P-05-216

Forsmark site investigation

Borehole: KFM08A

Determination of P-wave velocity, transverse borehole core

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Norwegian Geotechnical Institute, Oslo

November 2005

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Keywords: Rock mechanics, P-wave velocity, Anisotropy, AP PF 400-05-057.

Summary

The Norwegian Geotechnical Institute has carried out P-wave measurements on drill cores from borehole KFM08A at Forsmark, Sweden, in May 2005. Thirty-three P-wave velocity measurements have been carried out on 30 samples from a total of 900 m of drill core.

The results from the P-wave velocity measurements over the entire length of the investigated borehole section show that the maximum principal velocity, V_1, at the tested locations lies within the interval 5,091–5,782 m/s with an anisotropy ratio of between 1.04 and 1.14.

There is an apparent trend in the maximum principal velocity, V_1, of slightly reducing velocities with depth. V_1 lies between 5,285–5,678 m/s down to 500 m borehole length, with outlying values of 5,161 m/s at 343.75 m and 5,782 m/s at 487.90 m. Below 500 m the maximum principal velocity ranges between 5,091–5,463 m/s with no outlying values.

The anisotropy ratio, which is quite variable between 1.04 and 1.14, has an average of 1.10 and no readily apparent trend versus depth.

The orientation of the maximum principal velocity, θ_{V1}, is strongly related to the foliation direction, with no apparent trend in orientation versus depth, although there is a difference in average orientations above and below 350 m borehole length. In the upper part of the borehole (above 350 m) the orientation varies between 20° and 160° with an average of about 180°. In the lower part of the borehole the orientation span is between 135° and 180° with an average of about 160°. The orientation is neither parallel (180°), nor perpendicular (90°) to the foliation as might be expected.

Sammanfattning

Norges Geotekniske Institutt (NGI) har under maj 2005 utfört P-vågsmätningar på borrkärnor från borrhål KFM08A i Forsmark. Sammanlagt har 33 stycken hastighetsbestämningar av P-vågor utförts på 30 kärnprover från ett ca 1 000 m lång borrhål, där avsnittet 100–1 000 m är kärnborrat.

Resultaten visar för hela den undersökta borrhålssektionen en maximihastighet som varierar i intervallet 5 091–5 782 m/s och en anisotropikvot mellan 1,04 och 1,14.

Maximihastigheten uppvisar en avtagande trend mot djupet. Ner till 500 m borrhålslängd varierar maximihastigheten mellan 5 285–5 678 m/s, med undantag för två mätvärden. Vid 343,75 m respektive 487,90 m djup har P-vågshastigheter på 5 161 m/s respektive 5 782 m/s uppmätts. Från 500 m borrhålslängd och vidare nedåt varierar maximihastigheten mellan 5 091 och 5 463 m/s.

Anisotropikvoten, som alltså varierar mellan 1,04 och 1,14, har ett medelvärde på 1,10. Mätningarna visade i det avseendet ingen speciell tendens mot djupet.

Maximihastighetens orientering är starkt relaterad till foliationsriktningen. Det finns inte någon tydlig tendens till orienteringsförändring med djupet. Dock avviker medelvärdet för orienteringen i övre delen av borrhålet från medelvärdet i borrhålets nedre del. Ner till 350 m borrhålslängd varierar riktning mellan 20° och 160° med ett medelvärde vid 180°. Från 350 m djup och vidare neröver varierar däremot riktningen från 135° till 180° och har där ett medelvärde på 160°. Maximihastighetens orientering är varken parallell med eller vinkelrät mot foliationen, vilket möjligen skulle kunna förväntas.

Contents

1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on drill-cores from borehole KFM08A at Forsmark in Sweden in accordance with SKB's Activity Plan AP PF 400-05-057. Borehole KFM07A is c 1,000 m long, inclined at c 60° from the horizontal plane and has a diameter of c 77.3 mm. The borehole is drilled with so called telescopic technique, implying that the upper borehole section 0–100 m is percussion drilled, whereas the section c 100–1,000 m is core drilled. The drill-core diameter is c 50.5 mm. The positions of all telescopic boreholes drilled so far within or close to the Forsmark candidate area are shown in Figure 1-1

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski during the period 24th – 27th of May 2005 in compliance with SKB's method description MD 190.002.

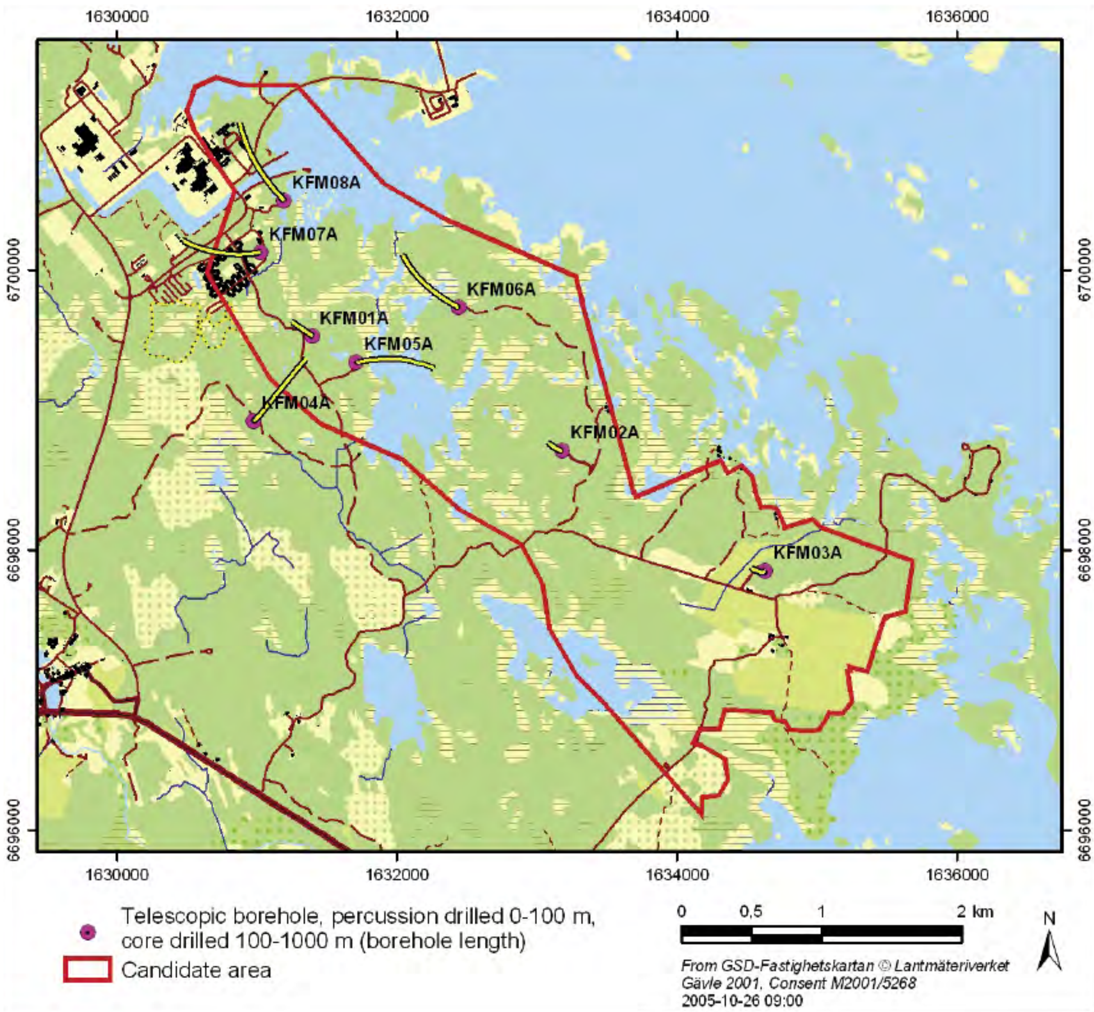

Figure 1-1. Location of all telescopic boreholes drilled up to August 2005 within or close to the Forsmark candidate area. The projection of each borehole on the horizontal plane at top of casing is also shown in the figure.

2 Objective and scope

The purpose of the testing is to determine the P-wave velocity transverse to the core axis. The P-wave velocity is a parameter used in the rock mechanical model which will be established for the candidate area selected for site investigations at Forsmark.

The number of core specimens tested and the number of tests performed are given in Table 2-1.

The results from the P-wave velocity measurements are presented in this report by means of tables, figures and spreadsheets.

Table 2-1. Total number of P-wave velocity specimens and measurements.

Borehole	P-wave velocity test specimens	P-wave velocity measurements
KFM08A	30	33

3 Equipment

The measurements were conducted using Panametrics Videoscan transducers with a natural frequency of 0.5 MHz. These were mounted in a special frame to hold them in contact with the core (see Figure 3-1). Special wave guides, metal shoes with a concave radius similar to the core, were installed between the transducers and the core. The equipment was designed and constructed specially for this contract by NGI, based on the information presented in SKB report entitled "Detection of Anisotropy by Diametral Measurements of Longitudinal Wave Velocities on Rock Cores" /Eitzenberger, 2002/.

A strong sine-wave pulse at the natural frequency of the transducers was used as the acoustic signal source. The arrival of the signals was measured using a PC with a high speed data acquisition board and software to emulate an oscilloscope (see Figures 3-2 and 3-3). The time pick for the first break was taken as the beginning of the first transition, i.e. the point where the received signal first diverges from the zero volts line. In order to provide consistent interpretation of the time pick, one operator (PC) made all the interpretations. The time pick was measured with a precision better than 0.01µs. The instrumentation was calibrated using a cylinder of aluminium of known acoustic velocity of the same diameter as the core. Several measurements were taken each day on the calibration piece to check the operation of the system.

A thin layer of a thick honey was used, as a coupling medium as this proved to be one of the most effective of different media tested and was easily removed by washing without damaging or contaminating the cores.

Figure 3-1. *Detail of NGI's apparatus for measuring acoustic P-wave travel time transverse a foliated borehole core. The aluminium cylinder for calibration of the device is on the right.*

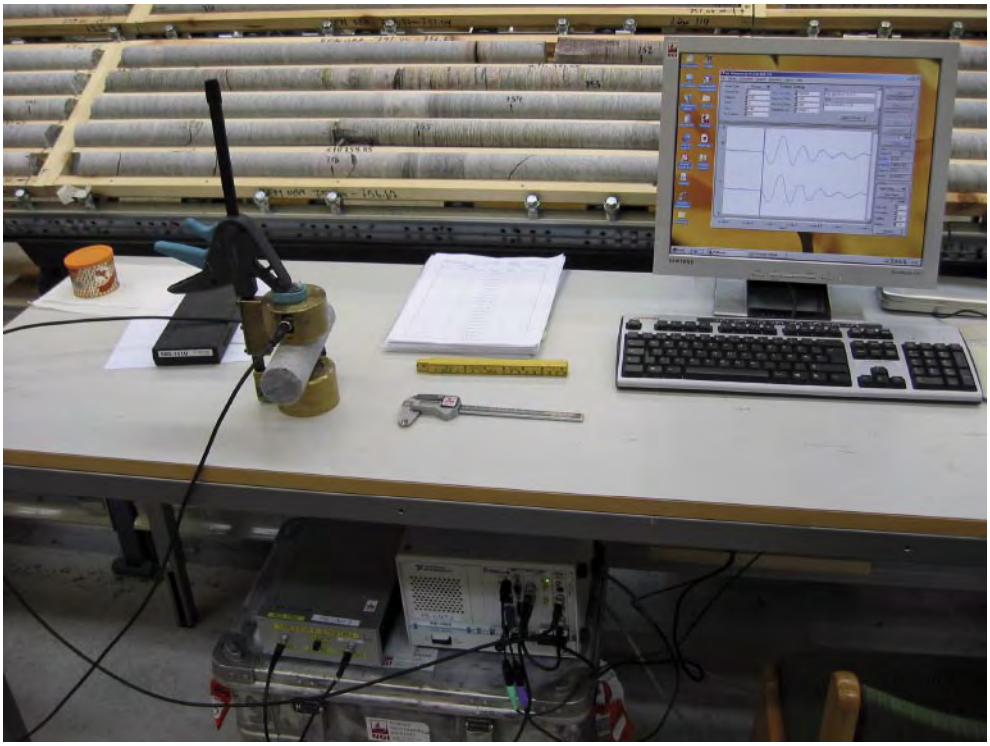

Figure 3-2*. NGI's equipment set-up for measuring acoustic P-wave travel time transverse a borehole core.*

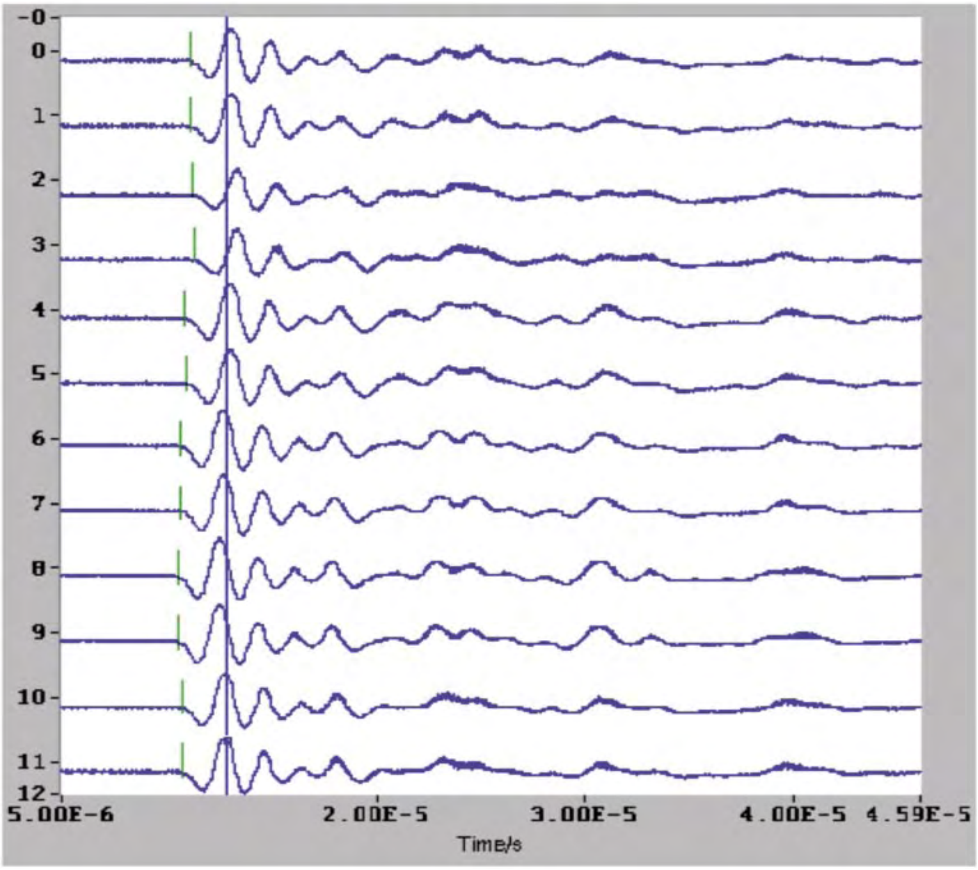

Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse a borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Thirty core specimens of a length of c 200–500 mm and diameter about 50 mm were selected from borehole KFM08A while the complete length of the core-drilled part of the borehole (section 100.55–999.50 m borehole length) was displayed on the racks in the core shed at Forsmark. The specimens were selected jointly by NGI and Björn Ljunggren representing SKB.

These specimens represent a foliated metamorphic granite and a fine-grained granite-granodiorite, with some veins of amphibolite and pegmatite, encountered over most of the length of the borehole. Geological logging of the core has been carried out by SKB. No detailed geological description has been attempted by NGI.

The depths used to describe the location are those marked on the core and core boxes at the time. Detailed description of the specimens is available from the detailed core log by SKB. At the time of sampling, the core had been exposed to the atmosphere at room temperature for an extended period and may be presumed to be air-dried, although no measurements of the moisture content were made.

4.2 Test method

Tests were made at 30° intervals around the core, starting at 0°, parallel with the foliation. However, where the foliation was not identifiable, the first test was made at a random orientation. The cores were all oriented such that successive measurements were made clockwise looking down the borehole (see Figure 4-1). The cores were marked by attaching a piece of self-adhesive tape that had been previously cut to the appropriate lengths and marked up with the locations for the tests. These marks were then transferred to the core with a permanent marker. The cores may thus be checked at any time to ascertain the location and orientation of the tests.

Each test sample comprised a minimum of two consecutive determinations of acoustic pulse travel time at each of six locations around the core (at 0°, 30°, 60°, 90°, 120° respectively 150°) at one cross section. The seating of the transducers and application of the coupling medium was adjusted in cases where there was a significant difference between the time picks, and additional measurements were made until two similar time picks were obtained. The average of the two measured time picks was recorded.

As the travel time includes a number of other factors, such as travel through the wave guides, time pick method, and delay due to the oscilloscope triggering on the rising part of the sine-wave, the determination of the true travel time was calibrated using an aluminium cylinder with known P-wave velocity. The correction factor determined in the calibration tests was subtracted from all the measurements on the rock cores.

The diameter of the core was measured using a calliper with an accuracy of 0.01 mm and the P-wave velocity determined by dividing the diameter (in mm) by the travel time (in µs) and multiplying by 1 000 to obtain the velocity in m/s.

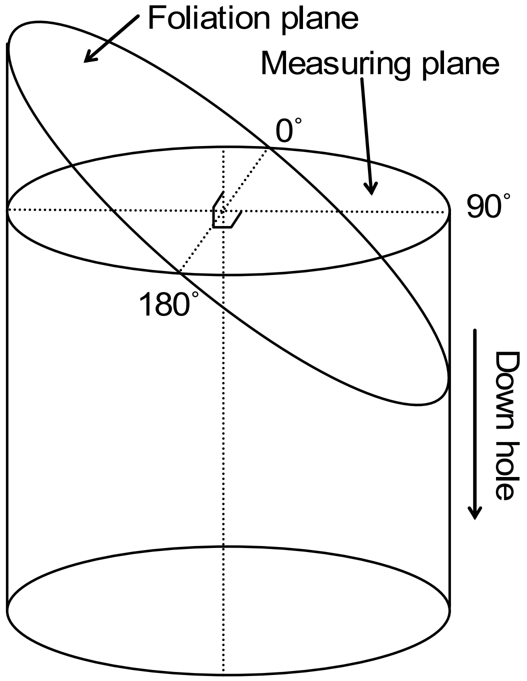

Figure 4-1. *Orientation of measurements.*

Analysis

Since the acoustic velocity is dependent on the elastic properties of the material, the results were analysed similarly to determining the stress or strain tensor in the material. In this case the velocity in the orientation θ is given by:

$$V_\theta = V_x\cos^2\theta + V_y\sin^2\theta + 2\cdot V_{xy}\sin\theta\cos\theta \qquad (1)$$

A simple regression analysis of the six measurements was used to determine the values of V_x, V_y, & V_{xy} (where the X-axis is parallel with the foliation where identifiable).

These values were used to model the complete velocity profile around the core.

The magnitude and orientation of the principal velocities, V_1, V_3, θ_{V1} and θ_{V3}, were determined from the Eigen-values and vectors of the 2D tensor matrix:

$$\begin{vmatrix} V_x & V_{xy} \\ V_{xy} & V_y \end{vmatrix} \qquad (2)$$

The results are reported as the maximum principal velocity, V_1, the minimum principal velocity, V_3, the anisotropy ratio, V_1/V_3, and the orientations of the principal velocities with respect to the foliation direction in the plane perpendicular to the core sample, θ_{V1} and θ_{V3}.

4.3 Nonconformities

Tests were made at 30° intervals around the core instead of 45° intervals, which were suggested in the Method Description. This was the only nonconformity to the controlling documents.

5 Results

5.1 Summary of results

The results of the determinations of the travel time and velocity for all the tests are presented in Table 5-1, whereas the velocity and anisotropy ratio are shown diagrammatically versus borehole length in Figures 5-1 and 5-2.

Table 5-1. Measurements of acoustic velocity, transverse core in borehole KFM08A, Forsmark. Depth in the first column refers to borehole length. (Orientation clockwise looking down hole, 0° is parallel with foliation.)

Depth m	Diameter mm	Corrected time, mS Parallel foliation			Perpendicular foliation			Velocity m/S Parallel foliation			Perpendicular foliation			Anisotropy ratio	Maximum velocity m/S	
		0°	30°	60°	90°	120°	150°	0°	30°	60°	90°	120°	150°			
200.60	50.54	9.48	9.54	10.04	10.32	10.17	9.74	5,331	5,297	5,033	4,897	4,969	5,188	1.09	5,331	
219.40	50.59	9.44	9.88	10.20	10.15	9.78	9.33	5,359	5,120	4,959	4,984	5,172	5,422	1.09	5,422	
238.70	50.71	9.28	9.60	9.97	10.22	9.80	9.45	5,464	5,282	5,086	4,961	5,174	5,366	1.10	5,464	
263.40	50.85	10.03	9.61	9.23	9.25	9.57	9.99	5,069	5,291	5,509	5,497	5,313	5,090	1.09	5,509	
279.40	50.84	8.98	8.92	9.30	9.29	9.21	9.12	5,661	5,699	5,466	5,472	5,520	5,574	1.04	5,699	
299.95	50.79	9.10	9.11	9.45	9.74	9.74	9.56	5,581	5,575	5,374	5,214	5,214	5,312	1.07	5,581	
321.70	50.85	9.38	9.53	10.18	10.42	10.15	9.62	5,421	5,335	4,995	4,880	5,009	5,285	1.11	5,421	
343.75	50.90	9.95	9.92	10.37	10.85	10.70	10.24	5,115	5,131	4,908	4,691	4,757	4,970	1.09	5,131	
361.75	50.67	9.38	9.80	10.05	9.93	9.44	9.29	5,401	5,170	5,041	5,102	5,367	5,454	1.08	5,454	
382.28	50.64	9.15	9.62	9.80	9.44	9.04	9.00	5,534	5,264	5,167	5,364	5,601	5,626	1.09	5,626	
399.00	50.86	9.67	10.47	10.77	10.52	10.09	9.63	5,259	4,857	4,722	4,834	5,040	5,281	1.12	5,281	
420.15	50.77	9.60	9.99	10.41	10.39	10.12	9.70	5,288	5,082	4,877	4,886	5,016	5,234	1.08	5,288	
439.50	50.69	9.06	9.52	9.84	9.84	9.57	9.15	5,594	5,324	5,151	5,151	5,296	5,539	1.09	5,594	
457.10	50.72	9.34	10.13	10.38	9.98	9.42	9.13	5,430	5,007	4,886	5,082	5,384	5,555	1.14	5,555	
487.90	50.65	8.82	9.18	9.25	9.20	8.96	8.75	5,742	5,517	5,475	5,505	5,652	5,788	1.06	5,788	
503.20	50.20	9.94	10.74	10.85	10.29	9.70	9.78	5,050	4,674	4,626	4,878	5,175	5,133	1.12	5,175	
521.40	50.72	10.02	10.58	10.79	10.41	9.86	9.79	5,061	4,794	4,700	4,872	5,144	5,180	1.10	5,180	
545.70	50.33	9.78	10.36	11.07	10.78	10.23	9.68	5,146	4,858	4,546	4,668	4,919	5,199	1.14	5,199	
559.00	50.38	9.36	9.48	10.08	10.34	10.01	9.55	5,382	5,314	4,998	4,872	5,033	5,275	1.10	5,382	
580.00	50.75	9.88	10.60	10.63	10.06	9.61	9.53	5,136	4,787	4,774	5,044	5,281	5,325	1.12	5,325	
597.90	50.84	9.47	9.85	10.24	10.29	9.77	9.44	5,368	5,161	4,964	4,940	5,203	5,385	1.09	5,385	
621.90	50.81	10.12	10.63	10.87	10.42	9.82	9.72	5,020	4,780	4,674	4,876	5,174	5,227	1.12	5,227	
642.40	50.64	9.50	9.96	10.01	9.66	9.37	9.32	5,330	5,084	5,059	5,242	5,404	5,433	1.07	5,433	
660.15	50.56	9.77	10.24	10.72	10.64	10.03	9.84	5,175	4,937	4,716	4,752	5,040	5,138	1.10	5,175	
680.00	50.46	9.40	9.75	10.04	9.95	9.59	9.35	5,368	5,175	5,025	5,071	5,261	5,396	1.07	5,396	
700.65	50.81	9.98	10.36	11.05	11.24	10.74	10.20	5,091	4,904	4,598	4,520	4,731	4,981	1.13	5,091	
720.75	50.69	9.96	10.47	10.92	10.74	10.33	10.08	5,089	4,841	4,642	4,719	4,907	5,028	1.10	5,089	
740.30	49.54	10.44	9.92	9.64	9.60	10.10	10.37	4,745	4,994	5,139	5,160	4,905	4,777	1.09	5,160	
758.75	50.61	9.63	9.89	10.43	10.56	10.30	9.86	5,255	5,117	4,852	4,792	4,913	5,132	1.10	5,255	
781.00	50.64	9.70	9.81	9.86	9.67	9.46	9.53	5,220	5,162	5,135	5,236	5,353	5,313	1.04	5,353	
321.70	50.86	9.32	9.49	10.19	10.40	10.13	9.66	5,457	5,359	4,991	4,890	5,020	5,265	1.12	5,457	Repeat
545.70	50.30	9.50	10.14	10.53	10.13	9.81	9.52	5,294	4,960	4,776	4,965	5,127	5,283	1.11	5,294	Repeat
758.75	50.59	9.75	9.87	10.41	10.64	10.41	10.03	5,188	5,125	4,859	4,754	4,859	5,043	1.09	5,188	Repeat

The results of model calculated principal velocities, the anisotropy ratio and orientation of the maximum velocity are presented in Table 5-2, and shown diagrammatically versus borehole length in Figures 5-3 to 5-5.

The results of calibration determinations for the system are shown in Appendix A. The results are also reported to SICADA, where they are traceable by the Activity Plan number.

Table 5-2. Determination based on model calculations of principal velocity and orientation, transverse core in borehole KFM08A, Forsmark. Depth in the first column refers to borehole length. (Orientation clockwise looking down hole, 0° is parallel with foliation where identified.)

Depth m	Maximum velocity V_1 m/s	Orien-tation θ_{V1}	Minimum velocity V_3 m/s	Orien-tation θ_{V3}	Aniso-tropy ratio	Foliation	
200.60	5,350	5°	4,889	95°	1.09	f	f= foliation (clearly identifiable)
219.40	5,413	160°	4,926	70°	1.10	f	n=no identifiable foliation
238.70	5,460	175°	4,985	85°	1.10	f	w=weak f oliation (not good)
263.40	5,539	75°	5,050	165°	1.10	f	s=strong foliation (good)
279.40	5,678	5°	5,453	95°	1.04	f	x=disturbed sample
299.95	5,589	20°	5,168	110°	1.08	f	
321.70	5,437	0°	4,871	90°	1.12	f	
343.75	5,161	10°	4,696	100°	1.10	f	
361.75	5,478	155°	5,034	65°	1.09	f	
382.28	5,669	145°	5,183	55°	1.09	f	
399.00	5,295	155°	4,703	65°	1.13	f	
420.15	5,285	170°	4,843	80°	1.09	f	
439.50	5,584	165°	5,102	75°	1.09	f	
457.10	5,568	150°	4,880	60°	1.14	f	
487.90	5,782	155°	5,444	65°	1.06	f	
503.20	5,219	140°	4,626	50°	1.13	f	
521.40	5,213	145°	4,704	55°	1.11	f	
545.70	5,219	160°	4,559	70°	1.14	f	
559.00	5,409	0°	4,882	90°	1.11	f	
580.00	5,362	140°	4,754	50°	1.13	f	
597.90	5,416	165°	4,925	75°	1.10	f	
621.90	5,242	145°	4,675	55°	1.12	f	
642.40	5,463	140°	5,054	50°	1.08	f	
660.15	5,206	160°	4,713	70°	1.10	f	
680.00	5,413	160°	5,019	70°	1.08	f	
700.65	5,093	175°	4,515	85°	1.13	f	
720.75	5,091	160°	4,651	70°	1.09	f	
740.30	5,178	70°	4,728	160°	1.10	n	
758.75	5,246	175°	4,774	85°	1.10	f	
781.00	5,343	135°	5,130	45°	1.04	n	
321.70	5,455	0°	4,872	90°	1.12	f	Repeat
545.70	5,324	155°	4,812	65°	1.11	f	Repeat
758.75	5,193	5°	4,751	95°	1.09	f	Repeat

5.2 Discussion

Accuracy and Repeatability

Calibration tests on an aluminium cylinder indicated a variation of ± 0.01 μs in determination of the time pick, equivalent to differences in velocity of about ± 6 m/s. Some of this variation may be explained by temperature variations, thickness of coupling medium and seating of the shoes. Similar variations may be expected from the measurements on the cores.

Tests on cores were repeated at three locations, 321.70 m, 545.70 m and 758.75 m, after the first series of tests were completed. These tests were repeated to investigate and determine typical values for repeatability of velocity determinations.

The repeatability of the diameter measurements was about ± 0.01mm which gives an error of about ± 1 m/s.

The differences between the two sets of measurements are summarised in Table 5-3.

No reason was identified for the unusually large difference between the two measurements at 545.70 m. Both sets of measurements are in the normal range and showed normal differences between the measurements and the model fit, which would suggest that the results are not affected by fractures. The differences are presumed to be due to slight differences in test location.

The differences in the measured velocities on the calibration cylinder and rock cores are presumably due to temperature changes, the problems in seating the transducers and obtaining good signal contact with the material, and due to the interpretation of the time pick.

Generally, there is a good fit between the measurements and the best fit line (model fit), which suggests that random type errors are relatively small. At 321.70 m the maximum difference was 43 m/s, 64 m/s at 545.70 m, and finally 23 m/s at 758.75 m, see Figure 5-6.

Typically in the entire series of tests, the average deviation between the measured value and the model fit is about 0.38% (about 20 m/s), with a maximum error of 1.4% (about 70 m/s).

The deviation between the model fitted to the data and the measured data reported here is similar to that in the previous work /Chryssanthakis and Tunbridge, 2003abcdefgh, 2004ab/. The results are also very consistent. It is therefore concluded that the measurement errors are similar to those determined previously.

Table 5-3. Differences between two sets of velocity measurements at the same depth.

Depth (borehole length)	Maximum. difference in measured velocity	Difference in anisotropy ratio of principal velocities	Difference in orientation of the maximum principal velocity
321.70 m	36 m/s	0.00	2°
545.70 m	297 m/s	0.04	6°
758.75 m	89 m/s	0.01	6°

It is therefore concluded that:

- the repeatability of the reported results for velocities is generally better than ± 100 m/s;
- the error in the orientation of the principal velocities is generally better than ± 10° where the anisotropy ratio is greater than 1.10 with greater errors below this limit (with an anisotropy ratio of less than about 1.03 the determination of the orientation is poorly constrained and has little significance in practice);
- errors in determining the anisotropy ratio and orientation are partly mitigated by the redundant data and regression analysis, and it is considered that the error in the anisotropy ratio is generally better than ± 0.02.

Conclusions

The results from the P-wave velocity measurements over the entire length of the borehole show that the maximum principal velocity, V_1, at the tested locations lies between 5,091–5,782 m/s with an anisotropy ratio of between 1.04 and 1.14.

There is an apparent trend in the maximum principal velocity, V_1, of slightly reducing velocities versus depth. V_1 lies between 5,285–5,678 m/s down to 500 m borehole length, with outlying values of 5,161 m/s at 343.75 m and 5,782 m/s at 487.90 m. Below 500 m the maximum principal velocity ranges between 5,091 and 5,463 m/s with no outlying values.

The anisotropy ratio is quite variable between 1.04 and 1.14 with an average of 1.10 and with no readily apparent trend versus depth.

The orientation of the maximum principal velocity, θ_{V1}, is strongly related to the foliation direction, with no apparent trend in orientation with depth, although there is a difference in average orientations above and below 350 m. In the upper part of the borehole (above 350 m) the orientation varies between 20° and 160° with an average of about 180°, whereas in the lower part of the borehole the orientation varies between 135° and 180° with an average about 160°. The orientation is neither parallel (180°), nor perpendicular (90°) to the foliation, as might be expected.

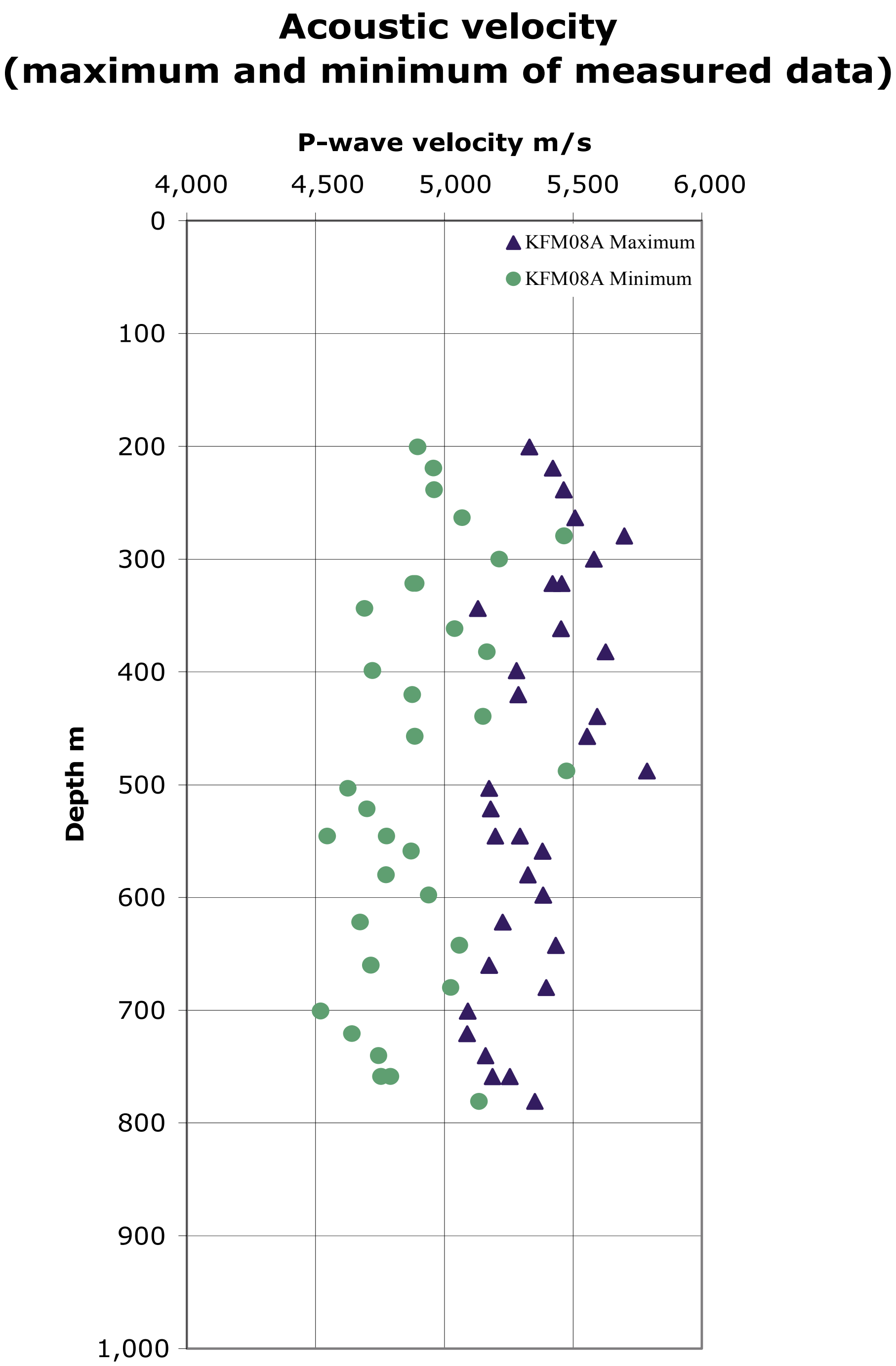

Figure 5-1. *Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KFM08A.*

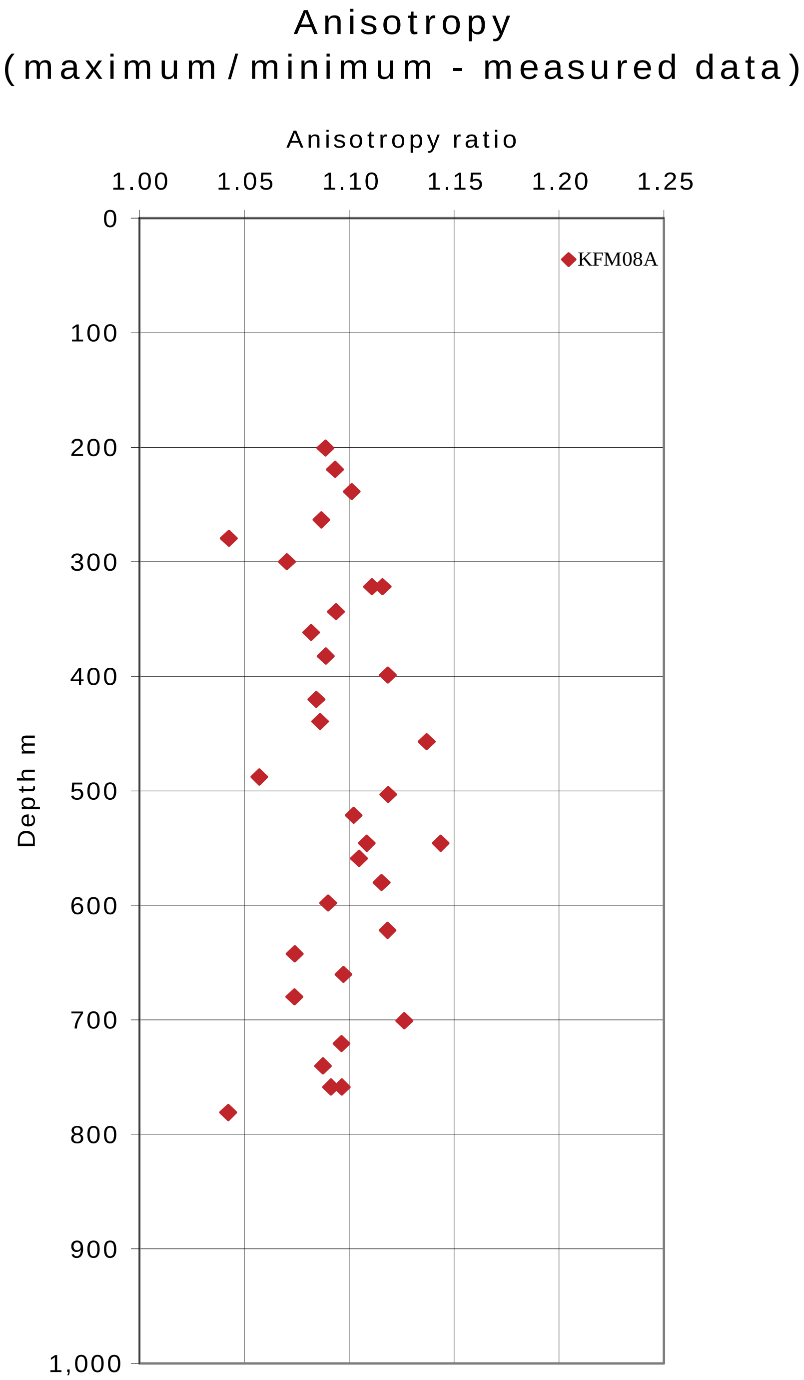

Figure 5-2. *Measured values of acoustic velocities anisotropy plotted versus borehole length in KFM08A.*

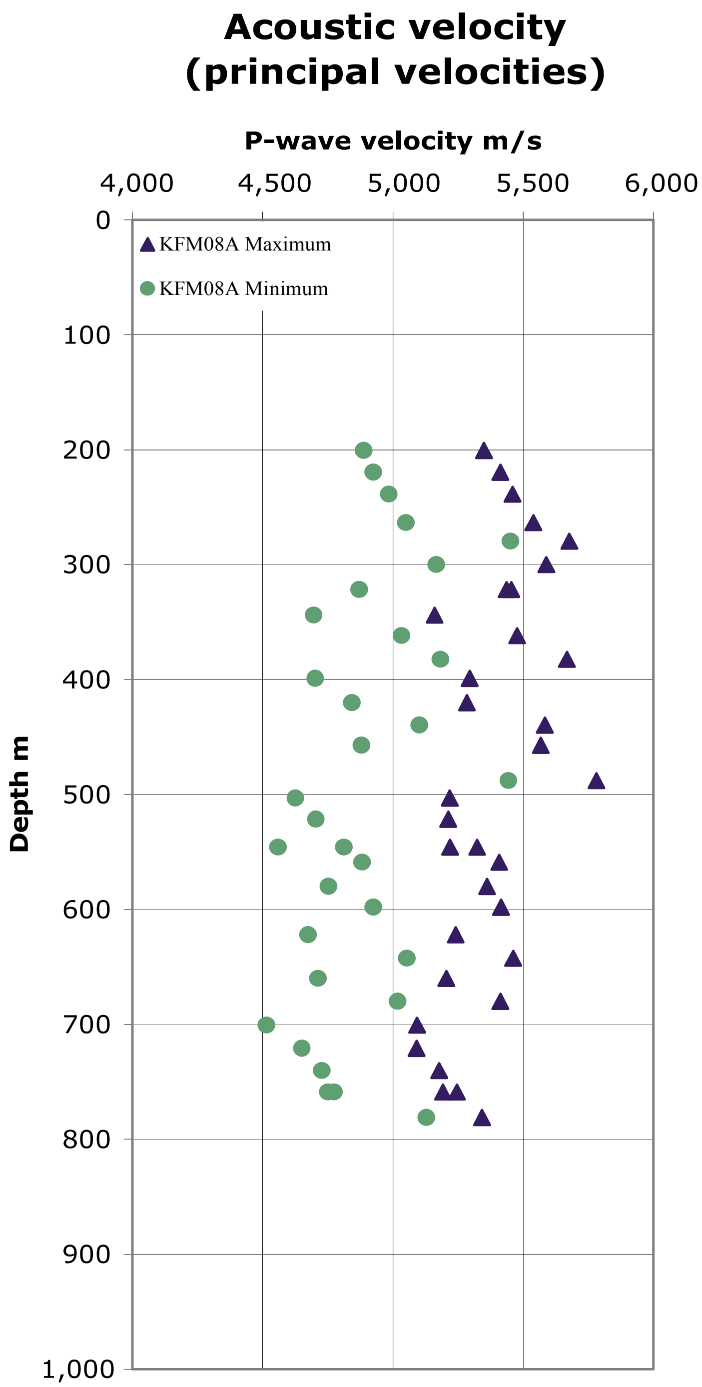

Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KFM08A.*

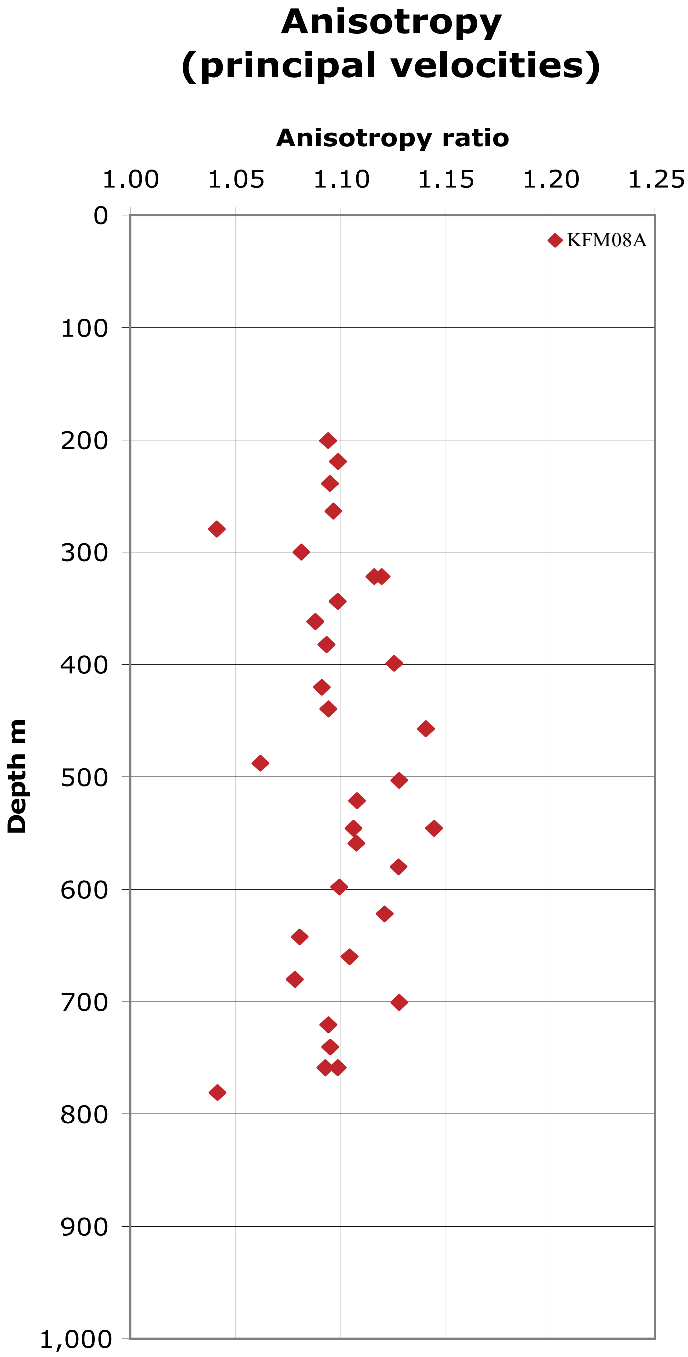

Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KFM08A.*

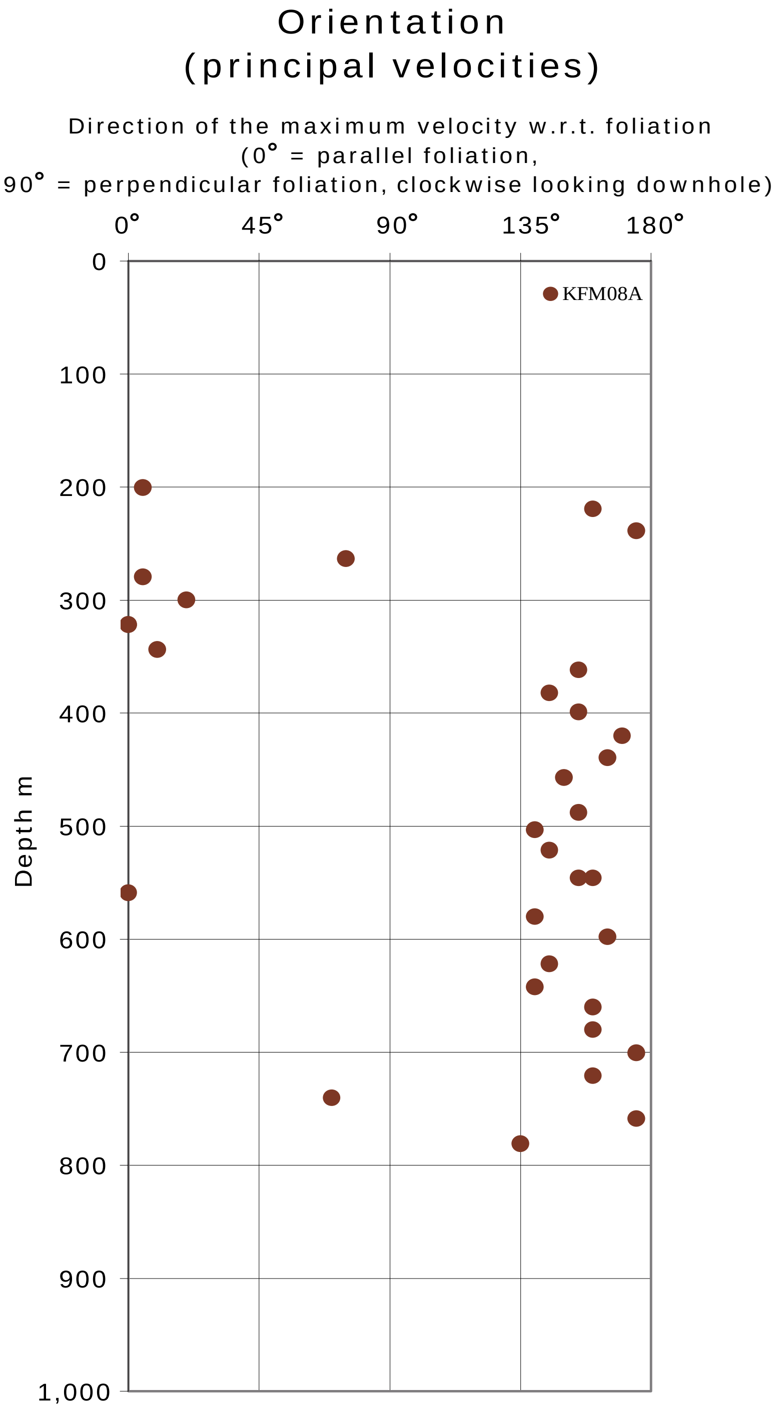

Figure 5-5. *Calculated orientation of the maximum principal acoustic velocity plotted versus borehole length in KFM08A.*

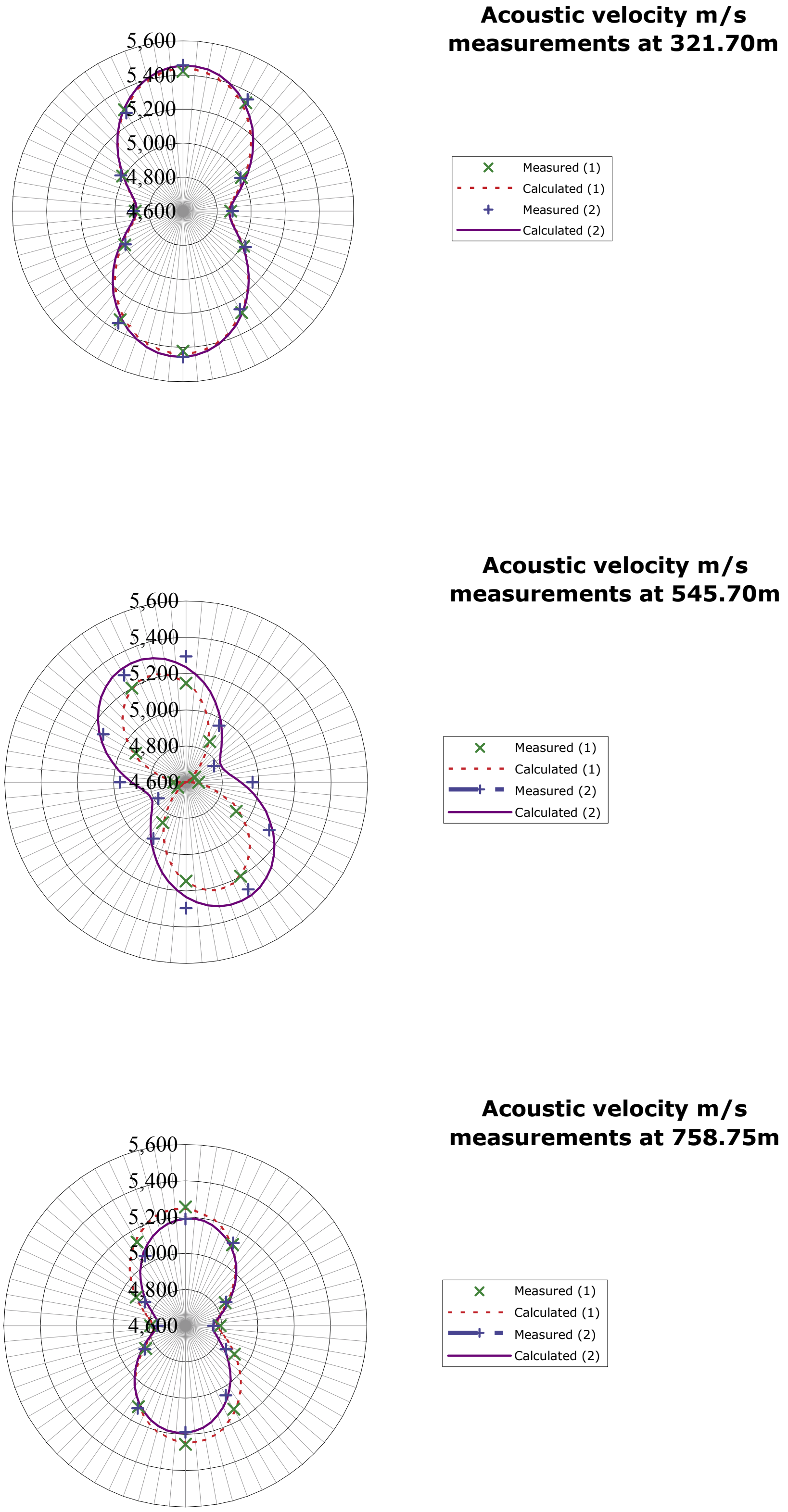

Figure 5-6. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at three different levels in borehole KFM08A.*

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Appendix A

Calibration measurements on aluminium cylinder of known velocity

Calibration measurements on aluminium cylinder, diameter 50.90 mm, with known velocity 6,320 m/s (this page).

Date and time	Known velocity m/s	Diameter mm	Time Measured S	Calculated S	Correction S
20050524 – 0930 hrs	6,320	50.90	9.18	8.05	1.12
20050524 – 1330 hrs	6,320	50.90	9.18	8.05	1.13
20050524 – 1600 hrs	6,320	50.90	9.18	8.05	1.13
20050525 – 0900 hrs	6,320	50.90	9.17	8.05	1.12
20050525 – 1200 hrs	6,320	50.90	9.16	8.05	1.11
Average			9.173		1.119