P-04-11

Oskarshamn site investigation

Borehole: KSH02A

Determination of P-wave velocity, transverse borehole core

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September 2003

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Keywords: Roch mechanics, Sonic velocity, AP 400-03-049.

Summary

The Norwegian Geotechnical Institute has carried out P-wave measurements on drill cores from borehole KSH02 at Simpevarp in September 2003. Fiftysix P-wave velocity measurements have been carried out from a total of 920 m of core.

The results from the P-wave velocity measurements show a consistent pattern over the whole length of the borehole with maximum velocities between 5900–6200 m/s and a low anisotropy ratio of between 1 to 1.04. From 870 m to 920 m there is a lower maximum velocity of 5500 m/s with one value of higher anisotropy ratio of about 1.19. Below 920 m the values of velocity and anisotropy are similar to those above 830 m.

The foliation is not identifiable over most of the core and the orientation of the principal velocities could not be identified relative to the foliation.

Contents

1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on cores from borehole KSH02 at Simpevarp in Sweden in accordance with SKB Activitetsplan AP 400-03-049 (SKB internal controlling document).

The work was carried out by Panayiotis Chryssanthakis and Paweł Jankowski during the period 1st–4th September 2003 in accordance with SKB's method description MD 190.002 version 1.0 (SKB internal controlling document).

2 General information

2.1 Description of the test specimens

Fifty six core specimens of length ca 200–500 mm and diameter about 50 mm were selected from borehole KSH02 while the complete length of the borehole (depth 80 m–1000 m) was displayed on the racks in the core shed at Simpevarp. These specimens represent the fine grain diorite with veins of fine-medium granite and pegmatite found over most of the length of the borehole. The specimens were selected together by NGI and Thomas Janson representing SKB.

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

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

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

A strong sine-wave pulse at the natural frequency of the transducers was used as the acoustic signal source. The arrival of the signals was measured using a PC with a high speed data acquisition board and software to emulate an oscilloscope (see Figure 2-3 and previous work by /Chryssanthakis and Tunbridge, 2003a,b,c/). 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 0.01 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.

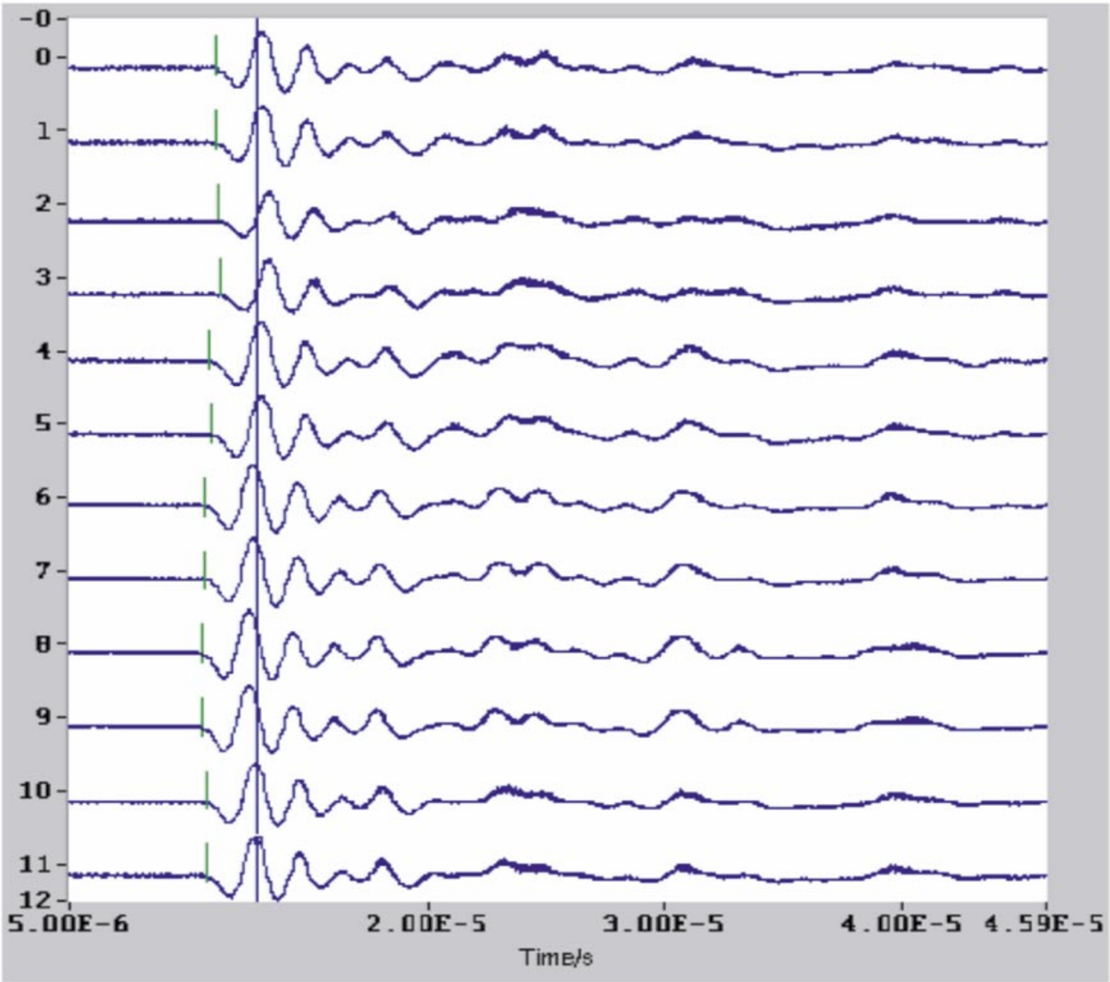


Figure 2-3. *Example traces from 12 measurements of P-wave travel time transverse borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

2.3 Test method

Tests were made at 30° intervals around the core, starting at 0° parallel with the foliation. However, the foliation was generally not identifiable and the tests were thus made at random orientations. The cores were all oriented such that successive measurements were made clockwise looking down the borehole (see Figure 2-4). 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 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 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.

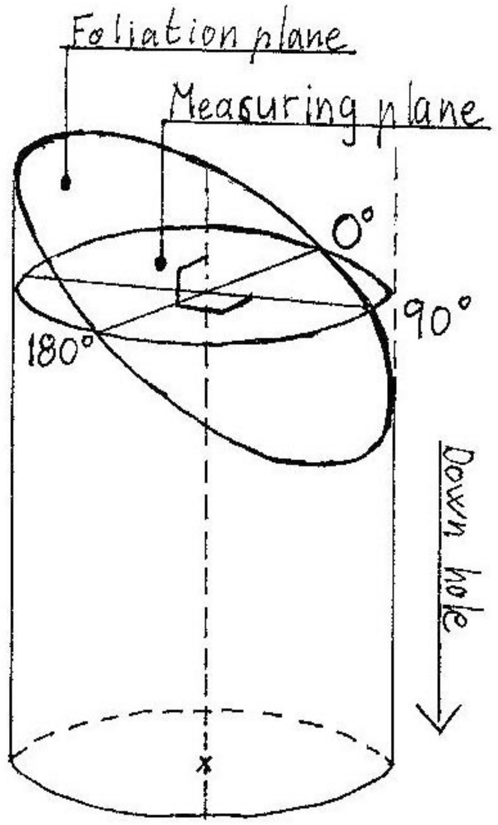


Figure 2-4. Orientation of measurements.

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:

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

3 Results

3.1 Summary of results

The results of measured values of travel time and velocity for all the tests are presented Table 3-1, and the velocity and anisotropy are shown diagrammatically against depth in Figures 3-1 and 3-2. It may be noted from Table 3-1 and Figure 3-1 that some lower velocities are encountered at depths e.g. 524.70 m and 565.70 m. These lower values are attributed to the open joints in the core and the change in foliation at the respective depths.

The results of calculated principal velocities and anisotropy are shown diagrammatically against depth in Figures 3-3 and 3-4. Since the cores did not exhibit any identifiable foliation the orientation of the principal velocities is not reported.

The results of calibration determinations for the system are shown in the Appendix A. The results are also reported to SICADA (FN 160).

3.2 Discussion

Accuracy and repeatability

Calibration tests on an aluminium cylinder indicated a variation of ± 0.03 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, 385.85 m and 888.60 m, after the first series of tests were completed. These tests were repeated to determine typical values for repeatability of velocity determinations. At 385.85 m the difference in magnitude of the velocities is about 20–120 m/s, and the anisotropy ratio differs by 0.02. At 888.60 m the difference in magnitude is about 40–90 m/s and the anisotropy ratio differs by 0.01. There was no visible foliation so that the orientations of the principal velocities could not be determined. 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 385.85 m the maximum difference was about 50 m/s while at 888.60 m the maximum difference was about 150 m/s, see Figure 3-5.

Typically in the whole series of tests the deviation between the measured value and the model fit is about 0.4% (about 25 m/s), with a maximum average error of 2.1% (about 100 m/s) (ignoring one value of 3.3% (about 150 m/s).

Table 3-1. Measurements of acoustic velocity, transverse core in borehole KSH02, Simpevarp (orientation clockwise looking down hole, 0° is parallel with foliation where identified).

Depth	Diameter	Corrected time, mS						Velocity m/S						
		Parallel	Perpendicular					Parallel	Perpendicular					
m	mm	foliation	foliation					foliation	foliation					Anisotropy
		0º	30º	60º	90º	120º	150º	0º	30º	60º	90º	120º	150º	ratio
201,85	50,20	8,25	8,28	8,26	8,29	8,28	8,23	6086	6064	6079	6057	6064	6101	1,01
219,80	50,13	8,10	8,09	8,13	8,18	8,13	8,11	6190	6198	6168	6130	6168	6183	1,01
235,15	50,21	8,03	8,10	8,10	8,02	8,08	8,05	6254	6200	6200	6262	6216	6239	1,01
249,60	50,19	8,30	8,32	8,34	8,35	8,41	8,20	6048	6034	6019	6012	5969	6122	1,03
267,40	50,21	8,29	8,23	8,28	8,36	8,37	8,26	6058	6102	6066	6007	6000	6080	1,02
279,40	50,23	8,08	8,05	8,07	8,09	8,03	8,12	6218	6241	6226	6210	6257	6188	1,01
293,65	50,16	8,64	8,73	8,77	8,60	8,45	8,50	5807	5747	5721	5834	5938	5903	1,04
308,15	50,18	8,09	8,13	8,15	8,10	8,14	8,09	6204	6174	6159	6197	6166	6204	1,01
323,25	50,00	8,15	8,22	8,07	8,13	8,17	8,13	6137	6084	6197	6152	6121	6152	1,02
338,90	50,02	8,44	8,45	8,32	8,34	8,38	8,48	5928	5921	6013	5999	5970	5900	1,02
355,40	50,07	8,15	8,10	8,15	8,14	8,13	8,15	6145	6183	6145	6153	6160	6145	1,01
371,95	50,04	8,49	8,79	8,95	8,70	8,65	8,46	5895	5694	5592	5753	5786	5916	1,06
385,85	50,03	8,42	8,47	8,54	8,53	8,53	8,42	5943	5908	5860	5867	5867	5943	1,01
385,85	50,01	8,45	8,55	8,59	8,70	8,73	8,69	5920	5851	5823	5750	5730	5756	1,03
400,20	50,05	8,35	8,31	8,28	8,19	8,22	8,28	5995	6024	6046	6113	6090	6046	1,02
412,55	50,07	8,34	8,26	8,28	8,28	8,25	8,25	6005	6063	6049	6049	6071	6071	1,01
421,85	50,04	8,17	8,22	8,22	8,11	8,18	8,17	6126	6089	6089	6172	6119	6126	1,01
435,10	50,02	8,25	8,32	8,50	8,49	8,32	8,26	6065	6013	5886	5893	6013	6057	1,03
447,10	50,08	8,32	8,36	8,39	8,42	8,46	8,46	6021	5992	5970	5949	5921	5921	1,02
464,20	49,98	8,48	8,56	8,69	8,79	8,91	8,69	5895	5840	5753	5687	5611	5753	1,05
480,40	50,02	8,30	8,36	8,33	8,28	8,21	8,23	6028	5985	6006	6043	6094	6079	1,02
498,25	50,00	8,35	8,42	8,36	8,50	8,49	8,40	5989	5940	5982	5884	5891	5954	1,02
511,20	50,09	8,59	8,75	8,56	8,46	8,43	8,47	5833	5726	5853	5922	5943	5915	1,04
524,70	50,18	9,36	9,39	9,60	9,47	9,55	9,37	5362	5345	5228	5300	5256	5357	1,03
536,60	50,02	8,63	8,69	8,42	8,42	8,47	8,58	5797	5757	5942	5942	5907	5831	1,03
550,90	50,70	8,49	8,39	8,38	8,37	8,41	8,44	5973	6044	6052	6059	6030	6009	1,01
559,55	50,06	8,82	8,72	8,61	8,59	8,58	8,64	5677	5742	5816	5829	5836	5795	1,03
565,70	50,10	10,11	9,78	9,98	10,49	10,28	10,36	4956	5124	5021	4777	4875	4837	1,07
588,60	49,95	8,17	8,20	8,43	8,39	8,35	8,14	6115	6093	5927	5955	5983	6138	1,04
604,80	50,04	8,46	8,41	8,47	8,54	8,54	8,55	5916	5952	5909	5861	5861	5854	1,02
617,45	50,02	8,18	8,23	8,20	8,26	8,24	8,20	6116	6079	6102	6057	6072	6102	1,01
634,80	50,04	8,26	8,28	8,25	8,28	8,37	8,22	6060	6045	6067	6045	5980	6089	1,02
649,30	50,10	9,00	9,07	9,18	8,94	8,87	8,96	5568	5525	5459	5605	5650	5593	1,03
665,40	50,15	8,39	8,30	8,30	8,36	8,33	8,38	5979	6044	6044	6000	6022	5986	1,01
673,85	50,14	8,15	8,19	8,17	8,14	8,11	8,15	6154	6124	6139	6161	6184	6154	1,01
690,50	50,17	8,23	8,19	8,16	8,24	8,21	8,20	6097	6127	6150	6090	6112	6120	1,01
719,60	50,04	8,40	8,59	8,62	8,65	8,60	8,31	5959	5827	5806	5786	5820	6023	1,04
731,30	49,90	8,12	8,14	8,15	8,12	8,21	8,14	6147	6132	6124	6147	6079	6132	1,01
748,65	49,88	8,40	8,42	8,21	8,27	8,14	8,20	5940	5925	6077	6033	6129	6084	1,03
765,75	50,02	8,14	8,21	8,18	8,12	8,13	8,07	6147	6094	6116	6162	6154	6200	1,02
779,10	50,10	8,22	8,25	8,34	8,31	8,26	8,26	6096	6074	6009	6030	6067	6067	1,01
795,45	50,04	8,24	8,24	8,31	8,35	8,27	8,23	6074	6074	6023	5994	6052	6082	1,01
805,80	50,12	8,20	8,22	8,24	8,24	8,27	8,20	6114	6099	6084	6084	6062	6114	1,01
817,35	50,14	8,16	8,11	8,14	8,19	8,17	8,11	6146	6184	6161	6124	6139	6184	1,01
830,95	50,16	10,61	10,51	10,51	10,87	10,82	10,94	4729	4774	4774	4615	4637	4586	1,04
844,75	50,13	8,33	8,36	8,32	8,41	8,33	8,39	6019	5998	6027	5962	6019	5976	1,01
860,30	50,08	8,62	8,67	8,51	8,42	8,46	8,51	5811	5778	5886	5949	5921	5886	1,03
872,30	50,11	9,00	8,90	8,96	9,09	9,17	9,10	5569	5632	5594	5514	5466	5508	1,03
888,60	50,10	10,04	10,78	10,36	9,88	9,11	9,05	4991	4648	4837	5072	5501	5537	1,19
888,60	50,10	10,58	10,34	9,71	9,12	9,41	10,72	4736	4846	5161	5495	5325	4674	1,18
900,65	50,14	9,01	9,02	9,13	8,88	8,87	9,06	5566	5560	5493	5648	5654	5535	1,03
914,80	50,12	9,22	9,23	9,17	9,10	9,21	9,43	5437	5431	5467	5509	5443	5316	1,04
931,55	50,03	8,10	8,09	8,11	8,19	8,13	8,10	6178	6186	6170	6110	6155	6178	1,01
946,75	50,10	8,24	8,17	8,21	8,20	8,16	8,19	6082	6134	6104	6111	6141	6119	1,01
958,80	50,10	8,22	8,30	8,25	8,15	8,16	8,24	6096	6038	6074	6149	6141	6082	1,02
970,10	50,15	8,47	8,44	8,48	8,55	8,54	8,43	5922	5943	5915	5867	5874	5950	1,01
985,75	50,09	8,57	8,48	8,31	8,30	8,34	8,37	5846	5908	6029	6036	6007	5986	1,03
993,40	50,00	8,12	8,11	8,13	8,11	7,98	8,06	6159	6167	6152	6167	6267	6205	1,02

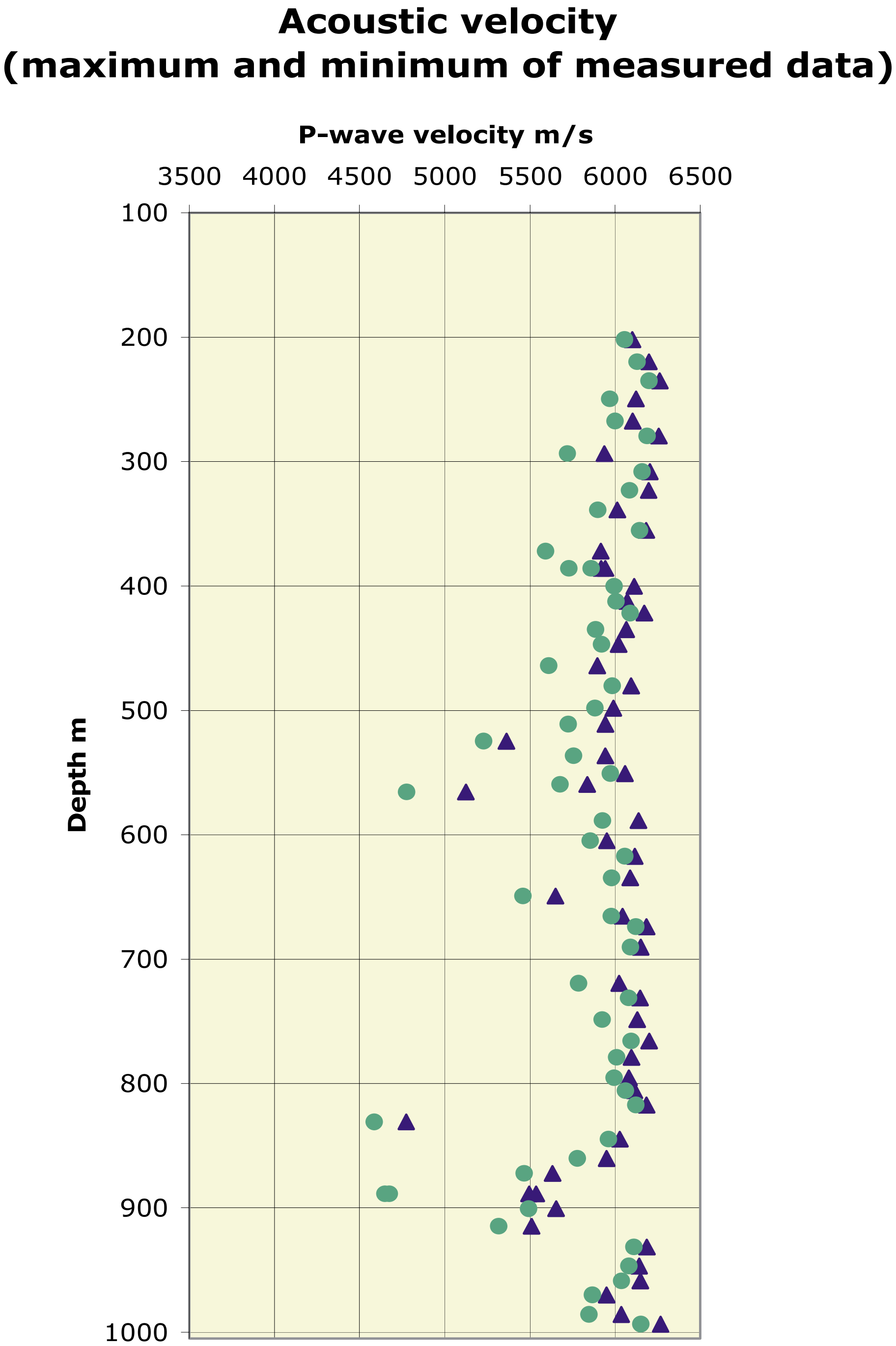


Figure 3-1. Measured values of maximum and minimum acoustic velocities plotted against depth down borehole KSH02.

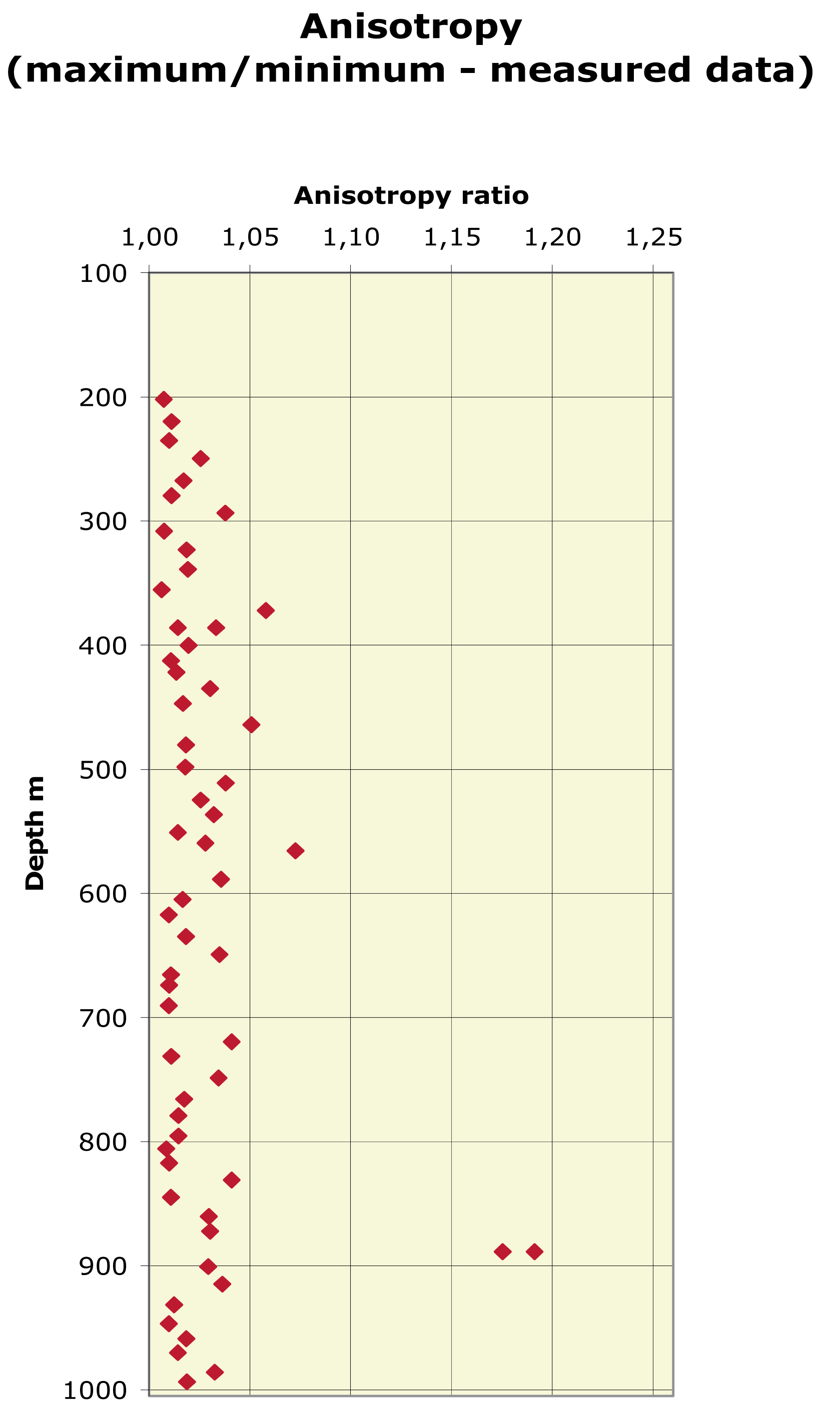


Figure 3-2. *Measured values of acoustic velocity anisotropy plotted against depth down borehole KSH02.*

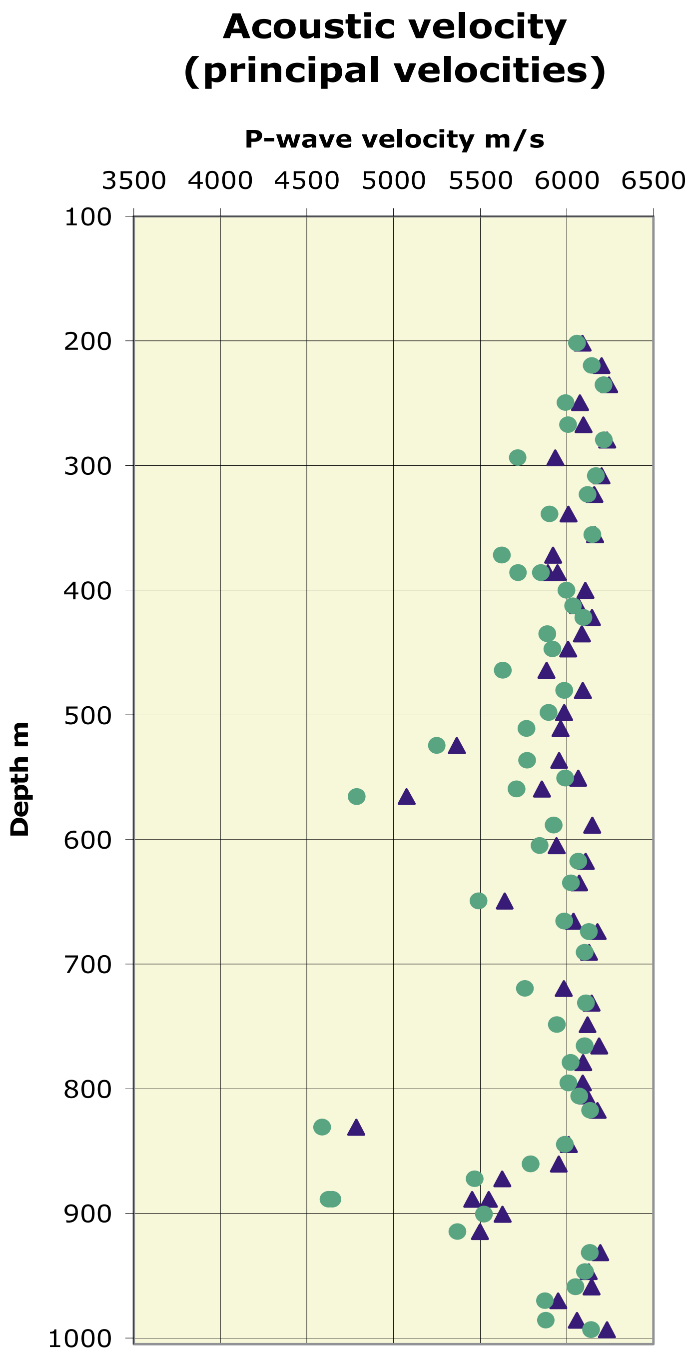


Figure 3-3. *Calculated values of maximum and minimum principal acoustic velocities plotted against depth down borehole KSH02.*

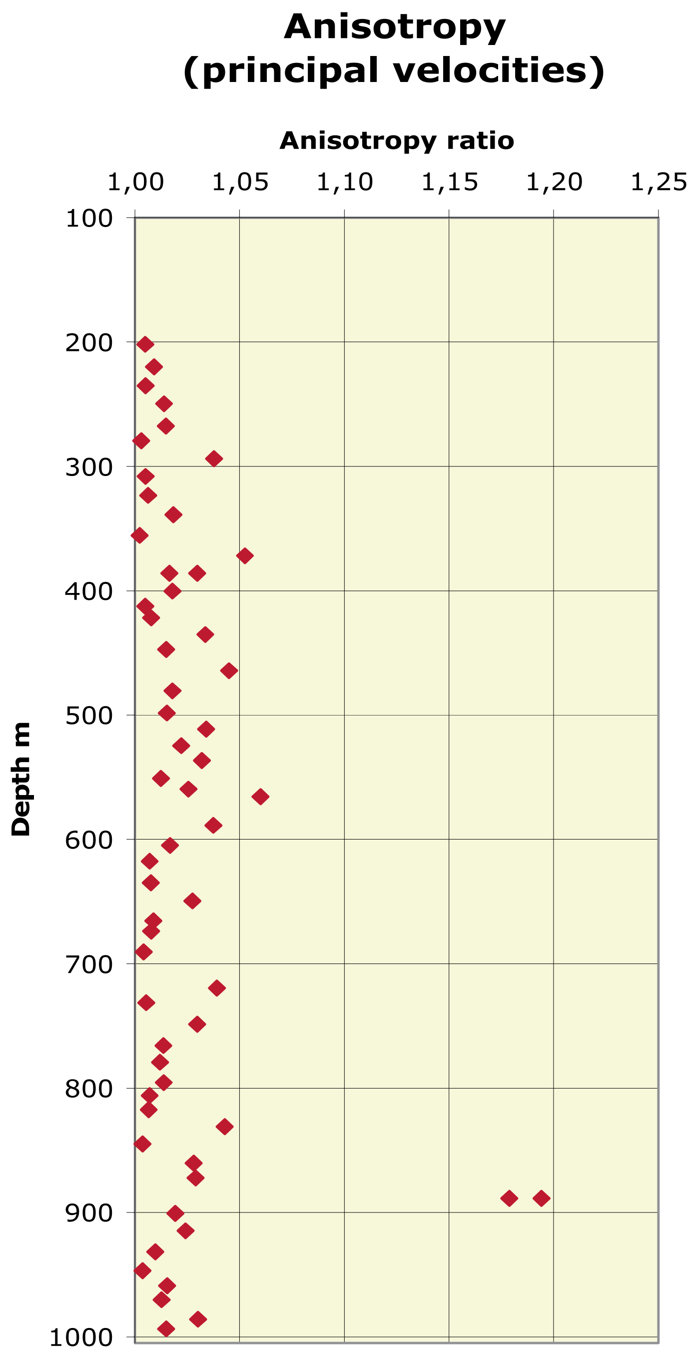
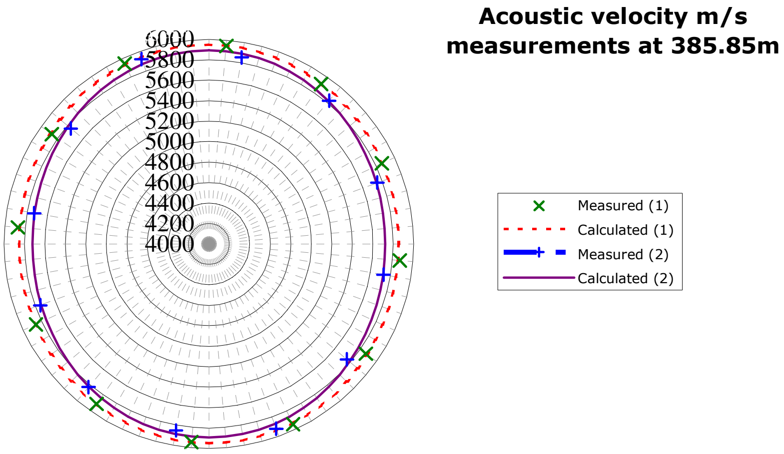


Figure 3-4. Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted against depth down borehole KSH02.



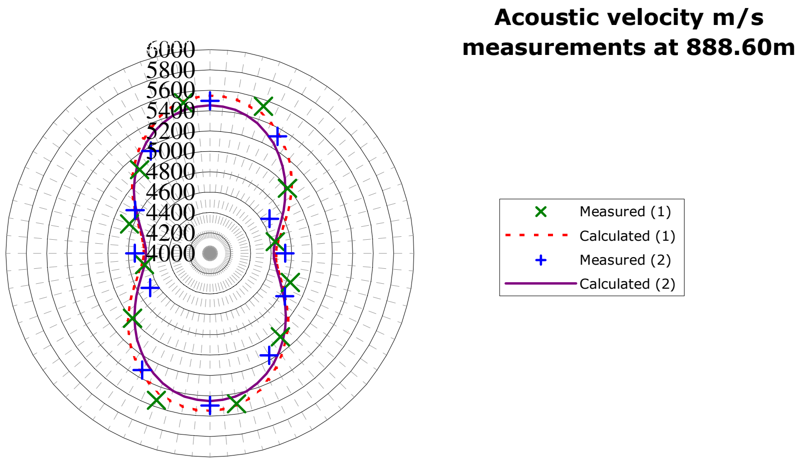


Figure 3-5. *Comparison of measured and calculated values (model fit) of acoustic velocity for each of two determinations at the same depths in borehole KSH02.*

Previous work /Chryssanthakis and Tunbridge, 2003a,b,c/ concluded 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.

The deviation between the model fitted to the data and the measured data is similar to the previous work. The results are also very consistent. It is therefore concluded that the measurement errors are probably similar to those determined in the previous work.

Conclusions

The results from the P-wave velocity measurements show a consistent pattern over the whole length of the borehole with maximum velocities between 5900–6200 m/s and a low anisotropy ratio of between 1 to 1.04. From 870 m to 920 m there is a lower maximum velocity of 5500 m/s with one value of higher anisotropy ratio of about 1.19. Below 920 m the values of velocity and anisotropy are similar to those above 830 m. There are four apparently randomly distributed tests with low principal velocities between 4700–5700 m/s.

The foliation is not identifiable over most of the core and the orientation of the principal velocities could not be identified relative to the foliation.

4 References

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Appendix A

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	Calculated µS	Correction µS
20030902 h 08:45	6320	50.90	9.18	8.05	–1.13
20030902 h 13:30	6320	50.90	9.20	8.05	–1.15
20030902 h 17:30	6320	50.90	9.21	8.05	–1.16
20030903 h 08:45	6320	50.90	9.20	8.05	–1.15
20030903 h 12:30	6320	50.90	9.20	8.05	–1.15
20030904 h 08:45	6320	50.90	9.19	8.05	–1.13
Average			**9.20**		**–1.14**