How to Reach the Final Rock Stress Model for Underground Works

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Abstract

A strategy and a flow chart for establishing the Final Rock Stress Model (FRSM) is proposed, see Figure 1. Development of FRSM consists of four major steps. In the first step one is defining the classes of rock stress and extracting existing data from databases. Together with geological and morphological information and borehole and drillcore data one establish the Best Estimate Stress Model (BESM). In the next step, called Stress Measurement Methods (SMM), new stress data from borehole methods and core-based methods are recorded and evaluated. Thereafter, data from direct and indirect stress measurements are combined in an Integrated Stress Determination (ISD) with or without support from numerical stress modeling. The combination of available information will generate the Final Rock Stress Model at a site or an area. Examples include the European stress map, stress decoupling in the North German Basin and stress perturbation from faults at the Swedish site for disposal of spent nuclear fuel

Introduction

The aim of a site or an area characterization for underground works is to produce a three-dimensional model containing information about topography, soils, rock mass lithology, structural geology, and hydrogeology. Such geological model is needed in analyzing the cause and effect on stresses from lithology boundaries, geological structures, faults and fracture zones intersecting the model. Although it is impossible to know all the details of the geological evolution of a site or an area it is worth the efforts to try to ascertain the stress state from the bulk knowledge of the site morphology, topography and geology and if possible to verify these information with additional data from boreholes and drillcores. We advocate stress measurements to be conducted after the best estimate stress model has been compiled. Sometimes numerical models can be of assistance in estimating the effect of geological parameter variations in the established 3-D stress model for a site.

In this contribution a strategy and flow chart is presented to establish the Final Rock Stress Model (FRSM) from a combination of available stress data from the Best Estimated Stress Model (BESM), new stress data from stress measurement methods on site (SMM) and integrated stress determination (ISD) using previous data plus numerical modelling.

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Derive the Final Rock Stress Model

Figure 1 presents the way forward in establishing a Best Estimate Rock Stress Model (BESM) and together with stress measurement methods (SMM) and Integrated Stress Determination Method (ISD) derive a Final Rock Stress Model (FRSM) for a site or an area (Zang and Stephansson, 2010).

BESM is established by collecting existing information from databases and analyzing field information about morphology, topography, geology and borehole and drillcore information. Prior to any *in situ* stress measurements, development of the BESM of the site or area is recommended. The established stress model should be used in selecting the appropriate stress measurement technique and assist in planning the measurements. After BESM is established and stress measurement conducted, an Integrated Stress Determination (ISD) is recommended.

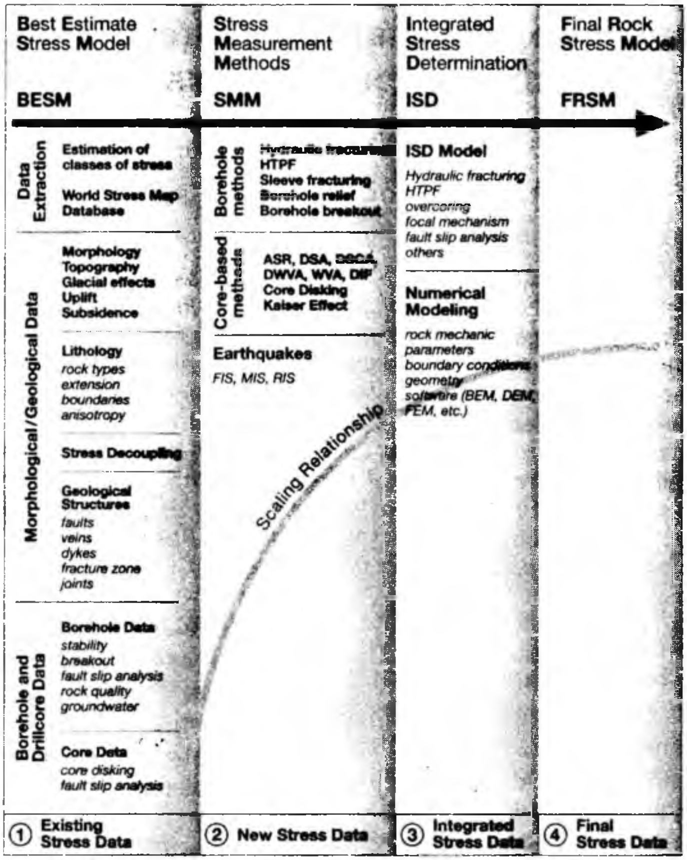

Fig. 1. Generation of the Final Rock Stress Model (FRSM) by combination of the Best Estimate Stress Model (BESM), new stress data from Stress Measurement Methods (SMM) and Integrated Stress Determination (ISD). After Zang and Stephansson (2010)

In that step data from different stress source (focal mechanism, fault slip analysis, borehole breakouts) information from BESM and results from different stress measurement methods are merged. Numerical stress models can be of great help in predicting and validating the virgin stress field and together with the results of the stress measurements and ISD it supports the establishment of the Final Rock Stress Model (FRSM) as presented in Fig. 1.

Best Estimate Stress Model

The data collection for establishing the Best Estimate Rock Stress Model (BESM) can be divided into three main groups:

- Data Extraction
- Morphological/Geological Data
- Borehole and Drill Core Data

The items listed in the left column of boxes can serve as a checklist in performing the first step in a stress analysis for a site or an area. After collecting the data and performing the mapping and analysis, the BESM can be established and the model should result in the best estimate of stress orientation and magnitude versus depth. Prior to any in-situ stress measurements at a site or an area, establishment of BESM is recommended.

Data Extraction – Classes of Stresses

As the first step in establishing the BESM one has to decide about the type of stresses that can exist at the site or in an area. There is no internationally agreed terminology and scheme for the different type of stresses existing in the Earth's crust. Recently, Zang & Stephansson (2010) presented a rock stress classification and terminology as shown in Figure 2. The first level of stresses distinguish between in-situ and perturbed in-situ stresses and for anisotropic or heterogeneous rock material the term structural or perturbed structural stress has to be used. The four second-level force contributors (A1-A4) to the in-situ stress tensor are originating from different forces in the Earth's crust. On the third hierarchical level, active tectonic stresses due to present state straining of the Earth's crust are divided into first order (plate scale), second order (mountain range) and third order (fault scale) stresses.

The different order tectonic stresses are scaled according to their coherent domain in the region in which a stress component is supposed to be uniform, both in magnitude and orientation. Figure 2 illustrates the broad-scale and local active forces responsible for the stresses of first- and second order tectonic stresses in the context of modern plate tectonics. Stress patterns at third order in Fig. 2 are explained by faults, seismic induced stress changes due to large earthquakes and volcanic eruptions, as well as local density contrast, e.g. from salt diapers or detachment horizons (Heidbach et al., 2007; Heidbach et al., 2010). For applied rock mechanics and rock engineering purposes gravitational and tectonic stresses are by far the most important.

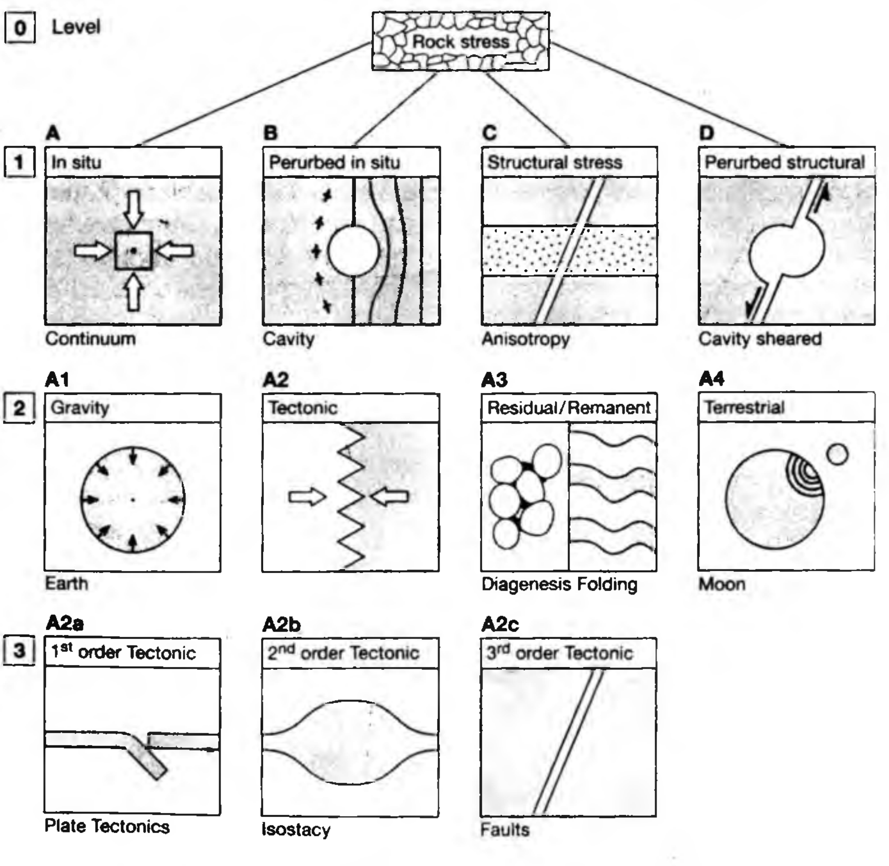

Fig. 2. Rock stress scheme and terminology at three hierarchical levels. Level 1 separates solid *(AC)* from excavated rock mass *(BD)*. Level 2 separates in-situ stress according to their origin forces. Level 3 separates tectonic stresses according to their coherent domains such as plate tectonics, isostacy and individual faults. After Zang and Stephansson (2010).

Data Extraction – Data and World Stress Map

Many authors have collected and summarized data on rock stresses and proposed expressions for the variation of the magnitude of the vertical and horizontal stresses with depth at specific sites and/or regions of the world. A summary of more than twenty references to publications of horizontal and vertical stresses versus depth is presented by Amadei & Stephansson (1997). In the recent text-book by Zang & Stephansson (2010), they present and discuss in-situ stress data in terms of magnitude-depth profiles and stress orientation maps.

When estimating the state of stress at any depth in the rock mass we make the assumption, that the state of stress can be described by three components: a vertical component due to the weight of the overburden at that depth and two horizontal components which are larger or smaller than the vertical stress. For the variation of vertical stress with depth, there has been a long series of in-situ stress measurements conducted and several data compilations done (Herget, 1974; Brown & Hoek, 1978; Amadei & Stephansson, 1997; Zang and Stephansson, 2010), that proofs that, in most cases, the magnitude of the vertical stress can be explained by the overburden weight only. Deviation from this rule exists and in particular in areas of young tectonics and volcanism and adjacent to major discontinuities in the rock mass. Relationship between vertical and horizontal stress for simple elastic homogeneous Earth stress models, and rock masses with transversely and orthotropic anisotropy are presented in Zang and Stephansson (2010).

Amadei & Stephansson (1997) and later Zang & Stephansson (2010) have pointed out that the generic, often linearly increasing stress magnitude versus depth relationships presented should be used with caution, as they are usually associated with scatter. The stresses at a site can vary locally due to topography, geological unconformities, stratification, geological structures such as faults, dikes, veins joints, folds etc. Therefore, in estimating the state of stress at a site or a region these local perturbations need to be considered as they cause deviation from the often-assumed linearity of stress changes with depth.

Measured variations of stress with depth have also demonstrated ´stress decoupling‘ (Haimson, 1980; Stephansson, 1993; Martin and Chandler, 1993; Roth and Fleckenstein, 2001) where stresses at shallow depth might be entirely different from stresses at great depth. Stress decoupling is valid for both stress magnitude and orientation.

The World Stress Map (WSM) is the global database for contemporary tectonic stress data from the Earth's crust. It was originally compiled by a research group as part of the International Lithosphere Programme (Zoback, et al., 1989). During the time period 1995-2008 the WSM Project was a research project of the Heidelberg Academy of Science and Humanities, Germany and run by the Institute of Geophysics at Karlsruhe University (Heidback et al., 2008). Since 2009 the World Stress Map Project is located at GFZ German Research Center for Geosciences, Potsdam, Germany (Heidbach et al., 2010).

Various academic and industrial institutions working in different disciplines of Earth sciences such as geodynamics, hydrocarbon exploitations and rock engineering use the World Stress Map. The uniformity and quality of the WSM is guaranteed through a) quality ranking of the data according to international standards, b) standardized regime assignment and c) guidelines for borehole breakout analysis and other methods.

To determine the tectonic stress orientation, different types of stress indicators are used in the World Stress Map. The 2008 release of WSM contains 21,750 data points and they are grouped into four major categories with the following percentage (www.gfz-potsdam.de) (Heidback et al., 2010):

- Earthquake focal mechanisms (72%)
- Wellbore breakouts and drilling induced fractures (20%)
- In-situ stress measurements (overcoring, hydraulic fracturing, borehole slotter (4%))
- Young geologic data (from fault slip analysis and volcanic vent alignments (4%)).

The seismologists and their analysis of the focal plane mechanisms related to large earthquakes provide the majority of data to the WSM. The relatively small percentage of in-situ stress measurements is due to the demanding quality ranking and the fact that many of the data are company owned.

At the very first stage of estimating the state of stress at a site or a region consultation of the World Stress Map is appropriate and often worth wile. A detail map of the area of interest can be provided free by WSM. The delivered map contains a legend of the most likely type of stress regime (normal, strike-slip and thrust faulting regime) in the area. Data can also be extracted from different depth interval and for different stress recording methods. If there is enough stress data from a region a map of smoothed direction of maximum horizontal stress can be ordered. Figure 3 shows an example of a smoothed maximum horizontal stress direction map of Western Europe (Zang and Stephansson, 2010).

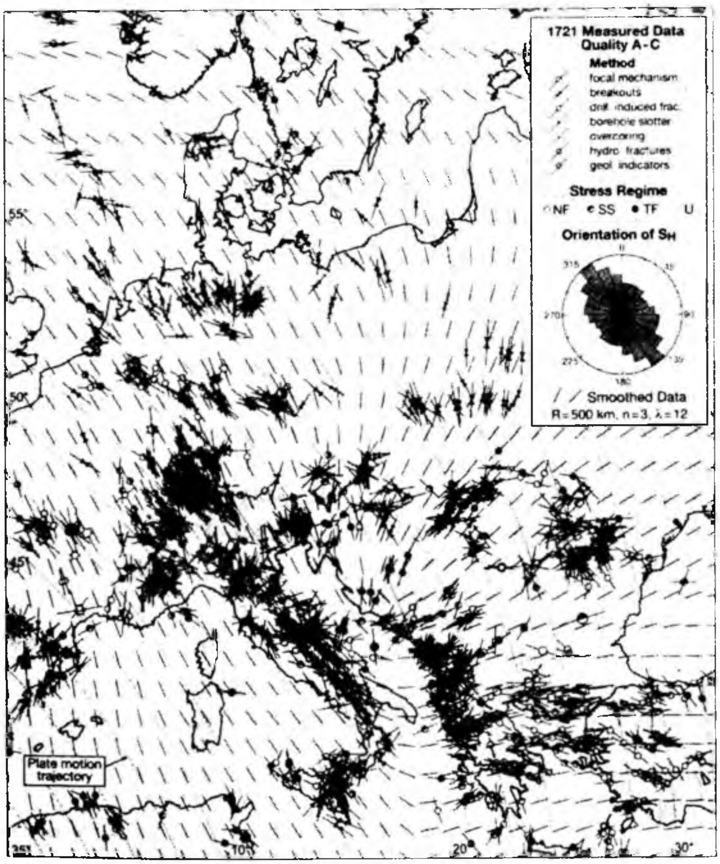

Fig. 3. Smoothed maximum horizontal stress direction map of Western Europe (short bars) based on stress 1721 entries from the World Stress Map. Thin grey lines show the relative plate motion trajectories of the African plate with respect to the Eurasian plate. Modified from (Heidback, 2007) and after (Zang and Stephansson, 2010).

Morphology and Geology

The issue of morphology and topography on estimating in situ stress is of particular interest when conducting rock engineering projects and related stress estimation and measurements in mountainous area, near valley slopes and at the top of high mountains and for mining projects e. g. at the slopes of open pit mines. The slopes and valley sides can create unbalanced stress concentrations of underground excavations located at the toe of the slopes and valleys and cause rock burst and spalling and other types of rock failure.

It is a difficult task to determine analytically the in situ stress field in a rock mass or a region with an irregular surface using the theory of linear elasticity. A summary of the developments and their application to different topography and gravity and tectonic loadings and rock mass anisotropy is presented in Amadei and Stephansson, 1997. All the derived analytical expressions predict tensile stress in the valley bottom and this is supported by the observations from the field in terms of a zone of fractured and loose rock masses and tendencies of up-warping phenomena in the bottom of valleys.

In steep mountainous areas or rock slopes the gravity loading alone cause high stress concentrations parallel with the surface of the slope. In rock engineering, these slopes have a tendency to cause spalling in the walls of a tunnel (Myrvang, 1993). Spalling is common phenomena in valley tunnels across the fjords in Norway and in valleys of young mountainous areas where topography is steep and rough.

The simplifying assumption that the principal rock stresses are vertical and horizontal with depth and that the vertical stress is equal to the weight of the overburden is not valid for areas with gentle to strong topography. The influence of morphology and topography has to be included in establishing the best-estimate stress model, BESM.

Glacial effects, uplift and subsidence very often cause a more intense fracturing and faulting in the uppermost parts of the Earth's crust. This disturbs the stress field so that for example in glaciated terrains like Scandinavia and Canada one often finds an excess of horizontal stresses and thrust faulting conditions in the uppermost couple of hundred meters of the rock (Stephanson, 1993).

Geological data

Understanding the geological history of a site or an area is very useful as it can be used to determine the evolution of the stress regime in which the site or area of interest is located. Such an approach has been applied recently to the area at Äspö Hard Rock Laboratory in Sweden (Hakami et al., 2002) A methodology for building a stress model has been suggested that involves different steps, starting with preliminary stress estimation, followed by steps for interpreting site-specific information. Factors that might influence the regional stresses and the in situ stresses at the site are listed. Since the Fennoscandian Shield, where Äspö is located, is a part of the Eurasian plate its geological history is presented in the context of plate tectonics. The role of current plate motion for the present day state of stress in the NW European sub-plate is highlighted, see also Fig. 3. The report (Hakami et al., 2002) is one of the very first attempts ever made to present a plan for a complete stress model of a specific site and where the tectonics and structure geology play an important part. With respect to determination the magnitude of the stresses with reasonable certainty, the authors advocate that in-situ stress measurements should be used.

Estimating in situ stresses requires a detail characterization of the site geology like lithology and lithological boundaries, its tectonic history, critical structures, erosion, uplift, influence of glaciation, hydrogeology, neotectonic and others. In the following sections a few of the most important geological factors to rock stress estimation are dealt with.

Lithology and lithological boundaries

In-situ stresses might vary significantly from one lithological unit to the next depending on the relative stiffness and strength between the individual rock masses. Abrupt changes are likely to appear at the contacts between different lithological units. Therefore, it is of utmost importance to perform a correct geological mapping and characterization of the site or area.

The influence of lithology on the distribution of horizontal stress at depth has been demonstrated by a large number of stress measurements conducted in sedimentary and volcanic rocks. A list of references is presented by Amadei and Stephansson, 1997. In general, one expects to find larger stress magnitudes in the more competent strata as stresses tend to concentrate in hard rocks surrounded by less competent and subjected to the same far-field stress field. However, there have been reported results from hydraulic stress measurements where instantaneous shut-in pressure was found to be lower in layers with high Young´s modulus and low Poisson's ratio and higher in layers with low Young´s modulus and high Poisson's ratio (Amadei and Stephansson, 1997). Similar results have also been reported for sedimentary rocks in relaxed-state basins. However, these are exceptions and in general, higher modulus rock types are more likely to carry higher than average stresses.

The term structural stress was introduced by Jaeger and Cook (Jaeger and Cook, 1979). Structural stresses are caused by anisotropy and heterogeneity of rock mass and are depicted from Zang and Stephansson (2010) with and without externally applied loads in Figure 4. Principal stress orientation in selected points are oriented parallel to the applied load for the homogeneous material (Fig. 4a, d). In case of anisotropic material the applied far-field stress is perturbed by the planes of anisotropy and principal stress orientation in the material are rotated towards the orientation of the rock anisotropy (Fig. 4b, e). In case of heterogeneous material (Fig. 4c, f) orientation and magnitude of stresses are perturbed in the vicinity of the defect. As a rule of thumb far-field stresses can be treated as undisturbed at distances of about three times the diameter of the defect.

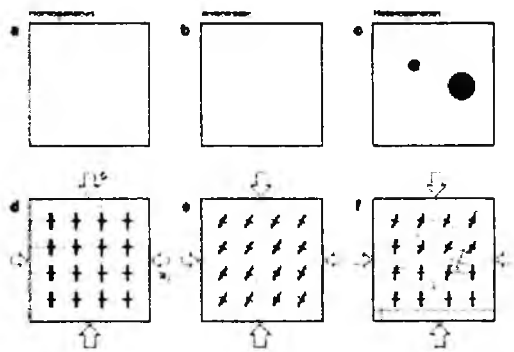

Fig. 4. Homogeneous (a), anisotropic (b), and heterogeneous (c) material effect principal stress orientation and magnitude (d-f). After Zang and Stephansson (2010).

Different stress regimes and stress decoupling

From results of stress measurements in vertical boreholes, it has been reviled that the type of stress regime at shallow depth may be entirely different from the stress regime at great depth. A recent example is described from the stress measurements for the Björkö geothermal project in the vicinity of Stockholm, Sweden (Ask and Stephansson, 2003) where the stresses in the uppermost 400 – 500 m are characterized by thrust faulting stress state where the vertical stress is the minimum principal stress. Below ca 500 m depth the stress state corresponds to a strike slip stress regime where the vertical stress is the intermediate principal stress. The stress measurements were conducted in the centre of the Björkö meteoritic impact with an estimated diameter of 10 km. The granitic rocks are severely fractured due to the impact. Another of the Swedish meteoritic impacts, Siljan impact structure in central-north Sweden shows a similar stress change with depth (Lund and Zoback, 1999). Both impact structures indicate somewhat lower stress magnitudes compared to the general situation in Fennoscandia. A similar stress change with depth as that at Siljan and Björkö in Sweden has been observed among others for the site investigations of the geothermal project in the Carnmenellis granite, Cornwall, UK (Cooling et al., 1988). These types of different stress regimes with depth are referred to stress decoupling and can have different reasons, e.g. a marked hiatus in the stratigraphy like a basement-cover situation, different lithology in a rock sequence, non-persistent far-field boundary stresses, post-glacial lithosphere flexure and major discontinuities intersecting the area. Post-glacial lithosphere flexure of the glaciated terrains is the most likely explanation for the stress change with depth for the mentioned three sites.

An interesting study related to stress decoupling in the Perm-Triassic rocks of eastern part of Eastern North German Basin (ENGB) is presented by Roth and Fleckenstein (2001). From data collected in the World Stress Map project it has been known that Central West-Europe is dominated by a NW-SE to NNW-SSE orientation of the maximum horizontal compressive stress (Fig. 3) by ridge push from the North Atlantic and the northward drift of Africa (Muller et al., 1992). From new analysis of fourarm-dipmeter data and televiewer loggings at interval from 1500 to 6700 m in deep boreholes and comparison with hydraulic fracturing stress measurements from the region, the substrata below the more than 1000 m thick Zechstein salt formation is dominated by a NNE-SSW striking orientation of the maximum horizontal stress. The 45 to 90 degrees difference in stress orientation above and below the detachment of the Zechstein salt formation is explained by decoupling of stresses (Fig. 5). Roth & Fleckenstein (2001) have suggested three hypothesis for this stress decoupling: a) influence of the large ancient suture zones, Trans-European Fault Zone and Elbe Fault System, with a NW-SE strike and bordering the basin; b) dominance of local stresses due to postglacial lithosphere flexure where the compressive stresses outside the edge of the Weichselian and earlier Fennoscandian ice sheets might have caused the reorientation of the stress field in the subsaline formations; c) a strong lithosphere barrier below the Northern margin of basin, derived from rheology/depths profiling and modelling, which proofs that stresses are attracted and reoriented to the observed N-S orientation.

In conclusion, as there is no indication for stress differences from the plate boundaries the stress decoupling in ENGB is likely to be due to contrast in competence (rigidity) between sedimentary rocks in North German Basin and Fennoscandian hard rocks.

Stress perturbation from fault

Geological structures such as faults, folds, dikes, veins, sills, fault striation or slickensides have long been used by structural geologists to indicate the paleostress, i.e. the state of stress prevailing at the time of genesis of the structure. Since the stresses that created the structure may have been modified due to later tectonic events, erosion, uplift, and glaciation etc. the structure and petrography fabric might not be correlated at all with the current stress field.

In order to determine the contemporary stress field one has to seek out the most recent geological structures and use as stress orientation indicators. As an example different volcanic vent alignments and inversion of fault-slip data are used for stress orientation in the World Stress Map database (Heidback et al., 2010). Fault-slip analysis as develop by Angelier (1989) and others for stress analysis of recent geological formations or inversion of data from slickensides on fracture surfaces in oriented drillcore samples (Hickman and Masauka, 1995) are powerful tools in stress determination of a site or an area.

The existence of geological structures and heterogeneities will effect the distribution and magnitude of *in situ* stresses and make the local stress field different from the regional stress field. When a regional stress field is approaching a major discontinuity, the stress transfer across the stress perturbation from the discontinuity is very much dependent upon the material property of the discontinuity. If it happens to be open structure the stresses cannot transect. If the structure has the same properties as the surrounding rocks the stresses are unaffected. If the material in the discontinuity

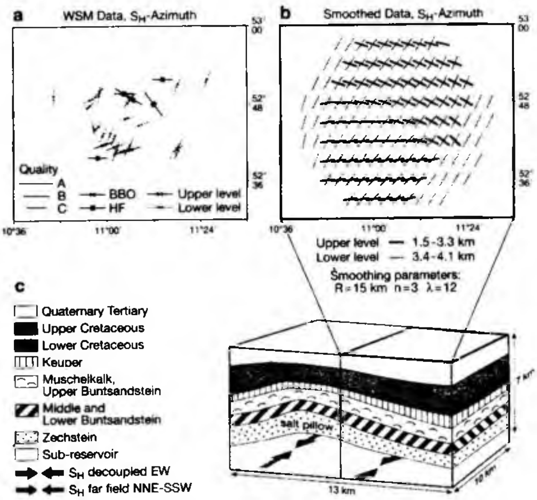

Fig. 5. Decoupling of stress in the eastern part of the North German Basin. a) Stress data entries from World Stress Map. b) Smoothed maximum horizontal stress orientations. c) Block diagram of geology and far-field stress orientation in the sub-reservoir rock and decoupled stress in the overburden. (After Heidback et al., 2007 and modified by Zang and Stephansson, 2010).

is more rigid than the surrounding rock mass the maximum principal stress is diverted perpendicular to the discontinuity and if it is less rigid the maximum stress will tend to divert parallel with the discontinuity. The classical example of the second situation is the stress field in the surrounding of the San Andreas Fault system often referred to as a weak fault in a strong crust (Hickman and Zoback, 2004).

The ongoing San Andreas Fault Observatory at Depth (SAFOD) project in the central part of the fault is motivated by the need to answer fundamental questions about the physical processes, including rock stresses, controlling faulting and earthquake generation within a major plate-bounding fault.

At a somewhat smaller scale Sugawara and Obara (1995) demonstrated the stress state in the vicinity of the Atotsugawa fault in Japan where overcoring stress measurements reviled a stress state where the least principal stress acted perpendicular to the fault plane in an area where otherwise thrust faulting is dominated.

A recent study about localized rotation of principal stress around faults and fractures from borehole B of the Taiwan Chelungpu-fault Drilling Project is published by Lin et al. (2010). They were using borehole breakouts and drilling-induced tensile fractures together with electrical images and photographs of the borehole wall to determine the relationship between faults and fractures and stress orientation changes. They report that stress state changes occurred frequently in the vicinity of faults, fractures and lithological boundaries.

Stress relieve from neotectonic faulting in the Northern parts of the Fennoscandian Shield has been reported by Bjarnason et al. (1989) and Amadei & Stephansson (1997). Measured stresses with hydraulic fracturing method in a borehole adjacent to the neotectonic Landsjärv fault show a marked stress anomaly compared to the average state of stress in Fennoscandia (Fig. 6). Magnitude of both minimum and mmaximum horizontal stress is reduced to half the expected value close to the fault at about 500 m depth.

Faults, fracture zones and dikes intersecting the rock mass at a site or region cause perturbation of the regional stress state. The amount of perturbation is very much governed by the strength and deformability of the discontinuity. Here we are faced with the problem of lack of strength and stiffness data about large structures and sometimes the difficulty delineate their orientation in space. Sometimes the application of simple numerical models of generic type can be of great value in analyzing the stress perturbation from planar structures.

Borehole and drillcore data

Information from borehole and drillcore data is important for the establishment of BESM. Borehole instabilities and breakouts and fault slip developed in the wall of the borehole give information about orientation of stresses. Sometimes the magnitude of stresses can be estimated from the shape of the breakout in combination with numerical modeling Shen (2008).

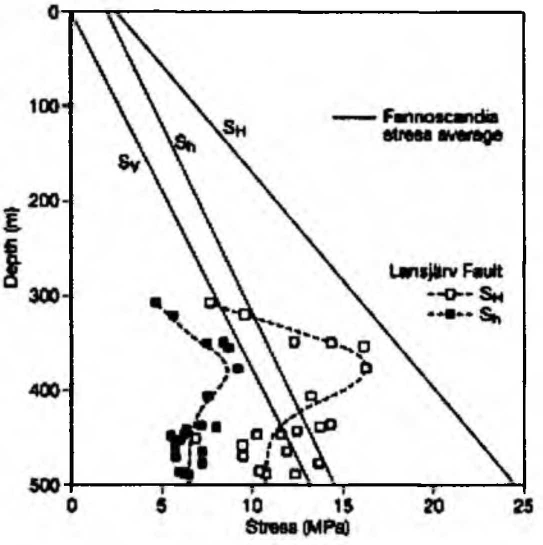

Fig. 6. Hydraulic stress measurements adjacent to the Lansjärv neotectonic fault, Northem Sweden. Average hydrofracturing stress data from Fennoscandia (solid lines) are shown to illustrate the stress anomaly at the fault. (After Bjarnason et al., 1989; modified by Zang & Stephansson, 2010).

Observation of geometry of core disking and fault slip on drillcores provides data about magnitude and orientation of the stresses in the plane perpendicular to the drillcore axis. Borehole breakout is now an established method to estimate the orientation of maximum and minimum principal stress in the plane perpendicular to the borehole axis. The breakouts are enlargements of the borehole wall caused by stress-induced failure of wells occurring 180° apart. In vertical wells, the diametrically faced zones of broken or fall-out rock material occur at the azimuth of minimum horizontal compressive stress and typically have a consistent orientation in a given well or field. The shape and depth of the breakouts depend on the type of rock and the magnitude of in situ stress. Hard rocks and high stresses tend to generate deep breakouts with relative small breakout angle. Breakouts can have a length of between centimetres up to several hundred meters.

Borehole breakouts in a well can be visualized using optical (camera), mechanical (calliper) or electrical resistivity (formation microscanner) and ultrasonic image (borehole televiewer) tools. A summary of theories of breakout formation, laboratory studies, techniques, equipment and evaluation procedures are presented by Amadei & Stephansson (1997) and Zang & Stephansson (2010). If data of borehole breakouts exist from a site the information is of great value for delineation the stress orientation of the BESM.

Once drillcores are available from a site or an area the search for and analysis of core disking should be included in the stress estimation program. Core disking is often an indication of high horizontal stresses and the geometry of the disks and the orientation of the disk saddle are indicators of stress orientation. The core breaks up into disks that are usually curved with the centre of curvature oriented towards the bottom of the borehole. The orientation of the crest line of the curved disk surface tends to coincide with the direction of the maximum principal stress. Laboratory testing and later numerical modelling has shown that once the radial stress in the core trunk during drilling exceeds the compressive strength of the rock core, disking starts to develop. Haimson & Lee (1995) in their study on core disking proposed that thinner disks are indicative of higher horizontal stresses and that the trough axis of saddle-shaped core disks often is aligned with the orientation of the maximum horizontal virgin stress. Less regular core disking might also develop due to existing discontinuities or fabrics in the rock mass. Application of high thrust during the drilling operation can generate too high horizontal tensile stress at the root of the drill core so that extensile micro-cracks are formed and coalescence to generate core disking (Kutter, 1993).

Stress Measurement Methods

In our opinion rock stress measurements should be performed after the establishment of best-estimate rock stress model. Data and information collected for BESM can also be used in selecting the best suited method for in-situ stress measurement(s) and/or core-based stress measurement(s). Amadei & Stephansson (1997) and more recently Zang & Stephansson (2010) and Ljungren et al. (2003) have presented overviews of the most important stress measurement methods.

Rock stress measurements in the Earth's crust can be classified according to their underlying physical principle, or according to the rock volume involved in the measurement technique. Crustal stress measurement techniques can be grouped into 5 different categories according to physical mechanism, experimental technique and ultimate borehole depth (Table 7.1 in Zang & Stephansson, 2010). Category (1) mechanism is related to rock fracture as applied to boreholes. The most important method of this category is hydraulic fracturing (HF) (Haimson, 1978; Amadei & Stephansson, 1997; Zang & Stephansson, 2010) where minimum stress and orientation of maximum stress perpendicular to the borehole axis is determined. One modification of HF is Hydraulic Tests on Pre-existing Fractures (HTPF) (Cornet & valette, 1894; Haimson & Cornet, 2003). The fluid pressure in HTPF balances exactly the normal stress across the pre-existing fracture. By combining pressure data from six and more fractures along the length of the borehole the 3D state of stress can be determined. As compared to HF, HTPF has the advantage of less limitation as regards geologic structures and the method does not require the determination of rock tensile strength. Sleeve fracturing (Stephansson, 1983), drilling-induced tensile fractures (Brudy & Zoback, 1999) and borehole breakouts (Bell & Gough, 1979) also belong to category 1 in the classification scheme.

Category (2) mechanisms are related to elastic strain relief due to coring. The technique can be further subdivided to surface relief methods, borehole relief methods and techniques that involve relief of large rock volumes with subsequent analysis of re-equilibrium deformation. Borehole relief methods can be further sub-classified according to the type of strain analysis at the borehole wall (see Zang & Stephansson, 2010). Strains can be measured diametral, at the flat end of the bore-hole, and at the surface of a conical or hemispherical end of a borehole. The Borre probe, the CSIR and CSIRO hollow inclusion cell are the most common tools applied in relief stress measurements (Sjoberg et al., 2003). Relief methods are the most widely used techniques in the engineering application of stress measurements for underground works.

Category (3) mechanism in the classification by Zang and Stephansson (2010) is related to crack-induced strain relief in drillcores. Microcracking is generated in stress relief when the rock is cut from the virgin stress field at the bottom or the wall of a borehole. Core-based methods can be further subdivided into the analysis of strain data like anelastic strain recovery (ASR), differential strain rate analysis (DRA), differential strain analysis (DSA); analysis of wave velocity data like differential wave-velocity analysis (DWVA) and wave velocity analysis (WVA). Cracking phenomena in drillcores and monitoring of related acoustic emissions by means of the Kaiser effect also belongs to this category.

Category (4) mechanisms, also called borehole seismic logging or indirect methods, combine the variation of physical rock properties with stress. Shear-wave polarization, shear wave splitting and analysis of Stonely waves are examples of wave propagation methods for stress analysis [1].

Finally, Category (5) for stress estimates is concerned with physical properties of pre-existing fault zones in the Earth's crust and related earthquakes. The end members are fault plane solutions (FPS). Focal mechanisms of earthquakes provide the orientation of principal stresses and this information dominates the overall entries of stress data in the World Stress Map described in Section 3.2. Stress inversion from focal mechanisms can be separated into natural seismicity (NS) and induced seismicity (IS). In contrast to NS, the term IS refers to typically minor earthquakes and tremors that are caused by human activities that perturb the crustal stress field. Zang and Stephansson (2010) refine IS into mining-induced seismicity (MIS) and fluid-induced seismicity (FIS). MIS includes seismic events and related rock bursts arising from stress changes associated with mining activities. FIS are caused by injection of fluids in liquid waste disposal or fracturing of hydrocarbon and geothermal reservoirs. Impoundment of large water reservoirs can generate FIS.

Stress inversions from induced seismic events, together with stress inversions from background natural seismicity, are useful tools to identify stress perturbations triggered by human activity.

Integrated Stress Determination Method (ISD)

The method of integrating the results of various stress measurement data obtained from applying different techniques to obtain a more reliable assessment of the virgin state of stress was introduced in the mid 1980s and is still under development. The integration method is based on a least square criterion (Tarantola & Valette, 1982) where all measurements are assumed to obey a Gaussian distribution

In 1993, F. H. Cornet presented the HTPF stress determination method together with the Integrated Stress Determination Method. Data from hydraulic fracturing (HF) and hydraulic testing on pre-existing fractures (HTPF) were integrated in order to obtain a better indication of the regional stress field. Ask et al. (2001) integrated hydraulic fracturing (HF) and HTPF for the Äspö Hard Rock Laboratory in Sweden is presented in the report by Ask et al. (2001). The same type of integration was done for two sites in southern France Cornet (1993) and for the geothermal project on Björkö, Sweden (Ask & Stephansson, 2003). Integration of CSIR and CSIRO overcoring stress data from Äspö Hard Rock Laboratory is presented by Ask et al. (2003) and integration of HF, HTPF and overcoring data on each side of the major fracture zone NE-2 by Ask (2006).

Numerical modelling

Numerical analyses with a variety of numerical techniques (FEM, BEM, DEM etc.) have been used in an attempt to predict or explain the in-situ stress field and in illustrating the effect of topography (Sturgul et al., 1976), stress distribution in a blocky rock mass subjected to a 2-D stress field (Stephansson et al., 1991), 3DEC modelling of the influence of large scale structures like faults on the in situ stress (Te Kamp et al., 1999). Inside and in the vicinity of faults and major fractures zones, both the magnitude and stress orientation will vary from point to point. Stress prediction in these areas is more uncertain and the variations of stresses will be larger, if it is ever possible to perform any stress measurements in these areas due to poor rock quality.

The numerical stress modelling shall help in obtaining an overall understanding of the state of stress between measurements. The modelling results shall also contribute to the estimation of the variability support in predicting the stresses in points or regions

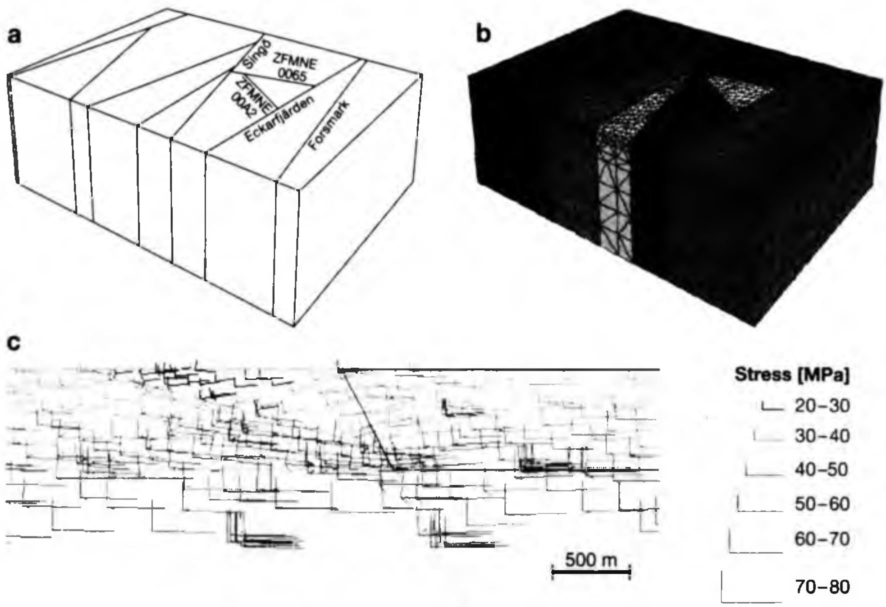

Fig. 7. Numerical stress modeling with distinct element code 3DEC. a) The model shows the orientation of the major fracture zones at the Forsmark site for spent nuclear fuel, Sweden. b) Overview of 3DEC model at the site. c) Principal stresses above and below a major shallow inclined deformation zone overlaying the rock mass for a future repository at about 500 m depth. (After Hakami, 2006).

and uncertainty in presenting the final rock stress model. An example of stress modelling from the completed site investigations for the final repository of spent nuclear fuel at Forsmark, Sweden is illustrated in Fig. 7 (Hakami, 2006). The site will host the Swedish repository of spent nuclear fuel. The 3DEC model consists of blocks with the same rock properties within a block surrounded by major deformation zones (faults). When equilibrium is obtained in the model the stress distribution is presented as a result, Fig. 7b. A detail of the orientation and magnitude of the maximum and minimum principal stresses for a region at a slightly inclined major deformation zone, called ZFMA2, is presented in Fig.7c. Notice the rotation of the principal stresses in the hanging wall of the deformation zone. The final repository at Forsmark will be located about 420 m below surface and at the footwall side of ZFMA2.

Conclusion

In order to reach the Final Rock Stress Model, (FRSM) at the site or area in question, see Fig. 1, we have to proceed in steps. (1) Define classes of likely stresses and collect all available stress data of the location and its surroundings. (2) Include topography, lithology and faults as well as borehole and drillcore stress data. (3) Measure stresses at the site and determine vertical and horizontal stresses versus depth. (4) Combine available and measured in situ stress data with earthquake and fault related stresses and perform an integrated stress analysis (5). To validate the results of the integrated stress analysis generate a 3D stress model with rock parameters measured, appropriate boundary conditions and solve the resulting momentum equations with appropriate numerical techniques and software. Perform a sensitivity analysis (6) and calibrate the model. (7) Finally, rate your final near-field rock stress model in context to the far-field stress pattern. Present the stress model as principal or horizontal stresses versus depth (8) with clear indications of variability and uncertainty in magnitude and orientation.

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