P-04-45

Oskarshamn site investigation

Borehole: KLX02

Determination of P-wave velocity, transverse borehole core

Panayiotis Chryssanthakis, Lloyd Tunbridge
Norwegian Geotechnical Institute, Oslo

March 2004

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1651-4416
SKB P-04-45

Oskarshamn site investigation

Borehole: KLX02

Determination of P-wave velocity, transverse borehole core

Panayiotis Chryssanthakis, Lloyd Tunbridge
Norwegian Geotechnical Institute, Oslo

March 2004

Keywords: Rock Mechanics, P wave velocity, Anisotropy.

Summary

The Norwegian Geotechnical Institute has carried out P-wave measurements on drill cores from borehole KLX02 at Simpevarp in December 2003. Forty-six P-wave velocity measurements have been carried out from a total of 1700 m of core.

The results from the P-wave velocity measurements show a variable pattern with maximum velocities between 4783–6556 m/s and a variable anisotropy ratio of up to 1.18, though generally under 1.08. At about 200 m depth the maximum velocity is about 5800 m/s and the maximum velocity generally reduces with depth to about 550 m depth where the velocity is about 5450–5600 m/s. From 550 m to about 1100 m depth the maximum velocity is very variable between 4783–6556 m/s, though values around 5500 m/s are most common. Between 1100 m and 1250 m depth there are four consistent values between 5350–5450 m/s. Below 1250 m depth the maximum velocity varies between 4963–5970 m/s with some apparent trends over short intervals. There does not appear to be any trend in the anisotropy ratio with depth and 80% of the values of anisotropy ratios are low values of between 1.00–1.08.

The foliation was weakly developed or not identifiable over large sections of the core and, in these areas, the orientation of the principal velocities could not be identified. In those sections where the foliation direction could be identified there is no consistent orientation of the principal velocities with respect to the foliation direction, though about 50% of these orientations lie between 0º and 30º from the foliation.

Contents

1	**Introduction**	7
2	**Objective and scope**	9
3	**Equipment and methods**	11
4	**Execution**	15
4.1	Sampling	15
4.2	Testing	15
5	**Results**	17
5.1	Summary of results	17
5.2	Discussion	25
6	**References**	27
Appendix A		28

1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on cores from borehole KLX02 at Simpevarp in Sweden in accordance with SKB Activitetsplan AP PF400-03-087 (SKB internal controlling document).

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski during the period 4–5 December 2003 in accordance with SKB's method description MD 190.002 version 1.0 (SKB internal controlling document).

KLX02 is an earlier borehole and was drilled at year 1992. Revaluation of the core logging made it easy to take cores for determines the P wave velocity transverse to the core axis. The core diameter is about 47.5 mm, which could be compared with the core diameter of about 51 mm for the new boreholes in the site investigation.

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 Simpevarp.

The number of tests performed and the number of joint sets is given in Table 2-1.

Table 2-1. Total number of P wave velocity specimens and measurements.

Borehole	P wave velocity test specimens	P wave velocity measurements
KAV01	46	49

The results from the P wave velocity measurements are presented in this report by means of tables, figures and spreadsheets.

3 Equipment and methods

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

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

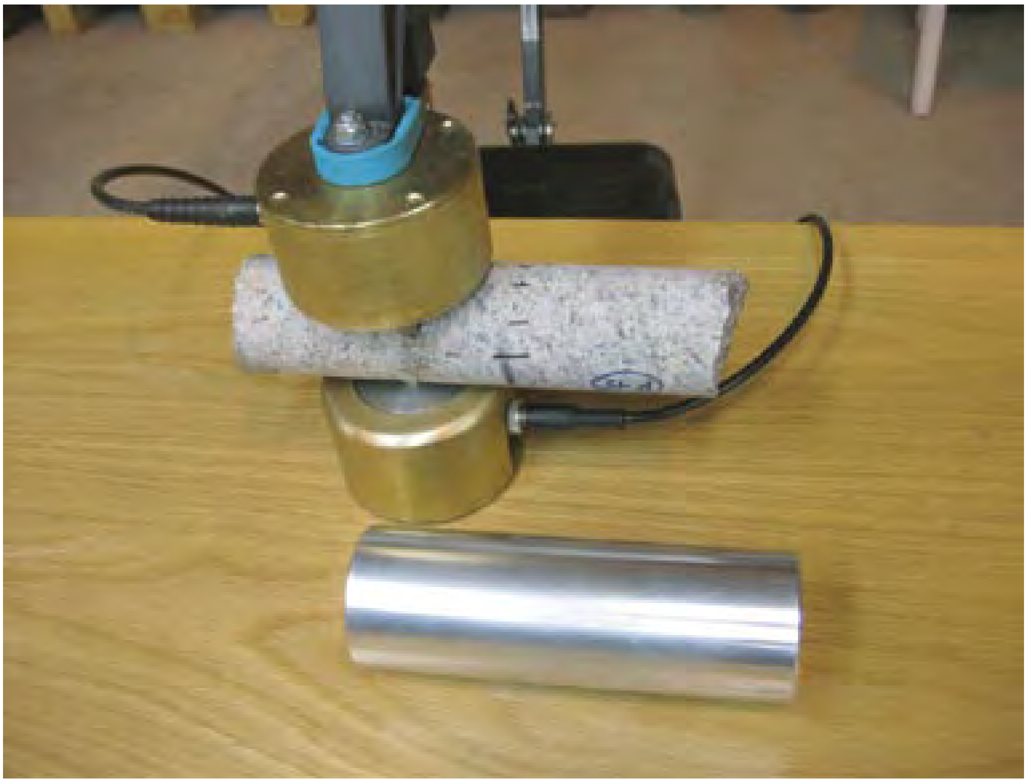

Figure 3-2. *Detail of NGI's apparatus for measuring acoustic P-wave travel time transverse borehole core. The aluminium cylinder for calibration of the device is in front.*

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, 2003 a–d/). 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 made all the interpretations. The time pick could be measured with a precision better than 0.01µs. 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.

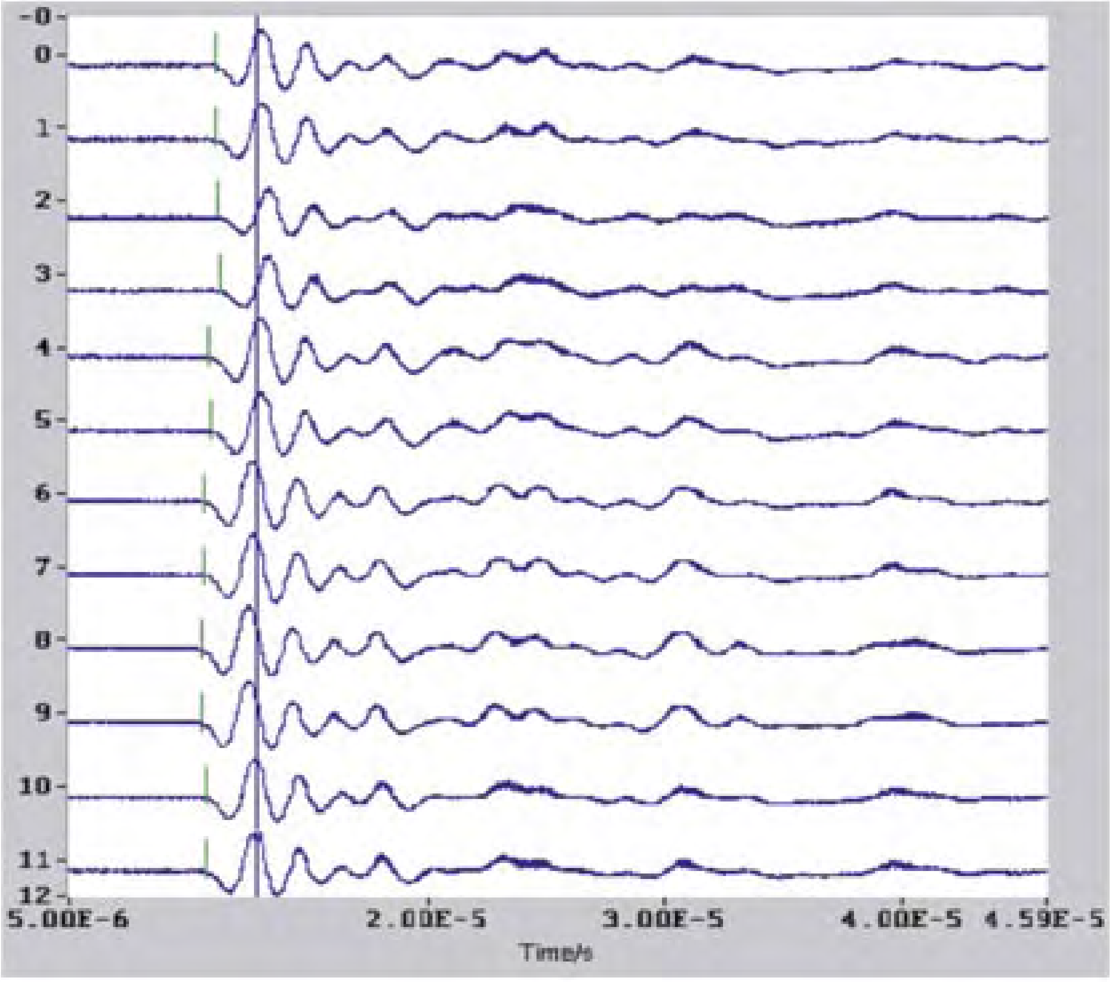

Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Forty-six core specimens of length ca 200–500 mm and diameter about 47 mm were selected from borehole KLX02 while the complete length of the borehole (depth 0–1700 m) was displayed on the racks in the core shed at Simpevarp. The specimens were selected jointly together by NGI and SKB.

The rocks can be classified as mainly metamorphic rocks which include mainly granite-monozodiorite rock of coarse to medium grained granodiorite with some areas of medium grained granite, and some veins of fine grained darker diorite. Geological logging of the 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 Testing

Tests were made at 30º intervals around the core, starting at 0º parallel with the foliation. However, the foliation was often not identifiable and in these cases the tests were started at random orientations. The cores were all oriented such that successive measurements were made clockwise looking down the borehole (see Figure 4). 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.

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.

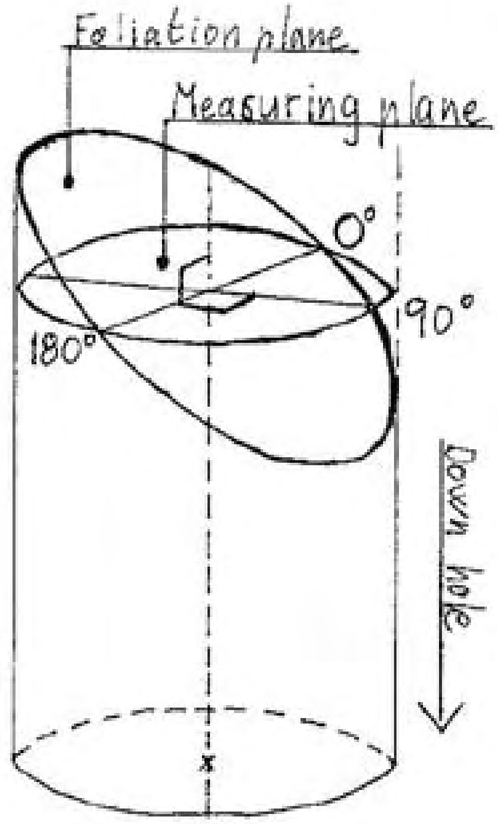

Figure 4-1. *Orientation of measurements.*

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:

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

A simple regression analysis of the six measurements was used to determine the values of V_x, V_y, and V_{xy} (where the X-axis is parallel with the foliation where identifiable).

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

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

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

5 Results

5.1 Summary of results

The results of measured values of travel time and velocity for all the tests are presented in Table 5-1, and the velocity and anisotropy are shown diagrammatically against depth in Figures 5-1 and 5-2.

The results of calculated principal velocities, anisotropy and their orientations are presented on Table 5-2 and are shown diagrammatically against depth in Figures 5-3, 5-4 and 5-5. The orientation of the principal velocities is reported only where the orientation of the foliation could be identified.

The results of calibration determinations for the system are shown in the Appendix A.
The results are also reported to SICADA (FN 234).

Table 5-1. Measurements of acoustic velocity, transverse core in borehole KLX02, Simpevarp. (Orientation clockwise looking down hole, 0º is parallel with foliation where identified.)

Depth m	Diameter mm	Corrected time, mS Parallel foliation 0º	30º	60º	Perpendicular foliation 90º	120º	150º	Velocity m/S Parallel foliation 0º	30º	60º	Perpendicular foliation 90º	120º	150º	Anisotropy ratio
216,90	47,50	8,30	8,24	8,10	8,15	8,25	8,19	5722	5763	5863	5827	5756	5798	1,02
246,60	47,43	8,43	8,18	8,63	8,84	8,91	8,53	5625	5797	5495	5364	5322	5559	1,09
272,00	47,12	8,05	8,12	8,14	8,28	8,28	8,04	5852	5802	5787	5690	5690	5859	1,03
304,14	47,05	8,16	8,42	8,55	8,61	8,44	8,21	5765	5587	5502	5463	5573	5730	1,06
336,45	47,28	8,34	8,48	8,37	8,36	8,36	8,33	5668	5574	5648	5654	5654	5675	1,02
366,60	47,20	8,62	9,12	9,42	8,97	8,15	8,38	5474	5174	5010	5261	5790	5631	1,16
396,10	47,04	8,99	8,54	8,35	8,68	8,96	8,88	5231	5507	5632	5418	5249	5296	1,08
425,10	47,20	8,20	8,54	8,48	8,41	8,34	8,16	5755	5526	5565	5611	5658	5783	1,05
455,85	47,03	8,63	8,61	8,76	8,87	8,77	8,86	5448	5461	5368	5301	5362	5307	1,03
485,84	47,40	8,54	8,70	9,05	9,01	8,70	8,55	5549	5447	5237	5260	5447	5543	1,06
516,05	46,97	8,48	8,40	8,34	8,23	8,34	8,45	5538	5590	5631	5706	5631	5557	1,03
539,97	47,03	8,53	8,54	8,68	8,62	8,67	8,53	5512	5506	5417	5455	5423	5512	1,02
575,40	47,18	9,33	9,59	9,92	9,91	9,44	9,21	5056	4919	4755	4760	4997	5122	1,08
604,35	47,37	8,67	8,63	8,60	8,39	8,57	8,58	5463	5488	5507	5645	5526	5520	1,03
634,75	46,79	9,18	9,16	9,39	9,39	9,16	9,30	5096	5107	4982	4982	5107	5030	1,03
668,75	47,05	8,21	8,23	8,34	8,52	8,50	8,37	5730	5716	5640	5521	5534	5620	1,04
683,70	46,80	7,70	7,89	7,93	7,95	7,94	7,79	6077	5930	5900	5885	5893	6006	1,03
703,40	46,88	7,77	7,75	7,69	7,63	7,66	7,71	6032	6048	6095	6143	6119	6079	1,02
731,70	47,30	8,23	8,39	8,37	8,03	8,11	8,25	5746	5636	5650	5889	5831	5732	1,04
762,80	47,45	8,78	8,78	8,84	9,18	9,08	8,94	5403	5403	5367	5168	5225	5307	1,05
790,85	47,54	8,70	8,65	8,64	8,63	8,65	8,64	5463	5495	5501	5508	5495	5501	1,01
820,87	47,32	8,56	8,75	8,59	8,31	8,23	8,41	5527	5407	5508	5693	5748	5625	1,06
849,03	46,82	7,67	8,23	8,57	8,34	7,85	7,54	6103	5688	5462	5613	5963	6208	1,14
874,37	47,36	8,78	8,67	8,76	8,64	9,07	9,04	5393	5461	5405	5480	5221	5238	1,05
898,40	47,40	7,42	7,35	7,29	7,21	7,29	7,38	6387	6447	6500	6573	6500	6421	1,03
923,30	47,30	7,57	7,67	7,75	7,83	7,78	7,68	6247	6165	6102	6039	6078	6157	1,03
947,05	47,46	8,36	8,66	9,06	8,85	8,65	8,52	5676	5479	5237	5362	5486	5569	1,08
979,10	47,49	10,34	10,91	11,19	10,62	9,80	10,23	4592	4352	4243	4471	4845	4641	1,14
992,22	47,52	8,44	8,52	8,61	8,84	8,68	8,47	5629	5576	5518	5374	5474	5609	1,05
1041,30	47,30	9,39	9,32	9,29	9,91	9,51	9,33	5036	5074	5091	4772	4973	5069	1,07
1080,85	47,31	8,43	8,47	8,55	8,64	8,58	8,47	5611	5584	5532	5475	5513	5584	1,02
1117,10	47,31	8,91	8,69	8,74	8,79	9,08	9,00	5309	5443	5412	5381	5209	5256	1,04
1164,80	47,30	8,88	8,83	9,07	9,25	9,16	8,92	5325	5356	5214	5113	5163	5302	1,05
1203,85	47,32	8,81	8,90	8,78	8,88	8,89	8,95	5370	5316	5388	5328	5322	5286	1,02
1243,60	47,51	8,92	8,93	9,00	9,33	9,31	9,01	5325	5319	5278	5091	5102	5272	1,05
1281,60	47,32	9,80	10,24	10,51	9,97	9,58	9,67	4828	4620	4502	4745	4939	4893	1,10
1318,50	47,33	10,46	9,64	10,54	11,62	11,42	10,70	4524	4909	4490	4073	4144	4423	1,21
1364,45	47,40	9,28	9,35	8,95	8,49	8,79	9,11	5107	5069	5295	5582	5391	5202	1,10
1407,70	47,49	9,26	8,85	9,05	9,59	9,52	9,23	5128	5365	5246	4951	4988	5144	1,08
1440,60	47,48	9,28	9,32	9,41	9,88	9,79	9,32	5115	5093	5045	4805	4849	5093	1,06
1479,90	47,61	10,09	9,88	10,65	11,62	11,49	10,49	4718	4818	4470	4097	4143	4538	1,18
1522,20	47,38	8,27	8,26	8,36	8,37	8,22	8,21	5728	5735	5666	5659	5763	5770	1,02
1560,00	47,30	8,41	8,45	8,60	8,78	8,80	8,55	5623	5596	5499	5386	5374	5531	1,05
1600,65	46,50	8,52	8,27	8,01	8,24	8,29	8,55	5457	5622	5804	5642	5608	5437	1,07
1642,05	47,35	8,02	8,00	7,99	8,03	8,16	8,07	5903	5917	5925	5895	5801	5866	1,02
1680,60	47,27	8,08	8,45	8,50	8,30	8,05	7,91	5849	5593	5560	5694	5871	5975	1,07
396,10	47,04	8,83	8,48	8,34	8,61	8,98	8,92	5326	5546	5639	5462	5237	5272	1,08
703,40	46,89	7,73	7,75	7,64	7,59	7,61	7,73	6065	6049	6136	6176	6160	6065	1,02
1560,00	47,28	8,49	8,40	8,54	8,77	8,81	8,44	5568	5627	5535	5390	5366	5601	1,05

Table 5-2. Determinations of principal velocity and orientation, transverse core in borehole KLX02, Simpevarp. (Orientation clockwise looking down hole, 0º is parallel with foliation where identified.)

Depth m	Maximum velocity m/s	Orientation	Minimum velocity m/s	Orientation	Anisotropy ratio	Foliation
216,90	5837	80º	5739	170º	1,02	n
246,60	5740	15º	5314	105º	1,08	n
272,00	5866	5º	5694	95º	1,03	n
304,14	5757	170º	5450	80º	1,06	n
336,45	5677	130º	5614	40º	1,01	n
366,60	5755	140º	5026	50º	1,15	n
396,10	5576	55º	5202	145º	1,07	n
425,10	5768	150º	5531	60º	1,04	n
455,85	5447	20º	5302	110º	1,03	n
485,84	5586	165º	5242	75º	1,07	w
516,05	5684	85º	5533	175º	1,03	n
539,97	5520	0º	5422	90º	1,02	n
575,40	5130	160º	4740	70º	1,08	w
604,35	5591	95º	5458	5º	1,02	n
634,75	5099	170º	5003	80º	1,02	n
668,75	5739	15º	5514	105º	1,04	n
683,70	6038	175º	5859	85º	1,03	w
703,40	6140	100º	6032	10º	1,02	n
731,70	5851	115º	5644	25º	1,04	n
762,80	5432	20º	5192	110º	1,05	w
790,85	5509	90º	5479	0º	1,01	n
820,87	5747	120º	5423	30º	1,06	n
849,03	6221	155º	5458	65º	1,14	w
874,37	5485	50º	5247	140º	1,05	n
898,40	6556	85º	6387	175º	1,03	w
923,30	6225	5º	6038	95º	1,03	n
947,05	5655	165º	5282	75º	1,07	n
979,10	4783	140º	4266	50º	1,12	n
992,22	5647	0º	5413	90º	1,04	n
1041,30	5110	10º	4895	100º	1,04	f
1080,85	5616	0º	5484	90º	1,02	w
1117,10	5448	50º	5222	140º	1,04	n
1164,80	5367	5º	5124	95º	1,05	n
1203,85	5363	50º	5307	140º	1,01	n
1243,60	5361	15º	5101	105º	1,05	w
1281,60	4963	140º	4546	50º	1,09	w
1318,50	4786	20º	4068	110º	1,18	f
1364,45	5511	100º	5037	10º	1,09	f
1407,70	5311	25º	4963	115º	1,07	w
1440,60	5163	10º	4838	100º	1,07	w
1479,90	4838	15º	4089	105º	1,18	n
1522,20	5772	155º	5668	65º	1,02	w
1560,00	5635	10º	5368	100º	1,05	w
1600,65	5758	70º	5432	160º	1,06	w
1642,05	5936	40º	5833	130º	1,02	n
1680,60	5970	145º	5544	55º	1,08	w
396,10	5616	55º	5211	145º	1,08	n
703,40	6177	95º	6040	5º	1,02	n
1560,00	5642	15º	5387	105º	1,05	w

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

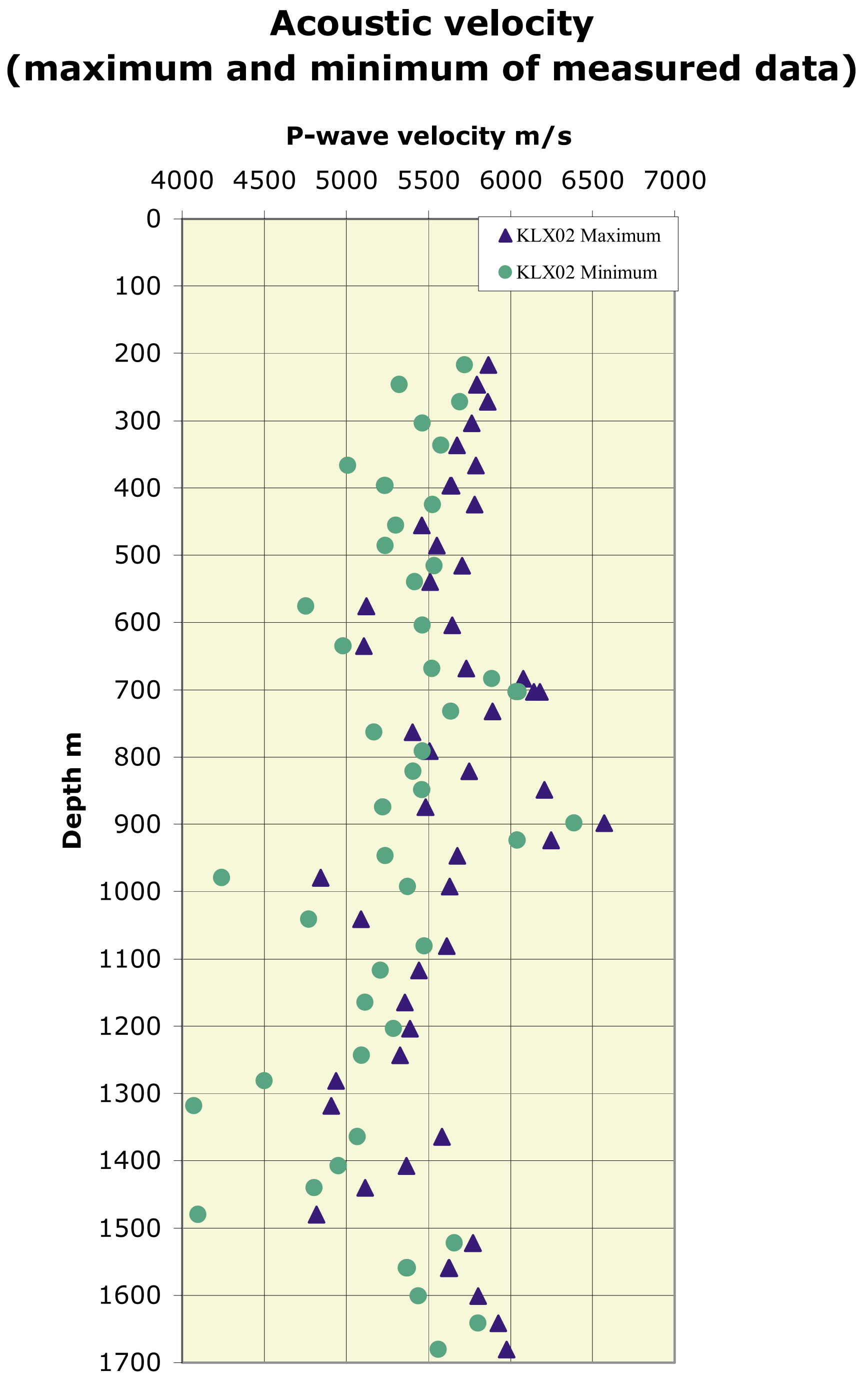

Figure 5-1. *Measured values of maximum and minimum acoustic velocities plotted against depth down borehole KLX02.*

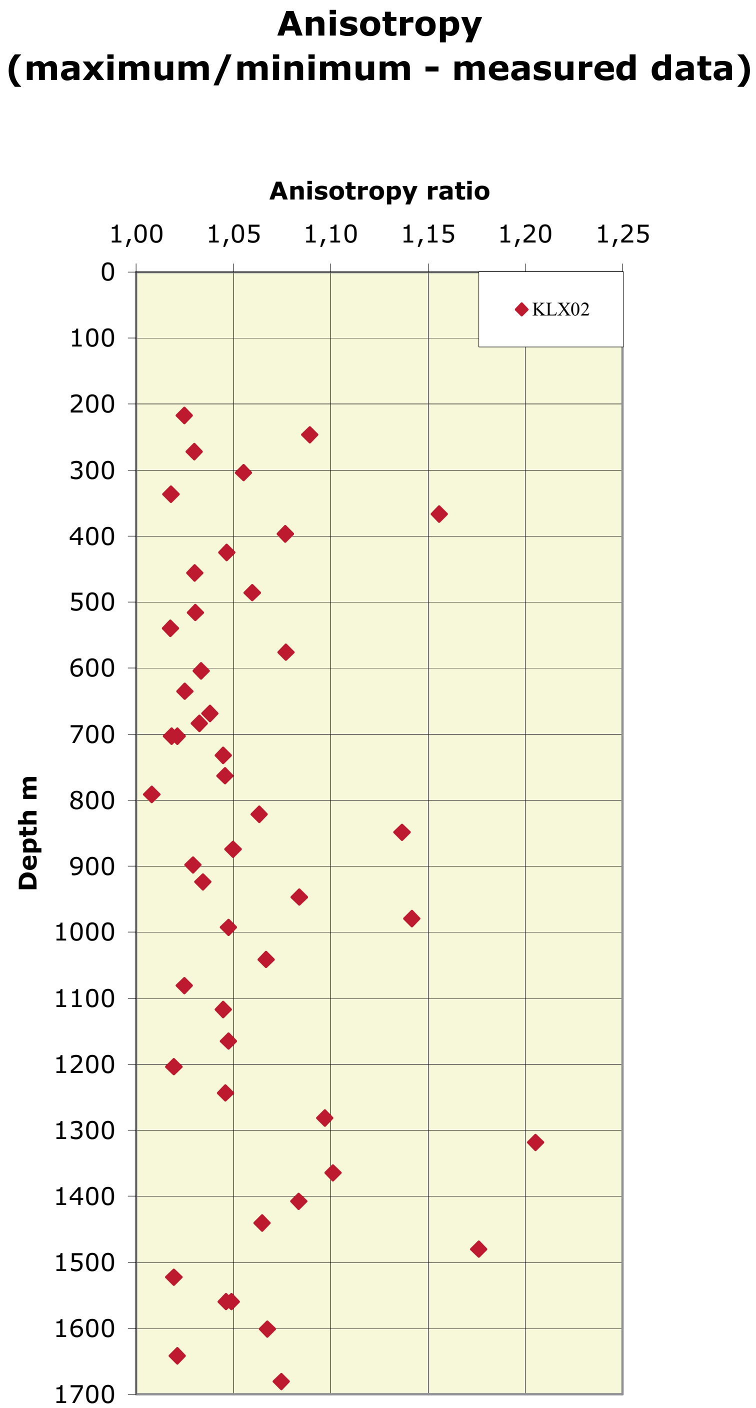

Figure 5-2. Measured values of acoustic velocity anisotropy plotted against depth down borehole KLX02.

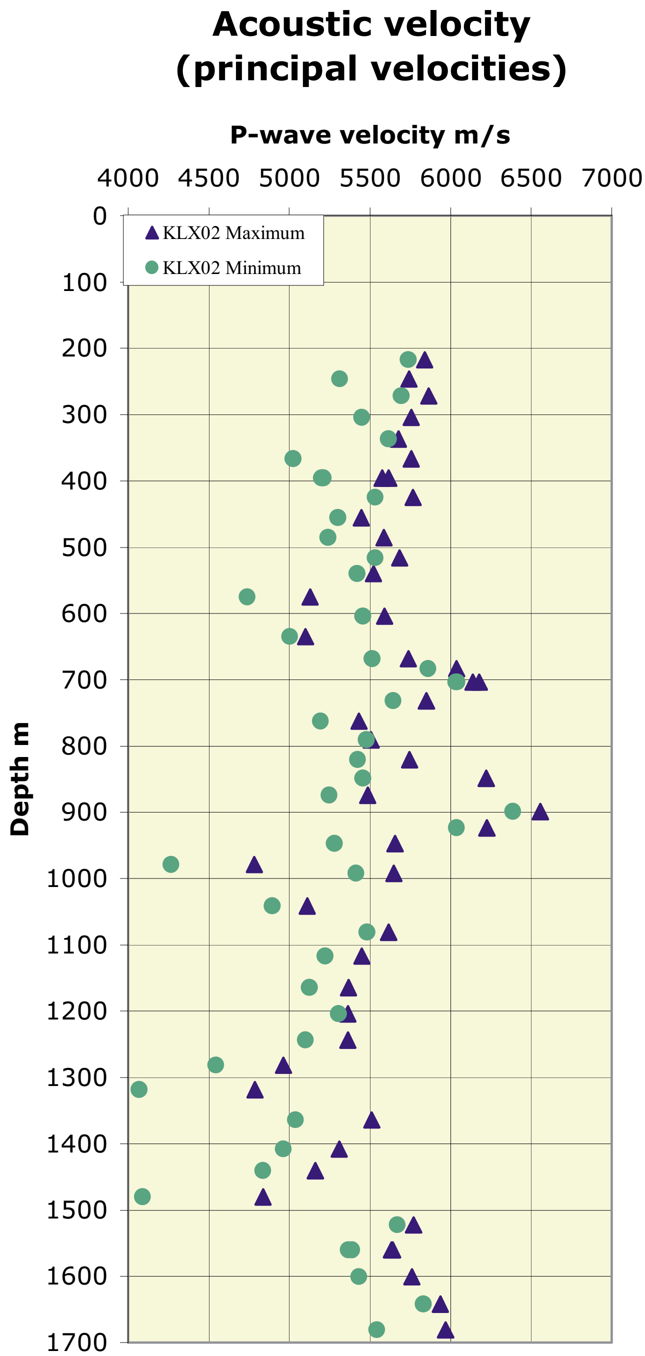

Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted against depth down borehole KLX02.*

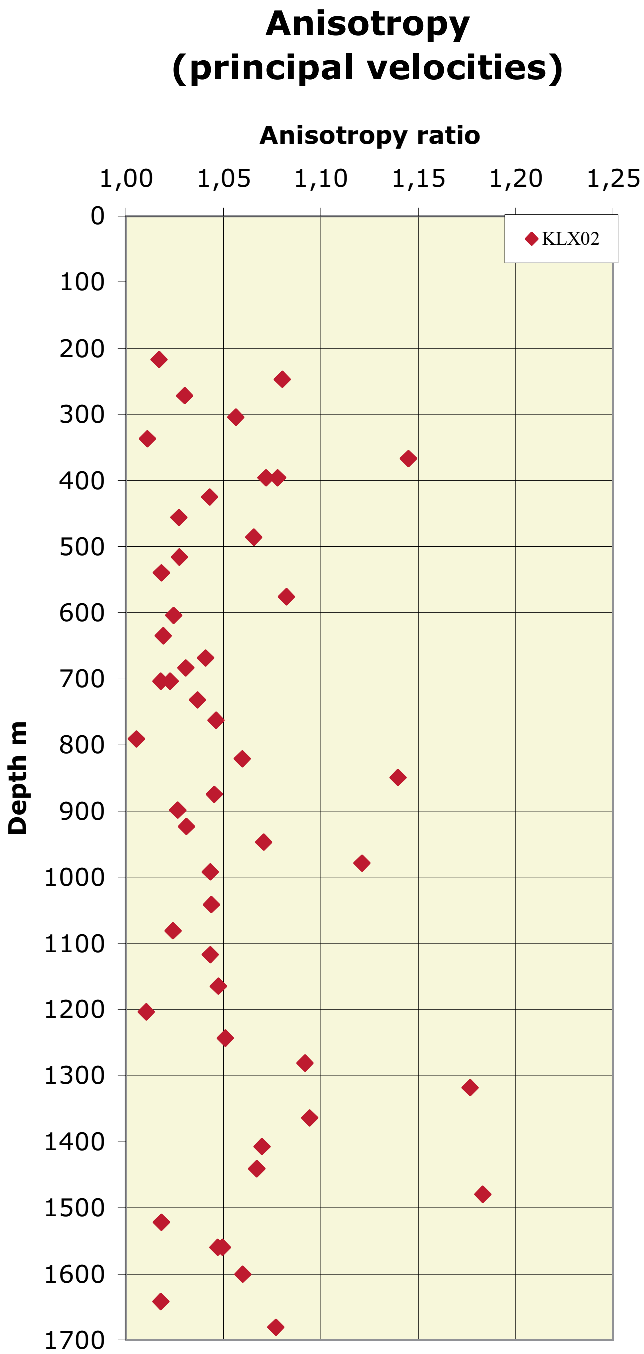

Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted against depth down borehole KLX02.*

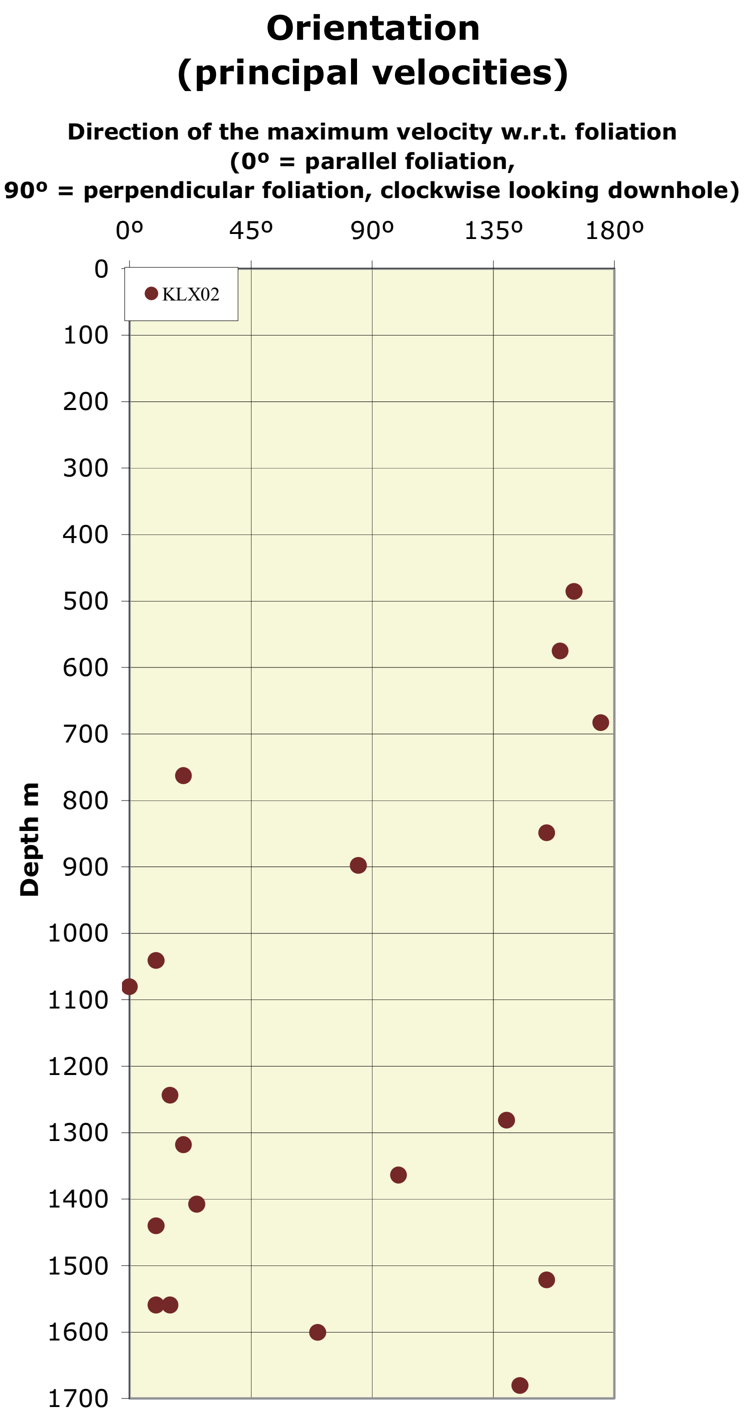

Figure 5-5. *Calculated orientation of the maximum principal acoustic velocity plotted against depth down borehole KLX02 where the orientation of the foliation could be identified.*

5.2 Discussion

Accuracy and Repeatability

Calibration tests on an aluminium cylinder indicated a variation of ± 0.02 μs in determination of the time pick, this represents a variation of about ± 15 m/s in velocity. 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 three locations, 396.10 m, 703.40 m and 1560.00 m, after the first series of tests were completed. These tests were repeated to determine typical values for repeatability of velocity determinations. At 396.10 m the difference in magnitude of the velocities is up to 95 m/s and the anisotropy ratio differs by 0.01. At 703.40 m the difference in magnitude is up to 42 m/s and the anisotropy ratio is the same. At 1560.00 m the difference in magnitude is up to 70 m/s and the anisotropy ratio is the same. The differences in the measured velocities are presumed due to the different positions of the transducers, 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. At 396.10 m the maximum difference was 93 m/s, at 703.40 m the maximum difference was 24 m/s, and at 1560.00 m the maximum difference was 78 m/s see Figure 5-6.

Typically in the whole series of tests the average deviation between the measured value and the model fit is about 0.57% (about 30 m/s), with a maximum error of 3.75% (about 210 m/s).

The deviation between the model fitted to the data and the measured data is somewhat better than in the previous work, for SKB:s site investigations /Chryssanthakis and Tunbridge, 2003 a–d/. The results are also very consistent. It is therefore concluded that the measurement errors are probably less than those determined in the previous work with the repeatability of velocity measurements better than ± 100m/s and the error in the anisotropy ratio better than ± 0.02. This is considered due to increasing operator experience.

Conclusions

The results from the P-wave velocity measurements show a variable pattern with maximum velocities between 4783–6556 m/s and a variable anisotropy ratio of up to 1.18, though generally under 1.08. At about 200 m depth the maximum velocity is about 5800 m/s and the maximum velocity generally reduces with depth to about 550 m depth where the velocity is about 5450–5600 m/s. From 550 m to about 1100 m depth the maximum velocity is very variable between 4783–6556 m/s, though values around 5500 m/s are most common. Between 1100 m and 1250 m depth there are four consistent values between 5350–5450 m/s. Below 1250 m depth the maximum velocity varies between 4963–5970 m/s with some apparent trends over short intervals. There does not appear to be any trend in the anisotropy ratio with depth and 80% of the values of anisotropy ratios are low values of between 1.00–1.08.

The foliation was weakly developed or not identifiable over large sections of the core and, in these areas, the orientation of the principal velocities could not be identified. In those sections where the foliation direction could be identified there is no consistent orientation of the principal velocities with respect to the foliation direction, though about 50% of these orientations lie between 0º and 30º from the foliation.

It is recommended that more work be done to identify the absolute orientation of the tests when the core itself is oriented so that the absolute orientation of the principal velocities can be determined.

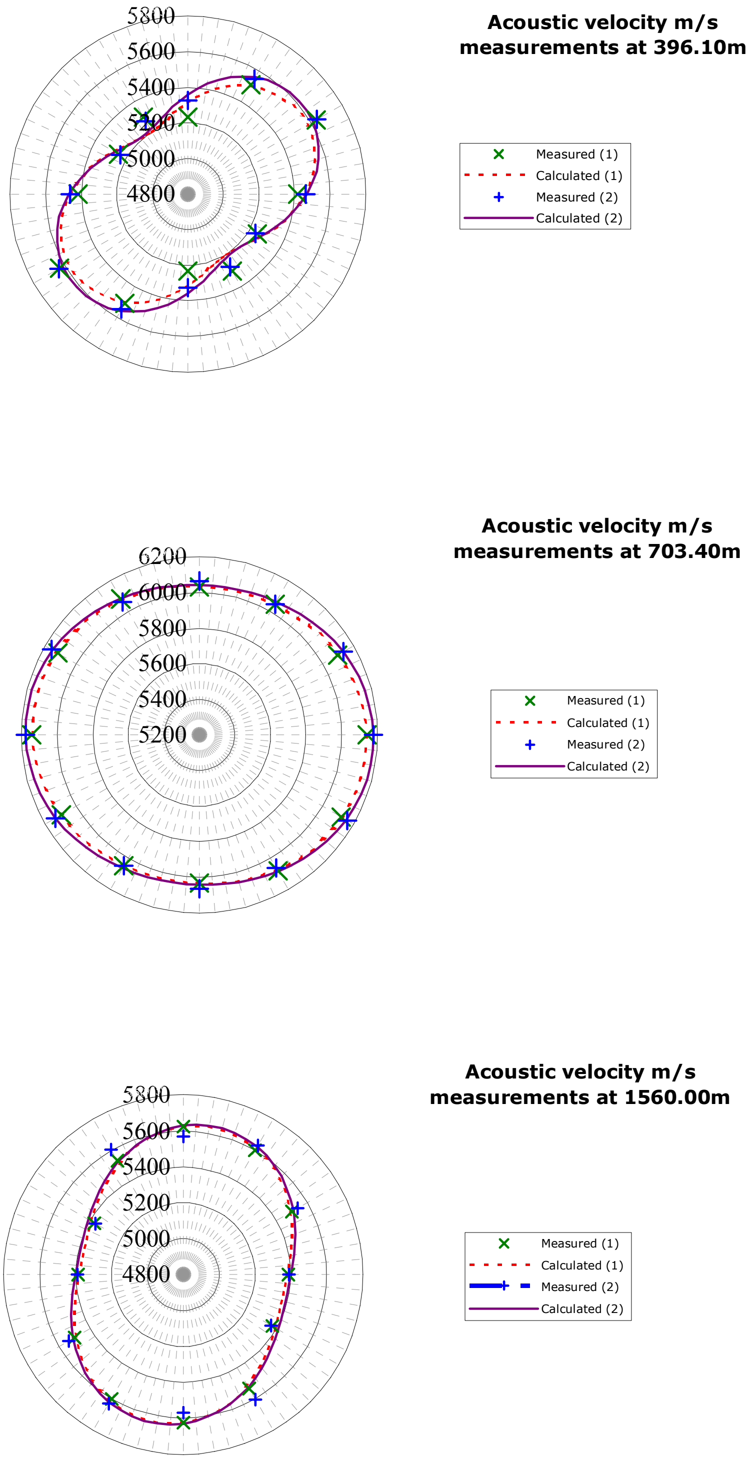

Figure 5-6. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of three determinations at the same depths in borehole KLX02.*

6 References

Chryssanthakis P, Tunbridge L, 2003a. Site investigation, Forsmark. Borehole: KFM 01A. Determination of P-wave velocity, transverse borehole core, SKB P-03-38. Svensk Kärnbränslehantering AB.

Chryssanthakis P, Tunbridge L, 2003b. Site investigation, Simpevarp. Borehole: KSH 01A. Determination of P-wave velocity, transvrse borehole core, SKB P-03-106. Svensk Kärnbränslehantering AB.

Chryssanthakis P, Tunbridge L, 2003c. Site investigation, Simpevarp. Borehole: KSH02. Determination of P-wave velocity, transverse borehole core, SKB P-04-11. Svensk Kärnbränslehantering AB.

Chryssanthakis P, Tunbridge L, 2003d. Site investigation, Simpevarp. ÄSPö pillar stability experiment. Sonic velocity in pilot hole cores, NGI, September 2003.

Eitzenberger A, 2002. Detection of Anisotropy by Diametral Measurements of Longitudinal Wave Velocities on Rock Cores, SKB IPR-03-17. Svensk Kärnbränslehantering AB.

Appendix A

Calibration measurements on aluminium cylinder diameter 50.90 mm with known velocity 6320 m/s (this page).

Calibration measurements on aluminium cylinder diameter 50.90 mm with known velocity 6320 m/s.

Date & time	Known velocity m/S	Diameter mm	Time Measured µS	Calculated µS	Correction µS
20031204 – 0915 hrs	6320	50,90	9.17	8.05	1.12
20031204 – 1315 hrs	6320	50,90	9.17	8.05	1.12
20031205 – 0930 hrs	6320	50,90	9.15	8.05	1.10
20031205 – 1300 hrs	6320	50,90	9.15	8.05	1.10
20031205 – 1700 hrs	6320	50,90	9.17	8.05	1.12
Average			**9.162**		**1.108**