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Äspö Hard Rock Laboratory

Determination of the Degree of Anisotropy on Cores from Äspö HRL

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Preface

This report is a continuation of the work performed in the Master's thesis performed by the author. In the thesis it was concluded that anisotropy could be detected by diametrical measurements of the p-wave velocity on rock cores. When SKB performed stress measurements in the Äspö Hard Rock Laboratory (Äspö HRL) area, it was decided that the investigated method should be used on the cores received. This report comprises the results from the measurements performed on the cores and a discussion on how large the degree of anisotropy has to be in order to affect the results of stress measurements.

During the work with this report the following people have made contributions: Thomas Janson (Golder Associates AB), Rolf Christiansson (SKB) and Erling Nordlund (LTU).

I am also thankful to Meirion Hughes (LTU) for correcting my spelling.

Andreas Eitzenberger

Abstract

AECL has, on a commission from SKB, performed stress measurements with a method called doorstopper, between May and June 2001, in two boreholes at Äspö HRL; one vertical and one horizontal. During the interpretations of the measurements, results that varied with direction were observed. If a property varies with direction, it is an indication that the rock might be anisotropic. In order to determine if that was the case, diametrical measurements of longitudinal (p-) wave velocity were conducted. The results of these measurements are presented in this report.

It has been found that the p-wave velocity varies depending on the angular position along the circumference of the core. The orientations of the maximum and minimum p-wave velocities were perpendicular to each other for most of the cores, indicating that the rock is transversally isotropic.

The degree of anisotropy for the cores from the horizontal borehole, calculated from p-wave velocities, varies between 1.06 and 1.11 (1.14 and 1.23 for Young's modulus). The difference in velocities for the cores from the vertical borehole indicates that the rock is generally isotropic, i.e. the anisotropy cannot be treated as planes perpendicular to one another. For these cores, the degree of anisotropy varies between 1.01 and 1.08 (1.02 and 1.18 for Young's modulus).

The velocity was measured near the edge and at the middle of the core. The velocities measured at the edge are not the same as the velocities at the middle. Also the degree of anisotropy differs between the edge and the middle. The differences are believed to be caused by either structural differences or by damage in some way during the drilling of the holes. The anisotropy found in the rock cores is normal for this rock type and too small to have any serious effect on the interpretation of the stress measurements.

Through a literature review it has been found that the degree of anisotropy, calculated with Young's modulus, has to be larger than 1.3 – 1.5 in order to have serious effects on the results of the stress measurements. If the anisotropy is smaller, the measurement errors of the stress measurement method will be the main parameter affecting the reliability of the results.

Sammanfattning

På uppdrag av SKB har AECL, Kanada, utfört bergspänningsmätningar i två borrhål, ett vertikalt och ett horisontellt, i Äspö HRL, mellan maj och juni 2001. Mätningarna är utförda med den så kallade Doorstopper metoden. Resultaten från mätningarna har visat att en variation i bergmassans egenskaper förekommer beroende på riktning (borrhålsriktning och mätorientering). Detta skulle indikera på en anisotropi i bergmassan. För att klargöra om anisotropi förekommer eller ej har P-vågsmätningar utförts diametralt runt de överborrade kärnorna. Resultaten från dessa mätningar presenteras i denna rapport.

Med hjälp av P-vågens hastighet, som mätts diametralt kärnan och i samma tvärsnitt, kan en uppfattning fås av kärnans grad av anisotropi, genom att jämföra resultaten från mätpunkt till mätpunkt runt kärnan.

Graden av anisotropi, förhållandet mellan största och minsta P-vågshastighet, för kärnorna i det horisontella borrhålet varierar mellan 1.06 och 1.11 eller mellan 1.14 och 1.23 för motsvarande E-moduler baserad på hastigheten. Orienteringen mellan största och minsta P-vågshastighet är för de flesta kärnorna 90 grader, dvs vinkelrät varandra. Detta indicerar att det intakta berget har en transversell isotropi. För det vertikala borrhålet varierar P-vågshastigheten mindre, förhållandet mellan största och minsta är mellan 1.01 och 1.08 eller 1.02 och 1.18 för motsvarande E-moduler. Detta indikerar att det intakta berget är mer isotropt i det vertikala hålet jämfört med det horisontella.

Två mätsnitt tvärs kärnorna är gjorda, ett nära änden av kärnan och ett i mitten av kärnan. Resultaten mellan de två snitten är inte lika, vilket visar att anisotropin varierar beroende på om mättningen är nära änden eller inte. Skillnaderna mellan tvärsnitten är orsakade av antingen geologiska karaktär eller av skador i samband med borrning/bearbetning av kärnänden (hålbotten innan överborrningen görs).

Den uppmätta anisotropin är vad som kan förväntas för dessa bergarter enligt tidigare erfarenheter (Amadei & Stephansson, 1997 m.fl.) och är för små för att påverka resultaten från spänningsmätningarna. Enligt litteraturgenomgång skall anistropin vara större än 1.3 till 1.5, mätt mellan största och minsta E-modul, för att resultaten från spänningsmätningarna behöver justeras.

Content

1 Introduction

1.1 Background

Swedish Nuclear and Waste Management Company (SKB) has been conducting stress measurements in the Äspö HRL area. The stress measurements have been performed in one vertical and one horizontal borehole (Janson and Stigsson, 2002). A method called doorstopper has been used to conduct the stress measurements. Only 4 out of 13 stress measurements performed in the vertical hole, and 3 out of 8 in the horizontal hole, succeeded. SwedPower also performed stress measurements in the horizontal hole, and they succeeded in 3 out of 4 with their triaxial cell. Also the strain, measured with the doorstopper, was unreasonably large. These two observations were believed to be caused by microcracks in the bottom of the drill hole. Another observation was that the evaluation of the data from biaxial tests, performed on the cores from the stress measurements, gave properties that differed depending on direction. The difference of properties, depending on direction, may depend on anisotropy of the rock mass, i.e. having different elastic properties in different directions. If the rock, in which stress measurements are conducted, is anisotropic, other theories have to be used to evaluate the stresses.

1.2 Objectives

The main objective is to determine if the rock cores, received during the stress measurements by the Deep Doorstopper Gauge (DDSG), are anisotropic. If the measurements show that the rock is anisotropic, the degree of anisotropy has to be determined. This is investigated by diametrical measurements of p-wave velocity. The second objective is to determine how large the degree of anisotropy has to be to affect stress measurements. This study is only based on literature concerning this matter. The third objective is to determine, if possible, if there is any difference between the velocities measured near the edge of the core compared with the velocities measured farther up the core. If this is the case, microcracks might be present.

1.3 Outline of the report

Chapter 2 comprises a short review of the areas concerning the scope of this report. Introductions are given about stress measurements, the doorstopper method, anisotropy and how it affects stress measurements.

Chapter 3 describes the test method used to conduct the p-wave velocity measurements. It is also explained how and why the measurements are conducted.

Chapter 4 presents the results from the p-wave velocity. The results from each of the two boreholes are presented in different sections.

Chapter 5 discusses the result obtained in Chapter 4. The conclusions that can be drawn from the result and discussion are summarized.

2 Literature review

2.1 Stress measurements

The properties of the rock mass have to be known to be able to do a design of a rock construction. Properties that are of great importance for the design in rock, and therefore important to know, are e.g. the rock types involved, the shape and orientation of joints, the strength of the rock and the *in situ* stress. To gain information about the *in situ* stresses prevailing in the bedrock, measurements have to be performed. There are many methods that can be used to measure the *in situ* stresses, but here only doorstopper is described, since it has been used during some of the stress measurements performed in Äspö HRL. For more information about other methods, see Amadei and Stephansson (1997)

2.1.1 Doorstopper

The measurements performed in this study are conducted on cores received from stress measurements in the Äspö HRL area. SKB has drilled according to an international standard called HQ-3. This gives the hole a diameter of 96 mm and the core a diameter of about 61.1 mm. The borehole is drilled into the rock mass until it reaches the area in which stress measurements are to be performed, the bottom of the hole is thereafter flattened and polished, see Figure 2-1 (Amadei and Stephansson, 1997). The doorstopper is glued onto the bottom of the hole. Two hours later, when the glue has dried, a zero reading is made. The drilling continues past the doorstopper and the rock is stress reliefed. Continuous readings are made and the stresses are determined from the strain measurements.

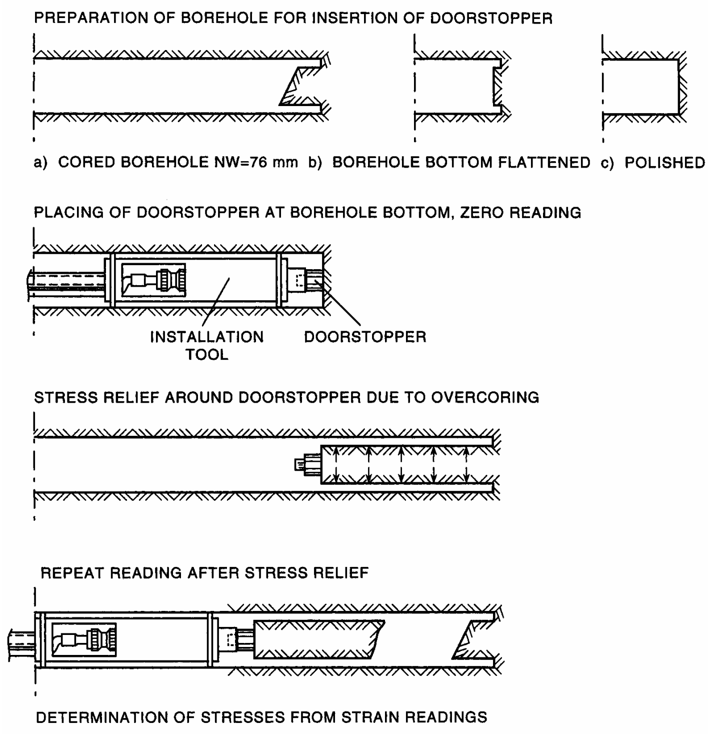


Figure 2-1. *The steps involved during stress measurements with the doorstopper method (Amadei and Stephansson, 1997).*

2.2 Anisotropy

A large amount of the rocks that are present in the earth upper crust, are anisotropic i.e. have different properties in different directions. This anisotropy is caused by, for instance, bedding, stratification, foliation, layering or jointing. These differences result in rock properties (physical, dynamic and mechanical) that differ with orientation. The range over which anisotropy may occur is large; from an intact specimen to the entire rock mass (Amadei, 1996).

The anisotropy is, for mathematical simplicity, often modelled as hexagonal (transversely isotropic) or orthorhombic (orthotropic) (Lekhnitskii, 1981). For the case when the rock has one axis of elastic symmetry of rotation, the rock is said to be transversely isotropic (Figure 2-2a). This is the simplest case of anisotropy and is often used to model e.g. gneisses, sandstones and basalts (Amadei, 1996). When there are three planes of elastic symmetry, the rock is said to be orthotropic (Figure 2-2b). This is used to model gneisses, granites and sandstones (Amadei, 1996). The planes of anisotropy are assumed to be parallel to the foliation or bedding planes. When the rock mass is cut by a single joint set, the rock mass can be modelled as transversely isotropic. If there are three sets of joints the rock mass can be modelled as orthotropic.

Figure 2-2. *Two specimens that show a) transverse isotropy and b) orthotropy.*

The coefficient or degree of anisotropy, k_E, is often defined as the ratio between the maximum, E, and the minimum, E', i.e. Young's modulus

$$k_E = \frac{E}{E'} . \tag{2.1}$$

Worotnicki (1993) has reviewed over 200 static and dynamic tests, and summarized the result by dividing the anisotropy into four groups: (1) quartzfeldspathic rocks (e.g. granites, quartz and arcose sandstones, granulates and gneisses), (2) basic/lithic rocks (e.g. basalt, lithic and greywacke sandstones and amphibolates), (3) pelithic clay and peltic micaceous rocks (e.g. mudstone, slates, phyllits and schists), and (4) carbonate rocks (e.g. limestones, marbles and dolomites). He concluded that for the quartzfeldspathic rock, the ratio E/E' is below 1.3 for 70 % of the cases, below 1.5 for 80 % and that there are only 3 % that have a ratio greater than 2. The carbonate rocks showed an intermediate degree of anisotropy, never exceeding 1.7. The group of rocks showing the highest degree of anisotropy is the pelitic clay and pelitic micaceous; only 33 % of the rocks analysed had a degree of anisotropy below 1.5, and only 50 % below 2.

The coefficient or degree of anisotropy can also be determined by the use of p-waves, propagating in different directions, usually perpendicular to one another. The degree of anisotropy, k_c, is defined as the ratio between the highest, c, and the lowest, c', velocities

$$k_c = \frac{c}{c'} . \tag{2.2}$$

The degree of anisotropy, determined with elastic wave velocity, varies between 1.0 and 1.44 for various rock types. Table 2-1 shows the degree of anisotropy for some rock types.

Table 2-1. Coefficient of anisotropy for various rocks (after Lama and Vutukuri, 1978).

Type of Rock	k_c
Sandstone	1.00
Gneiss, N.Y.	1.20
Gneiss, Mass.	1.27
Granodiorite gneiss	1.33
Lorraine shale	1.40
Green river rich shale	1.42
Chlorite schist	1.44

The degree of anisotropy determined by using Young's modulus differs from the ratio determined with the use of p-wave velocity. Young's modulus (dynamic), E_d, can be calculated, if the p-wave velocity, c_p, is known, using the relation (Goodman, 1989)

$$E_d = \frac{(1-2\nu)(1+\nu)}{(1-\nu)} \rho\, c_p^2 \tag{2.3}$$

where ρ is the density and ν is Poisson's ratio of the material in which the wave propagates. The density of the material does not change due to anisotropy Poisson's ratio does. If we however assume that Poisson's ratio is constant, then Young's modulus is a function only of the velocity and the relation between the two coefficients of anisotropy is $k_E = k_c^2$. See Table 2-2 below for more values. It can be seen that if the degree of anisotropy, determined with p-wave velocity, is 30 %, the anisotropy determined with the use of Young's modulus is 70 %.

Table 2-2. Relation between the coefficients of anisotropy (2.1) and (2.2).

E/E'	c/c'
1.00	1.00
1.05	1.02
1.10	1.05
1.20	1.10
1.30	1.14
1.40	1.18
1.50	1.22
1.70	1.30
2.00	1.41
2.50	1.58
3.00	1.73

2.3 The effect of anisotropy on stress measurements

The ratio, k_E, is used to determine if the rock is anisotropic or not (Amadei, 1996; Amadei and Stephansson, 1997, Rahn, 1984; Worotnicki, 1993). It is common to use an isotropic solution and an average value of Young's modulus [usually $E_{av} = 0.5(E + E')$] when analysing the stress measurements performed in anisotropic rock (Worotnicki, 1993). Measurements with a CSIRO HI cell, evaluated using an average Young's modulus usually give acceptable errors. The use of an average Young's modulus compensates for the anisotropy present. According to Worotnicki (1993), the errors will be intolerably high when the $k_E = E / E'$ ratio exceeds 1.3 to 1.5 (depending on the anisotropy of the shear modulus). This is valid if the borehole is parallel to the plane of isotropy. If the borehole is normal to the plane of anisotropy, the errors are smaller.

Amadei (1996) made a numerical example for a CSIR strain cell. The plane of anisotropy was parallel to the borehole and the elastic parameters were E = 35 GPa and G = 14 GPa. The ratio of E / E' was taken equal to 1, 1.5, 2 or 3. The ratio G / G' was taken equal to 1 or 2. Poisson's ratio, ν, was taken equal to 0.25 for the isotropic case and 0.27 for the anisotropic case. The results from the analyses are presented in Table 2-3.

Table 2-3. Magnitude of the three *in situ* stresses (MPa) for different anisotropic conditions (after Amadei, 1996).

	G/G' = 1				*G/G'* = 2			
	E/E' = 1	*E/E'* = 1.5	*E/E'* = 2	*E/E'* = 3	*E/E'* = 1	*E/E'* = 1.5	*E/E'* = 2	*E/E'* = 3
σ_1	3.83	3.87	3.93	4.14	3.04	3.08	3.15	3.34
σ_2	3.07	3.26	3.42	3.78	2.57	2.65	2.74	2.93
σ_3	0.24	0.32	0.38	0.51	0.33	0.37	0.41	0.48

It can be seen that the *magnitude* of the *in situ* stresses changes when the anisotropy increases (Amadei, 1996). For the cases where E / E' = 1.5 the error in σ_1, σ_2 and σ_3, compared to the isotropic solution, is 1, 6 and 33 %, respectively. When the ratio E / E' = 3 the errors in σ_1, σ_2 and σ_3, compared to the isotropic solution, are 8, 23 and 123 %, respectively. Also the *orientation* of the principle stresses is different for isotropic and anisotropic solutions (see Figure 2-3). It can bee seen that both σ_1 and σ_2 rotate as the ratio E / E' increases. The maximum error, if anisotropy is neglected, is 15° for the bearing of σ_1, 18° for σ_2 and 3° σ_3. The orientation of σ_3 is not affected by rock anisotropy.

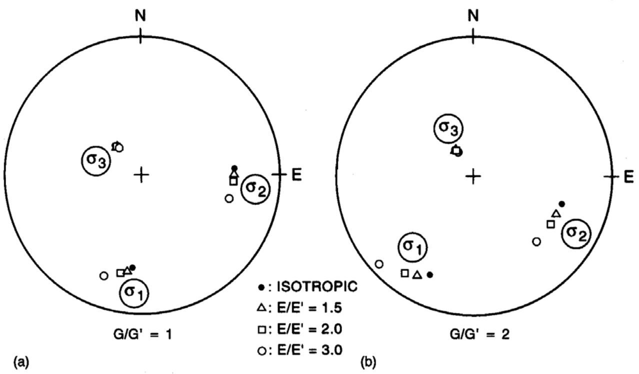


Figure 2-3. *Orientation of the principle stresses σ_1, σ_2 and σ_3 for different elastic conditions (Amadei, 1996).*

Another numerical example performed by Amadei (1996) shows the changes of the principal stress magnitudes due to changes in borehole orientation with respect to the plane of isotropy. The elastic properties are as mentioned above and the ratios E/E' and G/G' are equal to 2. The plane of isotropy dips at an angle of 30° and its dip direction varies between 0° (plane of isotropy is parallel to the borehole) and 90° (plane of isotropy is perpendicular to the borehole). The magnitude and orientation of the principal stresses are shown in Table 2-4 and Figure 2-4.

Table 2-4. Magnitude of the principal stresses when the dip of the isotropic plane changes dip direction (after Amadei, 1996).

	Isotropic	0°	15°	30°	45°	60°	75°	90°
σ_1	3.83	3.08	3.10	3.14	3.20	3.28	3.36	3.44
σ_2	3.07	2.38	2.47	2.58	2.71	2.84	2.96	3.06
σ_3	0.24	0.29	0.33	0.38	0.43	0.47	0.49	0.49

It is seen in Table 2-4 that the *magnitude* of the principal stresses depends on the orientation of the borehole with respect to the plane of isotropy. If the anisotropy of the rock is neglected, it results in a maximum error of 19 % for σ_1 (0°), 22 % for σ_2 (0°) and 104 % for σ_3 (90°). Figure 2-4 shows the changes in *orientation* of σ_1 and σ_2 with orientation of the borehole with respect to the plunge to the plane of isotropy. The orientation of σ_3 is almost unaffected by a change in dip direction. If the anisotropy of the rock is neglected, it results in a maximum error of 120 ° for the bearing of σ_1 (0°), 125 ° for σ_2 (60°) and 12 ° for σ_3 (90°).

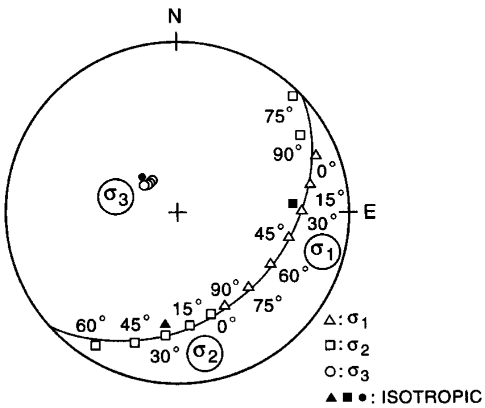


Figure 2-4. *Changes of the orientation of the principal stresses when the dip of the isotropic plane changes dip direction (Amadei, 1996).*

Also Rahn (1984) has concluded that neglecting anisotropy will affect the magnitude and orientation of the *in situ* stresses. Rahn performed numerical simulations of stress measurements with a doorstopper in transversal isotropic rock mass. With the assumption that both E/E' and G/G' are equal to 2, the *magnitude* of the *in situ* stresses can deviate between +116 % and –45 %, and the *orientation* of the *in situ* stresses can deviate up to 20°.

In a research facility in Cananda called URL, a similar facility to Äspö HRL, the rock, in which the excavation was conducted, was observed to be anisotropic due to a prevailing orientation of stress induced microcracks (Martin and Christiansson, 1991).

During the interpretation of the measurements, the rock was modelled both as isotropic and as transversally isotropic. The plane of transversal isotropy was parallel to the plane of the microcracks. The ratio of the shear moduli was about 2 and the modulus, perpendicular to the transversal plane of isotropy, is 30 GPa. Overcoring was conducted in two boreholes 25 m apart and drilled in different directions. The first borehole (PH3) was drilled nearly parallel to the preferred orientation of the cracks; the second (OC2) was drilled perpendicular to the plane of the cracks. The interpretation of the result with an isotopic solution showed that the orientation of σ_1 varied considerably (Figure 2-5). The variation was reduced to almost nothing when the anisotropy was considered in the interpretation. It can be seen that the orientation of σ_1 is rotated 45° when anisotropy is included. The magnitude of the stresses was reduced when the anisotropy was included in the interpretation. It has to be observed that the anisotropy detected in the rock cores is believed to relate from stress relief during excavation (Martin and Christiansson, 1991). The *in situ* anisotropy was determined to be less than 5 %.

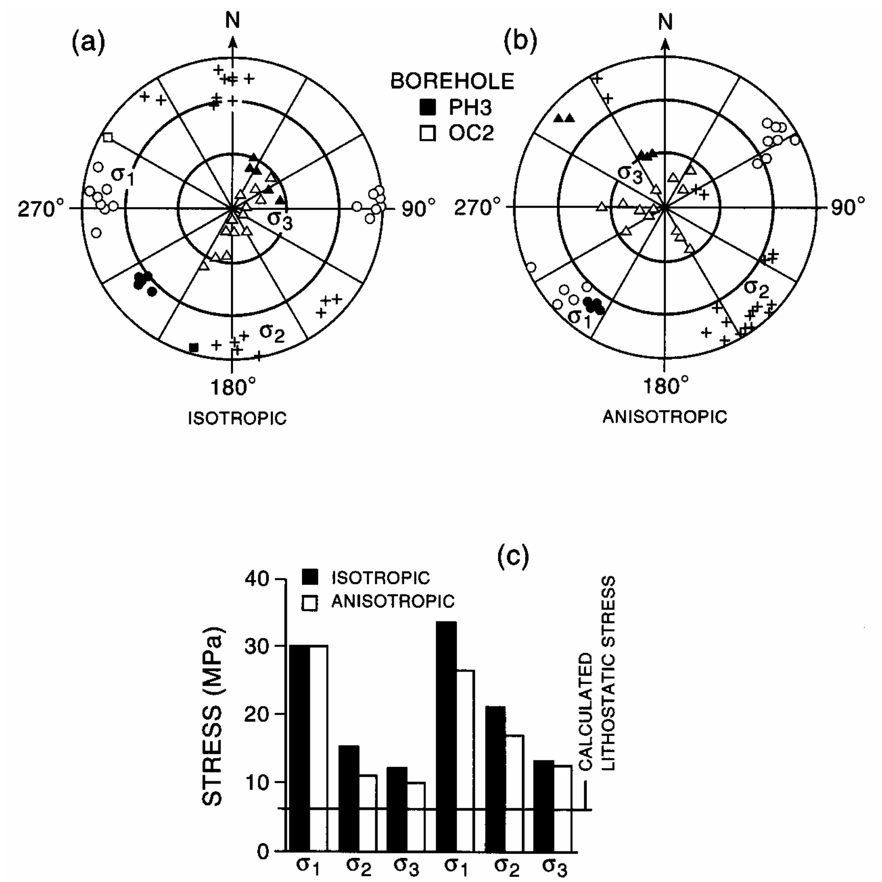


Figure 2-5. *The changes in orientation of* in situ *stresses (a) and (b) and, the changes in magnitude of* in situ *stresses (c), due to isotropic or anisotropic solution (Martin and Christiansson, 1991).*

3 Measurements

3.1 Test Method

The test method used when performing the measurements of the p-wave velocity is the modified method developed by LTU (Eitzenberger, 2002). The method is based on the suggestion given by ISRM (Brown, 1981). The modification of the method is the use of wave-guides between the core specimen and the transducers. This modification is done in order to increase the amplitude of the wave, and also increase the accuracy of the measurements.

3.1.1 Determination of the wave velocity

The method used to determine the p-wave velocity in laboratory specimen, is called the *high frequency ultrasonic pulse method* (Brown, 1981). The method can also be used to determine the s-wave velocity. Transducers are placed opposite to each other with a sample in between (Figure 3-1a). A pulse is generated and propagates from the transmitting transducer, through the sample to the receiving transducer. The time it takes for the pulse to travel between the transmitter and the receiver is measured and displayed by an oscilloscope. When the distance, d, between the transmitter and receiver, and the travel time, t, is known, the velocity, c, can be calculated using (Brown, 1981)

$$c = \frac{d}{t}. \tag{3.1}$$

The suggestions given by ISRM (Brown, 1981) are for measurements performed between plane and parallel end surfaces on the core (Figure 3-1a). The measurements performed in this report are performed diametrically. For the method developed by LTU (Eitzenberger, 2002), wave-guides should be used when performing diametrical measurements (Figure 3-1b). This is to increase the reliability of the measurements. The use of wave-guides increases the distance over which the wave has to travel. Hence the distance between the transducers in our test set-up is the sum of the diameter of the core and the thickness of the wave-guides. In order to obtain the travel time through the core, zero readings are performed with only wave-guides, without radii, between the transducers. The travel time measured as a zero reading is subtracted from the travel time measured when both a core and the wave-guides are between the transducers. See Eitzenberger (2002) for a more thorough description.

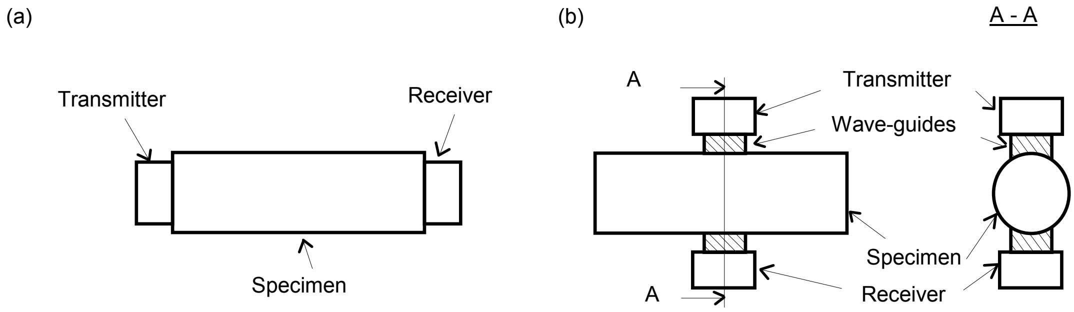


Figure 3-1. *Position of the transducers depending on which technique that is used. (a) Axial measurement suggestion by ISRM (Brown, 1981) and (b) diametrical measurement developed by LTU (Eitzenberger. 2002).*

3.1.2 Equipment

The equipment used to measure the p-wave velocity follows the recommendations given by the ISRM (Brown, 1981). The following equipment is used:

- LeCroy 9424 Quad 350 MHz Oscilloscope (1).
- Pulse generator PUNDIT that generates 10 pulses per second (2).
- Two cylindrical videoscan transducers from Panametrics, which can be used both as a transmitter and receiver. The transducers have an eigen frequency of 1 MHz and a diameter of 13 mm (3).
- A rig that ensures that the transducers are attached diametrically each other (4).

To obtain good acoustic contact between the transducers and the sample, a couplant was used. According to Li and Nordlund (1993) water can be used as a couplant instead of specially developed creams or aluminium foil. Water is more easy to use than other couplants available on the market and is therefore used as a couplant in all tests performed. This set-up of equipment follows the recommendation for laboratory testing given by the ISRM (Brown, 1981).

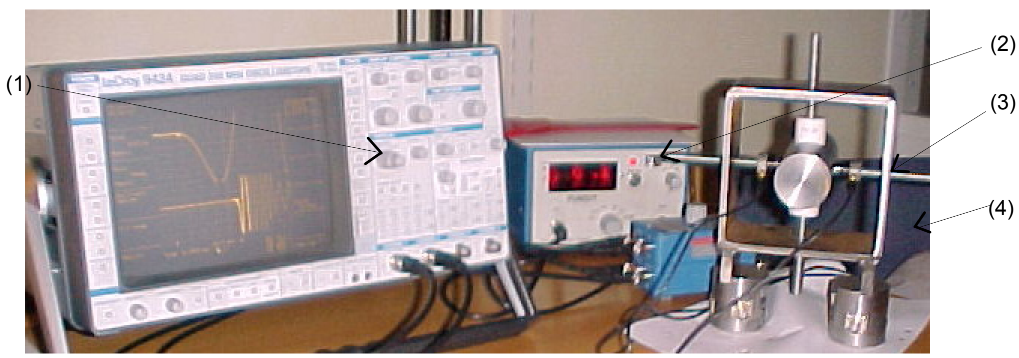


Figure 3-2. *The equipment used when performing p-wave velocity measurements*

3.1.3 Test Procedure

The following procedure is followed when performing the tests:

1. The test equipment is put together and tested.
2. The transducers are placed opposite to each other with two flat wave-guides in between. The zero time is read.
3. The cores are placed in the rig and a small stress is applied to hold the core in place.
4. Water is applied to the surfaces of the transducers, the wave-guides and the rock core to increase the coupling effect. The transducers are placed opposite to each other with the wave-guides and rock core in between. A small stress is applied to increase the coupling effect even further.
5. The travel time is measured with the oscilloscope and thereafter documented.
6. The diameter, where the measurement was performed, is measured.
7. The actual travel time is calculated by subtracting the zero time from the measured travel time.

The procedure from 3) to 7) is repeated for every test and test position. The above test procedure follows the recommendations given by the ISRM (Brown, 1981).

3.2 Tests

Measurements are to be performed on 14 rock cores received from the Äspö HRL area. Seven cores are from a horizontally drilled hole (KF0093A01) and seven cores are from a vertical hole (KA2599G01). The horizontal borehole is inclined 2° and the vertical is inclined 10°. The p-wave velocity measurements are conducted according to the suggestion given by LTU (Eitzenberger, 2002).

The cores from the horizontal borehole have been named after the distance from the starting point when performing the stress measurements. They are called: 28.87, 29.92, 30.07, 30.23, 30.89, 31.05 and 32.70. Four cores (28.87, 30.89, 31.05 and 32.70) consist of Äspö Diorite, where the last three are foliated; three cores (29.92, 30.07 and 30.23) consist of fine-grained Granite.

The cores from the vertical borehole have been named in the same manner. They are called: 107.29, 107.44, 107.79, 107.95, 128,28, 128.61 and 128.97. All cores are made of Äspö diorite, but there are some differences, the cores labelled 107.29-95 are relatively dark and have inclusions of large “eyes” of other minerals. The cores called 128.28-97 are bright and do not contain eyes.

All cores have a diameter of 60.6 to 61.0 mm, they are about 100 to 150 mm long except 30.89, which is about 50 mm long. The core 32.70 is a thick walled cylinder with an inner diameter of about 32 mm and a length of 480 mm. This is a core from stress measurements with the Borre Probe), employed by SwedPower AB.

The *in situ* stresses prevailing in the area are either parallel or perpendicular to the horizontal borehole. The vertical principle stress is perpendicular to the borehole. The maximum horizontal principle stress is parallel to the borehole and the minimum horizontal principle stress is perpendicular to the horizontal borehole. Position 0° is oriented in the direction of the vertical principle stress. This is not valid for 28.87 and 32.70 because they have no line marking their *in situ* orientation.

The vertical borehole is parallel to the vertical principle stress and perpendicular to the horizontal principle stresses. The line marked on the core, labelled 0° in this report, is oriented in the same direction as the major horizontal principle stress. Hence the minor horizontal principle stress is oriented in direction 90° (270°).

3.2.1 Anisotropy

P-wave velocity measurements are performed every 30° along the circumference of the cores between 0° and 180°, see Figure 3-3b. The line along the core is marked after drilling and is oriented in a known direction relative the principle stresses. During the measurements of the p-wave velocity, the line is determined as 0°. After measuring at this position the core is rotated 30° and new measurements are made. The measurements are performed near the edge, where the doorstopper is placed, and at the middle of the core, see Figure 3-3a. These measurements are conducted to see if the rock is anisotropic, which in the end might influence the interpretation of the *in situ* stresses.

3.2.2 Edge effects

Measurements are performed near the edge (8 mm) and at the middle of the core (55 mm from edge). These positions are chosen in order to see if the velocity measured at the edge differs from the velocity measured at the middle of the core. If the velocities differ, e.g. are lower at the edge, the rock near the edge might be damaged by the procedure performed in order to be able to place the doorstopper in the borehole. The bottom of the hole is flattened and polished before the doorstopper is glued onto the bottom of the hole. The flattening of the bottom of the borehole generates stress concentration due to the sharp edges created; this increases if the rock is anisotropic (Rahn, 1984). Increasing stresses can, if high enough, generate cracks. This increased amount of cracks can influence the stress measurements performed with the doorstopper method. If cracks are present, it can be observed with p-wave velocity measurements, especially if the cracks have a preferred orientation, which creates velocity anisotropy (Paterson, 1978). Comparison of the velocity measured at the edge and at the middle of the core, can show if cracks are present near the edge and therefore might affect the stress measurements.

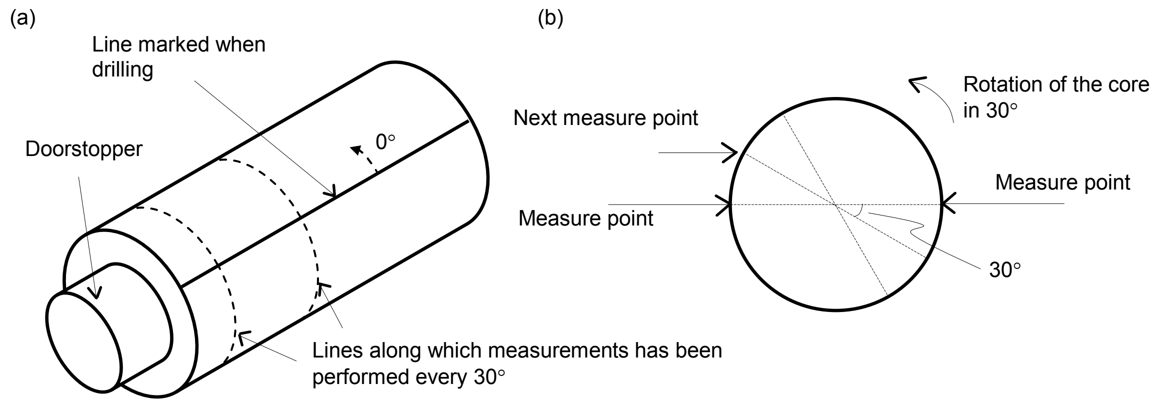


Figure 3-3. *Illustration of where on the core the measurements are performed. (a) Where along the core and (b) where along the circumference of the core the measurements are made.*

4 Result

4.1 The horizontal borehole

P-wave velocities have been measured at regular intervals on the circumference of seven rock cores taken from a depth of about 455 m. The measurements were performed near the edge and at the middle of the core, respectively. The measurements at regular intervals on the circumference of the core are done to see if the cores are anisotropic or not. The different positions along the core were chosen in order to investigate if the rock near the edge, where the doorstopper was placed during the stress measurements, is damage by the drilling of the borehole.

It can be seen that all the cores are anisotropic. The orientation of the maximum velocity is oriented in the direction of 150°/330°, as shown in Figure 4-1 and 4-2. The direction of the minimum velocity is oriented in the direction 60°/240°, i.e. perpendicular to the direction of maximum velocity. For the core 30.89, the velocity has its maximum in the direction of 180°/0° and its minimum perpendicular to the maximum, 90°/270°.

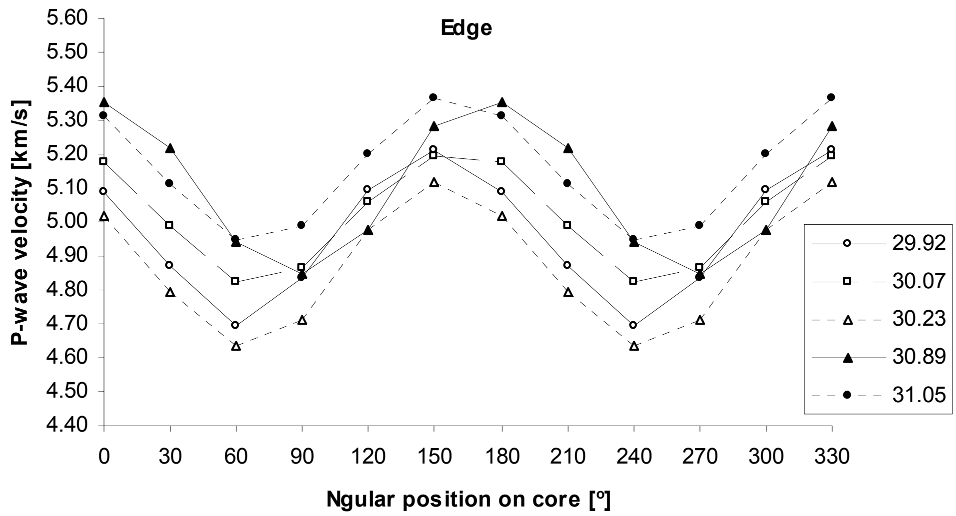


Figure 4-1. *Velocities measured at regular intervals on the circumference, near the edge, on five cores from the horizontal borehole.*

The measurements performed on core 28.87 and 32.70 cannot be compared to the other measurements with respect to orientation of the maximum/minimum velocities. There is no line drawn on the cores and therefore the directions of these two cores are unknown. The cores 28.87 and 32.70 have roughly the same ratio differences as the other five cores, see Figure 4-3.

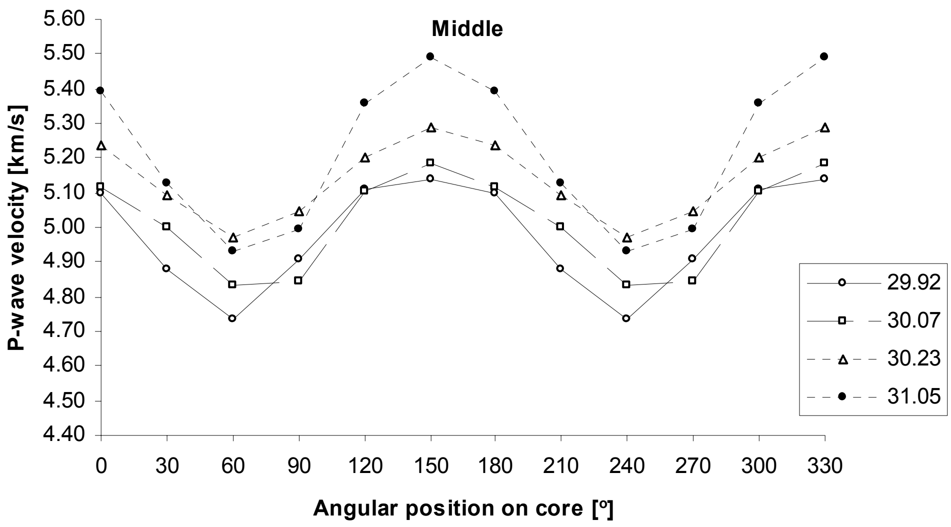


__Figure 4-2.__ Velocities measured at regular intervals on the circumference, at the middle, on four cores from the horizontal borehole.

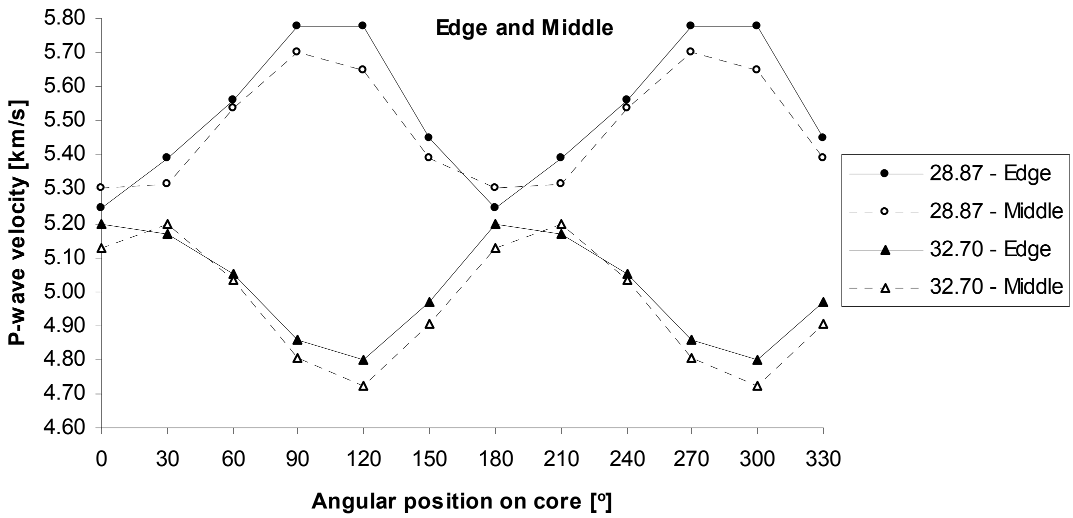
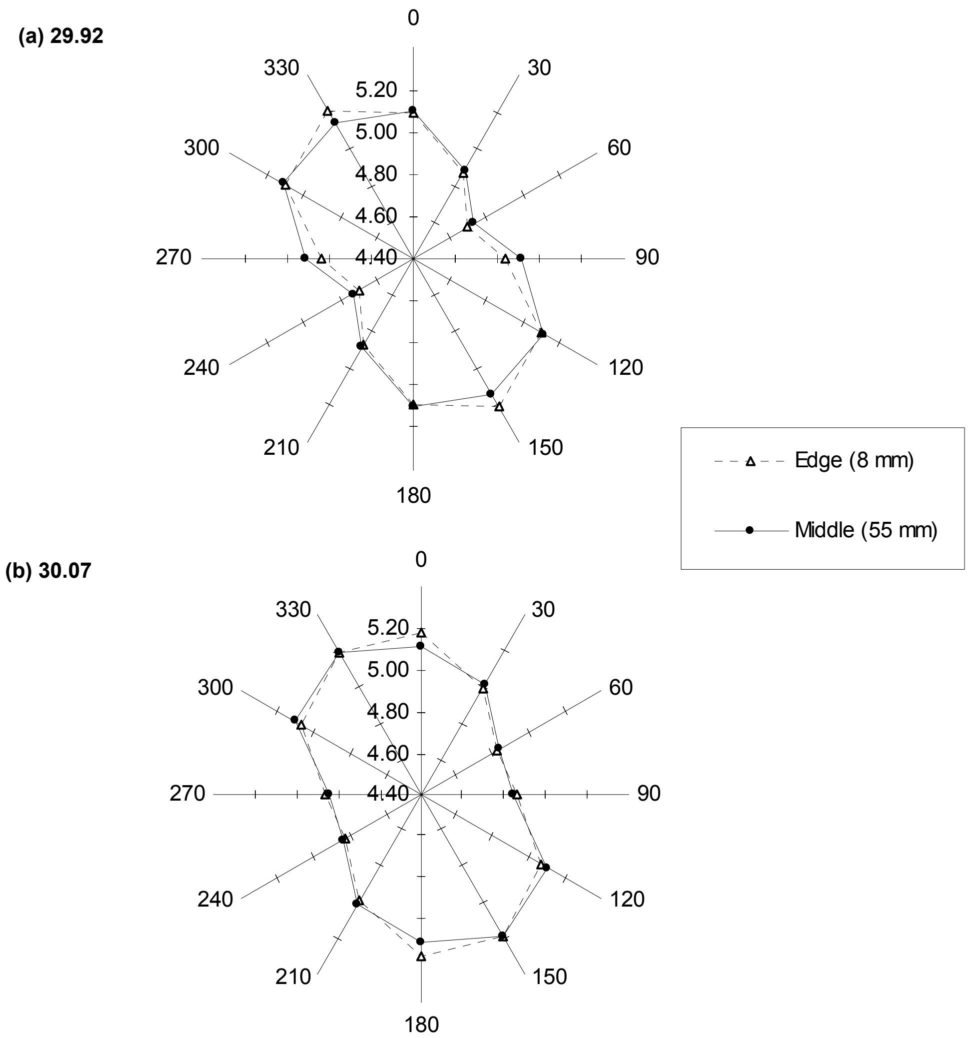


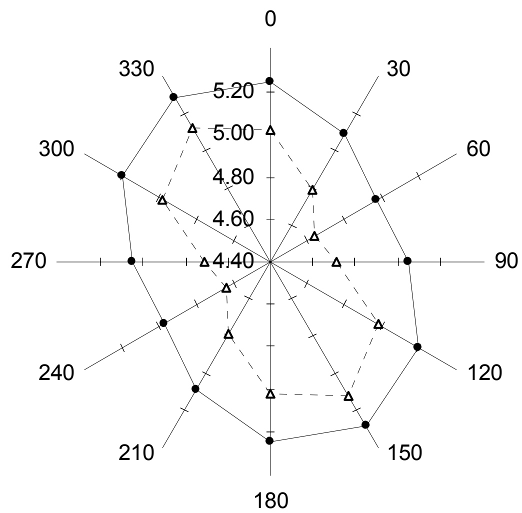
__Figure 4-3.__ Velocities measured at regular intervals on the circumference, both near the edge and at the middle, on the two cores from the horizontal borehole, which has an unknown in situ orientation, i.e. the 0° orientation is unknown.

If the velocities, measured at the edge and at the middle of the core, are compared with each other, differences can be seen (see Figure 4-4). For two of the cores (Figure 4-4c, d), the velocities at the edge are lower than the velocities measured at the middle. For two other cores (Figure 4-4a, b), it cannot be determined which of the positions that has the highest velocity. For the fifth core (Figure 4-4e) the velocity at the middle is lower than at the edge. On the core 30.89, measurements were only performed near the edge because the sample was too short, and therefore no comparisons could be done. The core 32.70 has another type of edge and is therefore not included in the comparison.

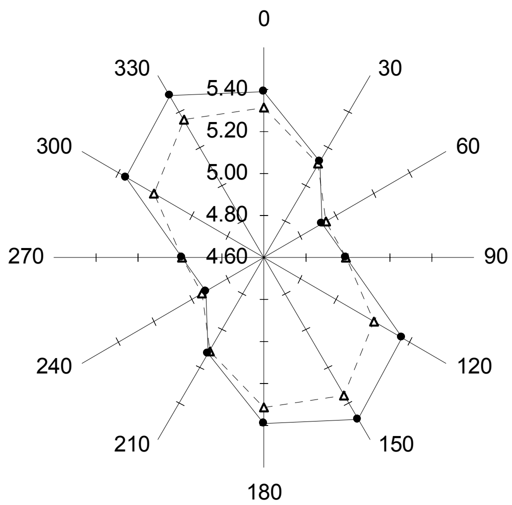
P-wave velocity [km/s] vs. position around core [°]



(c) 30.23


0
30
60
90
120
150
180
210
240
270
300
330
5.20
5.00
4.80
4.60
4.40

(d) 31.05


0
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270
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330
5.40
5.20
5.00
4.80
4.60

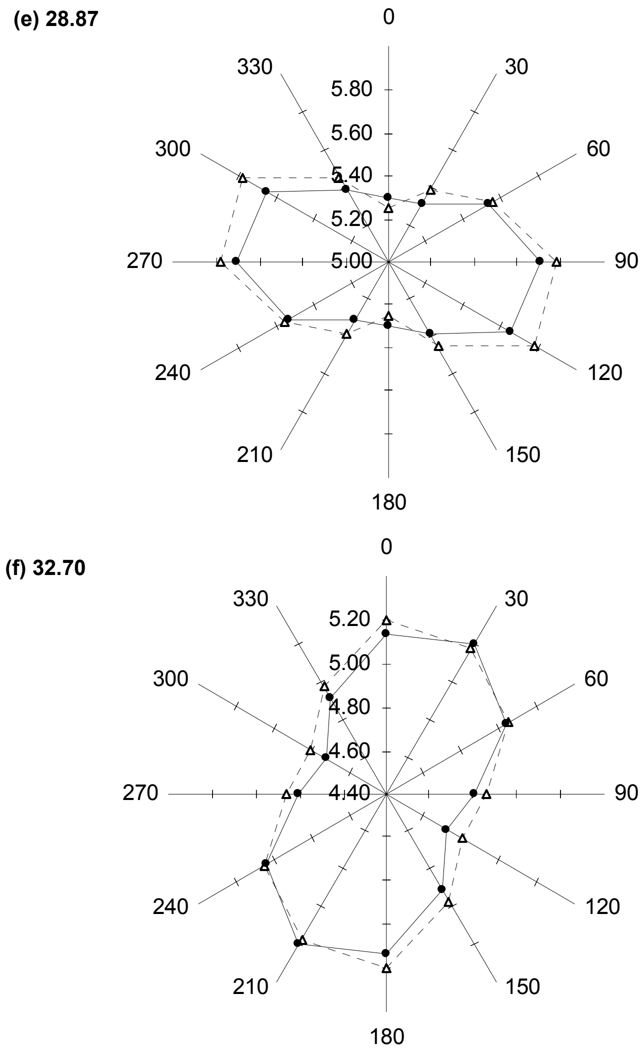


Figure 4-4. *The velocities measured near the edge and at the middle of the core. The velocities are measured at regular intervals on the circumference on six cores from the horizontal borehole.*

4.2 The vertical borehole

The measurements were performed in the same manner as they were for the cores from the horizontal borehole. The number of rock cores is seven. In the vertical hole, the cores are taken from different depths; four cores are taken from a depth of about 450 m (107.29-95) and three from a depth of about 470 m (128.28-97).

The cores from the vertical borehole are also anisotropic. The anisotropy is, however not as systematic as it is for the cores from the horizontal borehole. For example: the velocity at the edge of core 107.44 has its minimum velocity 30° from its maximum velocity, see Figure 4-5. The same is observed at the middle of core 107.29 (Figure 4-6). At the edge of core 107.79, the angle between the maximum and minimum p-wave velocity is 120° (or 60°), i.e. not 90° (Figure 4-5). At the middle of the same core the angle between maximum and minimum velocity is also 120° (or 60°) (Figure 4-6). Core 107.95 is the only core, out of these four, that has anisotropy where the maximum is 90 degrees from the minimum, see Figures 4-5 and 4-6. For this core the maximum velocity at the edge and middle is oriented in the direction 0°/180° and at the middle in direction 150°/330°.

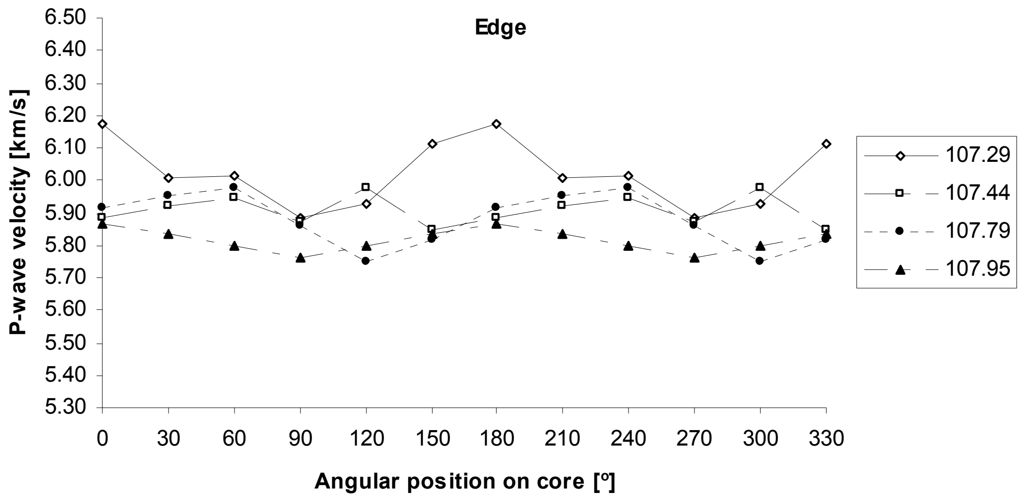


Figure 4-5. *Velocities measured at regular intervals on the circumference, at the edge, on four cores from the vertical borehole.*

The three cores labelled 128.28-97 show anisotropy, as seen in Figures 4-7 and 4-8. The anisotropy is systematic and has about the same ratio for all three cores. Two cores have the same orientation of the maximum velocity 90°/270°, and the same orientation of the minimum velocity 180°/0°. The third (128.61) has its maximum in direction 150°/330° and its minimum in direction 60°/240°.

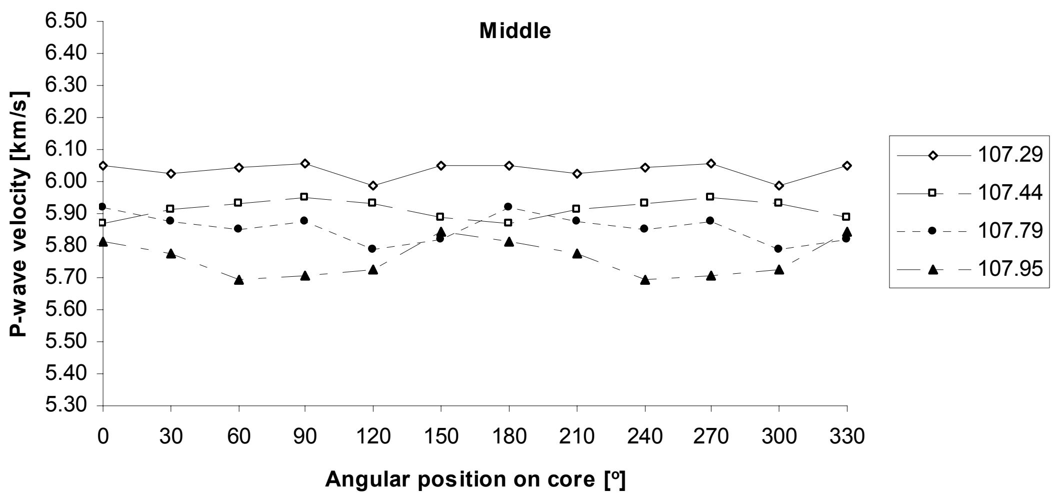


Figure 4-6. *Velocities measured at regular intervals on the circumference, at the middle, on four cores from the vertical borehole.*

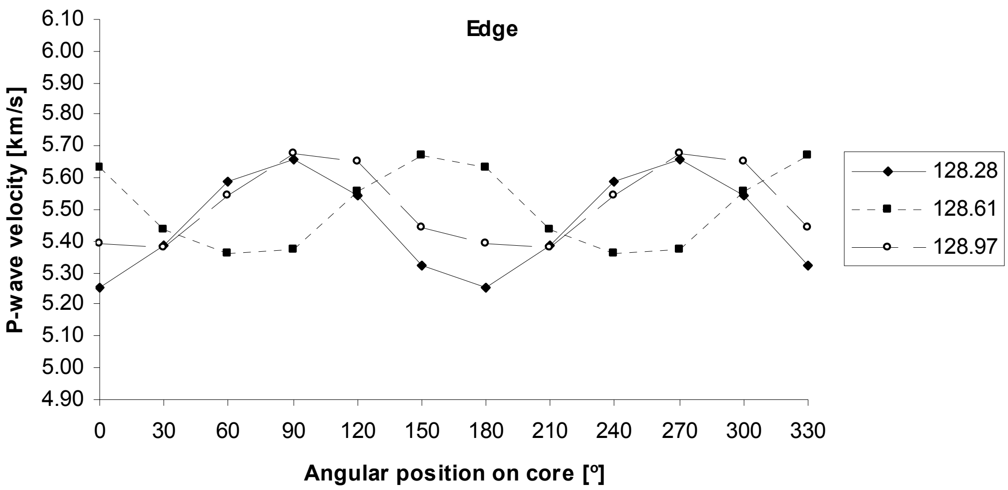


Figure 4-7. *Velocities measured at regular intervals on the circumference, at the edge, on three cores from the vertical borehole.*

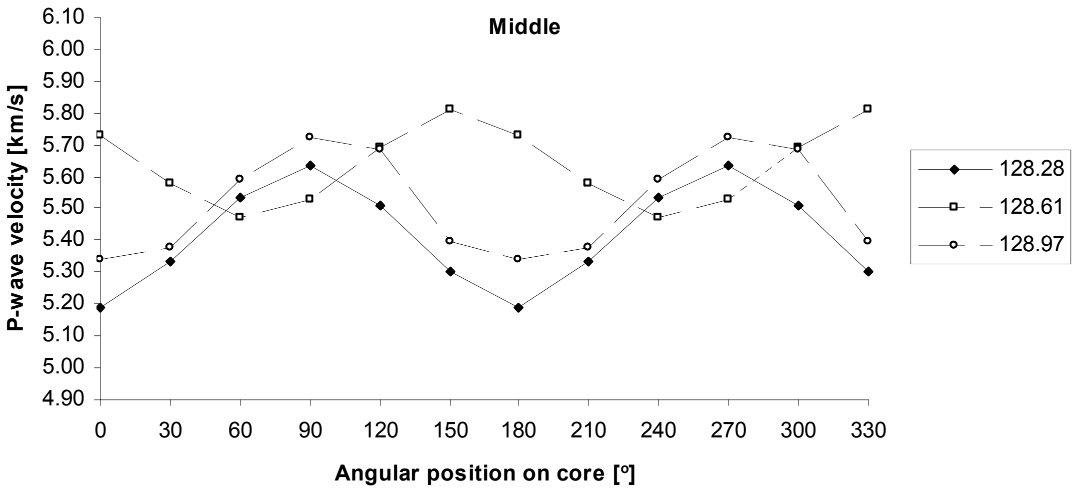
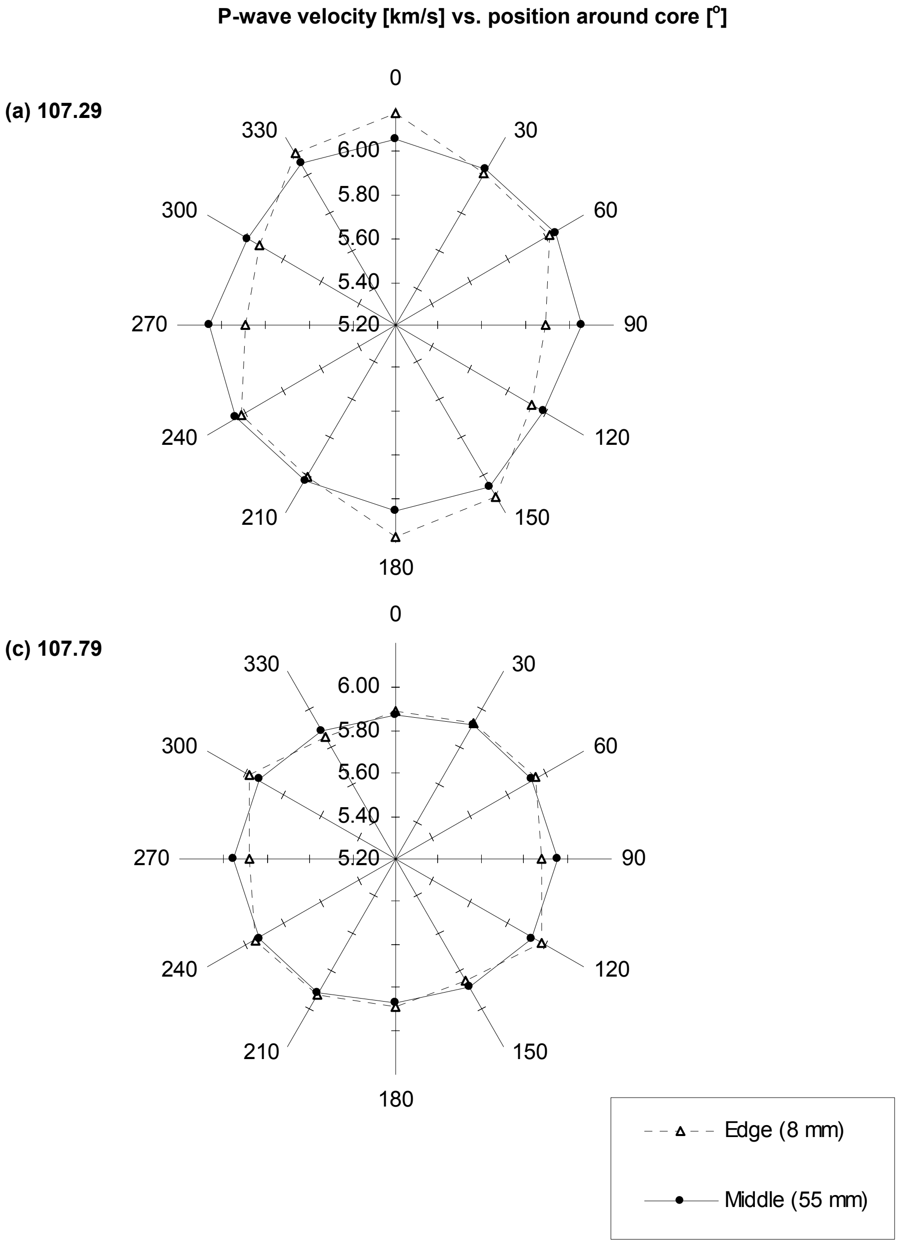
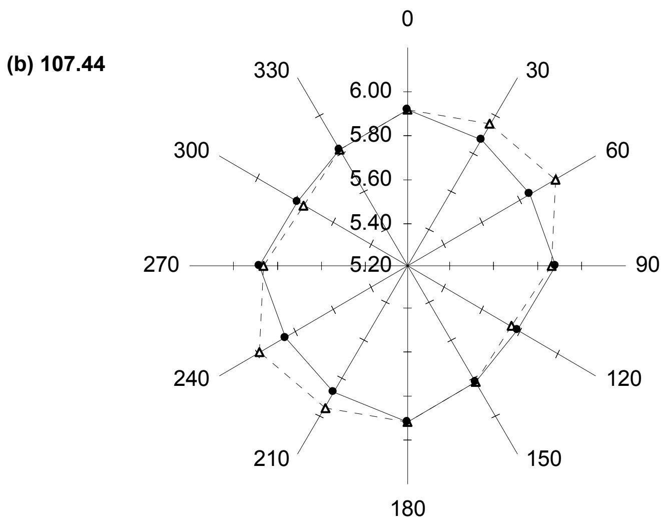


Figure 4-8. *Velocities measured at regular intervals on the circumference, at the middle, on three cores from the vertical borehole.*

Comparison of the velocity, measured at the edge and at the middle of the core, shows no obvious differences in velocities for the cores 107.29-95 (Figure 4-9). Sometimes the velocity at the edge is higher and sometimes the opposite is true. The same can be said about the cores 128.28-97, for the first core (Figure 4-10a), the velocity at the edge is higher, for the second (Figure 4-10b), the velocity at the middle is higher and for the third (Figure 4-10c) the velocities at the edge and middle are almost the same.





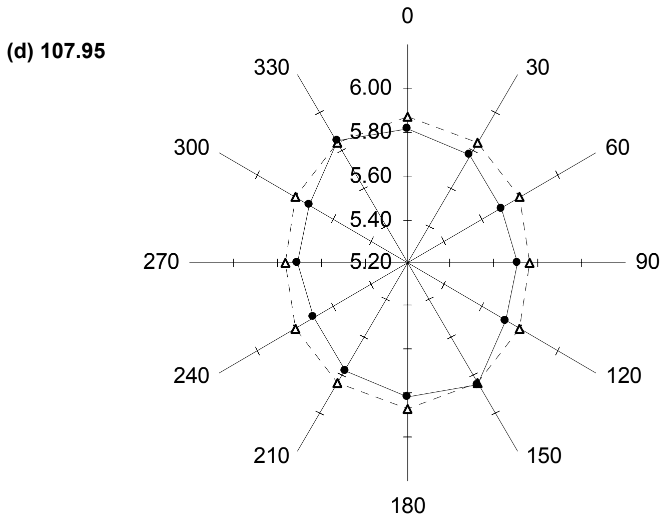


Figure 4-9. *The velocities measured near the edge and at the middle of the core. The velocities are measured at regular intervals on the circumference on the four cores from the vertical borehole.*

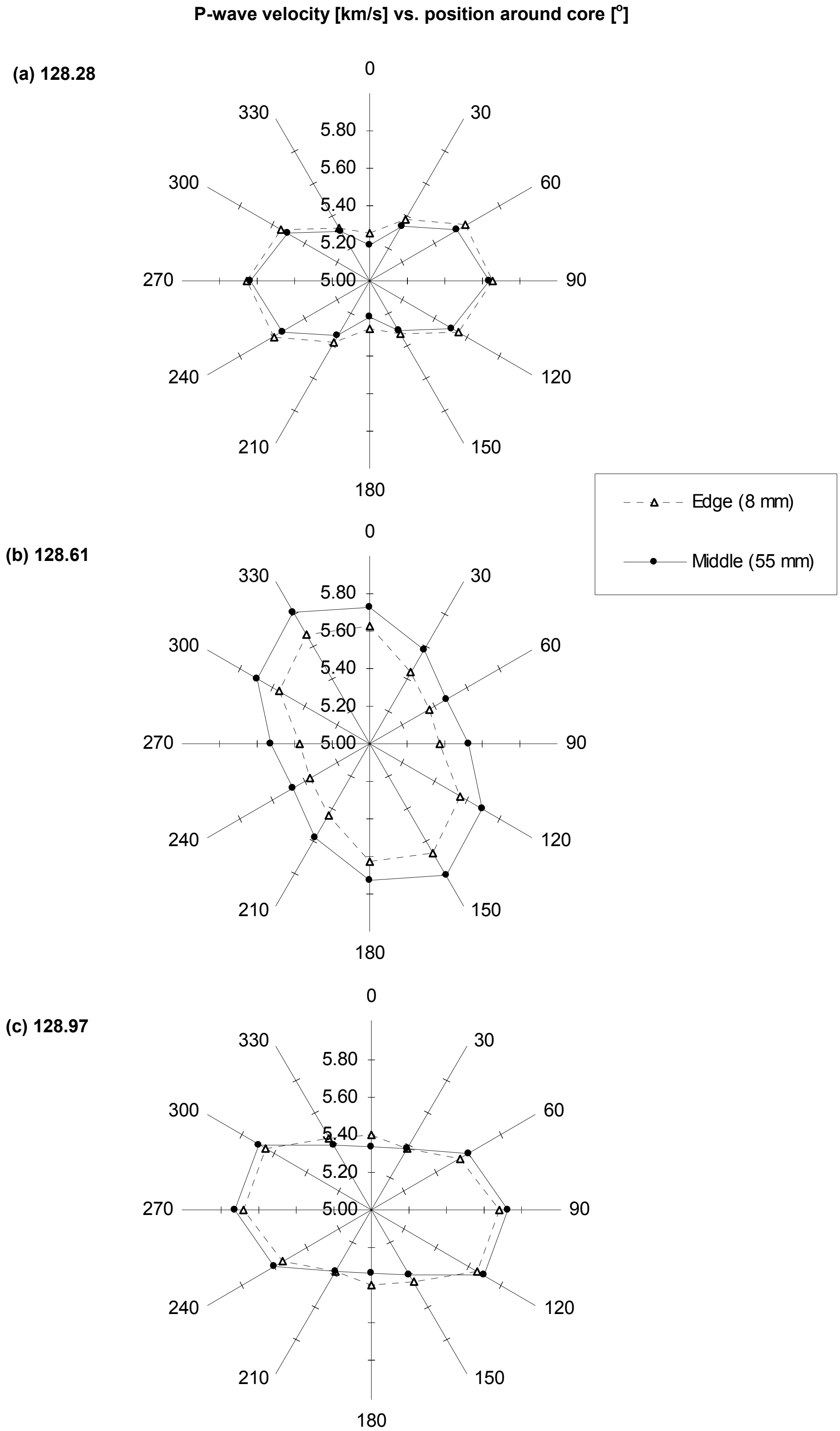


Figure 4-10. *The velocities measured near the edge and at the middle of the core. The velocities are measured at regular intervals on the circumference on the three cores from the vertical borehole.*

Additional measurements were conducted on core 107.79. These measurements were performed in order to see if there might be a local disturbance that affected the velocity locally. The measurements were performed with the transducer and receiver in opposite positions compared to those measurements already performed. This was to see if the velocity is affected if the transducer or the receiver is near the disturbance. The measurements were performed at the edge of core 107.79 (Edge 2). The other measurements were performed between the original measure points. This was done in order to see if the “eyes” present in the matrix influenced the velocity. Hence the measurements are performed every 30°, displaced 15° from the ones already performed. The measurements were performed at the middle of core 107.79 (Middle 2).

The results of these measurements are shown in Figure 4-11. It can be seen that the measurements gave the same results as the original measurements. The differences in velocity between the measurements are small, less than 0.04 km/s. The velocities measured at positions displaced 15°, follow the path of the original measurements.

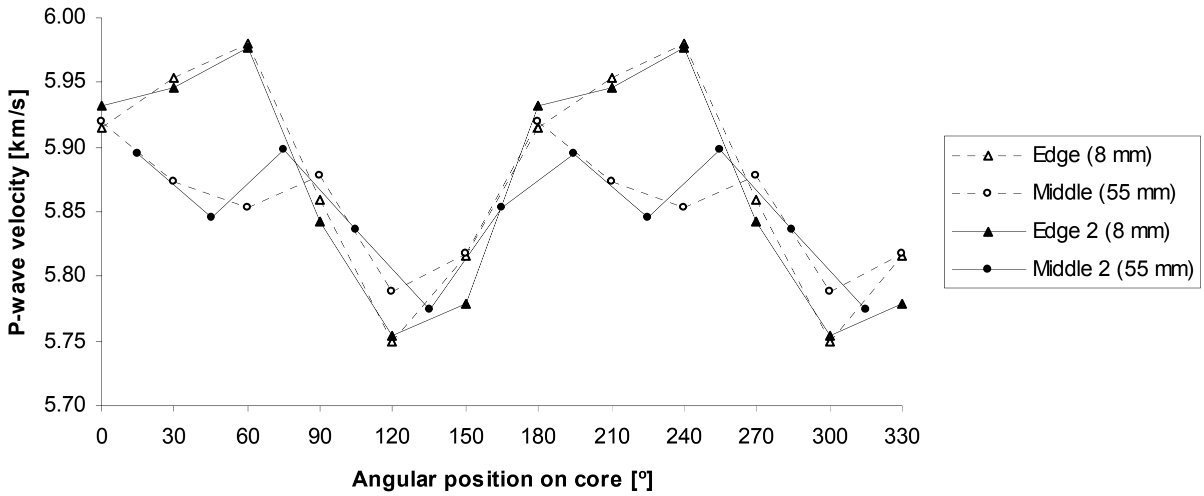


Figure 4-11. *Velocities measured at regular intervals on the circumference on core 107.79 from the vertical borehole. The velocity scale is different compared to the other figures.*

5 Discussion and conclusions

5.1 The horizontal borehole

The results indicate that the cores from the horizontal borehole are anisotropic i.e. different velocities in different directions with the maximum velocity perpendicular to the minimum velocity. It can, therefore, be assumed that the rock is transversal isotropic. The cores can be orthotropic but it cannot be determined by these measurements. Hence, the degree of anisotropy (the ratio of the maximum and minimum velocities), k_c, can be calculated using Equation 2.2. In Table 5-1 the velocities and the calculated degree of anisotropy are presented. The velocities are calculated from the data presented in appendix A. The degree of anisotropy for the cores from the horizontal borehole varies between 6 and 11 %. Also the degree of anisotropy, k_E, the ratio between the maximum and minimum Young's modulus is also calculated (Equation 2.1) and presented in Table 5-1.

Table 5-1. The degree of anisotropy for the tested cores from the horizontal borehole.

Core	Position	*c* (max) [km/s]	*c'* (min) [km/s]	k_c	k_E	Rock type
28.87	Edge	5.78	5.26	1.10	1.21	Äspö Diorite
	Middle	5.70	5.30	1.08	1.16	"
29.92	Edge	5.21	4.69	1.11	1.23	Fine-grained Granite
	Middle	5.14	4.73	1.09	1.19	"
30.07	Edge	5.19	4.83	1.07	1.14	"
	Middle	5.19	4.83	1.07	1.14	"
30.23	Edge	5.12	4.64	1.10	1.21	"
	Middle	5.29	4.97	1.06	1.12	"
30.89	Edge	5.35	4.85	1.10	1.21	Foliated Äspö Diorite
31.05	Edge	5.36	4.95	1.08	1.17	"
	Middle	5.49	4.93	1.11	1.23	"
32.07	"Edge"	5.20	4.80	1.08	1.17	"
	"Middle"	5.20	4.72	1.10	1.21	"

It can be seen that the degree of anisotropy varies between the edge and the middle of the core. Primarily two factors can cause this; damage due to stress concentration or by variations in rock fabric, i.e. grain size, shape and orientation of grains, mineral content or other structural differences

The distance between core 28.87 and core 32.70 is about 3.83 m. Over this length it can be expected that there are many variations in the fabric of the rock. The rock type, mineral content, grain size, amount of healed cracks, orientation of layering and other structural properties may vary over this length. The rock cores 28.87, 30.89, 31.05 and 32.70 consist of relatively large grained rock and have large mineral grains within the matrix. If there are large grains in the rock core, both visual and non-visual, the velocity may vary, especially if the large grains have irregular shapes and microcracks. The rock core 29.92, 30.07 and 30.23 contains smaller grains; here it might be healed joints or other disturbances that cause structural differences. Whether it is the damage or structural variations that are causing this difference in the degree of anisotropy, between the edge and the middle, cannot be determined from the data available.

Table 5-1 shows that the maximum velocity varies between the cores. These variations are depending on which rock type that the core consists of. The three cores 29.92, 30.07 and 30.23 have lower maximum velocities than the other four cores, except core 32.70. The cores 29.92, 30.07 and 30.23 consist of fine-grained granite, the other four (28.87, 30.89, 31.05 and 32.70) consist of Äspö diorite.

The degree of anisotropy may partly be caused by the removal of the rock from its *in situ* state. Removal of rock causes the rock to expand. The expansion often results in internal cracking, probably with a preferred orientation of the cracks. In URL Canada, it was found that the *in situ* anisotropy was less than 5 % (velocities in different directions) (Martin and Christiansson, 1991). In the removed cores it was found that the secant modulus was twice as large in one direction compared to a perpendicular direction. It was believed that the anisotropy in the cores was caused by stress-relieved microcracking. If this is the case, the anisotropy detected in our study may be caused by cracks generated while removing the core from its *in situ* state.

5.2 The vertical borehole

The degree of anisotropy, k_c and k_E, for the cores from the vertical borehole, was calculated using the same equations (2.2) and (2.1), which were used for the cores from the horizontal borehole, see Table 5.2. As seen in the previous chapter, the p-wave velocity measured at different angular positions along the circumference of the core varies. This variation does, however, not indicate a transversal isotropic behaviour as in the horizontal borehole. In Table 5-2 the velocities and the calculated degree of anisotropy are presented. The degree of anisotropy for the cores from the vertical borehole varies between 1 and 8 % (Equation 2.2). The velocities are calculated from the data presented in appendix A.

The p-wave velocities in cores 128.28-97 are lower than in the other cores (107.29-95). These differences are assumed to be a result of differences in grain size and matrix. The three cores (128.28-97), with well-defined maxima and minima, consist of rock with grains of similar size. In the four other cores (107.29-95), large mineral grains are present, which, if they are large enough, can affect the velocity of the p-waves.

An ocular investigation of the cores from the vertical borehole, especially 107.29-95, shows that the anisotropy at the edge is more pronounced than at the middle of the core (Figure 4-9). As in the horizontal cores, this is likely to be caused by structural differences or damage caused by the used method. The latter is contradicted by the fact that the maximum velocity is higher near the edge, than it is at the middle of the core.

Table 5-2. The degree of anisotropy for the tested cores from the vertical borehole.

Core	Position	*c* (max) [km/s]	*c'* (min) [km/s]	k_c	k_E	Rock type
107.29	Edge	6.17	5.88	1.05	1.10	Dark Äspö Diorite
	Middle*	6.05	5.99	1.01	1.02	“
107.44	Edge*	5.98	5.85	1.02	1.04	“
	Middle	5.95	5.87	1.01	1.03	“
107.79	Edge*	5.98	5.75	1.04	1.08	“
	Middle*	5.92	5.79	1.02	1.05	“
107.95	Edge	5.93	5.77	1.03	1.06	“
	Middle	5.86	5.72	1.02	1.05	“
128.28	Edge	5.66	5.25	1.08	1.16	Bright Äspö Diorite
	Middle	5.63	5.19	1.08	1.18	“
128.61	Edge	5.67	5.36	1.06	1.12	“
	Middle	5.81	5.47	1.06	1.13	“
128.97	Edge	5.68	5.39	1.05	1.11	“
	Middle	5.72	5.34	1.07	1.15	

*) Maximum and minimum velocity is not perpendicular to each other.

5.3 The affect of anisotropy on stress measurements

Many scientists have established that neglecting rock anisotropy when interpreting stress measurements, results in incorrect values of both magnitude and orientation of the *in situ* stresses (Amadei, 1996; Rahn, 1984; Wototniki, 1993). A higher degree of anisotropy will result in larger errors. It has been shown that if the degree of anisotropy is 1.5, errors up to 33 % in magnitude and a few degrees in orientation are generated (Amadei, 1996). Worotniki (1993) concluded that as long as the degree of anisotropy is lower than 1.5 (1.3 depending on the anisotropy of the shear modulus), the errors would remain reasonably low.

Worotniki (1993) developed a classification system in which rock anisotropy can be divided into four groups. This system implies that the Äspö diorite and the fine-grained granite should belong to the group called quartzfeldspathic rock. For that group it is found that 80 % of tested rock has a degree of anisotropy lower than 1.5. The measurements performed in this report, have shown that the rock has a degree of anisotropy (k_E) of 1.14 to 1.23 for the horizontal cores and 1.03 to 1.18 for the vertical cores. This is in accordance with the summary done by Worotniki (1993). The results can be seen as normal for this rock type.

It can, therefore, be determined that the degree of anisotropy in the cores tested, is low enough to have negligible effect on the result of the *in situ* stress measurements. Though, it has to be remembered that the measurement error of *in situ* stress measurements in good rock is ± 10-20% for the magnitude and ± 10-20° for the orientation (Amadei and Stephansson, 1997). For poorer rock the error is even larger.

5.4 Conclusion

In this report diametrical p-wave velocity measurement on rock cores has been performed. By interpretation of the measured p-wave velocity it has been determined that the rock, from the horizontal borehole, is anisotropic. The degree of anisotropy, calculated from the differences in p-wave velocities, varies between 1.06 and 1.11, and calculated from Young's modulus varies between 1.14 and 1.23. By interpretation of the measured p-wave velocity from the vertical borehole it can be determined that the rock is almost isotropic. The degree of anisotropy, calculated from the differences in p-wave velocities, varies between 1.01 and 1.08, and calculated from Young's modulus varies between 1.02 and 1.18. The anisotropy found can be determined as transversal. These results are normal for this type of rock.

It has been found that both the velocity and the degree of anisotropy vary depending on the position along the core. These variations indicate that there are differences in properties between the edge and the middle part of the core. These differences can be caused either by structural differences, that are natural, or by damage to the cores. It cannot be determined if the edge or the middle part of the core is more damaged. Neither is it possible to determine if the core is damaged by the method used to perform the stress mesurements nor if it is the removal of the core from its i*n situ* state, that causes the damage.

It can be concluded that if the degree of anisotropy is larger than 1.3 – 1.5, neglecting anisotropy will give errors that are intolerably high. If the degree of anisotropy is smaller, the errors in magnitude and orientation will generate errors that are small enough to accept.

When comparing the results with results from numerical simulations done by Amadei (1996), it can be concluded that the degree of anisotropy found in the rock cores from the two boreholes are too small to have any intolerable effect on the interpretation of the stress measurements. The normal measurement errors in stress measurements will probably affect the results more than neglecting the anisotropy.

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Appendix 1

Measurements performed on rock cores from the horizontal drill hole (KF0093A01)

Table A1-1. Measured travel time and diameter on cores from the horizontal borehole (KF0093A01).

Position	Time [μs]	Time [μs]	Time [μs]	Diameter [mm]
28.87 Edge				
90	13.09	13.10	13.14	60.45
120	13.08	13.14	13.11	60.50
150	13.70	13.73	13.76	60.45
180	14.16	14.16	14.20	60.50
210	13.86	13.84	13.85	60.45
240	13.52	13.55	13.51	60.50
28.87 Middle				
90	13.24	13.27	13.30	60.60
120	13.37	13.36	13.39	60.60
150	13.86	13.90	13.89	60.60
180	14.06	14.10	14.09	60.65
210	14.07	14.05	14.02	60.60
240	13.60	13.58	13.59	60.65
270	13.19	-	-	60.60
29.92 Edge				
90	15.20	15.19	15.18	60.70
120	14.53	14.57	14.55	60.70
150	14.30	14.28	14.29	60.70
180	14.54	14.62	14.54	60.70
210	15.10	15.14	15.08	60.70
240	15.55	15.59	15.57	60.70
270	15.27	15.21	15.22	60.70
0	14.52	-	-	60.70
29.92 Middle				
90	15.00	15.01	15.00	60.70
120	14.48	14.52	14.55	60.70
150	14.41	14.41	14.53	60.70
180	14.54	14.55	14.56	60.70
210	15.09	15.08	15.08	60.70
240	15.43	15.44	15.52	60.70
270	14.87	14.92	14.93	60.70
0	14.53	-	-	60.70
30.07 Edge				
90	15.12	15.15	15.11	60.75
120	14.67	14.65	14.62	60.75
150	14.33	14.36	14.33	60.75
180	14.38	14.36	14.39	60.75
210	14.87	14.78	14.81	60.75
240	15.21	15.25	15.23	60.75
270	15.06	15.08	15.06	60.75
0	14.30	-	-	60.75

Table A1-1. Continued.

Position	Time [μs]	Time [μs]	Time [μs]	Diameter [mm]
30.07 Middle				
90	15.17	15.18	15.18	60.75
120	14.50	14.54	14.59	60.75
150	14.43	14.35	14.28	60.75
180	14.52	14.52	14.51	60.75
210	14.78	14.84	14.74	60.75
240	15.22	15.16	15.24	60.75
270	15.06	15.12	15.08	60.75
0	14.45	-	-	60.75
30.23 Edge				
90	15.56	15.56	15.50	60.75
120	14.83	14.81	14.91	60.75
150	14.48	14.61	14.45	60.75
180	14.71	14.76	14.78	60.75
210	15.35	15.32	15.28	60.75
240	15.79	15.67	15.76	60.75
270	15.42	15.49	15.44	60.75
0	14.71	-	-	60.75
30.23 Middle				
90	14.70	14.64	14.68	60.70
120	14.35	14.29	14.30	60.75
150	14.10	14.14	14.14	60.75
180	14.21	14.25	14.25	60.75
210	14.55	14.59	14.57	60.75
240	14.89	14.83	14.86	60.75
270	14.68	14.71	14.70	60.75
0	14.28	-	-	60.75
30.89 Edge				
90	15.11	15.18	15.13	60.60
120	14.90	14.78	14.79	60.60
150	14.10	14.13	14.11	60.60
180	14.00	13.95	13.93	60.60
210	14.25	14.25	14.25	60.60
240	14.87	14.90	14.96	60.60
270	15.15	15.16	15.15	60.60
0	13.91	-	-	60.60

Table A1-1. Continued.

Position	Time [μs]	Time [μs]	Time [μs]	Diameter [mm]
31.05 Edge				
90	14.80	14.79	14.78	60.60
120	14.29	14.31	14.27	60.60
150	13.95	13.95	13.95	60.65
180	14.01	14.06	14.09	60.60
210	14.53	14.46	14.48	60.60
240	14.88	14.91	14.88	60.60
270	14.76	14.79	14.79	60.60
0	14.07	-	-	60.60
31.05 Middle				
90	14.83	14.79	14.77	60.70
120	13.93	13.96	13.99	60.65
150	13.67	13.73	13.70	60.70
180	13.88	13.94	13.88	60.70
210	14.52	14.45	14.49	60.75
240	14.95	14.97	14.95	60.70
270	14.70	14.73	14.70	60.70
0	13.80	-	-	60.70
23.70 Edge				
90	15.33	15.27	15.30	60.80
120	15.53	15.52	15.51	60.80
150	15.06	15.05	15.00	60.80
180	14.49	14.51	14.48	60.80
210	14.34	14.36	14.32	60.80
240	14.72	14.73	14.72	60.80
270	15.18	-	-	60.80
0	14.41	-	-	60.80
32.70 Middle				
90	15.15	15.14	15.16	60.80
120	15.34	15.30	15.28	60.80
150	14.85	14.86	14.91	60.80
180	14.32	14.36	14.35	60.80
210	14.41	14.41	14.38	60.80
240	14.68	14.70	14.65	60.80
270	15.10	-	-	60.80
0	14.29	-	-	60.80

Appendix 2

Measurements performed on rock cores from the vertical drill hole (KA2599G01)

Table A2-1. Measured travel time and diameter on cores from the vertical borehole (KA2599G01).

Position	Time [μs]	Time [μs]	Time [μs]	Diameter [mm]
107.29 Edge				
90	13.00	12.99	13.03	61.00
120	12.88	12.98	12.92	60.95
150	12.54	12.63	12.68	60.95
180	12.45	12.54	12.55	60.95
210	12.77	12.82	12.78	60.95
240	12.69	12.81	12.83	60.95
270	13.04	13.03	13.04	61.00
0	12.55	-	-	60.95
107.29 Middle				
90	12.61	12.76	12.75	60.95
120	12.79	12.82	12.84	60.95
150	12.67	12.75	12.73	60.95
180	12.65	12.72	12.77	60.95
210	12.70	12.79	12.78	60.95
240	12.69	12.73	12.76	60.95
270	12.76	12.78	12.74	60.95
0	12.61	-	-	60.95
107.44 Edge				
90	13.01	13.01	13.00	60.9
120	12.80	12.86	12.86	60.95
150	13.07	13.09	13.04	60.95
180	12.93	13.00	13.05	60.95
210	12.93	12.94	12.92	60.95
240	12.85	12.90	12.92	60.95
270	12.94	12.98	12.98	60.9
0	12.95	-	-	60.95
107.44 Middle				
90	12.83	12.88	12.85	60.95
120	12.89	12.93	12.93	60.95
150	12.98	12.98	13.03	60.95
180	12.94	13.04	13.10	60.95
210	12.94	12.95	12.97	60.95
240	12.91	12.91	12.93	60.95
270	12.85	12.87	12.83	60.95
0	13.00	-	-	60.95

Table A2-1. Continued.

Position	Time [μs]	Time [μs]	Time [μs]	Diameter [mm]
107.79 Edge				
90	13.00	13.04	13.06	60.90
120	13.20	13.25	13.25	60.90
150	13.06	13.13	13.17	60.95
180	12.89	12.95	12.97	60.90
210	12.83	12.89	12.89	60.90
240	12.83	12.82	12.85	60.95
270	12.99	-	-	60.90
0	12.91	-	-	60.90
107.79 Middle				
90	12.98	13.03	13.02	60.95
120	13.12	13.18	13.21	60.95
150	13.13	13.10	13.12	60.95
180	12.92	12.94	12.95	60.95
210	13.00	13.01	13.04	60.95
240	13.05	13.07	13.04	60.95
270	12.97	-	-	60.95
0	12.89	-	-	60.95
107.79 Edge 2				
270	13.09	13.03	13.07	60.90
300	13.22	13.23	13.22	60.90
330	13.16	13.21	13.19	60.95
0	12.89	12.88	12.95	60.90
30	12.86	12.91	12.88	60.90
60	12.83	12.85	12.83	60.95
90	13.07	-	-	60.90
107.79 Middle 2				
75	12.91	13.01	13.00	60.95
105	13.06	13.10	13.09	60.95
135	13.19	13.20	13.20	60.95
165	13.03	13.06	13.07	60.95
195	12.95	13.02	12.97	60.95
225	13.05	13.06	13.09	60.95
255	12.97	-	-	60.95

Table A2-1. Continued.

Position	Time [μs]	Time [μs]	Time [μs]	Diameter [mm]
107.95 Edge				
90	13.19	13.16	13.20	60.75
120	13.06	13.13	13.17	60.75
150	13.08	13.07	13.04	60.80
180	12.92	12.99	13.07	60.75
210	13.00	13.03	13.12	60.75
240	13.07	13.13	13.15	60.75
270	13.10	-	-	60.75
0	12.89	-	-	60.75
107.95 Middle				
90	13.27	13.27	13.35	60.80
120	13.17	13.26	13.34	60.80
150	13.04	13.00	13.10	60.80
180	13.06	13.10	13.13	60.80
210	13.19	13.12	13.21	60.80
240	13.30	13.30	13.37	60.80
270	13.32	-	-	60.80
0	13.11	-	-	60.80
128.28 Edge				
90	13.43	13.36	13.38	60.80
120	13.55	13.62	13.64	60.80
150	14.06	14.06	14.06	60.80
180	14.20	14.20	14.25	60.80
210	13.92	13.94	13.93	60.80
240	13.56	13.49	13.50	60.80
270	13.37	13.40	13.37	60.80
0	14.23	-	-	60.80
128.28 Middle				
90	13.40	13.45	13.45	60.80
120	13.66	13.68	13.70	60.80
150	14.11	14.13	14.10	60.80
180	14.35	14.35	14.36	60.80
210	14.04	14.01	14.06	60.80
240	13.64	13.61	13.62	60.80
270	13.42	13.43	13.45	60.80
0	14.32	-	-	60.80

Table A2-1. Continued.

Position	Time [μs]	Time [μs]	Time [μs]	Diameter [mm]
128.61 Edge				
90	13.90	13.96	13.99	60.80
120	13.59	13.57	13.59	60.80
150	13.34	13.39	13.36	60.80
180	13.43	13.44	13.45	60.80
210	13.76	13.79	13.92	60.80
240	13.96	14.00	13.98	60.80
270	13.97	13.97	14.00	60.80
0	13.37	-	-	60.80
128.61 Middle				
90	13.63	13.66	13.65	60.85
120	13.34	13.32	13.36	60.90
150	13.07	13.15	13.13	60.90
180	13.24	13.28	13.28	60.90
210	13.57	13.54	13.55	60.85
240	13.72	13.79	13.78	60.85
270	13.68	13.72	13.71	60.90
0	13.25	-	-	60.90
128.97 Edge				
90	13.33	13.36	13.39	60.85
120	13.39	13.43	13.40	60.85
150	13.81	13.83	13.82	60.85
180	13.88	13.92	13.97	60.85
210	13.94	13.95	13.96	60.85
240	13.60	13.66	13.60	60.85
270	13.28	-	-	60.85
0	13.97	-	-	60.85
128.97 Middle				
90	13.27	13.29	13.30	60.90
120	13.30	13.39	13.38	60.90
150	13.92	13.91	13.94	60.90
180	14.06	14.04	14.05	60.90
210	13.95	13.96	13.94	60.85
240	13.51	13.53	13.52	60.85
270	13.24	-	-	60.90
0	14.03	-	-	60.90

Appendix 3

Photographs of the rock cores from the boreholes (KF0093A01) and (KA2599G01)

Figure A3-1. *Photograph of four cores (107.29, 107.44, 107.79 and 107.95) from the vertical borehole (KA2599G01).*

Figure A3-2. *Photograph of three cores (128.28, 128.61 and 128.97) from the vertical borehole (KA2599G01).*

Figure A3-3. *Photograph of three cores (28.87, 30.89 and 31.05) from the horizontal borehole (KF0093A01).*

Figure A3-4. *Photograph of three cores (29.92, 30.07 and 30.23) from the horizontal borehole (KF0093A01).*

Figure A3-5. *Photograph of core 32.70 from the horizontal borehole (KF0093A01).*