P-04-181

Forsmark site investigation

Borehole: KFM04A

Determination of P-wave velocity, transverse borehole core

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Norwegian Geotechnical Institute, Oslo

June 2004

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Keywords: AP PF 400-04-02, Field note no Forsmark 303, Rock mechanics, P-wave velocity, Anisotropy.

Summary

The Norwegian Geotechnical Institute has carried out P-wave measurements on drill cores from borehole KFM04A at Forsmark in January 2004. Thirty-four P-wave velocity measurements have been carried out from a total of 900 m of core.

The results from the P-wave velocity measurements show a generally consistent pattern over the whole length of the borehole with maximum velocities between 4,887–5,843 m/s and a variable anisotropy ratio of between 1.01 to 1.09. From 158 m to 640 m borehole length the values of the maximum velocity appear to show a decreasing trend from between 5,391–5,843 m/s to 4,968–5,215 m/s, though there is considerable scattering of vales between 5,025–5,794 m/s at 400–500 m borehole length. Below 640 m the values of the maximum velocity are more consistent and generally lie between 5,099–5,537 m/s with an outlier of 4,887 m/s at 851 m borehole length. The anisotropy ratio is generally between 1.02–1.04, except around 250 m where it is about 1.08, and below about 800 m where the values are scattered between 1.01–1.09.

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 januar 2004 utfört P-vågsmätningar på borrkärnor från borrhål KFM04A i Forsmark. Sammanlagt utfördes 34 st hastighetsbestämningar av P-vågen på kärnprover som utvalts från borrkärnor med en sammanlagd längd av 900 m.

Resultaten uppvisar ett likformigt mönster längs hela borrhålslängden, där de högsta hastigheterna återfinns i intervallet 4 887–5 843 m/s och anisotropikvoten varierar mellan 1.01 och 1.09. Mellan borrhålslängden 158 m och 640 m indikerar resultaten en minskande trend, från 5 391–5 843 m/s till 4 968–5 215 m/s. Dock fås en stor spridning av resultaten mellan längderna 400 m och 500 m med hastigheter mellan 5 025–5 794 m/s. Under 640 m är resultaten mer likartade och hastigheterna ligger mellan 5 097–5 537 m/s med ett undantag för längden 851 m där den högsta hastigheten är 4 887 m/s. Anistropikvoten ligger generellt mellan 1.02–1.04, förutom kring borrhålslängden 250 m där kvoten är ungefär 1.08, och under 800 m där kvoten varierar mellan 1.01 och 1.09.

Den maximala hastighetens orientering är relativt varierande i förhållande till foliationsriktningen, utan någon 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 KFM04A at Forsmark in Sweden in accordance with SKB Activity Plan AP PF 400-04-02 (SKB internal controlling document).

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski during the period January 21–22, 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 tests performed and the number of joint sets is 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
KFM04A	34	37

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. 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 /Andreas Eitzenberger, 2002/. The equipment set-up is shown in Figure 3-1. The apparatus for measuring acoustic P-wave travel time is shown in Figure 3-2.

Figure 3-1. *NGI's equipment set up for measuring acoustic P-wave travel time transverse the drill core.*

Figure 3-2. *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.*

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 Figure 3-3 and previous work by /Chryssanthakis and Tunbridge, 2003a–b, 2004a–e/). 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 a consistent interpretation of the time pick, one operator made all the interpretations. The time pick could be 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 thick layer of honey (from a honey pot) was used as a coupling medium, as this proved to be one of the most effective medium and was easily removed by washing without damaging or contaminating the cores.

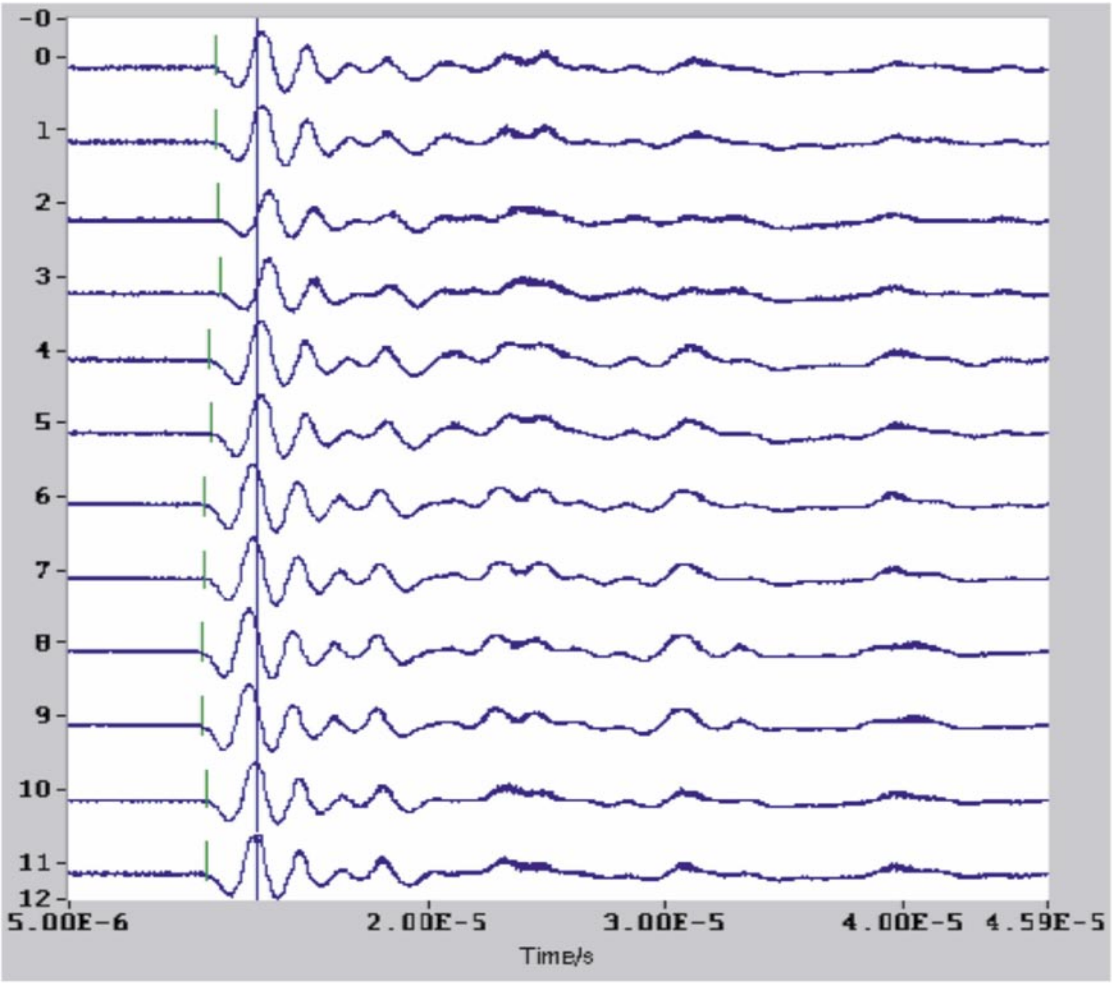


Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse the drill core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Thirty-four core specimens of length c. 200–500 mm and diameter about 50 mm were selected from borehole KFM04A while the complete length of the borehole (107–1,001 m) was displayed on the racks in the core shed at Forsmark. Borehole KFM04A is inclined c. 60° from the horizontal plane and hence vertical depth differs from borehole length by a faxtor of c. 0.87. The specimens were selected by NGI and SKB.

These specimens represent the foliated metamorphic granodiorite, granite to granodiorite and tonalite with same veins of amphibolite and felsic to intermediate volcanic rock, found along the major part of the borehole. Detailed description of the specimens is available from the detailed core log 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. 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 30º intervals around the core, starting at 0º parallel with the foliation. However, the foliation was generally not identifiable and the tests were thus made at random orientations. 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 length 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 0º, 30º, 60º, 90º, 120º and 150º) 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 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.

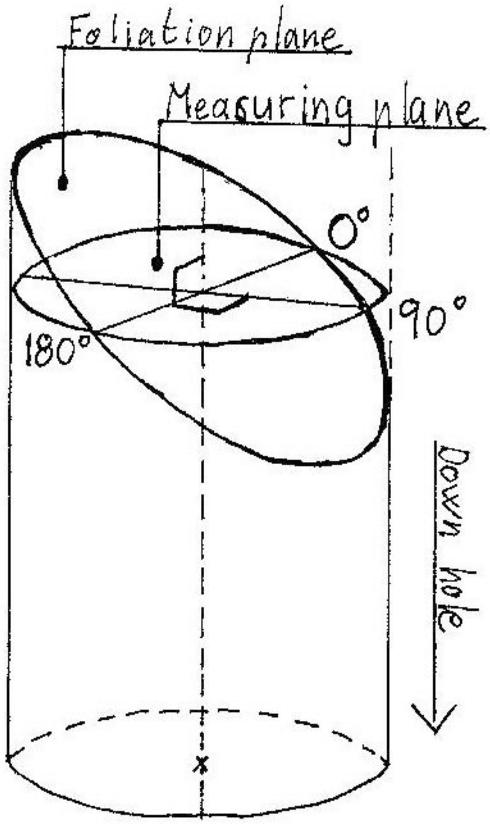


Figure 4-1. Orientation of measurements.

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 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 30º intervals around the core instead of 45° intervals 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 velocity, the anisotropy and the orientations of the principal velocities are presented in Table 5-2 and are 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 303).

5.2 Discussion

Accuracy and Repeatability

Calibration tests on an aluminium cylinder indicated a variation of ±0.05 μs in determination of the time pick, which represents a variation of about ±20 m/s in velocity. 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, 257.40 m, 685.35 m and 999.80 m borehole length, after the first series of tests were completed. These tests were repeated to determine typical values for the repeatability of velocity determinations. At 257.40 m the difference in magnitude of the velocities is 2–61 m/s, the anisotropy ratio differs by 0.01, and there is about 5° difference in orientation. At 685.35 m the difference in magnitude is 32–75 m/s, the anisotropy ratio differs by 0.01 and there is about 50° difference in orientation. Finally, at 999.80 m, the difference in magnitude is about 7–112 m/s, the anisotropy ratio is the same and the orientation is the same. The differences in the measured velocities are presumed to be due to the different positions of the transducers, the problems in seating the transducers and obtaining good signal contact with the rock and also due to the interpretation of the time pick.

Generally, there is a good fit between the measurements and the best fit line which suggests that random type errors are relatively small. At 257.40 m the maximum difference was 119 m/s, at 685.35 m 24 m/s, and at 906.60 m about 38 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 0.42% (about 23 m/s), with a maximum error of 2.47% (about 135 m/s).

The deviation between the model fitted to the data and the measured data is similar to the previous work for SKB:s site investigation /Chryssanthakis and Tunbridge, 2003a–b, 2004a–e/. The results are also very consistent. It is therefore concluded that the measurement errors are similar to those determined in the previous work with the repeatability of velocity measurements better than ±100 m/s and the error in the anisotropy ratio better than 0.02.

Conclusions

The results from the P-wave velocity measurements show a generally consistent pattern over the whole length of the borehole with maximum velocities between 4,887–5,843 m/s and a variable anisotropy ratio of between 1.01 to 1.09. From 158 m to 640 m borehole length the values of the maximum velocity appear to show a decreasing trend from between 5,391–5,843 m/s to 4,968–5,215 m/s, though there is considerable scattering of vales between 5,025–5,794 m/s at 400–500 m borehole length. Below 640 m the values of the maximum velocity are more consistent and generally lie between 5,099–5,537 m/s with an outlier of 4,887 m/s at 851 m. The anisotropy ratio is generally between 1.02–1.04, except around 250 m where it is about 1.08, and below about 800 m borehole length where the values are scattered between 1.01–1.09.

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.

Table 5-1. Measurements of acoustic velocity, transverse core in borehole KFM04A, Forsmark. (Orientation clockwise looking down hole, 0º is parallel with foliation where identified.)

Depth m	Diameter mm	Corrected time, mS: Parallel foliation 0º	Perpendicular foliation 30º	60º	90º	120º	150º	Velocity m/S: Parallel foliation 0º	Perpendicular foliation 30º	60º	90º	120º	150º	Anisotropy ratio
158,20	50,71	9,22	9,16	9,03	9,08	9,11	9,11	5498	5534	5613	5582	5564	5564	1,02
162,30	50,68	9,31	9,32	9,27	9,24	9,26	9,31	5441	5436	5465	5483	5471	5441	1,01
166,65	50,75	8,69	8,68	8,76	8,75	8,81	8,73	5837	5844	5791	5797	5758	5811	1,01
248,00	50,69	9,19	8,95	9,09	9,55	9,65	9,48	5513	5661	5574	5306	5251	5345	1,08
255,30	50,68	9,43	9,47	9,84	9,82	9,91	9,48	5372	5349	5148	5159	5112	5344	1,05
257,40	50,71	9,44	9,68	9,80	10,06	9,31	9,18	5370	5237	5172	5039	5445	5522	1,10
262,53	50,71	9,28	9,64	9,92	9,83	9,39	9,19	5462	5258	5110	5157	5398	5516	1,08
402,10	50,86	9,25	8,98	8,79	8,84	8,89	8,90	5496	5661	5784	5751	5719	5712	1,05
406,05	50,93	10,39	10,23	10,20	10,18	10,12	10,28	4900	4977	4991	5001	5031	4952	1,03
406,85	50,91	10,19	10,26	10,11	10,11	9,98	10,02	4994	4960	5034	5034	5099	5079	1,03
408,25	50,70	9,84	9,62	9,56	9,49	9,48	9,54	5150	5268	5301	5340	5346	5312	1,04
485,50	50,46	8,89	9,12	9,11	9,46	9,19	8,85	5674	5531	5537	5332	5488	5699	1,07
508,85	50,71	9,20	9,48	9,79	9,55	9,28	9,24	5510	5347	5178	5308	5462	5486	1,06
535,60	50,50	10,07	10,03	10,13	10,32	10,34	10,23	5013	5033	4983	4892	4882	4935	1,03
562,35	50,71	9,94	9,92	9,93	9,83	9,72	9,72	5100	5110	5105	5157	5215	5215	1,02
586,30	50,79	10,35	10,46	10,54	10,40	10,25	10,23	4905	4854	4817	4882	4953	4963	1,03
609,45	50,83	10,29	10,29	10,16	10,06	9,94	10,14	4938	4938	5001	5051	5112	5011	1,04
636,70	50,68	10,14	10,27	10,44	10,41	10,35	10,26	4996	4933	4853	4867	4895	4938	1,03
660,25	50,71	9,53	9,49	9,64	9,93	9,83	9,53	5319	5341	5258	5105	5157	5319	1,05
685,35	50,77	9,77	9,79	9,74	9,72	9,66	9,64	5195	5184	5210	5221	5254	5265	1,02
710,75	50,51	9,40	9,41	9,33	9,22	9,36	9,42	5371	5366	5412	5476	5394	5360	1,02
744,45	50,53	9,23	9,26	9,48	9,48	9,32	9,08	5472	5455	5328	5328	5419	5563	1,04
761,15	50,64	9,83	9,75	9,70	9,75	9,58	9,63	5150	5192	5219	5192	5284	5256	1,03
785,90	50,65	9,93	9,72	9,77	10,06	10,14	10,02	5099	5209	5182	5033	4993	5053	1,04
806,15	50,60	9,37	9,37	9,59	9,87	9,84	9,91	5398	5398	5274	5125	5140	5104	1,06
828,15	50,61	9,57	9,49	9,47	9,60	9,66	9,65	5286	5331	5342	5270	5237	5242	1,02
851,10	50,81	10,60	10,45	10,37	10,58	10,73	10,72	4792	4860	4898	4801	4734	4738	1,03
874,15	50,59	9,90	10,14	10,42	10,76	10,41	10,12	5108	4987	4853	4700	4858	4997	1,09
895,70	50,65	9,78	9,77	9,88	9,87	9,89	9,87	5177	5182	5125	5130	5119	5130	1,01
918,20	50,68	9,21	9,45	9,61	9,48	9,29	9,22	5500	5361	5272	5344	5453	5494	1,04
943,30	50,81	9,65	10,04	10,23	10,30	9,93	9,89	5263	5059	4965	4931	5115	5136	1,07
967,60	50,77	9,65	9,97	10,33	10,26	10,12	9,86	5259	5090	4913	4947	5015	5147	1,07
986,95	50,78	9,48	9,66	9,62	9,49	9,27	9,26	5354	5255	5277	5349	5476	5482	1,04
999,80	50,83	9,72	10,17	10,31	9,92	9,67	9,59	5227	4996	4928	5122	5254	5298	1,08
257,40	50,69	9,44	9,79	9,84	10,02	9,25	9,19	5368	5176	5149	5057	5478	5513	1,09
685,35	50,77	9,83	9,66	9,66	9,60	9,73	9,78	5163	5254	5254	5286	5216	5189	1,02
999,80	50,82	9,89	10,31	10,35	10,14	9,75	9,60	5137	4927	4908	5010	5210	5292	1,08

Table 5-2. Determinations of principal velocity and orientation, transverse core in borehole KFM04A, 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
158,20	5601	85°	5517	175°	1,02	s
162,30	5480	95°	5432	5°	1,01	s
166,65	5843	15°	5770	105°	1,01	s
248,00	5651	30°	5232	120°	1,08	s
255,30	5391	0°	5104	90°	1,06	s
257,40	5507	155°	5088	65°	1,08	f
262,53	5532	155°	5102	65°	1,08	f
402,10	5794	90°	5581	0°	1,04	f
406,05	5025	95°	4926	5°	1,02	f
406,85	5094	120°	4973	30°	1,02	f
408,25	5365	100°	5208	10°	1,03	f
485,50	5695	175°	5391	85°	1,06	f
508,85	5539	155°	5224	65°	1,06	f
535,60	5038	25°	4875	115°	1,03	f
562,35	5215	125°	5085	35°	1,03	f
586,30	4968	140°	4823	50°	1,03	f
609,45	5092	110°	4925	20°	1,03	s
636,70	4979	175°	4848	85°	1,03	s
660,25	5368	10°	5132	100°	1,05	s
685,35	5259	125°	5184	35°	1,01	s
710,75	5445	85°	5348	175°	1,02	s
744,45	5537	165°	5318	75°	1,04	s
761,15	5259	120°	5171	30°	1,02	s
785,90	5201	35°	4989	125°	1,04	s
806,15	5402	25°	5077	115°	1,06	f
828,15	5341	45°	5229	135°	1,02	f
851,10	4887	50°	4721	140°	1,04	f
874,15	5099	0°	4736	90°	1,08	f
895,70	5176	15°	5112	105°	1,01	f
918,20	5521	155°	5287	65°	1,04	f
943,30	5223	165°	4933	75°	1,06	f
967,60	5224	170°	4899	80°	1,07	f
986,95	5488	135°	5242	45°	1,05	f
999,80	5327	145°	4949	55°	1,08	f
257,40	5514	150°	5067	60°	1,09	f
685,35	5281	75°	5173	165°	1,02	s
999,80	5282	145°	4880	55°	1,08	f

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

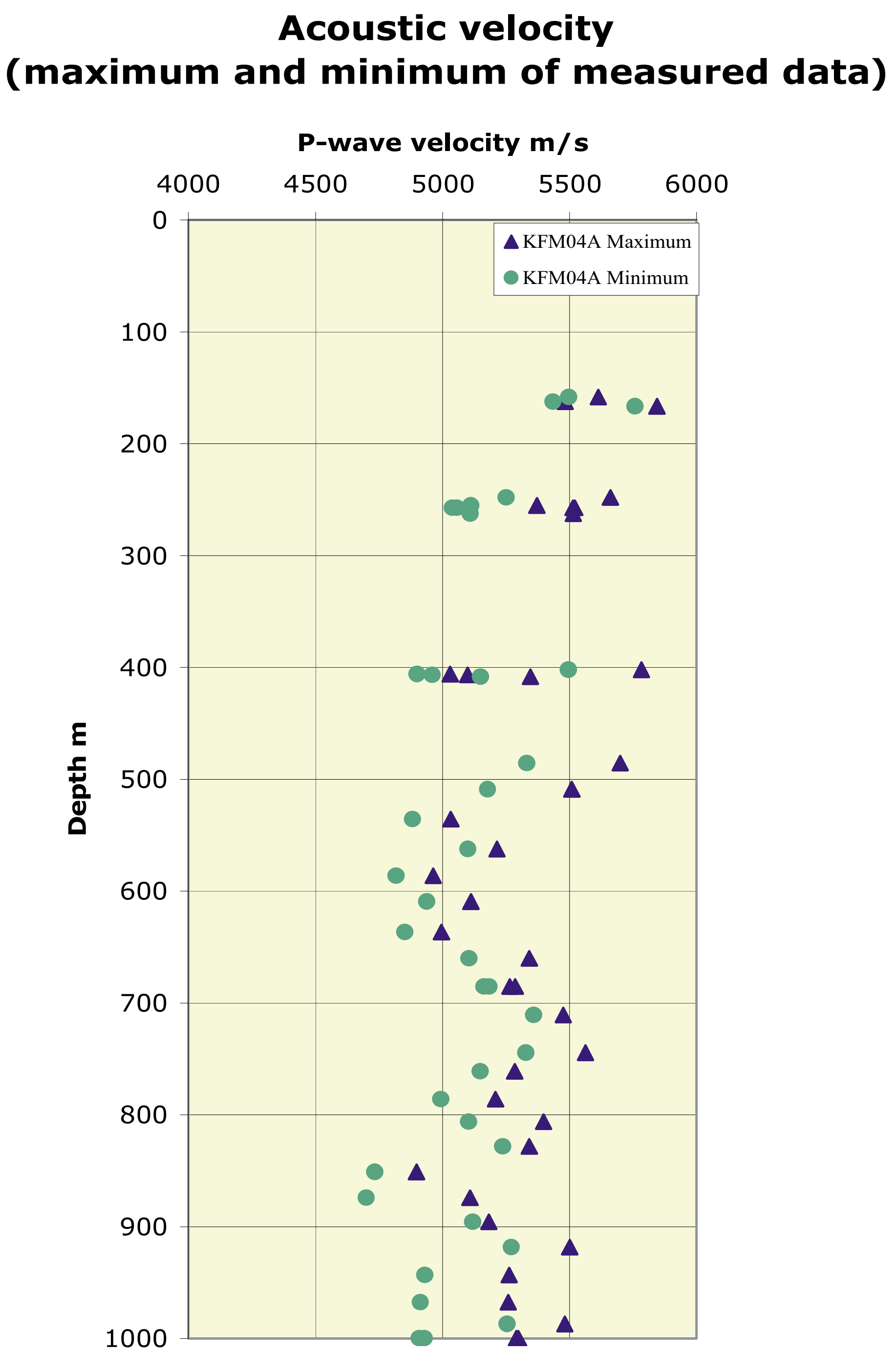


***Figure 5-1**. Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KFM04A.*

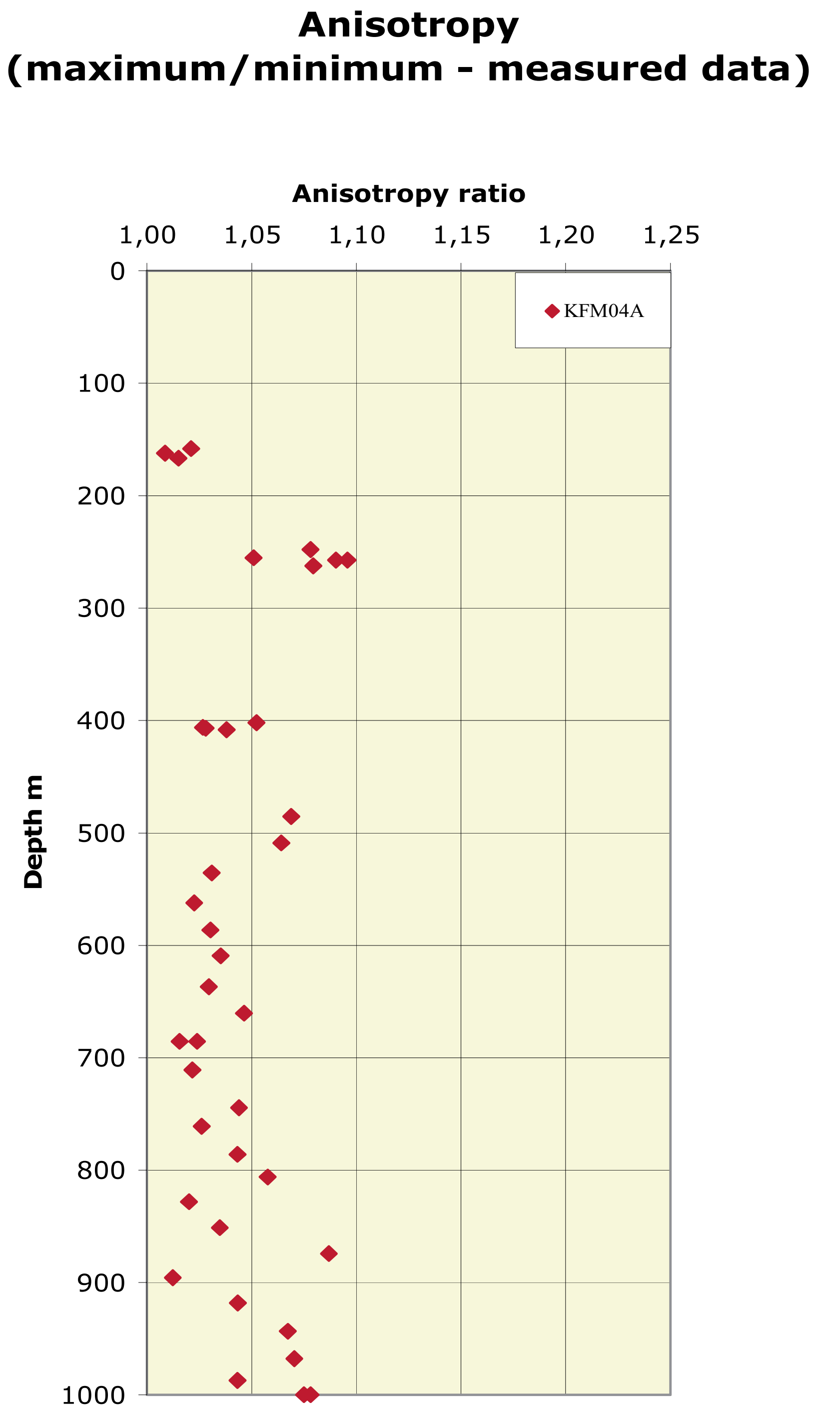


Figure 5-2.** Measured values of anisotropy in acoustic velocity plotted versus borehole length in KFM04A.**

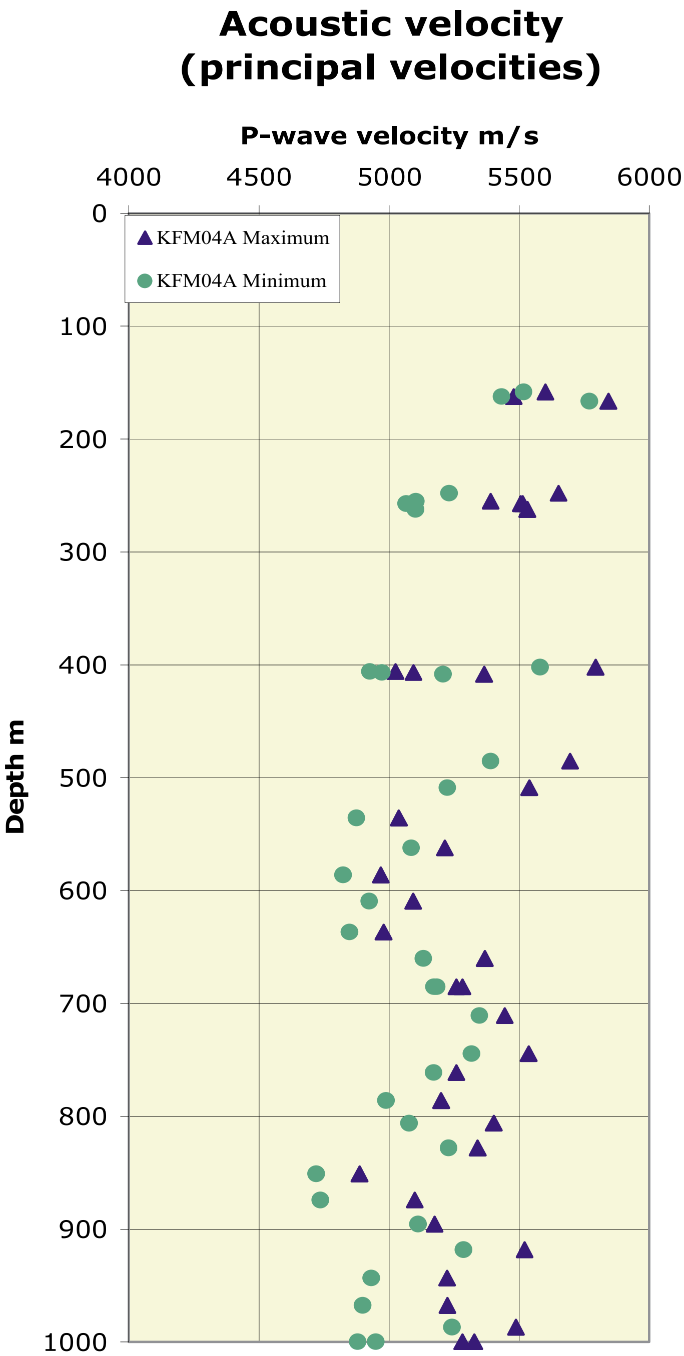


Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted against depth down borehole KFM04A.*

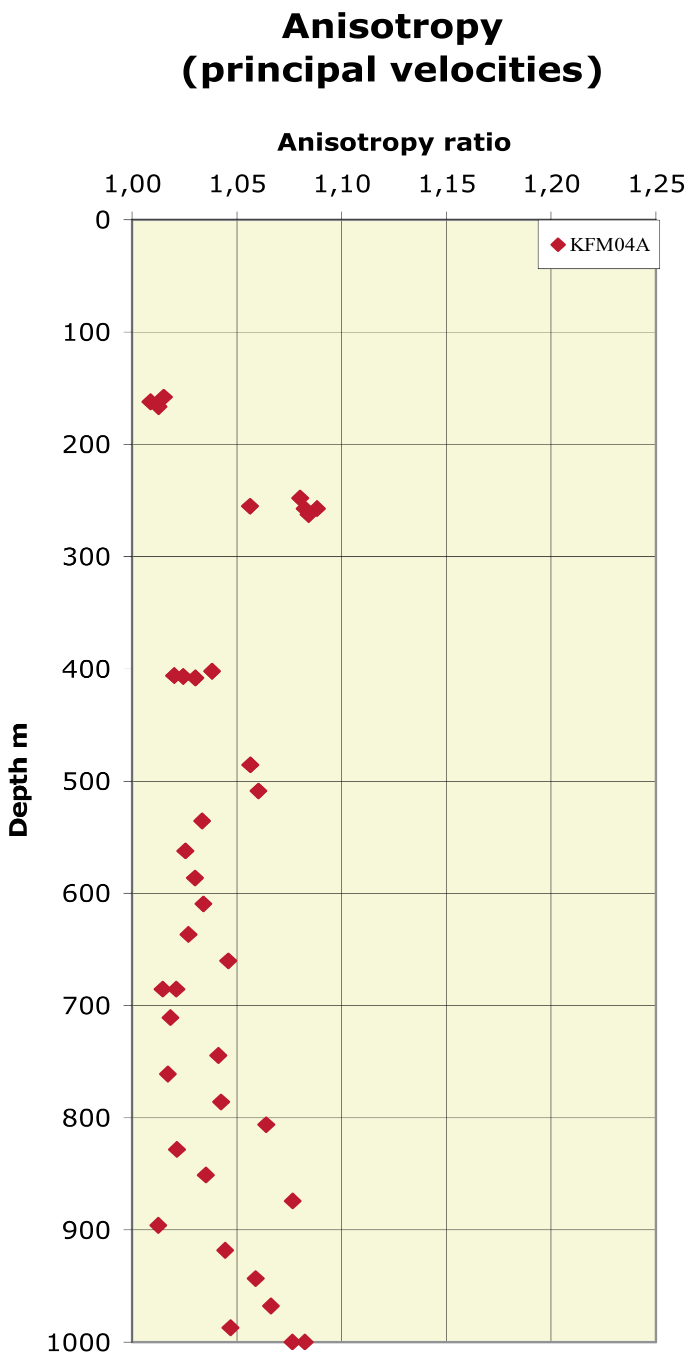


Figure 5-4. Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted against depth down borehole KFM04A.

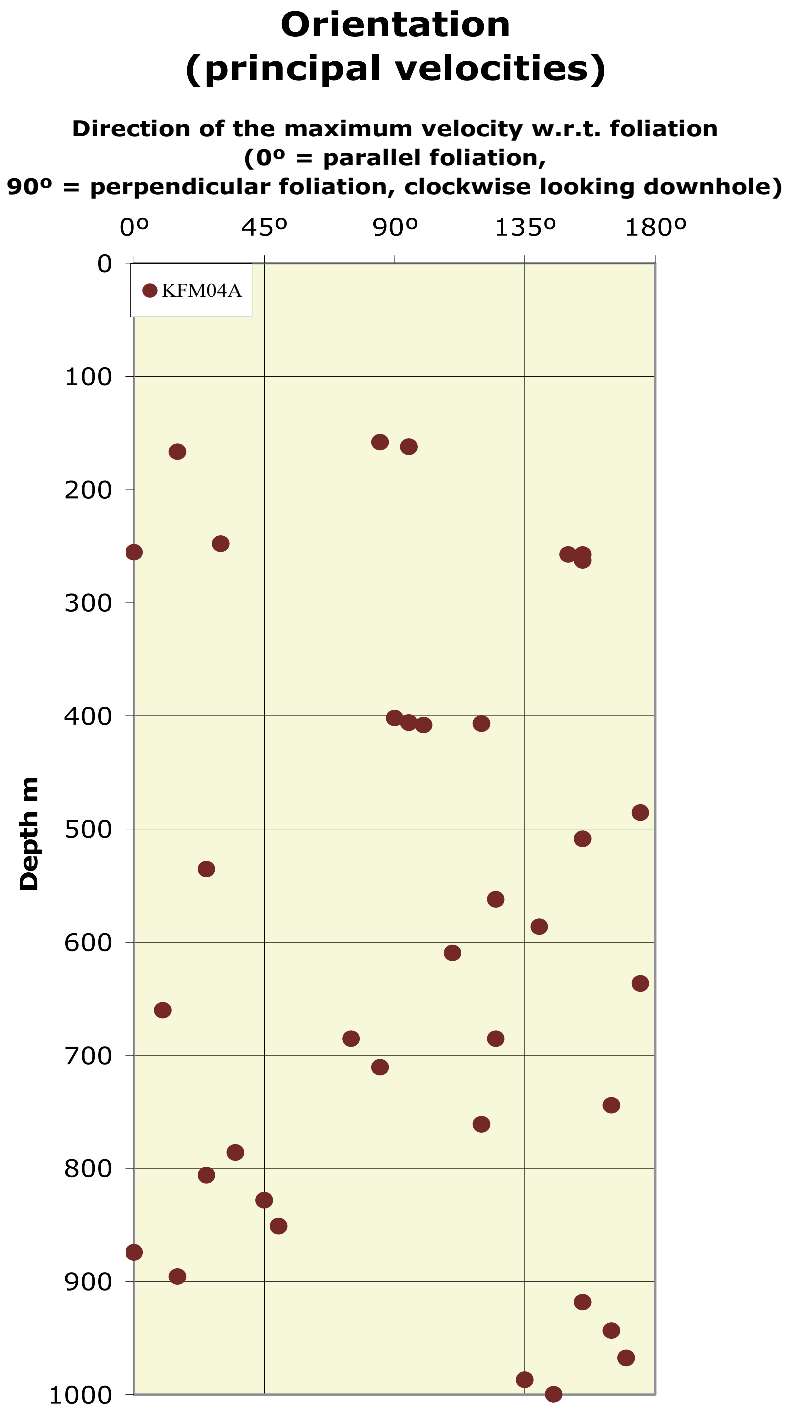
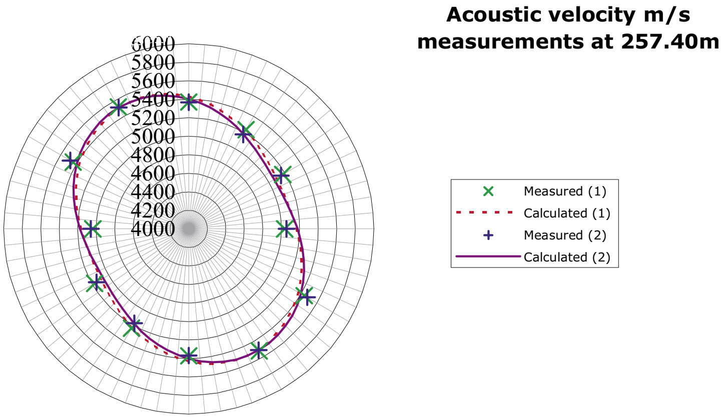
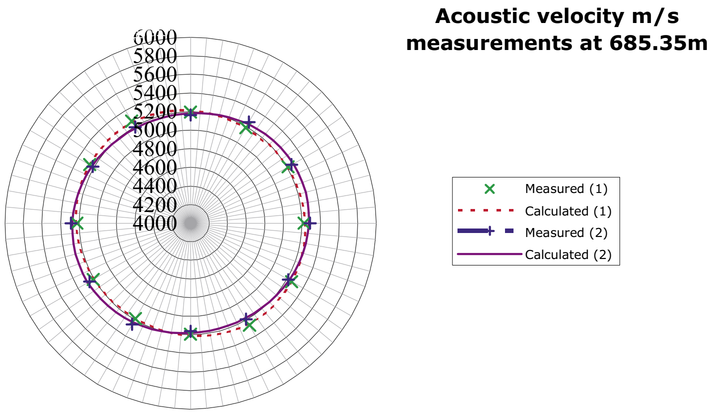


Figure 5-5. Calculated orientation of the maximum principal acoustic velocity plotted versus borehole length in KFM04A.





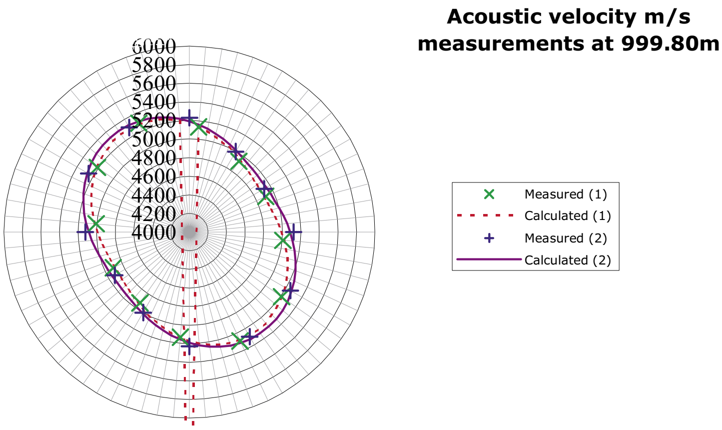


Figure 5-6. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of three determinations at the same depths in borehole KFM04A*.

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Appendix A

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

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

Date & time	Known velocity m/S	Diameter mm	Time Measured μS	Calculated μS	Correction μS
20040121–0930 hrs	6,320	50.90	9.16	8.05	1.11
20040121–1400 hrs	6,320	50.90	9.17	8.05	1.12
20040121–1730 hrs	6,320	50.90	9:16	8.05	1.11
20040122–0900 hrs	6,320	50:90	9.16	8.05	1.11
20040122–1100 hrs	6,320	50.90	9.20	8.05	1.15
Average			9.170		1.116