P-06-24

Forsmark site investigation

Borehole KFM09A

Determination of P-wave velocity, transverse borehole core

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Norwegian Geotechnical Institute, Oslo

September 2006

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Keywords: AP PF 400-05-110, Rock mechanics, P-wave velocity, Anisotropy.

Summary

The Norwegian Geotechnical Institute has carried out P-wave measurements on drill core samples from borehole KFM09A at Forsmark, Sweden, in December 2005. KFM09A has a diameter of 77.3 mm, is inclined c. 60º from the horizontal plane and has a total length of c. 800 m. Thirty-three P-wave velocity measurements were carried out on 30 drill core samples from KFM09A.

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 within the interval 5,215–6,061 m/s with an anisotropy ratio of between 1.02 to 1.18.

There is an apparent trend in the maximum principal velocity, V_1, indicating more variable and slightly increasing values versus depth. V_1 varies between 5,215–5,763 m/s, down to 600 m borehole length. Below that level the maximum principal velocity lies between 5,389–6,061 m/s with no outlying values.

The anisotropy ratio is quite variable between 1.02 to 1.12, with an outlying value of 1.18 at 725.00 m, and with an average of 1.05 and 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 trend in orientation versus depth. In the upper part of the borehole (above 600 m borehole length) the orientation lies in the regions 0°–30° and 135°–180°, with an average of about 165°. There are outlying values of 80° to 105° between 530.25 and 548.15 m. In the lower part of the borehole the orientation span is between 115° and 180° with an average of about 145°. The orientation is neither parallel (180°), nor perpendicular (90°) to the foliation as might be expected.

Sammanfattning

Norges Geotekniska Institut (NGI) har under December 2005 utfört P-vågsmätningar på borrkärnor från borrhål KFM09A i Forsmark. KFM09A har en diameter på ca 77,3 mm, är ansatt med en gradning av ca 60° från horisontalplanet samt har en total längd på nästan 800 m. Sammanlagt har 33 stycken hastighetsbestämningar av P-vågor utförts på 30 kärnprover.

Resultaten visar för hela borrhålets längd en maximihastighet, V_1, som varierar i intervallet 5 215–6 061 m/s och en anisotropikvot mellan 1,02–1,18.

Maximihastigheten visar en växlande och svagt ökande trend mot djupet. Från övre delen av borrhålet och ned till 600 m borrhålslängd varierar V_1 mellan 5 215–5 763 m/s. Från 600 m och vidare ned är variationsintervallet 5 389–6 061 m/s.

Anisotropikvoten, varierar som nämnts generellt mellan 1,02–1,12, och har ett medelvärde kring 1,05. Vid 725,00 m uppmättes dock ett avvikande värde på 1,18. Anisotropikvoten visar ingen speciell tendens mot djupet.

Maxhastighetens orientering är starkt relaterad till foliationsriktningen med en tydlig tendens till ändring med djupet. Från toppen av borrhålet och ned till 600 m borrhålslängd, är maxhastigheten orienterad 0° till 30° och 135° till 180°, med ett medelvärde omkring 165°. Det finns utanför liggande värden orienterade mellan 80° till 105° på djupen 530,25 m och 548,15 m. Från 600 m djup och vidare nedöver varierar riktningen från 115° till 180° med ett medelvärde kring 145°. Maxhastighetens 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 core samples from borehole KFM09A at Forsmark, Sweden. KFM09A is a conventional core drilled borehole, inclined c. 60º from the horizontal plane and with a total length of 799.67 m and a diameter of 77.3 mm. The drill core diameter is c. 50.5 mm. The samples selected for P-wave measurements were collected within the interval c. 200–796 m borehole length. All deep boreholes drilled in Forsmark up to December 2005 are shown in Figure 1-1. The SKB internal controlling documents for performance of this activity are presented in Table 1-1.

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski during the period 12th–15th of December 2005.

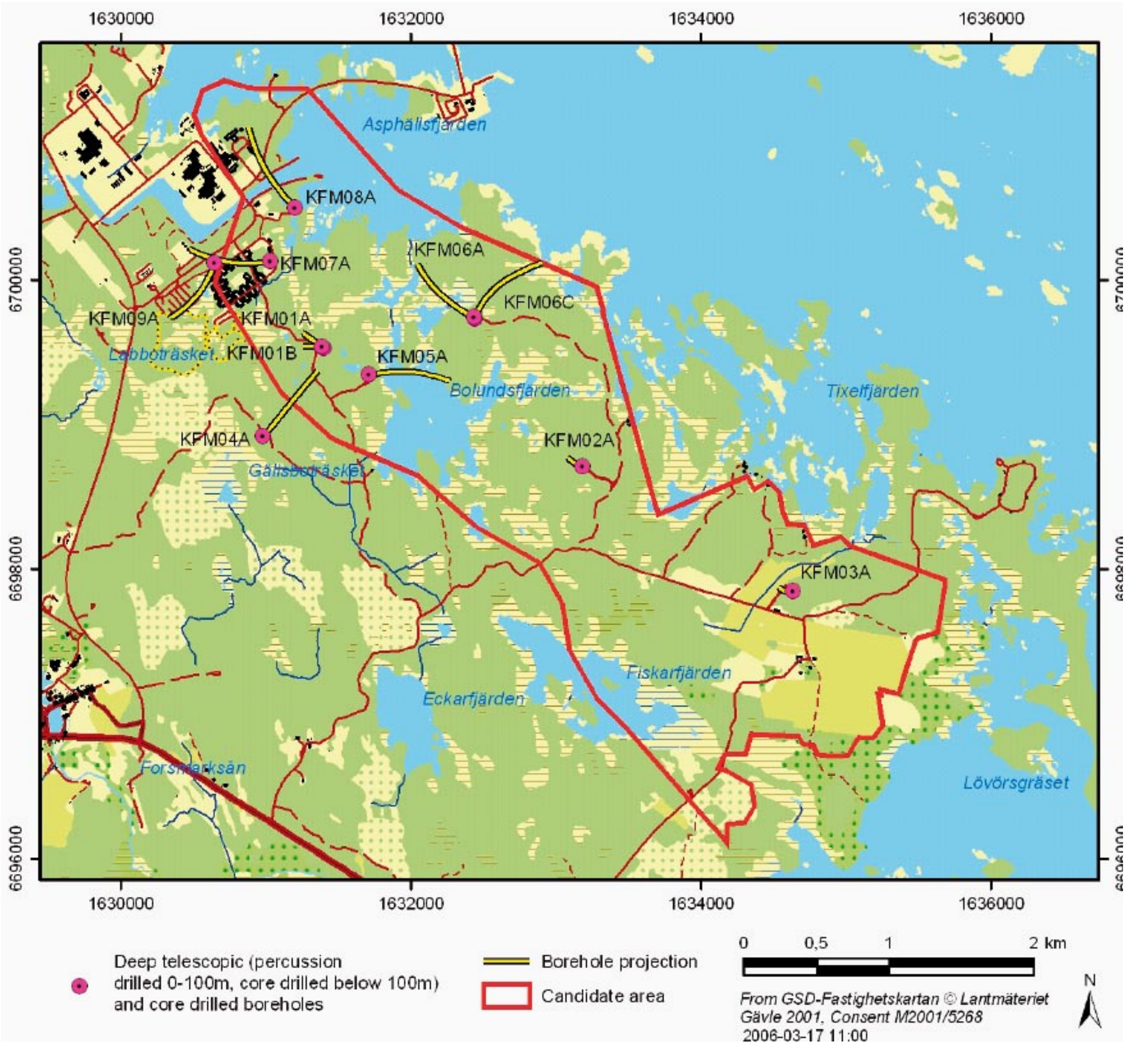

Figure 1-1. *Location of all deep boreholes, including borehole KFM09A, drilled up to December 2005 at the Forsmark site.*

Table 1-1. Controlling documents for performance of the activity.

Activity Plan	Number	Version
KFM09A - Bergmekaniska parameterbestämningar	AP PF 400-05-110	1.0
Method descriptions	**Number**	**Version**
Bestämning av P-vågens hastighet	SKB MD 190.002.	1.0

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
KFM09A	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/.

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 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 drill core. The aluminium cylinder for calibration of the device is on the right.*

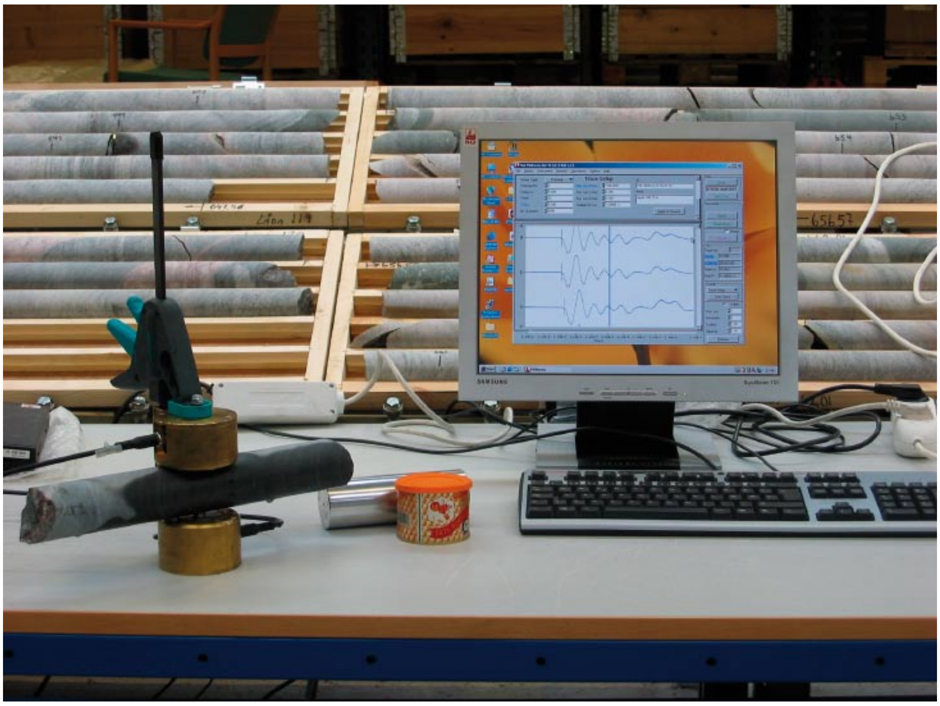

Figure 3-2. *NGI's equipment set-up for measuring acoustic P-wave travel time transverse a drill core.*

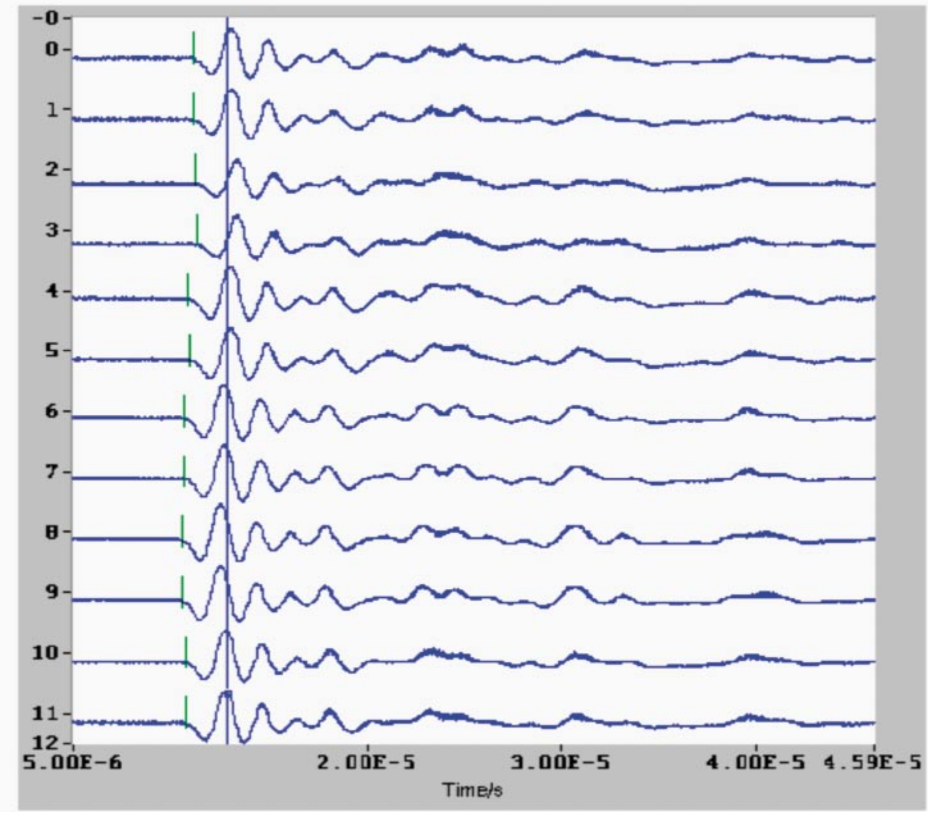

Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse a borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Thirty drill core specimens of a length of c. 200–500 mm and a diameter of about 50 mm were selected from the interval c. 200–796 m of borehole KFM09A while the complete drill core (length c. 7–799.67 m) 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 the major part of the borehole. Geological logging of core has been carried out by SKB. No detailed geological description has been attempted by NGI.

The levels used to describe the locations 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 to determine travel time across the diameter of the core were made at six locations at 30º intervals around the core (at 0º–180º, 30º–210º, 60º–240º,90º–270º, 120º–300º and 150º–330º), starting at 0º, 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 location. 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.

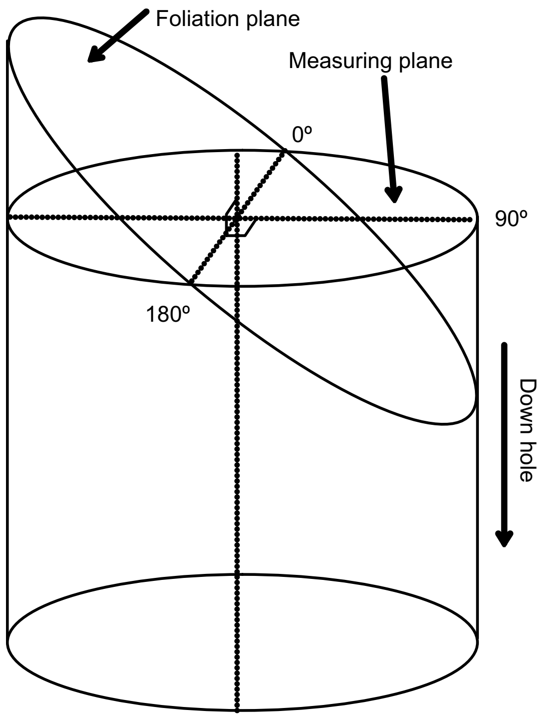

Figure 4-1. *Orientation of measurements*

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}. The velocity is the same in the opposite direction, the value at orientation 0° is the same as at 180° etc and for simplicity the orientations are reported in the first half circle (0°–179°) only.

4.3 Nonconformities

Tests were made at 30º intervals around the core instead of 45º 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 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.

Table 5-1. Meassurements of acoustic velocity transverse the drill core in borehole KFM09A, Forsmark.
(orientation clockwise looking down hole, 0º is parallel with foliation)

Depth m	Diameter mm	Corrected time, mS Parallel foliation			Perpendicular foliation			Velocity m/S Parallel foliation			Perpendicular foliation			Anisotropy ratio	
		0º	30º	60º	90º	120º	150º	0º	30º	60º	90º	120º	150º		
200,45	50,84	9,18	9,18	9,37	9,86	9,57	9,15	5541	5541	5428	5158	5315	5559	1,08	
229,80	50,53	9,72	9,70	9,91	9,95	9,76	9,78	5201	5212	5101	5081	5179	5169	1,03	
255,74	50,59	9,25	9,31	9,33	9,41	9,43	9,24	5472	5436	5425	5379	5367	5478	1,02	
286,32	50,71	9,25	9,38	9,60	9,68	9,64	9,51	5485	5409	5285	5241	5263	5335	1,05	
318,29	50,74	9,52	9,37	9,54	9,78	9,96	9,82	5332	5418	5321	5190	5097	5169	1,06	
349,20	50,65	9,34	9,64	10,37	10,26	9,95	9,48	5425	5256	4886	4939	5093	5345	1,11	
379,90	50,81	9,48	9,64	9,67	9,49	9,48	9,48	5362	5273	5257	5356	5362	5362	1,02	
410,00	50,80	9,41	9,53	9,68	9,62	9,54	9,41	5401	5333	5250	5283	5327	5401	1,03	
434,50	50,69	9,09	9,09	9,22	9,38	9,37	9,19	5579	5579	5500	5406	5412	5518	1,03	
471,05	50,69	9,00	9,30	9,55	9,52	9,23	9,08	5635	5453	5310	5327	5494	5585	1,06	
500,00	50,75	8,90	9,15	9,29	9,40	8,94	8,84	5705	5549	5465	5401	5679	5744	1,06	
512,10	50,85	8,88	9,08	9,31	9,48	9,41	9,12	5729	5603	5464	5366	5406	5578	1,07	
530,25	50,91	9,81	9,70	9,41	9,36	9,74	9,57	5192	5251	5413	5442	5229	5322	1,05	
548,15	50,66	9,08	9,15	9,03	8,97	8,99	9,04	5582	5539	5613	5650	5638	5607	1,02	
560,45	50,81	9,22	9,28	9,48	9,49	9,27	9,11	5513	5478	5362	5356	5484	5580	1,04	
573,40	50,64	9,38	9,56	9,66	9,61	9,49	9,36	5401	5299	5245	5272	5339	5413	1,03	
589,30	50,72	9,42	9,66	9,75	9,58	9,45	9,28	5387	5253	5204	5297	5370	5468	1,05	
606,80	50,68	9,12	9,36	9,65	9,73	9,61	9,31	5560	5417	5254	5211	5276	5446	1,07	
623,23	50,74	8,86	8,89	9,06	9,02	8,94	8,85	5730	5710	5603	5628	5678	5736	1,02	
635,40	50,76	8,95	9,06	9,04	8,93	8,83	8,85	5674	5605	5618	5687	5751	5738	1,03	
650,00	50,94	8,79	8,79	8,80	8,80	8,65	8,68	5798	5798	5791	5791	5892	5872	1,02	
665,20	50,92	8,92	8,84	8,86	8,76	8,65	8,74	5711	5763	5750	5816	5890	5829	1,03	
678,77	50,72	9,42	9,72	9,66	9,58	9,12	9,19	5387	5220	5253	5297	5564	5522	1,07	
694,34	50,77	9,60	9,79	9,74	9,51	9,21	9,33	5291	5188	5215	5341	5515	5444	1,06	
710,95	50,75	10,10	10,54	10,26	9,81	9,41	9,60	5027	4817	4948	5176	5396	5289	1,12	
725,00	50,82	9,43	10,16	10,90	10,80	9,99	9,37	5392	5004	4664	4707	5089	5426	1,16	
741,90	50,93	9,33	9,44	9,40	9,30	9,15	9,07	5461	5398	5421	5479	5569	5618	1,04	
759,22	50,68	8,48	8,94	9,12	9,11	8,59	8,39	5979	5672	5560	5566	5903	6044	1,09	
767,55	50,63	8,76	8,98	9,13	9,16	8,96	8,76	5782	5641	5548	5530	5653	5782	1,05	
796,30	50,75	8,76	8,92	9,06	8,89	8,79	8,65	5796	5692	5604	5711	5776	5870	1,05	
255,74	50,61	9,28	9,28	9,35	9,39	9,35	9,21	5456	5456	5415	5392	5415	5498	1,02	Repeat
530,25	50,91	9,85	9,75	9,40	9,28	9,33	9,63	5171	5224	5418	5488	5459	5289	1,06	Repeat
725,00	50,83	9,38	9,80	10,59	10,97	10,15	9,44	5421	5189	4802	4635	5010	5387	1,17	Repeat

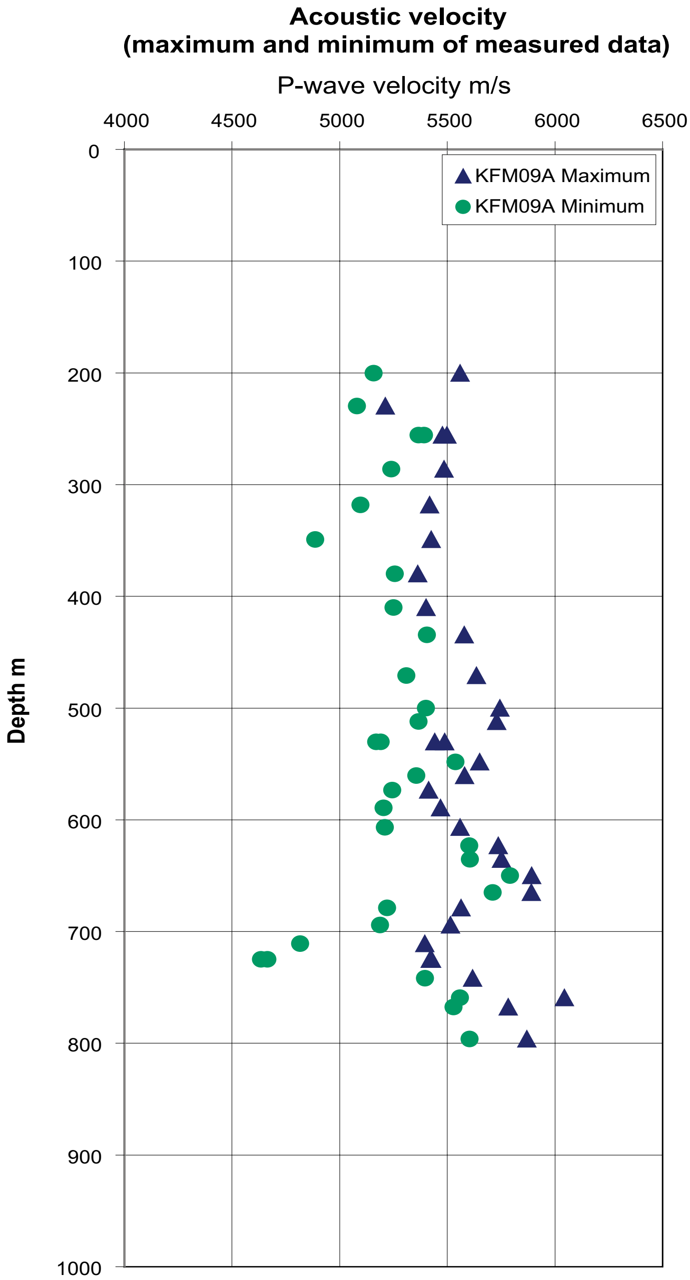

Figure 5-1. *Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KFM09A.*

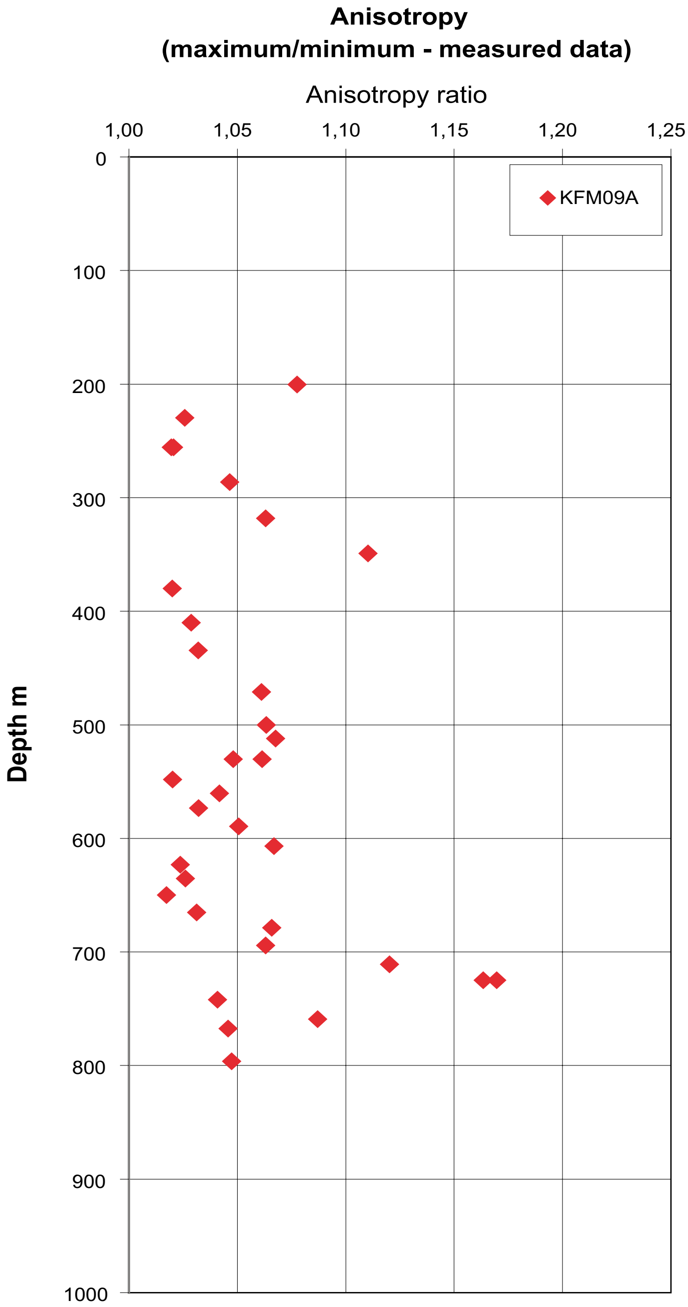

Figure 5-2. *Measured values of acoustic velocity anisotropy plotted versus borehole length in KFM09A.*

Table 5-2. Determinations of principal velocity and orientation transverse the drill core in borehole KFM09A, Forsmark.
(orientation clockwise looking down hole, 0º 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	
200,45	5612	5º	5235	95º	1,07	f	
229,80	5215	175º	5099	85º	1,02	w	
255,74	5478	5º	5374	95º	1,02	f	
286,32	5453	5º	5219	95º	1,04	f	
318,29	5410	30º	5099	120º	1,06	f	
349,20	5437	170º	4878	80º	1,11	f	
379,90	5385	135º	5272	45º	1,02	f	
410,00	5410	165º	5255	75º	1,03	f	
434,50	5597	15º	5401	105º	1,04	f	
471,05	5636	165º	5299	75º	1,06	f	
500,00	5763	160º	5418	70º	1,06	f	
512,10	5699	5º	5350	95º	1,07	f	
530,25	5408	80º	5208	170º	1,04	f	
548,15	5653	105º	5556	15º	1,02	f	
560,45	5571	160º	5353	70º	1,04	f	
573,40	5416	160º	5240	70º	1,03	f	
589,30	5452	150º	5207	60º	1,05	f	
606,80	5533	0º	5188	90º	1,07	f	
623,23	5749	165º	5613	75º	1,02	f	
635,40	5756	130º	5601	40º	1,03	f	
650,00	5874	135º	5773	45º	1,02	f	
665,20	5866	115º	5720	25º	1,03	f	
678,77	5551	140º	5196	50º	1,07	f	
694,34	5496	130º	5168	40º	1,06	f	
710,95	5389	125º	4829	35º	1,12	f	
725,00	5467	160º	4628	70º	1,18	f	
741,90	5597	135º	5384	45º	1,04	f	
759,22	6061	155º	5513	65º	1,10	f	
767,55	5797	165º	5516	75º	1,05	f	
796,30	5858	150º	5625	60º	1,04	f	
255,74	5482	170º	5395	80º	1,02	f	Repeat
530,25	5511	95º	5172	5º	1,07	f	Repeat
725,00	5481	170º	4667	80º	1,17	f	Repeat

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

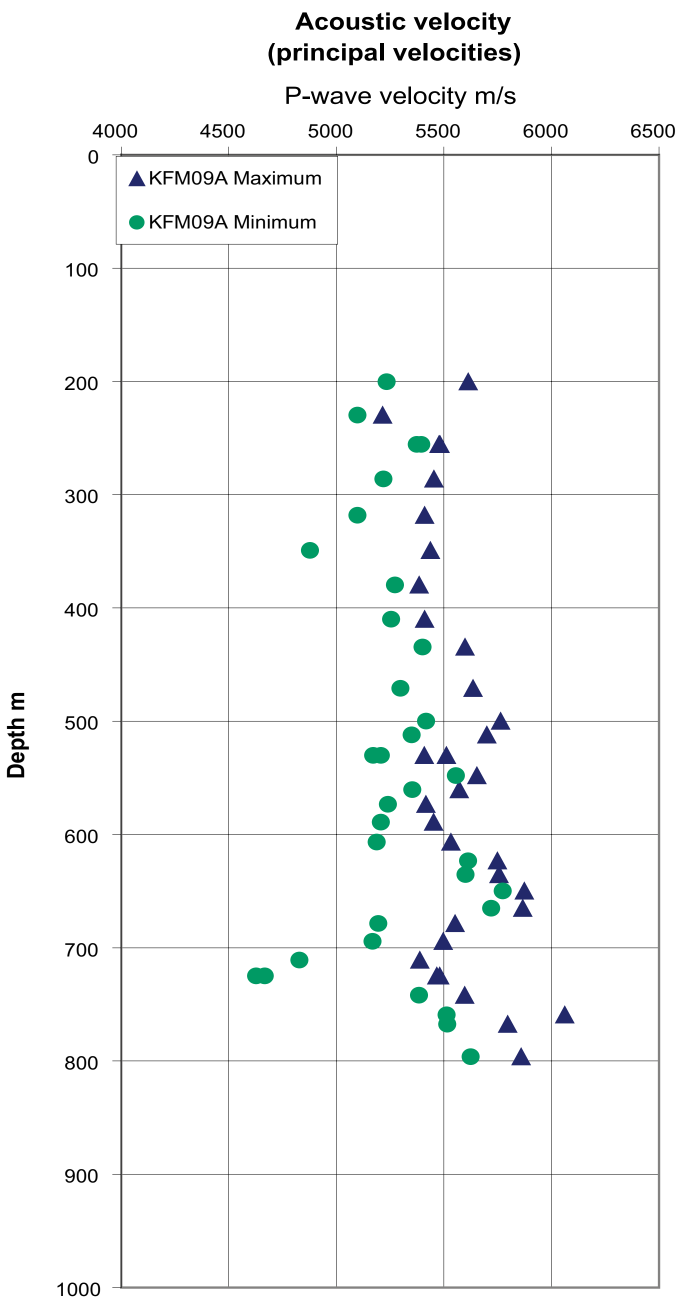

Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KFM09A.*

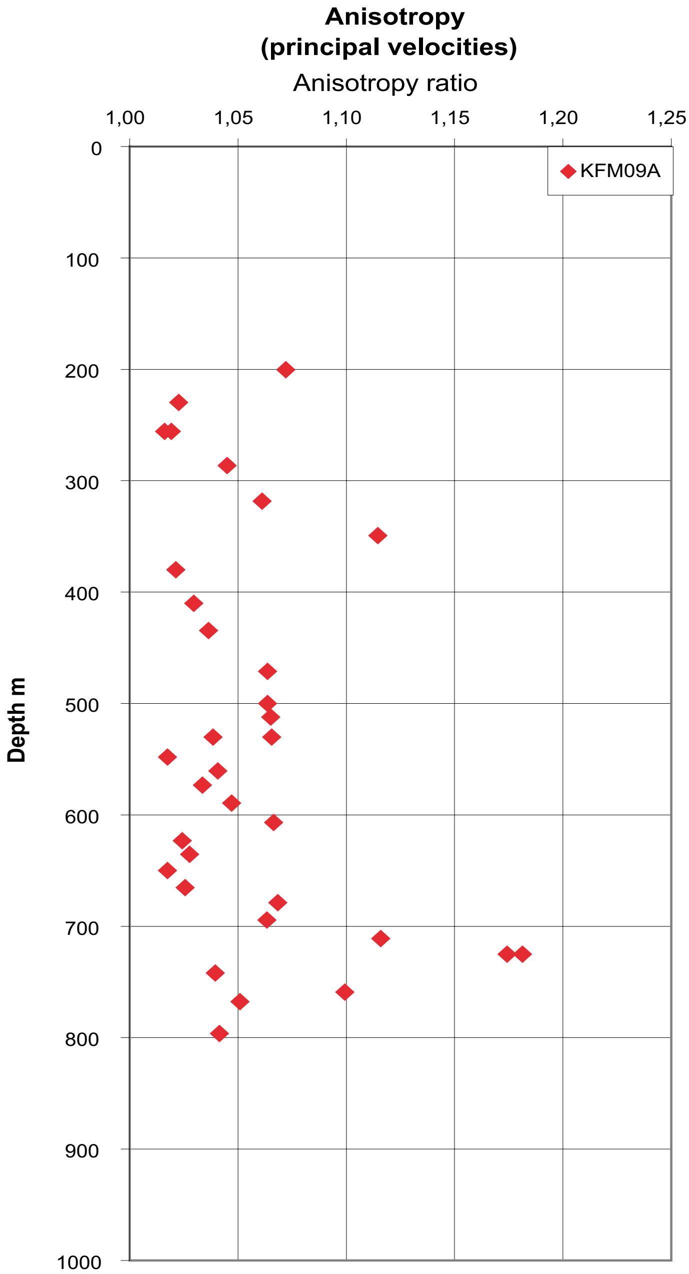

Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KFM09A.*

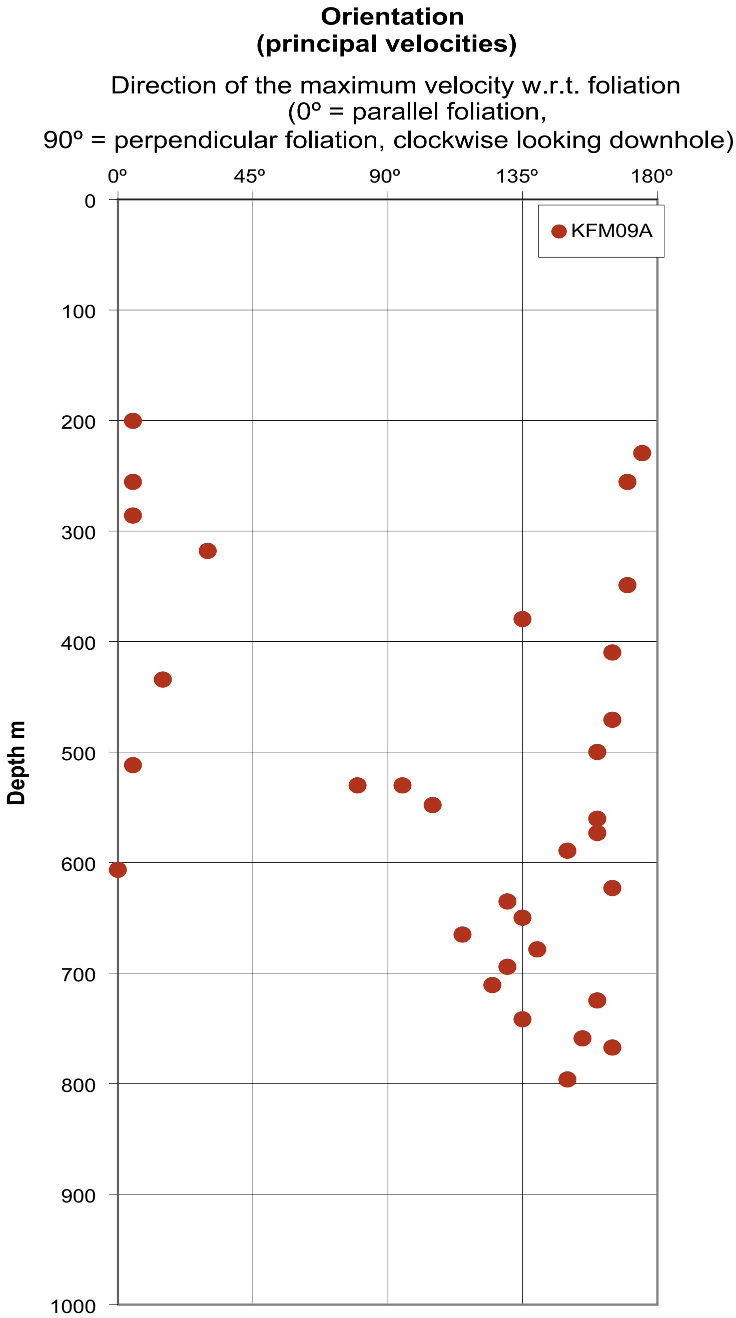

Figure 5-5. *Calculated orientation of the maximum principal acoustic velocity plotted versus borehole length in KFM09A.*

5.2 Discussion

Accuracy and repeatability

Calibration tests on an aluminium cylinder indicated a noise factor of ±0.02 μs in determination of the time pick, equivalent to differences in velocity of about ±12 m/s. Some of this noise may be explained by temperature variations, 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, 255.74 m, 530.25 m and 725.00 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.

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

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 255.74 m the maximum difference was 30 m/s, 98 m/s at 530.25 m, and finally 49 m/s at 725.00 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 0.34% (about 18 m/s), with a maximum error of 1.9% (about 99 m/s).

The deviation between the model fitted to the data and the measured data reported here is similar to the previous work /Chryssanthakis and Tunbridge 2003a–h, 2004ab, 2005abcd/. 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 larger 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.

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

Level (borehole length)	Maximum difference in measured velocity	Difference in anisotropy ratio of principal velocities	Difference in orientation of the maximum principal velocity
255.74 m	48 m/s	0.00	11°
530.25 m	230 m/s	0.03	15°
725.00 m	185 m/s	0.01	9°

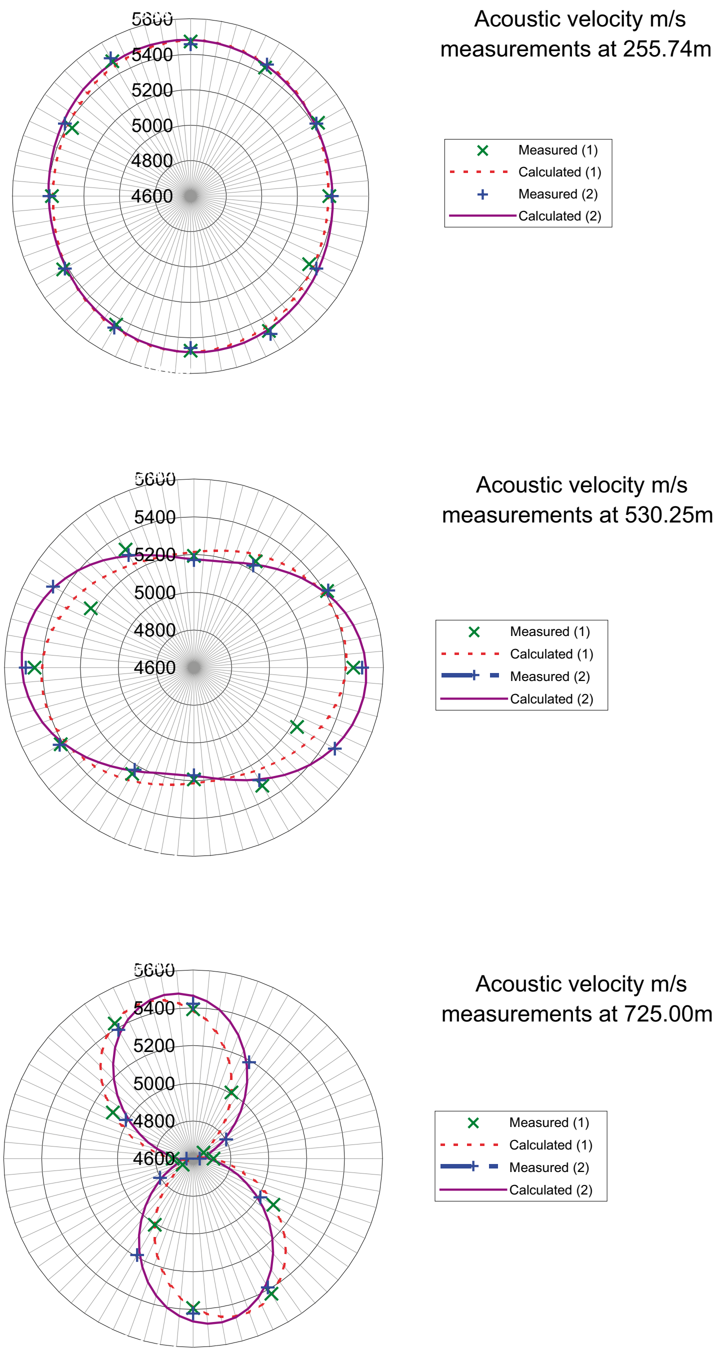

Figure 5-6. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at three different depths in borehole KFM09A.*

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 5,215–6,061 m/s with an anisotropy ratio of between 1.02 and 1.18.

There is an apparent trend in the maximum principal velocity, V_1, of more variable and slightly increasing velocities versus depth. V_1 lies between 5,215–5,763 m/s, down to 600 m. Below that level the maximum principal velocity ranges between 5,389–6,061 m/s with no outlying values.

The anisotropy ratio is quite variable between 1.02 to 1.12, with an outlying value of 1.18 at 725.00 m, and with an average of 1.05 and no readily apparent trend with depth.

The orientation of the maximum principal velocity, θV_1, is strongly related to the foliation direction, with an apparent trend in orientation versus depth. In the upper part of the borehole (above 600 m borehole length) the orientation varies between 0°–30° and 135°–180°, with an average of about 165° (note that velocity is the same in the opposite direction, values between 0°–30° are the same as between 180°–210°). There are outlying values of 80° to 105° between 530.25 and 548.15 m. In the lower part of the borehole the orientation span is between 115° and 180° with an average of about 145°. The orientation is neither parallel (180°), nor perpendicular (90°) to the foliation as might be expected.

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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 & time	Known velocity m/S	Diameter mm	Time Measured µS	Calculated µS	Correction µS
20051213 - 0900 hrs	6,320	50.90	9.24	8.05	1.18
20051213 - 1400 hrs	6,320	50.90	9.20	8.05	1.15
20051213 - 1600 hrs	6,320	50.90	9.20	8.05	1.14
20051214 - 0900 hrs	6,320	50.90	9.23	8.05	1.17
20051214 - 1130 hrs	6,320	50.90	9.19	8.05	1.13
Average			9.208	8.05	1.154