P-04-09

Forsmark site investigation

Borehole: KFM02A

Determination of P-wave velocity, transverse borehole core

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Norwegian Geotechnical Institute, Oslo

May 2004

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Keywords: Rock mechanics, P wave velocity, Anisotropy.

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 (NGI) has carried out P-wave measurements on drill cores from borehole KFM02A at Forsmark in June 2003. Seventy-four P-wave velocity measurements were performed on samples from a total of 902 m of core.

The results from the P-wave velocity measurements show a consistent pattern down to about 520 m depth with maximum velocities generally between 5400–5700 m/s and a low anisotropy ratio of generally between 1.00 to 1.12. Between about 520 m and 700 m depth, the maximum velocity becomes more consistent and is generally between 5400–5600 m/s while the anisotropy ratio is generally in excess of 1.1. Below about 700 m depth, the maximum velocity is somewhat more variable and reduces to generally between 5100–5500 m/s while the anisotropy ratio remains generally in excess of 1.1 with a maximum value of 1.24.

The orientation of the principal velocities is consistent along two directions, where the anisotropy ratio exceeds 1.1 (the orientations of the principal velocities are not well constrained mathematically for low anisotropy ratios). The orientation of the maximum velocity is typically 10°–30° or 160°–170° from the foliation direction (measured clockwise looking down the hole), and not parallel or perpendicular to the foliation as might have been expected. The tests below 850 m depth with orientations between 160°–170° generally have a high average error between the measured values and the best fit ellipse.

Sammanfattning

Norges Geotekniska Institut (NGI) har under juni 2003 utfört P-vågsmätningar på borrkärnor från borrhål KFM02A i Forsmark. Sammanlagt utfördes 74 st hastighetsbestämningar av P-vågen på kärnprover som utvalts från borrkärnor med en sammanlagd längd av 902 m.

Resultaten uppvisar ett konsistent mönster ner till ca 520 m djup, där de högsta hastigheterna generellt återfinns i intervallet 5400–5700 m/s. Anisotropikvoten är låg, i allmänhet mellan 1,00 och 1,12. Mellan ca 520 m och 700 m är hastigheterna mer ensartade i spannet 5400–5600 m/s. Anisotropikvoten överstiger här oftast 1,1. Under 700 m, slutligen, är maximihastigheten något mer variabel och minskar samtidigt till 5100–5500 m/s, medan anisotropikvoten ligger kvar på nivån >1,1 med ett maximivärde på 1,24.

Orienteringen av huvudhastigheterna är konsistent längs två riktningar, där anisotropikvoten överstiger 1,1 (för låga anisotropikvoter är huvudhastigheterna dock ej matematiskt välbestämda). De typiska orienteringsriktningarna för största P-vågshastigheten är 10–30°, alternativt 160–170° från foliationsriktningen (räknat medurs då man tittar neråt i borrhålsriktningen), dvs inte parallellt med eller vinkelrätt mot foliationsriktningen som hade kunnat förväntas. Mätningarna under 850 m med orienteringen 160–170° uppvisar i allmänhet ett större genomsnittligt fel mellan uppmätta värden och den bäst anpassade ellipsen.

Contents

1 Introduction

The Norwegian Geotechnical Institute (NGI) has carried out P-wave velocity measurements on cores from borehole KFM02A at Forsmark in Sweden in accordance with SKB Activity Plan AP PF 400-03-44 (SKB internal controlling document).

The work was carried out by Panayiotis Chryssanthakis and Pavel Jankowski during the period 10–18 of June 2003 in accordance with SKB's method description MD 190.002, Version 1.0 (SKB internal controlling document).

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 tests performed and the number of joint sets are 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
KFM02A	72	74

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

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. 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 /Eitzenberger, 2002/. The equipment is shown on the photograph in Figure 3-1.

Figure 3-2 shows the apparatus for measuring acoustic P-wave travel time.

***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 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 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 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 layer of honey (from a honey pot), 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.

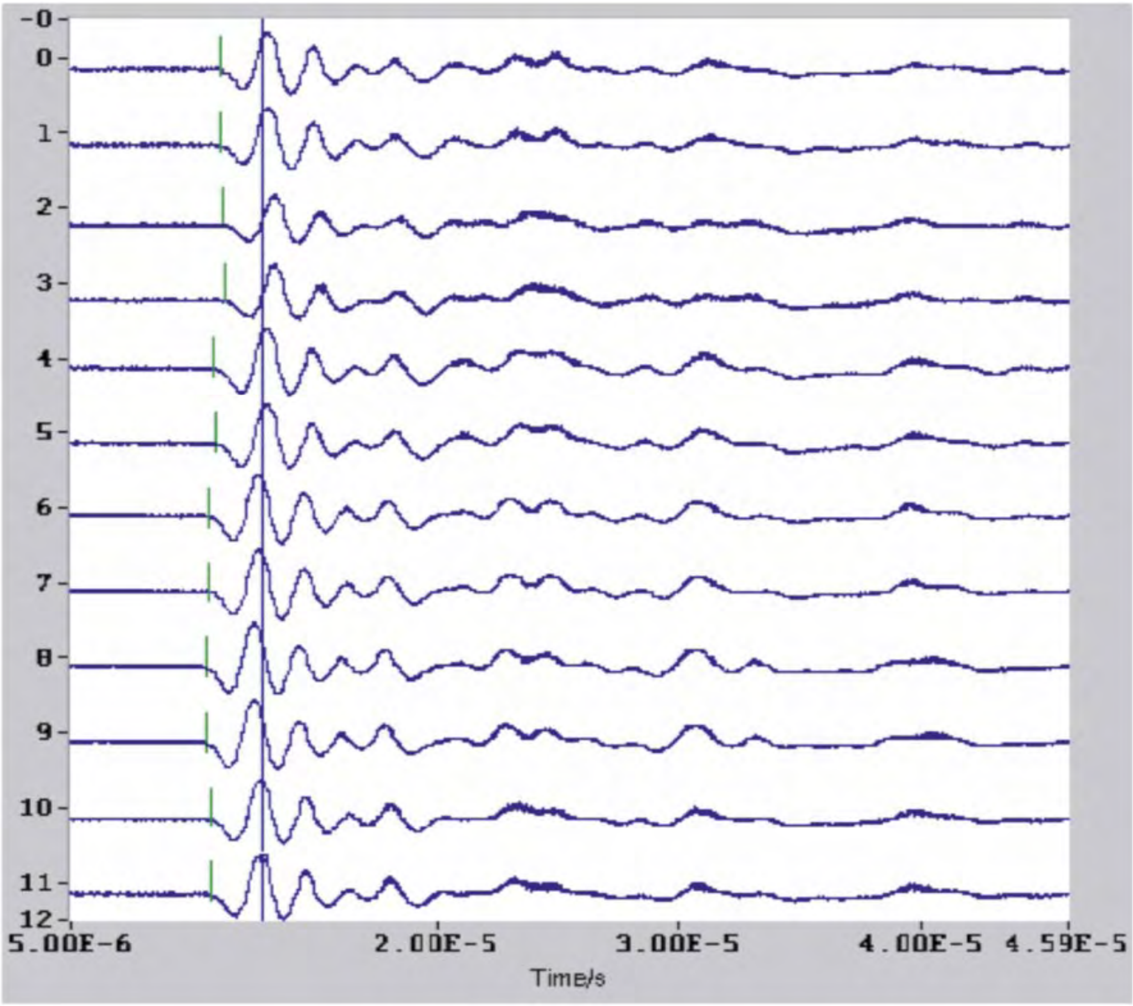


Figure 3-3. *Example traces from 12 measurements of P-wave travel time transverse borehole core (two from each orientation). Time picks marked with green lines. Picture captured from NGI's oscilloscope emulation software.*

4 Execution

4.1 Sampling

Seventy core specimens of lengths c 200–500 mm and diameter about 50.5–51.0 mm were selected from borehole KFM02A, while the complete core length of the borehole (depth 100 m –1002.3 m) was displayed on the racks in the core shed at Forsmark. These specimens represent the foliated granite-gneiss, diorite and tonalite found over most of the length of the borehole. The specimens were jointly selected by NGI and 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.

4.2 Test method

Tests were made at 30° intervals around the core, starting at 0° parallel with the foliation. 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 length 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° & 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.

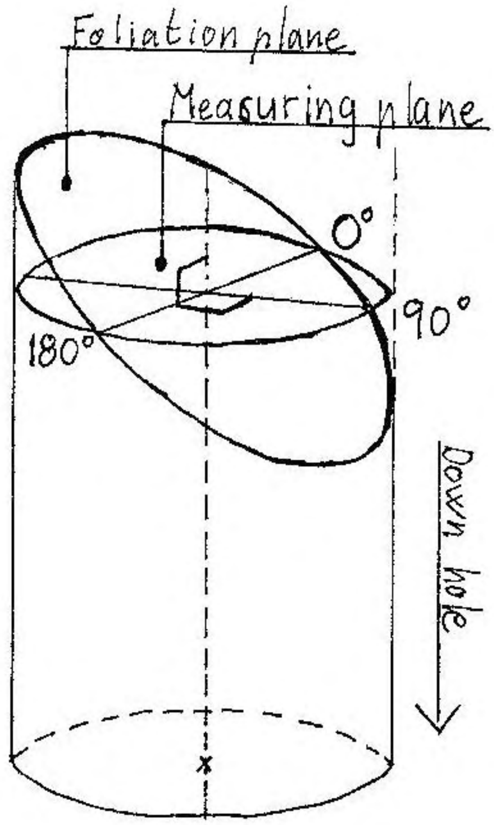


Figure 4-1. *Orientation of measurements.*

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 were determined from the Eigen values and vectors of the 2D tensor matrix:

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

4.3 Nonconformities

Tests were made at 30° intervals around the core instead of 45° intervals, which were suggested in the method description. None more nonconformity was done.

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 are shown diagrammatically versus borehole length in Figures 5-1 and 5-2.

The results of calculated principal velocity, the anisotropy and the orientations of the principal velocities are 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 (field note no Forsmark 141).

5.2 Discussion

Accuracy and Repeatability

Calibration tests on an aluminium cylinder indicated a variation of ±0.08 μs in determination of the time pick, equivalent to differences in velocity of about 35 m/s. 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, 399.20 m and 862.50 m, after the first series of tests were completed, see Figure 5-6. These tests were repeated to investigate and determine typical values for repeatability of velocity determinations. At 399.20 m the difference is about 10 m/s for the maximum velocity and about 100 m/s for the minimum, the anisotropy ratio differs by 0.2 and the orientation differs by 10°. At 862.50 m the difference is about 40 m/s for the maximum velocity and about 30 m/s for the minimum, the anisotropy ratio differs by 0.2 and the orientation is the same. The anisotropy ratios measured for the two depths were 1.11 respectively 1.12.

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 which suggests that random type errors are relatively small. Typically in the entire series of tests, the deviation between the measured value and the model fit is about 0.5%, with a maximum average error of 2.1% (excluding one extreme measurement with an error of 5.4%). This deviation between the model fitted to the data and the measured data is similar to the previous work /Chryssanthakis and Tunbridge, 2003 a–b/ and it is 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 exceeds 1.1 with larger 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 indicates that measurement errors will not have a large effect on the determination of the anisotropy ratio and orientation, and this appears to be confirmed by the general consistency in the results obtained.

Conclusions

The results from the P-wave velocity measurements show a consistent pattern down to about 520 m depth with maximum velocities generally between 5400–5700 m/s and a low anisotropy ratio of generally between 1 and 1.12. Within the interval about 520 m to 700 m, the maximum velocity becomes more consistent and is generally between 5400–5600 m/s while the anisotropy ratio is generally in excess of 1.1. Below about 700 m depth the maximum velocity is somewhat more variable and reduces to generally between 5100–5500 m/s while the anisotropy ratio remains generally above 1.1 with a maximum value of 1.24.

The orientation of the principal velocities is consistent along two orientations where the anisotropy ratio exceeds 1.1 (the orientations of the principal velocities are not well constrained mathematically for low anisotropy ratios). The orientation of the maximum velocity is typically 10°–30° or 160°–170° from the foliation direction (measured clockwise looking down the hole), and not parallel or perpendicular to the foliation as might have been expected. The tests below 850 m depth with orientations between 160°–170° generally have a high average error between the measured values and the best fit ellipse.

Table 5-1. Measurements of acoustic velocity, transverse core in borehole kfm02a, Forsmark. (Orientation clockwise looking down hole, 0° is parallel with foliation.)

Depth	Diameter	Corrected time, mS						Velocity m/S						
		Parallel foliation	Perpendicular foliation					Parallel foliation	Perpendicular foliation					
m	mm	0º	30º	60º	90º	120º	150º	0º	30º	60º	90º	120º	150º	Anisotropy ratio
191,50	50,92	8,91	8,80	8,77	8,71	8,77	8,85	5714	5785	5805	5845	5805	5753	1,02
216,70	50,85	9,03	8,85	8,83	8,94	9,04	9,07	5630	5745	5758	5687	5624	5605	1,03
230,30	50,74	9,58	9,73	9,54	9,21	8,92	9,13	5296	5214	5318	5508	5687	5557	1,09
302,50	50,80	9,17	9,00	9,02	9,08	9,13	9,26	5539	5643	5631	5594	5563	5485	1,03
310,10	50,83	9,03	9,06	8,97	8,85	8,87	8,87	5628	5609	5666	5742	5730	5730	1,02
322,40	50,84	9,09	9,22	9,49	9,64	9,64	9,32	5592	5513	5356	5273	5273	5454	1,06
326,60	50,85	9,32	9,39	9,74	10,28	10,20	9,62	5455	5414	5220	4946	4985	5285	1,10
334,70	50,73	9,22	9,25	9,51	9,87	9,93	9,50	5501	5483	5334	5139	5108	5339	1,08
351,30	50,71	9,93	9,99	9,70	9,63	9,40	9,46	5106	5075	5227	5265	5394	5360	1,06
358,60	50,74	9,18	9,19	9,53	9,82	9,94	9,72	5526	5520	5323	5166	5104	5219	1,08
364,60	50,94	9,32	9,78	10,12	9,78	9,22	9,11	5465	5208	5033	5208	5524	5591	1,11
370,40	50,87	9,31	9,49	10,09	10,25	9,77	9,32	5463	5359	5041	4962	5206	5457	1,10
381,75	50,84	9,74	9,53	9,31	9,37	9,44	9,60	5219	5334	5460	5425	5385	5295	1,05
399,20	50,76	9,86	10,60	11,00	10,80	10,20	9,79	5147	4788	4614	4699	4976	5184	1,12
399,20	50,76	9,78	10,34	10,71	10,70	10,23	9,77	5189	4908	4739	4743	4961	5195	1,10
409,35	50,79	9,79	9,45	9,50	9,83	10,45	10,40	5187	5374	5345	5166	4860	4883	1,11
434,80	50,81	9,52	9,91	9,93	9,93	9,47	9,23	5336	5126	5116	5116	5364	5504	1,08
447,10	50,66	9,80	9,48	9,33	9,31	9,49	9,76	5169	5343	5429	5441	5337	5190	1,05
456,60	50,65	9,16	9,25	9,49	9,72	9,79	9,41	5529	5475	5336	5210	5173	5382	1,07
459,70	50,58	11,24	10,89	10,69	10,77	10,91	11,11	4499	4644	4731	4696	4635	4552	1,05
472,80	50,82	9,12	9,22	9,56	9,89	10,04	9,60	5571	5511	5315	5138	5061	5293	1,10
481,70	50,55	9,48	9,33	9,53	9,62	9,71	9,60	5331	5417	5303	5254	5205	5265	1,04
485,90	50,70	9,39	9,53	9,72	9,66	9,64	9,59	5398	5319	5215	5248	5258	5286	1,04
495,80	50,85	9,35	9,90	10,39	10,24	9,60	9,21	5438	5136	4893	4965	5296	5520	1,13
496,60	50,84	9,09	9,12	9,10	8,89	8,89	8,89	5592	5574	5586	5718	5718	5718	1,03
498,80	50,85	9,84	10,02	10,43	10,61	10,58	10,20	5167	5074	4875	4792	4806	4985	1,08
508,25	50,94	9,14	9,21	9,21	9,15	9,03	9,09	5572	5530	5530	5566	5640	5603	1,02
522,80	50,64	9,35	9,33	9,67	9,98	9,97	9,50	5415	5427	5236	5073	5078	5330	1,07
528,60	50,95	8,95	9,10	9,59	10,04	9,83	9,19	5692	5598	5312	5074	5182	5543	1,12
535,00	50,79	9,56	9,41	9,63	9,98	10,46	10,17	5312	5397	5273	5088	4855	4993	1,11
553,20	50,75	9,69	9,92	10,52	10,89	10,42	9,92	5237	5115	4823	4660	4870	5115	1,12
586,40	50,86	9,25	9,22	9,59	9,96	10,21	9,98	5497	5515	5303	5106	4981	5095	1,11
603,00	50,93	9,43	9,91	10,42	10,11	9,51	9,33	5400	5138	4887	5037	5355	5458	1,12
620,90	50,96	9,37	9,30	9,98	10,79	10,62	10,08	5438	5479	5105	4722	4798	5055	1,16
631,50	51,02	9,62	9,94	10,43	10,59	10,00	9,67	5303	5132	4891	4817	5101	5275	1,10
645,20	50,64	8,91	9,25	9,69	9,83	9,39	8,98	5682	5474	5225	5151	5392	5638	1,10
649,55	50,85	9,47	9,37	9,60	9,97	10,48	10,33	5369	5426	5296	5099	4851	4922	1,12
661,50	50,78	9,40	9,21	9,69	10,40	10,77	10,21	5401	5513	5240	4882	4714	4973	1,17
670,70	50,71	9,42	9,70	10,05	9,92	9,33	9,14	5382	5227	5045	5111	5434	5547	1,10
682,60	50,68	9,71	9,32	9,33	9,49	9,92	10,24	5219	5437	5431	5339	5108	4948	1,10
697,60	50,71	9,75	9,24	9,24	9,49	10,06	10,29	5200	5487	5487	5343	5040	4927	1,11
700,50	50,56	9,91	10,31	10,83	10,33	9,65	9,24	5101	4903	4668	4894	5239	5471	1,17
706,65	50,66	9,32	9,59	10,25	10,81	10,59	9,83	5435	5282	4942	4686	4783	5153	1,16
712,60	50,71	9,64	9,56	9,86	10,73	10,78	10,05	5260	5304	5142	4725	4703	5045	1,13
724,50	50,79	10,01	9,51	9,69	10,37	10,86	10,77	5073	5340	5241	4897	4676	4715	1,14
733,10	50,61	9,59	9,40	9,76	10,53	10,79	10,40	5277	5383	5185	4806	4690	4866	1,15
746,05	50,81	9,71	9,81	10,02	10,40	10,34	9,87	5232	5179	5070	4885	4913	5147	1,07
754,80	50,75	9,46	9,75	10,34	10,82	10,57	10,05	5364	5204	4907	4690	4801	5049	1,14
769,65	50,75	9,56	9,45	10,03	10,57	10,68	10,25	5308	5369	5059	4801	4751	4950	1,13
781,00	50,83	9,71	9,80	10,10	10,66	10,65	9,93	5234	5186	5032	4768	4772	5118	1,10
789,85	50,89	10,07	9,93	10,40	10,98	11,12	10,65	5053	5124	4893	4634	4576	4778	1,12
802,25	50,76	10,10	9,95	10,38	11,03	11,38	11,15	5025	5101	4889	4601	4460	4552	1,14
809,60	50,64	10,21	10,15	11,00	11,51	11,42	10,79	4959	4988	4603	4399	4434	4693	1,13
819,00	50,69	10,09	9,67	9,52	9,62	10,28	10,47	5023	5241	5324	5268	4930	4841	1,10
832,30	50,85	9,41	9,37	9,91	10,32	10,19	9,88	5403	5426	5130	4927	4989	5146	1,10
847,10	50,85	9,69	9,92	10,50	10,81	10,72	10,10	5247	5125	4842	4703	4743	5034	1,12
851,80	50,65	9,55	10,12	10,66	10,65	10,24	9,79	5303	5004	4751	4755	4946	5173	1,12
858,05	50,65	10,05	9,80	9,94	10,46	10,81	10,80	5039	5168	5095	4842	4685	4689	1,10
862,50	50,62	9,69	9,60	9,86	10,59	10,78	10,24	5223	5272	5133	4779	4695	4943	1,12
862,50	50,62	9,77	9,66	9,86	10,50	10,74	10,24	5180	5239	5133	4820	4713	4943	1,11
871,40	50,71	10,63	11,34	12,56	12,02	11,08	10,39	4770	4471	4037	4218	4576	4880	1,21
879,10	50,72	9,76	10,24	10,75	10,73	9,85	9,67	5196	4952	4717	4726	5148	5244	1,11
891,40	50,75	9,65	9,42	9,91	10,87	11,06	10,65	5258	5387	5120	4668	4588	4765	1,17
900,25	50,71	9,88	9,83	10,22	10,87	11,07	10,48	5132	5158	4961	4664	4580	4838	1,13
906,70	50,66	8,76	8,71	8,48	8,83	8,66	8,52	5782	5815	5973	5736	5849	5945	1,04
917,20	50,78	9,54	9,13	9,66	10,42	10,88	10,49	5322	5561	5256	4873	4667	4840	1,19
928,20	50,76	8,36	8,55	8,93	9,29	9,24	8,69	6071	5936	5683	5463	5493	5840	1,11
944,35	50,78	9,74	9,64	10,02	10,50	10,70	10,08	5213	5267	5067	4835	4745	5037	1,11
951,00	50,54	9,56	9,95	10,74	11,50	10,66	9,70	5286	5079	4705	4394	4740	5209	1,20
960,00	50,51	9,86	9,81	10,46	11,31	11,18	10,29	5122	5148	4828	4465	4517	4908	1,15
974,60	50,53	10,40	11,54	12,61	12,54	10,93	10,31	4858	4378	4007	4029	4622	4900	1,22
990,30	50,81	9,64	9,46	9,54	10,17	10,24	9,99	5270	5370	5325	4995	4961	5085	1,08
997,00	50,77	9,61	10,28	10,92	10,92	10,22	9,66	5282	4938	4649	4649	4967	5255	1,14
1002,30	50,79	9,78	10,18	10,79	11,07	10,58	8,92	5192	4988	4706	4587	4800	5693	1,24

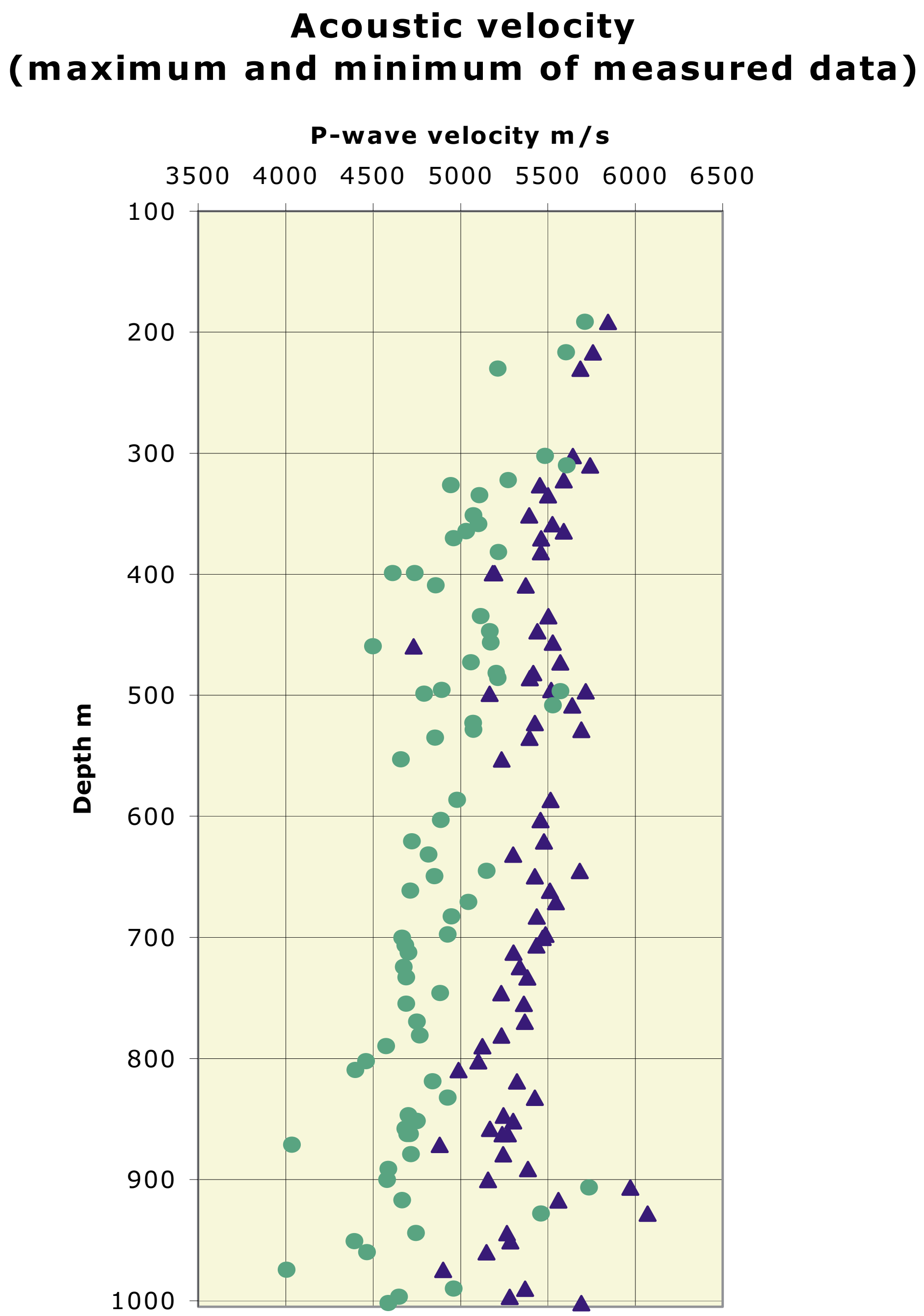


Figure 5-1. Measured values of maximum and minimum acoustic velocities plotted versus borehole length in KFM02A.

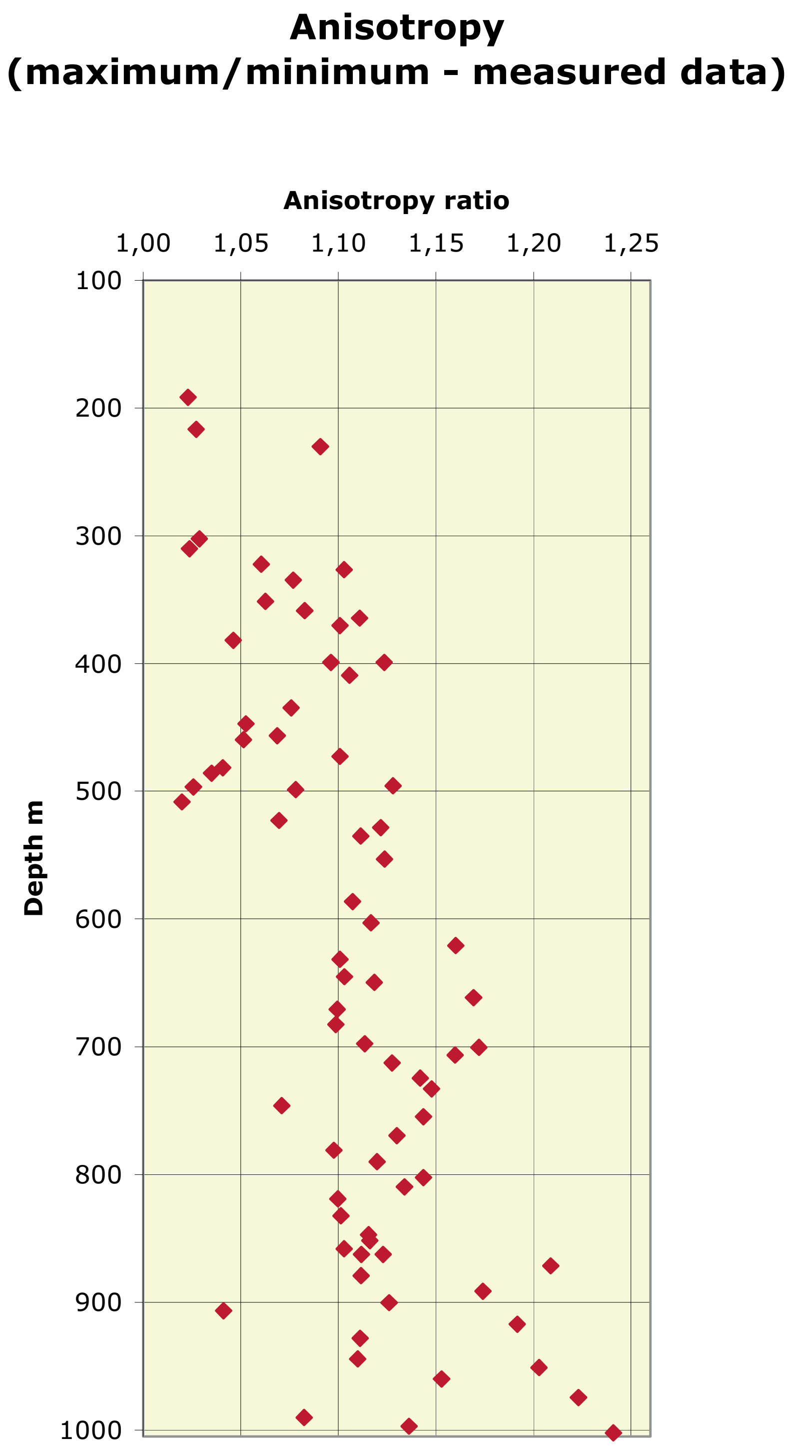


Figure 5-2. Measured values of acoustic velocities anisotropy plotted versus borehole length in KFM02A.

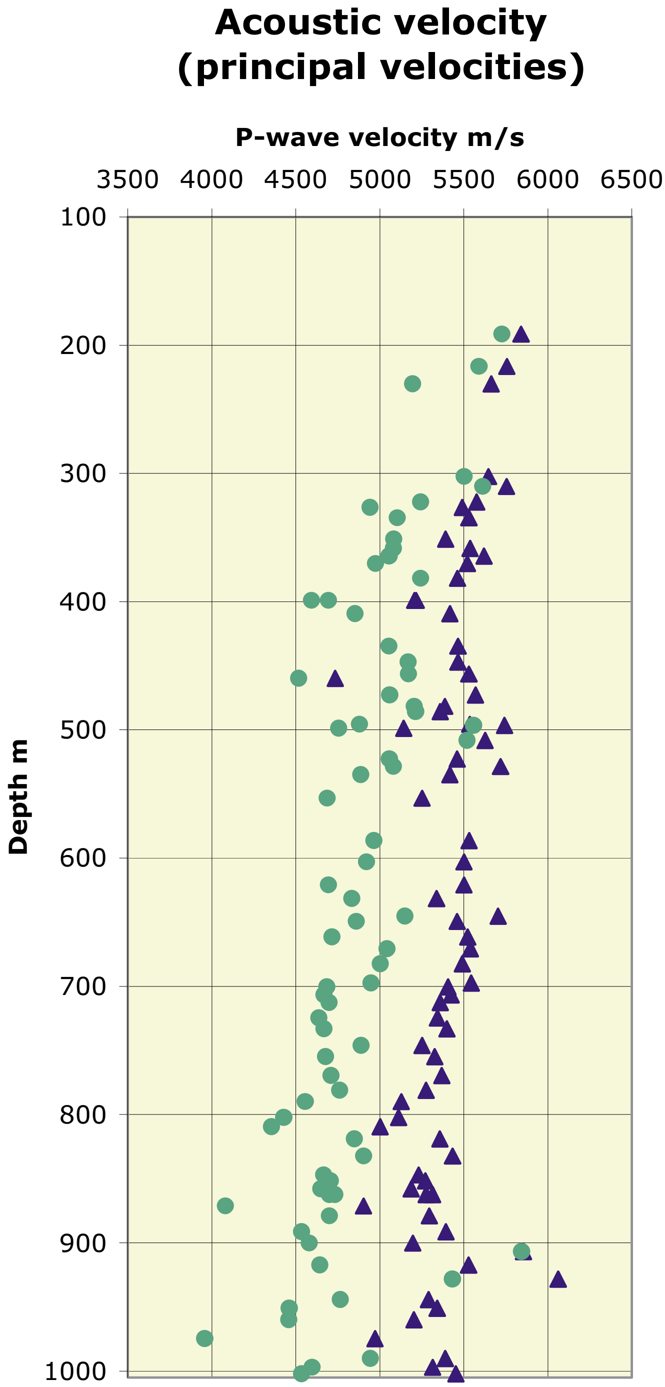


Figure 5-3. *Calculated values of maximum and minimum principal acoustic velocities plotted versus borehole length in KFM02A.*

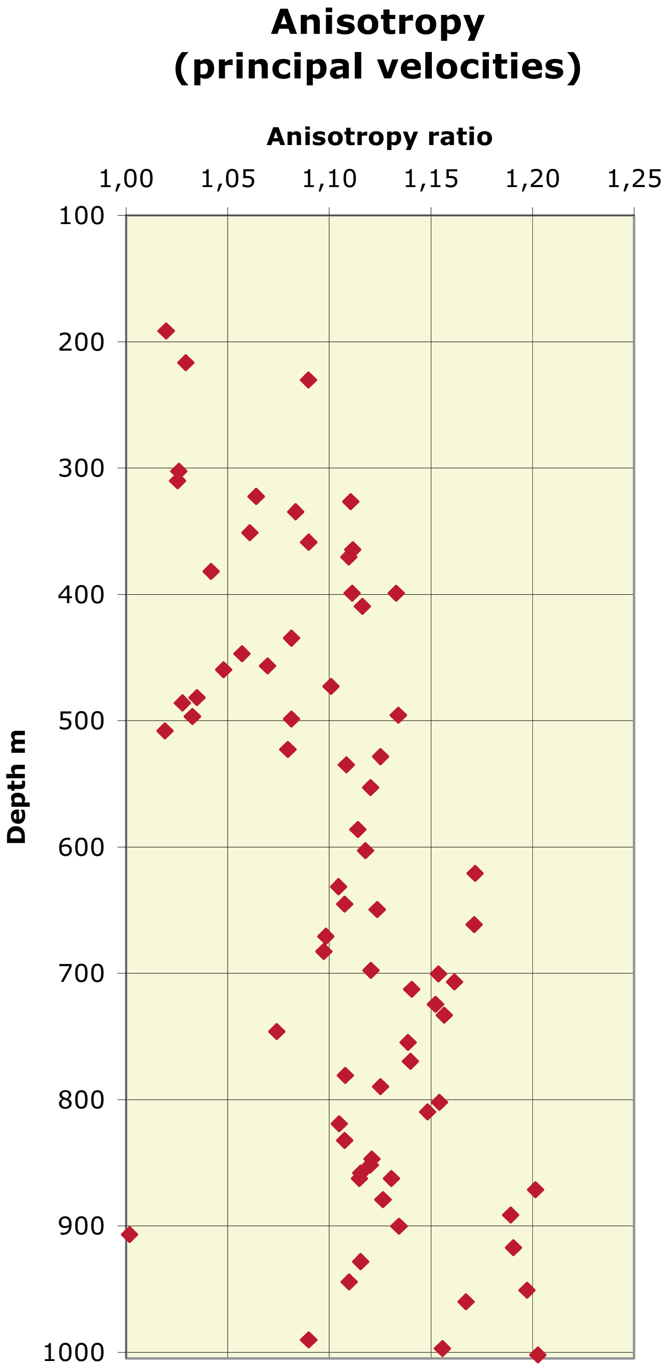


Figure 5-4. *Calculated values of maximum and minimum principal acoustic velocity anisotropy plotted versus borehole length in borehole KFM02A.*

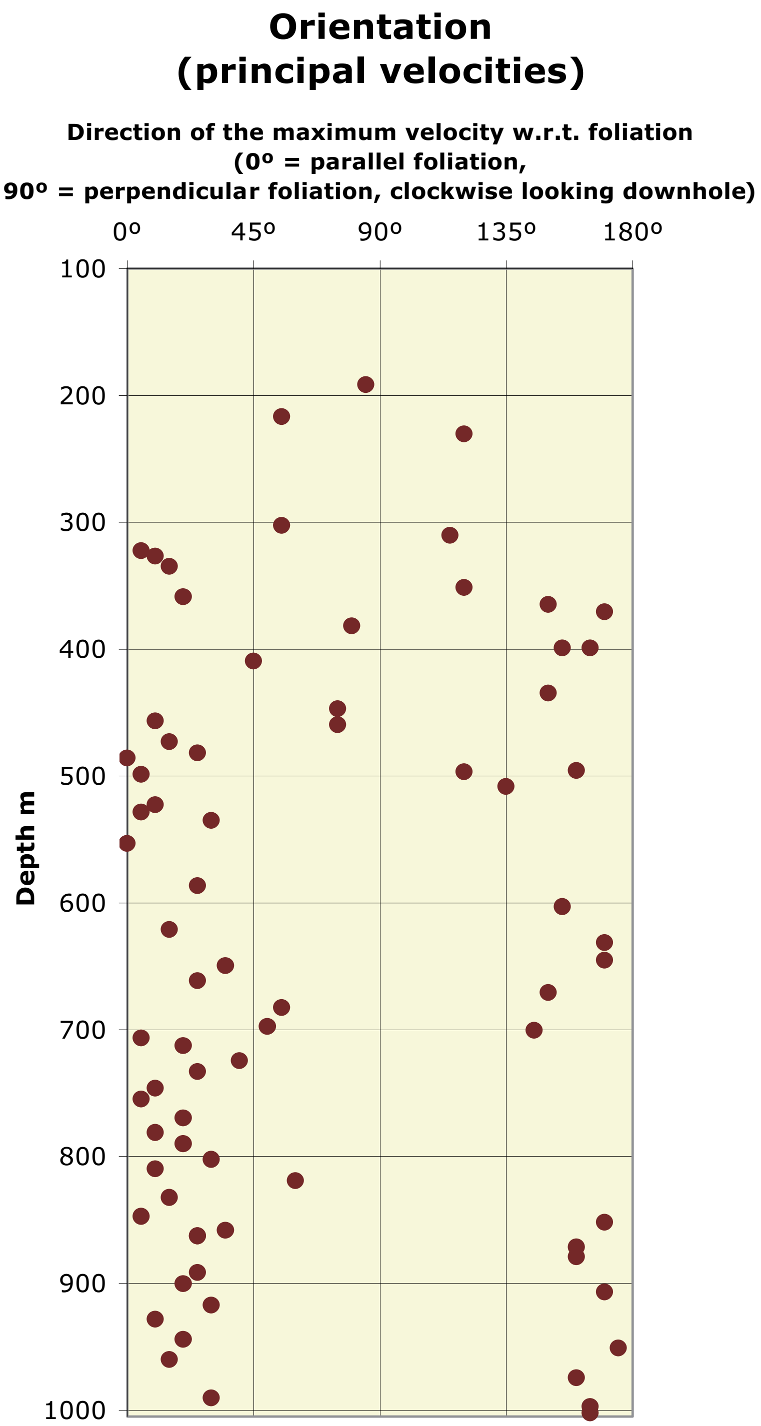
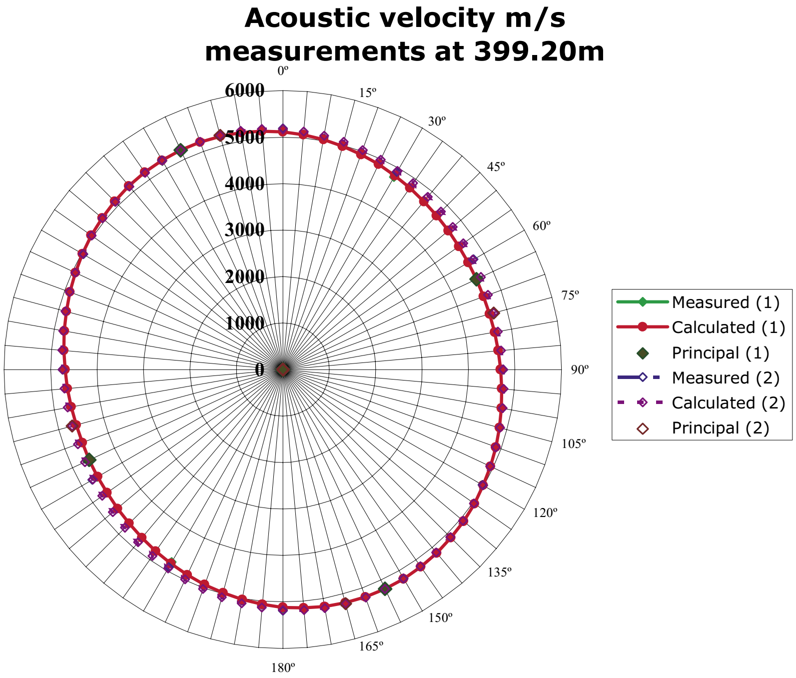


Figure 5-5. *Calculated orientation of the maximum principal acoustic velocity plotted versus borehole length in KFM02A.*



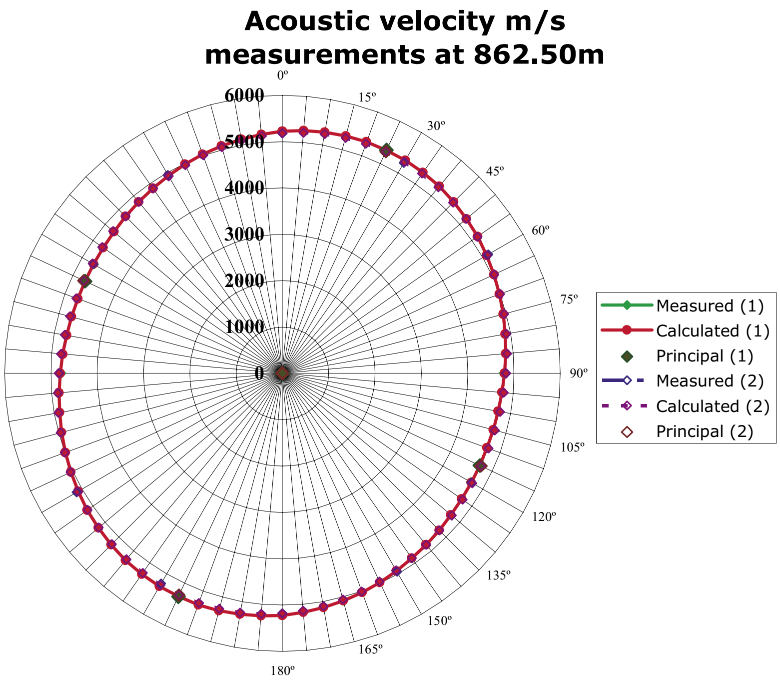


Figure 5-6. *Measured values of acoustic velocity plotted against orientation, together with calculated best fit ellipse and maximum and minimum principal velocities for two sets of measurements at depths of; (a) 399.20 m and (b) 862.50 m in borehole KFM02A.*

References

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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
20030611 kl.11:30	6320	50,90	9,19	8,05	–1,13
20030611 kl.18:30	6320	50,90	9,23	8,05	–1,18
20030612 kl.08:30	6320	50,90	9,18	8,05	–1,13
20030612 kl.13:30	6320	50,90	9,20	8,05	–1,14
20030612 kl.17:30	6320	50,90	9,16	8,05	–1,11
20030613 kl.08:30	6320	50,90	9,15	8,05	–1,10
20030613 kl.14:00	6320	50,90	9,19	8,05	–1,14
20030616 kl.10:30	6320	50,90	9,16	8,05	–1,11
20030617 kl.19:00	6320	50,90	9,19	8,05	–1,14
Average			**9,18**		**–1,13**