in how far the appearance of gas in drinking water horizons is amplified by activities of the hydrocarbon industry because in most cases baseline measurements (measurements of natural gas leakage before drilling activities) are missing in most areas.

On the other side, the hydraulic fracturing technology can also be used to reduce hazard and enhance safety. In Germany, *e.g.* in coal mining in the Saarland, the hydraulic fracturing technology was used to drain methane gas from the coal mine areas as a safety measure for the coal miners. In 1967/1968 eight hydraulic fractures in two deep wells at depths of about 600 m have been performed (presentation of Bergner, Saarbergwerke AG). Injection of ca. 155 m³ and 190 m³ fluid in the mine Luisenthal was performed with pressures of 22-25 MPa. The pressure build-up curve was interpreted as a modification of rock permeability by fissures and fractures created by the stress concentrations. The fractures reached about 150 m into the formation and later on have been mined through where the fractures could be investigated in-situ (Fig. 6). The gas produced from this activity was burned that time but according to the authors Schmidt-Koehl und Kneuper (1974) would have been sufficient for economic use.

Fig. 6: Hydraulic Fractures in a coal mine in Saarland region. The hydraulically produced fractures have been reached by the mine trajectory (RAG-Archiv Saar).

4. How Much Stress is in the Earth´s Crust?

4.1 About possibilities to measure stress orientations

Stress orientations can only be determined indirectly. All "measurement" methods do not really measure stress but observe deformations from which under certain assumptions about the rheology, the components of the stress tensor can be derived. Thus, stress determinations base on geological and geophysical measurements such as earthquake focal mechanism solutions, interpretation of borehole cross section geometries, geological indicators such as volcanic dykes and faults or overcoring measurements. In recent years numerous methods have been developed to determine the state of stress in the Earth´s crust. In general, two types of methods can be distinguished: those that disturb intact rock (overcoring, hydraulic fracturing) and those based on rock deformation without influence by the measurement (focal mechanism solutions, orientation of geological-tectonical structures, borehole breakouts). Using these methods the orientation of S_h can be determined. Only a few methods pose the potential to determine also stress magnitudes. Figure 7 provides an overview and a categorization of the most important stress indicators.

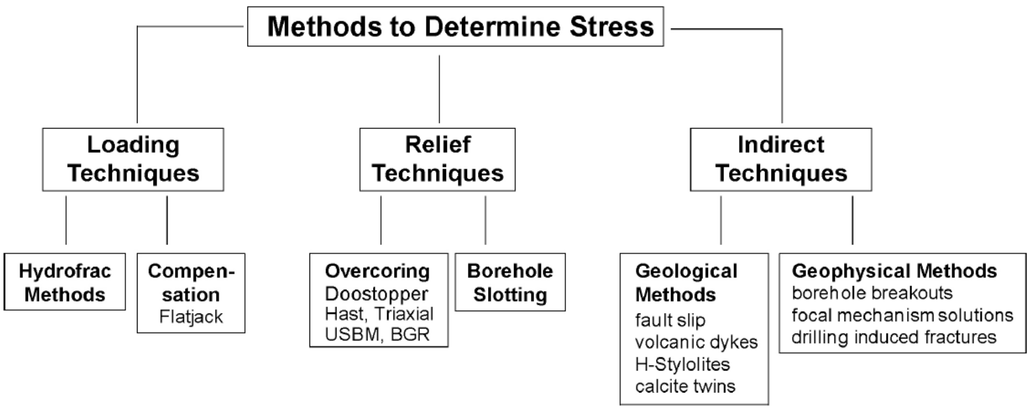


Fig. 7: Overview about the different methods to determine stress orientations or magnitudes of S_h (loading techniques) or the complete stress tensor (relief techniques).

The stress indicators do not only differ by used methodology but also by the rock volume, depth or time span for which they are representative. Data from wellbore breakouts are more or less available for the uppermost 6 km of the crust, despite from some deep industrial or scientific wells such as the continental drill hole KTB in Germany (Brudy, 1997). At greater depth focal mechanism solutions from earthquakes are the only means for information on stress regimes and orientation. Furthermore, it has to be considered that the different methods are valid for significantly different rock volumes (Ljunggren, 2003). Whereas overcoring represents 10^{-3} – 10^{-2} m³ of rock, breakouts 10^{-2} – 100 m³, focal mechanisms indicate the stress state in rather large volumina up to 10^9 m³. Thus, some methods are only conditionally useful to determine the stress in a larger region because local effects could have been responsible for the results of the measurement, such as anomalies in density, contrasts in material properties etc.

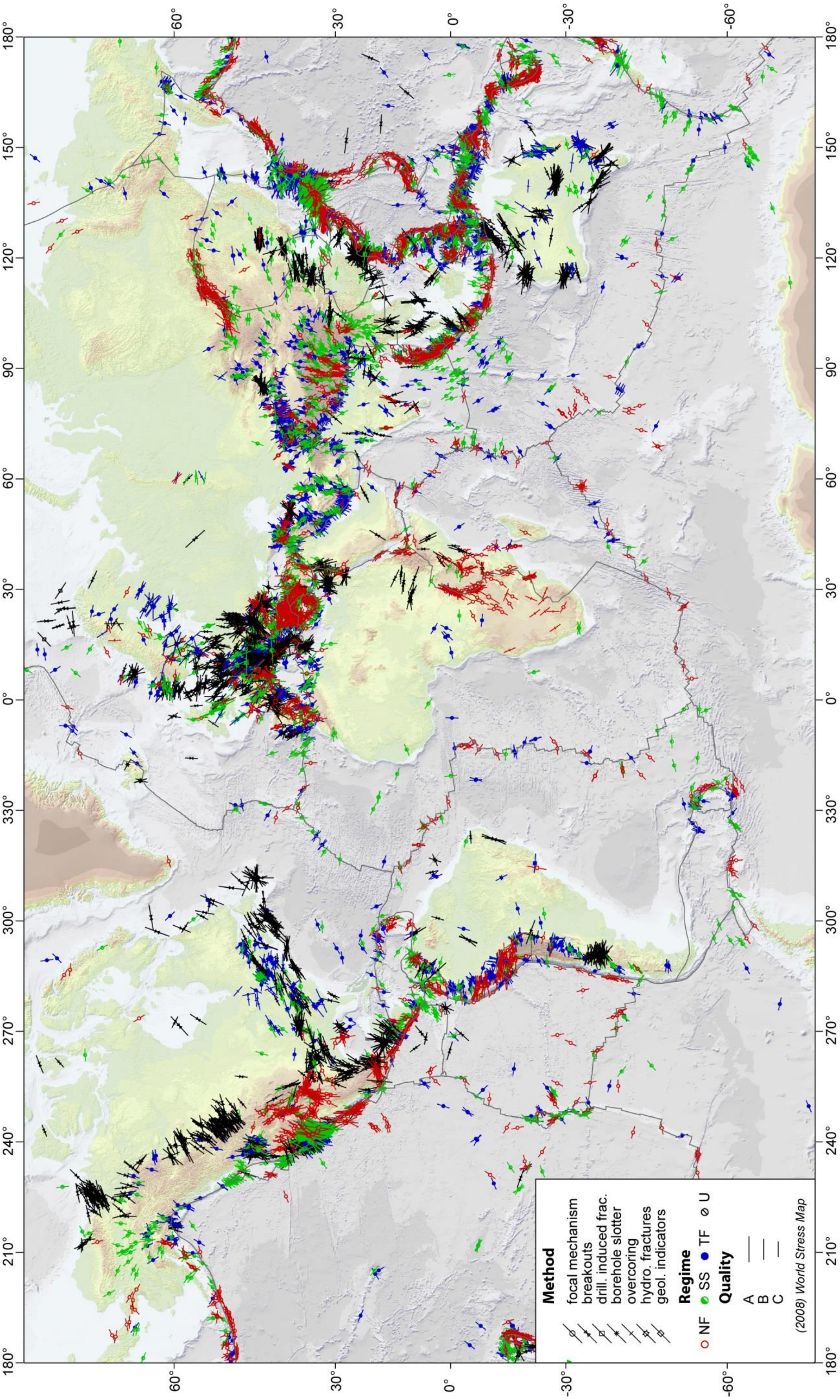
4.2 The World Stress Map Project (WSM Project)

To be able to compare the results of different stress indicators presented in the previous section was a challenge not easy to solve. A first regional compilation for Northern America (Sbar and Sykes, 1973) consisted of 52 data from overcoring, geological indicators, hydraulic fracturing and focal mechanism solutions of earthquakes and enabled the investigation of regional stress patterns. The newly emerging method of stress orientation determination from borehole breakouts (Bell and Gough, 1979) stimulated Karl Fuchs during his time as ILP president, to invent a global database in which data are compiled in a comparative manner, the birth of the World Stress Map (WSM) project.

The WSM project is a joint project of scientific institutions in Academia, industry and public with the goal to describe the stress pattern in the Earth´s crust and to investigate its sources. The ILP task force "World Stress Map Project" had a first highlight in a Nature publication (Zoback et al., 1989) when the World Stress Map contained data at 3,600 locations. After 6 years it ended successfully as ILP project and the results of the global compilation effort and its scientific interpretation was published in a JGR special volume. The WSM database had at that time app. 7,300 data records (Zoback, 1992).

Again it is owed to Karl Fuchs, who secured that the WSM would not be abandoned on a lonesome computer or floppy disk (for the young ones: a storage medium before CDs and USB-sticks). The international effort that had been put into the WSM database would have been lost. Therefore he convinced the Heidelberg Academy of Sciences and Humanities to set up a WSM research center. This was active between 1995 and 2008 at the Geophysical Institute of the University of Karlsruhe under the umbrella of the Heidelberg Academy of Sciences and Humanities. Karl Fuchs headed the project until 2000 and his successor Friedemann Wenzel and Karl Fuchs took care that the WSM is now an independent research project at Helmholtz-Centre Potsdam - GFZ German Research Centre for Geosciences. The third international WSM conference with more than 130 participants from 30 countries and proceedings in Tectonophysics (February 2010, vol. 462) was a scientific highlight. Today the unique and fundamental database of the WSM contains 21,750 data records (Heidbach et al., 2010).

The basic concept of the WSM is the standardized format of the data, a unique quality ranking scheme to guarantee the comparability of the data records from the different stress indicator on a global scale. The quality ranking scheme had been improved and extended during the first project phases in intense collaboration with international experts, new methods and gain of knowledge had been continuously incorporated (Zoback et al., 1991; Zoback, 1992, Sperner et al., 2003, Heidbach et al., 2010). The quality control considers different criteria such as the number of observations from which the mean for the orientation of S_h and the standard deviation is derived. For A-quality data the standard deviation has to be <15°, for B <20°, for C<25° and D<40°). Data with E Quality have no significance for stress interpretation but indicate that they have been checked. The visualization of the data is with stress maps showing the S_H orientation within the uppermost 40 km of the Earth´s crust and the stress regime (for those indicators that provide information about the regime, Fig. 8).


Method
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(2008) World Stress Map
180° 150° 120° 90° 60° 30° 0° 330° 300° 270° 240° 210° 180°
60° 30° 0° -30° -60°

Fig. 8: World Stress Map. The symbols show the orientation of the greatest horizontal principal stress S_h. The length of the symbols is a measure for the data quality, the color indicates the tectonic regime. Red is normal faulting, green denotes strike slip and blue thrust faulting regime.

More detailed description on quality ranking, guidelines for the use of the WSM database, stress indicators and software to generate stress maps are available under www.world-stress-map.org. Whereas at the beginning of the project in the mid-1980s the focus was on the investigation of the long-wavelength stress pattern in the intraplate regions (Zoback et al., 1989; Zoback, 1992; Müller et al., 1992), the systematic compilation of all stress information also along plate boundaries and in areas, which deviate from the general stress trends is in the focus today. This is important to investigate and quantify stress sources also on smaller scales (Fuchs and Müller, 2001; Tingay et al., 2005; Heidbach et al., 2007).

4.3 Quo vadis WSM?

Geomechanical-numerical models for georeservoirs, nuclear waste deposits and seismogenic regions have shown that the model independent kinematic data from satellite geodetic observations such as GPS or PS-InSAR, geological or geomorphological data even in combination with the WSM stress orientation database are insufficient to validate the stress state of the models. However, they could calibrate the models for stress changes *e.g.* due to fluid injection or co-seismic slip during an earthquake. For absolute quantitative statements such as the reactivation potential of faults or the so-called drilling window which is the range of mud pressures during drilling to achieve wellbore stability, stress magnitude data with depth have to be compiled. Only when these data can be used for model validation, geomechanical-numerical models can provide absolute quantitative results.

To meet these demands the WSM advances by implementing data sets on magnitude measurements and lithology (Q-WSM). Currently about 1200 such data are compiled and first analyzed (Zang et al., 2012). Therefore, a quality ranking scheme for stress magnitude measurements will be developed. This challenge can only be solved by intense international co-operation of academic and industrial experts, from the International Society of Rock Mechanics in combination with the hydrocarbon industry. A forth WSM conference is planned to discuss and further develop this new Q-WSM. Furthermore, a new release of the WSM database is in preparation for 2015 with probably an increase to > 30,000 data records.

4.4 Sources and Patterns of Tectonic Stress

An essential goal of the WSM project was to identify and investigate the stress sources and stress patterns. Stress sources act on very different spatial and temporal scales. The motion of tectonic plates determines the long-wave length contribution of the stress pattern (>1000 km). This is normally constant on a long time scale (> 1 Mio years, Zoback, 1992; Zoback et al., 1989; Heidbach et al., 2010). Huge active tectonic fault zones are regional stress sources which create transient deformations and thus temporal changes of the stress pattern (Fig. 9). Locally third order stress sources resulting from local density or strength contrasts or segments of active fault zones can govern the stress field. From the superposition of all natural stress sources results the *in situ* stress state. Table 1 provides an overview on the most important natural stress sources and the wavelengths of the resulting stress patterns. A graphical description about the stress sources is given in Figure 9.

In addition to the natural sources local anthropogenic impacts have to be taken into account. Examples are the impoundment of water reservoirs with the seasonal variation of vertical loads and pore pressures in the underground, mining, excavations of tunnels, drilling of wellbores. The excavation of material or additional loading by changing water levels the stress state is changed locally and in a first approach instantaneously.

Table 1: Overview on the most important natural stress sources in the Earth´s crust. The impact of the stress source at a certain location cannot be deduced from the wavelength because the wavelength is depending on the magnitude of the stress source.

Source	Example	Range of Influence[1]
Plate Boundary Forces	Collisional resistance, Ridge Push	10^3-10^7 km
Volume Forces	Contrasts in density and material properties such as strength and elasticity at mountain ranges, continental margins, Moho, sedimentary basins	10^2-10^4 km
Bending	Glaciation, subduction zones	10^2-10^4 km
Strong Earthquakes	Plate boundaries, intraplate earthquakes	10-10^2 km
Decoupling Horizons	Evaporitic layers, faults with low frictional coefficient, layers with high pore pressure	10-10^2 km
Geological Structures	Faults and fracture systems, diapirs, folded structures	0.01-10 km
Thermal Stresses	Magma intrusions, advection, fluid circulation	0.01-10 km

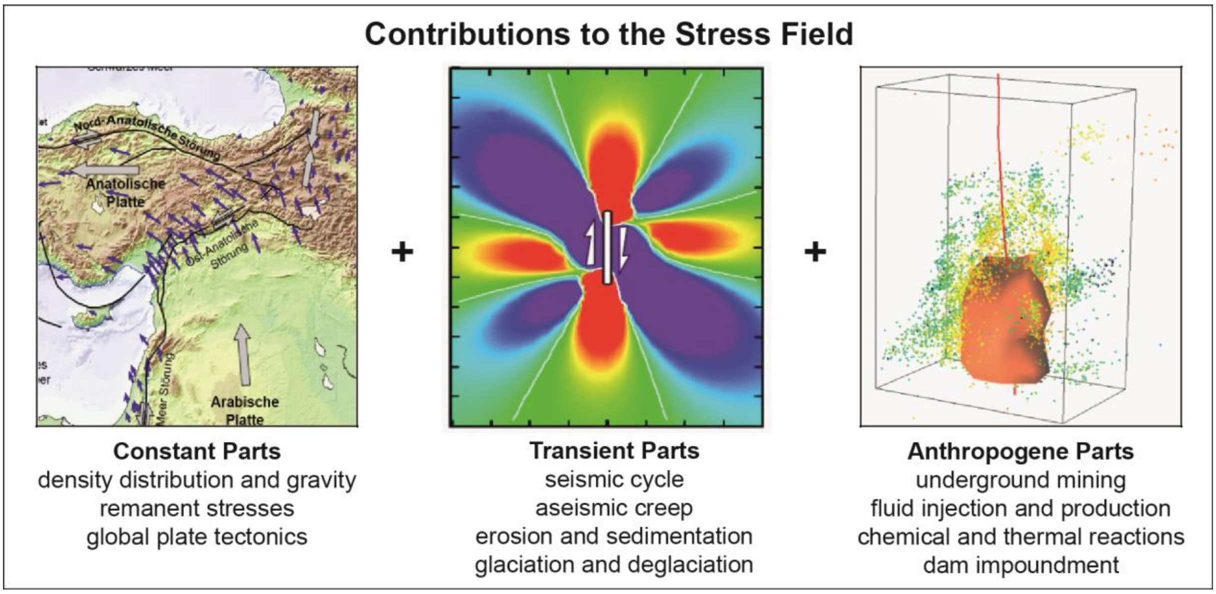

Fig. 9: Sources of stress on different spatial and temporal scales: 1) far field stress from density contrasts in the gravity field, remnant stresses from earlier processes and plate tectonics such as subduction and collision. 2) transient contributions from mass redistributions, stress from post-glacial rebound and not isostatically compensated stress changes and seismic cycles. 3) anthropogenic sources which can be time-independent such as mining activities or time –dependent such as fluid injections or production with varying production or injection rates. The modifications of the stress state through mining depends on fluid pressure, production rate, Volume and material characteristics. Furthermore, the processes can be coupled and are non-linear such as fluid diffusion into the rock matrix, fracture evolution, thermo-hydro-mechanical processes or thermo-chemical reactions.

On reservoir scale the injection or production of fluids and gases changes the state of stress in time and space. The resulting transient processes of fluid migration in porous media and the temperature changes from heat conduction and convection as well as chemical processes can modify the local stress state substantially. The consequences of these measures depend essentially on the rock strength and the initial stress state. If the state of stress is characterized by already high differential stress small stress changes can initiate plastic processes. On the other hand, if stress differences are small, rather small changes of the stress pattern can lead to local changes of the stress regime and to significant stress rotations (Sonder, 1990; Müller et al., 2010).

[1] The numbers given here are an approximation of the dimensions, which can vary from region to region.

4.5 Temperatures and Tectonic Stress at Depth and Dynamics of Planet Earth

At low pressures and temperatures rocks react in a brittle manner if the tectonic stresses exceed the rock strength when the minerals break cataclastically. At higher pressures and temperatures the intracrystalline deformations and grain sliding mechanisms lead to ductile creep of the rock. The transition from brittle to ductile deformation behavior depends on the mineral composition, the deformation rate and exponentially on the temperature. The rheological behavior of the lithosphere is thereby determined to a large extent by the temperature distribution in the Earth´s interior. Temperature contrasts in the Earth´s Mantle lead to density contrasts which are the cause for mantle convection and thus material transport, volcanic activities and finally are a driving mechanism for the movement of large tectonic units - plate tectonics. The latter modifies the crustal shape by deep trenches along subduction zones and orogeny in continental collision zones. In places, where the displacements induce strong increase in strain and stress, the high stresses can be released in form of earthquakes on short time scale or by plastic deformation on a longer time scale. Without these processes the percentage of marine crust would be much higher. In other words, only because of the tectonic processes that lead to hazards such as volcanic eruptions, earthquakes and tsunamis the landscape that man needs to survive was created. Thus, apart from the disastrous effects threatening lives, there is a creative power in these stress related processes which is essential for forming our living environment.

Elastic or plastic material properties (rheology) determines (limits) the maximum possible differential stresses with depth. By the exponential decrease of viscosity with temperature – which can in first approximation be described by an Arrhenius-type equation as an activated process – the transition from brittle to ductile behavior of crustal rocks is within a relatively narrow temperature range because already at 300° C most crustal minerals behave ductile. The rheological behavior of rocks is determined by the most ductile phase, thus most rocks are brittle at temperatures only less than 300°C. For greater crustal depths with temperatures above 300°C rock strength and thus maximum sustainable differential stress reduce exponentially (Fig. 10).

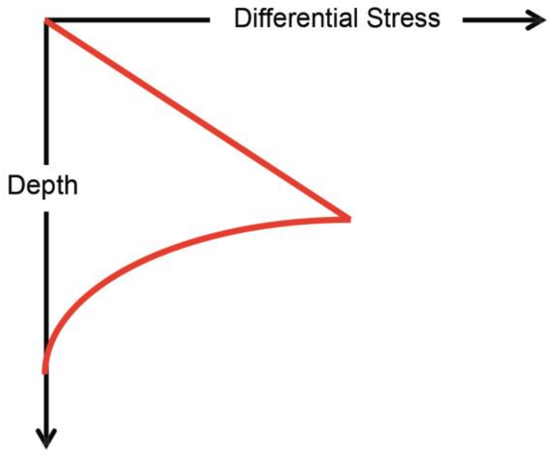

Fig. 10: Sketch of the vertical distribution of maximum differential stress in the crust. For the uppermost crust with low temperatures and low pressures, the differential stress is limited by frictional sliding. At greater depth ductile deformation is limiting the maximum sustainable differential stress.

This temperature-related distribution of deformation characteristics limits the size of potential fracture planes in the Earth´s crust, along which earthquakes could initiate. Geophysicists use the size of the fault zones to estimate the maximum possible magnitude on that plane. From geological observations the lateral extent can be defined, but not the extent to depth. The petro-physicist Frank Schilling emphasized the importance of the temperature distribution for brittle failure. The greatest sizes of fracture planes can occur in subduction zones where due to the subduction cold crustal material is transported to greater depth. The

300° isotherm is in most continental crusts at depths of about 10 km, in subduction zones the isotherm can be at depths to 50 or even 60 km. In so-called high-stress (Uyeda, 1982) subduction zones the angle of subduction is rather small. In comparison to the normal mostly very steeply dipping fracture zones in the continental crust, the fracture planes in low angle subduction zones can be much higher. To estimate the maximum possible earthquakes of an area, the size of the fracture plane and the frictional coefficient are required as input properties. Since the coefficients of friction of most rocks are rather similar, the strong earthquakes with very high magnitudes occur in subduction zones instead of plate interior crust (Fig. 11.). Also for these naturally occurring earthquakes ("tectonic events") the fluid pressure may play an important role as for induced earthquakes (see next section).

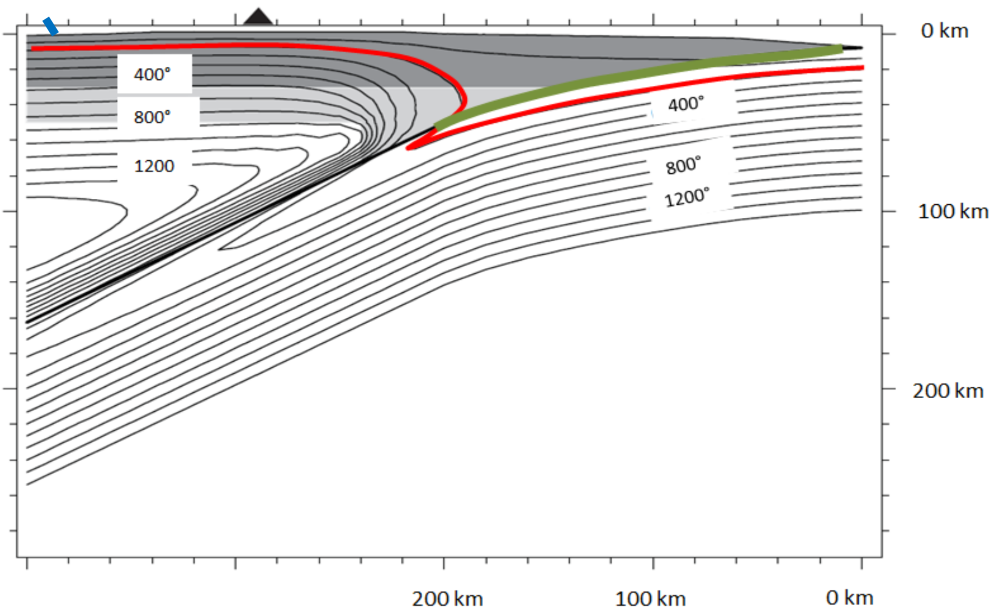

Fig. 11: Sketch of temperature distribution (after Peacock and Wang, 1999) in the Japanese subduction zone. The 300°C isotherm, which limits the brittle behavior of crustal rocks is marked in red. The profile of the maximum earthquake generating fault plane is marked in green in the subducted continental crust. Blue tick (left side) shows the profile of a typically 30-60° dipping fault plane in plate interior continental crust. In this the isotherm limits the depth extend of the seismogenic fault. For the same lateral extent of the fracture zone, earthquakes of M= 8 or larger normally occur along subduction zones and not in continental interiors.

5. Stress Changes with Time

Stress changes with time occur on different time scales depending on the stress sources. The movement of the tectonic plates in the order of several cm/year leads to continuous stress and strain accumulation on a long-term base. During an earthquake a part of these stresses are released quasi instantaneously along the fault plane and contemporarily there will be a stress readjustment in the immediate vicinity of the fault plane. The latter can lead to additional fault slip or reduce the tendency for slip on these faults depending on the distance and orientation of the faults to the ruptured fault zone. This relative stress change is considered as a change in *Coulomb Failure Stress* (King, 1994). With the *Coulomb Failure Stress Concept* the principal spatial progression of the earthquake sequence between 1939 and 1999 along the North Anatolian Fault system could be explained (Stein et al., 1997; Lorenzo-Martin et al., 2006). Transient processes within the earthquake cycle are important because stresses can change by creep or poro-elastic processes occurring after an earthquake. Aseismic creep has been detected by means of GPS observations in the past decade especially along subduction zones and shows the variety of natural processes of stress changes.

Human activities have caused significant changes in the underground not only instantaneously by excavation. For decades, oil and gas production has contributed to economic prosperity. These geotechnical measures have imposed changes in the underground such as local and regional subsidence (Weyburn, Ekofisk-platform) or seismicity in the vicinity of the reservoirs. In Germany earthquakes in the North German Basin (M=3 in 2012, M=4.4 in 2004) are under discussion because they could be caused by gas recovery in this area. Contrary to the induced seismicity of geothermal or hydrocarbon reservoirs during the stimulation (injection), when seismicity is observed during or immediately after injection, the production induced seismicity has a temporal shift to the onset of production, indicating a causal relationship with produced volumes and pressure reduction in the reservoir.

Subsidence above reservoirs can be explained by pore pressure reduction in the reservoir layers. The micro-seismicity from injections can be geomechanically explained by an increase of pore pressure which reduces the effective normal stress. The goal of stimulation measures in hydrocarbon industry is the enhancement of the hydraulic connection between wellbore and reservoir. The goal of stimulations in geothermal wells is to increase the permeability and thus the efficiency of the heat exchange in the underground by pressurization of the wellbore and modification of the stress field locally. In critically pre-stressed rock even small pressure increases can lead to reactivation of faults and lead to the observed and felt seismicity.

Serge Shapiro- former Humboldt fellow at the Geophysical Institute and now professor at FU Berlin uses the observed micro-seismicity during stimulations to characterize the reservoir (Shapiro, 1997; Shapiro et al., 1999). Tobias Müller, Emmy Noether Fellow and leader of a Emmy Noether junior research group *Seismic waves in porous media* at the Geophysical Institute and now at CSIRO investigates qualitatively and quantitatively together with the tectonic stress group of the Geophysical Institute the changes of the stress field as a function of changes in pore pressure using a poro-elastic concept of Rudnicki (1986) and Engelder and Fischer (1994). The interpretation is supported by measurements in hydrocarbon reservoirs, where it was found that during production from a reservoir not only the pore pressure is reduced but also the least principal stress magnitude (Fig. 12). A quasi-linear relationship between pore pressure change and stress change seems to be obvious.

By reduction of the minimum horizontal stress the shear stresses in the rock which are proportional to the difference between maximum and minimum stress can increase, which can lead to slip on fault planes and thus to the observed seismicity in connection to production. This process depends on the initial state of stress, the size of the reservoir, the produced volume and thus is a time-dependent process. Thus, it may take several years of production until a critical stress state will develop. In Lacq the first perceptible seismicity started ca. 10 years after the onset of the production (Grasso and Wittlinger, 1990, Grasso, 1992). In how far reservoir management can improve the pressure in the reservoir by *e.g.* waste water or CO_2 injection to reduce the seismicity, is a future task for geoscientists, not only from the Geophysical Institute of the University of Karlsruhe.

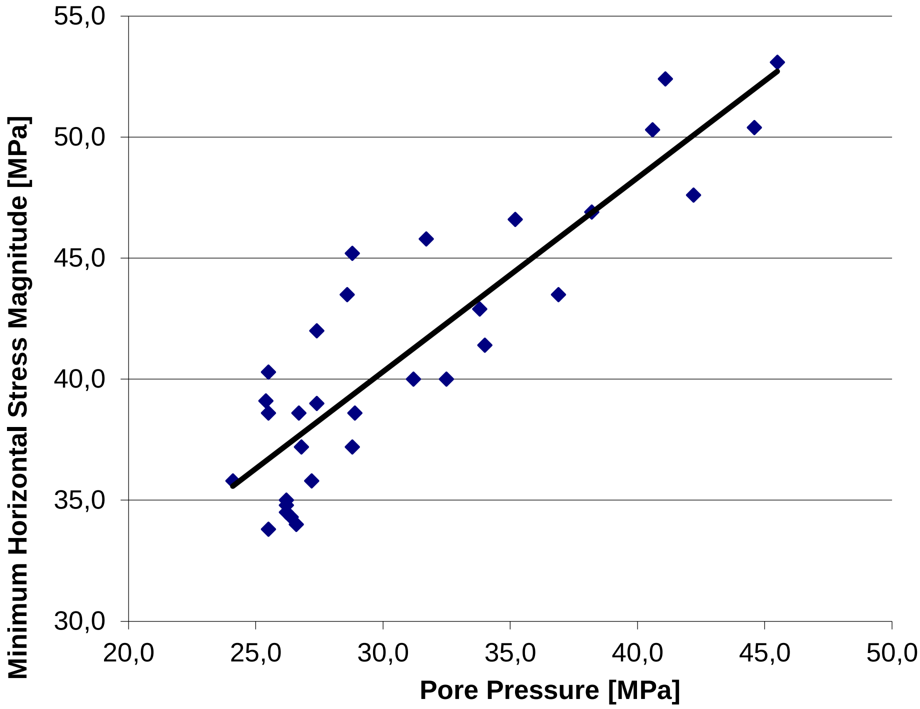

Fig. 12: Change of horizontal stress with change in pore pressure in the Ekofisk field. Data are from Teufel (1996). Due to the production the pore pressure has reduced from 48 MPa in 1969 to less than 25 MPa. The coupling of changes in horizontal stress to changes in pore pressure is around 70-80%.

6. Concluding Remarks

The Geophysical Institute and Karl Fuchs have contributed to modern reservoir management and geomechanical – numerical simulation of stress and strain accumulation and release for strong earthquakes and dynamical processes by systematical theoretical and applied projects about tectonic stresses, its sources, consequences, spatial variations (patterns) and temporal changes. This was motivated to a large extent by the analysis and interpretation of data, such as in the World Stress Map project, where the trends of regional and local stresses in orientations and magnitudes have been discovered. Those observations had been a surprise, but even more surprising were the consequences of those observations in terms of geodynamics and (reservoir) geomechanics as described above. E.g. for the Vrancea-Subduction zone stress analysis was essential to differentiate between the interpretations of the underlying process and to estimate the most probable scenario. In the Geophysical Institute the different disciplines found a kind of fertile soil for intense exchange and co-operation. Especially we benefit from the intense co-operation with the Geodetic Institute with the determination of horizontal and vertical displacements and strain. This will be fortified because the combined interpretation of geodetic and geophysical observations seems to be well established on a global scale, whereas there are only few projects on a regional scale such as the monitoring of gas caverns and CO_2 sequestration. The scientifically based combination of geodetic observations with geomechanical modeling will enable to assess the time-dependent processes of reservoir geomechanics which will be the prerequisite for a successful use of the underground. This is of great importance for the envisioned extended use of the underground for energy storage or synergies of underground use.

References

Anderson, E.M., 1905. The dynamics of faulting. Transactions of the Edinburgh Geological Society, 8: 387-402. Facsimile Reproduction doi: 10.1144/SP367.16.

Babcock, E.A., 1978. Measurement of subsurface fractures from dipmeter logs: AAPG Bulletin, v. 62 (7): 1111-1126. Reprinted in 1990, in Foster, N.H., and Beaumont, E.A., eds., Formation evaluation II--log interpretation: AAPG Treatise of Petrol. Geol. Reprint Series No. 17, p. 457-472.

Bell, J.S., and Babcock, E.A., 1986. The stress regime of the Western Canadian Basin and implications for hydrocarbon production: Bulletin of Canadian Petroleum Geology, 34 (3): 364-378.

Bell, J.S., and Gough, D.I., 1979. Northeast-southwest compressive stress in Alberta--Evidence from oil wells: Earth and Planetary Science Letters, 45: 475-482.

Bell, J.S., and Gough, D.I., 1981. Intraplate stress orientations from Alberta oil-wells, In: O'Connell, R.J., and Fyfe, W.S., eds., Evolution of the Earth. American Geophysical Union, Geodynamics Series, 5: 96-104.

Bell, J.S., and Gough, D.I., 1982. The use of borehole breakouts in the study of crustal stress. In: Zoback, M.D., and Haimson, B.C., eds., Workshop on hydraulic fracturing stress measurements [December 2-5], proceedings: U.S. Geological Survey Open-file Report 82-1075: 539-557. Also published in 1983, as Hydraulic fracturing and stress measurements: National Academy Press, p. 201-209.

Bergner, H.D., Saarbergwerke AG, Vortrag: Erfahrungen mit der Fractechnik im Saarkarbon.

Blümling, P., Fuchs, K., and Schneider, T., 1983. Orientation of the stress field from breakouts in a crystalline well in a seismic active area: Phys. of the Earth and Planet. Int., 33: 250-254.

Cox, J.W., 1970. The High Resolution Dipmeter reveals dip-related borehole and formation characteristics, paper D, in 11th Annual Logging Symposium Transactions: Society of Professional Well Log Analysts, 26 p.

Cox, J.W., 1982. Long-axis orientation in elongated boreholes: The Technical Review, v. 30, no. 3, December, p. 15-25. Also published in 1983, as paper J, in 24th Annual Logging Symposium Transactions: Society of Professional Well Log Analysts, 17 p.

Engelder, T., 1992. Stress Regimes in the Lithosphere. Princeton, NJ, 457 p.

Engelder, T., 1994. Deviatoric Stressitis: A Virus Infecting the Earth Science Community. EOS Transactions, 75: 209, 211-212.

Engelder, T., and Fischer, M. P., 1994. Influence of poroelastic behavior on the magnitude of minimum horizontal stress, Sh, in overpressured parts of sedimentary basins. Geology, 22: 949-952.

Fokker, P. A., 2006. Hydraulic fracturing in the hydrocarbon industry. ENGINE – ENhanced Geothermal Innovative Network for Europe Workshop 3, "Stimulation of reservoir and microseismicity". Kartause Ittlingen, Zürich, Switzerland

Fuchs, K., 2009. The Great Earthquakes of Lisbon 1755 and Aceh 2004 Shook the World - Seismologists' Societal Responsibility. The 1755 Lisbon Earthquake: Revisited, Geotechnical, Geological, and Earthquake Engineering, 7, DOI 10.1007/978-1-4020-8609-0_4.

Fuchs, K., and Müller, B., 2001. World Stress Map of the Earth: a key to tectonic processes and technological applications. Naturwissenschaften, 88: 357-371.

Gough, D.I., and Bell, J.S., 1981. Stress orientations from oil-well fractures in Alberta and Texas. Canadian Journal of Earth Sciences, 18: 638-645.

Gough, D.I., and Bell, J.S., 1982. Stress orientations from borehole fractures with examples from Colorado, east Texas, and northern Canada. Canadian J. of Earth Sci., 19 (7): 1358-1370.

Gough, D.I., Fordjor, C.K., and Bell, J.S., 1983. A stress province boundary and tractions on the North American plate. Nature, 305 (October 13): 619-621.

Gough, D.I., and Gough, W.I., 1987. Stress near the surface of the earth. Annual Review of Earth and Planetary Sciences, 15: 545-66.

Grasso, J. R., 1992. Mechanics of Seismic Instabilities Induced by the Recovery of Hydrocarbons. Pageoph., 139 (3/4): 507-534.

Grasso, J. R., and G. Wittlinger. 1990. Ten Years of Seismic Monitoring Over a Gas Field, Bulletin of the Seismological Society of America, 80 (2): 450-473.

Häring, M. O., Schanz, U., Ladner, F., and Dyer, B. C., 2008. Characterisation of the Basel 1 enhanced geothermal system. Geothermics, 37, 10.1016/j.geothermics.2008.06.002.

Heidbach, O., Reinecker, J., Tingay, M., Müller, B., Sperner, B., Fuchs, K. und Wenzel, F., 2007, Plate boundary forces are not enough: Second- and third-order stress patterns highlighted in the World Stress Map database. Tectonics, 26, TC6014, doi:10.1029/2007TC002133.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., and Müller, B., 2010a. Global crustal stress pattern based on the World Stress Map database release 2008. Tectonophysics, 462, doi:10.1016/j.tecto.2009.07.023.

Heidbach, O., Tingay, M., and Wenzel, F., 2010b. Frontiers in Stress Research. Tectonophysics, 462, doi:10.1016/j.tecto.2009.11.009.

Heim, 1878, Untersuchungen über den Mechanismus der Gebirgsbildung. Basel, B. Schwabe.

Jaeger, J. C., Cook, N. G. W., and Zimmermann, R. W., 2007. Fundamentals of Rock Mechanics. Oxford, Blackwell Publishing.

King, G. C. P., Stein, R. S., and Lin, J., 1994. Static Stress Changes and the Triggering of Earthquakes. Bull. Seism. Soc. Am., 84: 935-953.

Lorenzo-Martin, F., Roth, F., and Wang, R., 2006. Elastic and inelastic triggering of earthquakes in the North Anatolian Fault zone. Tectonophysics: 271-289.

Müller, B., Heidbach, O., Sperner, B., Negut, M., and Buchmann, T., 2010. Attached or not attached – evidence from crustal stress observations for a weak coupling of the Vrancea slab in Romania. Tectonophysics, 462, doi:10.1016/j.tecto.2009.08.022.

Müller, B., Zoback, M. L., Fuchs, K., Mastin, L., Gregersen, S., Pavoni, N., Stephansson, O., and Ljunggren, C., 1992. Regional patterns of tectonic stress in Europe. J. Geophys. Res., 97: 11783-11803.

Müller, B., Wehrle, V., et al., 1997. Short-scale variations of tectonic regimes in the western European stress province north of the Alps and Pyrenees. Tectonophysics: 199-219.

Osborn, S.G., Vengosh, A., Warner, N., and Jarckson, R., 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing, PNAS, May 17, 2011 , vol. 108 (no. 20): 8172-8176. www.pnas.org/cgi/doi/10.1073/pnas.1100682108

Rudnicki, J. W., 1986. Fluid mass sources and point forces in linear elastic diffusive solids. Mechanics of Materials, p. 383-393.

Sbar, M. L, and Sykes, L. R., 1973. Contemporary compressive stress and seismicity in eastern North America, an example of intraplate tectonics. Geol. Soc. Am. Bull. 84, 1861-1882.

Shapiro, S. A., Audigane, P., and Royer, J.-J., 1999. Large-scale in-situ permeability tensor of rocks from induced microseismicity. Geophys. J. Int., 137: 207-213.

Shapiro, S., Huenges, E., and Borm, G., 1997. Estimating the crust permeability from fluid-injection- induced seismic emission at the KTB site. Geophys. J. Int., 131: F15-F18.

Shapiro, S. A., Audigane, P., and Royer, J.-J., 1999. Large-scale in situ permeability tensor of rocks from induced microseismicity. Geophys. J. Int., 137: 207-213.

Sonder, L. J., 1990. Effects of density contrasts on the orientation of stresses in the lithosphere: Relation to principal stress directions in the transverse ranges, California. Tectonics, 9: 761-771.

Sperner, B., Müller, B., Heidbach, O., Delvaux, D., Reinecker, J., and Fuchs, K., 2003. Tectonic stress in the Earth's crust: advances in the World Stress Map project. In: D. A. Nieuwland, ed., New insights in structural interpretation and modelling. Special Publication: London, Geological Society, 212: 101-116.

Stein, R. S., Barka, A. A., and Dietrich, J. H., 1997. Progressive failure on the North Anatolian fault since 1939 by earthquake stress triggering. Geophys. J. Int., 128: 594-604.

Teufel, L. W., 1996. Influence of Pore pressure and production-induced Changes in Pore Pressure on In Situ Stress, edited by U. S. D. o. Energy, p. 54, Sandia National Labs.

Tingay, M., Müller, B., Reinecker, J., Heidbach, O., Wenzel, F., and Fleckenstein, P., 2005. Understanding tectonic stress in the oil patch: The World Stress Map Project. The Leading Edge, p. 1276-1282.

Uyeda, S., 1983. Comparative subductology. Episodes, 2: 19-24.

van Eck, T., Goutbeek, F., Haak, H., and Dost, B., 2006. Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in The Netherlands. Eng. Geol., 87: 105-121.

Zang, A., and Stephansson, O., 2010. Stress in the Earth's crust. Heidelberg, Springer, 323 p.

Zang, A., Stephansson, O., Heidbach, O., and Janouschkowetz, S., 2012. World Stress Map Database as a Resource of Rock Mechanics and Rock Engineering. Geotech. Geol. Eng., doi10.1007/s10706-012-9505-6.

Zoback, M. L., Zoback, M. D., Adams, J., Assumpção, M., Bell, S., Bergman, E. A., Blümling, P., Brereton, N. R., Denham, D., Ding, J., Fuchs, K., Gay, N., Gregersen, S., Gupta, H. K., Gvishiani, A., Jacob, K., Klein, R., Knoll, P., Magee, M., Mercier, J. L., Müller, B. C., Paquin, C., Rajendran, K., Stephansson, O., Suarez, G., Suter, M., Udías, A., Xu, Z. H., and Zhizhin, M., 1989. Global patterns of tectonic stress. Nature, 341: 291-298.