DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2008/71

Special core analysis for Hess Denmark South Arne Field

Permeability study on a set of reference core samples

Niels Springer & Hans Lorentzen

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

GEUS

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Contents

Enclosure: **- Data on CD-ROM**

Req. no.: 09201-571
File: SA_permrep.doc
SA_oilperm.xls

1. Introduction

At the request of Hess Denmark ApS, GEUS Core Laboratory has performed special core analysis (SCAL) on a set of reference core samples from the South Arne Field, Danish North Sea.

The experimental programme was specified in e-mail communications with Mr. Søren Christensen during January 2008. The plug samples, covering most previous cored wells in the South Arne field, had been analyzed earlier in electrical resistivity studies performed for Hess DK in 2005 and 2007. The following analytical programme was finally agreed on:

- Determination of gas and Klinkenberg corrected gas permeability at standard conditions
- Endpoint oil permeability at overburden conditions
- Electrical resistivity check measurements
- End trims for specific surface area analysis (by DTU Environment)

Preliminary data have been reported at regular intervals to Hess DK by e-mail comm. during the period April 2008 to October 2008. End trims were sent to DTU Environment after completion of the SCAL study.

2 Sampling and analytical procedures

The present permeability study includes 26 plug samples taken from the wells Rigs-1, Rigs-2/2A, Rigs-3, SA-1 and Baron-2. All samples are 1½" (38 mm) diameter plugs that have been used in previous SCAL studies for Hess DK. They represent chalk from the 3 chalk formations Ekofisk, Tor and Hod in the South Arne Field, table 2.1.

2.1 Plug quality screening

Please refer to the previous SCAL reports for X-ray CT-screening images [1, 2]

2.2 Preparation

The plugs were subjected to a short term hot Soxhlet cleaning in methanol and a light re-trimming to remove possible damage to plug ends from the earlier SCAL testing. A few plugs had fractured during the earlier testing and needed a serious trim. Therefore the plug bulk volume and dry weight does not align completely with data found in the previous reports.

2.3 Gas permeability

After drying at 110 ºC the samples were measured for conventional gas permeability and Klinkenberg corrected gas permeability at 400 psi (2.8 MPa) confining sleeve pressure. Results are listed in section 5.

2.4 Endpoint oil permeability

Samples were vacuum and pressure saturated in simulated formation brine for a week, table 2.2, and left to equilibrate in brine under a slight vacuum in an anaerobic jar for several weeks before flooding down started. An Archimedes test was conducted to check material balance. The samples were then installed in single core holders (resistivity cells) @ 145 psi hydrostatic confining pressure. The core holders were placed in an overburden rig in a temperature controlled room, and the confining pressure was next increased to 1200 psi [8.2 MPa] during a period of 1 hour. The plug resistivity was measured. The upstream line was filled with laboratory oil and oil flooding down started at an upstream pressure of 100-400 psi depending on chalk type and porosity. A water collection tube was installed in the downstream line as a control on water saturation in the plug sample during flooding down.

In general more than 20 PV's of oil was flooded through the samples, but for some very low permeability plugs less than 5 PV's were collected due to time constraints. The liquid permeability to oil K_o @ S_{wi} was measured and the oil phase pressure was then decreased. When stable flow and pressure conditions had been re-established a second reading of the endpoint oil permeability was obtained. This was done to assure consistent permeability determination. For a number of plugs much lower oil phase pressures than the original flooding down pressure had to be used before stable readings of permeability was observed. Liquid flow was now stopped and the samples left until the next day when a final resistivity reading was taken. The core holder was then dismantled and the plug transferred to Dean Stark extraction to determine the final S_{wi}. Results are presented in section 5.

[1] Springer, Niels: Special core analysis for Amerada Hess Denmark. South Arne Field. Electrical properties. Danmarks og Grønlands Geologiske Undersøgelse, Confidential Report nr. 24, 2005.

[2] Springer, Niels: Special core analysis for Hess Denmark. Well: Rigs-3: Electrical properties and permeability at overburden stress conditions. Danmarks og Grønlands Geologiske Undersøgelse, Confidential Report nr. 85, 2007 .

Table 2.1. SA permeability study; list of 26 reference plugs selected from 3 chalk formations in the South Arne oilfield and used in the present permeability survey. 'P' in the plug number indicates a former preserved plug, and 'A' is an additional plug taken before the SA resistivity study in 2005. The remaining plugs are routine plugs from the subject wells that were drilled between 1995 and 2006 by Amerada Hess DK, except Baron-2 that was originally drilled by Norsk Hydro in 1991.

Well	Formation	Plug #	Depth [m]
Rigs-2	Ekofisk	20	2801.50
Rigs-2		33	2805.10
Rigs-2		34	2805.30
Rigs-1		119	2806.09
SA-1		513P	3319.60
SA-1		528P	3329.60
SA-1		58A	3332.17
Rigs-3	Tor	13	3035.10
Rigs-3		39	3043.77
Rigs-3		41	3044.51
Rigs-3		74	3055.45
Rigs-3		82	3058.15
Rigs-2		132	2834.70
Rigs-2		211	2856.70
Rigs-1		214	2831.03
Rigs-1		258	2842.05
Rigs-2A		281	2974.70
Rigs-1		283	2848.57
SA-1		562P	3381.55
SA-1		580P	3390.35
SA-1		592P	3396.60
SA-1		603P	3403.55
Baron-2A	Hod	82P	2901.10
Baron-2A		83P	2902.10
Baron-2A		90P	2909.10
Baron-2A		101P	2920.13

Table 2.2. South Arne simulated formation water analysis. Measured physical properties for the formation water as well as the Light Liquid Paraffin oil used in the study appear below.

Subject brine: Syd Arne formation brine

Element	Concentration mg/L	Compound	Gram compound per 1 liter	3 liter	5 liter
Na total	32930				
Na+	32930	NaCl	83.707	251.122	418.54
Na+	0	NaHCO3	0.000	0.000	0.00
K+	522	KCl	0.995	2.986	4.98
Mg2+	665	MgCl2, 6H2O	5.561	16.683	27.81
Ca2+		CaCl2	0.000	0.000	0.00
Ca2+	5667	CaCl2, 2H2O	20.787	62.362	103.94
Sr2+	0	SrCl2, 6H2O	0.000	0.000	0.00
Ba2+		BaCl2, 2H2O	0.000	0.000	0.000
Cl-	63220				
HCO3-	0.0				

TDS:	**103004**	**mg/L**	~1.763 mol/L NaCl eqv.
pH:		**@ 23 C**	

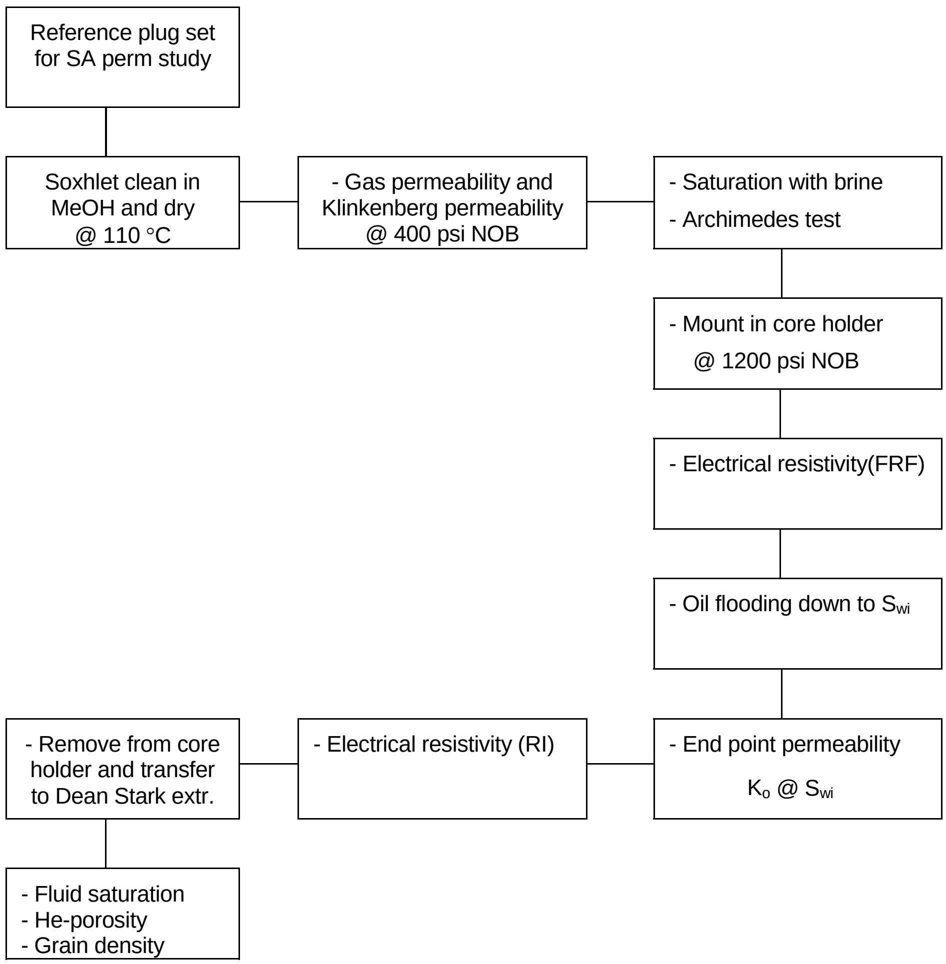
Comments: Slightly modified compared to the brine used in the 2005 study

Physical data:	**Resistivity Rw :**	**0.075**	**ohmm @ 25.0 ºC**
	Calculated Rw :	**0.074**	**ohmm @ 25.0 ºC**
	Density dw :	**1.068**	**g/cc @ 25.0 ºC**
	Calculated dw :	**1.066**	**g/cc @ 25.0 ºC**
	Viscosity:	**1.14**	**cP @ 25 ºC**

Lab oil: Isopar-L ™	**Density do :**	**0.764**	**g/cc @ 25.0 ºC**
	Viscosity:	**1.30**	**cP @ 25 ºC**
	IFT : *	**50-60**	**mN/m @ 25 ºC**

* in a lab oil-brine system

3 Flow diagram of the analytical procedures



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, 2nd ed. 1998).

4.1 Gas permeability

The plug is mounted in a Hassler core holder, and a confining pressure of 400 psi (28 barg) 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 [barg]. No back pressure is applied. The readings of the digital gas permeameter are checked regularly by measurement of permeable steel reference plugs.

4.2 Klinkenberg permeability

The Klinkenberg corrected gas permeability, sometimes termed the equivalent liquid permeability, is calculated from gas permeability measurements performed at 3 different mean pressures in the plug sample. The plug is mounted in a Hassler core holder, and a confining pressure of 400 psi (28 barg) is applied to the sleeve. Nitrogen gas pressures of 2, 4 and 7 [barg] (3, 5 and 8 [bara]) are applied at the upstream end of the plug, and the downstream pressure is regulated until a suitable flow is obtained. The differential pressure is kept approx. constant in order to maintain a similar flow regime during the 3 measurements. When a steady state is reached, the upstream pressure, the differential pressure across the plug and the flow reading is recorded. A linear regression of permeability on inverse mean pressure is performed for the 3 measurements, and the intercept on the permeability axis is the Klinkenberg corrected gas permeability.

Klinkenberg corrected gas permeabilities are only reported down to approx. 0.1 mD on normal routine terms. However, on request measurements can be carried out to a lower limit of 0.01 mD. The performance of the digital gas permeameter is checked regularly by measurements of permeable steel reference plugs.

Instrumental: GEUS digital gas permeameter M 1989 is a steady-state instrument using nitrogen as the measuring gas. It is designed and built by the laboratory. The instrument is equipped with Druck Ltd.® pressure transducer and Brooks Instruments® thermal mass flowmeters; for all flowrates a facility exist to measure gas flow downstream with a range of soap film flowmeters. This is used for calibration purpose or whenever the present flow rate is outside the limits of the thermal mass flowmeters.

4.3 Overburden measurements

The following field data were supplied by Amerada Hess DK:

Gross overburden pressure:	8260 psi
Reservoir pressure:	6260 psi
Net confining pressure:	2000 psi

which translates to a hydrostatic confing pressure of ~1200 psi as used in this study.

Overburden correction of porosity has been applied in line with previous measured data, re. reference to 2005 and 2007 studies given in section 2.

4.4 Liquid permeability

The plug is mounted in a hydrostatic core holder and a net confining pressure of 1200 psi (8.2 MPa) applied to the sleeve (in this study). The required LLP laboratory oil volumetric flow and pressure is delivered from a computer controlled pumping system that handles collection of all relevant data (Quizix SP 5000 system™). At least 2 different flowrate/differential pressure settings are recorded to secure a consistent determination of the liquid permeability. The laboratory oil has been de-aerated before use. Further details of the permeability measurement are given in section 2.

Assuming Darcy flow and Newtonian liquids, the following permeability equation is valid for axial flow in a cylindrical plug:

$$k_l = \frac{Q \times L \times \mu}{A \times \Delta p} \times C$$

Where k_l = liquid permeability at a specified saturation [mD]
Q = flow rate [mL/s]
L = plug length [cm]
A = plug area [cm^2]
Δp = differential pressure across the plug [atm]
C = a constant to convert to [mD]

Liquid permeability measurement may be combined with electrical measurements if a suitable core holder is used.

5 Results

Nomenclature

L	– sample length	[cm]
D	– sample diameter	[cm]
A	- sample area	[cm^2]
BV	– bulk volume	[cc]
PV	– pore volume	[cc]
Δ PV	– pore volume change	[ml]
GD	– grain density	[g/cc]
V	– volume	[ml]
Δ V	– volume change	[ml]
Ø,Φ	– porosity	[pct or frc]
S_w	- water saturation	[pct or frc]
S_{wf}	- final water saturation	[pct or frc]
$_i$	- Subscript for "initial"	
imp	- impedance	[ohm]
K_g	- gas permeability	[mD]
K_{el}	- Klinkenberg corrected gas permeability	[mD]
K_o	- oil permeability	[mD]

F or FRF	– formation resistivity factor	
F*	- intrinsic formation factor	
RI	– resistivity index	
m	– cementation exponent	
m*	- intrinsic porosity exponent	
n	– saturation exponent	
a	– Archie constant, or a dimensional correction factor in compressibility calculations	
R_o	- resistivity of water saturated sample	[Ω m]
R_w	- resistivity of formation water	[Ωm]
Z_o	- impedance of water saturated sample	[Ω]
Z_t	- impedance of sample at S_w < 1	[Ω]
nd/na	- not determined/analyzed	
WW_{calc}	- wet weight calculated from plug volume and core analysis data	[g]
WW_{meas}	- wet weight measured	[g]

5.1 Conventional core analysis

Table 5.1 below lists the routine core analysis data measured in the SA permeability study. The samples had previously been used in the SA Resistivity Study (2005) and a number of plugs needed a light end trim before being included in the present study. Therefore small deviations from the 2005 CCAL data may be observed for some plugs.

Table 5.1. SA permeability study; conventional gas and Klinkenberg gas permeability data (Nov. 2007 data) measured before the endpoint oil permeability study was initiated, and conventional porosity and grain density data measured after completion of the study (2008 data). A few samples having very low gas permeability could not be measured for Klinkenberg corrected gas permeability. Permeability was measured @ 400 psi confining sleeve pressure.

Sample ID	Depth [m]	Well ID	Gas Perm [mD]	Klink.Perm [mD]	Klink.Corr Coef.	Porosity [%]	Grain Dens [g/ccm]
Tor Fm data :							
132	2834.70	Rigs-2	6.14	3.636	0.995	43.32	2.706
211	2856.70	Rigs-2	4.28	2.491	0.995	38.73	2.701
214	2831.03	Rigs-1	0.50	0.208	0.995	19.64	2.713
258	2842.05	Rigs-1	2.92	1.564	1.000	34.58	2.708
281	2974.70	Rigs-2A	4.50	2.655	0.997	41.04	2.708
283	2848.57	Rigs-1	4.00	2.186	0.999	39.89	2.719
562P	3381.55	SA-1	0.97	0.456	0.999	27.12	2.711
580P	3390.35	SA-1	0.71	0.328	0.992	24.39	2.710
592P	3396.60	SA-1	1.15	0.562	0.999	28.37	2.712
603P	3403.55	SA-1	1.42	0.694	0.999	29.61	2.715
13	3035.10	Rigs-3	0.23	0.046	0.996	18.29	2.715
39	3043.77	Rigs-3	0.43	0.138	0.999	21.54	2.714
41	3044.51	Rigs-3	0.30	0.069	0.996	19.43	2.715
74	3055.45	Rigs-3	0.58	0.217	0.996	22.74	2.714
82	3058.15	Rigs-3	0.25	0.065	0.993	17.42	2.716
Ekofisk Fm data :							
20	2801.50	Rigs-2	1.15	0.439	0.999	35.50	2.686
33	2805.10	Rigs-2	1.73	0.772	0.998	39.23	2.689
34	2805.30	Rigs-2	2.40	1.288	0.977	42.73	2.691
119	2806.09	Rigs-1	0.83	0.331	0.997	31.40	2.700
58A	3332.17	SA-1	0.30	0.068	1.000	27.70	2.692
513P	3319.60	SA-1	0.24	0.028	0.996	28.38	2.707
528P	3329.60	SA-1	0.09	0.006	0.998	23.00	2.703
Hod Fm data :							
82P	2901.10	Baron-2A	0.06	~ 0		11.14	2.720
83P	2902.10	Baron-2A	0.03	~ 0		8.95	2.719
90P	2909.10	Baron-2A	0.24	0.037	0.990	24.07	2.717
101P	2920.13	Baron-2A	0.10	~ 0		19.14	2.707

5.2 Oil permeability at initial water saturation

Results are listed in the tables and diagrams below; additional raw data are included with the attached CD-ROM. "Best estimate" regression analysis data are listed in section 5.3. K_o @ S_{wi} in table 5.2 below is the mean value of two independent measurements of the oil permeability so far as they are reasonable alike. If it is suspected that Darcy flow conditions did not prevail in both measurements, the lowest differential pressure measurement was preferred. S_{wi} was calculated from flood down data and from Dean Stark extraction after test; the agreement is excellent for most samples. A preferred "best estimate" $S_{wi\ (avg.)}$ was calculated from the independent S_{wi} determinations with most confidence on the Dean Stark figure (weight 2:1).

Table 5.2. Endpoint oil permeability data and initial water saturations obtained in the SCAL study. $S_{wi\ (avg.)}$ is the preferred "best estimate" of the initial water saturation. An operator error ruined the flood down determination for the Hod Fm samples.

Plug no.	Depth	K_o @ Swi	Ø	Swi (Dean Stark)	Swi (Flood down)	Swi (avg.)
	[m]	[mD]	[%]	[%]	[%]	[%]
Tor Fm data :						
132	2834,70	1,599	43,2	16	19	17
211	2856,70	1,459	38,6	18	19	18
214	2831,03	0,095	19,4	34	40	36
258	2842,05	0,934	34,5	19	21	19
281	2974,70	1,525	40,7	14	16	15
283	2848,57	1,437	39,3	11	12	11
562P	3381,55	0,267	26,8	18	19	18
580P	3390,35	0,177	24,1	21	21	21
592P	3396,60	0,344	28,0	19	19	19
603P	3403,55	0,480	29,1	18	17	18
13	3035,10	0,042	18,1	21	23	22
39	3043,77	0,098	21,8	19	19	19
41	3044,51	0,055	19,1	21	19	20
74	3055,45	0,173	22,4	17	16	16
82	3058,15	0,051	17,2	22	20	21
Ekofisk Fm data :						
20	2801,50	0,239	35,5	33	34	33
33	2805,10	0,467	39,1	23	24	24
34	2805,30	0,785	42,7	22	22	22
119	2806,09	0,166	31,3	37	37	37
58A	3332,17	0,048	27,2	29	35	31
513P	3319,60	0,020	28,2	32	34	32
528P	3329,60	0,003	23,1	36	45	39
Hod Fm data :						
82P	2901,10	0,0013	11,0	30	nd	nd
83P	2902,10	0,0003	8,8	36	nd	nd
90P	2909,10	0,0293	23,8	31	nd	nd
101P	2920,13	0,0025	18,7	38	nd	nd

5.2.1 Resistivity check measurements

Electrical resistivity measurements for this set of plugs was reported in 2005 and the check measurements performed in the present study only serves to check if a homogeneous water saturation was obtained after oil flooding down. To do so, a resistivity index had to be measured after flooding down and therefore also an R_0 figure @ $S_w = 1$ before oil flooding down started. This (last) figure was measured immediately after the net 1200 psi stress had been applied to the plug, and no settling time (no creep) was allowed for. This causes the measured R_o figure to be lower than obtained in the 2005 study and therefore the calculated FRF and Archie 'm' figures to be lower as well. However, the similarity of the sample distributions in the 2005 and 2008 diagrams are striking.

A low R_0 figure will cause the calculated RI to be high compared with 2005 data, and that is also observed for the 2008 data. The resistivity index diagrams demonstrate a fairly linear distribution (not a curve) of plug data which points towards a likely homogeneous water distribution after flooding down to S_{wi} .

FRF and RI diagrams are not shown in the printed report. Reference is made to the spreadsheet on the attached CD-ROM that includes diagrams from the 2005 resistivity study for comparison.

Subject : Room condition data — **SA oil perm study**

Company : Hess DK — **GEUS Core Lab, 21.11.2008**

Tor Fm data :

Plug no.	Depth	CCAL data 2005			Data after careful plug trim and brine saturation 2008					Material balance data 2008		
	[m]	k_g [mD]	$Ø_{i(He)}$ [%]	GD [g/cc]	$L_{caliper}$ [cm]	Dry wt [g]	Wet wt [g]	$BV2_{(Arch)}$ [cc]	$PV2_{(Arch.)}$ [cc]	M_{grain} [g]	M_{fluid} [g]	$\cong M_{plug}$ [g]
Well: Rigs-1+2+2A												
132	2834.70	6.99	43.92	2.707	5.017	84.49	110.54	55.55	24.34	84.50	26.04	110.54
211	2856.70	4.50	38.83	2.707	5.025	93.06	116.36	56.19	21.83	93.01	23.36	116.37
214	2831.03	0.44	19.60	2.711	3.678	90.25	98.83	41.36	8.09	90.18	8.66	98.84
258	2842.05	2.73	34.61	2.710	4.694	93.49	112.99	52.76	18.28	93.44	19.56	113.00
281	2974.70	5.10	41.06	2.710	3.376	59.92	76.47	37.57	15.45	59.94	16.53	76.47
Well: Rigs-1+SA-1												
283	2848.57	4.29	40.16	2.712	4.798	88.05	110.99	53.87	21.36	88.17	22.85	111.02
562P	3381.55	0.96	27.22	2.710	3.855	85.55	98.06	43.24	11.64	85.62	12.46	98.08
580P	3390.35	0.75	24.50	2.707	5.495	126.57	142.62	61.71	14.92	126.67	15.96	142.63
592P	3396.60	1.09	28.29	2.707	5.213	113.58	131.21	58.41	16.42	113.67	17.57	131.24
603P	3403.55	1.35	29.62	2.708	5.073	108.49	126.40	56.75	16.64	108.60	17.81	126.41
Well: Rigs-3												
13	3035.10	0.23	18.20	2.717	4.672	117.18	127.36	52.76	9.70	116.99	10.38	127.37
39	3043.77	0.43	21.58	2.718	4.856	116.52	128.99	54.76	12.04	116.11	12.88	128.99
41	3044.51	0.30	19.33	2.718	4.956	122.51	134.03	55.92	10.89	122.38	11.66	134.04
74	3055.45	0.58	22.73	2.717	4.835	114.71	127.93	54.59	12.38	114.68	13.25	127.93
82	3058.15	0.25	17.47	2.719	4.727	120.05	129.91	53.42	9.30	119.96	9.95	129.91

Ekofisk Fm data :

Plug no.	Depth [m]	k_g [mD]	$Ø_{i(He)}$ [%]	GD [g/cc]	$L_{caliper}$ [cm]	Dry wt [g]	Wet wt [g]	$BV2_{(Arch)}$ [cc]	$PV2_{(Arch.)}$ [cc]	M_{grain} [g]	M_{fluid} [g]	$\cong M_{plug}$ [g]
Well: Rigs-1+2												
20	2801.50	0.98	35.54	2.690	5.094	97.37	118.66	56.16	19.98	97.32	21.38	118.70
33	2805.10	1.68	39.32	2.691	5.065	92.91	116.63	56.82	22.35	92.77	23.91	116.68
34	2805.30	2.52	43.11	2.694	5.021	86.08	111.62	55.87	23.92	86.06	25.60	111.66
119	2806.09	0.63	31.39	2.700	4.550	94.53	111.55	50.98	15.99	94.47	17.11	111.58
Well: SA-1												
58A	3332.17	0.28	27.49	2.685	4.910	107.84	124.05	55.32	15.16	107.84	16.22	124.05
513P	3319.60	0.27	28.52	2.708	5.026	108.85	125.73	56.14	16.06	108.55	17.18	125.73
528P	3329.60	0.09	23.34	2.709	5.324	124.34	138.85	59.66	13.89	123.98	14.87	138.85

Hod Fm data :

Plug no.	Depth [m]	k_g [mD]	$Ø_{i(He)}$ [%]	GD [g/cc]	$L_{caliper}$ [cm]	Dry wt [g]	Wet wt [g]	$BV2_{(Arch)}$ [cc]	$PV2_{(Arch.)}$ [cc]	M_{grain} [g]	M_{fluid} [g]	$\cong M_{plug}$ [g]
Well: Baron-2A												
82P	2901.10	0.04	10.24	2.720	5.011	136.88	143.52	56.59	6.29	136.81	6.73	143.54
83P	2902.10	0.01	8.31	2.721	3.760	105.39	109.36	42.50	3.80	105.29	4.07	109.36
90P	2909.10	0.34	24.39	2.715	5.204	121.19	136.25	58.75	14.13	121.14	15.12	136.26
101P	2920.13	0.08	18.96	2.704	3.213	79.22	86.51	36.13	6.83	79.22	7.31	86.53

* Plug 132 subject to slight pore collapse during test (fines production observed), $BV_{(Hg)}$ after test was 54.88 cc; grain loss also affects the fluid saturation determination

NB: A low experimental error would mean that column G and K have nearly identical figures

Tor Fm data :

Dean Stark extraction after test @ amb. cond			
Plug no.	S_w [%]	S_o [%]	S_g [%]
Well: Rigs-1+2+2A			
132	16	* 79	* 5
211	17.5	83	-0.5
214	34	65.5	0.5
258	18.5	81.5	-0.5
281	14	86	0
Well: Rigs-1+SA-1			
283	10.5	89.5	0
562P	18	81.5	0.5
580P	20.5	78.5	0.9
592P	19	80.5	0.5
603P	18	81.5	0.8
Well: Rigs-3			
13	21	78	1.0
39	19	80	1.0
41	20	79.5	0.5
74	16	83	1.0
82	22	77	1.1

Ekofisk Fm data :

Plug no.	S_w [%]	S_o [%]	S_g [%]
Well: Rigs-1+2			
20	33	**	**
33	23	**	**
34	22	**	**
119	36.4	63	0.6
Well: SA-1			
58A	29	72	-0.7
513P	31	67	1
528P	36	65	-0.8

Hod Fm data :

Plug no.	S_w [%]	S_o [%]	S_g [%]
Well: Baron-2			
82P	30	68	2
83P	35	62	3
90P	31	67	2
101P	37	62	1

** equipment failure, Sw calculated from correct wet weight before Dean Stark extraction; calc. Sw in good agreement with Sw from flood down data

Tor Fm data :

Plug no.	Plug data @ 1200 psi								
	L [cm]	A [cm^2]	Q 1 [ml/h]	Q 2 [ml/h]	**K_o 1 [mD]**	**K_o 2 [mD]**	**K_o @ Swi [mD]**	**Swi [%]**	**Ø [%]**
Well: Rigs-1+2+2A									
132*	4.999	10.99	64.79	32.39	1.587	1.611	1.599	16	43.19
211	5.019	11.16	60.64	29.46	1.469	1.449	1.459	18	38.63
214	3.676	11.23	5.36	2.69	0.094	0.096	0.095	34	19.42
258	4.691	11.22	41.49	20.45	0.934	0.935	0.934	19	34.51
281	3.369	11.08	94.19	45.35	1.542	1.508	1.525	14	40.74
Well: Rigs-1+SA-1									
283	4.789	11.19	64.18	29.51	1.484	1.390	1.437	11	39.31
562P	3.852	11.20	14.64	6.92	0.272	0.262	0.267	18	26.76
580P	5.493	11.22	6.75	3.25	0.178	0.175	0.177	21	24.09
592P	5.210	11.19	13.92	6.60	0.350	0.338	0.344	19	27.99
603P	5.069	11.17	19.57	9.61	0.480	0.480	0.480	18	29.15
Well: Rigs-3									
13	4.667	11.27	3.01	1.85	0.034	0.042	0.042	21	18.15
39	4.852	11.26	7.23	4.16	0.084	0.098	0.098	19	21.77
41	4.949	11.25	3.65	2.29	0.043	0.055	0.055	21	19.14
74	4.829	11.27	12.71	7.43	0.146	0.173	0.173	17	22.42
82	4.723	11.28	3.87	2.24	0.044	0.051	0.051	22	17.20

Ekofisk Fm data :

Well: Rigs-1+2									
20	5.091	11.01	4.03	2.64	0.210	0.239	0.239	33	35.45
33	5.059	11.19	8.16	5.28	0.415	0.467	0.467	23	39.11
34	5.016	11.11	13.30	8.88	0.676	0.785	0.785	22	42.66
119	4.548	11.19	3.18	2.09	0.145	0.166	0.166	37	31.28
Well: SA-1									
58A	4.906	11.25	0.58	0.58	0.048	0.048	0.048	29	27.23
513P	5.018	11.13	0.79	0.41	0.019	0.020	0.020	32	28.24
528P	5.320	11.19	0.13	0.07	0.003	0.003	0.003	36	23.10

Hod Fm data :

Well: Baron-2A									
82P	5.009	11.28	0.06	0.04	0.0013	0.0014	0.0013	30	10.99
83P	3.758	11.29	0.02	0.01	0.0003	0.0004	0.0003	36	8.83
90P	5.199	11.27	1.11	0.86	0.026	0.033	0.0293	31	23.85
101P	3.210	11.22	0.16	0.11	0.0024	0.0026	0.0025	38	18.66

* Plug 132 produced chalk fines during the flooding experiment that obviously subdued the oil perm
nd = not determined

Tor Fm data :

Perm raw data @ 1200 psi						Fl. down *	Fl. down ΔP **
Oil vol 1 [ml]	Time 1 [min]	≅ P 1 [psi]	Oil vol 2 [ml]	Time 2 [min]	≅ P 2 [psi]	prod. water [ml]	≅ P [psi]
Well: Rigs-1+2+2A							
25	23.15	98.5	11.5	21.30	48.50	19.3	100
31.2	30.87	98.5	19.0	38.70	48.50	17.6	100
7.2	80.65	98.5	4.0	89.08	48.50	4.8	100
25	36.15	98.5	10.2	29.93	48.50	14.4	100
50	31.85	98.5	10.0	13.23	48.50	12.9	100
Well: Rigs-1+SA-1							
25.0	23.37	98.2	32.0	65.07	48.20	18.6	100
11.0	45.08	98.2	10.5	91.00	48.20	9.4	100
9.5	84.50	98.2	11.0	203.00	48.20	11.7	100
19.0	81.90	98.2	15.0	136.40	48.20	13.2	100
15.0	46.00	98.2	10.0	62.42	48.20	13.7	100
Well: Rigs-3							
12.3	244	198	8.5	276	97.50	7.4	200
13.3	110	198	12.0	173	97.50	9.6	200
12.0	197	198	9.1	237	97.50	8.7	200
13.5	64	198	13.8	111	97.50	10.3	200
12.9	200	198	8.9	238	97.50	7.4	200

Ekofisk Fm data :

Well: Rigs-1+2							
20.0	297.57	47.1	20.0	455.03	27.1	13.2	100
20.0	147.04	47.1	20.0	227.33	27.1	16.8	100
20.0	90.25	47.1	20.0	135.1	27.1	18.5	100
20.0	377.5	47.1	20.0	573.9	27.1	10.0	100
Well: SA-1							
14.5	1493	27.8	14.5	1493	27.8	9.7	200
12.7	967	98.1	9.6	1410	48.1	10.4	400
2.2	1044	98.1	1.54	1411	48.1	7.5	400

Hod Fm data :

Well: Baron-2A							
1.43	1500	104.29	2.74	4282	64.22	***	400
0.4	1500	104.29	1.00	4281	64.22	***	400
20.2	1096	104.29	16.4	1145.5	64.22	***	400
4.06	1500	104.29	7.8	4282	64.22	***	400

* Fl. down = displaced brine collected during flooding down
** Fl. down ΔP = max. pressure differential applied during flooding down
*** operator failure, Sw calculated from Dean Stark data

5.3 Diagrams

This section contains scatter plots with petrophysical correlations for the 3 chalk formations in the South Arne Field. Overburden corrected porosity and conventional gas and Klinkenberg corrected gas permeability was used as the base parameter in the correlations. Observe that porosity is given as a fraction in the diagrams and correlation equations.

Observe that scatter diagrams of oil permeability vs. gas and Klinkenberg permeability could also be considered a control on the quality of the 3 independent techniques of measuring permeability. Theoretically one would expect a perfect correlation if operator and instrumental errors and bias are low.

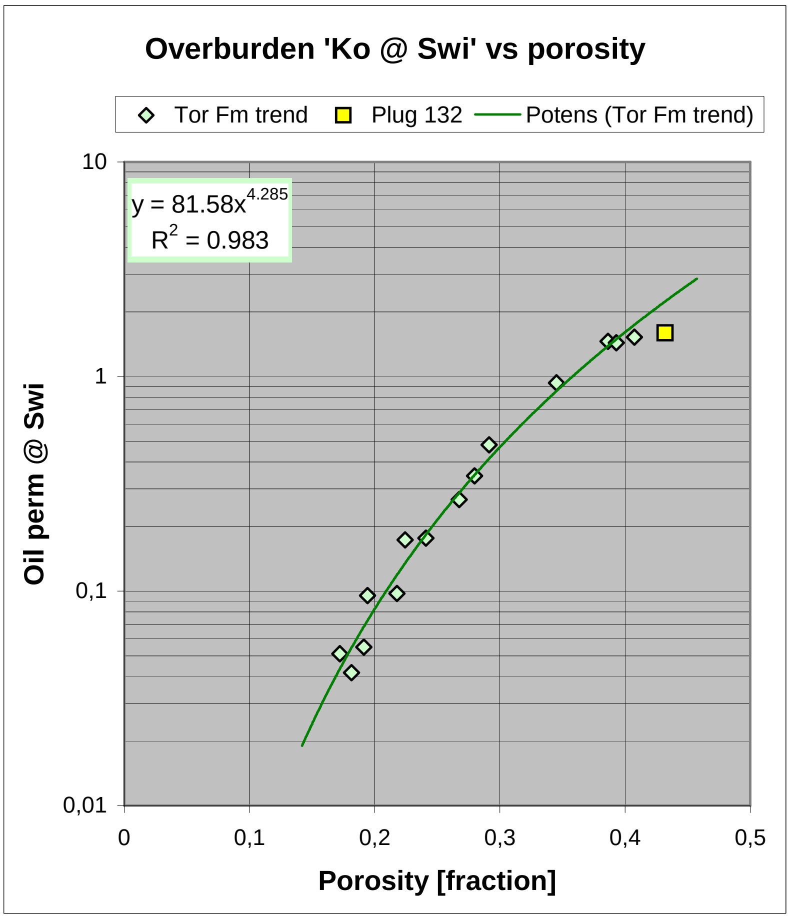
SA Oil perm Study; Tor Fm diagrams

Subject : Endpoint permeability	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formation : Tor
Effective overburden stress 1200 psi (hydrostatic)

Regression : K_o @ S_{wi} = $81.6\ \Phi^{4.28}$

Comment : Plug 132 experienced a slight pore collapse during measurement and was excluded from the regression analysis



SA Oil perm Study; Tor Fm diagrams

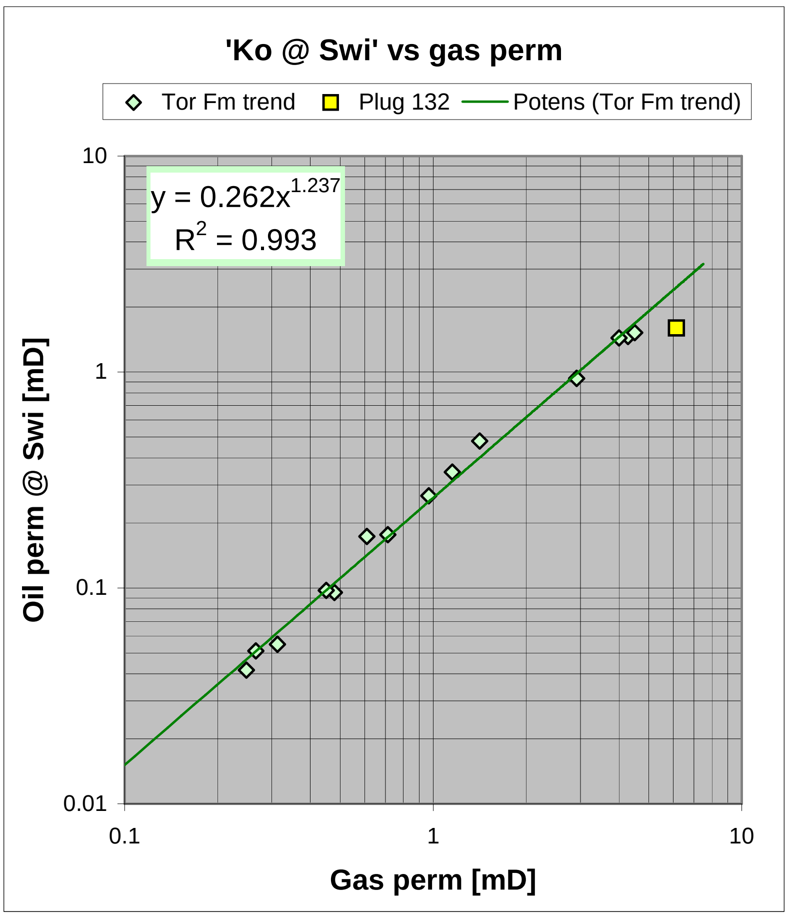
Subject : Endpoint permeability	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formation : Tor

Effective overburden stress 1200 psi (hydrostatic)

Regression : K_o @ S_{wi} = $0.262\ K_g^{1.24}$

Comment : Plug 132 experienced a slight pore collapse during measurement and was excluded from the regression analysis



SA Oil perm Study; Tor Fm diagrams

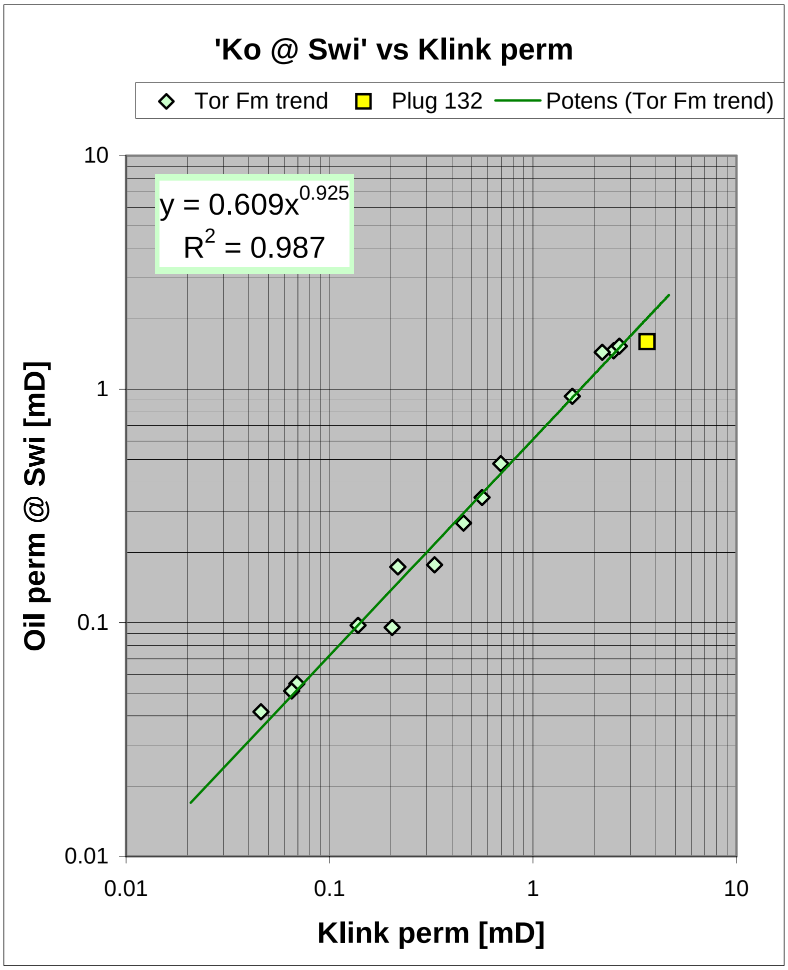
Subject : Endpoint permeability	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formation : Tor

Regression : K_o @ S_{wi} = $0.609\ K_{el}^{0.92}$

Effective overburden stress 1200 psi (hydrostatic)

Comment : Plug 132 experienced a slight pore collapse during measurement and was excluded from the regression analysis



SA Oil perm Study; Ekofisk Fm diagrams

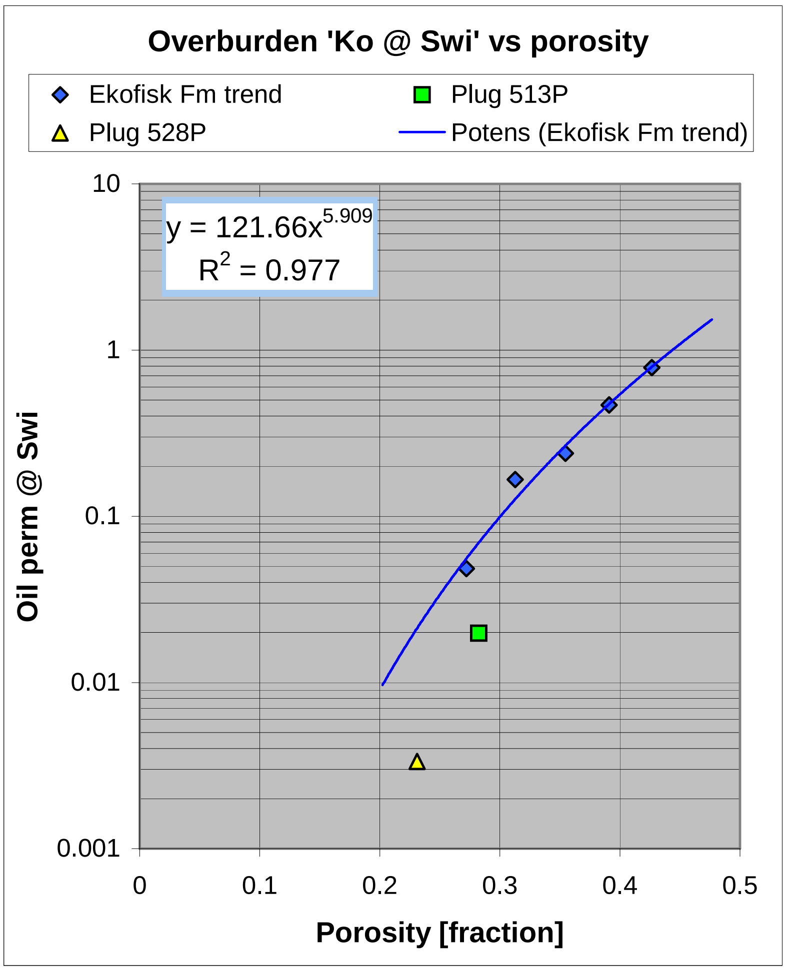
Subject : Endpoint permeability	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formation : Ekofisk

Regression : K_o @ S_{wi} = $122\ \Phi^{5.91}$

Effective overburden stress 1200 psi (hydrostatic)

Comment : Plugs 513P and 528P showed anomalous permeability behaviour and was excluded from the regression analysis



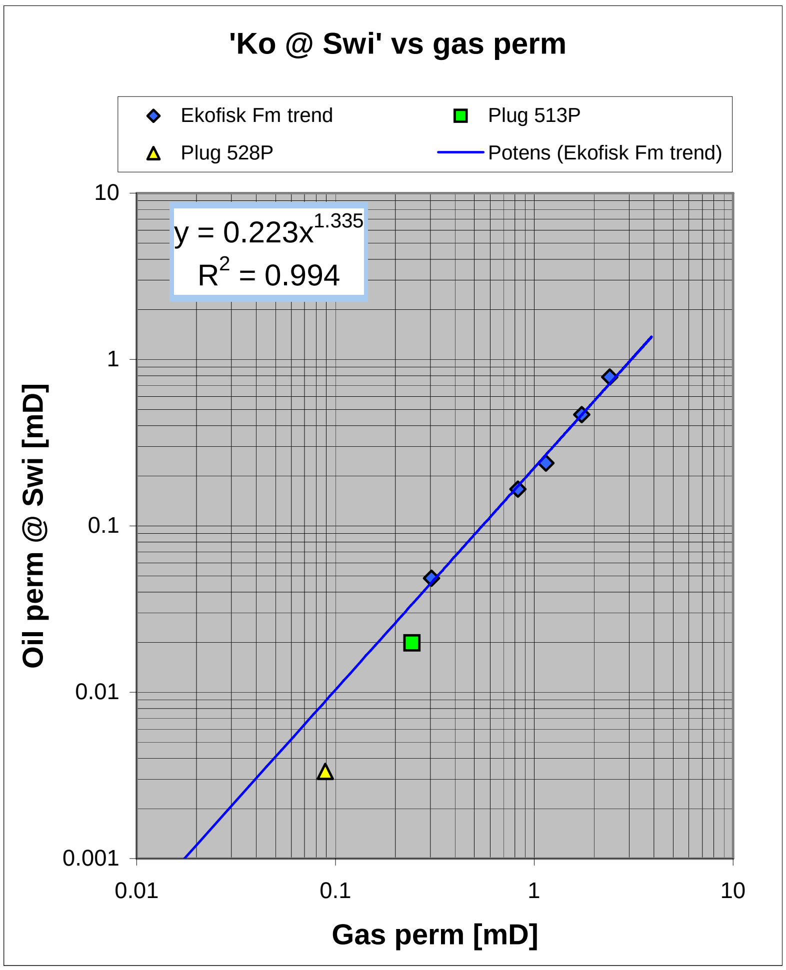
SA Oil perm Study; Ekofisk Fm diagrams

Subject : Endpoint permeability	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formation : Ekofisk — Regression : K_o @ S_{wi} = $0.223\ K_g^{1.33}$

Effective overburden stress 1200 psi (hydrostatic)

Comment : Plugs 513P and 528P showed anomalous permeability behaviour and was excluded from the regression analysis



SA Oil perm Study; Ekofisk Fm diagrams

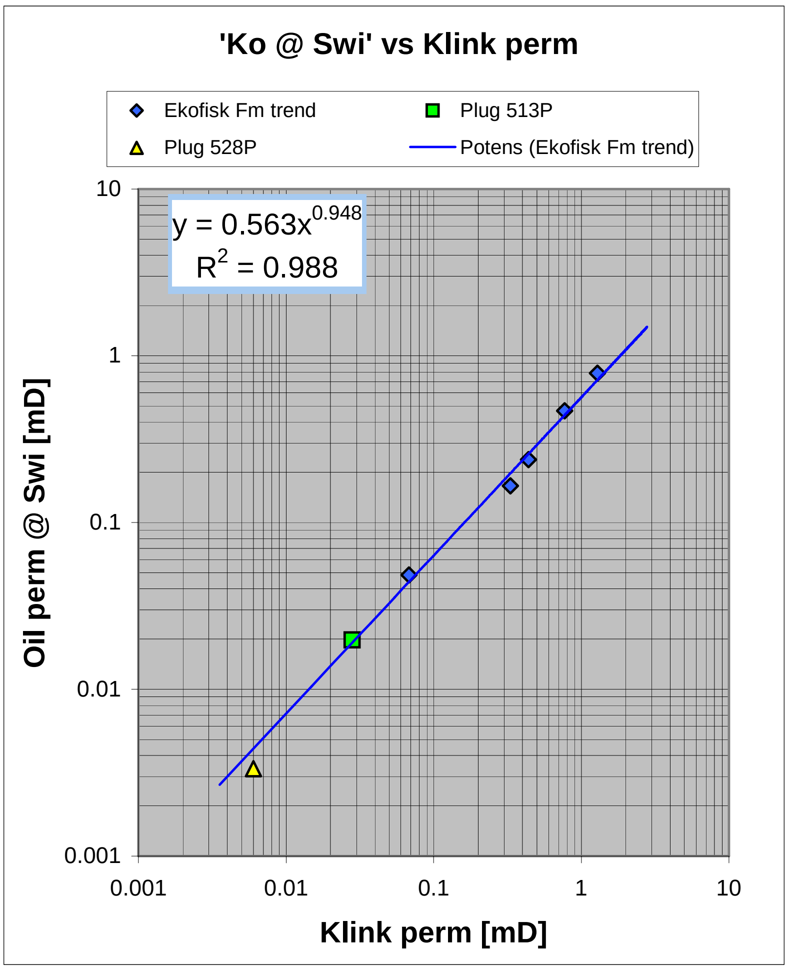
Subject : Endpoint permeability	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formation : Ekofisk

Effective overburden stress 1200 psi (hydrostatic)

Regression : K_o @ S_{wi} = $0.563\ K_{el}^{0.95}$

Comment : Plugs 513P and 528P showed anomalous permeability behaviour and was excluded from the regression analysis



SA Oil perm Study; Hod Fm diagrams

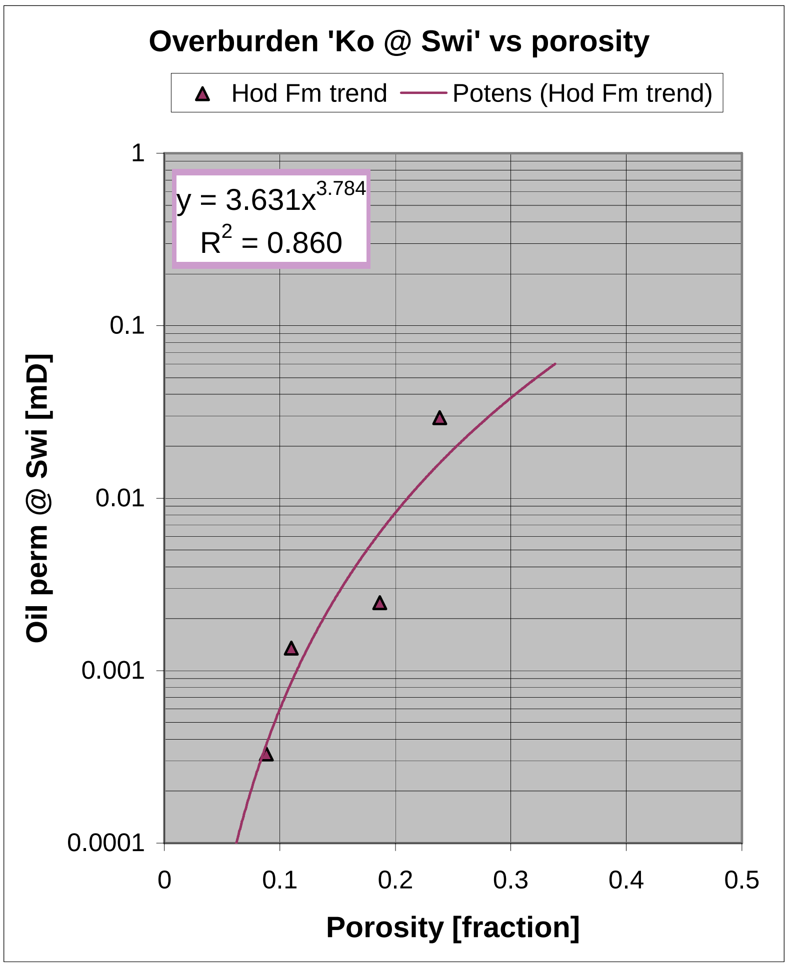
Subject : Endpoint permeability	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formation : Hod

Effective overburden stress 1200 psi (hydrostatic)

Regression : K_o @ S_{wi} = $3.63\ \Phi^{3.78}$

Comment :



SA Oil perm Study; Hod Fm diagrams

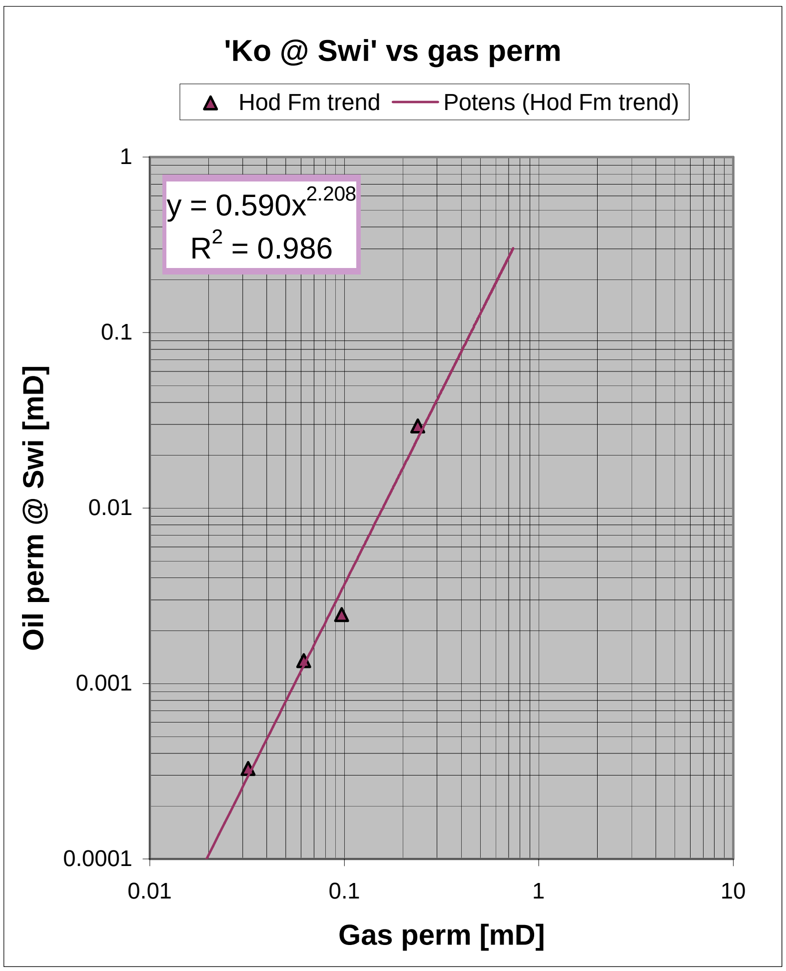
Subject : Endpoint permeability	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formation : Hod

Effective overburden stress 1200 psi (hydrostatic)

Regression : K_o @ S_{wi} = 0.590 $K_g^{2.21}$

Comment : Klinkenberg corrected gas perm could not be measured for most Hod Fm plugs



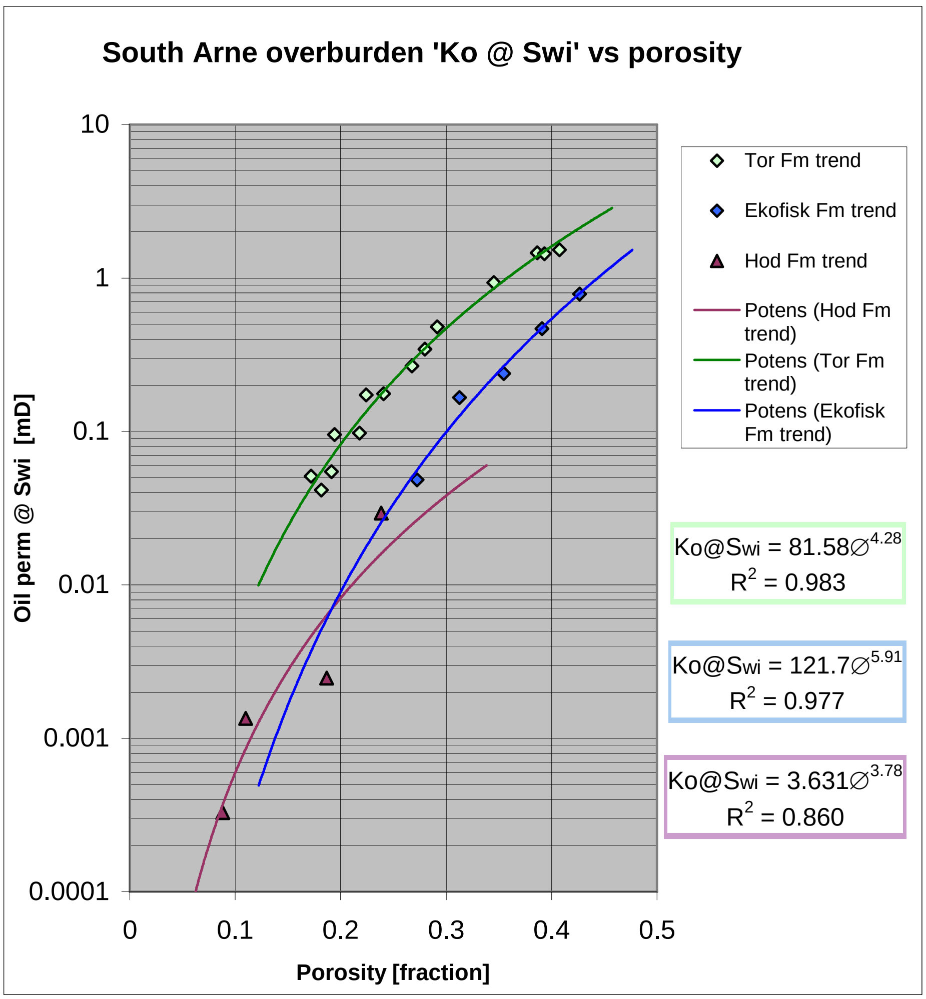
SA Oil perm Study; multi sample diagrams

Subject : Endpoint permeability	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formations : Ekofisk, Tor and Hod Regression :

Effective overburden stress 1200 psi (hydrostatic)

Comment :



SA Oil perm Study; multi sample diagrams

Subject : Initial water saturation	**SA oil perm study**
Company : Hess DK	**GEUS Core Lab, 01.12.2008**

Chalk formation :	Ekofisk	Regression :	S_{wi} = 0.118 $\Phi^{-0.83}$
Chalk formation :	Tor	Regression :	S_{wi} = 0.134 $\Phi^{-0.25}$

Effective overburden stress 1200 psi (hydrostatic)

Comment : Plugs 214 and 283 showed anomalous Swi figures and was excluded from the Tor regression analysis