New Developments of the Integrated Stress Determination Method and Application to the Äspö Hard Rock Laboratory, Sweden

Daniel Ask, Royal Institute of Technology, Department Land and Water Resources Engineering, Research Group Engineering Geology and Geophysics, SE-100 44 Stockholm, Sweden.

Abstract

My thesis "*New Developments of the Integrated Stress Determination Method and Application to the Äspö Hard Rock Laboratory, Sweden*" [*Ask, 2004*] is made up of two parts, one is new developments of the Integrated Stress Determination Method (ISDM) [*Cornet, 1993b*]; the other is analyses of existing stress measurements and application of the ISDM to data Äspö Hard Rock Laboratory (HRL), Sweden.

The new developments of the ISDM include incorporation of overcoring stress data from CSIR- and CSIRO-type of devices, and integration of these with data from hydraulic fracturing and hydraulic tests on pre-existing fractures (HTPF). It allows description of the regional stress field in the rock mass with up to 12 unknown stress parameters. Furthermore, it may also be used to constrain elastic parameters when hydraulic fracturing/HTPF data are combined with overcoring data; then 14 parameters are included in the stress model.

A wealth of stress measurements have been made in the Äspö HRL by the Swedish Nuclear Fuel and Waste Management Co. (SKB). Despite the large number of data, the stress field is not well constrained. Not only does the result vary depending on measuring technique, e.g. overcoring data indicated larger stress magnitudes compared to hydraulic fracturing data; but the results indicate non-linear stress magnitudes and orientations versus depth (i.e. a result discontinuities in the rock mass).

To evaluate the observed differences between existing hydraulic and overcoring stress data, a detailed re-interpretation was conducted. Several measurement-related uncertainties were identified, and as a result, a rational for reducing these uncertainties was also developed which effectively reduced the discrepancies between the hydraulic and overcoring measuring results. Modeling studies [*Berglund et al., 2003*] have shown that the redistribution of the stresses at Äspö HRL to a large extent can be correlated to a major discontinuity, the NE-2 Fracture Zone, which divides the rock stress data into two stress domains, the NW and SE domains, respectively. The effect of this zone was confirmed by my thesis, which suggests that the orientation of the maximal principal stress, σ_1, is equal to 124°N±13° for the NW domain and 139°N±18° for the SE domain. The application of the ISDM further verified the influence of the NE-2 Fracture Zone on the regional stress field. In the vicinity of the zone, the results indicate that the orientation of σ_1 is perpendicular to the strike of the NE-2 Fracture Zone; and that the intermediate and minimal principal stresses (σ_2 and σ_3, respectively) are oriented parallel to the strike and the dip direction, respectively. The principal stress magnitudes appear less influenced by the zone. Limited amount of data exist outside the zone of influence from the NE-2 Fracture Zone; hence, the regional stress tensor is difficult to define. Most likely, the orientation of the regional σ_1 orientation is about 140°N.

Introduction

Knowledge of the stress field is fundamental to most rock mechanic problems: Not only can the mechanical behavior of rock and rock mass be analyzed, but knowledge of the stress field also provides boundary conditions for rock engineering problems; insights to fluid flow (groundwater, petroleum, etc.); and explains fundamentals of mechanisms of plate tectonics and fault rupture. Rock stresses are commonly divided into primary and secondary sources, where secondary stresses are man-made, and primary, or in-situ, stresses are the cumulative product of events in the geological history, e.g. gravitational, tectonic, residual, and terrestrial stresses [e.g. *Amadei and Stephansson, 1997*].

The state of stress is defined as the mean stress per unit area, and as such, it is usually referred to as a local stress tensor [*Cornet, 1993a*]. Stress is normally described within the context of continuum mechanics and is defined as a second-order Cartesian tensor with six independent components. Thus, the determination of the local stress tensor requires appraisal of six independent variables, expressed in a chosen frame of reference. The unit area involved in the local stress tensor is usually described within the concept of Representative Elementary Volume (REV), which is defined as the smallest volume in which there is equivalence between the idealized continuum material and the real rock. Cornet [*1993a*] suggests that stress measurements preferably should be conducted within a volume of comparable size to the REV. Furthermore, smaller volumes should be avoided, whereas larger volumes are acceptable provided that the stress variation within the volume is negligible or taken into account.

Most stress measurements are conducted at a considerably smaller scale compared to the rock-engineering problem to be solved. The Integrated Stress Determination Method (ISDM) was developed by Cornet and Valette [1984] and Cornet [*1993b*] to determine the regional stress tensor from such measurements. The first version of the ISDM allowed determination of six functions of spatial coordinates of a large rock mass, which was be idealized by definition of an equivalent continuum [*Cornet, 1993b*].

The rock stress data at the Äspö HRL include both hydraulic fracturing and overcoring stress data. A main objective of my thesis was to develop the ISDM from these methods. The developments include: (1) a description of the regional stress field in a rock mass with up to 12 unknown model parameters; (2) application to overcoring data; and (3) application to combined data sets of hydraulic fracturing and overcoring stress data. The stress calculations were based on the Gradient method, which is based on the least squares criterion. To overcome potential of non-unique solutions associated with methods based on the least squares criterion, the Monte Carlo method was applied to obtain *a priori* information for the Gradient method.

At the Äspö HRL, hydraulic fracturing and overcoring stress data indicate non-linear stress distribution with depth and large discrepancies between the results of the two methods. Additional objectives of my thesis therefore was to find explanations to the observed differences between the stress measuring techniques, and to verify the influence of the NE-2 Fracture Zone on the regional stress field at the Äspö HRL suggested in modeling studies [e.g. *Berglund et al., 2003*].

The Integrated Stress Determination Method (ISDM), New Developments, and Application to the Äspö HRL

The Integrated Stress Determination Method (ISDM) was developed by Cornet and Valette [*1984*] as a tool to determine the stress field using hydraulic tests of pre-existing fractures (HTPF). The ISDM was also intended as a mean to integrate different types of stress measurement methods and stress indicators. A main benefit of this approach is that the determined stress field is consistent with a much larger amount of data; hence probably more reliable. So far, the ISDM has been used to determine the stresses using HTPF and hydraulic fracturing [e.g. *Cornet and Valette, 1984*], flat jack [*Cornet, 1996*], induced seismicity and focal mechanisms [e.g. *Julien and Cornet, 1987*], fault slips [*Angelier et al., 1982*], and various combinations of these [e.g. *Yin, 1994*]. My contribution to this list is the addition of the overcoring method for four different overcoring devices, and the integration of overcoring and hydraulic fracturing/HTPF data [*Paper 1; 6*].

Figure 1 summarizes the individual steps of the ISDM. For each case study, the following must be considered [*Ask, 2004*]:

1. the number and type of available data defines the parameterization of the stress field within the rock volume of interest;
2. the rock volume, which is defined by the distribution of the available stress data, should be considered with respect to the homogenization criterion. Existing discontinuities may lead to sub-divisions of the rock volume and data sets;
3. select mathematical algorithm (the Gradient method was applied in this thesis);
4. *a priori* values for the Gradient method are determined using global Monte Carlo simulation; and
5. the solution is verified.

When different types of stress measurements are integrated, care must be taken regarding the number of each data set, the nature of the different data sets, and involved volume during measurement. These differences can be overcome by definition and inclusion of misfit functions.

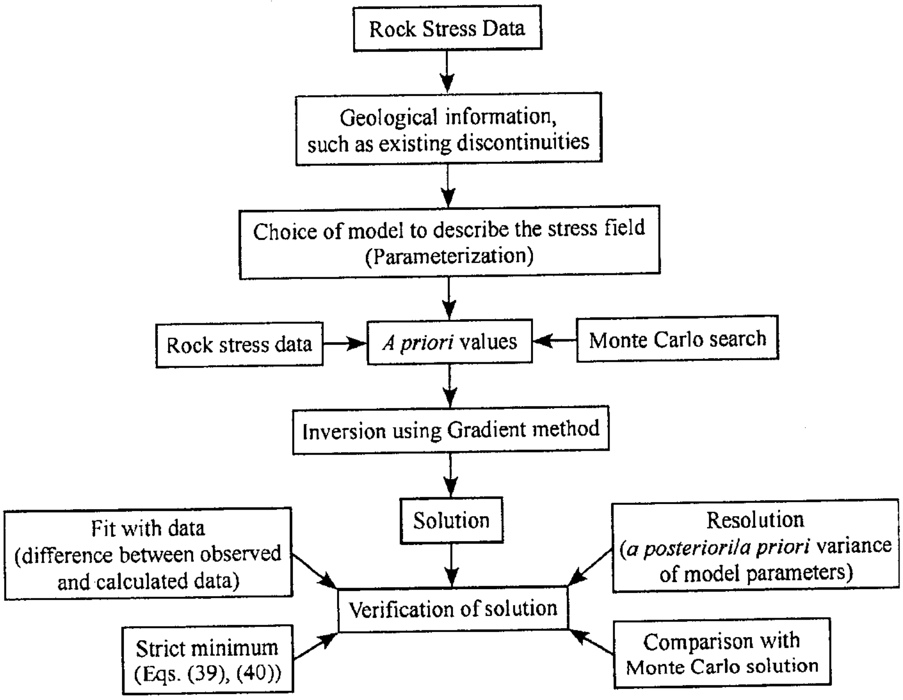


Figure 1. *Approach for stress determination using the ISDM based on the Gradient method. The stress data and the geological information control the parameterization of the stress field in the rock mass. A priori values for the Gradient method are derived from available stress data (in [Paper 1]) or from Monte Carlo simulations (in [Paper 6]). When a solution has been found, it is verified using four methods (after Ask [Paper 6]).*

Rock stress data at Äspö HRL and results of re-analysis

About 100 hydraulic fracturing [e.g. *Klee and Rummel, 2002*] and 140 overcoring measurements have been made [e.g. *Ljunggren and Klasson, 1996*] at the Äspö HRL. This study considers the hydraulic fracturing and overcoring stress data collected in the immediate surroundings of the Äspö HRL excavation, Figure 2, and generally excluding tests sampling secondary stress fields around the excavations.

The stress data are assumed to follow Gaussian distribution implying that each datum can be described with expected value, variance and covariances. Details how these are determined are given in the thesis.

Hydraulic stress data

The main observations from the analysis of hydraulic data are [*Ask, 2004*]:

- High compressibility equipments should be avoided, unless the effects of the high system compliance are corrected for, because these equipments yield larger uncertainties in the fracture normal stress.
- Impression packer systems should not be used in strongly inclined boreholes, because friction effectively removes the fracture imprint on an impression packer during mounting to ground surface.
- Data interpretation should preferably include estimates of maximum and minimum values of the fracture normal stress, which effectively limits the range.
- The hydraulic fracturing formula based on the re-opening pressure includes uncertainties [Ito et al., 1999, Rutqvist et al., 2000] and the magnitude of σ_H should therefore be used with care.
- In case of multiple fractures in the test section, verification of which fracture that has been tested in essential.

Overcoring stress data

The main observations from the overcoring data analysis are [*Ask, 2004*]:

- Gluing problems during Borre Probe measurements affect entire rosettes and the state of stress at the single test scale is not reliable for these tests (must be included to solve the local stress tensor) [*Paper 3*].
- About 25 % of the Borre Probe data were corrected with respect to temperature. These corrections are likely underestimation due to an erroneous location of the temperature-measuring gauge. It is estimated that about 2 MPa should be added to most Borre Probe results (based on strain drift during measurements using CSIRO HI cells).
- The strains during CSIRO HI stress measurements and biaxial tests are not sampled with sufficient frequency to enable evaluation of correct theoretical strain responses [*Paper 5*].
- Most CSIRO HI measurements suffer from boundary yielding, and an identification and approximate correction method is presented in Ask [*Paper 3*].
- A majority of the biaxial tests on CSIRO HI cores fractured during loading because too high biaxial loads were applied [*Paper 3*].
- The standard deviation of the principal stresses for the Borre Probe is larger than that of the CSIRO HI cells (±1.9 and ±1.5 MPa, respectively, based on Monte Carlo simulation) [*Paper 4*].
- The overcoring strain residuals are more concentrated around the central value (of zero μstrain or MPa) and have shorter tails compared to the normal distribution [*Paper 4*].
- The overcoring data at the single test scale do not indicate that sampling has favored good quality rock, i.e. there is no systematic overestimation of the stresses *at this scale* [*Paper 4*].

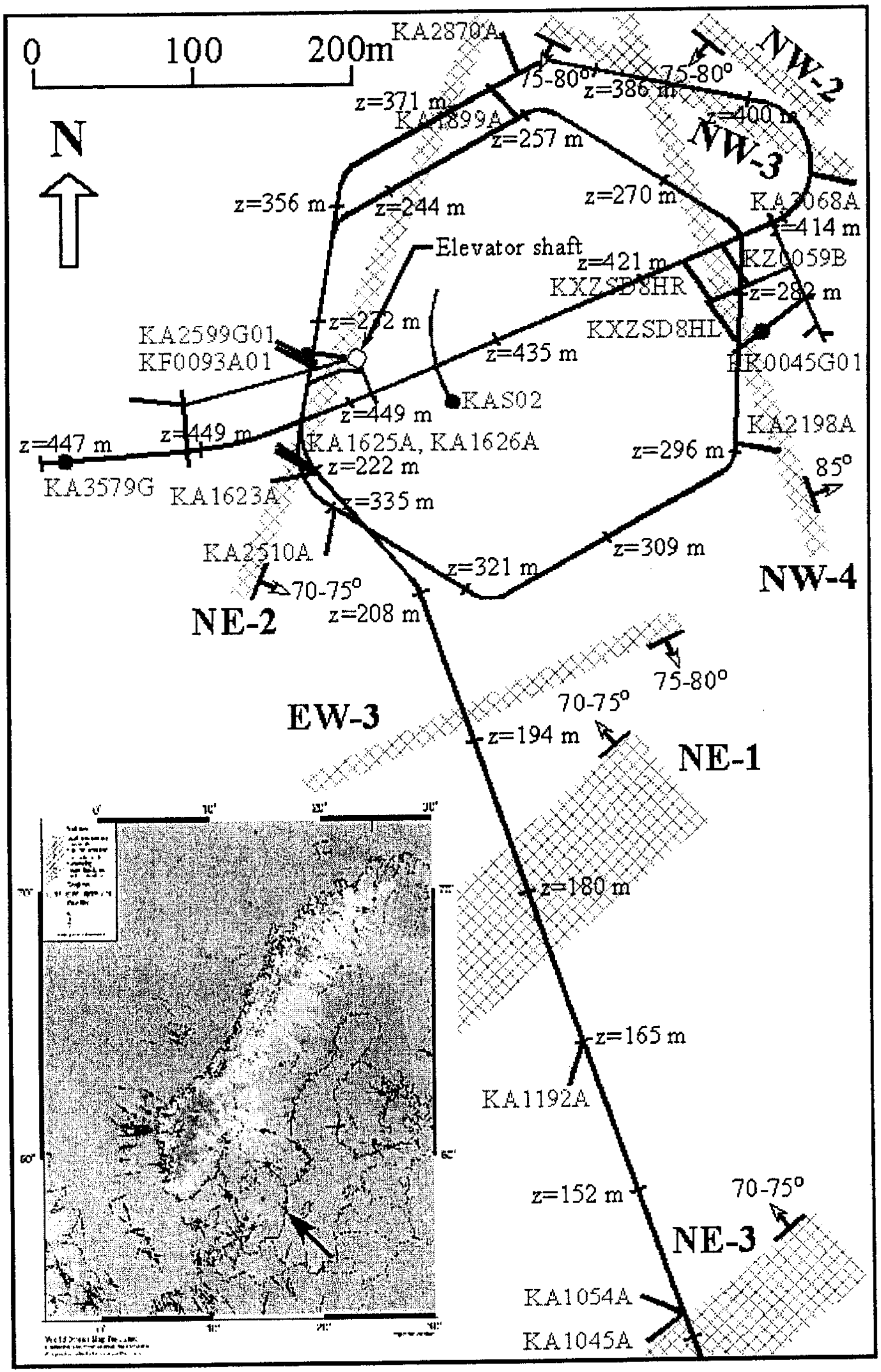


Figure 2. *Map of the Äspö HRL including major fracture zones at the tunnel intersection depth (modified after Ask [*Paper 3*]). Stress measurement boreholes are marked with lines and borehole names. Vertical boreholes are marked with circles and sub-vertical boreholes with circles and a solid line in the borehole direction. The location of the Äspö HRL is indicated by arrow of insert map [*Reinecker et al., 2003*].*

Parameterization of the stress field

The measured rock volume at Äspö HRL is discretized into sub-volumes in which the stress field is approximated by its first order linear expansion. The stress at a point X^m of the m^{th} measurement is given by [*Cornet, 1993b*]:

$$\sigma\left(X^m\right) = \sigma(X) + \left(x^m - x\right)\alpha^{[x]} + \left(y^m - y\right)\alpha^{[y]} + \left(z^m - z\right)\alpha^{[z]} \tag{1}$$

where $\sigma(X^m)$ and $\sigma(X)$ are the stress tensor in points X^m and X, respectively, and $\alpha^{[x]}$, $\alpha^{[y]}$, and $\alpha^{[z]}$ are second-order symmetrical tensors characterizing the stress gradient in the x-, y- and z-directions.

Equation 1 satisfies the following equilibrium constraints [*Cornet,1993b*]:

$$div\left(\sigma\left(X^m\right)\right) - \rho(X)b_i = 0 \tag{2}$$

where $\rho(X)$ is the density of the rock mass in the point X, and b_i is the gravitational acceleration ($b_i = g\delta_{i3}$; $\delta_{i3} = 0$ for $i \neq 3$; $\delta_{i3} = 1$ for $i = 3$). The first order approximation of the stress field requires determination of 22 parameters. If the data set is too small to determine all 22 parameters, the number of unknowns can be reduced using the following assumptions: (1) the lateral stress variations are zero; (2) one principal stress is vertical throughout the volume; (3) if 2 applies, the rock mass density is obtained from direct measurements on cores; (4) there is no rotation of principal stresses (in small rock volumes); (5) the stress field is continuous up to ground surface. If lateral stress gradient can be neglected, the stress field is characterized by 12 parameters according to:

$$\sigma\left(X^m\right) = \sigma(X) + \left(z^m - z\right)\alpha^{[z]} \tag{3}$$

Application of ISDM to hydraulic and overcoring stress data

For hydraulic fracturing/HTPF data, the fracture normal stress can be expressed as:

$$\left[\sigma\left(X^m\right)\vec{n}^m\right]\vec{n}^m = \sigma^m_{normal} \tag{4}$$

where n^m is the normal of the m^{th} fracture plane and includes the dip direction ϕ^m and the dip φ^m of the normal to the m^{th} fracture plane with respect to the vertical direction. With these definitions, Eq. 3 can be formulated in matrix form according to:

$$\sigma^m_n = \left(\left[SB\cdot\left(S^o + \left(z^m - z\right)\cdot AB\cdot A^o\cdot AB^T\right)\cdot SB^T\right]\vec{n}^m\right)\vec{n}^m \tag{5}$$

where matrices S^0 and A^0 represent the stress and gradient tensors, SB includes the Euler angles E_1 to E_3, which describe S^o and A^o in the geographical frame of reference, AB includes Euler angles E_4 to E_6, which describe A^o in the S^o frame of reference, z^m is the depth of the m^{th} fracture, and z is the chosen calculation depth.

For overcoring data, and using the parameterization defined by Eq. 3, the expression for σ_x^n of the n^{th} measurement in matrix form is:

$$\sigma^n_x = \left(\left[SB\cdot\left(S^o + \left(z^m - z\right)\cdot AB\cdot A^o\cdot AB^T\right)\cdot SB^T\right]\vec{n}^n_x\right)\vec{n}^n_x \tag{6}$$

where n_x^n is the direction of the local x-axis with respect to the geographical frame of reference (see *Paper 6* for more details). The expressions for the remaining stress components are analogous.

The inverse problem and its solution

The inversion is performed using a method developed by Cornet [*1993b*], based on the least squares criterion [*Tarantola and Valette, 1982*]. In this method, *a priori* knowledge of the unknown model parameters is assumed to exist (obtained using Monte Carlo simulation), which can be formulated in terms of expected value, variance and covariances. In practice, large error bars are placed on assumed central values for the unknown parameters. Using a hydraulic fracturing or HTPF data set to exemplify the inversion procedure, a vector π can be formulated which includes the expected values for both measurements and unknown model parameters:

$$\pi_0 = col\left[\left(z^m,\phi^m,\varphi^m,\sigma_n^m\right)^i,....,E_1,E_2,E_3,E_4,E_5,E_6,S_1,S_2,S_3,\alpha_1,\alpha_2,\alpha_3\right] \tag{7}$$

where z^m is the depth of the mth fracture plane, ϕ^m and φ^m are the dip direction and dip of the normal to the mth fracture plane, and σ_n^m is the fracture normal stress. Thus, for a 12-parameter problem, hydraulic fracturing and HTPF data involve 4m+12 = M components for m measurements. The corresponding covariance matrix is denominated C_o and is diagonal, because measurements and unknown parameters are assumed independent [*Cornet, 1993b*]. A vector function f(π) may be introduced in which the mth component is defined by:

$$f^m(\pi) = \sigma_n^m - \left(\left[SB \cdot \left(S^o + \left(z^m - z\right) \cdot AB \cdot A^o \cdot AB^T\right) \cdot SB^T\right] n^m\right) n^m \tag{8}$$

The problem is a conditional least square, i.e. is must also satisfy the condition f(π)=0. Tarantola and Valette [*1982*] demonstrated that this could be solved using the iterative algorithm based on the fixed-point method:

$$\pi_{n+1} = \pi_o + C_o F_n^T \left(F_n C_o F_n^T\right)^{-1} \left[F_n\left(\pi_n - \pi_o\right) - f\left(\pi_n\right)\right] \tag{9}$$

where F is a matrix of partial derivatives of f(π) valued at point π. The iterative procedure is stopped when $f(\pi_n)$ is sufficiently close to zero (10^{-6}). The procedure is repeated with different *a priori* values for the unknown parameters to verify that the final solution does not depend on the start value. This procedure can be time consuming and possibly inconclusive, but may be overcome by a global search for model parameters that yields a minimum misfit with the observed data, e.g. using Monte Carlo simulation as in this study.

Misfit functions

A combined inversion of hydraulic fracturing/HTPF and overcoring stress data implies that two methods with different physical nature, scale, and number of available data of each data set may differ. These differences may be overcome by definition and inclusion of misfit functions, which in this thesis, are based on the l_1-norm because this is more robust than the l_2-norm [*Parker and McNutt, 1980*]. For hydraulic fracturing and HTPF data, the misfit is defined by [e.g. *Yin, 1994*]:

$$\psi^h = \sum_{m=1}^{M} \left|\sigma_n^m - \sigma_{n,calc}^m\right| / \left(\delta_n^m + \delta_f^m\right) \tag{10}$$

where δ_n^m is the uncertainty of the normal stress determination and δ_f^m is associated with the maximum rotation of the fracture plane within the domain of uncertainty of its orientation. The uncertainty with respect to depth is very small and hence neglected.

For overcoring data, the misfit is defined by:

$$\psi^{oc} = \sum_{n=1}^{N} \left|\varepsilon_i^n - \varepsilon_{i,calc}^n\right| / \left(\delta_i^n + \delta_{bh}^n\right) \tag{11}$$

where ε_i is the strain, δ_i^n is the uncertainty of the strain measurement, and δ_{bh}^n is the uncertainty associated with the borehole direction. The overcoring misfit function is simplified, and neglects the uncertainty in strain associated with depth, corrections factors, rosette angle, and elastic parameters.

The global misfit function for a combined data set includes weighting factors and can be expressed as [*Yin, 1994*]:

$$\psi^{hoc} = \omega^h \psi^h + \omega^{oc} \psi^{oc} \tag{12}$$

Due to time constraints, a simplified global misfit was used that considers: (1) the volume or area involved by a given measurement in each method; and (2) the individual misfit related to the misfit obtained in the combined solution [*Paper 6*]. The weighting factors are expressed as:

$$\omega^h = \frac{A^h}{A^{REV}} \cdot \frac{\psi^h}{\psi^h_{\min}} \tag{13}$$

and

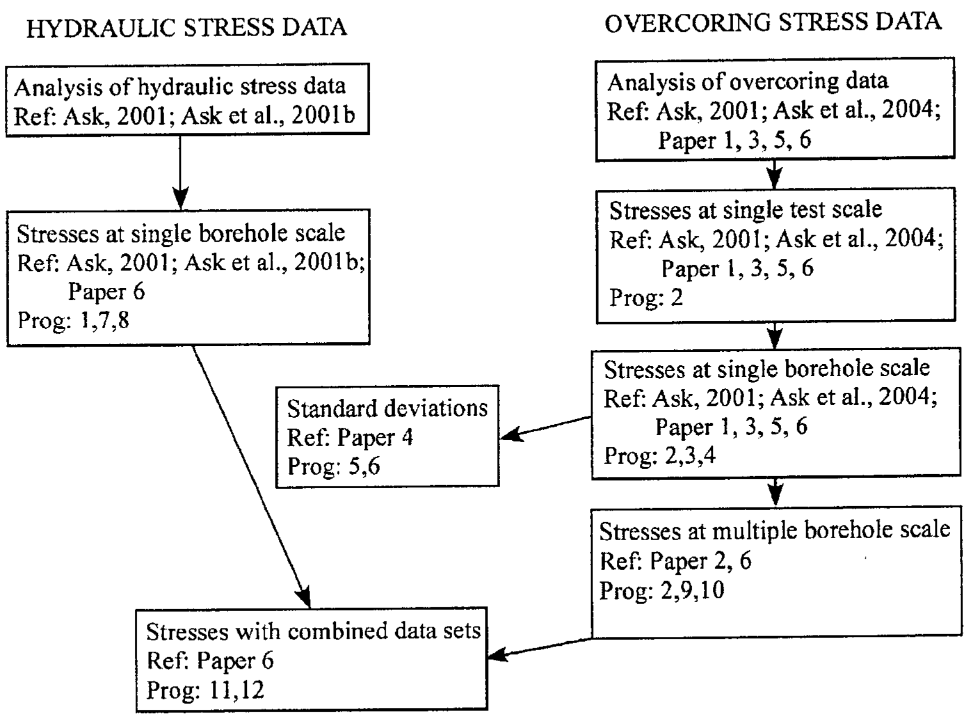
$$\omega^{oc} = \frac{V^{oc}}{V^{REV}} \cdot \frac{\psi^{oc}}{\psi^{oc}_{\min}} \tag{14}$$

where ω^h, A^h, and A^{REV} denote the weighting factor, the measurement area, and the area involved in the Representative Elementary Volume (REV), respectively. Corresponding notations for the overcoring data set are ω^{oc}, V^{oc} (measurement volume) and V^{REV} (REV volume). It is the ratio $\omega^h\psi^h/\omega^{oc}\psi^{oc}$ that determines the weighting of the two data sets in the combined inversion, which, in this simplified global misfit function, is independent of the size of the REV. The area involved during hydraulic fracturing measurements depends on the injected volume but was set to 1 m^2, which corresponds to one liter injected water into a fracture with a mean width of 1 mm (assuming no loss of water due to rock mass permeability). The volume involved in overcoring measurements was set to the average volume of the resulting hollow rock cylinder. The global misfit, which gives hydraulic fracturing/HTPF data more weight than the overcoring data, in a combined inversion thus becomes [*Paper 6*]:

$$\psi^{hoc} = \frac{A^h}{A^{REV}} \cdot \frac{\psi^h}{\psi^h_{\min}} + \frac{V^{oc}}{V^{REV}} \cdot \frac{\psi^{oc}}{\psi^{oc}_{\min}} \tag{15}$$

Results of Stress Calculations at the Äspö HRL

Figure 3 summarizes the procedure how the regional stress field were resolved at the Äspö HRL. Prior to the stress calculation, the stress data were subjected to a detailed analysis and considerations of the validity of the hypothesis on homogeneity, continuity, and linear elasticity of the rock mass. While the state of stress only was determined on the single borehole scale (SBS) for hydraulic fracturing data, it was determined on three scales for overcoring data; single test (STS), single borehole (SBS), and multiple borehole scale (MBS). The final step of the thesis work was to integrate the two data sets from hydraulic fracturing and overcoring. In this thesis summary, primarily chosen results at the multiple borehole scale (MBS) are presented.



1. Gradient method for hydraulic stress data with up to 7 unknown parameters
2. Standard least squares method for 4 types of cells using average E, v, K-factors
3. Standard least squares method for 4 types of cells using individual E, v, K-factors
4. Gradient method for overcoring stress data with 8 unknown parameters
5. Monte Carlo method for calculation of standard deviations
6. Jackknifing method for calculation of standard deviations
7. Gradient method for hydraulic stress data with up to 12 unknown parameters
8. Monte Carlo method for hydraulic stress data with up to 12 unknown parameters
9. Gradient method for overcoring stress data with up to 12 unknown parameters
10. Monte Carlo method for overcoring stress data with up to 12 unknown parameters
11. Gradient method for hydraulic and overcoring stress data with up to 14 unknown parameters
12. Monte Carlo method for hydraulic and overcoring stress data with up to 14 unknown parameters

Figure 3. *Progress of work to calculate the state of stress at the Äspö HRL.*

Single test and single borehole scale (STS and SBS)

At the single test and single borehole scale, the results for intermediate principal stress using overcoring data are presented in this summary (Fig. 4). As a result of identification and correction of measurement-related uncertainties, the scatter of intermediate principal stress magnitudes and orientations have been reduced both at the STS- and SBS-scale. The comparison with the minimum horizontal stress, σ_h from hydraulic data indicates a satisfactory agreement between methods, except for the depth interval 300-400m depth. The trend versus depth for the vertical stress, σ_v, from overcoring data is rather scattered but the average is similar to the trend of the theoretical vertical stress from the weight of the overburden [*Paper 3; 5*].

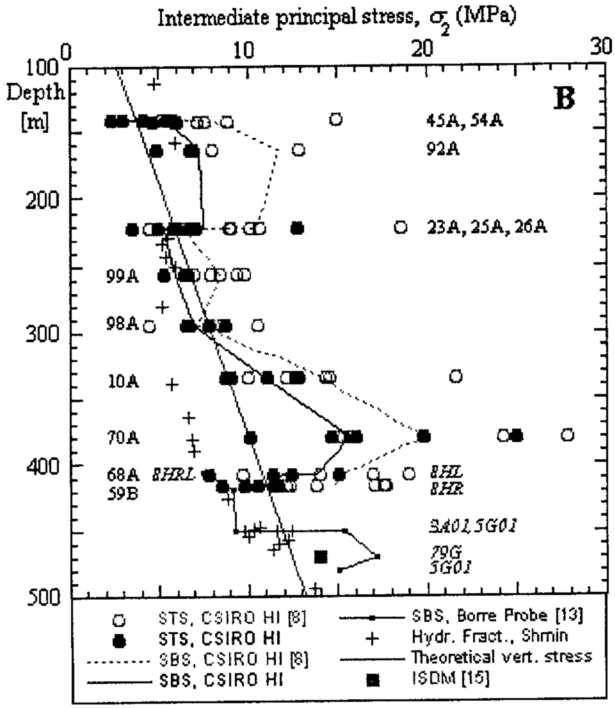


Figure 4. *Magnitude of intermediate principal stress, σ_2, and comparison between overcoring and hydraulic fracturing data (after Ask [Paper 5]).*

Multiple borehole scale (MBS)

As a result of the sub-division of the data sets with respect to the NE-2 Fracture Zone, the exclusion of heterogeneous data and data sampling secondary stress fields, and, because that study assumes no lateral stress variations, in order to reduce the involved rock volume, the number of data at the MBS-scale was diminished. The remaining stress data in the NW domain include 19 hydraulic and 224 overcoring strain measurements, whereas the data in the SE domain include nine hydraulic and 125 overcoring strain measurements.

In this thesis summary, only the results at the MBS-scale in the NW stress domain are presented (Fig. 5). In general, the results confirmed the results from the single test and single borehole scales, i.e. that the principal stresses are slightly inclined, and the stress data is influenced by the NE-2 Fracture Zone.

The solutions in the vicinity of the NE-2 Fracture Zone (both NW and SE domain) indicate that σ_1 is perpendicular to the zone, whereas the σ_2:σ_3–plane coincide with the NE-2 Fracture Zone.

The stress calculations using both the hydraulic and overcoring data sets aimed at constraining the average elastic parameters based on the hydraulic fracturing data, thus solving 14 model parameters, and to compare this solution with results based on the average elastic parameters obtained from biaxial tests on overcore samples. These calculations were planned to involve the suggested global misfit function and associated weighting factors, which give hydraulic data much more weight compared with the overcoring data. However, because the number of hydraulic data is few compared to the number of overcoring data, this could not be implemented when 12 or 14 model parameters are to be solved. The influence of the NE-2 Fracture Zone on the stress field was of higher priority, which is more clearly displayed using 12 or 14 parameters; hence, the inclusion of the misfit functions was cancelled. It is however recommended that these are applied in cases where the data sets are more balanced.

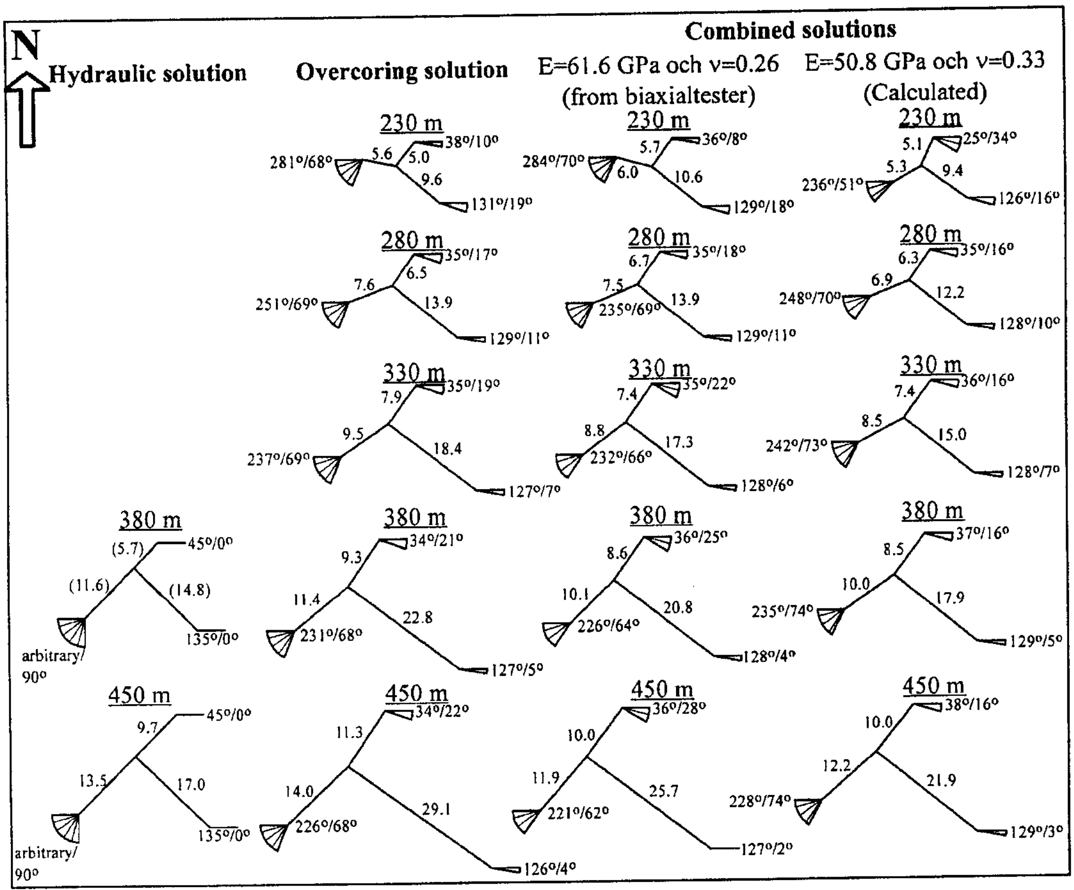


Figure 5. *Three-dimensional state of stress in the NW domain, with respect to the NE-2 Fracture Zone. Stresses are viewed from above and projected onto the horizontal plane. The length of each stress vector is proportional to the corresponding magnitude, the directions of the vectors correspond to the orientation with respect to geographical North, and the fan-shaped symbol describes the dip of the stress vector. Results of combined inversions in the NW domain with elastic parameters assumed known (E = 61.6 GPa and v = 0.26; modified after Ask [*Paper 6*]).*

The stress calculations using known and unknown average elastic parameters were found quite similar (Fig. 5). The results using unknown average elastic parameters yielded E=50.8 GPa and v=0.33, which may be compared with the results from the biaxial tests (E = 61.6 GPa and v = 0.26). The reasonably similar values of the average elastic parameters were expected because the re-analyzed hydraulic and overcoring data sets have similar magnitudes for most depths at Äspö HRL. The differences in the solutions when using known and unknown elastic parameters proved to be almost entirely a result of the different representation of the elastic parameters, i.e. the hydraulic fracturing data, in general, do not influence the solution of the combined data sets. An exception is the minor principal stress at 450 m depth, which approximately correspond to minimum horizontal stress, where the hydraulic fracturing contributes by fixing the magnitude to 10 MPa. The solution based on average elastic parameters from biaxial tests is, however, regarded more reliable because the amount of hydraulic data constraining the elastic parameters are small and are, in general, located at a larger depth than those of the overcoring data.

Conclusions

Results from this study reveal that the Integrated Stress Determination Method (ISDM) may effectively improve the interpretation of the regional stress field. The new developments of the ISDM and application to the Äspö HRL was successful and indicate, on contrary to what was believed prior to this study, that the stress field is well constrained with depth and with comparable results between different stress measuring methods. The study also verified that the NE-2 Fracture Zone influences the regional stress field, which is indicated by rotations of the principal stresses. The solutions in the vicinity of the NE-2 Fracture Zone (both NW and SE domain) indicate that σ_1 is perpendicular to the zone, whereas the σ_2:σ_3–plane coincide with the NE-2 Fracture Zone. The principal stress magnitudes seem less influenced by the zone.

References

Amadei, B. and Stephansson, O., 1997. *Rock Stress and Its Measurements*, Chapman and Hall Publ., London.

Angelier, J., Tarantola, A., Valette, B., and Manoussis, S., 1982. Inversion of field data in fault tectonics to obtain the regional stress field – I. Single phase fault populations: a new method for computing the stress tensor. *Geophys. J. R. Astr. Soc.*, **69**, p. 607-21.

Ask., D., 2003a; Paper 3. Evalution of measurement-related uncertainties in the analysis of overcoring rock stress data from Äspö HRL, Sweden: a case study. *Int. J. Rock Mech. Min. Sci.*, **40**, p. 1173-87.

Ask, D., 2004a. New developments of the integrated stress determination method and application to the Äspö Hard Rock Laboratory, Sweden. Doctoral Thesis, Royal Institute of Technology, Stockholm, ISSN 1650-8602; ISBN 91-7283-744-6.

Ask, D., 2004b; Paper 4. Statistical analysis of overcoring rock stress data and performance of overcoring devices at the Äspö Hard Rock Laboratory, Sweden. *Rock Mech. Rock Eng.*, in review.

Ask, D., 2004c; Paper 5. Measurement-related uncertainties in overcoring rock stress data at the Äspö HRL, Sweden, Part 2:Biaxial tests of CSIRO HI overcore samples. *Int. J. Rock Mech. Min. Sci.*, in review.

Ask, D., 2004d; Paper 6. New developments of the Integrated Stress Determination Method and application to rock stress data at the Äspö HRL. *Int. J. Rock Mech Min. Sci.*, in review.

Ask, D., 2004e. Analysis of overcoring rock stress data at the Äspö HRL, Sweden. Analysis of overcoring rock stress data from the CSIRO HI cells. SKB International Progress Report, IPR-04-06, Stockholm.

Ask, D., Cornet, F.H., and Stephansson, O., 2003; Paper 2. Integration of CSIR- and CSIRO-type of overcoring rock stress data at the Zedex Test Site, Äspö HRL, Sweden. *Proc. 10th International Congress on Rock Mechanics* (Eds. Handley, M., Stacey, D.), Johannesburg, South-Africa. SAIMM, p. 63-8.

Ask, D., Cornet, F.H., and Stephansson, O., 2004. Analysis of overcoring rock stress data at the Äspö HRL, Sweden. Analysis of overcoring rock stress data from the Borre Probe. SKB International Progress Report, IPR-04-05, Stockholm.

Ask, D., Stephansson, O., and Cornet, F.H., 2001a; Paper 1. Analysis of overcoring stress data in the Äspö region. *Proc. 38th US Rock Mechanics Symposium* (Eds. Elsworth D., Tinucci, J.P., Heasley, K.A.), Washington, USA. AA. Balkema Publ., p. 1401-5.

Ask, D., Stephansson, O., and Cornet, F.H., 2001b. Integrated stress analysis of hydraulic stress data in the Äspö region, Sweden. Analysis of hydraulic fracturing stress data and hydraulic tests on pre-existing fractures (HTPF) in boreholes KAS02, KAS03, and KLX02. SKB International Progress Report, IPR-01-26, Stockholm.

Berglund, J., Curtis, P., Eliasson, T., Ohlsson, T., Starzec, P., and Tullborg, E.-L., 2003. Update of the geological model 2002. SKB International Progress Report, IPR-03-34, Stockholm.

Bjarnason, B., Klasson, H., Leijon, B., Strindell, L. and Öhman, T., 1989. Rock stress measurements in boreholes KAS02, KAS03 and KAS05 on Äspö. SKB Progress Report 25-89-17, Stockholm.

Cornet, F.H. and Valette, B., 1984. In situ stress determination from hydraulic injection test data. *J. Geophys. Res.*, **89**, p. 11527-37.

Cornet, F.H., 1993a. Stresses in rock and rock masses. In: *Comprehensive Rock Engineering*, **3**, (J. Hudson, Ed.). Pergamon Press, Oxford, p. 297-327.

Cornet, F.H., 1993b. The HTPF and the integrated stress determination methods. In: *Comprehensive Rock Engineering*, **3**, (J. Hudson, Ed.). Pergamon Press, Oxford p. 413-32.

Cornet, F.H., 1996. A complete 3D stress determination for the design of an underground power station. *Proc. 2nd North Am. Rock Mech. Symp., NARMS'96* (Eds. Aubertin, M., Hassani, F., Mitri, H.), Montréal, Canada, A.A. Balkema Publ., Rotterdam, p. 755–61.

Gallagher, K., Sambridge, M., and Drijkoningen, G., 1991. Genetic algorithms: an evolution from Monte Carlo methods for strongly non-linear geophysical optimisation problems. *Geophys. Res. Lett.*, **18** (12), p. 2177-80.

Ito, T., Evans, K., Kawai, K., and Hayashi, K., 1999. Hydraulic fracturing reopening pressure and the estimation of maximum horizontal stress. *Int. J. Rock Mech. & Geomech. Abstr.*, **36**, p. 811-26.

Julien, Ph. and Cornet, F.H., 1987. Stress determination from aftershocks of the Campania-Lucania earthquake of November 23 1980. *Annales Geophysicae*, **5B** (3), p. 289-300.

Ljunggren, C. and Klasson H., 1996. Rock stress measurements at Zedex test area, Äspö HRL. Äspö Hard Rock Laboratory, Technical Note TN-96-08z, Stockholm.

MathWorks, 2001. *Matlab student version, release 12*. The MatWorks inc.

Menke, W., 1984. *Geophysical data analysis: Discrete inverse theory*. Academic Press, Inc., Orlando, Florida.

Parker, R.L. and McNutt, M.K., 1980. Statistics for one-norm misfit measure. *J. Geophys. Res.*, **85**, p. 4429-30.

Reinecker, J., Heidbach, O., Mueller, B., 2003. The 2003 release of the World Stress Map (avaliable online at www.world-stress-map.org).

Rutqvist, J., Tsang, C.-F., and Stephansson, O., 2000. Uncertainty in the principal stress estimated from hydraulic fracturing measurements due to the presence of the induced fracture. *Int. J. Rock Mech. & Geomech. Abstr.*, **37**, p. 107-20.

Tarantola A. and Valette B., 1982. Generalized non-linear inverse problem solved using the least square criterion. *Rev. Geophys. Space. Phys.*, **20**, p. 219-32.

Yin, J.M., 1994. Détermination du champ de contrainte regional à partir de measures hydrauliques et de mecanismes au foyer de microséismes induit. Doctoral Thesis, Institut de Physique du Globe de Paris, Paris.