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Forsmark site investigation

Borehole KFM07A

Determination of P-wave velocity transverse borehole core

Panayiotis Chryssanthakis, Lloyd Tunbridge
Norwegian Geotechnical Institute, Oslo

October 2005

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Keywords: Rock mechanics, P-wave velocity, Anisotropy, AP PF 400-05-033.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

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Summary

The Norwegian Geotechnical Institute has carried out P-wave measurements on drill cores from borehole KFM07A at Forsmark in March 2005. Thirty-three P-wave velocity measurements have been performed from a total of 900 m of core.

The results from the P-wave velocity measurements over the entire length of the borehole show maximum principal velocities, V_1, between 4,744–5,605 m/s and an anisotropy ratio between 1.04 and 1.15.

There is an apparent trend in the maximum principal velocity, V_1, reducing slightly with depth. It lies between 5,239–5,501 m/s down to 400 m borehole length, with outlying values of 4,744 m/s at 296.95 m and 4,794 m/s at 318.25 m. Below 600 m the maximum principal velocity varies within the range 4,774–5,217 m/s with no outlying values.

The anisotropy ratio is quite variable between 1.04 and 1.15 with an average of 1.10 and displays no readily apparent trend with depth.

The orientation of the maximum principal velocity, θ_{V1}, is strongly related to the foliation direction, with an apparent small trend in orientation with depth. In the upper part of the borehole the orientation varies between 145° and 170° with an average about 160°. In the lower part of the borehole the orientation is slightly more variable between 120° and 160° with an average about 140°. It is not parallel (180°) or perpendicular (90°) to the foliation as might be expected.

Sammanfattning

Norges Geotekniske Institutt (NGI) har under Mars 2005 utfört P-vågsmätningar på borrkärnor från borrhål KFM07A i Forsmark. Sammanlagt har 33 stycken hastighetsbestämningar av P-vågor utförts på kärnprover från ett ca 1 000 m långt kärnborrhål, där avsnittet ca 100–1 000 m är kärnborrat.

Resultaten visar för hela den undersökta borrhålessektionen en maximihastighet som varierar mellan 4 744–5 605 m/s och en anisotropikvot mellan 1,04–1,15.

Maximihastigheten uppvisar en avtagande trend mot djupet. Ned till 400 m borrhålslängd varierar maximihastigheten kring 5 239–5 501 m/s, med undantag för två mätvärden. Vid 296,95 m respektive 318,25 m har P-vågshastigheter på 4 744 m/s respektive 4 794 m/s uppmätts. Från 600 m borrhålslängd och vidare ned varierar maximihastigheten kring 4 774–5 217 m/s.

Anisotropikvoten varierar mellan 1,04–1,15, och har ett medelvärde kring 1,10. Mätningarna visade i det avseendet ingen speciell tendens mot djupet.

Maximihastighetens orientering är starkt relaterad till foliationsriktningen och visar en liten tendens till djupberoende. I den övre delen av borrhålet och ned till 400 m varierar riktningen från 145° till 170° med ett medelvärde kring 160°. Från 600 m och nedåt varierar riktningen mellan 120° och 160° med ett medelvärde kring 140°. Maximalhastighetens 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 drillcores from borehole KFM07A at Forsmark in Sweden in accordance with SKB's Activity Plan AP PF 400-05-023. 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 drillcore 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 1st–4th of March 2005 in compliance with SKB's method description MD 190.002.

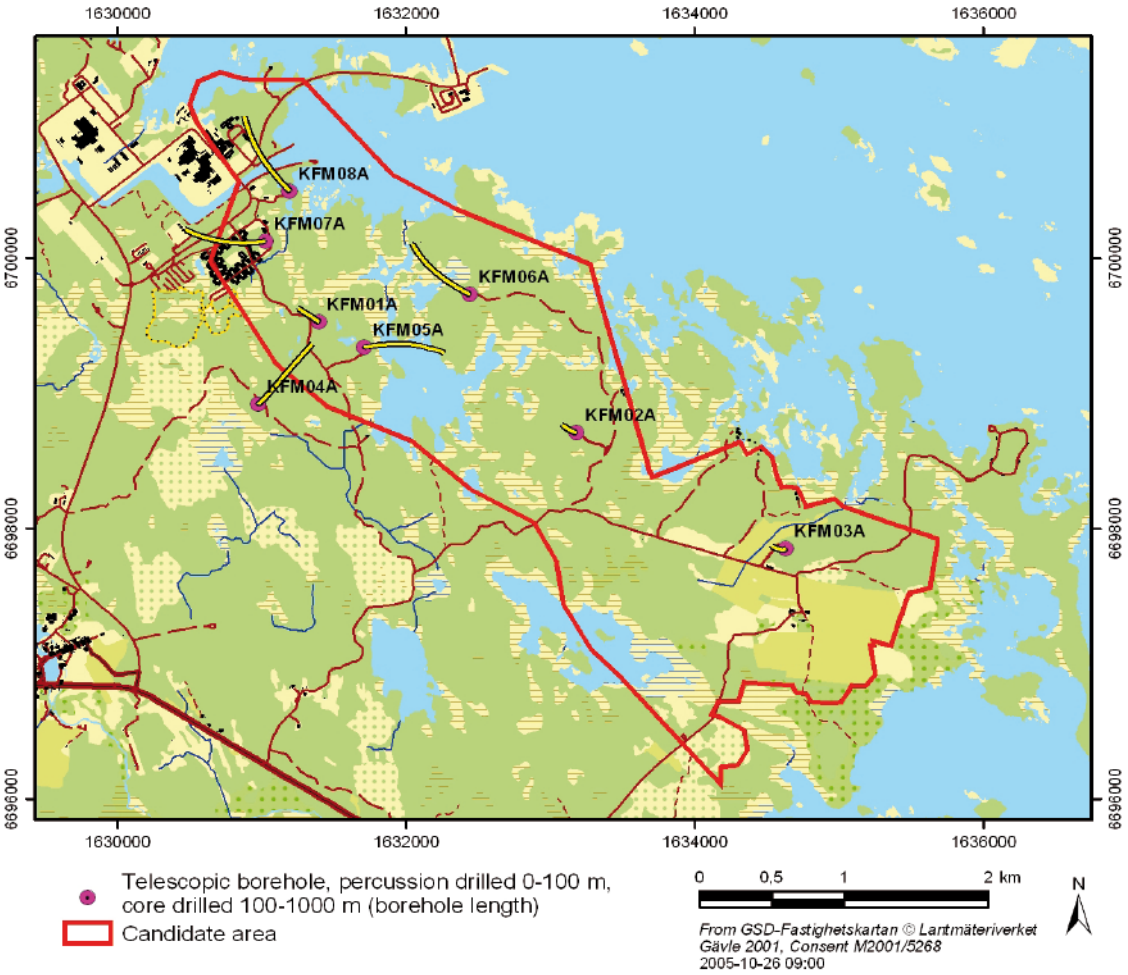

Figure 1-1. *Location of all telescopic boreholes drilled up to now within or close to the Forsmark candidate area. The projection of each borehole on the horizontal plane at top of casing is also shown in the figure.*

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
KFM07A	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 the SKB report entitled "Detection of Anisotropy by Diametral Measurements of Longitudinal Wave Velocities on Rock Cores" /Eitzenberger, 2002/.

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 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 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 0.01 μs. The instrumentation was calibrated using a cylinder of aluminium of known acoustic velocity of the same diameter as the core. Several measurements were 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 3-2**. NGI's equipment set-up for measuring acoustic P-wave travel time transverse borehole core.*

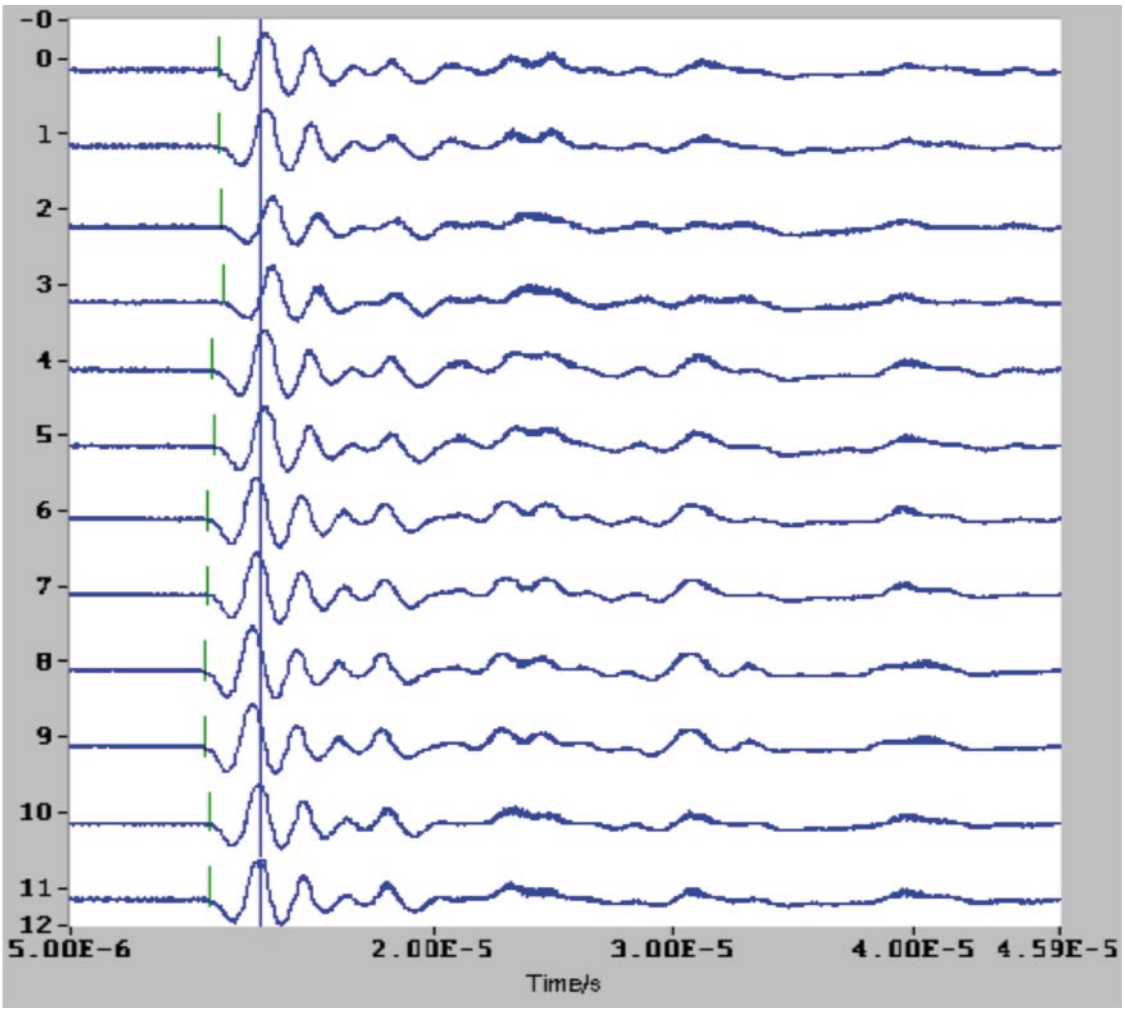

Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Thirty core specimens of the length c 200–500 mm and with a diameter of about 50 mm were selected from borehole KFM07A while the complete length of the core-drilled part of the borehole (section 100.40–1,000.55 m) was displayed on the racks in the core shed at Forsmark. The specimens were selected together by NGI and Thomas Janson/Björn Ljunggren representing SKB.

These specimens represent the foliated metamorphic granite and the fine grained granite-granodiorite, with some veins of amphibolite and pegmatite, found over most of the length of the borehole. Geological logging of 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, though no measurements of the moisture content were made.

4.2 Test method

Tests were performed 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 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.

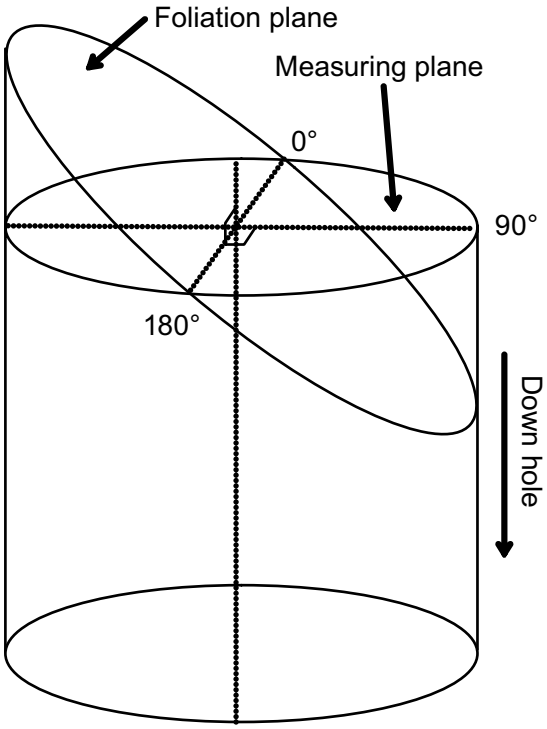

Figure 4-1. *Orientation of measurements.*

Analysis

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

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

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

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

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

The results of 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.

5.2 Discussion

Accuracy and repeatability

Calibration tests on an aluminium cylinder indicated a variation of ± 0.07 μs in determination of the time pick, equivalent to differences in velocity of about ± 50 m/s. Some of this variation may be explained by temperature variations (it was very cold at night and there were large temperature variations in the core store), thickness of the 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, 219.90 m, 461.80 m and 770.00 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.

At 219.90 m the difference in magnitude of the velocities is up to 109 m/s, the anisotropy ratio differs by 0.02 and there is about 5° difference in orientation. At 461.80 m the difference in magnitude of the velocities is up to 121 m/s, the anisotropy ratio differs by 0.02 and there is about 5° difference in orientation. Finally, at 770.00 m the difference in magnitude of the velocities is 82 m/s, the anisotropy ratio differs by 0.01 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 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 219.90 m the maximum difference was 60 m/s, and at 461.80 m as well as at 770.00 m the maximum difference was 18 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 0.39% (about 20 m/s), with a maximum error of 1.8% (about 100 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.

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 maximum principal velocities, V_1, between 4,744–5,605 m/s and an anisotropy ratio between 1.04 and 1.15.

There is an apparent trend in the maximum principal velocity, V_1, reducing slightly with depth. It lies between 5,239–5,501 m/s, down to 400 m, with outlying values of 4,744 m/s at 296.95 m and 4,794 m/s at 318.25 m. Below 600 m the maximum principal velocity lies between 4,774–5,217 m/s with no outlying values.

The anisotropy ratio is quite variable between 1.04 to 1.15 with an average of 1.10 and with no readily apparent trend with depth.

The orientation of the maximum principal velocity, θ_{V1}, is strongly related to the foliation direction, with an apparent small trend in orientation with depth. In the upper part of the borehole the orientation varies between 145° and 170° with an average of about 160°. In the lower part of the borehole the orientation is slightly more variable between 120° and 160° with an average about 140°. It is not parallel (180°) or perpendicular (90°) to the foliation as might be expected.

Table 5-1. Measurements of acoustic velocity, transverse core in borehole KFM07A, Forsmark (orientation clockwise looking down hole, 0° is parallel with foliation).

		Corrected time, mS						Velocity m/S								
Depth m	Dia-meter mm	Parallel foliation			Perpendicular foliation			Parallel foliation			Perpendicular foliation			Aniso-tropy ratio	Maximum velocity m/S	
		0°	30°	60°	90°	120°	150°	0°	30°	60°	90°	120°	150°			
201.30	50.85	9.56	9.96	10.51	10.42	10.19	9.73	5,316	5,103	4,836	4,878	4,988	5,224	1.10	5,316	
219.90	50.75	9.33	9.80	10.21	10.25	9.85	9.29	5,437	5,176	4,968	4,949	5,150	5,460	1.10	5,460	
242.30	50.83	9.66	9.99	10.26	10.26	10.14	9.77	5,259	5,086	4,952	4,952	5,010	5,200	1.06	5,259	
256.70	50.51	9.88	10.40	10.71	10.32	9.75	9.56	5,110	4,854	4,714	4,892	5,178	5,281	1.12	5,281	
296.95	50.58	10.87	11.28	11.62	11.36	10.88	10.67	4,651	4,482	4,351	4,451	4,647	4,738	1.09	4,738	
318.25	50.92	10.69	11.17	12.09	12.12	11.37	10.81	4,761	4,557	4,210	4,200	4,477	4,708	1.13	4,761	
341.30	50.68	9.61	9.86	9.88	9.89	9.62	9.53	5,271	5,137	5,127	5,122	5,266	5,315	1.04	5,315	
362.35	50.66	9.75	9.94	10.11	9.89	9.82	9.65	5,193	5,094	5,009	5,120	5,156	5,247	1.05	5,247	
381.20	50.33	9.30	9.40	9.58	9.60	9.23	9.13	5,409	5,352	5,251	5,240	5,450	5,510	1.05	5,510	
402.00	50.56	10.18	10.96	11.53	11.35	10.74	10.20	4,964	4,611	4,383	4,453	4,706	4,955	1.13	4,964	
424.95	50.87	10.19	10.47	10.75	10.64	10.20	10.02	4,990	4,856	4,730	4,779	4,985	5,074	1.07	5,074	
438.10	50.88	9.81	10.40	10.97	10.87	10.37	9.95	5,184	4,890	4,636	4,679	4,904	5,111	1.12	5,184	
461.80	50.85	9.56	10.09	10.59	10.60	10.02	9.59	5,316	5,037	4,800	4,795	5,072	5,300	1.11	5,316	
486.20	50.39	9.72	10.46	10.71	10.58	10.01	9.59	5,182	4,815	4,703	4,761	5,032	5,252	1.12	5,252	
512.55	50.54	10.18	10.91	11.47	11.55	10.88	10.25	4,962	4,630	4,404	4,374	4,643	4,928	1.13	4,962	
530.85	50.63	9.31	9.94	9.96	9.56	9.12	9.12	5,435	5,091	5,081	5,293	5,549	5,549	1.09	5,549	
532.50	50.29	9.15	9.93	10.13	10.03	9.73	9.20	5,493	5,062	4,962	5,012	5,166	5,463	1.11	5,493	
556.20	50.66	9.73	10.22	10.77	10.88	10.26	9.78	5,204	4,955	4,702	4,654	4,935	5,177	1.12	5,204	
575.20	50.77	9.77	10.40	10.56	10.21	9.73	9.47	5,194	4,879	4,806	4,970	5,215	5,358	1.12	5,358	
589.85	50.70	10.00	10.52	11.06	10.91	10.43	10.04	5,068	4,817	4,582	4,645	4,859	5,047	1.11	5,068	
611.15	50.59	10.82	11.57	11.63	11.32	10.71	10.48	4,674	4,371	4,348	4,467	4,722	4,825	1.11	4,825	
636.15	50.80	10.88	11.40	11.61	11.25	10.79	10.61	4,667	4,454	4,374	4,514	4,706	4,786	1.09	4,786	
656.25	50.55	10.56	10.74	10.68	10.32	10.10	10.23	4,785	4,705	4,731	4,896	5,003	4,939	1.06	5,003	
672.60	50.73	9.88	10.34	10.61	10.54	10.20	9.87	5,132	4,904	4,779	4,811	4,971	5,137	1.07	5,137	
698.10	50.70	10.55	11.08	10.73	10.08	9.76	10.03	4,804	4,574	4,723	5,027	5,192	5,052	1.14	5,192	
724.10	50.77	10.83	11.14	11.40	10.99	10.51	10.48	4,686	4,555	4,452	4,618	4,828	4,842	1.09	4,842	
739.25	50.79	10.17	10.49	10.28	9.77	9.81	9.93	4,992	4,840	4,938	5,196	5,175	5,112	1.07	5,196	
748.80	50.71	10.61	11.27	11.43	11.57	10.79	10.42	4,777	4,498	4,435	4,381	4,698	4,864	1.11	4,864	
770.00	50.43	11.13	11.87	11.96	11.43	10.68	10.61	4,529	4,247	4,215	4,410	4,720	4,751	1.13	4,751	
783.40	50.91	10.42	11.28	11.21	10.76	10.27	10.14	4,884	4,511	4,540	4,729	4,955	5,018	1.11	5,018	
219.90	50.75	9.36	10.00	10.23	10.25	9.74	9.48	5,419	5,073	4,959	4,949	5,208	5,351	1.10	5,419	Repeat
461.80	50.85	9.59	10.09	10.45	10.34	9.94	9.56	5,300	5,037	4,864	4,916	5,113	5,316	1.09	5,316	Repeat
770.00	50.42	11.06	11.74	11.81	11.22	10.61	10.60	4,557	4,293	4,268	4,492	4,750	4,754	1.11	4,754	Repeat

Table 5-2. Determinations of principal velocity and orientation, transverse core in borehole KFM07A, Forsmark (orientation clockwise looking down hole, 0° is parallel with foliation where identified).

Depth m	Maximum velocity V_1 m/s	Orientation θ_{V1}	Minimum velocity V_3 m/s	Orientation θ_{V3}	Anisotropy ratio	Foliation	
201.30	5,300	170°	4,814	80°	1.10	s	
219.90	5,473	165°	4,907	75°	1.12	s	
242.30	5,241	170°	4,912	80°	1.07	s	
256.70	5,286	145°	4,724	55°	1.12	s	
296.95	4,744	150°	4,363	60°	1.09	s	
318.25	4,794	170°	4,177	80°	1.15	s	
341.30	5,315	150°	5,097	60°	1.04	s	
362.35	5,239	150°	5,034	60°	1.04	s	
381.20	5,501	155°	5,236	65°	1.05	s	
402.00	4,994	160°	4,363	70°	1.14	s	
424.95	5,075	155°	4,729	65°	1.07	s	
438.10	5,184	165°	4,618	75°	1.12	s	
461.80	5,348	165°	4,758	75°	1.12	s	
486.20	5,252	155°	4,662	65°	1.13	s	
512.55	4,978	165°	4,336	75°	1.15	s	
530.85	5,605	140°	5,061	50°	1.11	s	
532.50	5,479	160°	4,907	70°	1.12	s	
556.20	5,235	165°	4,641	75°	1.13	s	
575.20	5,350	145°	4,791	55°	1.12	s	
589.85	5,093	165°	4,579	75°	1.11	s	
611.15	4,823	145°	4,312	55°	1.12	s	
636.15	4,790	145°	4,377	55°	1.09	s	
656.25	4,998	125°	4,688	35°	1.07	s	
672.60	5,154	160°	4,758	70°	1.08	w	
698.10	5,195	125°	4,595	35°	1.13	s	
724.10	4,860	140°	4,467	50°	1.09	s	
739.25	5,217	120°	4,867	30°	1.07	s	
748.80	4,858	155°	4,360	65°	1.11	s	
770.00	4,774	140°	4,183	50°	1.14	s	
783.40	5,045	140°	4,500	50°	1.12	s	
219.90	5,411	160°	4,909	70°	1.10	s	Repeat
461.80	5,335	160°	4,847	70°	1.10	s	Repeat
770.00	4,793	140°	4,245	50°	1.13	s	Repeat

f = foliation (clearly identifiable), n = no identifiable foliation, w = weak foliation (not good), s = strong foliation (good), x = disturbed sample.

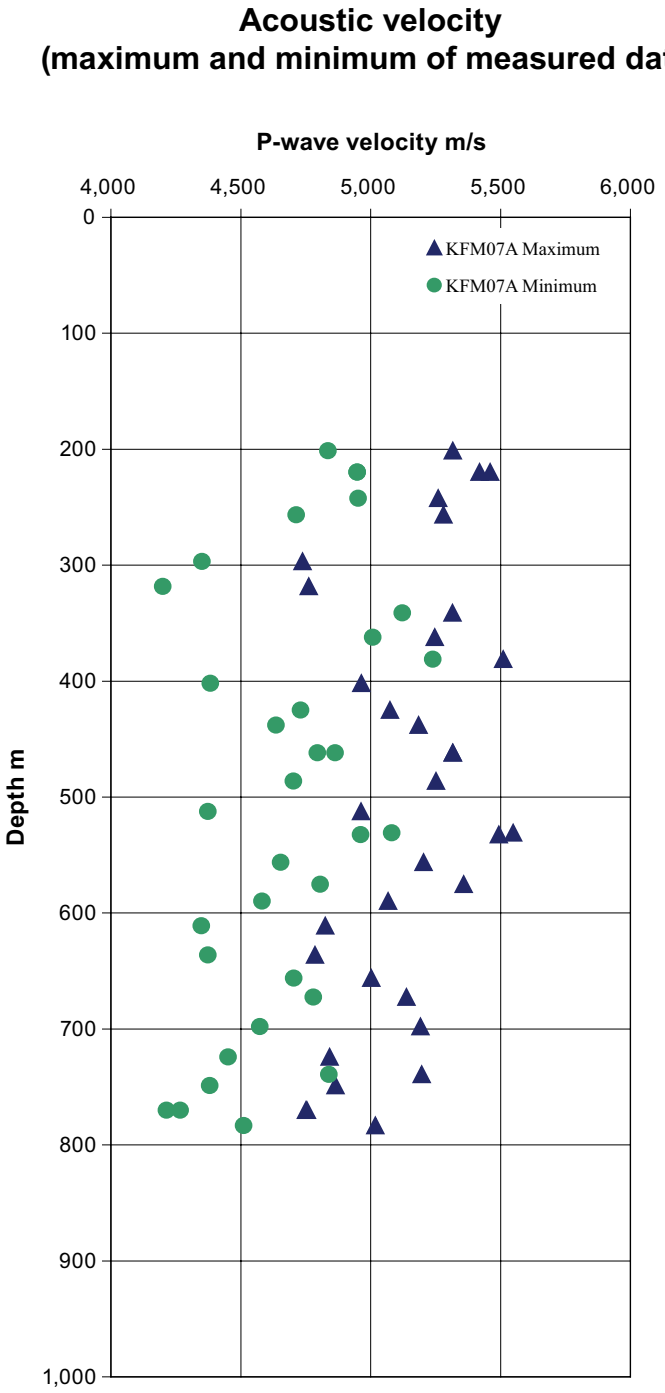

Figure 5-1. *Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KFM07A.*

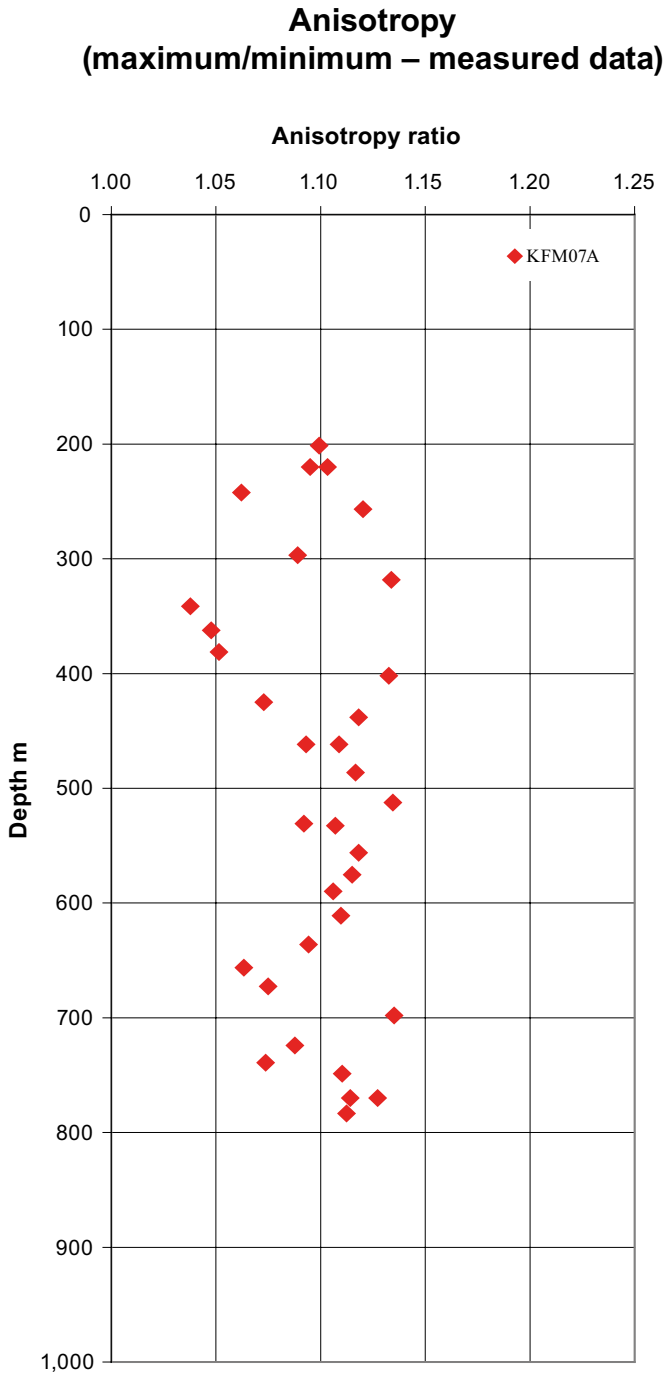

Figure 5-2. *Measured values of acoustic velocities anisotropy plotted versus borehole length in KFM07A.*

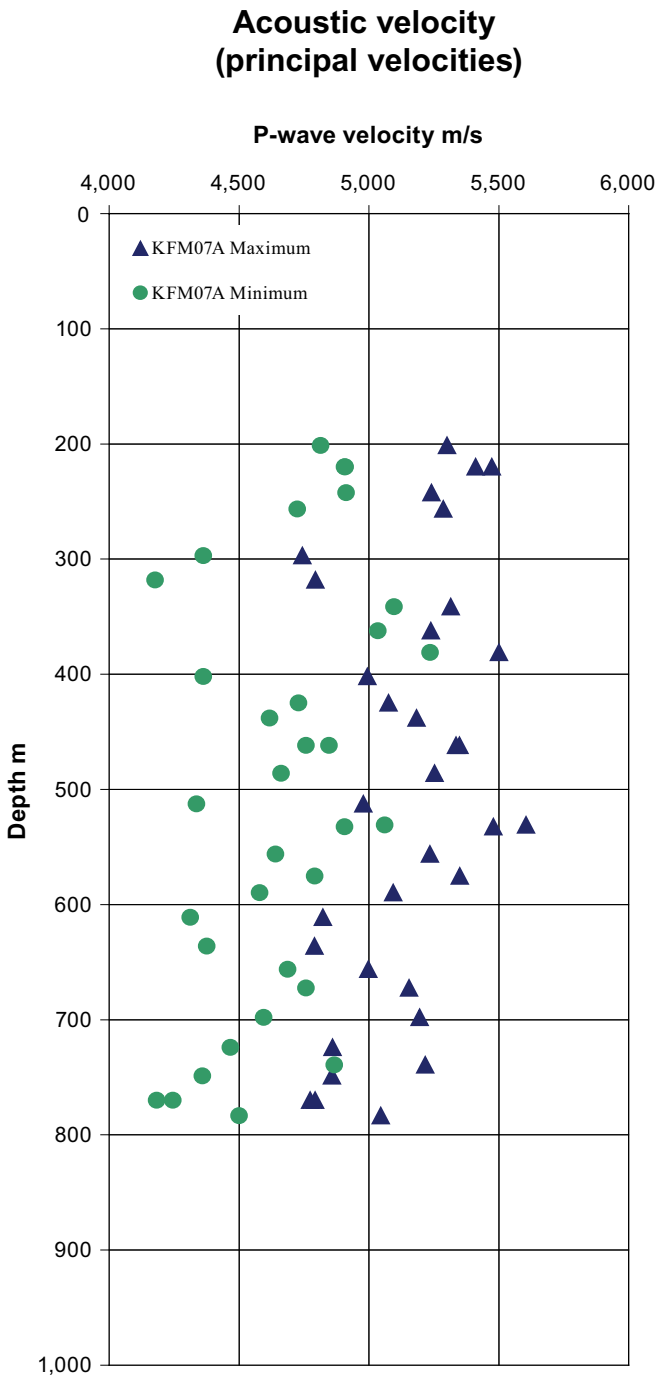

Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KFM07A.*

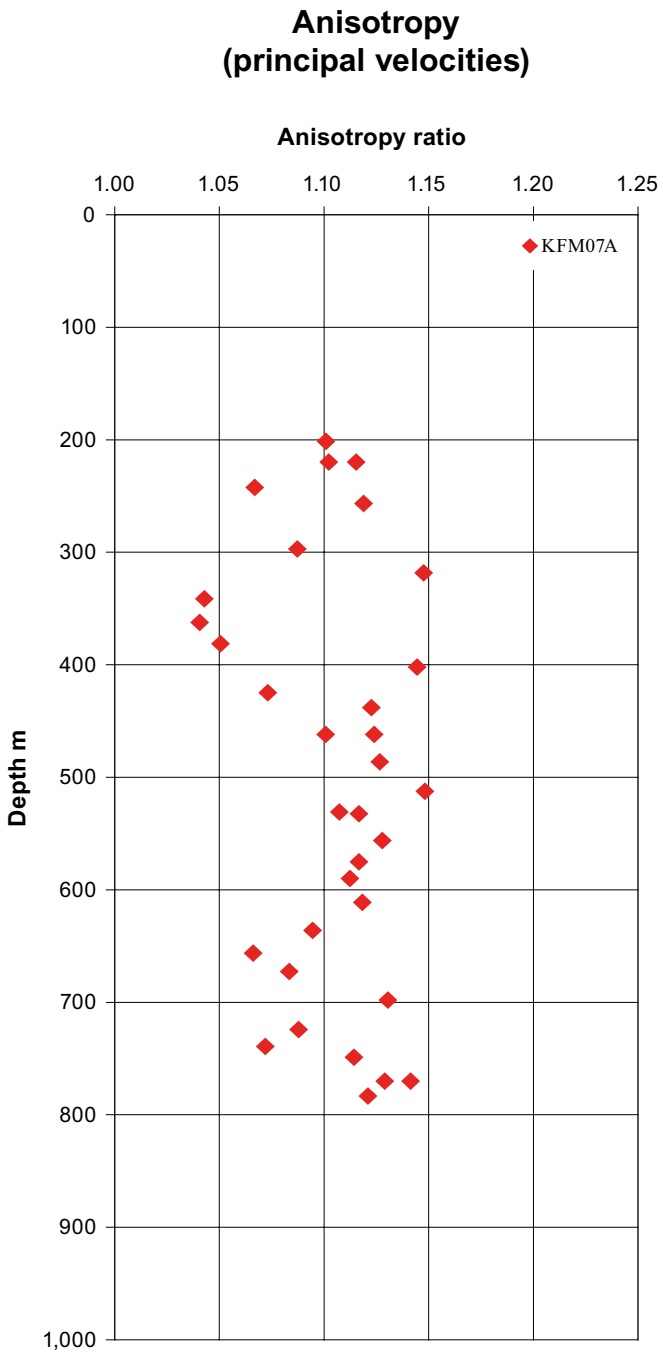

Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KFM07A.*

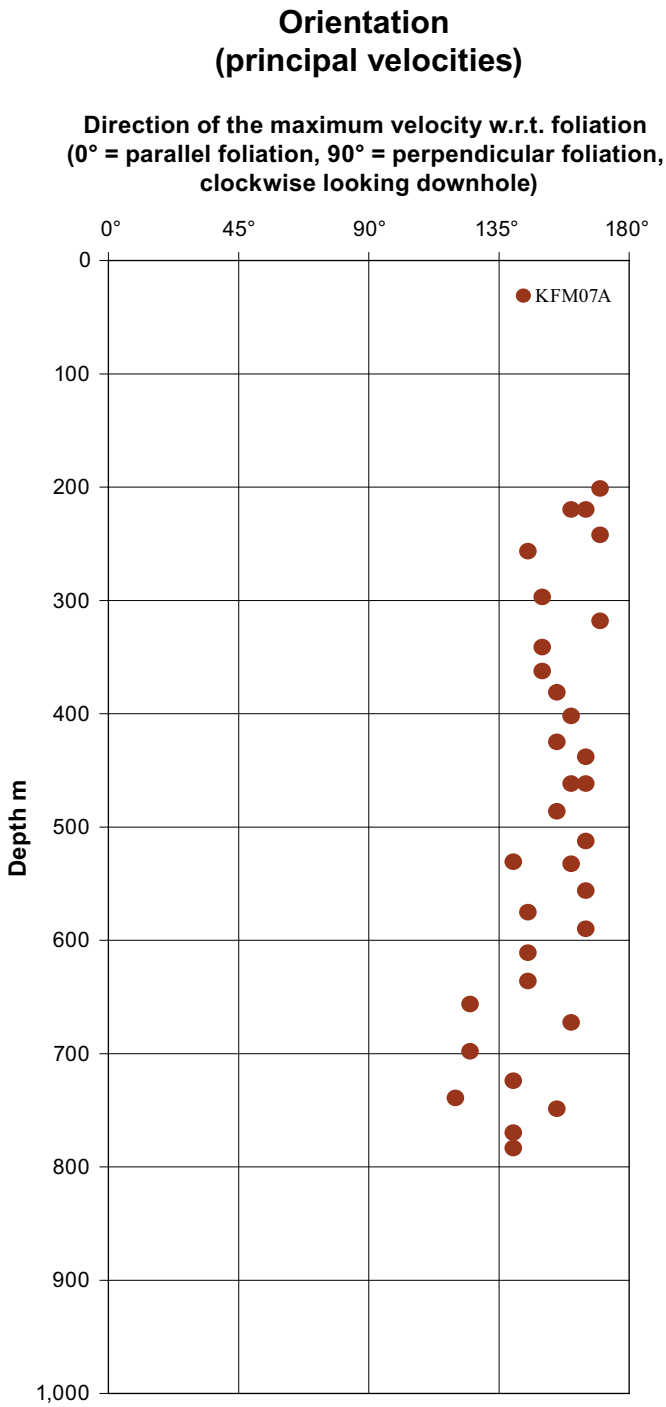

Figure 5-5. *Calculated orientation of the maximum principal acoustic velocity plotted versus borehole length in KFM07A.*

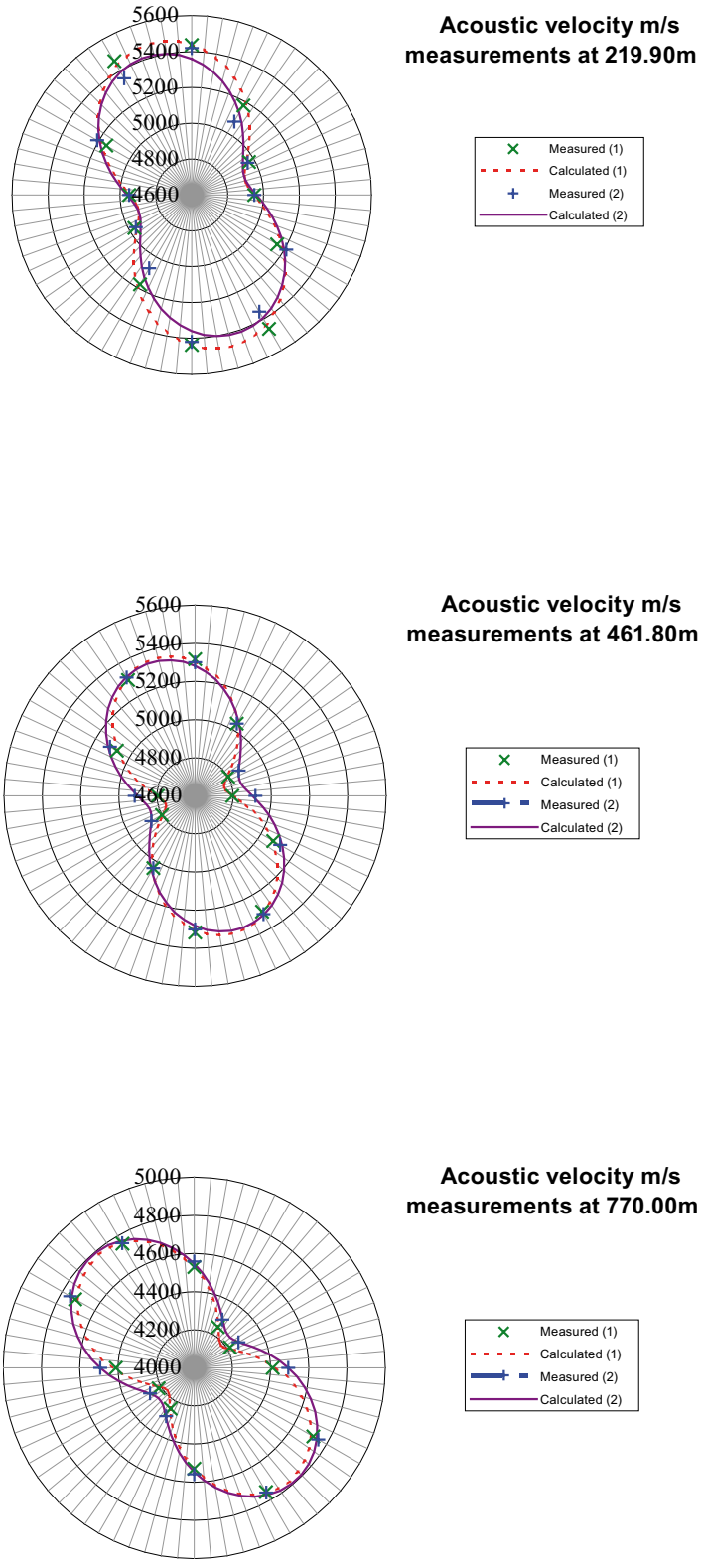

Figure 5-6. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at three different depths in borehole KFM07A.*

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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 μS	Calculated μS	Correction μS
20050302–0930 hrs	6.320	50.90	9.08	8.05	1.03
20050302–1300 hrs	6.320	50.90	9.15	8.05	1.10
20050302–1600 hrs	6.320	50.90	9.22	8.05	1.16
20050303–0900 hrs	6.320	50.90	9.15	8.05	1.10
20050303–1200 hrs	6.320	50.90	9.20	8.05	1.15
Average			9.159		1.105