P-03-38

Forsmark site investigation

Borehole: KFM01A
Determination of P-wave velocity, transverse borehole core

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May 2003

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ISSN 1651-4416
SKB P-03-38

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Summary

The Norwegian Geotechnical Institute (NGI) has carried out P-wave measurements on drill cores from borehole KFM01A at Forsmark in February 2003. Thirty P-wave velocity measurements have been carried out from a total of 908 m of core.

The results from the P-wave velocity measurements show a consistent pattern down to about 500 m depth with maximum velocities between 5400–5700 m/s and a low anisotropy ratio of between 1 to 1.1. Below 500 m the maximum velocity reduces gradually with depth to under 5000 m/s and the anisotropy ratio increases to a maximum of 1.2. At 1001 m depth there was a one very low measurement of maximum velocity of 4400 m/s. The orientation of the principal velocities is quite consistent with depth, especially if only the results with an anisotropy ratio greater than 1.1 are evaluated (the orientations of the principal velocities are not well constrained mathematically for low anisotropy ratios). The orientation of the maximum velocity is typically 160º–165º from the foliation direction (measured clockwise looking down the hole), and not parallel or perpendicular to the foliation as might have been expected.

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1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on cores from borehole KFM01A at Forsmark in Sweden in accordance with SKB Activitetsplan AP PF400-03-10 dated 2003-02-18.

The work was carried out by Panayiotis Chryssanthakis and Lloyd Tunbridge during the period 24–26 of February 2003 in accordance with SKB's method description MD 190.002 ver 1.0.

2 General Information

2.1 Description of the test specimens

Twenty-eight core specimens of length ca 200–500 mm and diameter about 50.5–51.0 mm were selected from borehole KFM01A while the complete length of the borehole (depth 100 m–1008 m) was displayed on the racks in the core shed at Forsmark. These specimens represent the foliated granite-gneiss found over most of the length of the borehole. The specimens were selected together by NGI and Rolf Christiansson representing SKB. The samples were selected in the typical granite. The spacing was approximate 50 m down to a depth of 400 m, then decreased to 30 m, and to a spacing of 20 m for the last 160 m of core.

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.

2.2 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 SKB report entitled Detection of Anisotropy by Diametral Measurements of Longitudinal Wave Velocities on Rock Cores by Andreas Eitzenberger dated September 2002. The equipment is shown on the photograph in Figure 2-1.

Figure 2-1. *NGI's apparatus for measuring acoustic P-wave travel time transverse borehole core.*

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, Figure 2-2. 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 (LT) 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 taken each day on the calibration piece to check operation of the system.

A thick honey 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.

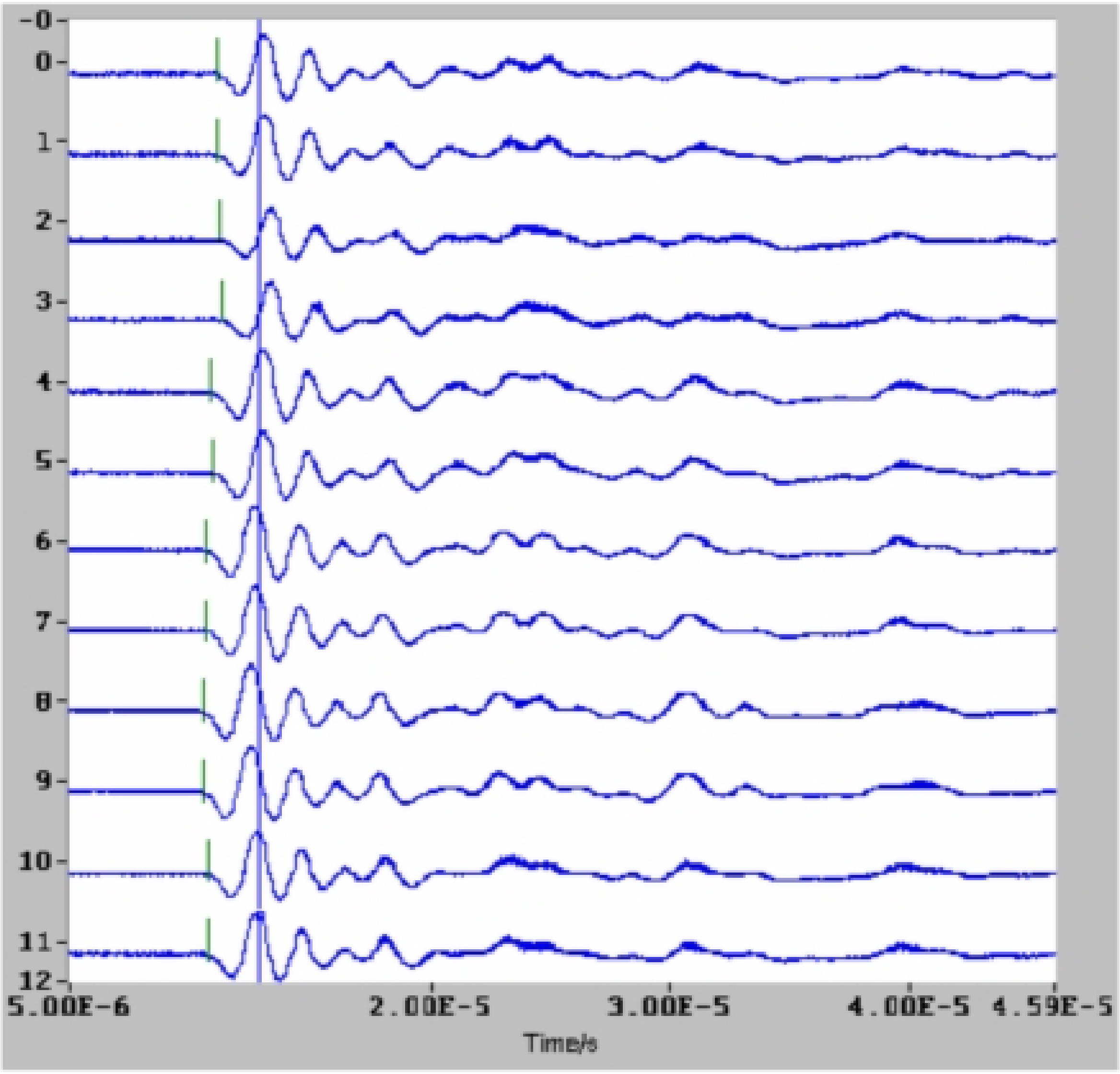

Figure 2-2. *Traces from 12 measurements of P-wave travel time transverse borehole core (two from each orientation) from BH KFM01A at 735.10 m depth (second set of measurements). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

2.3 Test method

Tests were made at 30º intervals around the core, starting at 0º parallel with the foliation. The cores were all oriented such that successive measurements were made clockwise looking down the borehole, see Figure 2-3. 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 permanent marker. The cores may thus be checked at any time to ascertain the location and orientation of the tests.

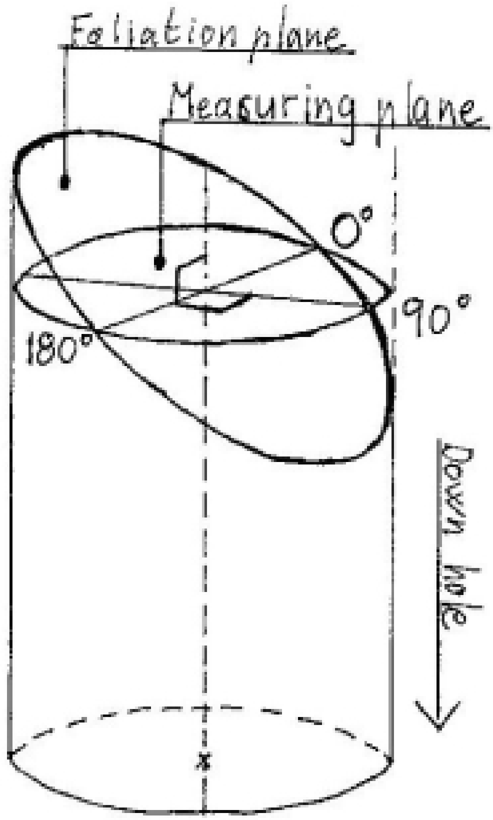

Figure 2-3. Orientation of measurements.

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 1000 to obtain the velocity in m/s.

Analysis

Since the acoustic velocity is dependant 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:

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

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).

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

The magnitude and orientation of the principal velocities was determined from the Eigen values and vectors of the 2D tensor matrix:

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

3 Results

3.1 Summary of results

The results of the determinations of the travel time and velocity for all the tests are presented in the appendix, page 19, and the velocity and anisotropy are shown diagrammatically against depth in Figures 3-1 and 3-2.

The results of the determination of the principal velocities and their orientations are shown in Table 3-1, and shown diagrammatically against depth in Figures 3-3, 3-4 and 3-5.

The results of calibration determinations for the system are shown in the appendix, page 18.

3.2 Discussion

Accuracy and Repeatability

Calibration tests on an aluminium cylinder indicated a variation of ±0.10 μs in determination of the time pick. Some of this variation may be explained by temperature variations, thickness of coupling medium and seating of the shoes. Similar variations may be expected from the measurements on the cores.

Tests on cores were repeated at two locations, 487.81 m and 735.10 m, after the first series of tests were completed. These tests were repeated as the oscilloscope traces in the original tests were somewhat noisy. It was decided to investigate the effect of poor signal response on the repeatability of the velocity determinations and determine typical values for repeatability of velocity determinations. At 487,81 m the difference in magnitude of the principal velocities is about 120 m/s, the anisotropy ratio is the same and the orientation differs by 10°. At 735.10 m the difference in magnitude is about 300 m/s for the maximum velocity and less than 100 m/s for the minimum. The anisotropy ratios measured were 1.04 and 1.08 and there is about 30° difference in orientation. The orientations of the principal velocities are not well constrained mathematically for low anisotropy ratios and the difference in orientation is therefore not particularly surprising. The differences in the measured velocities are presumed due to the problems in seating the transducers and obtaining good signal contact with the rock and 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, see Figure 3-6. Typically in the whole series of tests the deviation between the measured value and the model fit is about 0,6%, with a maximum average error of 2,2%. There does not appear to be a strong correlation between the apparent quality of the received signal and the apparent error determined by this method.

It is therefore considered that the repeatability of the reported results for velocities is probably in the region of ±100–200 m/s. The error in the orientation of the principal velocities is probably in the region of ±10°–20° where the anisotropy ratio is greater than 1.1 with greater errors below this limit. 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 in the region of ±0,02–0,05. The magnitude of the anisotropy suggests that errors of this magnitude will not have a large effect on the determination of the anisotropy ratio and orientation, and this appears to be confirmed by the generally consistent results obtained. However, more work needs to be done to quantify the accuracy and repeatability of the measurements.

Conclusions

The results from the P-wave velocity measurements on the cores show a consistent pattern down to about 500 m depth with maximum velocities between 5400–5700 m/s and a low anisotropy ratio of between 1–1.1. Below 500 m the velocity reduces gradually with depth to under 5000 m/s and the anisotropy ratio increases to up to 1.2. At 1001 m depth the was a very low measurement of maximum velocity of 4400 m/s.

The orientation of the principal velocities is quite consistent with depth, especially if only the results with an anisotropy ratio greater than 1.1 are evaluated (the orientations of the principal velocities are not well constrained mathematically for low anisotropy ratios). The orientation of the maximum velocity is typically 160º–165º from the foliation direction (measured clockwise looking down the hole), and not parallel or perpendicular to the foliation as might have been expected.

Table 3-1. Calculated principal acoustic velocities and orientation, transverse core in borehole KFM01A, Forsmark.

Depth m	Max Vel m/s	Orientation (Figure 2-3)	Min Vel m/s	Orientation (Figure 2-3)	Anisotropy ratio
105,46	5432	85º	5176	175º	1,05
162,00	5345	0º	5113	90º	1,05
206,85	5578	140º	5225	50º	1,07
253,35	5553	155º	5066	65º	1,10
264,61	5630	150º	5129	60º	1,10
304,39	5415	155º	5163	65º	1,05
350,54	5433	30º	5255	120º	1,03
384,65	5431	105º	5034	15º	1,08
413,90	5542	140º	5315	50º	1,04
452,35	5531	105º	5196	15º	1,06
487,81	5721	150º	5172	60º	1,11
487,81	5606	160º	5054	70º	1,11
516,20	5327	165º	4449	75º	1,20
522,08	5527	50º	5086	140º	1,09
568,38	5327	100º	4930	10º	1,08
592,53	5061	165º	4568	75º	1,11
632,15	5483	115º	4903	25º	1,12
648,56	5445	135º	5140	45º	1,06
669,35	5295	85º	4928	175º	1,07
688,70	5266	155º	4586	65º	1,15
705,46	5156	150º	4794	60º	1,08
735,10	5456	115º	5057	25º	1,08
735,10	5168	85º	4988	175º	1,04
763,68	4864	155º	4237	65º	1,15
798,60	4937	160º	4155	70º	1,19
824,50	5257	170º	4604	80º	1,14
852,27	5109	155º	4750	65º	1,08
877,45	5225	15º	4562	105º	1,15
908,48	4719	165º	4007	75º	1,18
942,56	5026	155º	4383	65º	1,15
963,24	4959	160º	4138	70º	1,20
981,15	5229	165º	4362	75º	1,20
993,11	5372	160º	4637	70º	1,16
1001,17	4388	140º	3681	50º	1,19

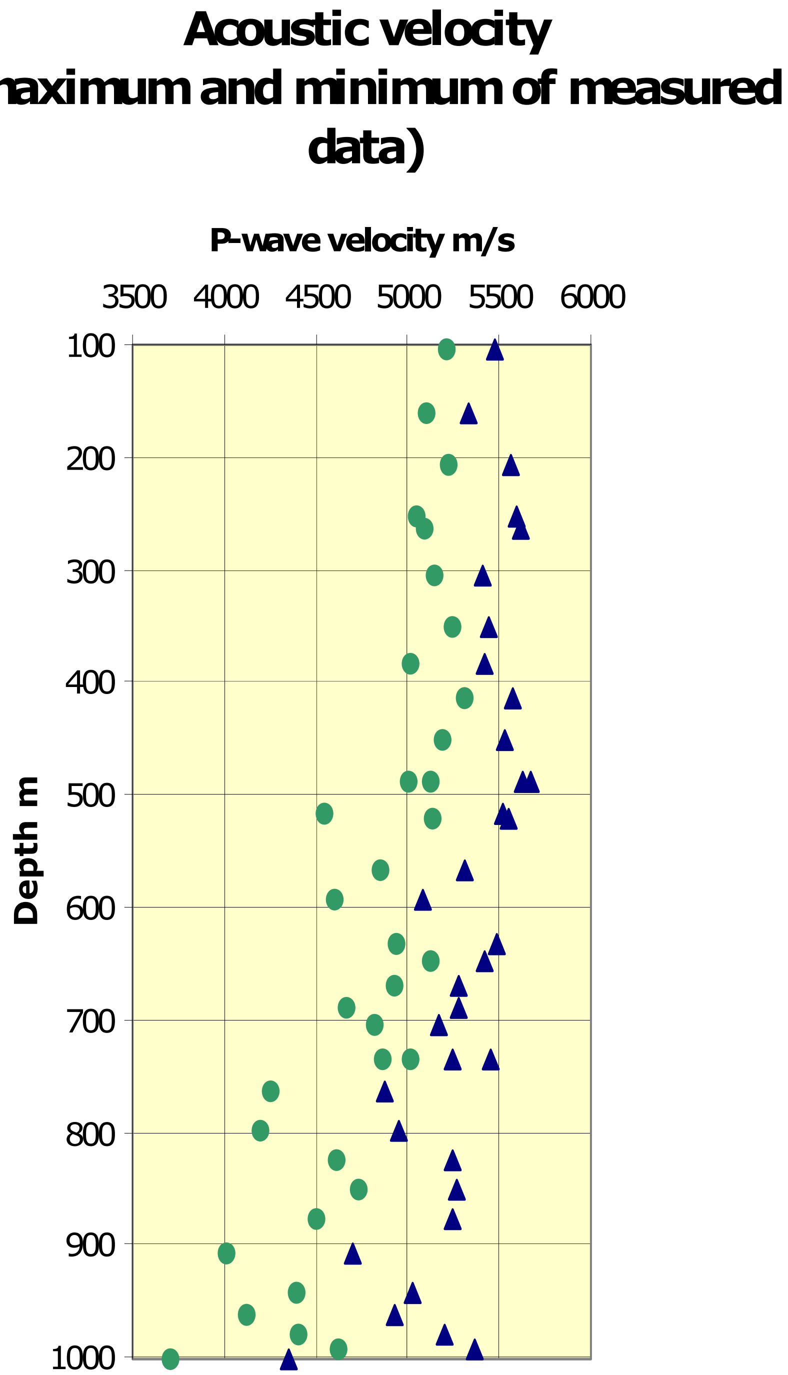

Figure 3-1. *Measured values of maximum and minimum acoustic velocities plotted against depth down borehole KFM01A.*

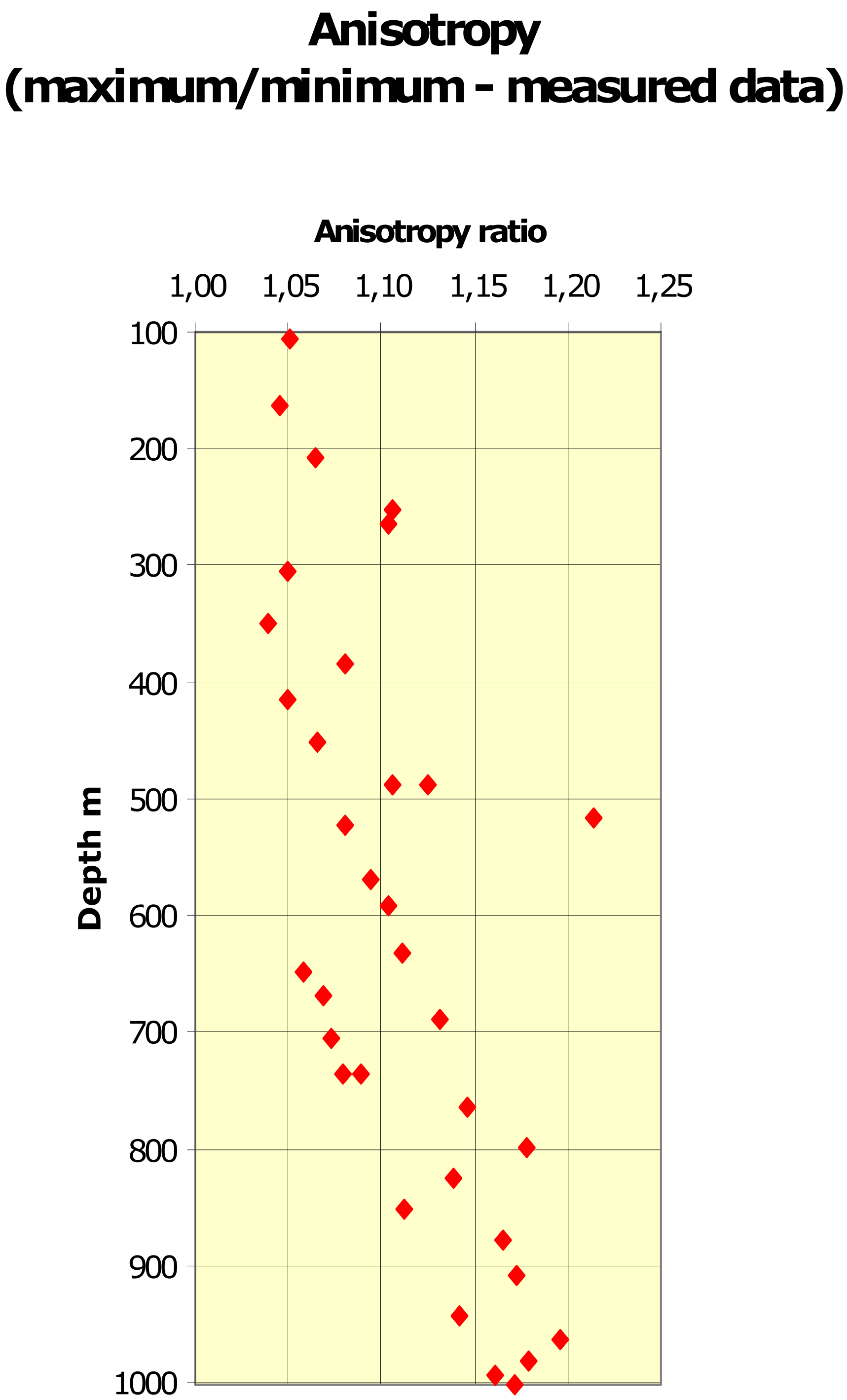

Figure 3-2. *Measured values of acoustic velocities anisotropy plotted against depth down borehole KFM01A.*

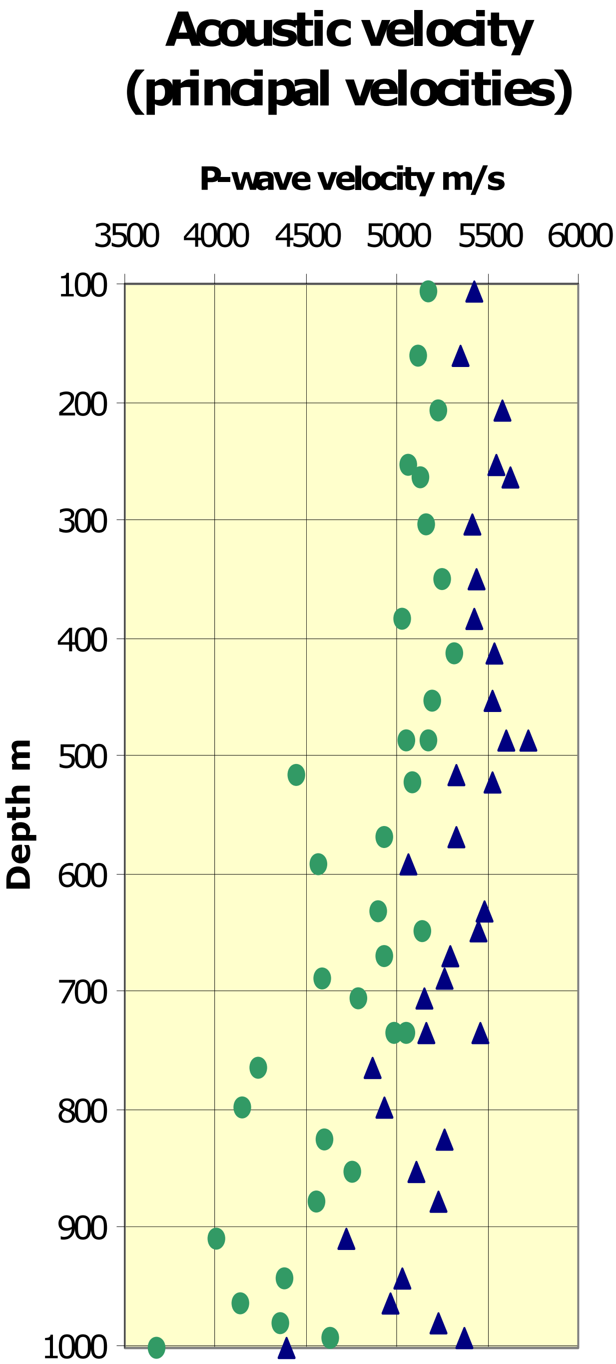

Figure 3-3. *Calculated values of maximum and minimum principal acoustic velocities plotted against depth down borehole KFM01A.*

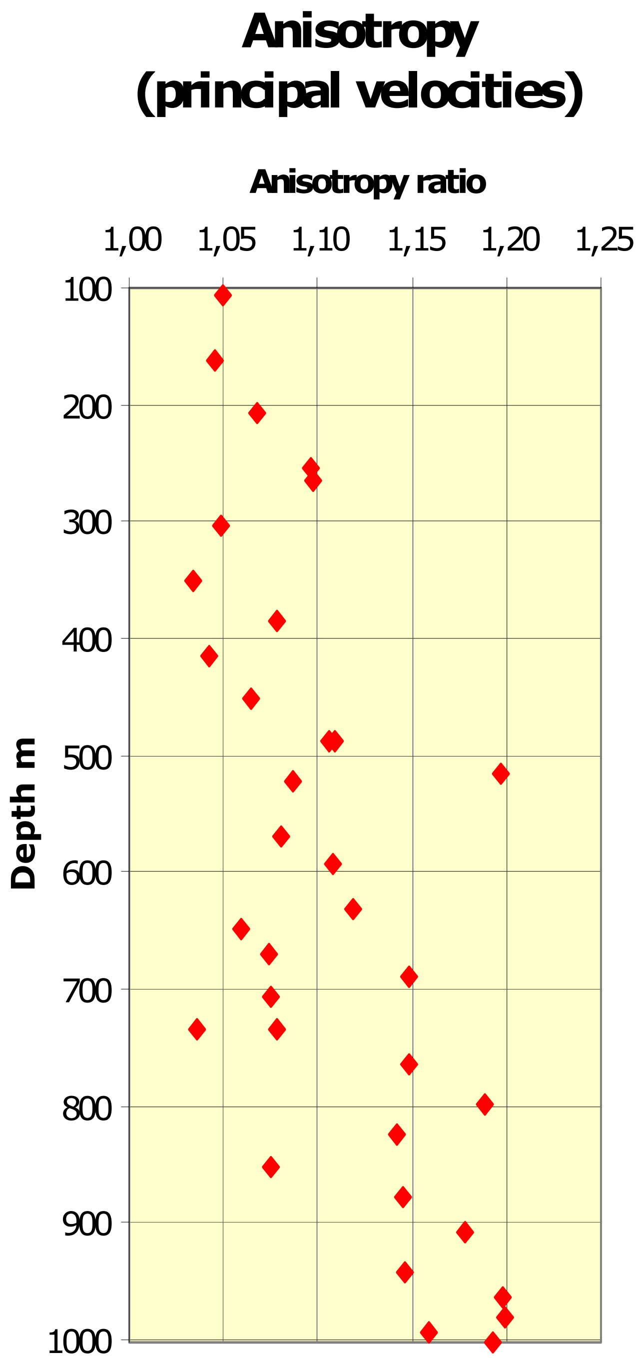

Figure 3-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted against depth down borehole KFM01A.*

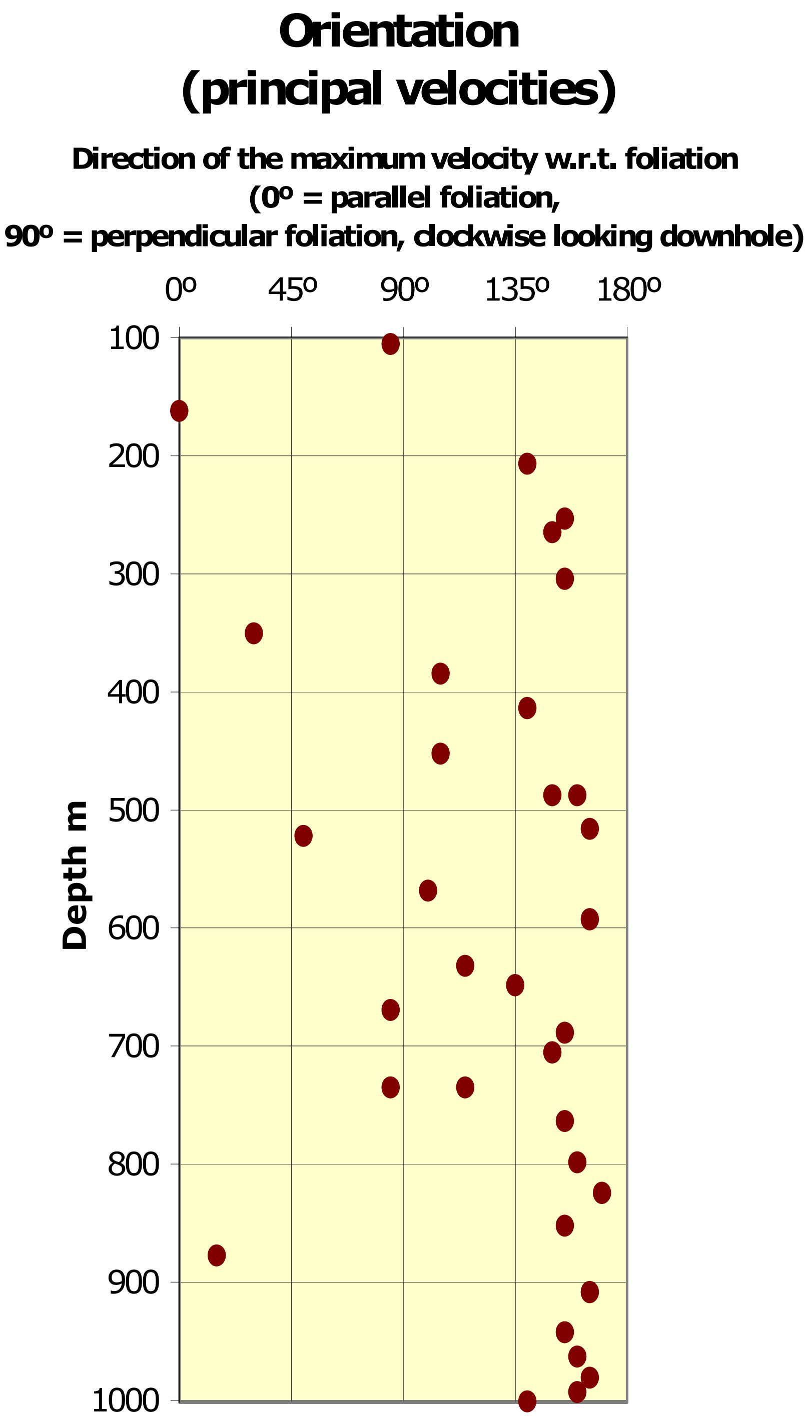

Figure 3-5. *Calculated orientation of the maximum principal acoustic velocity plotted against depth down borehole KFM01A.*

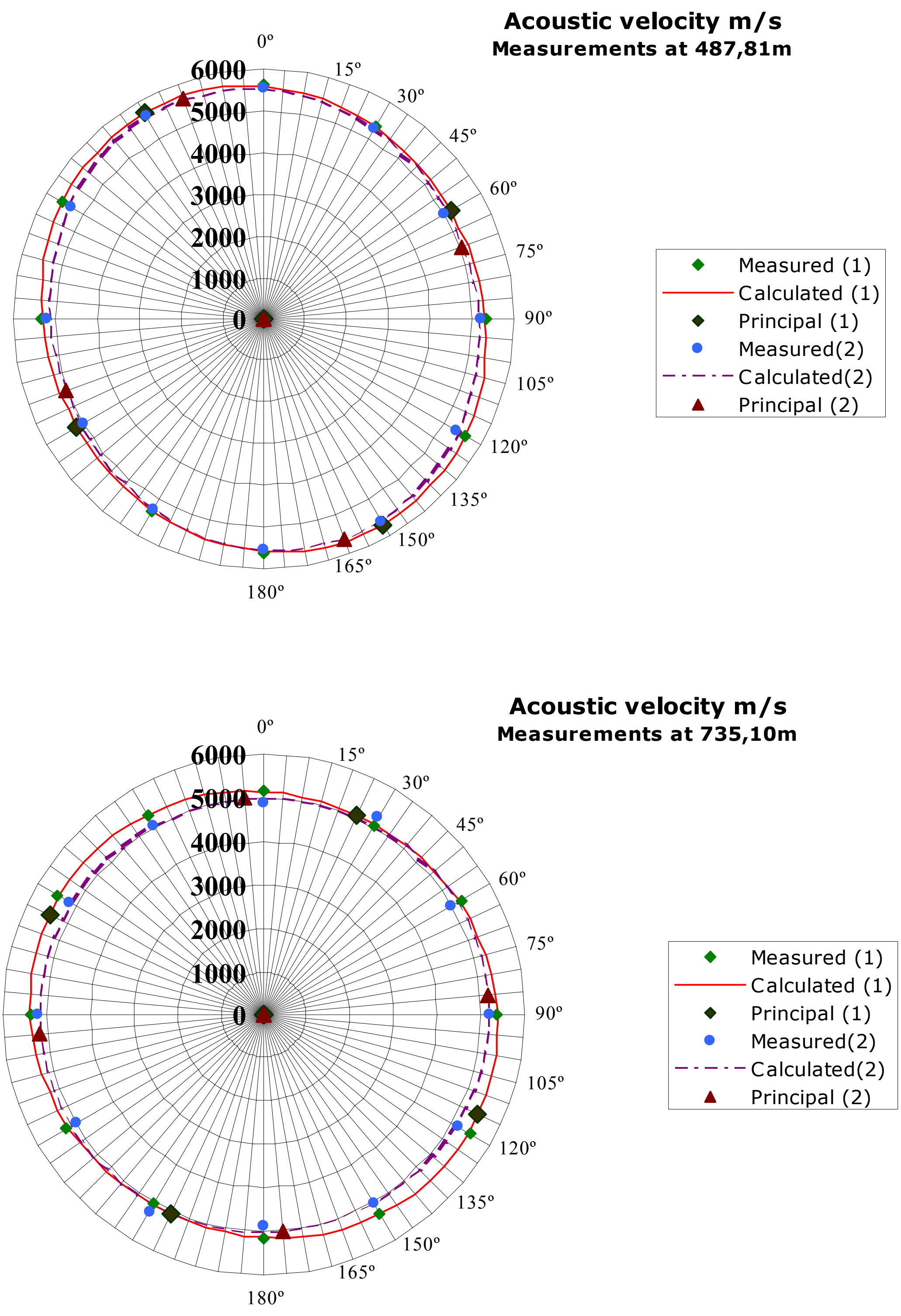

Figure 3-6. *Measured values of acoustic velocity plotted against orientation, together with calculated best fit ellipse and maximum and minimum principal velocities for two sets of measurements at depths of; (a) 487,81 m and (b) 735.10 m in borehole KFM01A.*

4 References

Eitzenberger, Andreas. Detection of Anisotropy by Diametral Measurements of Longitudinal Wave Velocities on Rock Cores, SKB report in press, September 2002.

Janson, Thomas. Metodebeskriving för: bestämning av p-vågens hastighet. SKB report MD 190.002 ver 1.0, 2002-01-28

Appendix

Calibration measurements on aluminium cylinder diameter 50,90 mm with known velocity 6320 m/s (this page).

Data table as supplied on Excel file for SICADA database (next page).

Calibration measurements on aluminium cylinder diameter 50,90 mm with known velocity 6320 m/s.

Date and time	Known Velocity m/S	Diameter mm	Time Measured µS	Time Calculated µS	Time Correction µS
20030222	6320	50,9	9,22	8,05	–1,17
20030224	6320	50,9	9,12	8,05	–1,07
20030225 morning	6320	50,9	9,31	8,05	–1,26
20030225 afternoon	6320	50,9	9,14	8,05	–1,09
20030225 kl.1501	6320	50,9	9,11	8,05	–1,06
20030225 kl.1645	6320	50,9	9,24	8,05	–1,19
20030225	6320	50,9	9,31	8,05	–1,26

Borehole KFM01A P-wave velocity measurements (orientation: see Figure 2-3).

Depth m	Diameter mm	Time measured, µS Parallel foliation 0º	Time measured, µS Perpendicular foliation 30º	60º	90º	120º	150º	Velocity m/S Parallel foliation 0º	Velocity m/S Perpendicular foliation 30º	60º	90º	120º	150º	Anisotropy ratio
105,46	50,80	9,73	9,74	9,46	9,27	9,55	9,72	5219	5214	5371	5478	5317	5227	1,05
162,00	50,95	9,55	9,66	9,83	9,98	9,85	9,59	5336	5272	5181	5103	5173	5311	1,05
206,85	50,57	9,31	9,56	9,67	9,45	9,12	9,08	5430	5290	5228	5349	5546	5567	1,06
253,35	50,80	9,08	9,93	10,05	9,68	9,48	9,26	5592	5116	5055	5249	5359	5487	1,11
264,61	50,86	9,16	9,67	9,98	9,60	9,32	9,05	5550	5260	5094	5299	5455	5621	1,10
304,39	50,73	9,37	9,69	9,84	9,71	9,51	9,43	5412	5233	5153	5222	5332	5380	1,05
350,54	50,62	9,29	9,38	9,40	9,50	9,65	9,60	5447	5394	5383	5326	5244	5271	1,04
384,65	50,50	10,06	9,90	9,72	9,31	9,38	9,56	5018	5099	5193	5422	5382	5280	1,08
413,90	50,60	9,27	9,52	9,47	9,33	9,27	9,07	5459	5313	5341	5421	5459	5576	1,05
452,35	50,70	9,65	9,77	9,47	9,17	9,23	9,45	5255	5187	5352	5530	5491	5366	1,07
487,81	50,72	8,99	9,54	9,89	9,48	9,09	8,94	5643	5314	5126	5348	5577	5671	1,11
487,81	50,77	9,19	9,60	10,15	9,72	9,55	9,02	5525	5286	5003	5221	5317	5629	1,13
516,20	50,72	9,19	10,68	11,16	11,09	10,50	9,92	5520	4750	4545	4572	4829	5114	1,21
522,08	50,71	9,68	9,26	9,14	9,55	9,88	9,87	5237	5477	5549	5308	5133	5138	1,08
568,38	50,82	10,04	10,47	9,74	9,57	9,61	10,06	5060	4852	5216	5308	5286	5050	1,09
592,53	50,62	9,97	10,53	10,98	11,00	10,52	10,15	5078	4805	4609	4602	4810	4985	1,10
632,15	50,66	10,12	10,26	10,03	9,41	9,23	9,56	5004	4936	5051	5381	5486	5300	1,11
648,56	50,73	9,55	9,80	9,90	9,55	9,35	9,38	5313	5177	5125	5313	5423	5406	1,06
669,35	50,60	10,23	9,96	9,72	9,59	9,67	10,26	4947	5078	5206	5274	5231	4932	1,07
688,70	51,09	9,85	10,74	10,95	10,94	10,21	9,68	5185	4758	4664	4668	5005	5276	1,13
705,46	50,75	9,99	10,54	10,45	10,42	10,02	9,82	5078	4816	4855	4869	5063	5169	1,07
735,10	50,84	9,86	10,14	9,72	9,49	9,31	9,55	5154	5014	5231	5355	5459	5324	1,09
735,10	50,91	10,47	9,70	10,23	9,80	9,86	10,13	4861	5249	4975	5196	5164	5024	1,08
763,68	50,95	10,64	11,66	11,96	11,57	11,06	10,44	4787	4368	4259	4404	4605	4881	1,15
798,60	50,67	10,39	11,34	12,06	11,85	11,25	10,23	4875	4467	4202	4276	4504	4951	1,18
824,50	50,75	9,92	10,02	10,96	11,01	10,33	9,66	5117	5063	4631	4610	4911	5252	1,14
852,27	50,96	10,62	10,14	10,72	10,76	10,19	9,67	4799	5024	4754	4734	4999	5268	1,11
877,45	50,87	9,94	9,70	10,31	11,30	10,80	10,47	5116	5245	4932	4502	4711	4857	1,16
908,48	50,92	10,82	11,66	12,69	12,43	11,67	10,98	4704	4368	4011	4095	4364	4636	1,17
942,56	50,84	10,42	11,16	11,35	11,56	10,38	10,12	4877	4554	4478	4398	4896	5024	1,14
963,24	51,00	10,33	11,49	12,36	11,91	10,97	10,48	4935	4437	4125	4283	4647	4865	1,20
981,15	50,79	9,89	10,63	11,52	11,47	10,53	9,77	5136	4779	4409	4427	4822	5199	1,18
993,11	50,81	9,65	10,23	10,98	10,69	10,07	9,46	5263	4967	4626	4754	5046	5369	1,16
1001,17	50,90	12,33	13,63	13,71	12,80	11,71	11,80	4127	3733	3712	3975	4347	4312	1,17