P-04-203

Forsmark site investigation

Borehole: KFM05A

Determination of P-wave velocity, transverse borehole core

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Norwegian Geotechnical Institute

July 2004

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Summary

The Norwegian Geotechnical Institute (NGI) has carried out P-wave measurements on drill cores from borehole KFM05A at Forsmark in June 2004. Thirty-two P-wave velocity measurements have been carried out from a total of 902 m of core.

The results from the P-wave velocity measurements over the entire length of the borehole show maximum velocities between c 5,000–5,800 m/s and a variable anisotropy ratio between 1.03 to 1.15. The maximum velocity appears to be approximately constant versus depth in the range of 5,400–5,800 m/s, with outlying low values of 5,092 m/s at 250 m borehole length, and 5,029–5,240 m/s between 486 m and 545 m. Also the anisotropy ratio appears to be constant with depth and lies between 1.03 to 1.10 with outlying high values of 1.15 at 363.80 m and 1.12 at 721.30 m.

The orientation of the maximum velocity is quite variable relative to the foliation, with no consistent or preferred direction, and it is neither parallel nor perpendicular to the foliation as might have been expected.

Sammanfattning

Norges Geotekniska Institut (NGI) har under juni 2004 utfört P-vågsmätningar på borrkärnor från borrhål KFM05A i Forsmark. Sammanlagt utfördes 32 st hastighetsbestämningar av P-vågen på kärnprover som utvalts från borrkärnor med en sammanlagd längd av 902 m.

Resultaten längs hela borrkärnan uppvisar en maximihastighet på mellan ca 5 000–5 800 m/s och en anisotropikvot varierande mellan 1,03 och 1,15. Den maximala hastigheten är relativt konstant och ligger mellan 5 400–5 800 m/s. Undantaget är vid längden 250 m, där hastigheten är 5 092 m/s, och mellan kärnlängderna 486–545 m, där hastigheten ligger mellan 5 029–5 250 m/s.

Maximihastighetens orientering är relativt varierande i förhållande till foliationsriktningen, utan någon konsistent eller dominerande riktning. Orienteringen är heller inte parallell eller vinkelrät mot foliationen, vilket hade förväntats.

Contents

1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on cores from borehole KFM05A at Forsmark in Sweden in accordance with the SKB Activity Plan AP PF 400-04-67 (SKB internal controlling document).

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski during the period 7th–8th June 2004 in compliance with SKB's method description MD 190.002, Version 1.0 (SKB internal controlling document).

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
KFM05A	29	32

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 the 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 volt 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 0.01 μs. The instrumentation was calibrated using a cylinder of aluminium of known acoustic velocity of the same diameter as the core. Several measurements were made each day on the calibration piece to check the state of 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 the drill core. The aluminium cylinder for calibration of the device is on the left.*

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

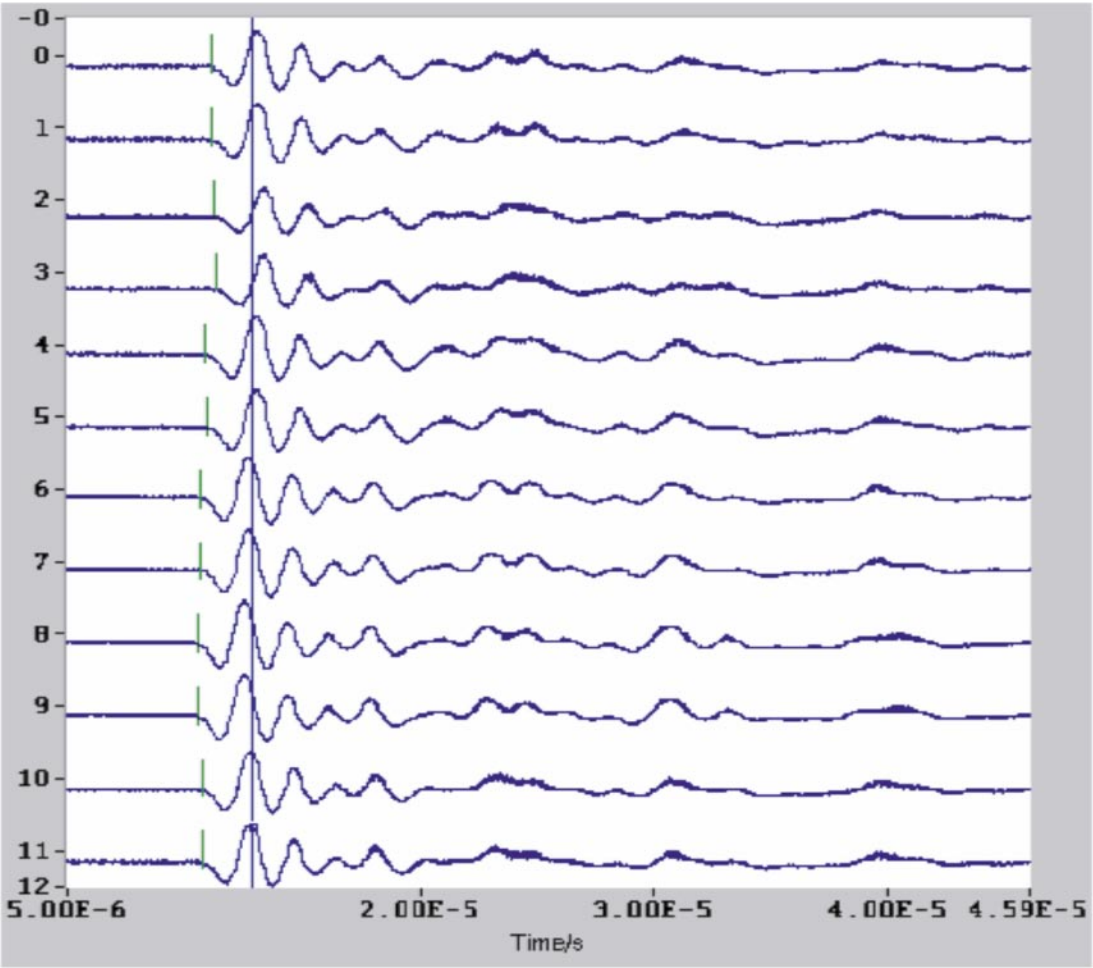


Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse the drill core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Twenty-nine core specimens of length c 200–500 mm and diameter about 50 mm were selected from borehole KFM05A while the complete length of the borehole (100.3 m–1,002.7 m) was displayed on the racks in the core shed at Forsmark. Borehole KFM05A is inclined c 60° from the horizontal plane, and hence vertical depth differs from borehole length by a factor c 0.87. The specimens were selected together by NGI and SKB.

These specimens represent the foliated granite-gneiss, granodiorite and tonalite with same veins of amphibolite and pegmatite, found along the major part of the borehole. Geological core logging had previously 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 of sampling. 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, though 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° and 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 was 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.

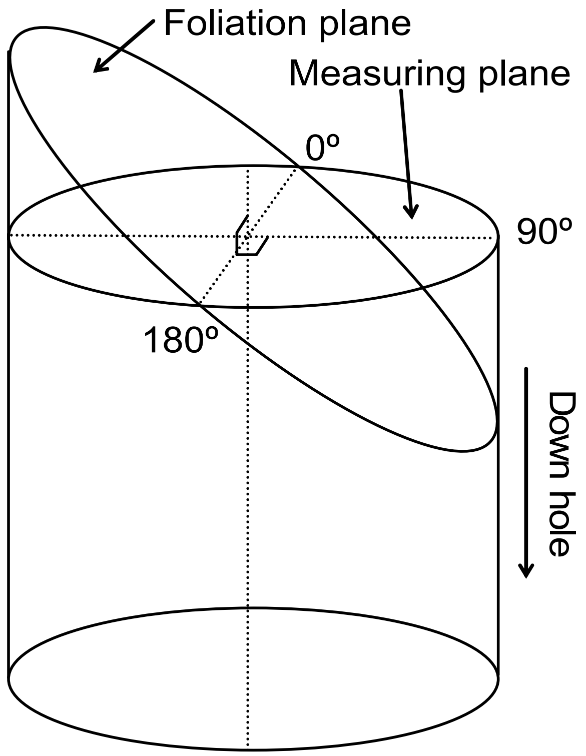


Figure 4-1. *Orientation of measurements.*

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, and 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 were determined from the Eigen values and vectors of the 2D tensor matrix:

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

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, and the velocity and anisotropy are shown diagrammatically versus borehole length in Figures 5-1 and 5-2.

The results of calculated principal velocities and their orientations, and the anisotropy ratio 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 (field note no Forsmark 371).

5.2 Discussion

Accuracy and Repeatability

Calibration tests on an aluminium cylinder indicated a variation of ± 0.025 μs in determination of the time pick, equivalent to differences in velocity of about ± 15 m/s. Some of this variation may be explained by variations in temperature, 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, 381.15 m, 545.18 m and 679.70 m, after the first series of tests were completed. These tests were repeated to investigate and determine typical values for the repeatability of velocity determinations.

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

At 381.15 m the difference in magnitude of the velocities is 0–75 m/s, the anisotropy ratio is the same as for the first measurement and there is no difference in orientation. At 545.18 m the difference in magnitude of the velocities is 36–70 m/s, the anisotropy ratio is the same, and there is about 5° difference in orientation. Finally, at 679.70 m the difference in magnitude of the velocities is 6–68 m/s, the anisotropy ratio differs by 0.02, and there is no difference in orientation.

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 also 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 381.15 m the maximum difference was 31 m/s, at 545.18 m 44 m/s, and at 679.70 m 25 m/s, see Figure 5-6.

Typically in the entire series of tests, the average deviation between the measured value and the model fit is about 0.3% (about 15 m/s), with a maximum error of 1.04% (about 50 m/s).

The deviation between the model fitted to the data and the measured data reported here is somewhat better than in the previous work /Chryssanthakis and Tunbridge, 2003a, b, c, d, e, f/. The results are also very consistent. It is therefore concluded that the measurement errors are similar to those determined previously with the repeatability of velocity measurements better than ± 100 m/s; the error in the orientation of the principal velocities is generally less than ± 10°, and the error in the anisotropy ratio is generally falls below ± 0.02.

Conclusions

The results from the P-wave velocity measurements over the entire length of the borehole show maximum velocities between c 5,000–5,800 m/s and a variable anisotropy ratio between 1.03 to 1.15. The maximum velocity appears to be approximately constant with depth and lies between 5,400–5,800 m/s, with outlying low values of 5,092 m/s at 250 m, and 5,029–5,240 m/s between 486 m and 545 m. The anisotropy ratio appears to be constant versus depth between 1.03 to 1.10 with outlying high values of 1.15 at 363.80 m and 1.12 at 721.30 m.

The orientation of the maximum velocity is quite variable relative to the foliation, with no consistent or preferred direction, and is neither parallel nor perpendicular to the foliation as might been expected.

Table 5-1. Measurements of acoustic velocity, transverse core in borehole KFM05A, Forsmark. (Orientation clockwise looking down hole, 0° is parallel with foliation).

Depth m	Diameter mm	Corrected time, mS Parallel foliation 0°	Perpendicular foliation 30°	60°	90°	120°	150°	Velocity m/S Parallel foliation 0°	Perpendicular foliation 30°	60°	90°	120°	150°	Anisotropy ratio
165.50	50.79	9.51	9.83	10.02	9.80	9.32	9.25	5339	5165	5067	5181	5447	5489	1,08
186.15	50.81	9.19	9.22	9.32	9.39	9.50	9.38	5527	5509	5449	5409	5346	5415	1.03
204.90	50.82	9.78	9.76	9.39	9.11	9.06	9.37	5194	5205	5410	5576	5607	5421	1.08
226.89	50.74	10.20	10.05	9.80	9.43	9.31	9.77	4973	5047	5176	5379	5448	5191	1.10
250.00	50.76	10.15	9.96	10.18	10.67	10.69	10.30	4999	5094	4984	4756	4747	4926	1.07
272.50	50.65	9.41	9.62	9.80	9.69	9.43	9.33	5380	5263	5166	5225	5369	5427	1.05
292.20	50.59	9.94	9.66	9.33	9.28	9.51	9.83	5088	5235	5420	5449	5318	5145	1.07
310.60	50.79	9.67	9.77	9.58	9.30	9.21	9.46	5250	5197	5300	5459	5512	5367	1.06
325.37	50.75	9.52	9.74	9.64	9.44	9.21	9.08	5329	5208	5262	5374	5508	5587	1.07
346.25	50.79	9.10	9.24	9.21	9.05	8.96	8.96	5579	5494	5512	5610	5666	5666	1.03
363.80	50.72	9.40	9.37	9.86	10.66	10.56	10.04	5394	5411	5142	4756	4801	5050	1.14
381.15	50.84	9.76	9.34	9.09	9.17	9.41	9.71	5207	5441	5591	5542	5401	5234	1.07
403.73	50.68	8.90	8.94	9.17	9.47	9.28	9.02	5692	5666	5524	5349	5459	5616	1.06
422.70	50.70	9.47	9.89	10.22	10.09	9.77	9.51	5352	5124	4959	5023	5187	5329	1.08
444.00	50.65	9.16	9.33	9.28	9.14	8.96	9.00	5527	5427	5456	5539	5651	5625	1.04
462.85	50.48	9.74	9.68	9.51	9.36	9.41	9.54	5181	5213	5306	5391	5362	5289	1.04
486.26	50.84	10.21	10.18	9.94	9.81	9.75	9.96	4978	4992	5113	5180	5212	5102	1.05
501.00	50.43	10.46	10.30	9.93	9.82	9.92	10.13	4819	4894	5077	5133	5082	4976	1.07
525.05	50.66	9.67	9.83	10.16	10.30	10.05	9.80	5237	5152	4984	4917	5039	5167	1.07
545.18	49.74	9.93	10.06	10.75	10.92	10.57	10.13	5007	4942	4625	4553	4704	4908	1.10
569.00	50.25	9.29	9.24	9.57	9.97	10.05	9.75	5407	5436	5249	5038	4998	5152	1.09
592.12	50.40	9.34	8.91	8.73	8.74	9.06	9.36	5394	5654	5771	5764	5561	5382	1.07
608.20	50.67	9.01	9.20	9.51	9.55	9.32	9.06	5621	5505	5326	5304	5434	5590	1.06
622.50	50.40	9.67	9.49	9.38	9.21	9.39	9.70	5210	5309	5371	5470	5365	5194	1.05
644.44	50.40	9.26	9.15	9.39	9.75	9.74	9.43	5441	5506	5365	5167	5173	5342	1.07
666.05	50.81	9.08	9.09	9.22	9.38	9.22	8.99	5593	5587	5509	5415	5509	5649	1.04
679.70	50.65	10.25	10.25	9.81	9.54	9.55	10.01	4940	4940	5161	5307	5302	5058	1.07
721.30	50.77	9.26	8.97	9.03	9.61	10.03	9.81	5480	5658	5620	5281	5060	5173	1.12
742.68	50.49	9.09	9.33	9.70	9.71	9.51	9.23	5552	5409	5203	5198	5307	5468	1.07
381.15	50.84	9.70	9.47	9.09	9.20	9.46	9.79	5239	5366	5591	5524	5372	5191	1.08
545.18	49.72	9.80	10.13	10.63	10.75	10.41	10.01	5072	4906	4676	4623	4774	4965	1.10
679.70	50.66	10.24	10.15	9.77	9.59	9.59	9.88	4945	4989	5183	5280	5280	5126	1.07

Table 5-2. Determinations of principal velocity and orientation , transverse core in borehole KFM05A, Forsmark. (Orientation clockwise looking down hole, 0° is parallel with foliation where identified)

Depth m	Maximum velocity m/s	Orientation	Minimum velocity m/s	Orientation	Anisotropy ratio	Foliation	
165.50	5498	145°	5064	55°	1.09	f	
186.15	5525	20°	5359	110°	1.03	w	
204.90	5629	105°	5176	15°	1.09	f	
226.89	5435	105°	4969	15°	1.09	f	
250.00	5092	20°	4743	110°	1.07	s	
272.50	5436	155°	5174	65°	1.05	s	
292.20	5464	80°	5087	170°	1.07	s	
310.60	5504	110°	5191	20°	1.06	s	
325.37	5559	135°	5198	45°	1.07	s	
346.25	5683	130°	5493	40°	1.03	s	
363.80	5453	15°	4731	105°	1.15	s	
381.15	5603	75°	5202	165°	1.08	s	
403.73	5719	5°	5384	95°	1.06	s	
422.70	5366	160°	4959	70°	1.08	s	
444.00	5652	130°	5423	40°	1.04	f	
462.85	5395	100°	5185	10°	1.04	f	
486.26	5218	105°	4974	15°	1.05	f	
501.00	5152	95°	4842	5°	1.06	f	
525.05	5240	175°	4925	85°	1.06	f	
545.18	5029	0°	4552	90°	1.10	f	
569.00	5450	20°	4976	110°	1.10	f	
592.12	5809	70°	5366	160°	1.08	w	
608.20	5635	170°	5292	80°	1.06	f	
622.50	5450	80°	5189	170°	1.05	w	
644.44	5508	20°	5156	110°	1.07	w	
666.05	5642	175°	5446	85°	1.04	w	
679.70	5331	100°	4904	10°	1.09	w	
721.30	5694	35°	5064	125°	1.12	w	
742.68	5542	175°	5171	85°	1.07	w	
381.15	5579	75°	5182	165°	1.08	s	Repeat
545.18	5060	175°	4612	85°	1.10	f	Repeat
679.70	5317	100°	4951	10°	1.07	w	Repeat

f= foliation (clearly identifiabl
n=no identifiable foliation
w=weak f oliation (not good)
s=strong foliation (good)

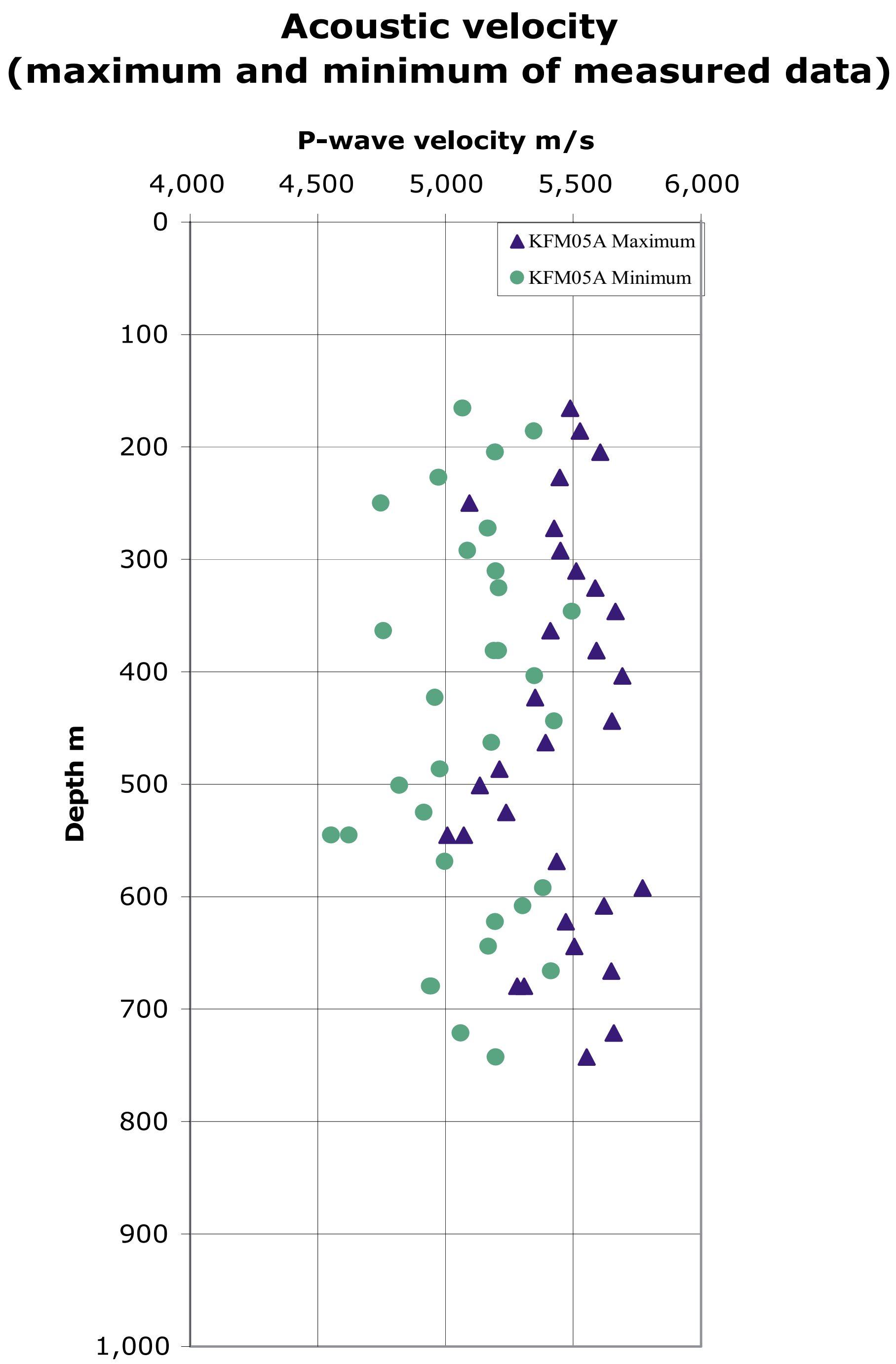


Figure 5-1. *Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KFM05A.*

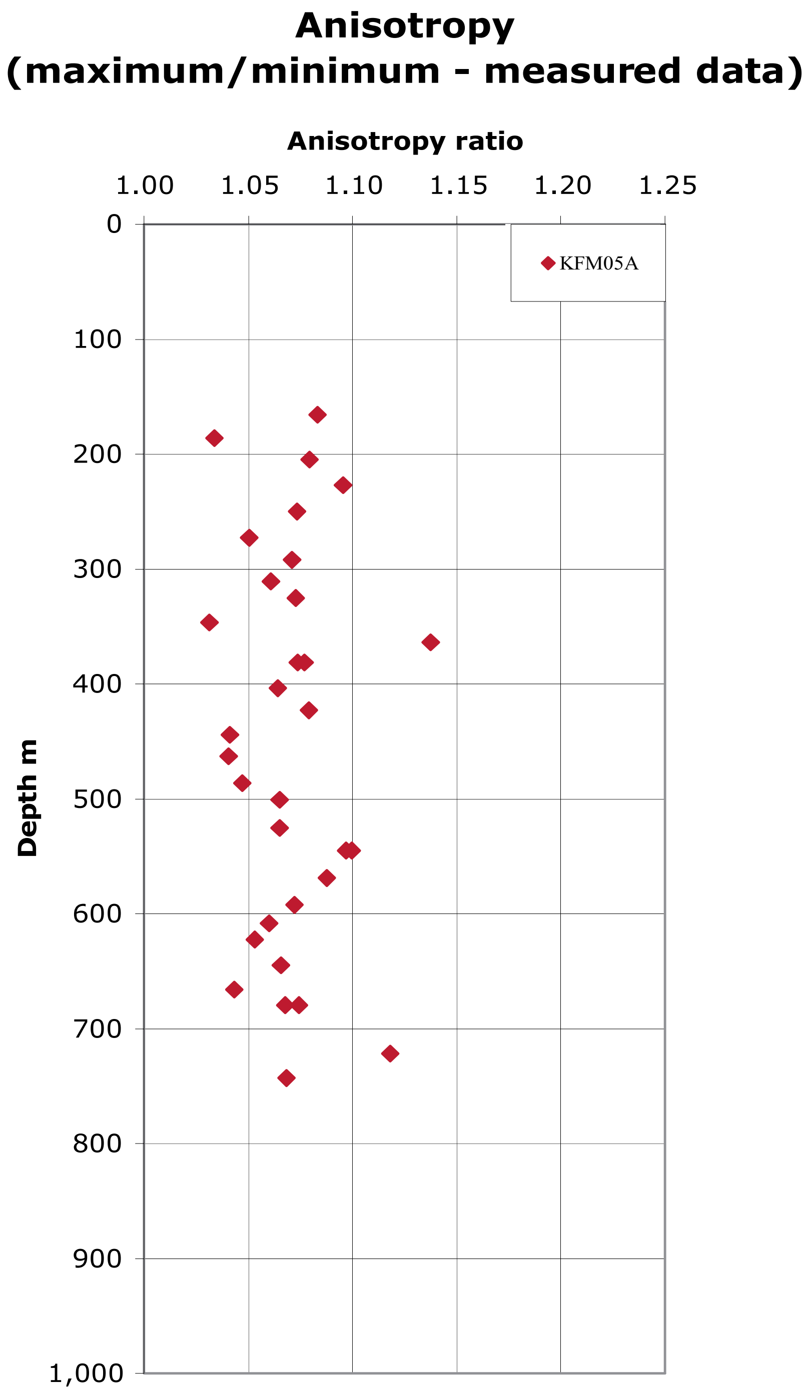


Figure 5-2. *Measured values of acoustic velocities anisotropy plotted versus borehole length in KFM05A.*

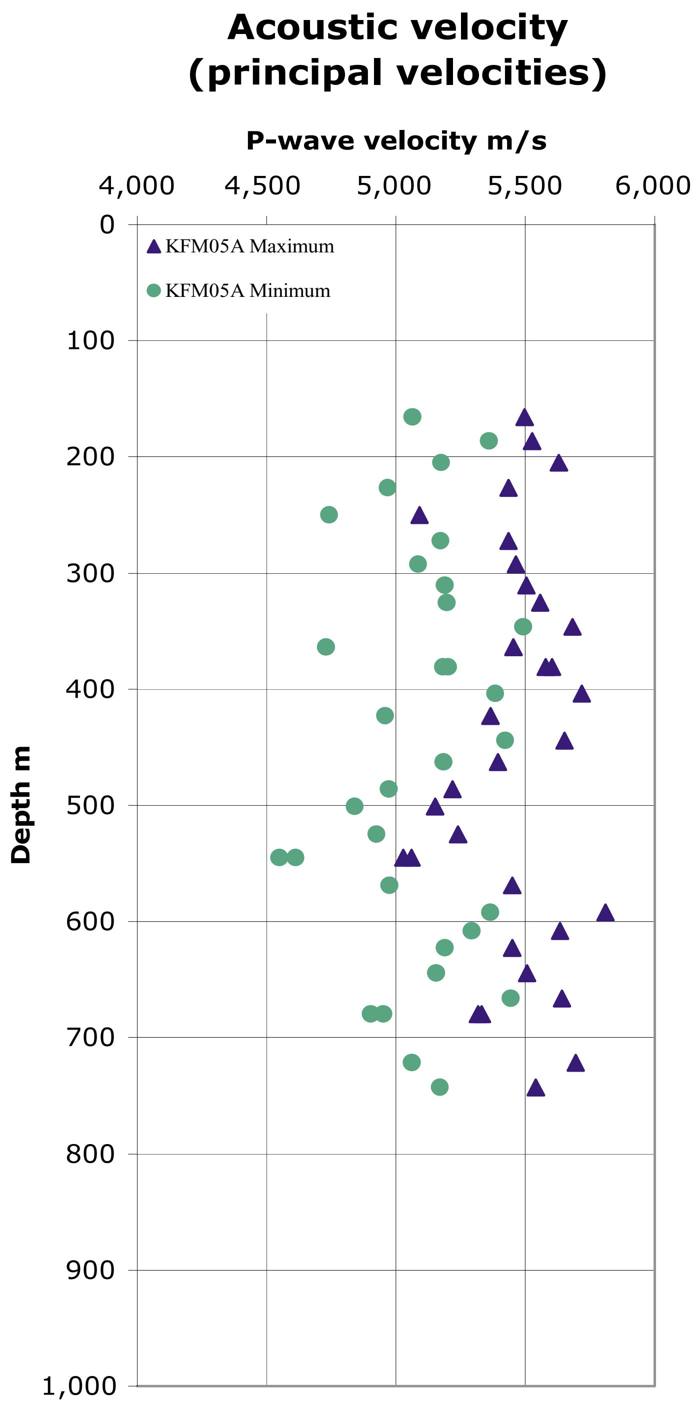


Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KFM05A.*

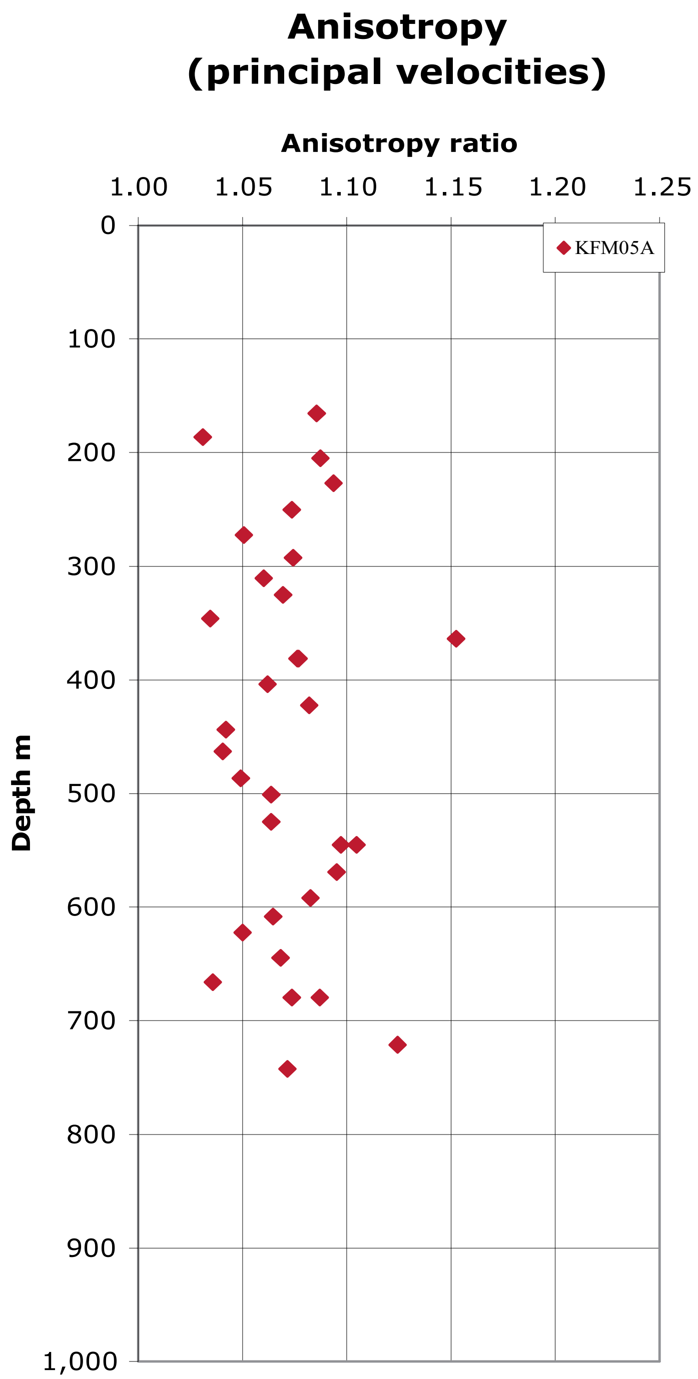


Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KFM05A.*

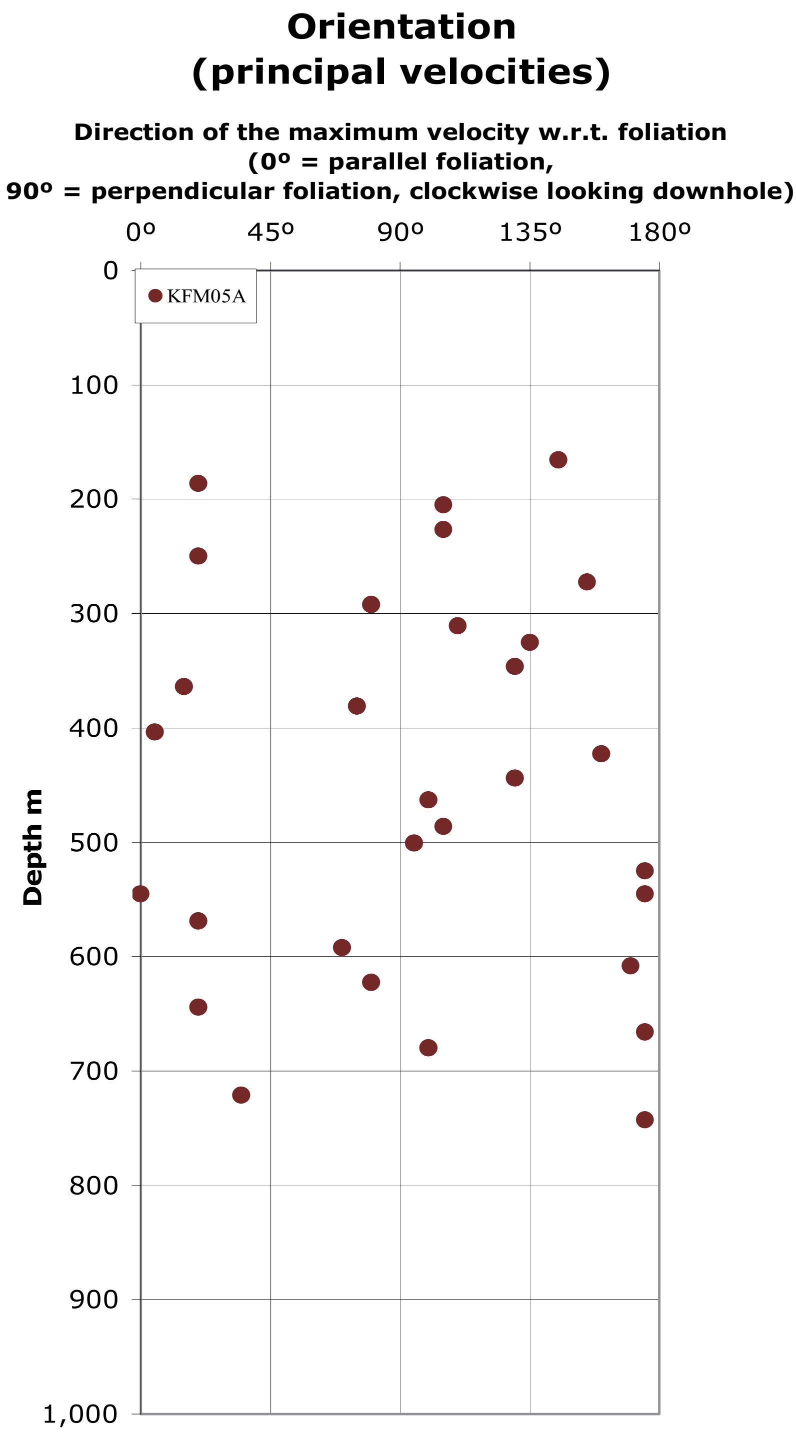
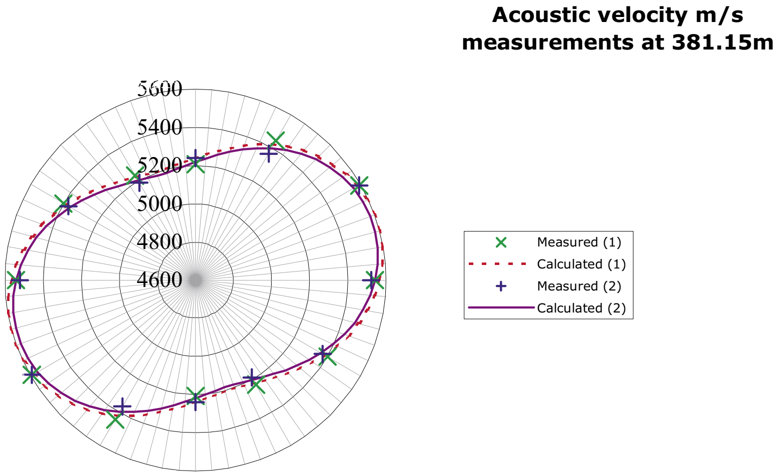
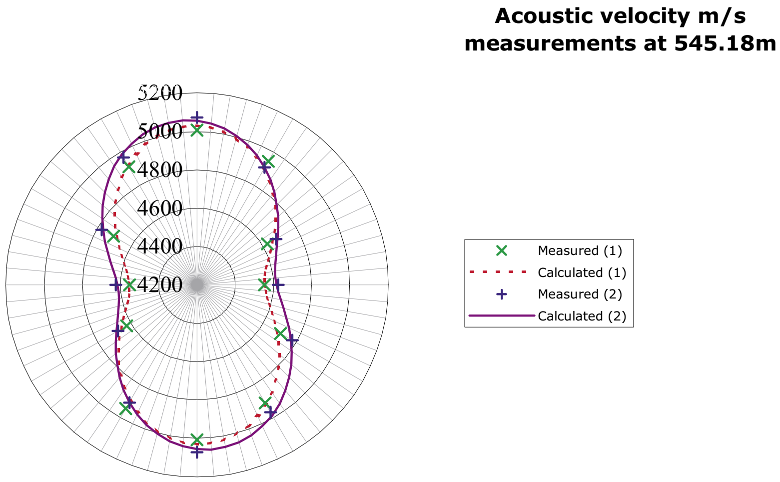


Figure 5-5. *Calculated orientation of the maximum principal acoustic velocity plotted versus borehole length in KFM05A.*





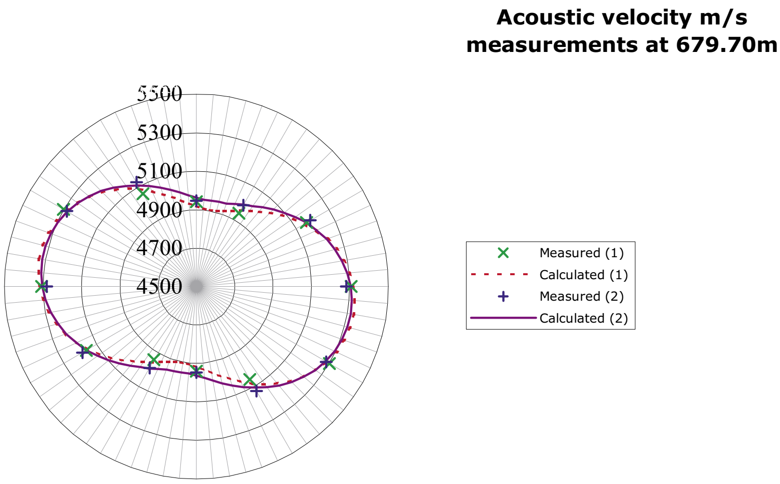


Figure 5-6. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at three different depths in borehole KFM05A.*

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Appendix A

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 µS	**Calculated µS**	**Correction µS**
20040607 – 1530 hrs	6,320	50.90	9.19	8.05	1.14
20040607 – 1630 hrs	6,320	50.90	9.17	8.05	1.12
20040608 – 0900 hrs	6,320	50.90	9.14	8.05	1.09
20040608 – 1200 hrs	6,320	50.90	9.18	8.05	1.13
20040608 – 1530 hrs	6,320	50.90	9.17	8.05	1.12
Average			9.170		1.116