DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/106

Special Core Analysis for Chalk Background Velocity Project

Ultrasonic velocity measurements on plug samples of chalk from the wells Q-1, Otto-1, T-3, Gert-1, West Lulu-1, Baron-2, I-1 and Cecilie-1B

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The Chalk Background Velocity Project is funded by the South Arne Group

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G E U S

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1. Introduction

By request of Dr. Peter Japsen, GEUS on behalf of the Chalk Background Velocity Project (CBV Project), GEUS Core Laboratory has carried out conventional core analysis on 32 1.5" plug samples from 8 wells in the Danish Central Graben area. After conventional core analysis ultrasonic velocity determination was performed on a subset of 20 samples.

The analytical programme was specified by Dr. Peter Japsen and contained the following services:

- Conventional core analysis: gas permeability, He-porosity, and grain density.
- P and S velocities measured at reservoir overburden pressure on dry samples equilibrated at controlled humidity. All samples were measured at a hydrostatic confining pressure of 75 bar, and two samples, one from Gert-1 and one from Cecilie-1B, were also measured at hydrostatic confining pressures of 125 and 200 bar.
- P and S velocities measured on water saturated plugs at reservoir overburden pressure. All samples were measured at a hydrostatic confining pressure of 75 bar.

The measurements were conducted in the period from March 8th to June 30th 2004.

Presentations of preliminary results was given for the Chalk Background Velocity Project on 25th May 2004, 9th August 2004, and 29th September 2004.

The Chalk Background Velocity Project is funded by the Syd Arne Group.

2. Sampling and analytical procedure

2.1 Sample material

Thirty-two (32) new 1.5" plug samples of chalk were taken at the start of the project. A total of eight wells

Table 2.1. Basic sample data and conventional core analysis results.

Sample id.	Well id.	Depth	Formation or unit	Gas perm (mD)	Porosity (%)	Gr. dns. (g/ml)	Length (mm)	Diameter (mm)	Selected for sonic meas.
1	Q-1	10125.25 ft	Ekofisk [2)]	0.003	14.35	2.721	38.43	37.62	+
2	Q-1	10132.50 ft	Ekofisk [2)]	0.002	8.97	2.724	38.23	37.59	+
3	Q-1	10138.08 ft	Ekofisk [2)]	0.018	14.43	2.720	38.18	37.70	+
4	Q-1	10147.25 ft	Ekofisk [2)]	0.009	9.91	2.706	39.41	37.58	+
5	Otto-1	8473.84 ft	Tor [2)]	0.43	19.06	2.720	40.39	37.61	
6	Otto-1	8495.00 ft	Hod [2)]	0.33	19.23	2.716	38.68	37.59	+
7	Otto-1	8497.00 ft	Hod [2)]	4.4	21.96	2.717	39.71	37.58	
8	Otto-1	8504.00 ft	Hod [2)]	0.52	20.72	2.720	39.44	37.60	+
9	T-3	8440.33 ft	Tor [2)]	0.42	19.10	2.718	38.38	37.57	+
10	T-3	8526.75 ft	Tor [2)]	0.86	24.77	2.717	39.31	37.56	+
11	T-3	8532.08 ft	Tor [2)]	0.77	24.69	2.717	39.24	37.50	
12	T-3	8568.33 ft	Tor [2)]	1.62	24.24	2.719	31.05	37.58	
13	Gert-1	12838.90 ft	Hidra [2)]	0.009	11.28	2.680	37.68	37.63	+
14	Gert-1	12846.42 ft	Hidra [2)]	0.003	6.85	2.706	35.79	37.63	+
15	Gert-1	12854.50 ft	Hidra [2)]	0.005	3.92	2.699	39.67	37.62	
16	Gert-1	12858.58 ft	Hidra [2)]	0.005	3.70	2.698	35.80	37.59	+
17	West Lulu-1	11159.51 ft	Hod [2)]	0.002	6.32	2.726	35.91	37.64	+
18	West Lulu-1	11187.33 ft	Hod [2)]	0.003	6.68	2.724	38.49	37.59	
19	West Lulu-1	11213.33 ft	Hod [2)]	0.004	8.01	2.723	37.94	37.63	+
20	West Lulu-1	11246.42 ft	Hod [2)]	0.003	7.11	2.724	41.14	37.64	
21	Baron-2	2855.55 m	Ekofisk [2)]	0.17	26.90	2.706	40.56	37.50	+
22	Baron-2	2858.55 m	Ekofisk [2)]	0.057	24.69	2.708	39.30	37.56	+
23	Baron-2	2860.48 m	Ekofisk [2)]	0.047	16.68	2.698	38.20	37.62	+
24	Baron-2	2867.03 m	Ekofisk [2)]	0.070	21.87	2.704	35.53	37.55	+
25	I-1	9504.00 ft	Sola [1)]	0.056	24.80	2.701	33.01	37.58	
26	I-1	9508.50 ft	Tuxen [1)]	0.075	26.73	2.696	39.42	37.57	+
27	I-1	9523.90 ft	Tuxen [1)]	0.016	17.43	2.735	30.10	37.51	
28	I-1	9538.50 ft	Tuxen [1)]	0.019	16.95	2.716	21.75	37.55	
29	Cecilie-1B	2393.81 m	Våle [2)]	- [3)]	12.29	2.712	26.72	37.60	
30	Cecilie-1B	2402.61 m	Ekofisk [2)]	0.011	14.90	2.709	34.18	37.60	
31	Cecilie-1B	2407.50 m	Ekofisk [2)]	0.41	22.36	2.710	36.58	37.57	+
32	Cecilie-1B	2420.76 m	Ekofisk [2)]	0.002	7.21	2.705	38.49	37.62	+

1) From Nielsen & Japsen (1991).
2) From Jakobsen (2004).
3) Measurement not possible – plug damaged.

were sampled with four plugs from each well. Table 2.1 presents the sample numbers, wells, and sample depths.

2.2 Sample preparation before ultrasonic measurements and conventional core analysis

The samples were cleaned in Soxhlet extractors by refluxing in turn with methanol and toluene. Then the plugs were trimmed to a length of approximately 1.5" and dried at 60 ^{o}C. They were stored in a desiccator until conventional core analysis.

All the samples underwent conventional core analysis with measurement of gas permeability, He-porosity, and grain density. Results are given in Table 2.1. Refer to Chapter 4 for a description of the conventional core analysis methods.

A subset of 20 plug samples was selected from the initial set of 32 plugs. The selected samples are indicated in

Table 2.2. Water saturation of samples at time of ultrasonic measurement in humidity dried state.

Sample id.	Weight at He-por determ. (g)	Bulk vol. at He-por determ. (ml)	Helium porosity (%)	Pore vol. at He-por determ. (ml)	Weight at sonic meas. in humidity dry state (g)	Weight increase in humidity dry state (g)	Sw at sonic meas. in humidity dry state (%)
1	99.77	42.81	14.35	6.14	100.17	0.40	6.5
2	105.61	42.60	8.97	3.82	106.13	0.52	13.6
3	98.81	42.71	14.43	6.16	99.12	0.31	5.0
4	107.41	44.04	9.91	4.36	107.60	0.19	4.4
6	94.68	43.15	19.23	8.30	94.74	0.06	0.7
8	94.72	43.91	20.72	9.10	94.77	0.05	0.6
9	93.99	42.74	19.10	8.16	94.05	0.06	0.7
10	89.40	43.73	24.77	10.83	89.44	0.04	0.4
13	99.67	41.90	11.28	4.73	99.84	0.17	3.6
14	100.66	39.94	6.85	2.74	100.96	0.30	11.2
16	102.25	39.83	4.86	1.94	102.61	0.36	18.6
17	102.16	40.00	6.32	2.53	102.31	0.15	5.9
19	105.99	42.30	8.01	3.39	106.18	0.19	5.6
21	88.63	44.80	26.90	12.05	88.82	0.19	1.6
22	89.17	43.72	24.69	10.79	89.43	0.26	2.4
23	95.84	42.64	16.68	7.11	96.08	0.24	3.4
24	83.43	39.49	21.87	8.64	83.71	0.28	3.2
26	86.49	43.77	26.73	11.70	86.73	0.24	2.1
31	85.63	40.69	22.36	9.10	85.57	-0.06	-0.7
32	107.83	42.96	7.21	3.10	108.27	0.44	14.2
Rigs213	60.31	27.91	20.43	5.70	60.32	0.01	0.2
Rigs220	57.47	31.11	31.66	9.85	n.a.	n.a.	n.a.

n.a. = Not analyzed
Weight, porosity, and bulk volume of sample Rigs1-213 from Høier (2002) Table 2.2
Weight, porosity, and bulk volume of sample Rigs1-220 from Høier (2000) Tables 2.1 and 2.2

the last column of Table 2.1. Further work was restricted to this subset of 20 plugs. Two samples from well Rigs-1 identified as Rigs213 and Rigs220 also measured by Høier (2000, 2002) were included for quality control purposes.

2.3 Ultrasonic measurements of humidity dried samples

After conventional core analysis the samples were placed in a humidity-controlled oven at 60 °C and 40 % relative humidity until weight measurements showed that an equilibrium state was established. Table 2.2 presents the equilibrium weights and the water saturations calculated from these weights. The uncertainty, ΔS, of the water saturation values is dependent i.a. on the porosity of the sample. An empirical estimate is given as

$$\Delta S \sim 15 / \Phi \qquad \text{Eq. 2-1}$$

where Δ and Φ are in percent units (p.u.).

The water saturation values show a considerable scatter, ranging from zero to 19 %. The highest water saturation values tend to occur with the low porosity samples.

The humidity dried samples were mounted in a modified AutoLab 500 Ultrasonic core holder (New England Research) and the ultrasonic transit times were measured with a Tektronix Model TDS3012 2-channel digital phosphor oscilloscope connected to a PAR spike-generator. The ultrasonic transducers have centre frequencies at 700 kHz.

P- and S-waves were measured on the humidity-dried plugs at 75 bar hydrostatic confining pressure. Confining pressure was controlled with a Quizix SP-5400 high-pressure pump system. The confining pressure was initially increased to 20 bar in 5 minutes to secure a good seal of the confining rubber sleeve. Pressure was subsequently increased from 20 to 75 bar in 30 minutes, and the sample allowed to equilibrate at 75 bar for 30 minutes before measurement of the ultrasonic P- and S-signals. The ultrasonic data were saved digitally for later analysis. When unloading the core holder, the confining pressure was decreased continually from 75 to 0 bar during a time period of 30 minutes. A time schedule for the analysis is given in Table 2.3.

Table 2.3. Time schedule for ultrasonic measurements at hydrostatic confining pressure 75 bar on samples in humidity dried state.

Step no.	Description	Cumulate time hh:mm
1	Mount sample in core holder	00:15
2	Increase pressure to 10 bar in 5 min	00:20
3	Increase pressure to 75 bar in 30 min	00:50
4	Equilibration at 75 bar for 30 minutes	01:20
5	Measure ultrasonic velocity at 75 bar	01:35
6	Decrease pressure to 0 bar in 20 min	01:55
7	Dismount sample	02:10

Table 2.4. Time schedule for ultrasonic measurements on samples 13 and 31: Measurement at three pressure steps, 75 bar, 125 bar, and 200 bar.

Step no.	Description	Cumulate time hh:mm
1	Mount sample in core holder	00:15
2	Increase pressure to 10 bar in 5 min	00:20
3	Increase pressure to 75 bar in 30 min	00:50
4	Equilibration at 75 bar for 30 minutes	01:20
5	Measure ultrasonic velocity at 75 bar	01:35
6	Increase pressure to 125 bar in 30 minutes	02:05
7	Equilibration at 125 bar for 30 minutes	02:35
8	Measure ultrasonic velocity at 125 bar	02:50
9	Increase pressure to 200 bar in 30 minutes	03:20
10	Equilibration at 200 bar for 30 minutes	03:50
11	Measure ultrasonic velocity at 200 bar	04:05
12	Decrease pressure to 0 bar in 20 min	04:25
13	Dismount sample	04:40

Two of the samples, with identifications 13 and 31, were measured with an extended analytical programme that included ultrasonic measurements at the confining pressure steps 75, 125, and 200 bar (Table 2.4).

Ultrasonic repeat measurements were performed on a total of 9 samples.

Calibration of the ultrasonic measurements is described in Section 2.7, precision and reproducibility are described in Section 2.9, while the technique for analysing the ultrasonic signals are described in Sections 4.4 and 4.5.

2.4 Ultrasonic measurements of water saturated samples

After ultrasonic measurement in humidity dried state, the samples were cleaned briefly in a Soxhlet with methanol, and were dried at 60 °C.

Table 2.5. Water saturation of samples at time of ultrasonic measurement in S_W = 100 % state.

Sample id.	Weight at He-por determ. (g)	Bulk vol. at He-por determ. (ml)	Helium porosity (%)	Pore vol. at He-por determ. (ml)	Weight at sonic meas. in S_W=100% state (g)	Weight increase in S_W=100% state (g)	Sw at sonic meas. in S_W=100% state (%)	Water vol. minus PV in S_W=100% state (ml)
1	99.77	42.81	14.35	6.14	105.95	6.18	100.8	-0.05
2	105.61	42.60	8.97	3.82	109.64	4.03	105.7	-0.22
3	98.81	42.71	14.43	6.16	104.81	6.00	97.5	0.15
4	107.41	44.04	9.91	4.36	111.57	4.16	95.5	0.20
6	94.68	43.15	19.23	8.30	102.76	8.08	97.6	0.20
8	94.72	43.91	20.72	9.10	103.57	8.85	97.5	0.23
9	93.99	42.74	19.10	8.16	101.89	7.90	97.0	0.25
10	89.40	43.73	24.77	10.83	99.94	10.54	97.5	0.27
13	99.67	41.90	11.28	4.73	104.21	4.54	96.3	0.18
14	100.66	39.94	6.85	2.74	103.26	2.61	95.4	0.13
16	102.25	39.83	4.86	1.94	104.22	1.97	102.0	-0.04
17	102.16	40.00	6.32	2.53	104.42	2.26	89.6	0.26
19	105.99	42.30	8.01	3.39	109.15	3.16	93.5	0.22
21	88.63	44.80	26.90	12.05	100.48	11.85	98.5	0.18
22	89.17	43.72	24.69	10.79	99.86	10.69	99.2	0.08
23	95.84	42.64	16.68	7.11	102.77	6.93	97.6	0.17
24	83.43	39.49	21.87	8.64	91.80	8.37	97.1	0.25
26	86.49	43.77	26.73	11.70	98.12	11.63	99.6	0.05
31	85.63	40.69	22.36	9.10	94.76	9.13	100.5	-0.05
32	107.83	42.96	7.21	3.10	110.74	2.91	94.1	0.18
Rigs213	60.31	27.91	20.43	5.70	65.82	5.51	96.8	0.18
Rigs220	57.47	31.11	31.66	9.85	67.17	9.70	98.7	0.13

n.a. = Not analyzed
Weight, porosity, and bulk volume of sample Rigs1-213 from Høier (2002) Table 2.2
Weight, porosity, and bulk volume of sample Rigs1-220 from Høier (2000) Tables 2.1 and 2.2

The samples were saturated with water by a vacuum/pressure saturation procedure, which included vacuum saturation for one day followed by pressure saturation at 100 bar for 2 days. The samples were weighed before and after the saturation procedure and Table 2.5 presents the calculated water saturations. The calculated deviation from a fully saturated state, i.e. S_W=100 %, may be given as the difference between the calculated water volume and the calculated pore volume of the sample. This value is given as the column *Water vol. minus PV in S_W=100% state* of Table 2.5. The mean value is 0.17 ml with a maximum of 0.27 ml. These values seems to be a reasonable representation of the combined uncertainties of the He-porosity, bulk volume, wet weight, and dry weight determinations. It is concluded that within the uncertainty the samples were fully saturated with water.

Table 2.6. Time schedule for ultrasonic measurements at hydrostatic confining pressure 75 bar on samples in water saturated state S_W=100%.

Step no.	Description	Cumulate time hh:mm
1	Mount sample in core holder	00:15
2	Increase pressure to 20 bar in 5 min	00:20
3	Equilibration at 20 bar for 60 minutes	01:20
4	Increase pressure to 75 bar in 30 min	01:50
5	Equilibration at 75 bar for 30 minutes	02:20
6	Measure ultrasonic velocity at 75 bar	02:35
7	Decrease pressure to 0 bar in 20 min	02:55
8	Dismount sample	03:10

The water used for saturation of the samples was tap water equilibrated with crushed chalk and filtered.

The procedure for ultrasonic measurement of the samples in water saturated state was similar to the measurements in humidity dried state (Table 2.3) except that an equilibration period was added at a confining pressure of 20 bar. A time schedule for the analysis is given in Table 2.6.

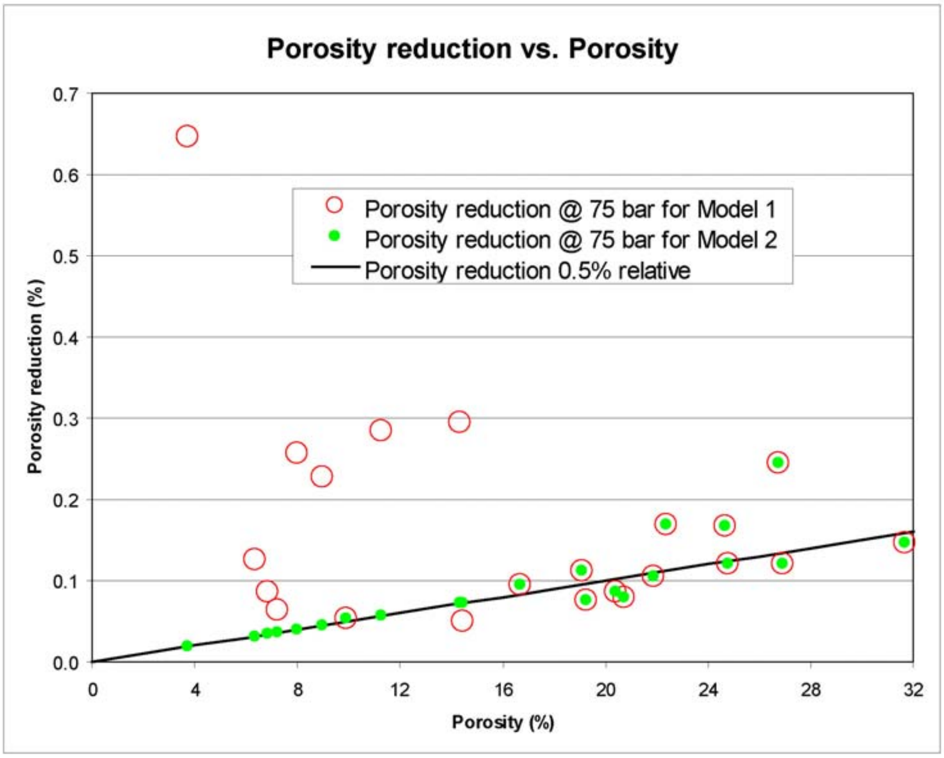


Fig. 2.1. Porosity reduction vs. porosity. Model 1 is as measured. Model 2 assumes a porosity reduction of 0.5 % of the pore volume for samples where the water production was not in equilibrium.

2.5 Pore volume reduction and length reduction

During measurement of samples in water saturated state, the outlet from the ultrasonic core holder was connected with a Mettler balance and the production of water was continuously logged. From the water production data two models for the pore volume reduction were established.

Model 1 assumes that the amount of produced water, W_w corresponds to the pore volume reduction, ΔPV

$$\Delta PV = W_W / \rho_w \quad \text{Eq. 2-2}$$

where ρ_W is the water density. Model 1 is presented in Fig. 2.1 and it is evident that most of the low porosity samples show aberrant high porosity reduction values. Plotting the water production versus time reveals that for a number of samples the water production had not ceased when the ultrasonic measurement was conducted. Clearly, the water production had not reached equilibrium. On mounting a sample in the ultrasonic core holder an amount of water is inevitably trapped between the sample and the end fittings and sleeve. For samples with reasonable permeability this water escapes during the 60 minutes equilibration at 20 bar (Table 2.6), but for samples with very low permeability the production of this water continued during the whole measurement and spoiled the porosity reduction determination.

Model 2 then assumes the same expression as Model 1 for the samples that had reached equilibrium at the time of ultrasonic measurement (Eq. 2-2) but for the disequilibrium samples assumes

$$\Delta PV = PV * 0.005 \quad \text{Eq. 2-3}$$

Table 2.7. Calculated porosity reduction and length reduction at a confining pressure of 75 bar

Sample id.	State of fluid production	Gas perm. (mD)	Measured porosity (%)	Porosity reduction (%)	Reduced porosity (%)	Measured length (mm)	Length reduction (mm)	Reduced length (mm)
1	No equilibrium	0.003	14.35	0.07	14.28	38.38	0.01	38.37
2	No equilibrium	0.002	8.97	0.04	8.93	38.34	0.01	38.33
3	No equilibrium	0.018	14.43	0.07	14.36	38.34	0.01	38.33
4	Equilib. OK	0.009	9.91	0.05	9.86	39.41	0.01	39.40
6	Equilib. OK	0.33	19.23	0.08	19.15	38.63	0.01	38.62
8	Equilib. OK	0.52	20.72	0.08	20.64	39.39	0.01	39.38
9	Equilib. OK	0.42	19.10	0.11	18.99	38.40	0.01	38.39
10	Equilib. OK	0.86	24.77	0.12	24.65	39.40	0.02	39.38
13	No equilibrium	0.009	11.28	0.06	11.22	37.62	0.01	37.61
14	No equilibrium	0.003	6.85	0.03	6.82	35.86	0.00	35.86
16	No equilibrium	0.005	3.70	0.02	3.68	35.72	0.00	35.72
17	No equilibrium	0.002	6.32	0.03	6.29	35.76	0.00	35.76
19	No equilibrium	0.004	8.01	0.04	7.97	37.90	0.01	37.89
21	Equilib. OK	0.17	26.90	0.12	26.78	40.55	0.02	40.53
22	Equilib. OK	0.06	24.69	0.17	24.52	39.33	0.02	39.31
23	Equilib. OK	0.05	16.68	0.09	16.59	38.22	0.01	38.21
24	Equilib. OK	0.07	21.87	0.11	21.76	35.63	0.01	35.62
26	Equilib. OK	0.08	26.73	0.24	26.49	39.42	0.03	39.39
31	Equilib. OK	0.41	22.36	0.17	22.19	36.64	0.02	36.62
32	No equilibrium	0.002	7.21	0.04	7.17	38.49	0.00	38.49
Rigs213	Equilib. OK	0.3	20.43	0.09	20.34	24.76	0.01	24.75
Rigs220	Equilib. OK	1.25	31.66	0.15	31.51	27.88	0.01	27.87

i.e. the pore volume reduction is calculated as a fixed percentage , 0.5 %, of the pore volume. Model 2 completely removed the aberrant porosity reduction values of Model 1, cf. Fig. 2.1, and is thus adopted in this work.. Table 2.7 reports the equilibrium state judged from the Mettler log, the measured He-porosity values and the calculated reduced porosity values.

The length of a sample is important for the calculation of the ultrasonic velocity. A model for calculation of the reduction in sample length, ΔL, is applied that assumes isotropic contraction of the pore volume without any change to the grain volume:

$$\Delta L = L\left(1 - \sqrt[3]{1 - \Delta\Phi}\right) \qquad \text{Eq. 2-4}$$

where L is the length of the sample and ΔΦ is the porosity reduction. Table 2.7 reports lengths measured without confining pressure at the time of humidity equilibration, and the reduced lengths according to Eq. 2-4. The reduced lengths of Table 2.7 are used for all ultrasonic velocity calculations.

2.6 Procedure for the ultrasonic measurements

A plug sample was mounted in an ultrasonic core holder with an ultrasonic transmitter at one end and an ultrasonic receiver at the other end. A rubber sleeve was mounted around the cylinder surface to isolate the plug sample from the hydrostatic pressure medium. The ultrasonic equipment is described in more detail in Chapter 4 Analytical methods. Contact paste was not used. Hydrostatic pressure was applied to the sample with a Quizix SP-5400 high-pressure pump system. Except for the initial pressure build-up, which must take place fairly rapidly to ensure a good seal of the rubber sleeve, all pressure changes were applied with the pressure ramping facility of the Quizix pump system, which provides a linear evolution of pressure vs. time. Time schedules for the pressurisation are given in Tables 2.3, 2.4, and 2.6.

If a water saturated sample was going to be measured, the outlet of the core holder was connected to a cuvette placed on a Mettler balance and data logging of the balance was started. This allowed quantification of the fluid production during sample pressurization and ultrasonic measurement and thus enabled determination of the pore volume reduction, and sample length reduction.

The temperature in the laboratory during the ultrasonic measurements was 23 ± 2 °C.

The P- and S-wave data were saved digitally in csv-format for later analysis. Screen-dumps from the oscilloscope were saved in tif-format. Cf. Chapter 6 for data documentation.

A number of repeat measurements were performed. These measurements are indicated in Tables A.1 to A.6 with a "_ch" attached to the sample identification. At repeat measurements care was taken to assure that the S1 and S2 directions were the same as in the original measurements. S1 and S2 velocity determinations are thus comparable.

2.7 Calibration of ultrasonic measurements

The AutoLab 500 Ultrasonic core holder has an inherent system delay, mainly due to the time required for the ultrasonic signal to travel through the ultrasonic transmitter and receiver units. It is determined by calculating a 4-point linear regression on 4 calibration standards of different lengths and constant ultrasonic velocity. Three of the calibration standards (Alu1, Alu2, and Alu3) are aluminium plug samples of known length; the fourth calibration standard is a configuration where the ultrasonic transducers are mounted head-to-head, i.e. with a sample length of zero. A total of four calibrations were performed during the present work. The system delays are listed in Table 2.8 and the correlation coefficients for the associated linear regressions are listed in Table 2.9. Cf. Chapter 6 for documentation of the full ultrasonic calibration.

2.8 Analysis of the ultrasonic signal

Analysis of the ultrasonic signal was done by the program *firstarrival* made by Ødegaard A/S that determines the arrival of the ultrasonic wave train from a table of amplitude versus time in a csv-file. Refer to Chapter 4 Analytical methods for a thorough description.

2.9 Precision and reproducibility of ultrasonic data

The precision of the ultrasonic results may be assessed from 1) precision evaluation of the actual analytical data for each sample and 2) measurements on secondary standard Alu6061. The reproducibility of the ultrasonic results may be assessed from 3) repeat measurements of two samples, Rigs213 and Rigs220, that were measured in an earlier study, and 4) repeat measurements within the present study.

1. Precision evaluation of the actual analytical data for each sample

The precision of the ultrasonic measurements may be assessed from the precision parameters reported by the program *firstarrival* and an estimate of the uncertainty of the plug length determination. Precision estimates for all measurements are presented in Tables A.1 to A.6 of Appendix 1. The uncertainty of the plug length is estimated to be 0.1 mm for all samples and this leads to the error given in the column "Error on velocity from length". The *firstarrival* parameter "Global uncertainty", i.e. the precision of picking the right signal is listed in column "Global uncertainty". The risk of picking a wrong signal for the ultrasonic velocity calculation increases with the value of this parameter. When the parameter "Global uncertainty" exceeds approximately 0.5 a significant risk of picking a wrong signal is probably present. For most of the picks with high "Global uncertainty" values the *firstarrival* program was guided by the *forced pick* procedure, cf. Section 4.5 "The arrival picker program". The *firstarrival* parameter "Local uncertainty", i.e. the error due to signal noise is listed in column "Error on velocity from noise". The column "Total error" is the sum of the errors "Error on velocity from length" and "Error on velocity from noise".

The mean total error for all the 166 measurements of P, S1 and S2 ultrasonic velocities is 0.34 %, cf. Tables A.1 to A.6. Errors of this size mainly reflect the uncertainty of the plug length measurements. Only two errors exceeds 1.0 %, namely an error of 1.4 % for the measurements of S1 on sample 17 in the water saturated state, and an error of 1.1 % for the measurement of S2 on sample 32 also in the water saturated state.

The errors listed in Tables A.1 to A.6 do not include possible systematic errors or calibration inaccuracies and shall thus only be regarded as minimum errors.

Table 2.8 System delay at confining pressure 75 bar.

Calibration id.	P signal (us)	S1 signal (us)	S2 signal (us)
Calib. mar-04	12.7024	23.6636	24.2939
Calib. apr-04	12.7268	23.7072	24.3240
Calib. may-04	12.7319	23.7151	24.3447
Calib jun-04	12.7205	23.6536	24.3153

Table 2.9 Correlation coefficient R^2 for system delay regressions at confining pressure 75 bar.

Calibration id.	P signal	S1 signal	S2 signal
Calib. mar-04	0.9989	0.9998	0.9998
Calib. apr-04	0.9991	0.9998	0.9998
Calib may-04	0.9994	0.9997	0.9997
Calib jun-04	0.9990	0.9998	0.9998

Table 2.10 Measurements on standard Alu6061.

Calibration id.	Ultrasonic P velocity (m/s)	Deviation from nominal P velocity (%)	Ultrasonic S1 velocity (m/s)	Deviation from nominal S velocity (%)	Ultrasonic S2 velocity (m/s)	Deviation from nominal S velocity (%)
Nominal value	6396.0		3125.0		3125.0	
Calib. mar-04	6417.7	0.34	3129.4	0.14	3124.0	-0.03
Calib. apr-04	6499.6	1.62	3121.4	-0.12	3121.7	-0.11
Calib. may-04	6428.6	0.51	3117.9	-0.23	3121.1	-0.12
Calib. jun-04	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

n.a. = Not analyzed

2. Measurements on standard Alu6061

Standard Alu6061 is a secondary standard of aluminium provided by New England Research.. It was measured three times during the work. The results are listed in Table 2.10 together with the nominal sonic velocities for the standard. The results indicate a mean error of 0.82 % for P measurements, and a mean error of 0.13 % for S1 and S2 measurements.

3. Reproducibility of measurements on Rigs-1 samples

To check the reproducibility of the ultrasonic measurements two samples that have previously been measured during the Rock Physics Project (RPP project, Høier, 2000; Høier, 2002) financed by the EFP-98 research programme were included in the test programme. The new and the old measurements are compared in Table 2.11. The S1 and S2 directions of the samples in the RPP measurements are not known, therefore, to be comparable the S1 and S2 velocities are averaged.

Table 2.11. Comparison of ultrasonic measurements on samples Rigs213 and Rigs220 from the Rock Physics Project (RRP) and from the present work..

Sample id.	Saturation state	Ultrasonic P velocity, RPP project (m/s)	Ultrasonic P velocity, this project (m/s)	Deviation (%)	Ultrasonic S velocity, RPP project (m/s)	Ultrasonic S velocity, this project (m/s)	Deviation (%)
Rigs213 1)	Air saturated	4296 3)	4311.90	0.4	2597 3)	2570.33	-1.0
Rigs213 1)	Water saturated	4437 4)	4412.52	-0.6	2486 4)	2481.35	-0.2
Rigs220 2)	Water saturated	3335 5)	3344.61	0.3	1825 5)	1837.29	0.7

Note 1: In Høier (2002) this sample is identified as sample 213 from well Rigs-1.
Note 2: In Høier (2000) this sample is identified as sample 220 from well Rigs-1.
Note 3: From Høier (2002) Table 5.1.
Note 4: From Høier (2002) Table 5.2.
Note 5: From Høier (2002) Table 5.4.

Table 2.12. Mean deviation of repeat measurements within the present project. The number of samples for each mean is given in parenthesis.

	Mean deviation of P measurements	Mean deviation of S1 measurements	Mean deviation of S2 measurements
Humidity dried samples	1.1 % (N=9)	1.7 % (N=5)	1.6 % (N=5)
Water saturated samples	0.4 % (N=6)	0.6 % (N=3)	0.6 % (N=4)

The conditions of the ultrasonic measurements in Høier (2000, 2002) and the present project were similar, but not identical. All measurements were performed with a hydrostatic confining pressure of 75 bar. Høier (2002) used the program *firstarrival* to pick the arrival of the ultrasonic signals same as the present project. Høier (2002) also recalculated the data from Høier (2000) with *firstarrival* to make them more comparable to the later data. In Table 2.11 the recalculated values of Høier (2002) have been used for sample Rigs220.

Høier (2002) dried sample Rigs213 at 110 °C and then allowed it to equilibrate at room condition in the laboratory for 2 weeks. During ultrasonic measurement a water saturation of 1 % was calculated (Table 2.2. of Høier, 2002). The ultrasonic results are referred in Table 2.11 under the heading "Air saturated". The comparable measurement in the present project refers to the same sample dried at 60 °C and then equilibrated at the same temperature and a controlled humidity of 40 % relative humidity. During ultrasonic measurement a water saturation of 0.2 % was calculated, cf. Table 2.2.

The conditions for the water saturated samples during ultrasonic measurement were very similar. They were saturated with formation water prepared by the same procedure, and saturated by the same combined vacuum and pressure saturation procedure, cf. Section 2.4. For sample Rigs213 Høier (2002) reports a water saturation of 98 %, while this study reports a water saturation of 96.8 % (cf. Table 2.5). For sample Rigs220 Høier (2000) reports a water saturation of 100.1 %, while this study reports a water saturation of 98.7 % (cf. Table 2.5). The saturation states of the samples are thus very comparable.

Table 2.11 indicates a mean reproducibility of 0.4 % for the P velocities and 0.6 % for the S velocities. This is considered very satisfactory as the numbers include any velocity variations relating to changes caused by sample handling, cleaning etc. during the time interval from the measurements of Høier (2000, 2002) and the measurements of the present project.

4. Reproducibility of measurements within the present work

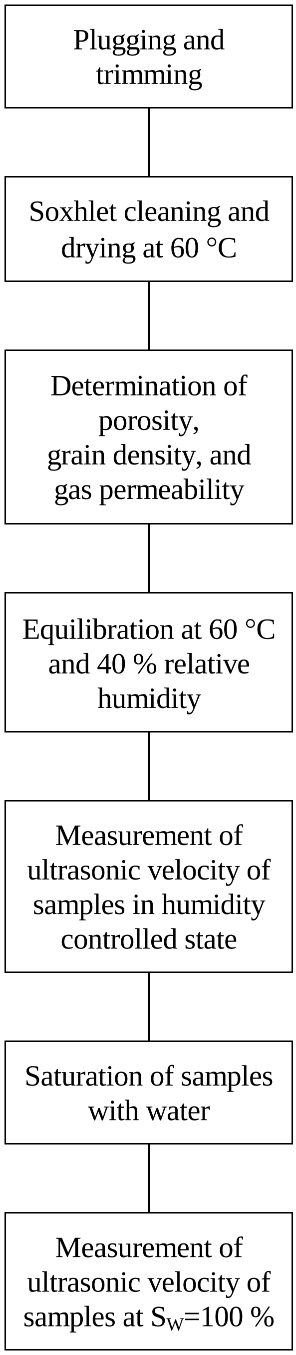
A total of 9 repeat measurements were performed on humidity dried samples, and a total of 6 repeat measurements were performed on water saturated samples. Table 2.12 summarises the results. The water saturated measurements is seen to have excellent reproducibility, while the humidity-dried measurements have much inferior reproducibility. This probably reflects the difficulty with controlling the saturation state of some of the humidity-dried samples.

The mean reproducibility for P determinations is generally 30 % better than for S determinations. This applies to both humidity dried samples and water saturated samples.

Summary of precision and reproducibility

Precision and reproducibility the ultrasonic velocity determinations are considered to be better than 1 %, except for some samples in humidity equilibrated state where precision and reproducibility may deteriorate to 2 %.

3. Flow chart of the analytical procedure



4. Analytical methods

The following is a short description of the methods used by GEUS Core Laboratory. For a more detailed description of methods, instrumentation and principles of calculation the reader is referred to API recommended practice for core analysis procedure (API RP 40, 1998).

4.1 Gas permeability

The plug is mounted in a Hassler core holder, and a confining pressure of 400 psi applied to the sleeve. The specific permeability to gas is measured by flowing nitrogen gas through a plug of known dimensions at differential pressures between 0 and 1 bar. No back pressure is applied. The readings of the digital gas permeameter are checked regularly by routine measurement of permeable steel reference plugs.

4.2 He-porosity and grain density

The porosity is measured on cleaned and dried samples. The porosity is determined by subtraction of the measured grain volume and the measured bulk volume. The Helium technique, employing Boyle's Law, is used for grain volume determination, applying a double chambered Helium porosimeter with digital readout, whereas bulk volume is measured by submersion of the plug in a mercury bath using Archimedes principle. Grain density is calculated from the grain volume measurement and the weight of the cleaned and dried sample.

4.3 Precision of conventional core analysis data

Table 4.1 gives the precision (= reproducibility) at the 68% level of confidence (+/- 1 standard deviation) for routine core analysis measurements performed at GEUS Core Laboratory.

Table 4.1. Precision of conventional core analysis data.

Measurement	Range, mD	Precision
Grain density		0.003 g/cc
Porosity		0.1 porosity-%
Gas Permeability	0.001-0.01 0.01-0.1 > 0.1	25% 15% 4%

4.4 Ultrasonic measurements

The transit time of P- and S-waves in a plug sample is measured by a Tektronix Model TDS3012 two-channel digital phosphor oscilloscope, connected to a spike-generator (PAR Scientific Instruments) and a modified AutoLab 500 Ultrasonic core holder from New England Research. The P- and S-wave transducers have nominal centre frequencies at 700 kHz.

The ultrasonic velocity, *V*, is calculated from the following equation.

$$V = \frac{L}{t_{transit} - t_{delay}} \quad \text{.......... Eq. 4-1}$$

where *L* is the sample length, $t_{transit}$ is the measured total travel time, and t_{delay} is the system delay. The system delay is an inherent system property representing the time taken for the ultrasonic signal to travel through the transducers plus any delays caused by the electronics. One way to determine the system delay is by measuring the transit time of the system without any plugs. A more precise determination is obtained by measuring the transit time for a series of plugs with uniform velocity and known length. The system delay is then determined as the transit time at length zero as calculated by a linear regression. This principle is illustrated in Fig. 4.1. Depending on the task, GEUS uses either a series of three aluminium plugs of lengths 15, 25 and 36 mm or a series of three acrylic plugs of lengths 20, 35 and 50 mm for calibration. In addition a fourth data point is obtained for both series by including a measurement where the ultrasonic transducers are mounted head-on-head, equivalent to a plug of length zero.

The system is tested against a reference plug made from aluminium, Alu6061, with known P and S velocities, supplied by New England Research.

4.5 The arrival picker program

Whenever possible a program named *firstarrival* is used for determining the transit time of the ultrasonic signals. The program was developed by Ødegaard A/S. Compared to manual picking of the transit time the use of a computer program eliminates the subjectivity of manual picking, and objective information about precision becomes available. The input to the program consists of 1) a comma-separated file (csv-file) listing time and signal amplitude, 2) a search interval specifying the time interval to be searched, and 3) a parameter specifying whether a positive or a negative deflection from zero shall be picked.

firstarrival identifies the first amplitude extremum of the ultrasonic signal and determines the transit time, the amplitude and two uncertainty parameters, a global uncertainty and a local uncertainty, for the arrival event.

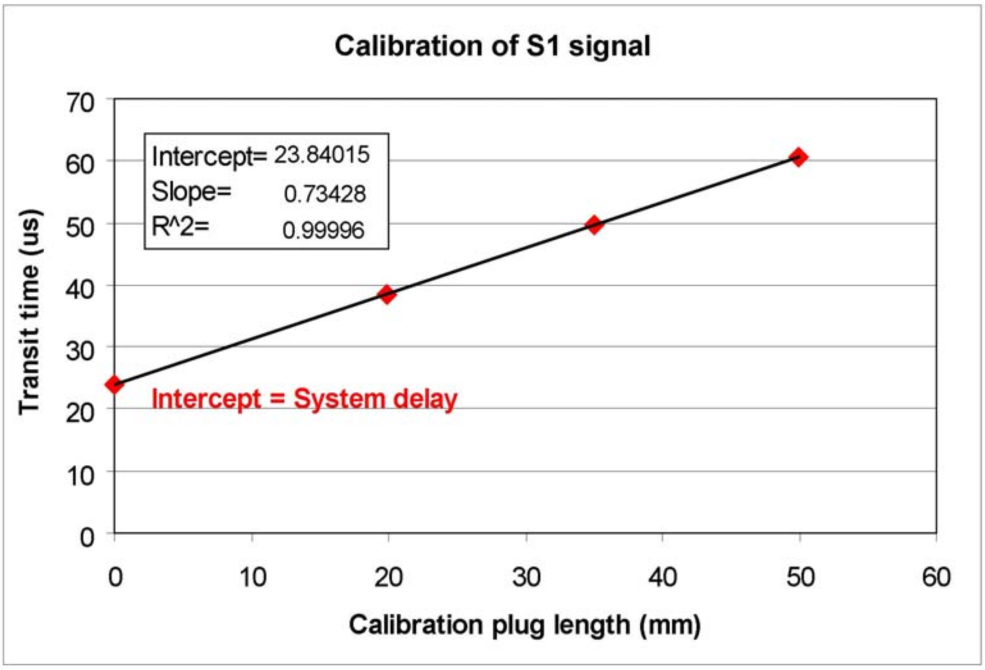


Fig. 4.1 Determination of the system delay from a regression on 4 data points.

The first amplitude extremum is used as the arrival event rather than the first deviation from the baseline because this causes the algorithm to be much more robust in case of noisy data. The difference between the two methods is negligible, because the same procedure is used for both calibration and sample measurements and because the width of signal peaks are nearly constant (being governed by the 700 kHz centre frequency).

On some occasions when the ultrasonic signal is very noisy the *firstarrival* program may pick a wrong signal peak and thus result in a wrong transit time. Or the program may fail to detect a signal peak at all. Therefore, the transit time determinations of the *firstarrival* program are always checked manually. In case they are deemed wrong it is first attempted to force *firstarrival* to pick the correct extremum by reducing the search interval – a procedure termed *forced picking*. If this procedure fails manual picking of the transit time is performed - a procedure termed *manual picking*. In case of forced picking objective information about precision is still available. In case of manual picking objective information about precision is not available.

The output from the *firstarrival* program consists of 1) a pick of the extremum identified as the arrival of the ultrasonic signal, 2) a global uncertainty parameter, 3) a local uncertainty parameter, and 4) an amplitude at the pick.

<u>Picking the arrival of the ultrasonic signal</u>

firstarrival looks for an event consisting of two consecutive local extrema with amplitudes of opposite sign. The search can be limited to a given time interval and to a given polarity, i.e. the sign of the first extremum. In a typical ultrasonic signal the desired event will give the maximum output in the following non-linear object function:

$$\frac{\left| FirstExtremumAmplitude - 2 * SecondExtremumAmplitude \right|}{HeadAmplitude} \qquad \text{Eq. 4-2}$$

Where the HeadAmplitude denotes the maximum absolute amplitude of the signal in an interval ending just before the onset of the half period containing the first extremum. The length of the interval has been set to 5 mean periods, i.e. 5 divided by the mean frequency. The precise time of the first extremum is found using Newton-Raphson local optimisation starting from the solution determined previously and using sinc interpolation between the samples.

<u>The global uncertainty:</u>

To describe how easy it is to identify the desired event, the global uncertainty is defined as the ratio of the object function for the second largest value and the largest value. The global uncertainty takes values between 0 and 1, where 0 represents a very easy case and 1 means that two or more picks were equally good, in fact equally bad.

<u>The local uncertainty (Error-band):</u>

To describe how much the picked time could be wrong due to additive noise moving the chosen extremum of the observable signal, the local uncertainty is computed. The chosen HeadAmplitude is used as a noise estimate in that computation.

<u>Amplitude at pick</u>

The amplitude of the Newton-Raphson optimisation at the picked time is reported as the amplitude at the pick.

5. Results of the ultrasonic measurements

The results of the ultrasonic measurements are presented in the following tables and figures:

Table 5.1: Ultrasonic results of 21 samples (incl. Rigs213) dried at humidity controlled conditions (60 °C, 40 % relative humidity) and measured with a confining pressure of 75 bar.
Table 5.2: Ultrasonic results of 22 samples (incl. Rigs213 and Rigs220) fully saturated with water (S_W=100 %) and measured with a confining pressure of 75 bar.
Table 5.3: Ultrasonic results of two samples (nos. 13 and 31) dried at humidity controlled conditions (60 °C, 40 % relative humidity) and measured in turn at confining pressures of 75, 125, and 200 bar.

Values reported in Tables 5.1 to 5.3 as "Mean S velocity" are the mean of S1 and S2 measurements. Basic data for the underlying P, S1 and S2 measurements are given in Tables A.1 to A.6.

In the following figures samples in the humidity-dried state are referred to as *Gas saturated samples*. The ultrasonic velocity have been plotted as follows:

Fig. 5.1 V_S vs. V_P for samples in the *gas saturated* and *water saturated* state.
Fig. 5.2. V_P vs. porosity for samples in the *gas saturated* and *water saturated* state.
Fig. 5.3. V_S vs. porosity for samples in the *gas saturated* and *water saturated* state.
Fig. 5.4. V_P in *water saturated* state vs. V_P in *gas saturated* state.
Fig. 5.5. V_S in *water saturated state* vs. V_S in *gas saturated* state.
Fig. 5.6. Ratio V_P/V_S for samples in the *gas saturated* and *water saturated* state.
Fig. 5.7. V_P and V_S vs. confining pressure for sample nos. 13.
Fig. 5.8. V_P and V_S vs. confining pressure for sample nos. 31.
Fig. 5.9 V_S vs. V_P for sample 13.
Fig. 5.10. V_S vs. V_P for sample 31.

In Figs. 5.1 to 5.6 the ultrasonic results are compared with the modified upper Hashin-Shtrikman (‘MUHS’) model presented by Walls et al. (1998). This model describes how the dry bulk and shear moduli, *K* and *G* increase as porosity is reduced from a maximum value, ϕ_{max}, to zero porosity. Here the model is presented with the high-porosity parameters of Japsen et al. (2004) combined with the low-porosity parameters of Walls et al. (1998):

K_s = 65 GPa, G_s = 27 GPa for ϕ = 0%
$K_{\phi max}$ = 1.5 GPa, $G_{\phi max}$ = 2.5 GPa for ϕ_{max}= 45%

where the low-porosity end-members, K_s and G_s, are moduli of the solid at zero porosity. The prediction of the MUHS model for the dry rock properties are used as input to Gassmann’s equations for calculating the properties of fully water saturated chalk samples.

Table 5.1. Results of ultrasonic measurements – humidity dried samples 60 °C, 40 % relative humidity.

Sample id.	Well id.	Gas perm (mD)	Porosity (%)	Reduced porosity (%)	Grain density (g/ml)	P velocity (m/s)	S1 velocity (m/s)	S2 velocity (m/s)	Mean S velocity (m/s)	P / S Ratio
1	Q-1	0.003	14.35	14.28	2.721	3947.90	2470.08	2463.11	2466.60	1.601
2	Q-1	0.002	8.97	8.93	2.724	3809.06	2487.63	2484.25	2485.94	1.532
3	Q-1	0.018	14.43	14.36	2.720	4565.64	2689.62	2684.18	2686.90	1.699
4	Q-1	0.009	9.91	9.86	2.706	4999.22	2924.66	2910.07	2917.37	1.714
6	Otto-1	0.33	19.23	19.15	2.716	4011.13	2436.30	2431.91	2434.10	1.648
8	Otto-1	0.52	20.72	20.64	2.720	4042.53	2424.08	2423.21	2423.64	1.668
9	T-3	0.42	19.10	18.99	2.718	3924.27	2375.41	2378.52	2376.97	1.651
10	T-3	0.86	24.77	24.65	2.717	3560.11	2162.80	2158.41	2160.61	1.648
13	Gert-1	0.009	11.28	11.22	2.680	4921.17	2927.56	2924.84	2926.20	1.682
14	Gert-1	0.003	6.85	6.82	2.706	5079.40	3043.50	3044.33	3043.91	1.669
16	Gert-1	0.005	3.70	3.68	2.698	4699.53	2779.95	2790.49	2785.22	1.687
17	West Lulu-1	0.002	6.32	6.29	2.726	5524.85	3074.23	3066.46	3070.34	1.799
19	West Lulu-1	0.004	8.01	7.97	2.723	5234.62	2988.33	2987.47	2987.90	1.752
21	Baron-2	0.17	26.90	26.78	2.706	3587.62	2179.81	2185.08	2182.44	1.644
22	Baron-2	0.06	24.69	24.52	2.708	3469.73	2168.74	2158.69	2163.72	1.604
23	Baron-2	0.05	16.68	16.59	2.698	4404.68	2641.34	2635.04	2638.19	1.670
24	Baron-2	0.07	21.87	21.76	2.704	3764.95	2308.84	2307.02	2307.93	1.631
26	I-1	0.08	26.73	26.49	2.696	3155.82	2085.77	2080.65	2083.21	1.515
31	Cecilie-1B	0.41	22.36	22.19	2.710	3867.87	2328.33	2347.50	2337.91	1.654
32	Cecilie-1B	0.002	7.21	7.17	2.705	4852.66	2836.39	2837.12	2836.76	1.711
Rigs213	Rigs-1	0.3	20.43	20.34	2.716	4311.90	2587.22	2553.44	2570.33	1.678

Table 5.2. Results of ultrasonic measurements – water saturated state, S_W=100%.

Sample id.	Well id.	Gas perm (mD)	Porosity (%)	Reduced porosity (%)	Grain density (g/ml)	P velocity (m/s)	S1 velocity (m/s)	S2 velocity (m/s)	Mean S velocity (m/s)	P / S Ratio
1	Q-1	0.003	14.35	14.28	2.721	3863.42	2007.58	2015.37	2011.47	1.921
2	Q-1	0.002	8.97	8.93	2.724	4001.06	n.u.	n.u.	n.u.	n.u.
3	Q-1	0.018	14.43	14.36	2.720	4469.80	2463.57	2477.63	2470.60	1.809
4	Q-1	0.009	9.91	9.86	2.706	4983.85	2756.79	2741.32	2749.06	1.813
6	Otto-1	0.33	19.23	19.15	2.716	4105.68	2264.49	2265.28	2264.89	1.813
8	Otto-1	0.52	20.72	20.64	2.720	4111.58	2263.13	2255.78	2259.45	1.820
9	T-3	0.42	19.10	18.99	2.718	3974.37	2179.71	2166.21	2172.96	1.829
10	T-3	0.86	24.77	24.65	2.717	3620.09	1950.22	1952.72	1951.47	1.855
13	Gert-1	0.009	11.28	11.22	2.680	4892.34	2797.13	2795.91	2796.52	1.749
14	Gert-1	0.003	6.85	6.82	2.706	5119.09	n.u.	n.u.	n.u.	n.u.
16	Gert-1	0.005	3.70	3.68	2.698	4849.78	n.u.	n.u.	n.u.	n.u.
17	West Lulu-1	0.002	6.32	6.29	2.726	5497.70	2962.01	2947.56	2954.79	1.861
19	West Lulu-1	0.004	8.01	7.97	2.723	5228.16	2838.16	2827.87	2833.01	1.845
21	Baron-2	0.17	26.90	26.78	2.706	3471.16	1865.75	1863.59	1864.67	1.862
22	Baron-2	0.06	24.69	24.52	2.708	3425.03	1829.15	1823.52	1826.33	1.875
23	Baron-2	0.05	16.68	16.59	2.698	4319.03	2432.66	2416.59	2424.62	1.781
24	Baron-2	0.07	21.87	21.76	2.704	3783.77	2062.67	2068.80	2065.73	1.832
26	I-1	0.08	26.73	26.49	2.696	3185.16	1756.03	1750.55	1753.29	1.817
31	Cecilie-1B	0.41	22.36	22.19	2.710	3807.16	2058.03	2071.97	2065.00	1.844
32	Cecilie-1B	0.002	7.21	7.17	2.705	4832.14	n.u.	2589.20	2589.20	1.866
Rigs213	Rigs-1	0.3	20.43	20.34	2.716	4412.52	2478.99	2483.70	2481.35	1.778
Rigs220	Rigs-1	1.25	31.66	31.51	2.703	3344.61	1839.94	1834.64	1837.29	1.820

n.u. Measurement not useful.

Table 5.3. Results of ultrasonic measurements – samples dried at 60 °C, 40 % relative humidity, and measured at confining pressures 75, 125 and 200 bar.

Sample id.	Well id.	Confining pressure (bar)	Gas perm (mD)	Porosity (%)	Reduced porosity (%)	Grain density (g/ml)	P velocity (m/s)	S1 velocity (m/s)	S2 velocity (m/s)	Mean S velocity (m/s)	P / S Ratio
13	Gert-1	75	0.009	11.28	11.22	2.680	4921.17	2927.56	2924.84	2926.20	1.682
13	Gert-1	125	0.009	11.28	11.22	2.680	4941.08	2938.20	2932.66	2935.43	1.683
13	Gert-1	200	0.009	11.28	11.22	2.680	4937.70	2937.76	2932.18	2934.97	1.682
31	Cecilie-1B	75	0.41	22.36	22.19	2.710	3867.87	2328.33	2347.50	2337.91	1.654
31	Cecilie-1B	125	0.41	22.36	22.19	2.710	3903.28	2347.90	2362.08	2354.99	1.657
31	Cecilie-1B	200	0.41	22.36	22.19	2.710	3940.92	2359.99	2374.84	2367.42	1.665

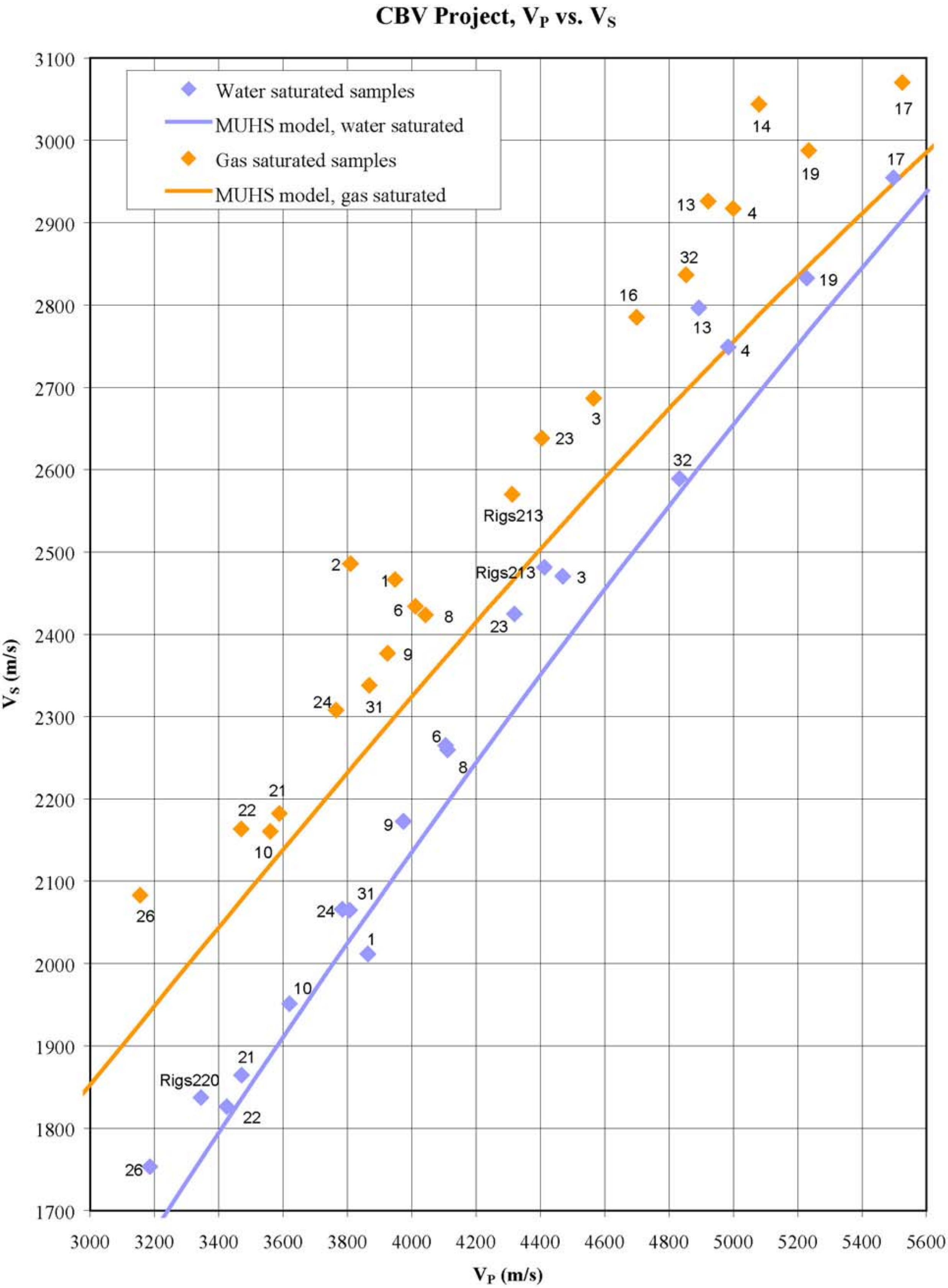


Fig. 5.1. V_S vs. V_P for samples in gas saturated and water saturated state..

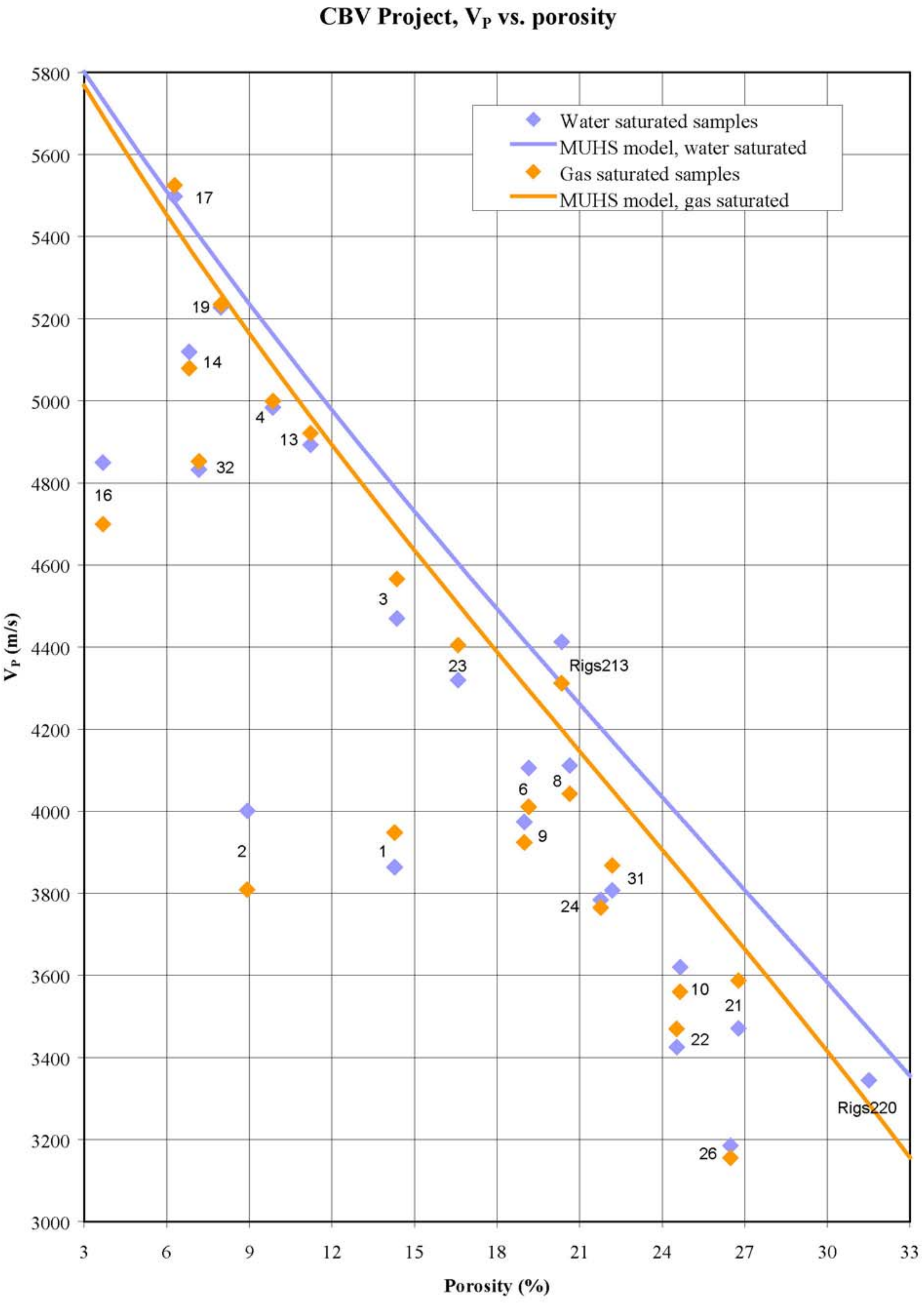


Fig. 5.2. V_P vs. porosity for samples in gas saturated and water saturated state. Please note that each sample is only labelled once, i.e. each label refers to both a gas saturated and a water saturated measurement, except for sample Rigs220 where only a water saturated measurement is available.

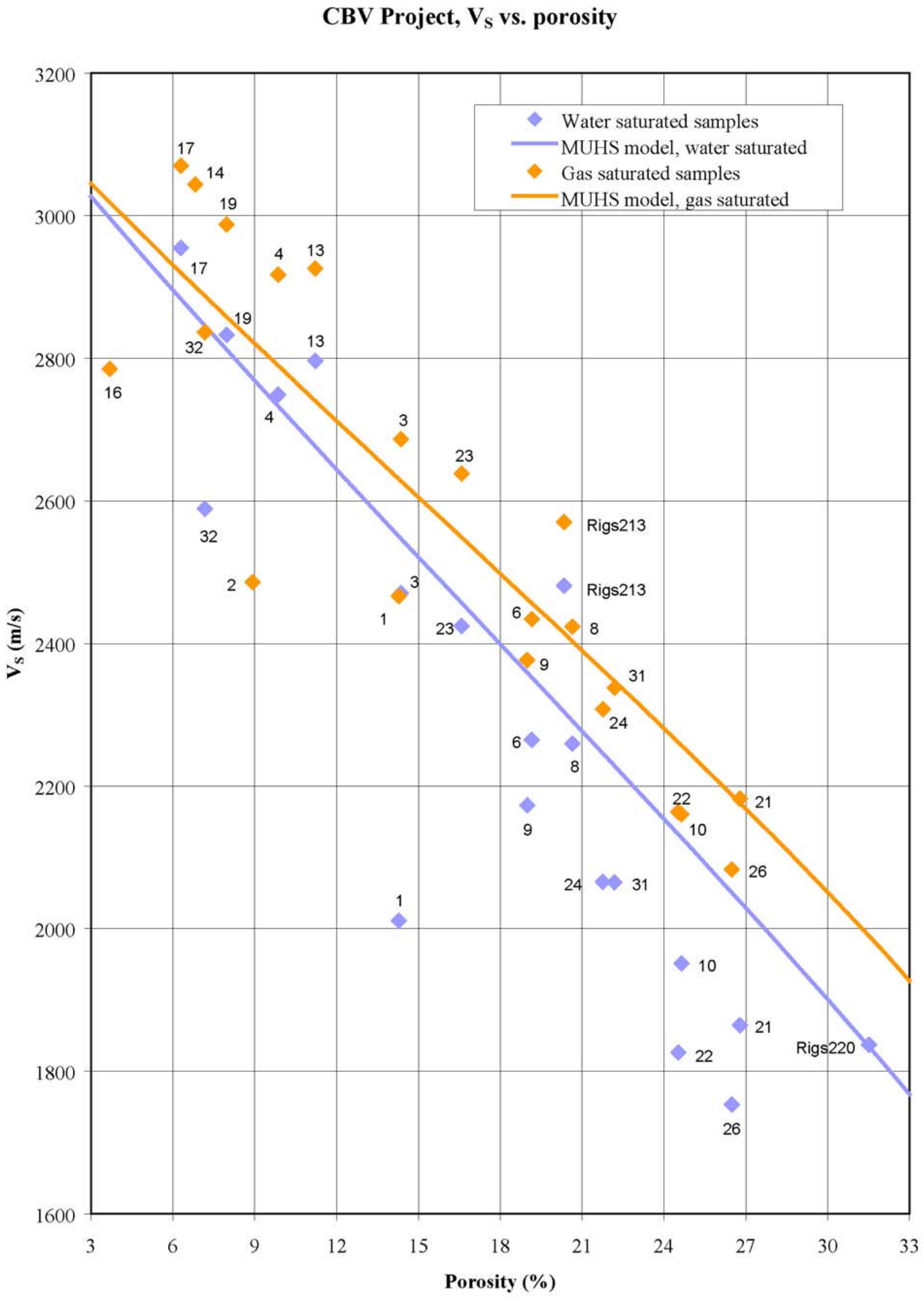


Fig. 5.3. V_S vs. porosity for samples in gas saturated and water saturated state.

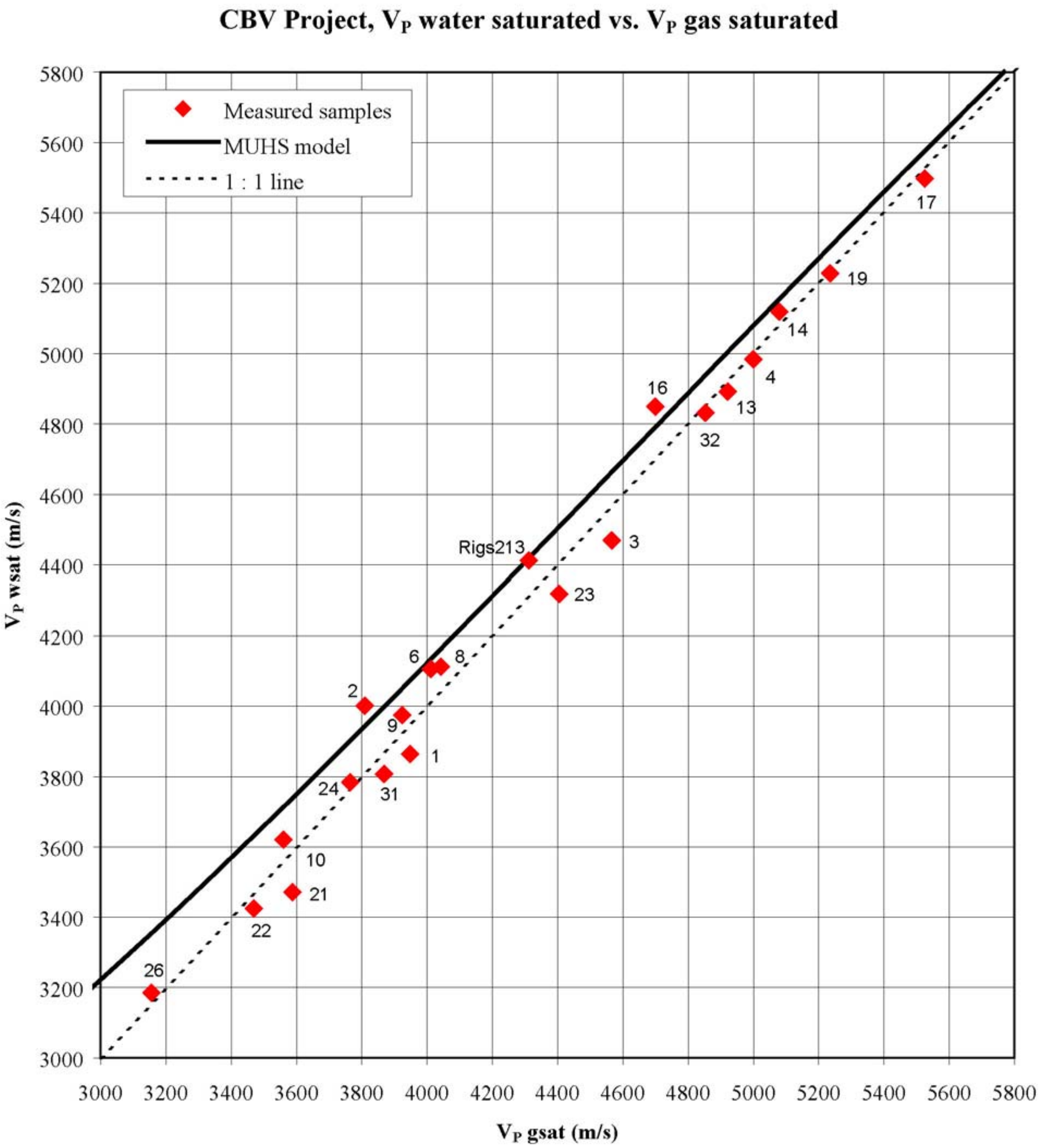


Fig. 5.4. V_P in water saturated state vs. V_P in gas saturated state.

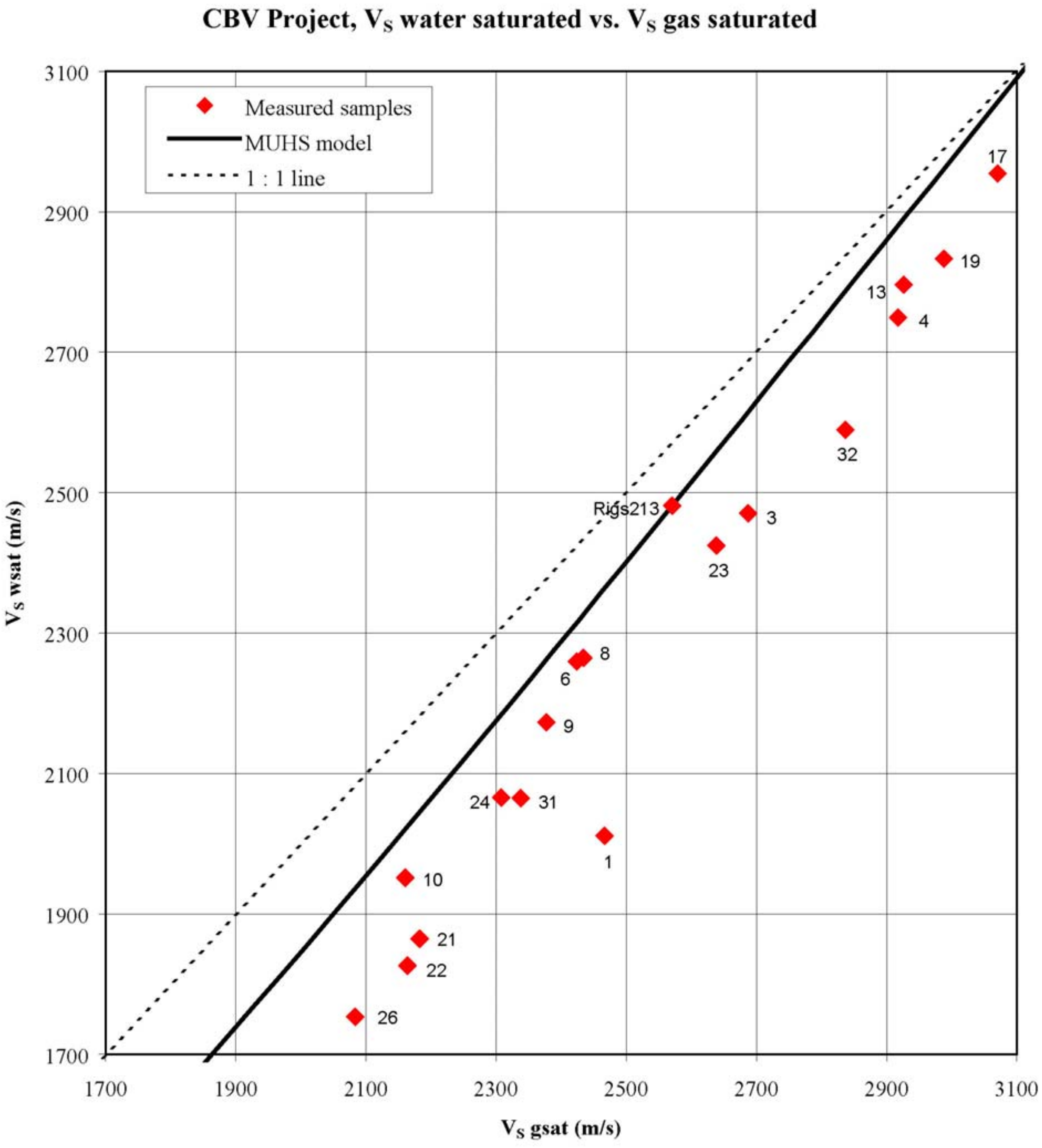


Fig. 5.5. V_S in water saturated state vs. V_S in gas saturated state.

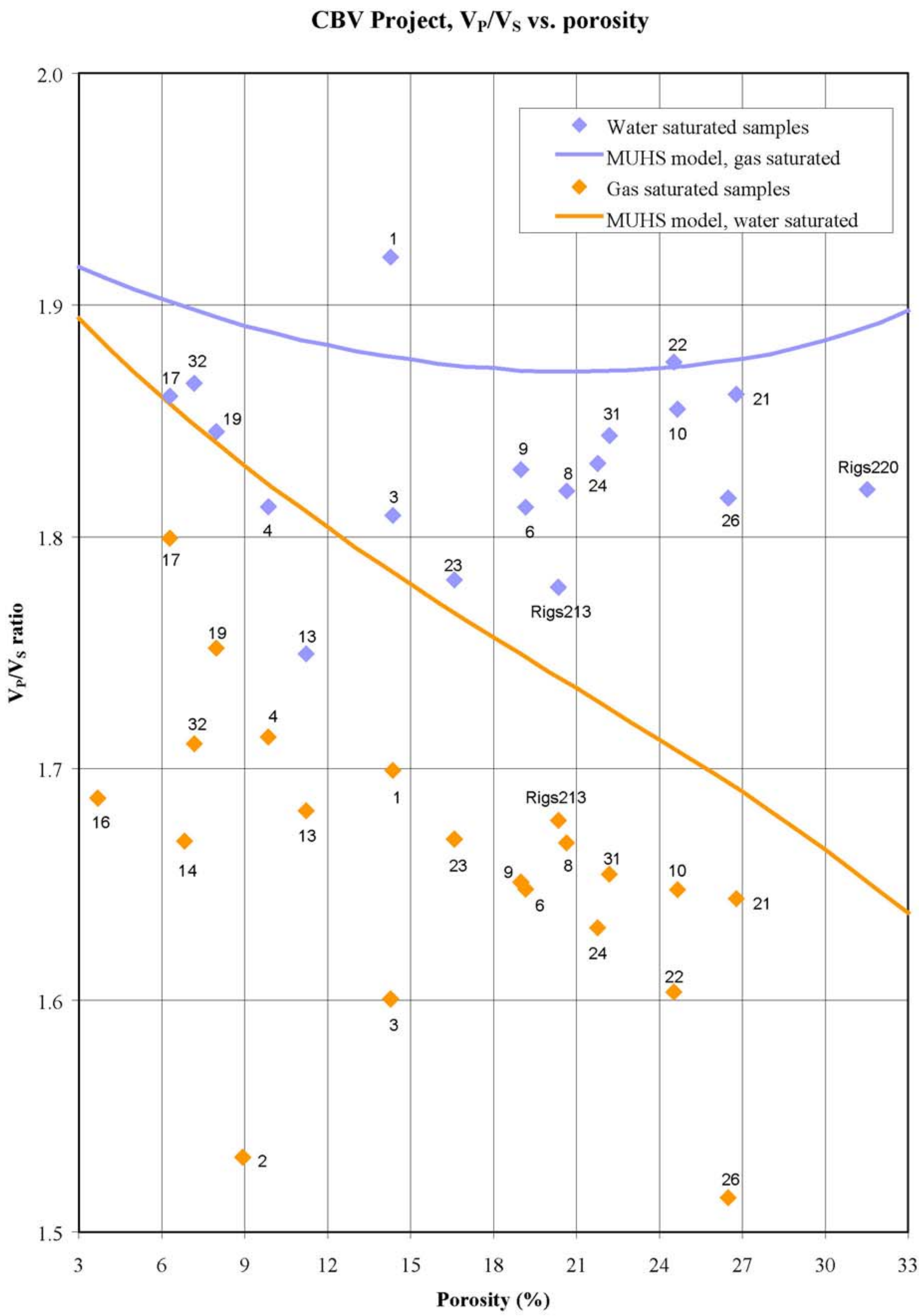


Fig. 5.6. V_P/V_S ratio vs. porosity for samples in gas saturated and water saturated state.

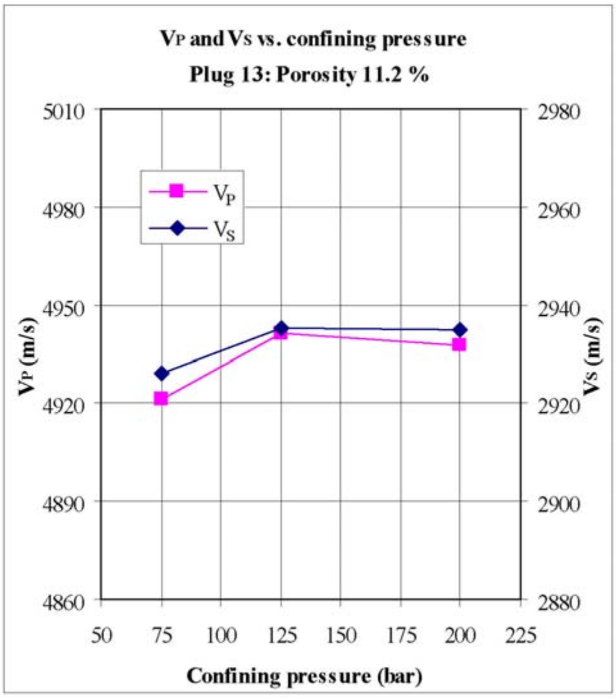


Fig. 5.7. Ultrasonic velocities V_P and V_S plotted against confining pressure for sample 13. Note that V_P and V_S are plotted on separate Y-axes.

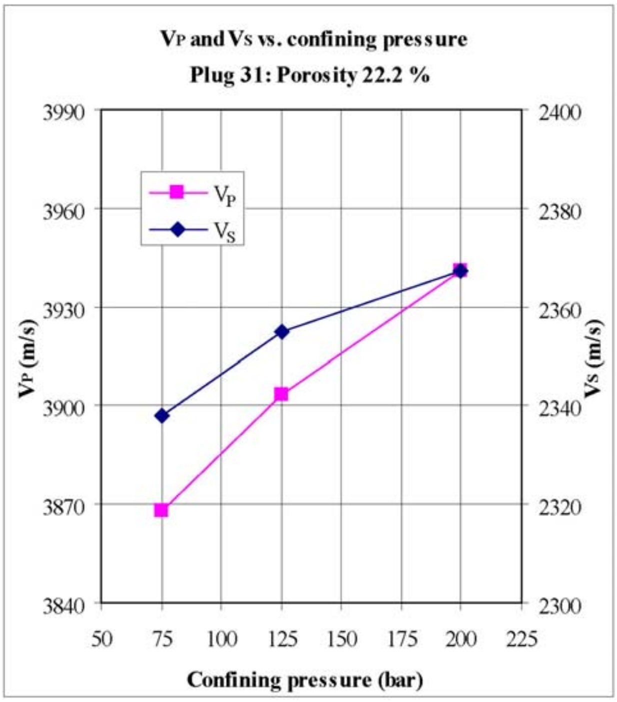


Fig. 5.8. Ultrasonic velocities V_P and V_S plotted against confining pressure for sample 31. Note that V_P and V_S are plotted on separate Y-axes.

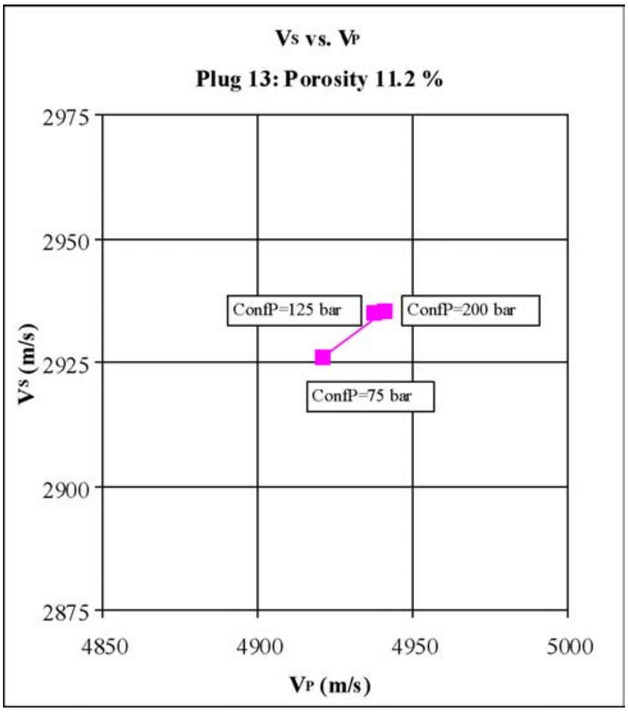


Fig. 5.9. Ultrasonic velocity V_S plotted against ultrasonic velocity V_P for sample 13. Measurements are labelled with confining pressure.

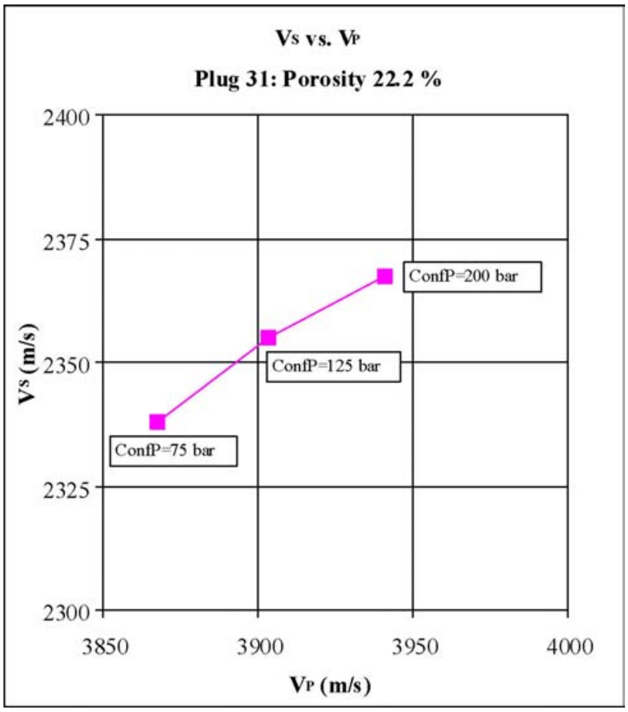


Fig. 5.10. Ultrasonic velocity V_S plotted against ultrasonic velocity V_P for sample 31. Measurements are labelled with confining pressure.

6. Documentation of data

This report comes in two versions: one with an attached CD and one without.

The CD contains all the ultrasonic data of the present work. The sample data for measurements in humidity dried state can be found in the “HumidityDry” folder, and the sample data for measurements in the S_W=100 % state can be found in the “WaterSat” folder. The calibration data can be found in the "CalibrationData" folder. At the top level, all results and plots are placed in the spreadsheet *sonic_cbv.xls*, which is an Excel97 file.

Each folder "HumidityDry", "WaterSat", and "CalibrationData" contains a file firstarrival_<id.>.doc, which contains the output from the *firstarrival* program, cf. Section 4.5 for a description of the output.

In the folders "HumidityDry" and "WaterSat" sample folders contain the following files:

1) Files with wave train data stored in comma separated files (*.csv)
2) Screen-dumps of the oscilloscope in tif format (*.tif)

For these files the filenames are constructed as follows:
<sample id.>_<state_><measurement type>_<hydrostatic pressure>_<date>.<file type>

where

<sample id.> is the identification of the sample
<state_> is either missing indicating humidity dried state or *maet* indicating water saturated state
<measurement type> is given as P (P-wave) or S1 (S1-wave) or S2 (S2-wave)
<hydrostatic pressure> is the hydrostatic pressure in bar
<date> is a shorthand date with format ddmmyy
<file type> is csv or tif

Every sample folder for water saturated samples in addition contains

3) An Excel file <sample id.>.xls with a Mettler log and the calculation of pore volume reduction

The clock of the oscilloscope, the clock of the attached PC, and the clock of the Quizix pump system were kept synchronized within ½ minute within the data acquisition period April 5th to June 30th 2004 to allow comparison of the Mettler logs and the ultrasonic data.

7. References

API RP40, 1998. Recommended practices for core analysis. *American Petroleum Institute, Recommended Practices **40**, second edition.*

Høier, C., 2002. Special core analysis for the Rock Physics project (EFP-2001) ENS J.nr. 1313/01-0006. Ultrasonic velocity measured on plugs from the Ekofisk and Tor formation. Samples taken from the wells: Rigs-1, Rigs-2 and SA-1, the South Arne Field. *Danmarks og Grønlands Geologiske Undersøgelse Rapport **2002/23***, 26 pp.

Høier, C., 2000. Special core analysis for the Rock Physics project (EFP-98) ENS J.nr. 1313/98-0007. Ultrasonic velocity measured on plugs from the wells: Rigs-1, Rigs-2 and SA-1, the South Arne Field. *Danmarks og Grønlands Geologiske Undersøgelse Rapport **2000/19***, 71 pp.

Jakobsen, F., 2004. *Unpublished work prepared for the Chalk Background Velocity project, GEUS*.

Japsen, P., Bruun, A., Fabricius, I. L., Rasmussen, R., Mavko, G., Vejbæk, O. V. & Pedersen, J. M. 2004. Influence of porosity and pore fluid on acoustic properties of chalk: AVO-response from oil, South Arne Field, North Sea. *Petroleum Geoscience **10***, 319-330.

Nielsen, L.H. & Japsen, P., 1991. Deep wells in Denmark 1935-1990, *Danm. Geol. Unders. Ser. A **31***, 178 pp.

Walls, J. D., Dvorkin, J. & Smith, B. A. 1998. Modeling seismic velocity in Ekofisk Chalk. *Society of Exploration Geophysicists 68th annual conference*. 1016–1019.

Appendix 1. Basic data, results, and precision

Basic data, results and precision parameters for all measurements are presented in Tables A.1 to A.6.

These tables report the full output from the *firstarrival* program in the columns labelled *First arrival of <id..> signal*, *Local uncertainty*, *Global uncertainty*, and *Amplitude at pick*. This is true even for measurements where the identification of the ultrasonic signal, and thus the calculation of an ultrasonic velocity, failed.
In these instance the output from *firstarrival* is reported but the velocity and precision parameters are marked with the Excel symbol #I/T denoting that the data values are absent. In addition the measurement is commented "Not useful".

Tables A.1 to A.3 reports data from measurement of the samples in humidity dried state, i.e. 60 °C and 40 % relative humidity.
Tables A.4 to A.6 reports data from measurement of the samples in fully water saturated state, i.e. S_W = 100 %.

Table A.1. Basic data, results, and precision of ultrasonic measurements.
Ultrasonic P signals, samples measured in humidity dried state, 60 °C, 40 % relative humidity

Sample id.	File id.	Reduced porosity (%)	Reduced length (mm)	First arrival of P signal (us)	Local un-certainty (us)	Global un-certainty	Ampli-tude at pick (mV)	P velocity (m/s)	Error on velocity from length (m/s)	Error on velocity from noise (m/s)	Error on velocity Total error (m/s)	Total error (%)	Comment
1	Plug1_P_75_por_080304	14.28	38.37	22.4542	0.0188	0.06	84.0	3934.74	10	3	14	0.3	
1_ch	Plug1_P_75_310304	14.28	38.37	22.3894	0.0121	0.04	97.2	3961.07	10	2	12	0.3	
2	Plug2_P_75_por_100304	8.93	38.33	22.5949	0.0176	0.05	53.6	3875.09	10	3	13	0.3	
2_ch	Plug2_P_75_010404	8.93	38.33	22.9439	0.0181	0.05	51.2	3743.03	10	3	13	0.3	
3	Plug3_P_75_por_110304	14.36	38.33	21.0759	0.0098	0.04	54.3	4577.63	12	2	14	0.3	
3_ch	Plug3_P_75_250304	14.36	38.33	21.1200	0.0148	0.06	49.7	4553.65	12	3	15	0.3	
4	Plug4_P_75_180304	9.86	39.40	20.6345	0.0206	0.08	53.2	4967.54	13	5	18	0.4	
4_ch	Plug4_P_75_010404	9.86	39.40	20.5346	0.0340	0.13	47.7	5030.90	13	8	21	0.4	
6	Plug6_P_75_180304	19.15	38.62	22.3307	0.0175	0.06	88.5	4011.13	10	3	14	0.3	
8	Plug8_P_75_por_100304	20.64	39.38	22.4429	0.0168	0.05	91.0	4042.88	10	3	13	0.3	
8_ch	Plug8_P_75_070404	20.64	39.38	22.4446	0.0102	0.03	111.6	4042.17	10	2	12	0.3	
9	Plug9_P_75_190304	18.99	38.39	22.4840	0.0234	0.08	65.9	3924.27	10	4	14	0.4	
10	Plug10_P_75_190304	24.65	39.38	23.7650	0.0102	0.03	126.3	3560.11	9	2	11	0.3	
13	Plug13_P_75_110304	11.22	37.61	20.3345	0.0191	0.07	54.1	4928.26	13	5	18	0.4	
13_3p	Plug13_P_75_290304	11.22	37.61	20.3565	0.0232	0.07	52.1	4914.09	13	6	19	0.4	
13_3p	Plug13_P_125_290304	11.22	37.61	20.3147	0.0142	0.05	86.2	4941.08	13	3	17	0.3	Pconf 125 bar
13_3p	Plug13_P_200_290304	11.22	37.61	20.3199	0.0118	0.44	110.1	4937.70	13	3	16	0.3	Pconf 200 bar
14	Plug14_P_75_120304	6.82	35.86	19.7689	0.0139	0.05	45.3	5074.07	14	4	18	0.3	
14_ch	Plug14_P_75_310304	6.82	35.86	19.7541	0.0248	0.08	49.3	5084.72	14	6	21	0.4	
16	Plug16_P_75_250304	3.68	35.72	20.3027	0.0408	0.13	23.2	4699.53	13	9	23	0.5	
17	Plug17_P_75_260304	6.29	35.76	19.1743	0.0121	0.04	59.2	5524.85	15	3	19	0.3	
19	Plug19_P_75_170304	7.97	37.89	19.9417	0.0175	0.06	44.5	5234.62	14	5	18	0.4	
21	Plug21_P_75_230304	26.78	40.53	24.0006	0.0107	0.03	114.1	3587.62	9	2	10	0.3	
22	Plug22_P_75_230304	24.52	39.31	24.0313	0.0191	0.07	65.1	3469.73	9	3	12	0.3	
23	Plug23_P_75_240304	16.59	38.21	21.3768	0.0113	0.04	55.0	4404.68	12	2	14	0.3	
24	Plug24_P_75_240304	21.76	35.62	22.1627	0.0238	0.07	47.2	3764.95	11	4	15	0.4	
26	Plug26_P_75_240304	26.49	39.39	25.3903	0.0117	0.03	87.4	3104.36	8	1	9	0.3	
26_ch	Plug26_P_75_060404	26.49	39.39	24.9832	0.0135	0.04	92.4	3207.27	8	2	10	0.3	
31_3p	Plug31_P_75_300304	22.19	36.62	22.1700	0.0254	0.09	61.5	3867.87	11	4	15	0.4	
31_3p	Plug31_P_125_300304	22.19	36.62	22.0841	0.0100	0.03	100.3	3903.28	11	2	12	0.3	Pconf 125 bar
31_3p	Plug31_P_200_300304	22.19	36.62	21.9945	0.0099	0.03	118.5	3940.92	11	2	13	0.3	Pconf 200 bar
32	Plug32_P_75_260304	7.17	38.49	20.6430	0.0214	0.07	29.0	4846.66	13	5	18	0.4	
32_ch	Plug32_P_75_060404	7.17	38.49	20.6234	0.0103	0.03	37.1	4858.65	13	2	15	0.3	
Rigs213	Rigs213_P_75_150304	20.34	24.75	18.4430	0.0271	0.07	50.7	4311.90	17	6	24	0.6	Por from GEUS rap. 2002/23

Table A.2. Basic data, results, and precision of ultrasonic measurements.
Ultrasonic S1 signals, samples measured in humidity dried state, 60 °C, 40 % relative humidity

Sample id.	File id.	Reduced porosity (%)	Reduced length (mm)	First arrival of S1 signal (us)	Local un-certainty (us)	Global un-certainty	Ampli-tude at pick (mV)	S1 velocity (m/s)	Error on velocity from length (m/s)	Error on velocity from noise (m/s)	Total error (m/s)	Total error (%)	Comment
1	Plug1_S1_75_por_080304	14.28	38.37	39.3545	0.0120	0.07	-172.5	2445.42	6	1	7	0.3	
1_ch	Plug1_S1_75_310304	14.28	38.37	39.0444	0.0138	0.03	-350.4	2494.73	7	1	7	0.3	
2	Plug2_S1_75_por_100304	8.93	38.33	41.9183	0.1331	0.88	-56.2	#I/T	#I/T	#I/T	#I/T	#I/T	S1 signal not useful
2_ch	Plug2_S1_75_010404	8.93	38.33	39.0736	0.0246	0.06	-266.2	2487.63	6	2	8	0.3	
3	Plug3_S1_75_por_110304	14.36	38.33	28.2630	0.1381	0.88	-8.4	#I/T	#I/T	#I/T	#I/T	#I/T	S1 signal not useful
3_ch	Plug3_S1_75_250304	14.36	38.33	37.9150	0.0122	0.03	-200.3	2689.62	7	1	8	0.3	
4	Plug4_S1_75_180304	9.86	39.40	37.2449	0.0160	0.04	-202.4	2901.28	7	1	9	0.3	
4_ch	Plug4_S1_75_010404	9.86	39.40	37.0294	0.0215	0.07	-184.0	2948.05	7	2	9	0.3	
6	Plug6_S1_75_180304	19.15	38.62	39.5157	0.0134	0.03	-355.7	2436.30	6	1	7	0.3	
8	Plug8_S1_75_por_100304	20.64	39.38	39.9445	0.0238	0.09	-332.4	2418.77	6	1	8	0.3	
8_ch	Plug8_S1_75_070404	20.64	39.38	39.8733	0.0129	0.03	-366.9	2429.39	6	1	7	0.3	
9	Plug9_S1_75_190304	18.99	38.39	39.8232	0.0174	0.04	-254.1	2375.41	6	1	7	0.3	
10	Plug10_S1_75_190304	24.65	39.38	41.8734	0.0152	0.05	-416.3	2162.80	5	1	6	0.3	
13	Plug13_S1_75_110304	11.22	37.61	27.0122	0.1912	0.78	-4.2	#I/T	#I/T	#I/T	#I/T	#I/T	S1 signal not useful
13_3p	Plug13_S1_75_290304	11.22	37.61	36.5115	0.0209	0.06	-209.2	2927.56	8	2	9	0.3	
13_3p	Plug13_S1_125_290304	11.22	37.61	36.4650	0.0149	0.04	-315.9	2938.20	8	1	9	0.3	Pconf 125 bar
13_3p	Plug13_S1_200_290304	11.22	37.61	36.4669	0.0168	0.04	-375.6	2937.76	8	1	9	0.3	Pconf 200 bar
14	Plug14_S1_75_120304	6.82	35.86	32.1044	0.1536	0.93	-30.6	#I/T	#I/T	#I/T	#I/T	#I/T	S1 signal not useful
14_ch	Plug14_S1_75_310304	6.82	35.86	35.4448	0.0199	0.08	-220.5	3043.50	8	2	10	0.3	
16	Plug16_S1_75_250304	3.68	35.72	36.5120	0.0304	0.07	-60.2	2779.95	8	2	10	0.4	
17	Plug17_S1_75_260304	6.29	35.76	35.2946	0.0268	0.13	-242.3	3074.23	9	2	11	0.4	
19	Plug19_S1_75_170304	7.97	37.89	36.3446	0.0096	0.02	-192.4	2988.33	8	1	9	0.3	
21	Plug21_S1_75_230304	26.78	40.53	42.2587	0.0328	0.04	-134.1	2179.81	5	2	7	0.3	
22	Plug22_S1_75_230304	24.52	39.31	41.7885	0.0112	0.03	-232.1	2168.74	6	1	6	0.3	
23	Plug23_S1_75_240304	16.59	38.21	38.1290	0.0172	0.04	-226.0	2641.34	7	1	8	0.3	
24	Plug24_S1_75_240304	21.76	35.62	39.0902	0.0213	0.04	-215.9	2308.84	6	1	8	0.3	
26	Plug26_S1_75_240304	26.49	39.39	42.8038	0.0139	0.03	-318.6	2057.86	5	1	6	0.3	
26_ch	Plug26_S1_75_060404	26.49	39.39	42.2983	0.0146	0.04	-345.6	2113.69	5	1	6	0.3	
31_3p	Plug31_S1_75_300304	22.19	36.62	39.3914	0.0222	0.08	-220.1	2328.33	6	1	8	0.3	
31_3p	Plug31_S1_125_300304	22.19	36.62	39.2603	0.0213	0.05	-300.5	2347.90	6	1	8	0.3	Pconf 125 bar
31_3p	Plug31_S1_200_300304	22.19	36.62	39.1804	0.0192	0.05	-329.0	2359.99	6	1	8	0.3	Pconf 200 bar
32	Plug32_S1_75_260304	7.17	38.49	37.3536	0.0282	0.07	-129.8	2811.21	7	2	9	0.3	
32_ch	Plug32_S1_75_060404	7.17	38.49	37.1127	0.0279	0.06	-154.3	2861.57	7	2	10	0.3	
Rigs213	Rigs213_S1_75_150304	20.34	24.75	33.2310	0.0407	0.23	-141.0	2587.22	10	3	14	0.5	Por from GEUS rap. 2002/23

Table A.3. Basic data, results, and precision of ultrasonic measurements.
Ultrasonic S2 signals, samples measured in humidity dried state, 60 °C, 40 % relative humidity

Sample id.	File id.	Reduced porosity (%)	Reduced length (mm)	First arrival of S2 signal (us)	Local un-certainty (us)	Global un-certainty	Ampli-tude at pick (mV)	S2 velocity (m/s)	Error on velocity from length (m/s)	Error on velocity from noise (m/s)	Total error (m/s)	Total error (%)	Comment
1	Plug1_S2_75_por_080304	14.28	38.37	40.0421	0.0103	0.02	-226.4	2436.51	6	1	7	0.3	
1_ch	Plug1_S2_75_310304	14.28	38.37	39.7056	0.0146	0.04	-215.8	2489.71	6	1	7	0.3	
2	Plug2_S2_75_por_100304	8.93	38.33	41.9227	0.1333	0.92	-56.2	#I/T	#I/T	#I/T	#I/T	#I/T	S2 signal not useful
2_ch	Plug2_S2_75_010404	8.93	38.33	39.7248	0.0257	0.05	-150.2	2484.25	6	2	8	0.3	
3	Plug3_S2_75_por_110304	14.36	38.33	28.2713	0.1382	0.90	-8.5	#I/T	#I/T	#I/T	#I/T	#I/T	S2 signal not useful
3_ch	Plug3_S2_75_250304	14.36	38.33	38.5741	0.0258	0.09	-95.1	2684.18	7	2	9	0.3	
4	Plug4_S2_75_180304	9.86	39.40	37.9310	0.0157	0.04	-132.1	2889.39	7	1	9	0.3	
4_ch	Plug4_S2_75_010404	9.86	39.40	37.7385	0.0150	0.03	-124.0	2930.76	7	1	9	0.3	
6	Plug6_S2_75_180304	19.15	38.62	40.1745	0.0130	0.03	-190.4	2431.91	6	1	7	0.3	
8	Plug8_S2_75_por_100304	20.64	39.38	40.5449	0.0120	0.03	-232.6	2423.21	6	1	7	0.3	
8_ch	Plug8_S2_75_070404	20.64	39.38	40.5449	0.0129	0.03	-240.0	2423.21	6	1	7	0.3	
9	Plug9_S2_75_190304	18.99	38.39	40.4323	0.0099	0.02	-142.1	2378.52	6	1	7	0.3	
10	Plug10_S2_75_190304	24.65	39.38	42.5406	0.0133	0.03	-242.0	2158.41	5	1	6	0.3	
13	Plug13_S2_75_110304	11.22	37.61	27.0486	0.1706	0.75	-4.5	#I/T	#I/T	#I/T	#I/T	#I/T	S2 signal not useful
13_3p	Plug13_S2_75_290304	11.22	37.61	37.1537	0.0175	0.04	-106.1	2924.84	8	1	9	0.3	
13_3p	Plug13_S2_125_290304	11.22	37.61	37.1194	0.0113	0.03	-165.6	2932.66	8	1	9	0.3	Pconf 125 bar
13_3p	Plug13_S2_200_290304	11.22	37.61	37.1215	0.0156	0.04	-203.4	2932.18	8	1	9	0.3	Pconf 200 bar
14	Plug14_S2_75_120304	6.82	35.86	32.0831	0.1476	0.90	-30.9	#I/T	#I/T	#I/T	#I/T	#I/T	S2 signal not useful
14_ch	Plug14_S2_75_310304	6.82	35.86	36.0718	0.0296	0.07	-132.9	3044.33	8	2	11	0.4	
16	Plug16_S2_75_250304	3.68	35.72	37.0937	0.0102	0.02	-123.3	2790.49	8	1	9	0.3	
17	Plug17_S2_75_260304	6.29	35.76	35.9543	0.0225	0.08	-176.7	3066.46	9	2	10	0.3	
19	Plug19_S2_75_170304	7.97	37.89	36.9785	0.0275	0.08	-110.0	2987.47	8	2	10	0.3	
21	Plug21_S2_75_230304	26.78	40.53	42.8440	0.0121	0.03	-400.4	2185.08	5	1	6	0.3	
22	Plug22_S2_75_230304	24.52	39.31	42.5031	0.0121	0.03	-158.2	2158.69	5	1	6	0.3	
23	Plug23_S2_75_240304	16.59	38.21	38.7938	0.0254	0.05	-120.4	2635.04	7	2	9	0.3	
24	Plug24_S2_75_240304	21.76	35.62	39.7326	0.0175	0.04	-144.1	2307.02	6	1	7	0.3	
26	Plug26_S2_75_240304	26.49	39.39	43.4808	0.0151	0.03	-207.4	2052.85	5	1	6	0.3	
26_ch	Plug26_S2_75_060404	26.49	39.39	42.9747	0.0137	0.03	-210.3	2108.46	5	1	6	0.3	
31_3p	Plug31_S2_75_300304	22.19	36.62	39.8932	0.0179	0.04	-173.2	2347.50	6	1	7	0.3	
31_3p	Plug31_S2_125_300304	22.19	36.62	39.7969	0.0132	0.03	-245.0	2362.08	6	1	7	0.3	Pconf 125 bar
31_3p	Plug31_S2_200_300304	22.19	36.62	39.7136	0.0119	0.03	-270.6	2374.84	6	1	7	0.3	Pconf 200 bar
32	Plug32_S2_75_260304	7.17	38.49	37.9648	0.0393	0.12	-78.0	2815.12	7	3	10	0.4	
32_ch	Plug32_S2_75_060404	7.17	38.49	37.7544	0.0298	0.11	-83.2	2859.12	7	2	10	0.3	
Rigs213	Rigs213_S2_75_150304	20.34	24.75	33.9878	0.0461	0.09	-61.0	2553.44	10	3	14	0.5	Por from GEUS rap. 2002/23

Table A.4. Basic data, results, and precision of ultrasonic measurements – Samples measured in S_W=100 % state.
Ultrasonic P signals, samples measured in S_W=100 % state.

Sample id.	File id.	Reduced porosity (%)	Reduced length (mm)	First arrival of P signal (us)	Local un-certainty (us)	Global un-certainty	Ampli-tude at pick (mV)	P velocity (m/s)	Error on velocity from length (m/s)	Error on velocity from noise (m/s)	Total error (m/s)	Total error (%)	Comment
1	Plug1_maet_P_75_180504	14.28	38.37	22.6586	0.0168	0.05	53.1	3863.42	10	3	13	0.3	
2	Plug2_maet_P_75_180504	8.93	38.33	22.2529	0.0189	0.05	64.1	4024.12	10	3	14	0.3	
2_ch	Plug2ch_maet_P_75_210604	8.93	38.33	22.3685	0.0210	0.06	60.2	3978.00	10	4	14	0.4	
3	Plug3_maet_P_75_210404	14.36	38.33	21.2779	0.0108	0.03	86.1	4469.80	12	2	14	0.3	
4	Plug4_maet_P_75_190504	9.86	39.40	20.6329	0.0102	0.03	156.7	4983.85	13	2	15	0.3	
6	Plug6_maet_P_75_210404	19.15	38.62	22.1142	0.0110	0.03	124.1	4103.39	11	2	13	0.3	
6_ch	Plug6ch_maet_P_75_300604	19.15	38.62	22.1218	0.0116	0.04	134.7	4107.96	11	2	13	0.3	
8	Plug8_maet_P_75_190504	20.64	39.38	22.3045	0.0107	0.03	156.5	4111.58	10	2	12	0.3	
9	Plug9_maet_P_75_220404	18.99	38.39	22.3607	0.0118	0.03	122.1	3974.37	10	2	12	0.3	
10	Plug10_maet_P_75_220404	24.65	39.38	23.5817	0.0112	0.03	138.7	3620.09	9	2	11	0.3	
13	Plug13_maet_P_75_210504	11.22	37.61	20.4149	0.0098	0.03	174.8	4892.34	13	2	15	0.3	
14	Plug14_maet_P_75_210504	6.82	35.86	19.7249	0.0105	0.04	144.0	5123.64	14	3	17	0.3	
14_ch	Plug14ch_maet_P_75_220604	6.82	35.86	19.7425	0.0126	0.05	141.2	5114.55	14	3	18	0.3	
16	Plug16_maet_P_75_240504	3.68	35.72	20.0916	0.0138	0.04	84.0	4849.78	14	3	17	0.3	
17	Plug17_maet_P_75_240504	6.29	35.76	19.2317	0.0115	0.04	162.4	5496.79	15	3	19	0.3	
17_ch	Plug17ch_maet_P_75_220604	6.29	35.76	19.2347	0.0123	0.04	162.1	5498.62	15	4	19	0.3	
19	Plug19_maet_P_75_120504	7.97	37.89	19.9750	0.0112	0.04	154.4	5228.16	14	3	17	0.3	
21	Plug21_maet_P_75_120504	26.78	40.53	24.4040	0.0121	0.04	102.3	3471.16	9	2	10	0.3	
22	Plug22_maet_P_75_130504	24.52	39.31	24.2035	0.0174	0.05	72.1	3425.03	9	2	11	0.3	
23	Plug23_maet_P_75_130504	16.59	38.21	21.5732	0.0104	0.04	129.4	4319.03	11	2	13	0.3	
24	Plug24_maet_P_75_170504	21.76	35.62	22.1400	0.0119	0.04	104.2	3783.77	11	2	13	0.3	
26	Plug26_maet_P_75_250504	26.49	39.39	25.0928	0.0123	0.04	59.1	3185.16	8	2	10	0.3	
31	Plug31_maet_P_75_170504	22.19	36.62	22.3940	0.0161	0.05	62.1	3787.99	10	3	13	0.3	
31_ch	Plug31ch_maet_P_75_230604	22.19	36.62	22.3023	0.0198	0.07	75.3	3826.33	10	3	14	0.4	Fracture taped
32	Plug32_maet_P_75_260504	7.17	38.49	20.6949	0.0136	0.04	91.1	4829.91	13	3	16	0.3	
32_ch	Plug32ch_maet_P_75_230604	7.17	38.49	20.6927	0.0138	0.05	96.0	4834.38	13	3	16	0.3	
Rigs213	Rigs213_maet_P_75_050404	20.34	24.75	18.3121	0.0169	0.05	58.4	4412.52	18	4	22	0.5	Por from GEUS rap. 2002/23
Rigs220	Rigs220_*_75_maet_190404	31.51	27.87	21.0341	0.0113	0.03	132.2	3344.61	12	2	14	0.4	Por from GEUS rap. 2000/19

Table A.5. Basic data, results, and precision of ultrasonic measurements.
Ultrasonic S1 signals, samples measured in S_W=100 % state.

Sample id.	File id.	Reduced porosity (%)	Reduced length (mm)	First arrival of S1 signal (us)	Local uncertainty (us)	Global uncertainty	Amplitude at pick (mV)	S1 velocity (m/s)	Error on velocity from length (m/s)	Error on velocity from noise (m/s)	Error on velocity Total error (m/s)	Error on velocity Total error (%)	Comment
1	Plug1_maet_S1_75_180504	14.28	38.37	42.8202	0.0327	0.10	-53.6	2007.58	5	2	7	0.3	
2	Plug2_maet_S1_75_180504	8.93	38.33	34.6097	0.0875	0.57	-6.8	#I/T	#I/T	#I/T	#I/T	#I/T	
2_ch	Plug2ch_maet_S1_75_210604	8.93	38.33	34.7631	0.1140	0.83	-6.4	#I/T	#I/T	#I/T	#I/T	#I/T	
3	Plug3_maet_S1_75_210404	14.36	38.33	39.2227	0.0235	0.08	-146.2	2463.57	6	1	8	0.3	
4	Plug4_maet_S1_75_190504	9.86	39.40	38.0003	0.0266	0.06	-176.0	2756.79	7	2	9	0.3	
6	Plug6_maet_S1_75_210404	19.15	38.62	40.7650	0.0178	0.05	-322.7	2258.32	6	1	7	0.3	
6_ch	Plug6ch_maet_S1_75_300604	19.15	38.62	40.6620	0.0195	0.06	-330.1	2270.67	6	1	7	0.3	
8	Plug8_maet_S1_75_190504	20.64	39.38	41.1078	0.0202	0.05	-315.1	2263.13	6	1	7	0.3	
9	Plug9_maet_S1_75_220404	18.99	38.39	41.2741	0.0313	0.10	-190.3	2179.71	6	2	7	0.3	
10	Plug10_maet_S1_75_220404	24.65	39.38	43.8583	0.0166	0.04	-293.4	1950.22	5	1	6	0.3	
13	Plug13_maet_S1_75_210504	11.22	37.61	37.1542	0.0363	0.09	-173.9	2797.13	7	3	10	0.4	
14	Plug14_maet_S1_75_210504	6.82	35.86	31.9467	0.3842	0.90	-9.0	#I/T	#I/T	#I/T	#I/T	#I/T	
14_ch	Plug14ch_maet_S1_75_220604	6.82	35.86	26.2088	0.2198	0.98	-5.6	#I/T	#I/T	#I/T	#I/T	#I/T	
16	Plug16_maet_S1_75_240504	3.68	35.72	26.5214	0.1643	0.69	-6.5	#I/T	#I/T	#I/T	#I/T	#I/T	
17	Plug17_maet_S1_75_240504	6.29	35.76	35.7608	0.4159	0.96	-20.9	2966.45	8	35	43	1.4	
17_ch	Plug17ch_maet_S1_75_220604	6.29	35.76	35.8048	0.2503	0.66	-31.5	2957.57	8	21	29	1.0	
19	Plug19_maet_S1_75_120504	7.97	37.89	37.0592	0.0508	0.13	-116.6	2838.16	7	4	11	0.4	
21	Plug21_maet_S1_75_120504	26.78	40.53	45.4323	0.0235	0.07	-200.3	1865.75	5	1	6	0.3	
22	Plug22_maet_S1_75_130504	24.52	39.31	45.1971	0.0255	0.04	-109.7	1829.15	5	1	6	0.3	
23	Plug23_maet_S1_75_130504	16.59	38.21	39.4135	0.0348	0.12	-168.9	2432.66	6	2	9	0.4	
24	Plug24_maet_S1_75_170504	21.76	35.62	40.9749	0.0247	0.09	-208.5	2062.67	6	1	7	0.3	
26	Plug26_maet_S1_75_250504	26.49	39.39	46.1373	0.0259	0.05	-103.2	1756.03	4	1	5	0.3	
31	Plug31_maet_S1_75_170504	22.19	36.62	41.5978	0.0233	0.04	-190.2	2046.86	6	1	7	0.3	
31_ch	Plug31ch_maet_S1_75_230604	22.19	36.62	41.4125	0.0229	0.08	-196.1	2069.20	6	1	7	0.3	Fracture taped
32	Plug32_maet_S1_75_260504	7.17	38.49	40.6600	0.1271	0.88	-22.1	#I/T	#I/T	#I/T	#I/T	#I/T	
32_ch	Plug32ch_maet_S1_75_230604	7.17	38.49	27.1873	0.1079	0.94	-5.6	#I/T	#I/T	#I/T	#I/T	#I/T	
Rigs213	Rigs213_maet_S1_75_050404	20.34	24.75	33.6487	0.0840	0.45	-78.1	2478.99	10	6	16	0.7	Por from GEUS rap. 2002/23
Rigs220	Rigs220_*_75_maet_190404	31.51	27.87	38.8089	0.0164	0.04	-307.9	1839.94	7	1	7	0.4	Por from GEUS rap. 2000/19

Table A.6. Basic data, results, and precision of ultrasonic measurements.
Ultrasonic S2 signals, samples measured in S_W=100 % state.

Sample id.	File id.	Reduced porosity (%)	Reduced length (mm)	First arrival of S2 signal (us)	Local un-certainty (us)	Global un-certainty	Ampli-tude at pick (mV)	S2 velocity (m/s)	Error on velocity from length (m/s)	Error on velocity from noise (m/s)	Error on velocity Total error (m/s)	Error on velocity Total error (%)	Comment
1	Plug1_maet_S2_75_180504	14.28	38.37	43.3631	0.0294	0.10	-27.0	2015.37	5	1	7	0.3	
2	Plug2_maet_S2_75_180504	8.93	38.33	35.1484	0.0419	0.88	-4.1	#I/T	#I/T	#I/T	#I/T	#I/T	
2_ch	Plug2ch_maet_S2_75_210604	8.93	38.33	35.3396	0.0413	1.00	-3.6	#I/T	#I/T	#I/T	#I/T	#I/T	
3	Plug3_maet_S2_75_210404	14.36	38.33	39.7646	0.0180	0.06	-92.1	2477.63	6	1	8	0.3	
4	Plug4_maet_S2_75_190504	9.86	39.40	38.6977	0.0180	0.04	-104.2	2741.32	7	1	8	0.3	
6	Plug6_maet_S2_75_210404	19.15	38.62	41.3922	0.0117	0.02	-163.7	2258.72	6	1	6	0.3	
6_ch	Plug6ch_maet_S2_75_300604	19.15	38.62	41.3148	0.0114	0.02	-172.5	2271.85	6	1	7	0.3	
8	Plug8_maet_S2_75_190504	20.64	39.38	41.7812	0.0151	0.03	-207.8	2255.78	6	1	7	0.3	
9	Plug9_maet_S2_75_220404	18.99	38.39	42.0140	0.0186	0.05	-134.3	2166.21	6	1	7	0.3	
10	Plug10_maet_S2_75_220404	24.65	39.38	44.4627	0.0114	0.02	-222.4	1952.72	5	1	5	0.3	
13	Plug13_maet_S2_75_210504	11.22	37.61	37.7768	0.0290	0.09	-132.0	2795.91	7	2	10	0.3	
14	Plug14_maet_S2_75_210504	6.82	35.86	38.9373	0.1257	0.62	-26.1	#I/T	#I/T	#I/T	#I/T	#I/T	
14_ch	Plug14ch_maet_S2_75_220604	6.82	35.86	38.8756	0.1199	0.74	-18.2	#I/T	#I/T	#I/T	#I/T	#I/T	
16	Plug16_maet_S2_75_240504	3.68	35.72	33.0051	0.1148	0.89	-6.0	#I/T	#I/T	#I/T	#I/T	#I/T	
17	Plug17_maet_S2_75_240504	6.29	35.76	36.4754	0.1334	0.44	-23.0	2942.55	8	11	19	0.6	
17_ch	Plug17ch_maet_S2_75_220604	6.29	35.76	36.4549	0.1185	0.69	-25.0	2952.57	8	10	18	0.6	
19	Plug19_maet_S2_75_120504	7.97	37.89	37.7245	0.0317	0.08	-72.4	2827.87	7	2	10	0.3	
21	Plug21_maet_S2_75_120504	26.78	40.53	46.0743	0.0249	0.05	-98.2	1863.59	5	1	6	0.3	
22	Plug22_maet_S2_75_130504	24.52	39.31	45.8802	0.0226	0.04	-72.1	1823.52	5	1	6	0.3	
23	Plug23_maet_S2_75_130504	16.59	38.21	40.1347	0.0201	0.05	-96.3	2416.59	6	1	8	0.3	
24	Plug24_maet_S2_75_170504	21.76	35.62	41.5405	0.0243	0.07	-111.0	2068.80	6	1	7	0.3	
26	Plug26_maet_S2_75_250504	26.49	39.39	46.8242	0.0183	0.03	-86.1	1750.55	4	1	5	0.3	
31	Plug31_maet_S2_75_170504	22.19	36.62	42.0833	0.0174	0.04	-120.2	2061.98	6	1	6	0.3	
31_ch	Plug31ch_maet_S2_75_230604	22.19	36.62	41.9336	0.0190	0.04	-134.3	2081.96	6	1	7	0.3	Fracture taped
32	Plug32_maet_S2_75_260504	7.17	38.49	39.1388	0.3223	0.00	-4.6	2597.76	7	21	28	1.1	
32_ch	Plug32ch_maet_S2_75_230604	7.17	38.49	39.2578	0.0890	0.71	-4.7	2580.64	7	6	13	0.5	
Rigs213	Rigs213_maet_S2_75_050404	20.34	24.75	34.2600	0.0668	0.16	-43.8	2483.70	10	5	15	0.6	Por from GEUS rap. 2002/23
Rigs220	Rigs220_*_75_maet_190404	31.51	27.87	39.4828	0.0226	0.05	-136.3	1834.64	7	1	8	0.4	Por from GEUS rap. 2000/19