Working Report 2012-01

A Test Case of the Deformation Rate Analysis (DRA) Stress Measurement Method

Phil Dight

Ariel Hsieh

Kimmo Kemppainen

Erik Johansson

John A Hudson

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POSIVA OY

FI-27160 OLKILUOTO, FINLAND

Tel +358-2-8372 31

Fax +358-2-8372 3709

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Phil Dight, Ariel Hsieh

Australian Centre for Geomechanics

Kimmo Kemppainen

Posiva Oy

Erik Johansson

Saanio & Riekkola Oy

John A Hudson

Rock Engineering Consultants, UK

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ABSTRACT

As part of Posiva's site and ONKALO investigations, the *in situ* rock stress has been measured by a variety of techniques, including hydraulic fracturing, overcoring, and convergence measurements. All these techniques involve direct measurements in a drillhole or at the rock surface. An alternative method is to test drillhole core in a way that enables estimation of the magnitudes and orientations of the *in situ* rock stress. The Kaiser Effect (KE) and Deformation Rate Analysis (DRA) are two ways to do this. In the work reported here, a 'blind' DRA test was conducted on core obtained from the POSE (Posiva's Olkiluoto Spalling Experiment) niche in the ONKALO. The term 'blind' means that the two first authors of this report, who conducted the tests at the Australian Centre for Geomechanics, did not know the depths below surface at which the cores had been obtained. The results of this DRA Test Case are presented, together with an explanation of the DRA procedure. Also, additional information that would help in such DRA testing and associated analysis is explained.

One of the problems in comparing the DRA results with the known Olkiluoto stress field is that the latter is highly variable across the site, as experienced by the previous *in situ* stress measurements and as predicted by numerical analysis. The variability is mainly caused by the presence of the large brittle deformation zones which perturb the local stress state. However, this variability reduces with depth and the stress field becomes more stable at the ~350 m at which the drillhole cores were obtained. Another compounding difficulty is that the stress quantity, being a second order tensor, requires six independent components for its specification. In other words, comparison of the DRA results and the known stress field requires comparison of six different quantities. In terms of the major principal stress orientation, the DRA results predict an orientation completely different to the NW-SE regional stress direction that is thought to be present in the ONKALO POSE niche, the actual result being 49° from the local stress measurement at depth -345 m. On the other hand, the magnitudes of the principal stresses are not too dissimilar from those measured by other methods.

Thus, the DRA test case has not shown the method to be invalid, especially since in the 'blind' test not all the background information was provided—as would be the case if the DRA method were being used in the normal way. On other hand, neither has the DRA test case shown the method to be a valid way of measuring/estimating the *in situ* stress field. We conclude, therefore, that the DRA method remains an interesting and complementary approach, especially since such tests on drillhole cores are cheaper and often easier than 'conventional' stress measurement methods, and should be considered as a helpful supplement to the other methods.

Keywords: Olkiluoto, ONKALO, nuclear waste disposal, stress measurements, Deformation Rate Analysis, Kaiser Effect.

ESIMERKKITAPAUS JÄNNITYSTILAN MITTAAMISEKSI DRA (DEFORMATION RATE ANALYSIS) -MENETELMÄLLÄ

TIIVISTELMÄ

Kallion jännitystilan mittauksia on tehty osana Posivan ja ONKALOn tutkimuksia useilla eri menetelmillä mukaan lukien hydraulinen murtaminen, irtikairaus ja konvergenssimittaukset. Kaikki nämä menetelmät edellyttävät suoria mittauksia joko kairareiässä tai kallion pinnalla. Vaihtoehtoinen menetelmä on käyttää kairasydäntä, josta mittaamalla voidaan määrittää kallion jännitystilan suuruudet ja suunnat. Ns. Kaiser efekti (KE) ja Deformation Rate Analysis (DRA) ovat tapoja tutkia kairasydäntä. Tässä työssä tehtiin ”sokea” DRA-koe kairasydämillä, jotka olivat kairattu ONKALOn POSE-tutkimustilasta. Termi ”sokea” viittaa tässä kahteen raportin ensimmäiseen kirjoittajaan. jotka suorittavat kokeen Australiassa tietämättä tarkalleen sijaintia ja syvyyttä, josta näytteet olivat otettu. Raportissa esitetään menetelmän kuvaus ja kerrotaan testin tulokset. Lisäksi raportin lopussa mainitaan lisäseikkoja, jotka auttaisivat testin ja analyysin tekemistä jatkossa.

DRA-tulosten ja Olkiluodon tunnetun jännitystilan vertaamisen ongelma on, että tutkimusalueen jännitystila on hyvin vaihteleva. Tämän ovat osoittaneet aiemmat in situ jännitystilamittaukset ja suoritetut numeeriset mallinnukset. Pääsyy vaihteluun on suurten hauraiden deformaatiovyöhykkeiden esiintyminen alueella, jotka ovat ”sekoittaneet” alueen jännitystilaa. Vaihtelu kuitenkin heikkenee syvällä kalliossa, ja on vakaampi alkaen noin 350 m syvyydestä, josta DRA-näytteetkin on otettu. Toinen vertailua vaikeuttava asia on, että kallion jännitystila on tensorisuure, ja sen määrittäminen vaatii kuuden riippumattoman tekijän määrittämistä. Toisin sanoen DRA-tulosten ja tunnetun jännitystilan vertaaminen vaatii näiden kuuden eri tekijän vertaamista. Kun tarkastellaan tulosten pääjännitysten suuntaa, voidaan todeta, että DRA-tulokset ennustavat jännitystilan suunnaksi täysin muuta kuin luode-kaakko, jonka on ajateltu edustavan jännitystilan suuntaa ONKALOn POSE-tutkimustilassa, eron ollessa 49°. Toisaalta pääjännitysten suuruudet ovat hyvin samankaltaiset verrattuna muilla menetelmillä saatuihin tuloksiin.

DRA testimittaus ei siten tulosten mukaan osoittanut käyttökelvottomaksi etenkin, kun huomioidaan, että ”sokkotestissä” ei ollut käytössä kaikki se tieto, joka normaalisti on käytössä ko. mittauksissa. Toisaalta DRA-menetelmä ei myöskään osoittautunut tavaksi mitata kallion jännitystilaa. Johtopäätöksenä voidaan todeta, että DRA-menetelmä on mielenkiintoinen menetelmä etenkin, koska mittaukset kairasydämistä ovat halvempia ja usein helpompia kuin perinteiset jännitystilamittausmenetelmät, ja menetelmä voidaankin arvioida hyödyllisenä lisänä muille menetelmille.

Avainsanat: Olkiluoto, ONKALO, ydinjätteen loppusijoitus, jännitystilamittaus, Deformation Rate Analysis, Kaiser Effect

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PREFACE

This report has been prepared for Posiva Oy as part of the Olkiluoto site investigation research work. The Deformation Rate Analysis, other testing and data reduction were undertaken by the two senior authors at the Australian Centre for Geomechanics, University of Western Australia.

The DRA test case project was commissioned by Matti Hakala from KMS-Hakala Oy and Kimmo Kemppainen from Posiva Oy. Erik Johansson from Saanio & Riekkola Oy and John Hudson from Rock Engineering Consultants contributed the work to finalize the report.

1 INTRODUCTION

1.1 Rock mass stresses and indirect stress measurement methods

To characterise the Olkiluoto rock mass for the purpose of hosting a radioactive waste repository, one of the key parameters is the *in situ* rock stress. There is a considerable history of stress measurements at many rock mass sites worldwide plus research into stress measurement methods, e.g. Amadei and Stephansson 1997, a Special Issue of the International Journal of Rock Mechanics and Mining Sciences (IJRMMS 2003) which contains the four ISRM Suggested Methods for Stress Measurement, specialist conferences on rock stress, e.g. Xie 2010, and the recent book by Zang & Stephansson 2010. Despite extensive work on the subject of *in situ* rock stress, problems are often experienced during stress measurement campaigns; whichever stress measurement methods are used. This is partly due to the fact that stress is a second order tensor quantity with six independent components and partly due to the difficulties of making remote measurements in a borehole using the two main methods of overcoring and hydraulic fracturing. Additionally, the stress field is generally not uniform across the site of interest: it is perturbed by factors such as the discontinuous, inhomogeneous and anisotropic nature of rock masses (Hudson & Feng 2010), so that the actual stress field in the rock mass varies from point to point, making confirmation of the measurement results difficult to achieve.

For these reasons, engineers and researchers have considered whether information about the *in situ* rock stress can be obtained from drillhole cores. Is it possible to test the cores in some way that will indicate the *in situ* rock stresses? One of the methods suggested is to use the Kaiser Effect (Zang & Stephansson 2010, Tang & Hudson 2010). The idea is that the microstructure of the *in situ* rock, having been subjected to the *in situ* stress, will have been damaged through the generation of microcracks. If, therefore, a rock core is tested in uniaxial compression in the laboratory, it will remain quiescent until the *in situ* stress level is reached, after which there will be acoustic emission as the microcracks continue to be propagated. Because stress is a second order tensor quantity with six independent components, six such compression tests have to be conducted in six different directions, meaning that the tests have to be conducted on sub-cores from the original drill core. There are major advantages in being able to establish the rock stress from a drill core in terms of speed, convenience and cost.

In fact, there have been many attempts to identify the *in situ* stress from diamond drill core since Dr Kaiser, (Kaiser 1950, 1953), established that materials have a memory of the stress to which they have been subjected, even when tested well below their maximum strength in the so-called ‘elastic’ range. Kaiser (1950) discovered that acoustic emission could determine the previous maximum stress that the sample had experienced through the onset of a significant amount of noise/sound. The effect became known as the Kaiser Effect. The phenomenon has been confirmed in many laboratory tests (e.g. Goodman 1963, Kurita & Fujii 1979 and Lavrov 2002). The effect has also been shown to measure the maximum previous stress measured in core recovered from diamond drilling (Villaescusa *et al*. 2003).

However, the Kaiser Effect test remains an enigma because there are good geological reasons why it cannot be a valid test (Lehtonen *et al.* 2011). In addition to any damage that has been introduced into the rock core during the drilling, the *in situ* stresses have then been removed both from the rock core surfaces and internally, but the rock sample is going to be tested in a series of uniaxial tests without the confining stress that was present when the maximum principal stress *in situ* stress was applied. In addition, there can be time-dependent effects (stress relaxation effects) related to the stress removal—which could affect the microfracturing. Indeed, over time, the whole stress memory might be lost. In terms of testing the six sub-cores, what is the effect of loading these rock cores in the laboratory on the microfracturing process when the applied stress is at different orientations to the microfractures? In some directions, reactivation of the existing microfractures could occur in an extensional mode; in other directions, the reactivation could occur in a shear mode. It is not generally possible to guarantee that the rock core is co-axially loaded in line with the major principal stress orientation, unless there is other information available relating to the geological history or previous stress measurements made by another method. Despite all these factors, as mentioned several researchers have obtained good results with its use, e.g. Windsor *et al*. 2010.

1.2 The Deformation Rate Analysis (DRA) method

The ability to obtain a measure of the stress field from core is clearly an incentive for any site investigation, because alternative methods can be more expensive or logistically difficult, the alternatives being regular hydraulic fracturing (HF) and hydraulic fracturing of pre-existing fractures (HTPF), the HI/CSIRO overcoring cell, the doorstopper overcoring cell and the borehole slotter. Each approach has its merits and demerits, depending on access and the assumptions used. The HI/CSIRO method assumes isotropic behaviour of the rock in most applications. By using the program of Amadei (1996) the results from the HI/CSIRO cell can accommodate the influence of anisotropy when estimating in situ stress. However, other than the CSIRO cell using Amadei’s analysis and DRA/AE, all methods assume isotropic behaviour of the rock, but this is rarely observed, especially in mineralised systems in the mining context. All techniques provide an essentially point sample stress field value in terms of a large rock mass and hence the motivation to obtain as many samples as possible to provide representative stress magnitudes and directions for numerical modelling. For this, the HF technique has a superior ability to obtain more statistically representative samples; however, the assumptions in this technique can limit its usefulness because it assumes that one of the principal stresses is parallel to the borehole axis.

The method used in this study is called the Deformation Rate Analysis (DRA) technique (Yamamoto *et al*. 1990). Using suitably orientated sub-samples (six in number) from orientated drillhole core, the method provides six independent measurements to solve the complete stress tensor by exploiting the ability of the rock to retain a ‘memory’ of its recent stress history. This ‘memory’ can be interrogated by stressing the sub-sample cores beyond the stress that they have been subjected to *in situ*. Although similar to the Kaiser Effect method, this method relies on the fact that the previous stress level in a sample can be detected by determining the strain difference between two successive cycles of loading (known then as the inelastic strain). Mathematically, this is expressed as:

$$\Delta\varepsilon_{i,j}(\sigma) = \varepsilon_j(\sigma) - \varepsilon_i(\sigma) \tag{1.1}$$

where ε_i (σ) is the axial strain in the sub-core in the first loading and ε_j (σ) is the axial strain in the second loading of the applied stress σ.

Dight (2006) showed that, using this DRA technique, each load applied to a sample could be determined, not just the previous maximum load. This is important because there had been several reported studies that had shown that the KE was over-estimating the *in situ* stress when compared to adjacent hydraulic fracturing and overcoring tests, suggesting that the KE result is not necessarily the current *in situ* stress as first assumed. This is clear from the geological principles outlined in Lehtonen *et al*. (2011). But, by careful examination of the results using the DRA method, the component of the *in situ* stress aligned along the axis of the sample could be determined (with a knowledge of the orientation of the sample in 3D space).

It was noted then that the maximum previous stress the sample had experienced was generally greater than the component of the *in situ* stress along the axis of the sub-sample, except where the axis of the hole is closely aligned to one of the principal stresses. One possible reason for this phenomenon is that the core is subjected to a higher stress during the coring process (Li & Schmitt 1998), an effect noted in the HI stress measurements and doorstopper stress measurements (e.g. Martin & Christiansson 1991). This can be demonstrated via a 3D stress analysis as well, and was reported by other authors at the *In Situ* Stress Symposium in Norway in 2006 (Lehtonen & Särkkä 2006, Lim *et al*. 2006). More recently, this has also been demonstrated in Australia for samples of rock recovered from the sides of underground development where the expected overstress due to mining can be distinguished from the *in situ* stress. The results of the DRA testing has been shown to coincide with the most recent deformation event in terms of orientation (Dight 2009, Dight & Bogacz 2009, Dight & Synman 2010) which has wide implications for the mining industry. Indeed the work present in Dight & Synman 2010 shows excellent correlation with HI testing undertaken three years after the DRA work was completed.

Thus, in view of the fact that the DRA method might prove useful in supplementing the *in situ* stress knowledge at the Olkiluoto site, a DRA test case was established. The test was conducted ‘blind’; in other words, the researchers conducting the test, i.e. the first two authors of this Working Report, were unaware of the locations from which the supplied rock cores had been taken. It was then possible to compare the DRA test results with existing knowledge of the stress state in the ONKALO.

2 CORE SAMPLES FOR THE DRA TEST CASE EXAMPLE

The cores were obtained from the rock mechanics niche in the ONKALO (Figure 2-1) and the drillhole ONK-PP259 at the site where a large diameter hole had been drilled for other stress measurement tests (the POSE experiment), see Figures 2-2 and 2-3.

Figure 2-1. *The rock mechanics niche in the ONKALO from which the ONK-PP259 drillhole cores were obtained. The niche is excavated in diatexitic gneiss, veined gneiss and pegmatitic granite.*

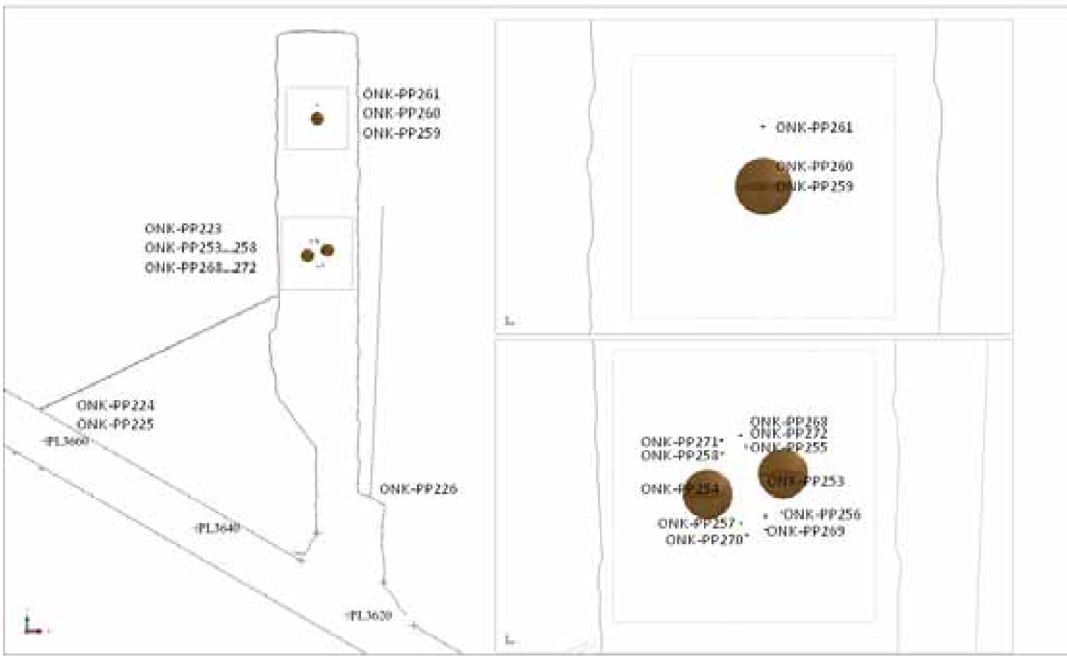


Figure 2-2. *The location of drillhole ONK-PP259 at the far end of the rock mechanics POSE niche (see Figure 2-1) in the ONKALO at a depth of 345 m.*

The rock is a fairly coarse grained pegmatitic granite, as can be seen in Figure 2-4. The coarse crystalline grain is not the main difficulty for the test work; however, the distribution of large grains does introduces a greater scale effect influence in the 19 mm diameter sub-samples than if the sample had a larger diameter relative to the grain size. In this case, the measurement of the modulus is highly variable in the samples with the same orientation. The P-wave velocity confirms the large variability in the modulus, see Table 3-2.

Figure 2-3. *The ONK-PP259 vertical drillhole was drilled on the centreline of this ∅1.5 m hole, i.e. before the hole was reamed.*

Figure 2-4. *The ONK-PP269 drillhole core used for the DRA tests. The depth markings show that the core was obtained from 3 m to 7 m below the niche floor.*

3 DEFORMATION RATE ANALYSIS AND KAISER EFFECT TESTING

It should be noted that the results reported here for the (DRA) test case are without any correction of the induced stress due to the proximity to the underground opening or the drilling process.

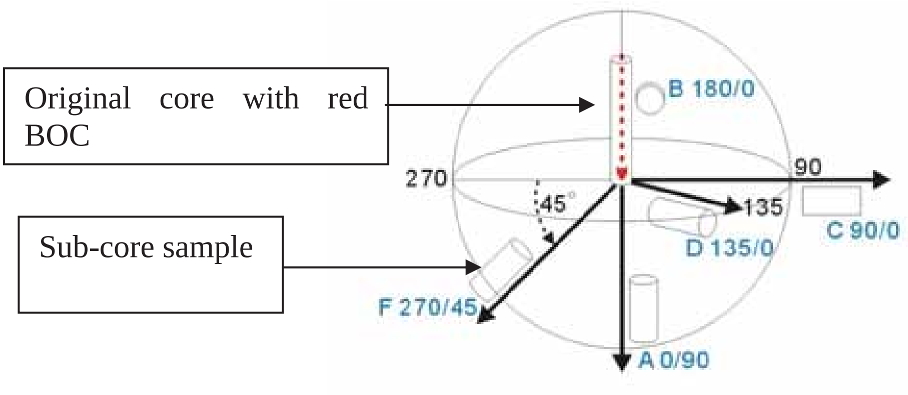
3.1 The sub-core samples

Sub-samples of the original cores illustrated in the previous Section were obtained. The sub-sample orientations and nomenclature are illustrated in Figure 3-1. Figure 3-1a is a typical stick of oriented core that has been sampled according to the orientations shown in Figure 3-1b.

In Figure 3-2, the apparatus for holding the sub-core in the testing machine is shown. The bars connecting the outsides of the rings are for axial strain measurements and the acoustic emission transducers can be seen clamped against the sample sides.

The sub-core diameter was typically 17 to 20 mm and length 40 to 50 mm (depending on the original core diameter). End planarity was specified to be within 0.02 mm which coincides with the ISRM specification on end preparation for UCS testing, but greater than this tolerance was achieved. The test samples were also measured for compliance with a strict requirement for parallelism. The true orientation of the samples in space is then calculated from the orientation and survey of the hole.

Figure 3-1a. *Typical sub-core sample orientations and markup. The lines along the core have been measured from the bottom of core mark (BOC), which was marked as 0 degrees when looking downward on a core.*



Relative to a vertical axis (trend/plunge)	Sample Identifiers
000°/90°	A 1-3
180°/00°	B 1-3
090°/00°	C 1-3
135°/00°	D 1-3
180°/45°	E 1-3
270°/45°	F 1-3

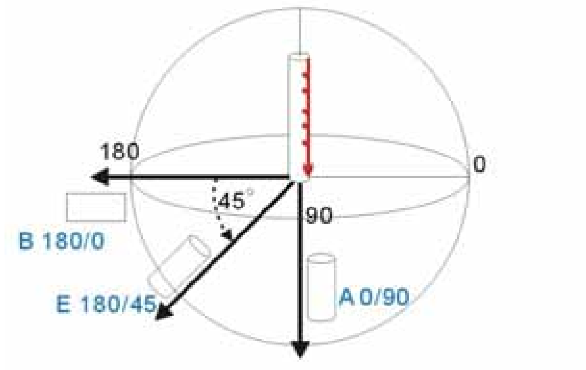


Figure 3-1b. *Sub-core sample orientations and nomenclature. Red line is the bottom of core mark, which was marked as 0 degrees when looking downward on a core.*

All samples have eight strain gauges—four lateral and four diametral. The position of the gauges was 0° and 180° and 90° and 270° (which also allowed a greater understanding of the anisotropic nature of the rock).

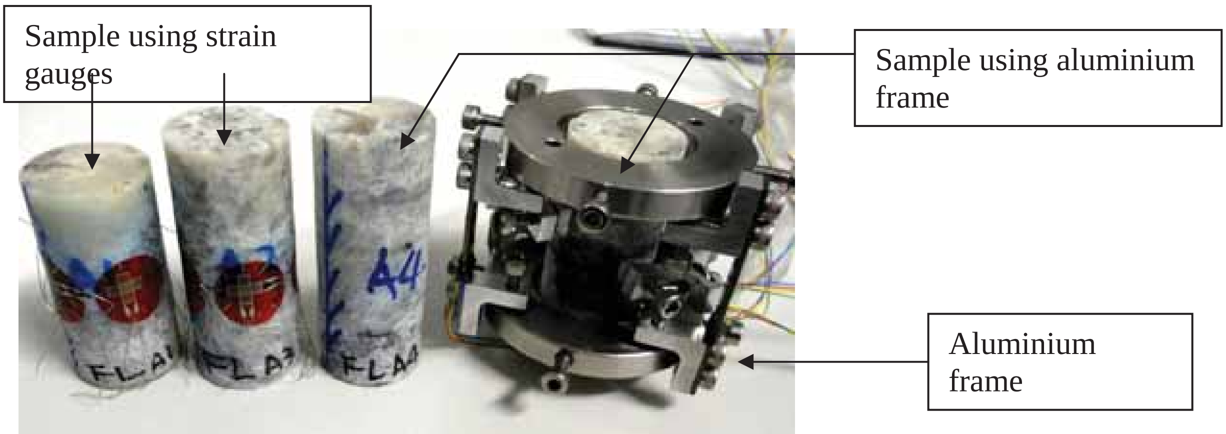


Figure 3-2. *The sub-cores used for the DRA testing programme. The aluminium frame is equipped with four axial and two lateral strain gauges.*

3.2 Summary of the sub-core sample properties

In all tests undertaken, the elastic modulus, Poisson's ratio, density, diameter and P-wave velocity were recorded, as presented in Table 3-1.

The results given in Table 3-1 show that the modulus is highly anisotropic, between 40 GPa and 82 GPa. Note that this spread in the modulus is typical for the Olkiluoto rocks, the mean Young's modulus being 60 MPa (Hakala *et al*. 2007). This variation is confirmed by the P-wave velocity of each sample. The variability in modulus not only exists in different orientations, but also in sub-samples with the same orientation (i.e. the rock is also inhomogeneous). For example, sample groups B and C show more than 25 GPa difference in modulus. Each sub-sample group (i.e. A1, B1,…F1) has been recovered in close proximity to each other and so the variability observed would be representative of the changes over a distance of 2 m if it were confirmed by more samples. By averaging the results for the same orientation (i.e. averaging A1, A2 and A3), the anisotropy in the same group might be eliminated. This would be the correct procedure for obtaining a 'representative' stress measurement. However, without a much larger sample, this might also bias the resultant stress distribution.

Table 3-1. *Characteristics of the sub-core samples used for the DRA tests.*

Sample	Modulus GPa	Poisson's ratio	Density t/m^3	Diameter mm	P-wave velocity m/s
A1	40.4	0.208	2.60	18.8	5312
A2	45.5	-	2.61	18.8	5222
A3	61.2	0.205	2.59	18.8	5601
B1	73.3	0.194	2.70	18.8	6046
B2	62.1	0.235	2.61	18.8	5866
B3	47.1	0.275	2.58	18.85	5287
C1	63.4	0.223	2.64	18.8	6128
C2	68.3	0.202	2.63	18.8	5808
C3	63.4	0.237	2.56	18.9	5432
D1	66.3	0.169	2.62	18.8	5488
D2	45.5	0.188	2.67	18.8	5234
D3	60.6	0.218	2.70	18.8	5757
E1	82.5	0.191	2.70	18.85	6511
E2	50.5	0.157	2.65	19.05	5565
E3	43.1	0.272	2.75	19.05	5258
F1	68.3	0.179	2.65	19	5817
F2	48.0	0.191	2.65	19.05	5622
F3	56.4	0.189	2.67	19.05	5661
Mean	58.1	0.208	2.65	18.89	5687
Max	82.5	0.275	2.76	19.1	6511
Min	40.4	0.157	2.56	18.8	5222
Standard Deviation	11.4	0.032	0.05	0.11	332

3.3 Testing procedure and data reduction

The sub-core samples were tested axially without confinement. Axial loading of each core involved two cycles of loading; the first and second cycle involved slowly loading the core up to a stress at least above the *in situ* stress. Once each reload was achieved, it was rapidly removed so as not to induce a 'memory' of a higher stress into the core. The transducers were logged during these two cycles and all data saved in a spreadsheet format. Results for the full load/unload cycle were recorded and the results analysed and interpreted. Note that this test procedure does not rely on the theory of elasticity to obtain a result. The samples were also tested for acoustic emission and P-wave velocity.

The transformation of the laboratory measurements into the principal stresses and associated orientations involves a sequence of complex processes, but these processes are well described in the published literature and it is not the intention to provide the detail in this report. A summary of the procedures is provided below.

- The relative orientations of each sub-cored sample are specifically defined for each measurement location.

- These are transformed into a general 3-dimensional stress tensor by simple stress rotation procedures (e.g. Jaeger *et al*. 2007). The stress tensor comprises normal (σ) and shear (τ) stresses, in relation to the reference grid, i.e. the borehole orientation imposed on the orientations of each individual sub-cored samples, as shown in Matrix 1.

$$\begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix} \quad \text{Matrix 1 (where the } \tau_{ij} \text{ are not equal to zero)} \qquad (3.1)$$

The calculation of the principal stresses is completed by solving the eigenvalues for Matrix 1 (Markland 1974), which correspond to σ_{11}, σ_{22}, and σ_{33} as shown in Matrix 2.

$$\begin{bmatrix} \sigma_{11} & 0 & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & \sigma_{33} \end{bmatrix} \quad \text{Matrix 2 Principal stresses} \qquad (3.2)$$

The true orientations of σ_{11}, σ_{22}, and σ_{33} in 3-dimensional space, independent of the orientation of the borehole, are calculated by solving the eigenvectors for each principal stress.

The same procedure is applied to the determinations of the degree of anisotropy, i.e. magnitude and orientation of the Young's modulus and Poisson's ratio and has been used to ascertain the principal stress directions for the P-wave velocity (Dight & Dyskin 2007, 2008).

Eigenvector analysis is then conducted (as described above) to determine the principal directions and the magnitudes of these quantities as shown in Figure 3-3 (Table C) in the analysis sheets.

3.4 *In situ* stress results from the DRA measurements

The results for the stress field obtained by combining all the sub-samples tested are presented in Figure 3-3. In this case, the maximum principal stress is interpreted to be orientated at 040° trend and 42° plunge with magnitude 26.8 MPa; the intermediate principal stress is oriented 303°/8° with a magnitude of 16.7 MPa; and the minimum principal stress at 204°/47° with a magnitude of 13.2 MPa. The results are shown in Table C in Figure 3-3.

Also shown in Table D in Figure 3-3 is the *k* factor. This is a factor used to provide the ratio of the mean horizontal stress to the mean vertical stress, i.e.

$$k = \{(\sigma_{xx} + \sigma_{yy})/2\}/\sigma_{zz} \quad (3.3)$$

3.5 Interpreting DRA results and discussion of the results obtained for the Olkiluoto cores

A consequence of measuring the modulus in six sub-directions is that it is possible to infer the anisotropy that may be inherent in the coarse crystalline material. Each sub-sample from the same orientation contains different percentages of quartz, feldspar and other minerals and these minerals, plus their configuration, control the modulus. The stress field in each sample should not be influenced by the contained mineral. However, and from previous experience, the stress field often does correlate with the high modulus direction. In this case, the modulus probably cannot be relied upon when determining the three principal stresses. The velocity is another supportive tool for examining the modulus and stress field. The P-wave velocity was also found to be highly anisotropic in the material. In addition to the modulus and P-wave velocity, the Poisson's ratio was measured.

Client	POSIVA Oy Olkiluoto									Phreatic surface	Vertical depth below surface
Table A	Hole ID	Easting	Northing	Collar RL	Hole length	Distance down hole	Azimuth	Plunge	Density		
							0	90.00	26.43		720.00

Table B	DRA set	Subset						Mean	Standard Deviation	Azimuth or trend	Plunge	Comments
		1	2	3	4	5	6					
	a	20	18.26	19.9				19.39	0.98	0	90	
	b	19.5	17	19.46				18.65	1.43	180	0	
	c	19	20	17.3				18.77	1.37	90	0	
	d	15	17.5	17				16.50	1.32	135	0	
	e	15	14	12				13.67	1.53	180	45	
	f	15.5	15	15				15.17	0.29	270	45	

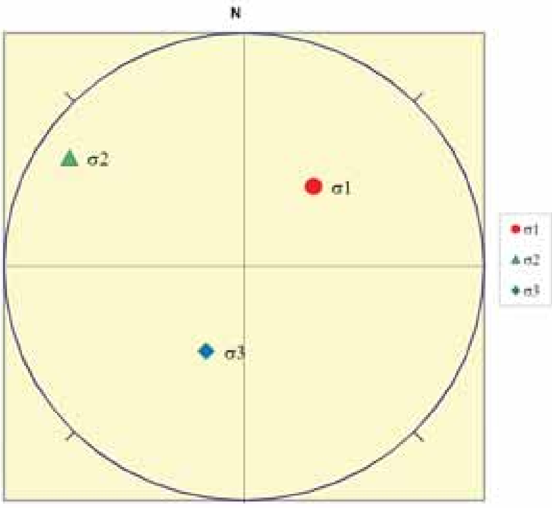
Table C

RESULTS

Stress	Trend	Plunge	MPa
σ_1	40.2	41.8	26.8
σ_2	302.7	8.4	16.7
σ_3	203.6	47.0	13.4
$\sigma_1 : \sigma_2 : \sigma_3$	2.01 : 1.25 : 1.00		

Can not deduce

Figure A



density	2.6	2.61	2.59	
	2.7	2.61	2.58	
	2.64	2.63	2.56	
	2.62	2.67	2.7	
	2.7	2.65	2.75	
	2.65	2.65	2.67	
Average				2.64

modulus	40.4	57.5	61.2	
	73.3	62.1	47.1	
	63.4	68.3	63.4	
	66.3	45.5	60.6	
	82.5	50.5	43.1	
	68.3	48	56.4	
Average				58.77

poisson's	0.208	0.181	0.205	
	0.194	0.235	0.275	
	0.223	0.202	0.237	
	0.169	0.188	0.218	
	0.191	0.157	0.272	
	0.179	0.191	0.189	
Average				0.21

Seismic	5312	5222	5808
	6046	5866	5287
	6128	5808	5432
	5488	5234	5757
	6511	556	5258
	5817	5622	5661

Stress	20	18.26	19.9
	19.5	17	19.46
	19	20	17.3
	15	17.5	17
	15	14	12
	15.5	15	15

Comparison between calculated overburden and vertical stress from DRA testing

Table D			
	Distance down hole		
	Overburden depth		720.00
	Overburden (MPa)		19.03
	DRA test	σ_z	19.4
		k	0.97

Table E		
	Phreatic surface	0
	Atmospheric head (m)	0
	Pressure (MPa)	0.00

Table F			Stress	Plunge	Trend	Shadow Trend°
With pore pressure		σ_z	19.39	90	0	0
		σ_{H1}	20.92	0	45.7	225.7
		σ_{H2}	16.50	0	135.7	315.7

Table G			Stress	Plunge	Trend	Shadow Trend°
Without pore pressure		σ_z	19.39	90	0	0
		σ_{H1}	20.92	0	45.7	225.7
		σ_{H2}	16.50	0	135.7	315.7

***Figure 3-3**. The integrated stress results from all the DRA tests. (Note that the depth of 720 m given in the sheet was estimated from the vertical stress estimate in Table D at the time of testing and is not the actual depth.)*

Other than the variation in stiffness and early stage deformation, if the rock core is taken from a block sample which was recovered near to an underground opening, an induced stress will be created in the sample, in particular having a high normal stress component parallel to the opening surface. This induced stress will leave its mark in the strain response and possibly mislead the DRA result. This phenomenon is suspected to be observed in the C orientation (90°/0°). The acoustic emission indicates no internal damage or bending (Figure 3-4), while the results indicate three possible inelastic points—around 10 MPa, 19 MPa and 25 MPa (Figure 3-5).

It is common that the DRA result can display more than one turning/inelastic point. However, in most cases the turning points, which are not related to *in situ* stress, also coincide with bursts of acoustic emission. These bursts or jumps are considered as related to microcracks which cannot represent a general deformation property of the whole sample and so the inelastic points coinciding with acoustic emission jumps should be ignored. In the case of the group C sub-samples, it was not certain that the 10 MPa is caused by early stage deformation, induced stress or *in situ* stress.

Using the *in situ* stresses determined by the DRA method, a preliminary stress analysis was undertaken to ascertain the impact of an opening on the induced stresses, noting that this study was done before knowing the actual geometry of the opening from which the cores were obtained. The results of these analyses are presented in Figures 3-6a (assuming a tunnel orientated approximately north south, and Figure 3-6b for a tunnel orientated approximately east-west). Both plots would suggest that, if a sample were recovered from the floor, then there would be a small influence on the core due to the induced stress. In the case of sample C, it is possible that both the *in situ* stress (mean 18.8 MPa) and the induced stress (25 MPa) can be observed in the strain difference curves.

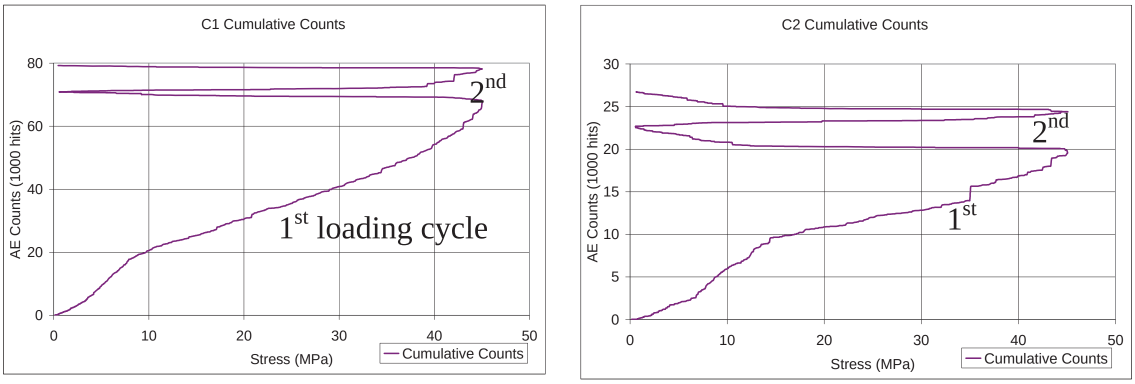


Figure 3-4. *The acoustic emission responses from sample C1 and C2; there is no obvious hit rate increase in the first loading cycle on both samples.*

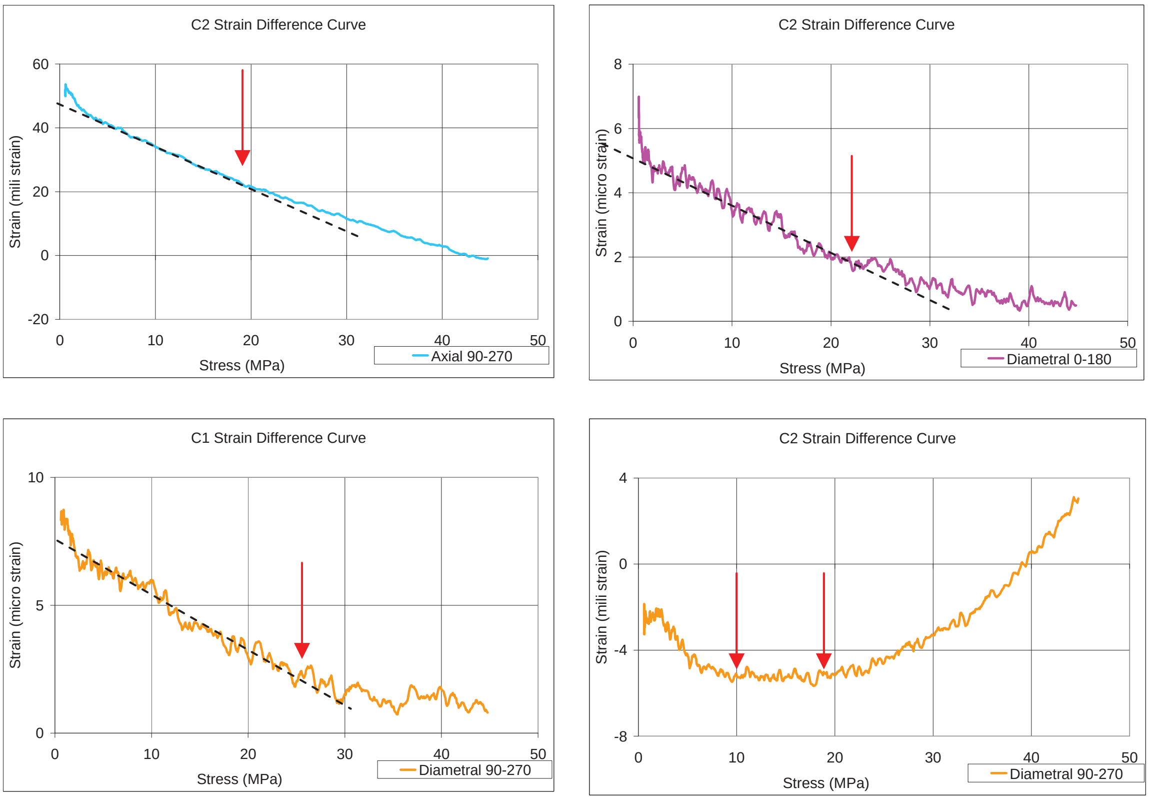


Figure 3-5. *The DRA responses from axial and lateral strain gauges of samples C1 and C2, all the graphs have the inflection points at/after 20 MPa and one has 2 inflection points: 10 MPa and 19 MPa. This compares well with the test result discussed later undertaken by Posiva where the C direction is σ_{xx} and should be 18.9 or 19.5 MPa.*

There is an alternative explanation for the higher inelastic turning point at 25 MPa: it might be created by the proximity of the stress level in the test to 70% UCS which would be above the crack initiation stress. That is the inelastic properties might arise from crack instead of in situ stress or the induced stress. Since early stage deformation usually occurs with increasing acoustic emission activity and, because the tests were blind, there was no information relating to induced stress, so it was considered that the inelastic point at 20 MPa is the *in situ* stress for sample group C.

The principal elastic moduli magnitudes and orientations are shown in Figure 3-7. Based on these results, the mean modulus is anisotropic (1.32:1). However the variability in the same direction is large and could have a significant effect on point samples for stress measurement (e.g. a CSIRO HI stress measurement conducted at 45° to the inferred stress direction).

The distribution of Poisson's ratio is presented in Figure 3-8. There is little variability in these results.

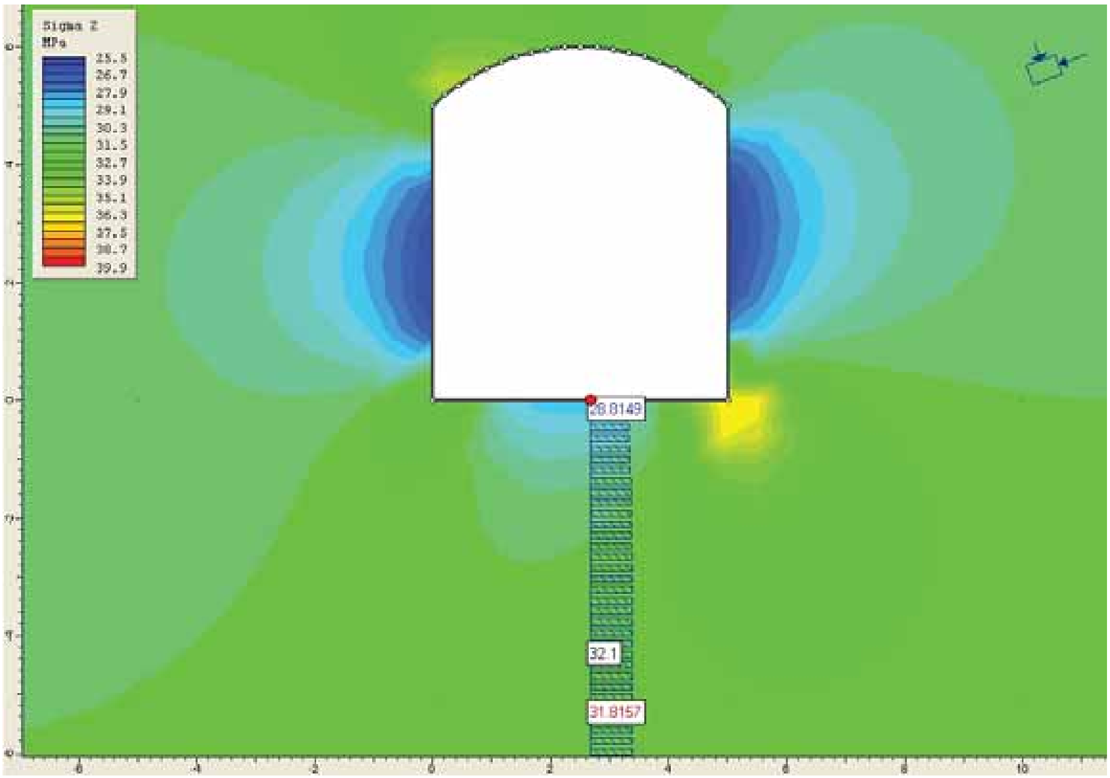


Figure 3-6a. *Stress distribution around a 5 m wide opening at NS direction, assuming that it oriented approximately north.*

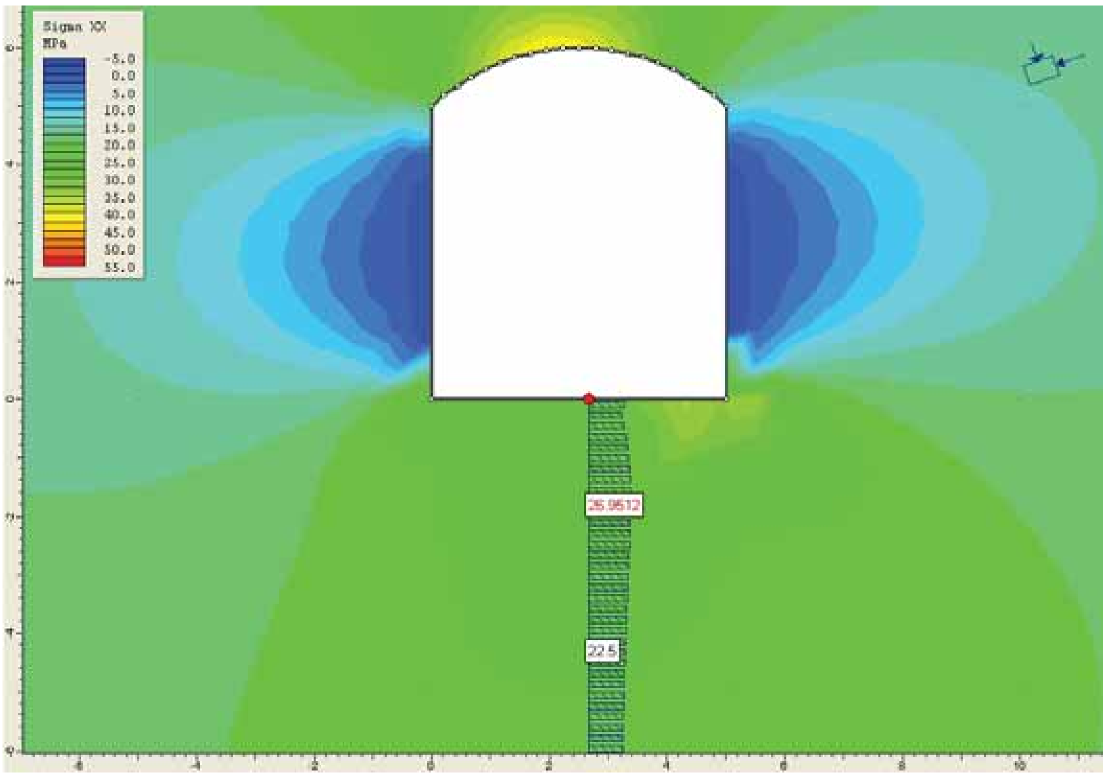


Figure 3-6b. *Stress distribution around a 5 m wide opening at EW direction, assuming that it oriented approximately south.*

An estimate of the stress field via the Kaiser Effect has also been undertaken, although with less certainty. The results are shown in Figure 3-9, with the values being higher than the DRA values. One possible reason for the KE emission is the induced stress in the core due to the process of sampling. The best way to examine this relation is using 3D stress analysis and examining the induced stress due to the *in situ* stress and the measured KE from the samples. This is shown in Figure 3-10. For ease of a generalised approach to the stress analysis using Examine3D, the results have been transformed into a horizontal plane.

The results suggest that there is a correlation between the KE measured results and the calculated results based on the estimated *in situ* stress.

Client	POSIVA Oy Olkiluoto									Phreatic surface	Vertical depth below collar
Table A	Hole ID	Easting	Northing	Collar RL	Hole length	Distance down hole	Azimuth	Plunge	Density		
							0	90.00	28.81		

Table B	DRA set	Subset						Mean	Standard Deviation	Azimuth or trend	Plunge	Comments
		1	2	3	4	5	6					
	a	40.4	57.5	61.2				53.03	11.10	0	90	
	b	73.3	62.1	47.1				60.83	13.15	180	0	
	c	63.4	68.3	63.4				65.03	2.83	90	0	
	d	66.3	45.5	60.6				57.47	10.75	135	0	
	e	82.5	50.5	43.1				58.70	20.94	180	45	
	f	68.3	48	56.4				57.57	10.20	270	45	

Table C

RESULTS

Modulus	Trend	Plunge	GPa
E1	55.7	0.8	68.8
E2	146.0	24.2	58.1
E3	323.9	65.7	52.0
$E_1:E_2:E_3$	1.32 : 1.12 : 1.00		
(E1+E2+E3)/3	60		

E	40.4	57.5	61.2	
	73.3	62.1	47.1	
	63.4	68.3	63.4	
	66.3	45.5	60.6	
	82.5	50.5	43.1	
	68.3	48	56.4	
E-Average		58.8		
E SD		11.3		

Figure A

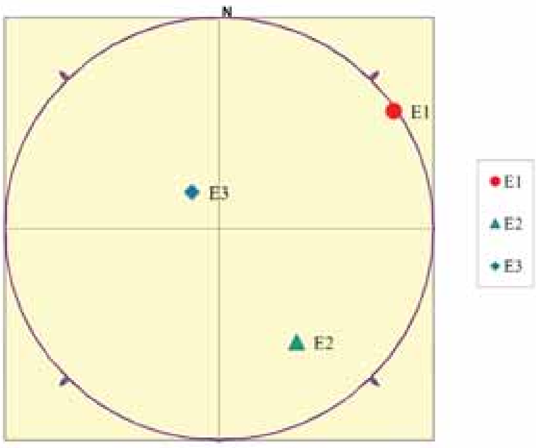


***Figure 3-7**. Principal elastic moduli magnitudes and orientations for the sub-core samples. Note the high standard deviation, indicating large variability in the same direction.*

Client	POSIVA Oy Olkiluoto									Phreatic surface	Vertical depth below collar
Table A	Hole ID	Easting	Northing	Collar RL	Hole length	Distance down hole	Azimuth	Plunge	Density		
							0	90.00	28.81		

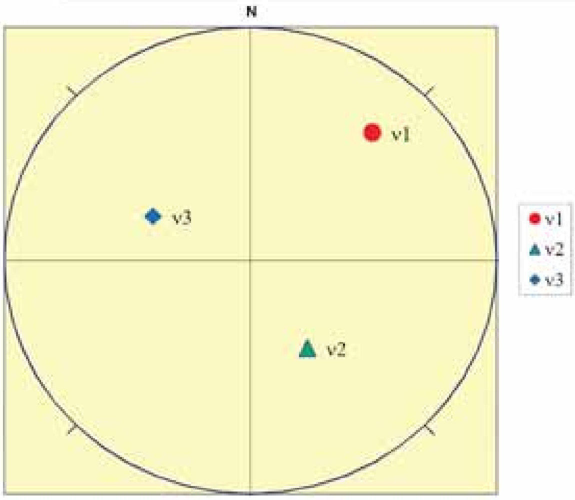
Table B	DRA set	Subset						Mean	Standard Deviation	Azimuth or trend	Plunge	Comments
		1	2	3	4	5	6					
	a	0.208	0.181	0.205				0.20	0.01	0	90	
	b	0.194	0.235	0.275				0.23	0.04	180	0	
	c	0.223	0.202	0.237				0.22	0.02	90	0	
	d	0.169	0.188	0.218				0.19	0.02	135	0	
	e	0.191	0.157	0.272				0.21	0.06	180	45	
	f	0.179	0.191	0.189				0.19	0.01	270	45	

Table C

RESULTS

	Trend	Plunge	Poissons Ratio
v1	42.1	17.2	0.27
v2	148.4	42.4	0.20
v3	295.5	42.6	0.18
$v_1:v_2:v_3$	1.51 : 1.12 : 1.00		
(v1+v2+v3)/3	0.22		

Figure A



v				
	0.208	0.181	0.205	
	0.194	0.235	0.275	
	0.223	0.202	0.237	
	0.169	0.188	0.218	
	0.191	0.157	0.272	
	0.179	0.191	0.189	
Average		0.21		
ST -Dev		0.03		

Figure 3-8. *The magnitudes and orientations of the principal values of Poisson's ratio for the sub-core samples.*

Client	Finland - Olkiluoto									Phreatic surface	Vertical depth below surface
Table A	Hole ID	Easting	Northing	Collar RL	Hole length	Distance down hole	Azimuth	Plunge	Density		
									28.80		1050.00

Table B	DRA set	Subset						Mean	Standard Deviation	Azimuth or trend	Plunge	Comments
		1	2	3	4	5	6					
	a	30	34	27				30.33	3.51	0	90	
	b		29.2	29.5				29.35	0.21	180	0	
	c			28				28.00	#DIV/0!	45	0	
	d	28.5		27.9				28.20	0.42	135	0	
	e	39.7	34	33				35.57	3.61	180	45	
	f			20				20.00	#DIV/0!	270	45	

Table C

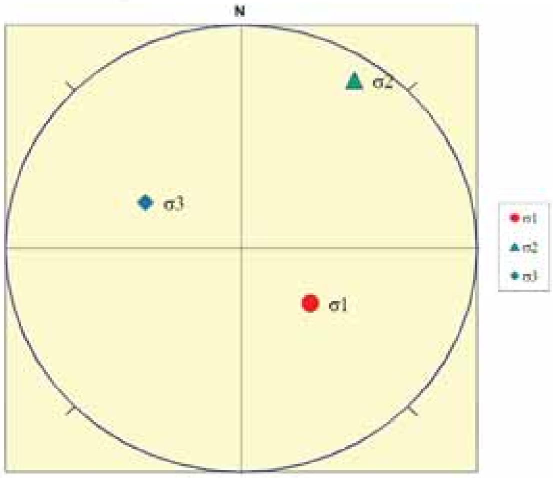
RESULTS

Stress	Trend	Plunge	MPa
σ1	129.9	48.3	39.5
σ2	32.5	6.5	28.5
σ3	296.8	41.0	18.5
$\sigma_1:\sigma_2:\sigma_3$	2.13 : 1.54 : 1.00		

Can not deduce

30.24
30.33

Figure A



density	2.9	2.9	2.84	
	2.93	2.88	2.83	
	2.9	2.93	2.79	
	2.9	2.87	2.83	
	2.9	2.93	2.85	
	2.91	2.91	2.84	
Average				2.88

modulus	40.4	57.5	61.2	
	73.3	62.1	47.1	
	63.4	68.3	63.4	
	66.3	45.5	60.6	
	82.5	50.5	43.1	
	68.3	48	56.4	
Average				58.77

poisson's ratio	0.208	0.181	0.205	
	0.194	0.235	0.275	
	0.223	0.202	0.237	
	0.169	0.188	0.218	
	0.191	0.157	0.272	
	0.179	0.191	0.189	
Average				0.21

Seismic	5312	5222	5808
	6046	5866	5287
	6128	5808	5432
	5488	5234	5757
	6511	556	5258
	5817	5622	5661

Comparison between calculated overburden and vertical stress from DRA testing

Table D	Distance down hole		
	Overburden depth		1050.00
	Overburden (MPa)		30.24
	DRA test	σ_z	30.3
		k	0.93

Figure 3-9*. The principal stress magnitudes and directions estimated by the Kaiser Effect method. The equivalent overburden would be approximately 1050 m and this did not seem possible.*

Calculated from 3D Stress Analysis				Measured Kaiser Effect				Measured Insitu Stress			
Stress	dip dirn	dip	MPa	Stress	trend	plunge	MPa	Stress	Trend	Plunge	MPa
σ1	43	31	49.5	σ1	37.0	21.0	40.2	σ1	216.0	35.0	26.8
σ2	275	45	22.3	σ2	268.0	60.0	29.4	σ2	99.0	32.0	16.7
σ3	152	28	17.5	σ3	135.0	21.0	18.3	σ3	340.0	39.0	13.4

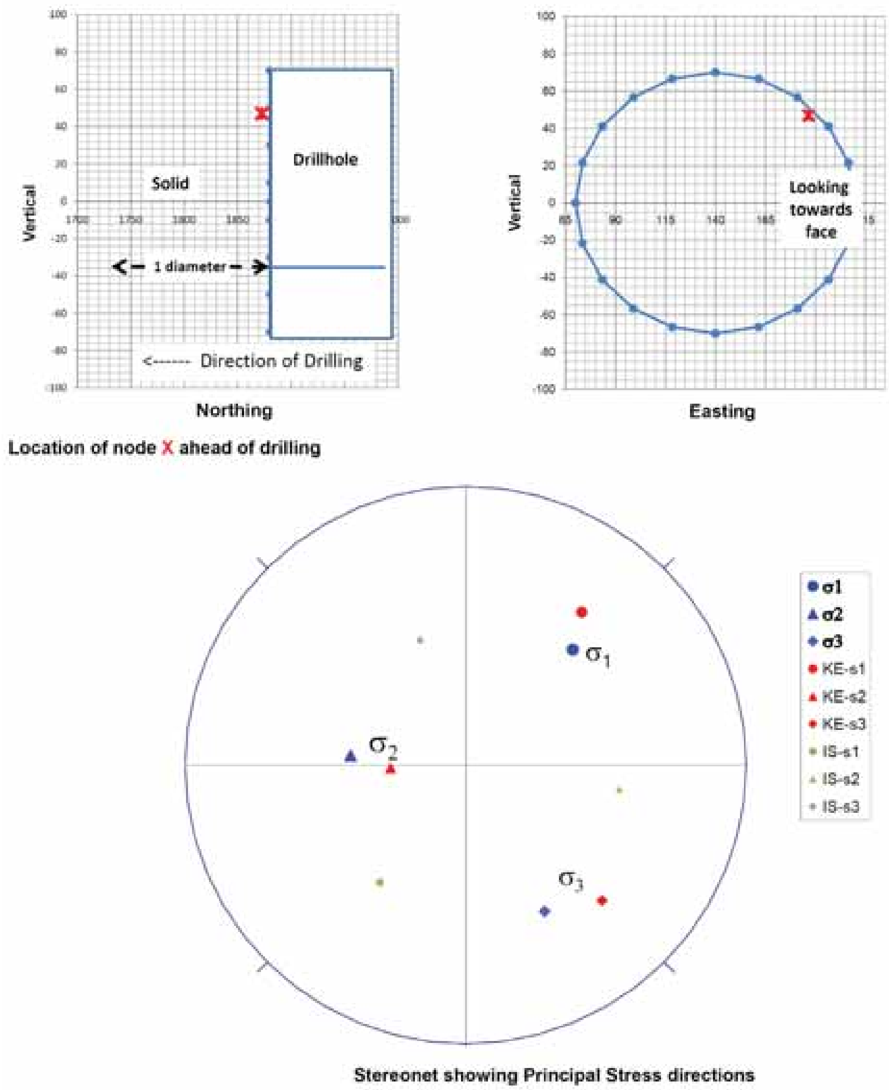


Figure 3-10. *Matrix analysis considering the stresses created ahead of the drilling/coring face, which result in overstress sometimes being registered in the core. In this case, the relation between the overstress orientation created by the* in situ *stress and the measured KE effect are similar. Note that, for presentational purposes, the stresses have been rotated to an equivalent horizontal hole to suit the Examine3D software grids.*

4 COMPARISON OF THE DRA RESULTS AND THE KNOWN STRESS STATE AT OLKILUOTO

The stress state in the Olkiluoto rock mass around the ONKALO has been measured by a variety of techniques (Posiva 2009, Posiva 2011) and varies with location. However, the stress measurement shown in Figure 4-1 and associated numerical stress modelling indicates that the rock stresses are rather scattered near the surface; whereas, at the deeper levels, where there are less fractures and these are subject to a higher closing stress, the stress field is more stable and in line with the NW-SE direction of the Scandinavian regional stress. Thus, in Figure 4-1, we can consider the stereograms in the left column and the one in the centre of the top row as being indicative of the stress field at the location where the cores were taken. These indicate a NW-SE direction for the major principal stress which is in agreement with the regional trends. The figure in the lower left corner was undertaken at exactly the same location as the DRA test.

The orientation of the major principal stress as determined from DRA and as shown in Figure 4.2 (i.e. NE-SW) is therefore not in agreement with the ONKALO measurements at that depth, and in fact it is off by almost ~90°, which is the maximum error possible. However when compared to the results for the niche (EDZ -345) it is 49° off. Despite this, the principal stress magnitudes are more in line with the known stress field. The magnitudes at the 340-350 m in the ONKALO are 23–35 MPa for major principal stress (Figure 4-1); whereas, the DRA method indicated 27 MPa and the KE method 40 MPa.

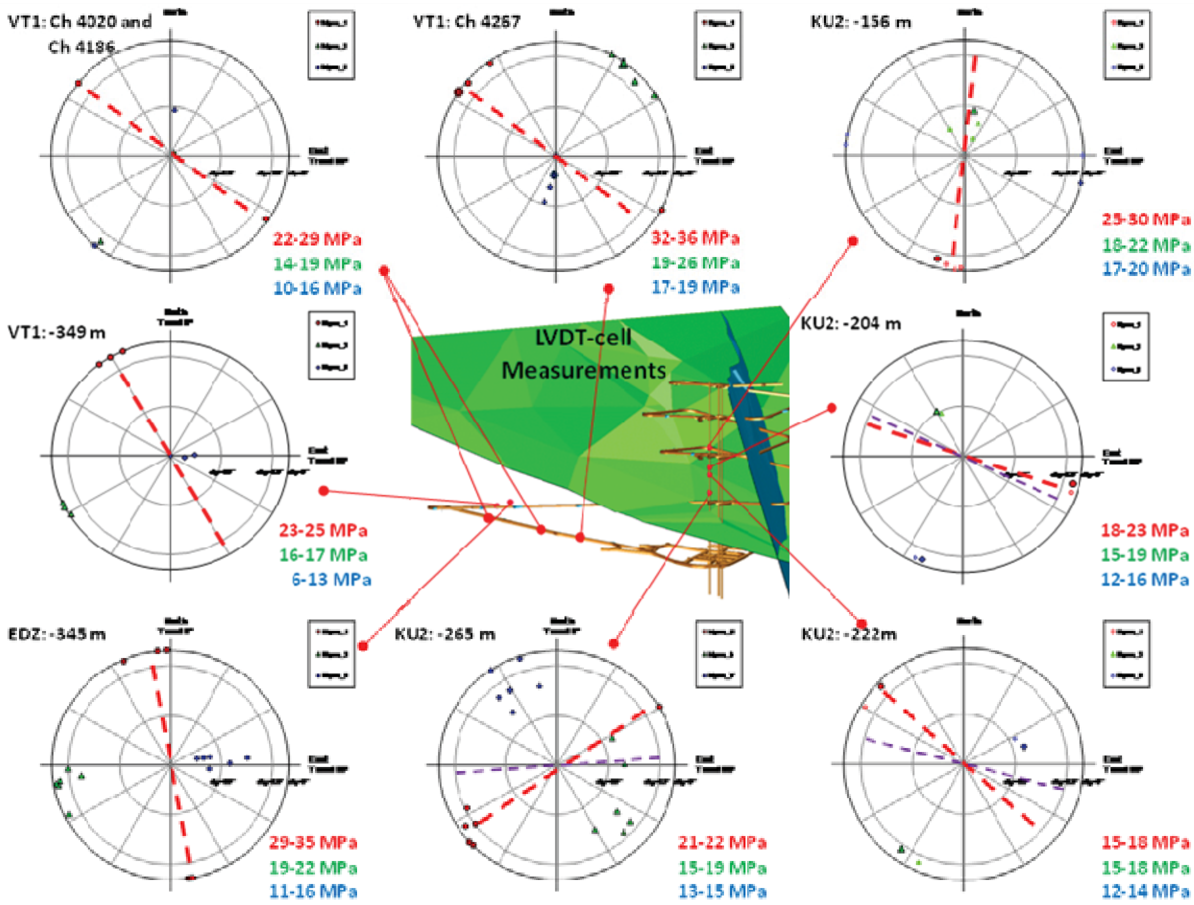


Figure 4-1. *Summary of stress measurements made in the ONKALO. Note that EDZ-345 is the location where the DRA samples were taken (Posiva 2011).*

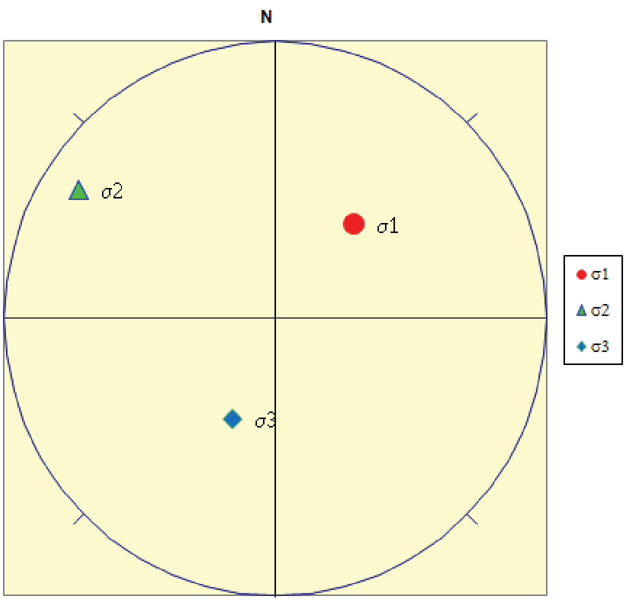


Figure 4-2. *Orientation of the principal stresses as determined by the DRA blind test.*

5 CONCLUSIONS

5.1 Overall conclusion

The DRA testing programme in Olkiluoto has produced conflicting results to the general trend expected which is predominantly NW-SE. On the one hand, the orientation of the maximum principal stress is out by 49° for the similar result in the niche EDZ-345; on the other hand, the magnitudes of the principal stresses are in the range that we would expect at this depth. This second result does indicate that the DRA results do have value. After all, the blind testing could have been supplied with cores near the surface where the principal stresses would have been much lower and one of them would have been close to zero.

Comparison of the DRA results with the stresses around the POSE niche is compounded by the fact that the latter are not known with certainty. The stress measurements in the ONLALO have been characterised by considerable scatter so the exact stress field is unknown.

However, the DRA results are encouraging and do provide an extra tool in the stress measurement toolkit. Moreover, the reliability of such DRA testing would be enhanced by the use of more site information, as explained in the next section.

5.2 Further information that would help such blind/non-blind DRA tests

To provide a more reasoned assessment of the estimated *in situ* stress results, the following information would be helpful.

- Sample depth below surface.
- Geological maps showing the location of any major faults or shear zones, plus the lithological boundaries.
- A DIPS file of structural mapping data showing the orientation and defect type.
- The size and orientation of the underground opening from which the original cores were obtained.
- Depth below the excavation floor from which the original cores were obtained.
- Time from core drilling to testing.

Once there is confidence in the principal stress orientations, further original cores could be sub-sampled in the principal stress directions to see if the results were confirmed.

REFERENCES AND BIBLIOGRAPHY

Amadei, B. 1996. Importance of anisotropy when estimating and measuring *In situ* stresses in rock. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr*. Vol 33, No 3, pp 293-325.

Amadei, B. & Stephansson, O. 1997. *Rock Stress and its Measurement*. Chapman & Hall, London, 1997, 490p.

Dight, P.M. 2006. Determination of in situ stress from oriented core. *Proc. Int. Symp. on In-situ Rock Stress*, Trondheim, Norway, June 19-21.

Dight, P.M. 2009. DRA Testing For GoldFields Agnew Mine. Australian Centre for Geomechanics Report.

Dight, P.M. & Bogacz, W. 2009. The application of a deposit tectogenesis in pit slope geotechnical engineering: A case example**.** *Proc. Int. Symp. on Rock Slope Stability in Open Pit and Civil Engineering,* 7-8 November 2009 Santiago Chile.

Dight, P.M. & Dyskin, A. 2007. Accounting for the Effect of Rock Mass Anisotropy in Stress Measurements.

Dight, P.M. & Dyskin, A. 2008. On the Determination of Rock Anisotropy for Stress Measurements SHIRMS – Y. Potvin, J. Carter, A. Dyskin, R. Jeffrey (eds).

Dight, P.M. & Synman, L. 2010. Stress Measurement for St Barbara Mines Gwalia Deeps Project – one of the world's deepest underground haulage mines. *Pre-print for publication at the 5th International Seminar on Deep and High Stress,* Santiago Chile 6th to 8th October 2010.

Jaeger, J.C., Cook, N.G.W. & Zimmerman, R.W. 2007. Fundamentals of Rock Mechanics. 4th Edn. Blackwell, Oxford, (1st Edn. Jaeger and Cook, 1969) 2007. 475p.

Goodman, R.E. 1963. Sub-audible noise during compression of rocks. Bull. Geol. Soc. Am. 74:487-490.

Hakala, M., Kuula, H. & Hudson, J. 2007. Estimating the transversely isotropic elastic intact rock properties for *in situ* stress measurement data reduction: A case study of the Olkiuoto mica gneiss, Finland. *Int. J. Rock Mech. Min. Sci*. Vol 44, pp 14-46.

Hakala, M., Sjöberg, J., Hudson, J., Christiansson, R., Johansson, E. & Riikonen S. 2006. Quality control and interpretation of *in situ* stress measurement data. *Proc. Int. Symp. on In-situ Rock Stress*, Trondheim, Norway, June 19-21.

Hudson, J.A. & Feng, X.-T. 2010. Variability of *in situ* stress. In F. Xie (Ed.), *Proceedings Rock Stress and Earthquakes*. Taylor & Francis, London.

IJRMMS 2003. Special Issue on Rock Stress Estimation. *Int. J. Rock Mech. Min. Sci.*

Kaiser, J. 1950. An investigation into the occurrence of noises in tensile tests or a study of acoustic phenomena in tensile tests. PhD thesis, Tech Hochsch. Munchen, Munich.

Kaiser, J. 1953. Erkenntnisse und Folgerungen aus der Messung von Gerauschen bei Zugbeanspruchung von metallischen Werstoffen. Archiv Eisenhuttenwesen. 24:43-45.

Kurita, K. & Fujii, N. 1979. Stress memory of crystalline rocks in acoustic emission. *Geophys. Res. Lett.* 6:9-12.

Lavrov, A. 2002. The Kaiser effect in rocks: principles and stress estimation techniques. *Int. Jn Rock Mech. Min. Sci*. 40:151-171.

Lehtonen, A.V. & Särkkä, P. 2006. Evaluation of rock stress estimation by the Kaiser effect. *Proc. Int. Symp. on In-situ Rock Stress*, Trondheim, Norway, June 19-21.

Lehtonen, A.V., Cosgrove, J.W., Hudson J.A. & Johansson, E. 2011. An Examination of In Situ Rock Stress Estimation Using the Kaiser Effect. Submitted to Engineering Geology.

Li, Y. & Schmitt D.R. 1998. Drilling-induced core fractures and in situ stress. *Journal of Geophysical Research*, Vol 103 No.B3 pp 5225-5239

Lim, S.S., Martin, C.D. & Christiansson, R. 2006. Estimating in-situ stress magnitude from core disking. *Proc. Int. Symp. on In-situ Rock Stress*, Trondheim, Norway, June 19-21.

Markland, J. 1974. The analysis of principal components of orientation data. *Int. Jn Rock Mech. Min. Sci.* 11:157-163.

Martin, C.D & Christiansson, R. 1991. Overcoring in highly stressed granite – The influence of microcracking. *Int J Rock Mech Min Sci Geomech Abstr*; 28(1):53–70.

Posiva 2009. Olkiluoto Site Description 2008. POSIVA Report 2009-01. Posiva Oy, Olkiluoto.

Posiva 2011. Olkiluoto Site Description 2010. POSIVA Report 2011-xx. Posiva Oy, Olkiluoto. (in preparation)

Tang, C.A. & Hudson, J.A. 2010. *Rock Failure Mechanisms—Explained and Illustrated.* Taylor & Francis, London, 2010, 322p.

Villaescusa, E., Windsor, C., Li, J., Baird, G. & Seto, M. 2003. Stress measurements from cored rock. MERIWA Report M329.

Windsor, C. R., Villaescusa, E. & Machuca, L.A. 2010. A comparison of rock stresses measured by WASM AE with results from other techniques that measure the complete rock stress tensor. In F. Xie (Ed.), *Proceedings Rock Stress and Earthquakes*. Taylor & Francis, London, pp. 211–216.

Xie, F. (Ed.) 2010. Rock Stress and Earthquakes. *Proc. 5th Int. Symp. on In-Situ Rock Stress (ISRS-V)*. Beijing, China, Taylor & Francis, London, 2010, 877p.

Yamamoto, K., Kuwahara, Y., Kato, N. & Hirasawa, T. 1990. Deformation rate analysis: a new method for in-situ stress estimation from inelastic deformation of rock samples under uniaxial compression. Tohoku Geophysical J., 33:1-13.

Zang, A. & Stephansson, O. 2010. *Stress Field of the Earth's Crust*. Springer, 2010, 322p.