DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/48

# Special core analysis for Hess Denmark. Well: Rigs-4

## Electrical properties and permeability at overburden stress conditions

Niels Springer & Hans Lorentzen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/48

# Special core analysis for Hess Denmark. Well: Rigs-4

## Electrical properties and permeability at overburden stress conditions

Niels Springer & Hans Lorentzen

GEUS Core Laboratory

Confidential report

Copy No.

To be released 31.07.2015

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE END ENERGY

GEUS

# Contents



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

Req. no.: 09201-594
File: Rigs-4_SCALrep.doc
Rigs-4_electrical.xls

# 1. Introduction

At the request of Hess Denmark ApS, GEUS Core Laboratory has performed special core analysis on samples from the Rigs-4 well, the South Arne Field, Danish North Sea.

The experimental programme was specified in e-mail communications with Ms. Cathrine Børkop during August-September 2008. The following analytical programme was finally agreed on in a contract dated November 6, 2008:

- X-ray CT-screening of plugs for SCAL
- Standard core analysis on plugs for SCAL
- Determination of insoluble residue and clay mineralogy
- Liquid permeability at overburden conditions
- Electrical properties at overburden conditions

Preliminary data have been reported to Hess DK by e-mail comm. during the period January 2009 to April 2010.

# 2 Sampling and analytical procedures

The resistivity study was carried out on 8 plug samples taken from the Tor and Hod Formation chalk in the Rigs-4 well. Earlier resistivity studies conducted for Hess DK is the South Arne Field and Rigs-3 studies completed in 2005 and 2007. The equipment and techniques are essentially the same as used in the former studies. [1, 2]

## 2.1 Plug quality screening

A total of 20 plugs of 38 mm diameter were received from Core Laboratories® UK, table 2.1, and later delivered to the scanning facility at Department of Chemical Engineering, the Technical University of Denmark. During the X-ray CT-screening, two longitudinal cuts perpendicular to each other are recorded for each plug. Scanning images and details of the instrumental settings are given in chapter 7.

## 2.2 Preparation and initial characterization

Hess DK preselected 7 plugs for the resistivity study, 3 plugs representing the Tor Fm chalk and 4 plugs representing the Hod Fm chalk. In agreement with GEUS Core Laboratory it was decided to include a fifth Hod Fm plug to obtain the maximum possible spread in porosity when measuring the Formation Resistivity Factor to get the best accuracy in the calculation of the cementation exponent 'm'. All plugs had previously been Soxhlet cleaned during the conventional core analysis (CCAL) study but went through an additional cold flush cleaning with methanol and toluene before special core analysis (SCAL) test. The plugs were then dried at 110 °C and analyzed for routine poro-perm. A determination of the insoluble residue (ISR) and clay mineral composition was included with the experimental programme, but plug trims were not at hand; therefore a copy set of 38 mm diameter plugs were drilled close to the original plugs, cleaned and analyzed for ISR and clay mineralogy. CCAL and mineralogical data are presented in chapter 5.

## 2.3 Electrical properties and liquid 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 another week before electrical measurement commenced.The samples were then installed in single resistivity cells and a hydrostatic confining pressure of 145 psi [1 MPa] was applied.  Approx. 2-3 PV's of fresh brine was flushed through the samples to displace air from the core holder. Pressure was then increased to 1200 psi [8.2 MPa] hydrostatic conf. P and the sample left to settle until the next day. The amount of liquid expelled was used to calculate the porosity reduction. Liquid flow was then started and when stable conditions was observed, consequtive readings of flowrate and differential pressure were recorded. Liquid flow was now stopped and during the next week  a number of resistivity readings were taken to determine the formation resistivity factor FRF.

The resistivity index RI to an air-brine system was measured by a technique developed for low permeability samples by Springer et al. [3] Applying this technique, Hess DK requested samples be measured at 3 different water saturations viz. 50%, 40% and 20%. Subsequently samples were flushed with 5-10 PV's of 2x,  2.5x and 5x diluted formation brine (table 2.3-2.5) in core holders for approx. one week. The core holders were then dismantled and the samples left to settle in an anaerobic jar under a slight vacuum for another week in the subject diluted brine. Samples were then removed from the vacuum jar and left to evaporate under laboratory conditions until a precalculated weight had been reached and the original brine concentration re-established, ie. the diluted brines were up-concentrated 2x, 2.5x and 5x. The samples had  now attained 50%, 40% or 20% water saturation  respectively, and were ready to be measured for the resistivity index RI at overburden conditions. The RI (air-brine system) was measured with the samples mounted in single resistivity cells during a period of one week until stable readings were obtained. The advantage of using an air-brine system is that an even saturation distribution can be obtained within the plug samples during 1-2 weeks[3].

Data for ‘RI’ and 'FRF' as well as Archie parameters 'm' and ‘n’ are presented in chapter 5.

*Table 2.1. Rigs-4 resistivity study; list of former routine core analysis plugs received for screening. Samples selected for resistivity measurement after CT-screening are indicated (x).*

| Plugs | | | | CT scanning | RI and FF |
|---|---|---|---|---|---|
| **Fm** | **Core depth** | **Plug** | **Issues** | **GEUS** | **GEUS** |
| Tor | 2865.00 | HS1 | | **x** | |
| Tor | 2865.16 | 1H1 | | | |
| Tor | 2865.40 | 1H2 | Homogeneous, oil stained | **x** | (x) |
| Tor | 2865.71 | 1H3 | Heterogeneous, not fully oilstained, | **x** | (x) |
| Tor | 2866.00 | HS2 | | **x** | |
| Tor | 2866.40 | 2H2 | | **x** | |
| Tor | 2867.00 | HS3 | | **x** | |
| Tor | 2867.14 | 3H1 | | | |
| Tor | 2867.40 | 3H2 | Homogeneous, oil stained, | **x** | (x) |
| Tor | 2867.67 | 3H3 | Heterogeneous, not fully oilstained, | **x** | |
| | | | | | |
| Hod | 2908.74 | 44H3 | Homogeneous, oil stained | **x** | (x) |
| | | | | | |
| Hod | 2910.00 | HS32 | | **x** | |
| Hod | 2910.19 | 46H1 | | | |
| Hod | 2910.44 | 46H2 | Homogeneous, oil stained | **x** | (x) |
| Hod | 2910.70 | 46H3 | Homogeneous, oil stained | **x** | (x) |
| Hod | 2910.94 | 46H4 | Homogeneous, oil stained | **x** | |
| Hod | 2911.00 | HS33 | | **x** | |
| Hod | 2911.18 | 47H1 | Homogeneous, oil stained | | |
| Hod | 2911.40 | 47H2 | Homogeneous, oil stained | **x** | (x) |
| Hod | 2912.00 | HS34 | | **x** | |
| Hod | 2912.15 | 48H1 | | | |
| Hod | 2912.40 | 48H2 | Homogeneous, oil stained | **x** | (x) |
| Hod | 2912.70 | 48H3 | Homogeneous, oil stained | **x** | |
| | | | | | |
| Hod | 2913.70 | 49H3 | Homogeneous, oil stained | **x** | |
| Hod | 2914.42 | 50H2 | Homogeneous, oil stained | **x** | |

*Table 2.2. South Arne simulated formation water analysis. Measured physical properties appear below.*

| | | | | | |
|---|---|---|---|---|---|
| | | | **Subject brine: Syd Arne formation brine** | | |

| **Element** | **Concentration** | **Compound** | **Gram compound per** | | |
|---|---|---|---|---|---|
| | **mg/L** | | **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:** | **1.093** | **cP @ 25 ºC** |

*Table 2.3. South Arne simulated formation water analysis diluted 2 times to allow a final water saturation of 50% in the resistivity index study. Measured physical properties appear below.*

**Subject brine: SA formation brine - 50%**

| Element | Concentration | Compound | Gram compound per | | |
|---|---|---|---|---|---|
| | mg/L | | 1 liter | 3 liter | 5 liter |
| **Na total** | 16465 | | | | |
| Na+ | 16465 | NaCl | 41.854 | 125.561 | 209.27 |
| Na+ | 0 | NaHCO3 | 0.000 | 0.000 | 0.00 |
| K+ | 261 | KCl | 0.498 | 1.493 | 2.49 |
| Mg2+ | 333 | MgCl2, 6H2O | 2.781 | 8.342 | 13.90 |
| Ca2+ | | CaCl2 | 0.000 | 0.000 | 0.00 |
| Ca2+ | 2834 | CaCl2, 2H2O | 10.394 | 31.181 | 51.97 |
| Sr2+ | 0 | SrCl2, 6H2O | 0.000 | 0.000 | 0.00 |
| Ba2+ | | BaCl2, 2H2O | 0.000 | 0.000 | 0.000 |
| | | | | | |
| Cl- | 31610 | | | | |
| HCO3- | 0.0 | | | | |

| | | | | | |
|---|---|---|---|---|---|
| **TDS:** | **51502** | **mg/L** | **~** | 0.881 | mol/L NaCl eqv. |
| **pH:** | | **@ 23 C** | | | |

Comments: Slightly modified from original SA brine and diluted 2 times

| | | | |
|---|---|---|---|
| **Physical data:** | **Resistivity Rw :** | **0.129** | **ohmm @ 25.0 ºC** |
| | **Calculated Rw :** | **0.130** | **ohmm @ 25.0 ºC** |
| SA brine 50% | **Density dw :** | **1.032** | **g/cc @ 25.0 ºC** |
| | **Calculated dw :** | **1.032** | **g/cc @ 25.0 ºC** |
| | **Viscosity:** | | **cP @ 25 ºC** |

*Table 2.4. South Arne simulated formation water analysis diluted 2.5 times to allow a final water saturation of 40% in the resistivity index study. Measured physical properties appear below.*

**Subject brine: Syd Arne brine 40%**

| Element | Concentration | Compound | Gram compound per | | |
|---|---|---|---|---|---|
| | mg/L | | 1 liter | 3 liter | 5 liter |
| **Na total** | 13172 | | | | |
| Na+ | 13172 | NaCl | 33.483 | 100.449 | 167.41 |
| Na+ | 0 | NaHCO3 | 0.000 | 0.000 | 0.00 |
| K+ | 209 | KCl | 0.398 | 1.195 | 1.99 |
| Mg2+ | 266 | MgCl2, 6H2O | 2.224 | 6.673 | 11.12 |
| Ca2+ | | CaCl2 | 0.000 | 0.000 | 0.00 |
| Ca2+ | 2267 | CaCl2, 2H2O | 8.316 | 24.947 | 41.58 |
| Sr2+ | 0 | SrCl2, 6H2O | 0.000 | 0.000 | 0.00 |
| Ba2+ | | BaCl2, 2H2O | 0.000 | 0.000 | 0.000 |
| | | | | | |
| Cl- | 25288 | | | | |
| HCO3- | 0.0 | | | | |

| | | | | |
|---|---|---|---|---|
| **TDS:** | **41202** | **mg/L** | **~** | 0.705 mol/L NaCl eqv. |
| **pH:** | | **@ 23 C** | | |

Comments: Slightly modified from original SA brine, and diluted 2.5 times

| **Physical data:** | | | |
|---|---|---|---|
| SA brine 40% | **Resistivity Rw :** | **0.159** | **ohmm @ 25.0 ºC** |
| | **Calculated Rw :** | **0.158** | **ohmm @ 25.0 ºC** |
| | **Density dw :** | **1.026** | **g/cc @ 25.0 ºC** |
| | **Calculated dw :** | **1.025** | **g/cc @ 25.0 ºC** |
| | **Viscosity:** | | **cP @ 25 ºC** |

*Table 2.5. South Arne simulated formation water analysis diluted 5 times to allow a final water saturation of 20% in the resistivity index study. Measured physical properties appear below.*

**Subject brine: Syd Arne brine - 20%**

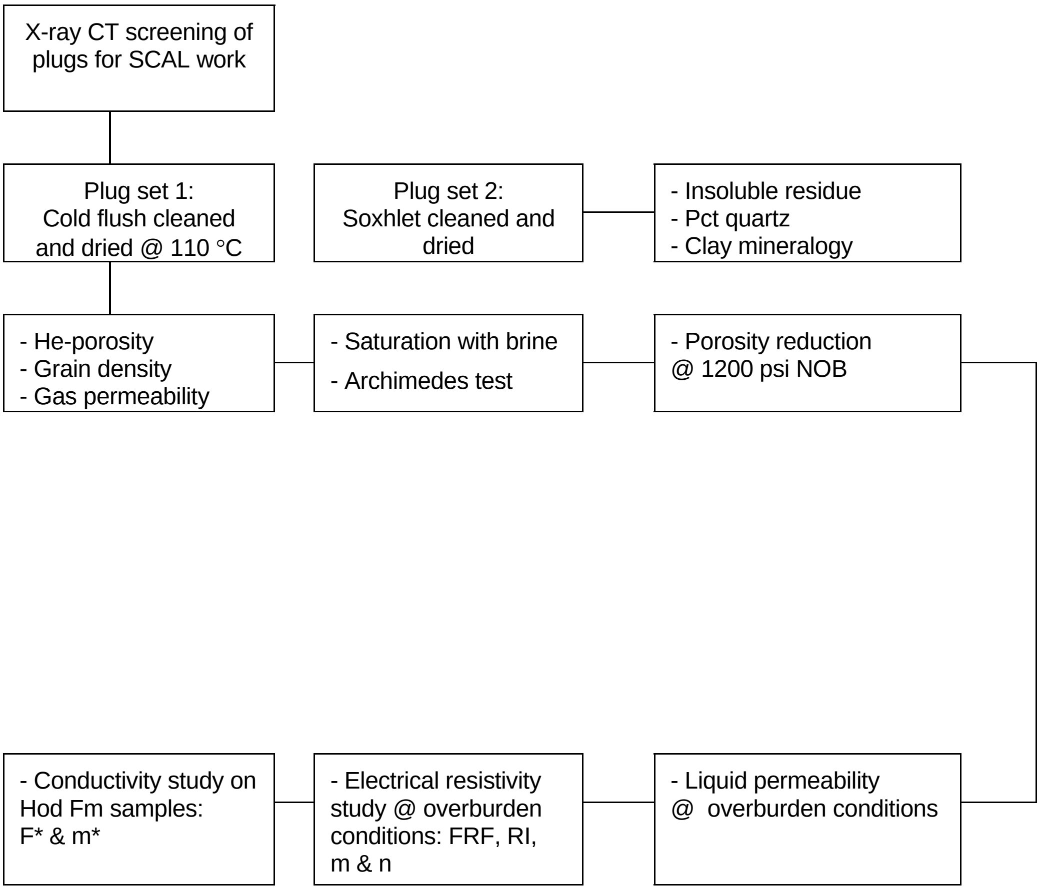
| Element | Concentration | Compound | Gram compound per | | |
|---|---|---|---|---|---|
| | mg/L | | 1 liter | 3 liter | 5 liter |
| **Na total** | 6586 | | | | |
| Na+ | 6586 | NaCl | 16.741 | 50.224 | 83.71 |
| Na+ | 0 | NaHCO3 | 0.000 | 0.000 | 0.00 |
| K+ | 104 | KCl | 0.198 | 0.595 | 0.99 |
| Mg2+ | 133 | MgCl2, 6H2O | 1.112 | 3.337 | 5.56 |
| Ca2+ | | CaCl2 | 0.000 | 0.000 | 0.00 |
| Ca2+ | 1133 | CaCl2, 2H2O | 4.156 | 12.468 | 20.78 |
| Sr2+ | 0 | SrCl2, 6H2O | 0.000 | 0.000 | 0.00 |
| Ba2+ | | BaCl2, 2H2O | 0.000 | 0.000 | 0.000 |
| | | | | | |
| Cl- | 12643 | | | | |
| HCO3- | 0.0 | | | | |

| | | | |
|---|---|---|---|
| **TDS:** | **20599** | **mg/L ~** | 0.352 mol/L NaCl eqv. |
| **pH:** | | **@ 23 C** | |

Comments: Slightly modified from original SA brine and diluted 5 times

| **Physical data:** | | | |
|---|---|---|---|
| SA brine 20% | **Resistivity Rw :** | **0.286** | **ohmm @ 25.0 ºC** |
| | **Calculated Rw :** | **0.293** | **ohmm @ 25.0 ºC** |
| | **Density dw :** | **1.012** | **g/cc @ 25.0 ºC** |
| | **Calculated dw :** | **1.011** | **g/cc @ 25.0 ºC** |
| | **Viscosity:** | | **cP @ 25 ºC** |

# 3 Flow diagram of the analytical procedures



# 4 Analytical Methods

Electrical measurements are performed at 25 ± ½ ºC, and to the guidelines established by the Society of Core Analysts [4]. A temperature log may be provided on request and included with the attached CD-ROM.

## 4.1 Insoluble residue and amount of quartz in the residue

The sample is crushed and dried, and calcite is removed by using a buffered acetic acid at pH 4.5. This mild dissolution of the calcite is carried out in order to avoid dissolution of non – calcite minerals. The amount of insoluble residue is given as a weight percent rel. to the original dry sample weight.

X – ray diffraction ( XRD ) is carried out on randomly oriented specimens using a Philips 1050 goniometer with Co - $K\alpha$ radiation ( pulse – high selection and Fe – filter ). The amount of quartz in the residue is determined using quartz 4.5 - 45 µm in size as a standard. The result is given as a weight percent rel. to the insoluble residue.

## 4.2 Conventional measurements

GEUS Core Laboratory follow the procedures established by API in their recommended practice for core-analysis procedure (API RP 40, 2$^{nd}$ ed. 1998).

***He-porosity and grain density :*** Room condition porosity is measured on cleaned and dried samples in an unconfined sample cup. The method uses Boyle's Law to determine sample grain volume in a double cell Helium porosimeter with digital readout. Bulk volume is measured by submersion of the plug in a mercury bath using Archimedes principle. The porosity is then obtained by subtraction of the measured grain volume from the measured bulk volume.

Grain density is calculated from the grain volume measurement and the weight of the cleaned and dried sample. The Helium porosimeter is calibrated against a number of massive stainless steel plugs with known volume before plug samples are measured.

***Un-corrected gas permeability :*** The plug is mounted in a Hassler core holder, and a confining pressure of 400 psi [2.8 MPa] 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.

***Klinkenberg corrected gas 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 [2.8 MPa] 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.

## 4.3 Overburden measurements

The following field data were supplied by 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 in the electrical properties study.

**Porosity**: The initial porosity is determined at room conditions. Archimedes test is applied to the fully saturated plug sample, and in combination with the sample grain density the porosity is calculated. During testing the sample pore volume decreases as overburden increases. This is observed as an amount of liquid expelled from the sample into a graduated tube, or constantly monitored using an electronic Mettler balance connected to a PC. The final reading is taken after a fixed time or when a stable level has been reached on the balance. The porosity reduction is calculated as the relative decrease in the initial porosity:

$$\text{Ø}_i = \frac{V_{pi}}{V_{bi}}$$

$$\text{Ø}_{i+\Delta p} = \frac{V_{pi} - \Delta V_p}{V_{bi} - \Delta V_p}$$

The porosity reduction is then given as:

$$\frac{\text{Ø}_{i+\Delta p}}{\text{Ø}_i} \cdot 100\% = \frac{V_{pi} - \Delta V_p}{V_{bi} - \Delta V_p} \cdot \frac{V_{bi}}{V_{pi}} \cdot 100\%$$

Where $\text{Ø}_i$ = initial porosity
$V_{pi}$ = initial pore volume
$V_{bi}$ = initial bulk volume
$\text{Ø}_{i+\Delta P}$ = new porosity induced by a certain change $\Delta p$ in confining stress.
$\Delta V_p$ = change in pore volume due to the change in confining stress.

The initial change in the pore volume that occurs from room conditions to the lowest confining stress applied in the study is extrapolated from a liquid production curve (produced liquid vs effective confining stress).

## 4.4 Formation resistivity factor

In a “clean” formation (non-shaly) the formation factor F is described by Archie’s equation:

$$F = \frac{R_0}{R_w} = \frac{a}{\text{Ø}^m}$$

Where
$R_0$ = resistivity of sample @ $S_w$ = 100%
$R_w$ = resistivity of formation brine
Ø = porosity
a = constant
m = cementation exponent

For a plug sample F is calculated from the following formula:

$$F = \frac{1}{R_w} \cdot \frac{z \cdot A}{L}$$

Where $R_w$ = resistivity of brine in ohm-m
z = impedance of plug sample in ohm @ $S_w$ = 100%
A = area of the plug in $m^2$
L = length of plug in m

Rearranging Archie's equation for the formation factor:

log F = -m log Ø + log a

produces a straight-line relationship in a double logarithmic diagram where F is plotted as a function of Ø. The constant 'a' is then determined as the intercept and the cementation exponent 'm' as the slope of the best fit straight line. Values for 'm' are usually preferred for a = 1, which is expected from theoretical grounds. Therefore a set of regression constants are given for a regression line which has been biased through (1,1).

The measurement of F is performed with the plug mounted in a 2-electrode resistivity core holder at an overburden pressure >400 psi. The plug is allowed to settle for more that 24 hours. The porosity reduction/pore volume compressibility is recorded consecutively. The plug resistance is measured as the impedance to an AC signal of 5-20 kHz frequency depending on rock properties (minimum phase angle). Data logging is performed using the HP 4276A LCZ-meter controlled by a PC. The resistivity of the brine is measured in a conductivity meter (Radiometer Analytical CDM 210). The measured formation brine resistivity is checked against a model calculated resistivity.

## 4.5 Core conductivity

Excess conductivity due to Cation Exchange Capacity (CEC) effects from conductive clay minerals can be corrected for by measuring the conductivity of plug samples to a range of different brine salinities as described by Waxman & Smits[7] or the two-salinity method described by Worthington[10]. The corrected Archie formation resistivity factor F* and the $BQ_v$ factor in the Waxman-Smits equation is calculated from linear regression:

$$C_o = \frac{1}{F^*} \cdot (BQ_v + C_w)$$

where $C_o$ = Conductivity of 100% saturated sample
$C_w$ = Conductivity of brine

F* and $BQ_v$ is determined from the slope and intercept of the regression line in a $C_o$ vs $C_w$ diagram.

Measurements of core conductivity are performed at overburden conditions at 25 ºC or at reservoir conditions in an owen as required. Samples are installed in single resistivity core holders and flushed with 10 PV's of a specified brine or NaCl solution. Overburden or reservoir pressure is applied and pore volume compressibility recorded as the samples are left overnight to equilibrate. The first conductivity reading is then taken. The samples are now flushed with 3 PV's of the same brine and left to stabilize for at least 24 hours before the second conductivity is recorded. Consecutive readings may be taken during the following week.

The procedure is repeated for each brine or NaCl solution. The two-electrode method is normally applied and the conductivity measured to an AC signal of 5-20 kHz frequency until minimum phase angle have been detected. Data logging is performed using the HP 4276A LCZ-meter controlled by a PC.

## 4.6 Resistivity index

In a “clean” formation (non-shaly) Archie determined experimentally that the water saturation could be expressed by the following equation:

$$S_w{}^n = \frac{FR_w}{R_t} = \frac{R_o}{R_t} = \frac{1}{RI}, \qquad RI = \frac{R_t}{R_o}$$

where
$S_w$ = water saturation
n = saturation exponent
F = formation resistivity factor
RI = resistivity index
$R_0$ = resistivity of sample @ $S_w$ = 100% in ohm-m
$R_t$ = resistivity of sample @ $S_w$ < 100% in ohm-m
$R_w$ = resistivity of brine in ohm-m

Rearranging Archie’s equation for the water saturation :

$$RI = S_w{}^{-n}$$

and

$$\log(RI) = -n \ \log(S_w)$$

In a double logarithmic diagram consecutive values of $S_w$ and RI shall produce a straight line from which the saturation exponent 'n' can be determined as the slope.

The measurement of RI is performed with the plug mounted in a resistivity core holder at an overburden pressure >400 psi. The plug is allowed to settle for more that 24 hours. The porosity reduction/pore volume compressibility can not normally be measured but is estimated from other sources, preferebly an overburden experiment. The two-electrode method is normally applied and the resistance measured as the impedance to an AC signal of 5-20 kHz frequency depending of the resistivity cell design and the type of rock (minimum phase angle). Data logging is performed using the HP 4276A LCZ-meter controlled by a PC.

Drainage of the sample may be carried out using a porous plate, and therefore the measurement of RI is conveniently combined with air/brine or oil/brine capillary pressure experiments. For low permeability material this may take very long time and often uneven saturation profiles are generated in the samples that will affect the resistivity measurement. For such low permeability samples a different desaturation technique may be applied [3]. A diluted formation brine is used and the samples allowed to evaporate under room conditions to a precalculated weight whereby a specific water saturation is obtained and the original brine concentration restored. A homogeneous brine distribution is normally obtained within a week due to diffusion and capillary forces. The non-wetting phase is air.

# 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 | – 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] |
| $\tau$ | - tortuosity | |

| | | |
|---|---|---|
| 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] |
| $C_o$ | - core conductivity | [S/m] |
| $C_w$ | - formation water conductivity | [S/m] |
| $Z_o$ | - 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 Mineralogy

The insoluble residue is mainly quartz, approx. 2 wt-% is other minerals ie. clay and pyrite. The clay type is identified as smectitic minerals (sm in table 5.1 below), most probably the illite-smectite-chlorite mixed-layer minerals described previously [5, 6].

*Table 5.1. Rigs-4 resistivity study; insoluble residue (ISR), quartz content and clay type in the insoluble residue in Hod Fm chalk. Dry clean sample material analyzed was 40 – 60 [g] per plug sample.*

| Plug ID | Depth [m] | ISR * [wt-%] | Qz in ISR * [wt-%] | Clay XRD of ISR |
|---|---|---|---|---|
| M1 | 2895.36 | 12.1 | 9.8 | sm |
| M2 | 2906.47 | 7.6 | 5.3 | sm |
| M3 | 2910.25 | 5.6 | 3.4 | sm |
| M4 | 2911.55 | 4.4 | 2.8 | sm |
| M5 | 2913.57 | 5.1 | 2.8 | sm |

Analytical data by GEUS Clay Minerals Lab    * rel to whole rock sample weight

## 5.2 Conventional core analysis

Tables 5.2 and 5.3 below lists the routine core analysis data measured before the SCAL test. The plug set was measured twice, as received after routine (Soxhlet) cleaning and after cold flush cleaning in single core holders at GEUS Core Laboratory.

*Table 5.2. Rigs-4 resistivity study; conventional steady state gas and Klinkenberg corrected gas permeability measured on routine core analysis plug set (Soxhlet cleaned) received from Core Laboratories ® UK. Gas permeability was measured @ 400 psi confining sleeve pressure.*

| Sample ID | Fm | Depth [m] | Gas Perm [mD] | Klink.Perm [mD] | Klink.Corr Coef. | Porosity [%] | Grain Dens [g/ccm] |
|---|---|---|---|---|---|---|---|
| 1H2 | Tor | 2865.40 | 0.81 | 0.380 | 0.998 | | |
| 1H3 | | 2865.71 | 0.71 | 0.394 | 0.999 | | |
| 3H2 | | 2867.40 | 0.30 | 0.082 | 0.994 | | |
| 3H3 | | 2867.67 | 0.50 | 0.283 | 0.999 | | |
| 44H3 | Hod | 2908.74 | nd | nd | nd | | |
| 46H2 | | 2910.44 | 0.20 | 0.021 | 0.995 | | |
| 46H3 | | 2910.70 | 0.23 | 0.049 | 0.992 | | |
| 47H2 | | 2911.40 | 0.47 | 0.156 | 0.993 | | |
| 48H2 | | 2912.40 | 0.18 | 0.029 | 0.963 | | |

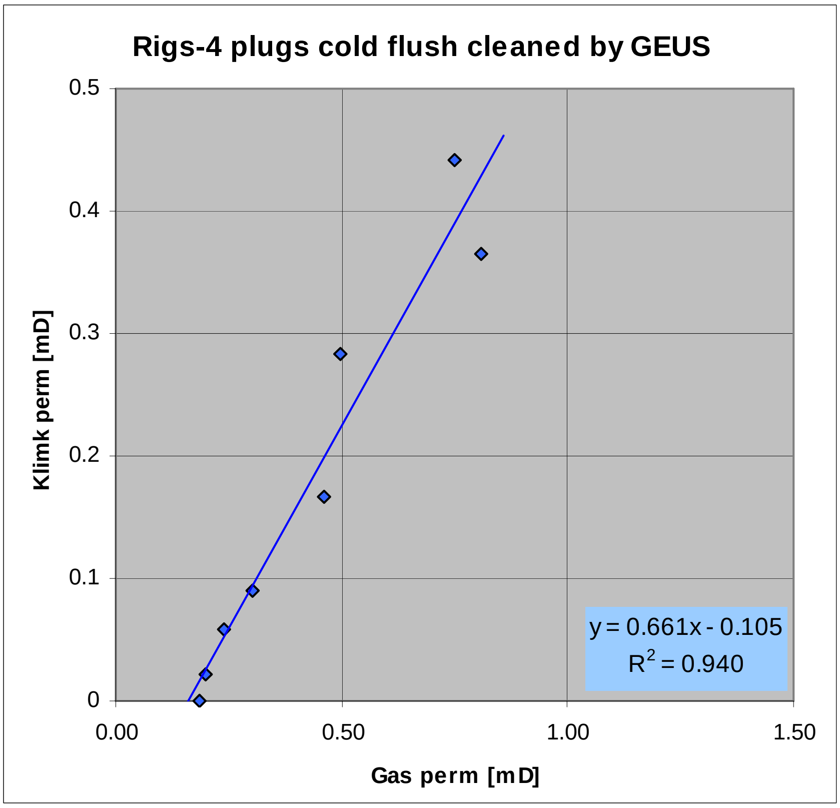
*Table 5.3. Rigs-4 resistivity study; conventional core analysis data measured after additional cold flush, miscible liquids cleaning of plugs selected for the electrical study. Gas permeability was measured @ 400 psi confining sleeve pressure. He-porosity was measured un-confined.*

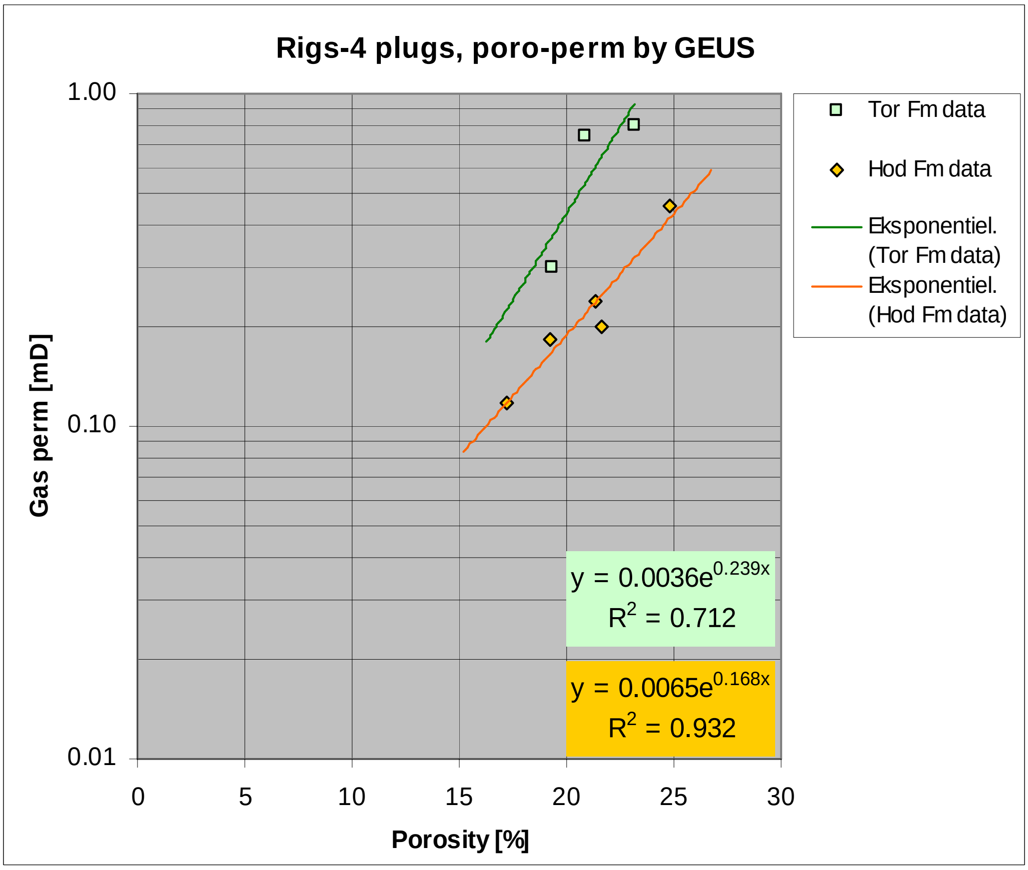
| Sample ID | Fm | Depth [m] | Gas Perm [mD] | Klink.Perm [mD] | Klink.Corr Coef. | Porosity [%] | Grain Dens [g/ccm] |
|---|---|---|---|---|---|---|---|
| 1H2 | Tor | 2865.40 | 0.81 | 0.366 | 1.000 | 23.14 | 2.713 |
| 1H3 | | 2865.71 | 0.75 | 0.441 | 1.000 | 20.84 | 2.713 |
| 3H2 | | 2867.40 | 0.30 | 0.091 | 0.993 | 19.28 | 2.711 |
| 44H3 | Hod | 2908.74 | 0.118 | nd | nd | 17.17 | 2.710 |
| 46H2 | | 2910.44 | 0.20 | 0.021 | 0.998 | 21.65 | 2.709 |
| 46H3 | | 2910.70 | 0.24 | 0.058 | 0.994 | 21.34 | 2.712 |
| 47H2 | | 2911.40 | 0.46 | 0.167 | 0.996 | 24.76 | 2.709 |
| 48H2 | | 2912.40 | 0.18 | 0.007 | 1.000 | 19.22 | 2.711 |

The He-porosity figure from table 5.3 is not always used directly in the following SCAL test; the initial porosity figure may be a mean value between the He-porosity and an Archimedes porosity that is routinely measured on saturated plugs before the SCAL test is initiated.

Scatter diagrams are shown in fig. 5.1.

*Figure 5.1. Rigs-4 resistivity study; conventional core analysis data measured after additional cold flush, miscible liquids cleaning of plugs selected for the electrical study. Gas permeability was measured @ 400 psi confining sleeve pressure. He-porosity was measured un-confined.*



## 5.3 Electrical properties

The scanning images in chapter 7 show Tor Formation plugs are fairly homogeneous and clay and silica content is known to be low. The Hod Formation plugs are unusually homogeneous with insoluble residue (mainly quartz) of 5-12 wt-%, ref. table 5.1. Measurement of sample resistivity was technically uncomplicated, and there is no reason to suspect that a fixed regression through (1,1) in a double logaritmic plot is not valid for the samples. However, some unexpected resistivity index data was obtained for the Rigs-4 chalk (ref. comments below).

### 5.3.1 Formation Resistivity Factor

Results are listed in figures 5.2-5.5 below; raw data are included with the attached CD-ROM. "Best estimate" regression analysis data are listed in table 5.4. The following resistivity index study used a special evaporation technique[3] that required saturating the plugs with different diluted formation brines. That allowed measuring the FRF and 'm' at 3 different brine salinities to check for possible excess conductivity effects due to the insoluble residue in the Hod Fm chalk, table 5.4

*Table 5.4. Archie's cementation exponent 'm' for the Tor and Hod Fm chalk in the Rigs-4 well. For the Hod Fm 'm' was determined for 3 different brine salinities.*

| Chalk formation | Archie's 'm' from linear regression | Formation water salinity [mg/L] |
|---|---|---|
| Tor Fm | 1.98 | 103,000 |
| Hod Fm | 2.00 | 103,000 |
| | 1.98 | 51,500 |
| | 1.97 | 20,600 |

### 5.3.2 Liquid permeability

The overburden liquid permeability at $S_w = 1$ was measured during the FRF study; data and scatter diagrams are given in figure 5.6.

### 5.3.3 Core conductivity $C_o/C_w$

Table 5.5 is a listing of calculated conductivity values for the 5 Hod Fm samples; single sample diagrams are presented in figures 5.7-5.11 below. The three different brine formulations and measured and calculated physical properties are given in table 2.2-2.5. If the calculated and measured conductivity (resistivity) differs, the measured value is preferred in the calculations.

*Table 5.5. Rigs-4, Hod Fm chalk. Archie data corrected for excess conductivity; measurements performed in a temperature controlled laboratory @ 25 °C. Regression analysis gives m* = 2.01.*

| Plug no. | Depth m | $Ø_{113\ bar}$ % | F* | m* | $BQ_v$ |
|---|---|---|---|---|---|
| 44H3 | 2908.74 | 16.6 | 36.63 | 2.01 | 0.509 |
| 46H2 | 2910.44 | 21.4 | 22.88 | 2.03 | 0.176 |
| 46H3 | 2910.70 | 20.9 | 23.42 | 2.02 | 0.279 |
| 47H2 | 2911.40 | 24.2 | 17.18 | 2.00 | 0.271 |
| 48H2 | 2912.40 | 19.0 | 26.95 | 1.98 | 0.062 |

### 5.3.4 Resistivity Index

The study involved measurement of RI at three water saturation steps: 50, 40 and 20 % $S_w$ using a special evaporation technique[3]. This was done to cut experimental time that may otherwise be very long for porous plate drainage of very low permeable samples. The evaporation method was introduced to overcome some well established side effects with the traditional methods (porous plate and centrifuge), eg. uneven saturation profiles in the plugs (centrifuge, porous plate until drainage equilibrium has been obtained) and a drainage threshold that may be high (> 60% $S_w$ ) due to limitations in the porous plate specs. This means that the slope of the regression line (ie. the saturation exponent 'n') cannot be determined with sufficient accuracy. However, the evaporation method depends on an air-brine system (a favourable mobility ratio) to obtain fast equilibrium in the plugs. According to Worthington et al. [8,9] this may introduce bias in the measurements when rocks with a significant micro-porosity and/or multimodal pore size distribution are measured.

Results are listed in figure 5.12-5.15; raw data are included with the attached CD-ROM. "Best estimate" regression analysis data are listed in table 5.6 below.

*Table 5.6. Archie's saturation exponent 'n' for the Tor and Hod Fm chalk in the Rigs-4 well.*

| Chalk formation | Archie's 'n' from linear regression | @ $S_w$ [%] |
|---|---|---|
| Tor Fm | **1.81** | multi sample data |
| | 2.11 | 50 |
| | 1.96 | 40 |
| | 1.70 | 20 |
| Hod Fm | **1.80** | multi sample data |
| | 2.13 | 50 |
| | 1.92 | 40 |
| | 1.70 | 20 |

**Observations:** The core conductivity study show close to zero intercept in the $C_o/C_w$ plot for brines covering the salinity range of approx. 20,000 – 100,000 mg/L indicating no shale effect and a negligible surface conductivity for a fully saturated rock. This conclusion may, however, not be valid for brine saturations < 100% [8,9].

The resistivity index study show a systematic decreasing 'n' with $S_w$ for both the Tor and Hod Formation chalk, a behaviour normally seen for shaly sands but not to be expected for a clean chalk with a uni-model pore size distribution. It is not likely to be an instrumental artefact, but rather a rock property of the microporous chalk or an effect of the method used to desaturate the samples (or both). [9]

### 5.3.5 FRF, $C_o/C_w$ , RI, Archie 'm' and 'n' scatter diagrams

Relevant tables and scatter plots are included with pages 20-33 below.

*Figure 5.2. Archie's cementation exponent 'm' for the Tor Fm chalk in the Rigs-4 well.*

**Subject: Formation Resistivity Factor data** **Well: Rigs-4**
**Company : Hess DK**
**Overburden FRF data and cementation exponent 'm'** **GEUS Core Lab, 01.09.2009**

**Reservoir unit: Tor Fm** **Regression 'm' : 1.98**

| Well | Plug no. | Depth | Overburden data @ 1200 psi confining P | | | | |
|---|---|---|---|---|---|---|---|
| | | [m] | $K_l$ [mD] | Ø [%] | FRF | τ | Archie 'm' |
| **Rigs-4** | 1H2 | 2865.40 | 0.22 | 22.65 | 19.39 | 4.4 | 2.00 |
| | 1H3 | 2865.71 | 0.11 | 20.43 | 23.35 | 4.8 | 1.98 |
| | 3H2 | 2867.40 | 0.07 | 18.81 | 26.48 | 5.0 | 1.96 |

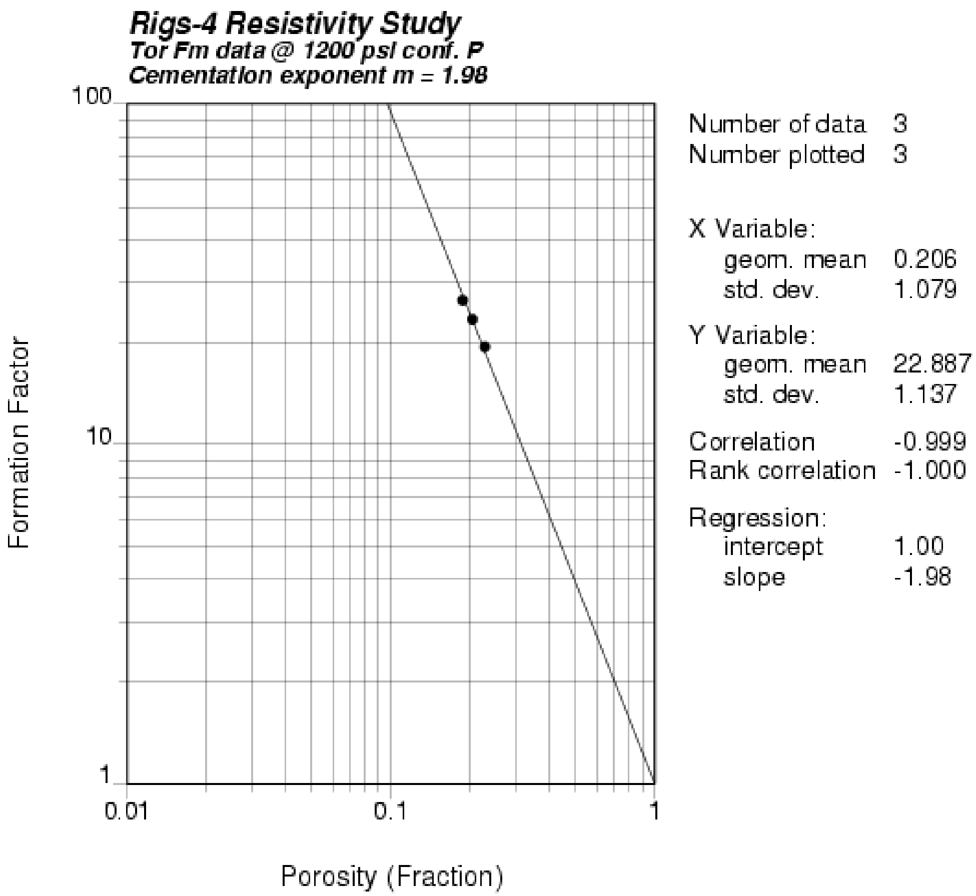


*Figure 5.3. Archie's cementation exponent 'm' for the Hod Fm chalk relative to the simulated formation brine composition given in table 2.2.*

| **Subject: Formation Resistivity Factor data** | **Well: Rigs-4** |
|---|---|
| **Company : Hess DK** | |
| **Overburden FRF data and cementation exponent 'm'** | **GEUS Core Lab, 01.09.2009** |

**Reservoir unit: Hod Fm** **Regression 'm' : 2.00**
**normal brine conc.**

| Well | Plug no. | Depth | Overburden data @ 1200 psi confining P | | | | |
|---|---|---|---|---|---|---|---|
| | | [m] | $K_l$ [mD] | Ø [%] | FRF | τ | Archie 'm' |
| Rigs-4 | 44H3 | 2908.74 | 0.013 | 16.64 | 35.19 | 5.9 | 1.99 |
| | 46H2 | 2910.44 | 0.027 | 21.37 | 22.67 | 4.8 | 2.02 |
| | 46H3 | 2910.70 | 0.031 | 20.92 | 23.09 | 4.8 | 2.01 |
| | 47H2 | 2911.40 | 0.083 | 24.19 | 16.88 | 4.1 | 1.99 |
| | 48H2 | 2912.40 | 0.028 | 18.98 | 26.79 | 5.1 | 1.98 |

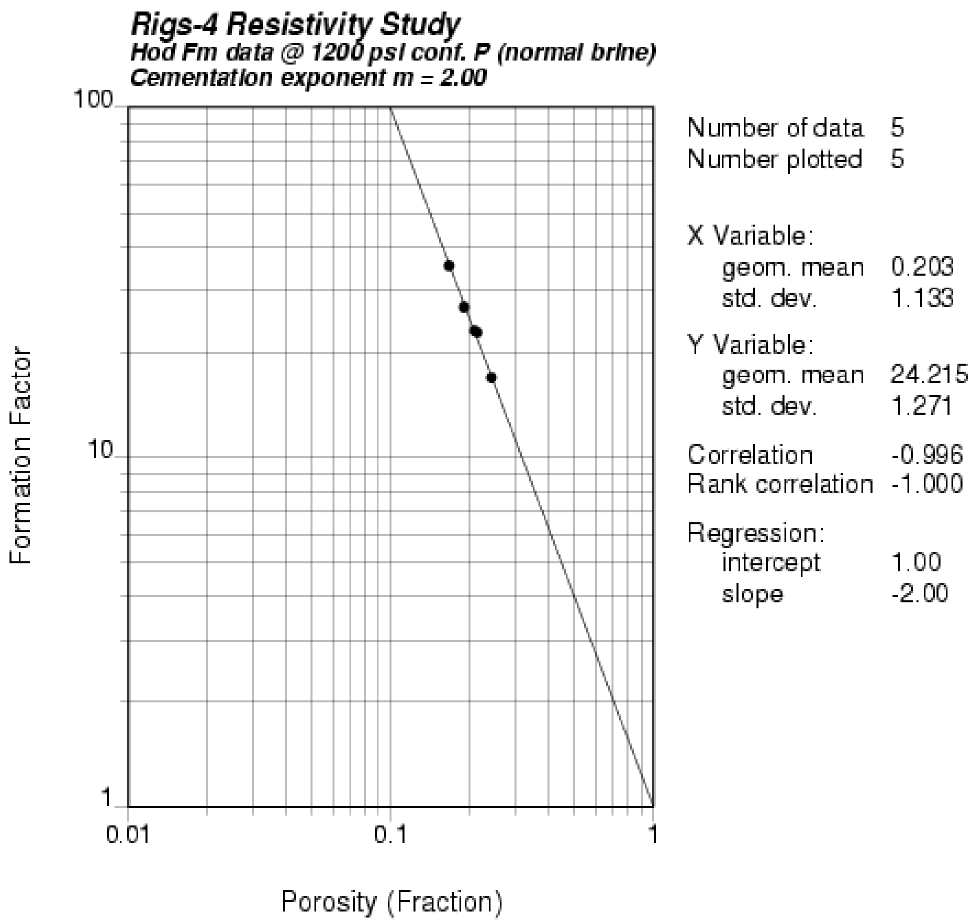


*Figure 5.4. Archie's cementation exponent 'm' for the Hod Fm chalk relative to a 2x diluted formation brine composition given in table 2.3.*

**Subject: Formation Resistivity Factor data** — **Well: Rigs-4**

**Company : Hess DK**

**Overburden FRF data and cementation exponent 'm'** — **GEUS Core Lab, 01.09.2009**

**Reservoir unit: Hod Fm** — **Regression 'm' : 1.98**

**½ brine conc.**

| Well | Plug no. | Depth | Overburden data @ 1200 psi confining P | | | | |
|---|---|---|---|---|---|---|---|
| | | [m] | $K_l$ [mD] | Ø [%] | FRF | τ | Archie 'm' |
| Rigs-4 | 44H3 | 2908.74 | 0.013 | 16.64 | 34.19 | 5.7 | 1.97 |
| | 46H2 | 2910.44 | 0.027 | 21.37 | 21.74 | 4.6 | 2.00 |
| | 46H3 | 2910.70 | 0.031 | 20.91 | 22.04 | 4.6 | 1.98 |
| | 47H2 | 2911.40 | 0.083 | 24.19 | 16.35 | 4.0 | 1.97 |
| | 48H2 | 2912.40 | 0.028 | 18.98 | 26.55 | 5.0 | 1.97 |

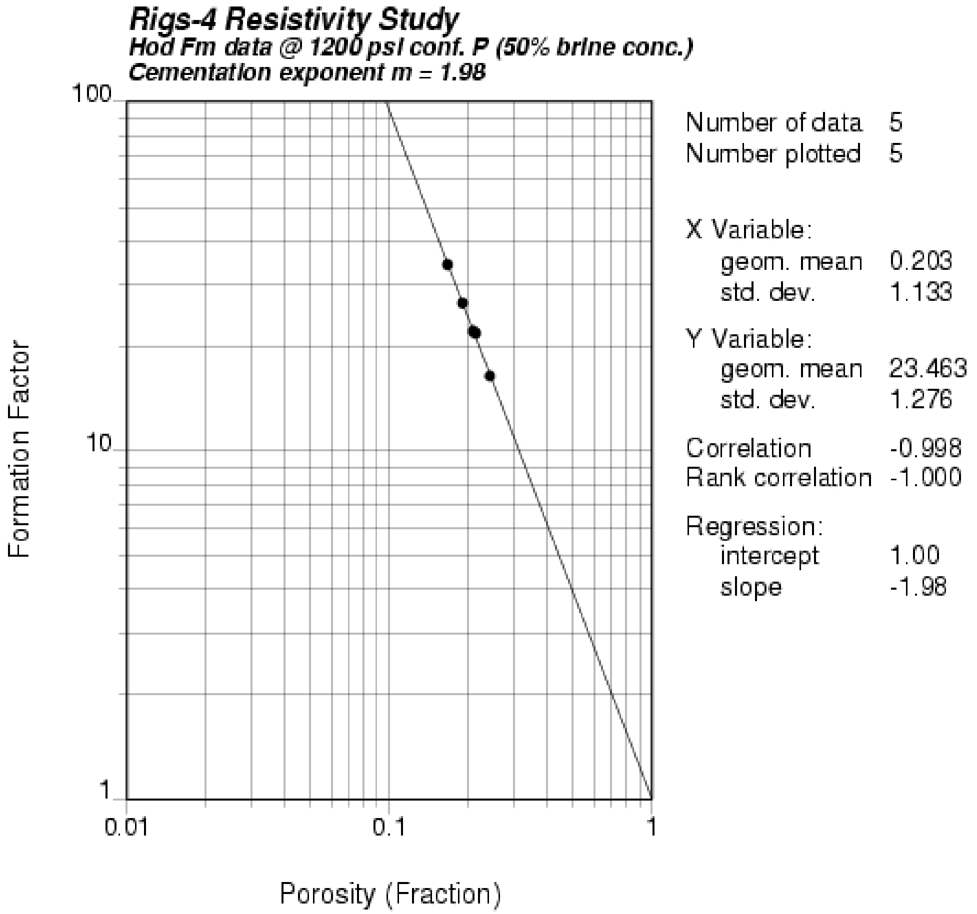


*Figure 5.5. Archie's cementation exponent 'm' for the Hod Fm chalk relative to a 5x diluted formation brine composition given in table 2.4.*

**Subject: Formation Resistivity Factor data** **Well: Rigs-4**
**Company : Hess DK**
**Overburden FRF data and cementation exponent 'm'** **GEUS Core Lab, 01.09.2009**

**Reservoir unit: Hod Fm** **Regression 'm' : 1.97**
**$^{1}/_{5}$ brine conc.**

| Well | Plug no. | Depth | Overburden data @ 1200 psi confining P | | | | |
|---|---|---|---|---|---|---|---|
| | | [m] | $K_l$ [mD] | Ø [%] | FRF | $\tau$ | Archie 'm' |
| **Rigs-4** | 44H3 | 2908.74 | 0.013 | 16.64 | 32.07 | 5.3 | 1.93 |
| | 46H2 | 2910.44 | 0.027 | 21.37 | 22.53 | 4.8 | 2.02 |
| | 46H3 | 2910.70 | 0.031 | 20.91 | 22.42 | 4.7 | 1.99 |
| | 47H2 | 2911.40 | 0.083 | 24.19 | 16.25 | 3.9 | 1.96 |
| | 48H2 | 2912.40 | 0.028 | 18.98 | 26.68 | 5.1 | 1.98 |

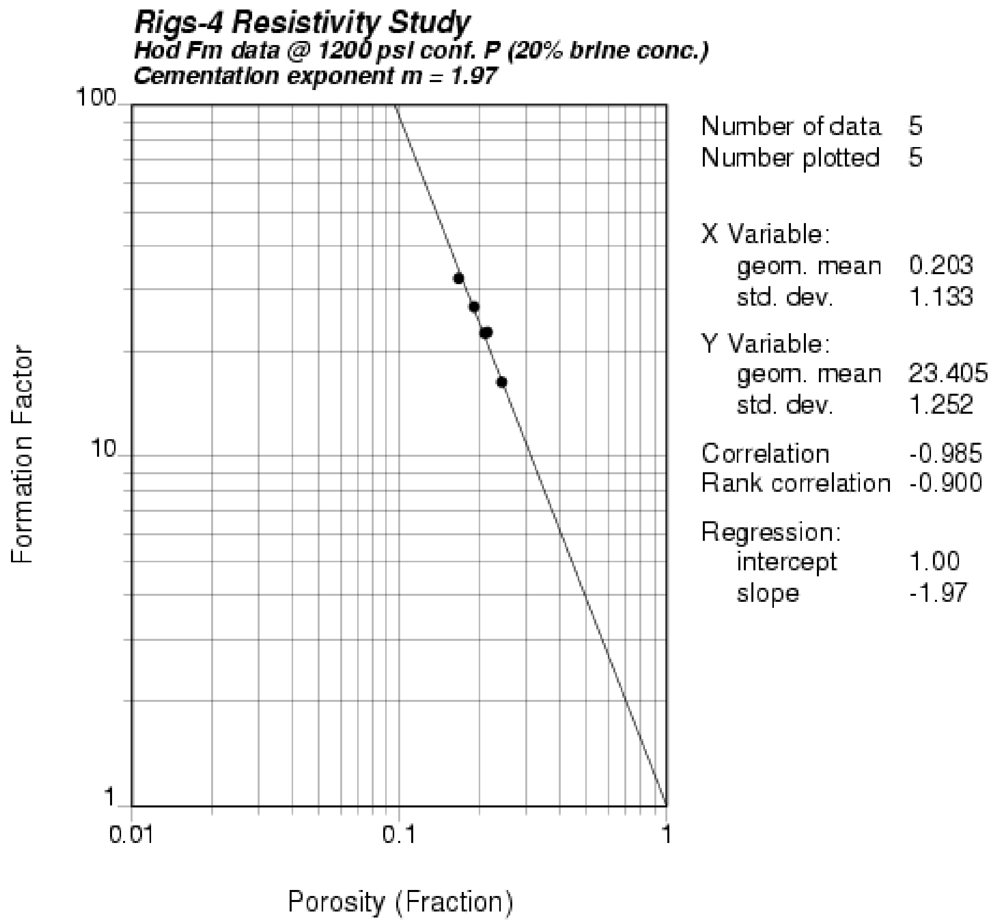


*Figure 5.6. Specific liquid permeability measured for the Tor and Hod Fm chalk in the Rigs-4 well.*

**Subject: Liquid permeability** **Well: Rigs-4**

**Company : Hess DK**

**Overburden poro-perm data**

**Reservoir unit :** **Tor and Hod Fm**

| Plug no. | Fm | Depth | Plug data @ 1200 psi | | | |
|---|---|---|---|---|---|---|
| | | [m] | $K_l$ [mD] | Ø [%] | FRF | Archie 'm' |
| 1H2 | Tor | 2865.40 | 0.217 | 22.6 | 19.39 | 2.00 |
| 1H3 | | 2865.71 | 0.107 | 20.4 | 23.35 | 1.98 |
| 3H2 | | 2867.40 | 0.065 | 18.8 | 26.48 | 1.96 |
| 44H3 | Hod | 2908.74 | 0.013 | 16.6 | 35.19 | 1.99 |
| 46H2 | | 2910.44 | 0.027 | 21.4 | 22.67 | 2.02 |
| 46H3 | | 2910.70 | 0.031 | 20.9 | 23.09 | 2.01 |
| 47H2 | | 2911.40 | 0.083 | 24.2 | 16.88 | 1.99 |
| 48H2 | | 2912.40 | 0.028 | 19.0 | 26.79 | 1.98 |

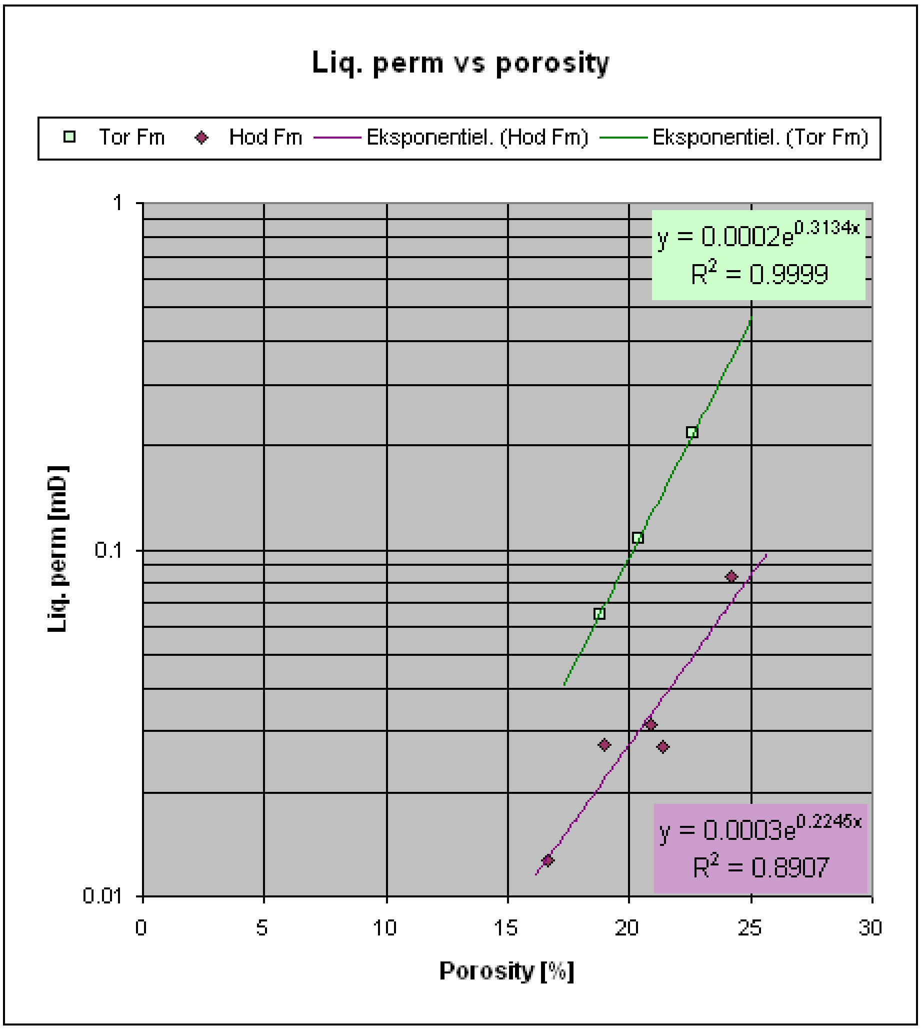


*Figure 5.7. Determination of F* and m* in Hod Fm chalk in the Rigs-4 well.*

| **Subject: Core conductivity measurements @ overburden conditions (1200 psi)** | **Well: Rigs-4** |
|---|---|
| **Company : Hess DK** | **GEUS Core Lab, 01.07.2010** |

| **Plug no. :** | **44H3** | **m* :** | **2.01** | **Conventional data** | |
|---|---|---|---|---|---|
| Depth [m]: | 2908.74 | | | $k_g$ [mD]: | 0.12 |
| Fm | Hod | | | $Ø_{i(He)}$ [%]: | 17.2 |

| **Brine concentration K [mg/L]** | **Brine conductivity Cw @ 25 °C [S/m]** | **Core conductivity Co @ 25 °C [S/m]** |
|---|---|---|
| 20,600 | 3.50 | 0.11 |
| 51,500 | 7.75 | 0.23 |
| 103,000 | 13.33 | 0.38 |

| | |
|---|---|
| $Ø_{1200\ psi}$ : | 0.166 |
| 1/F* : | 0.0273 |
| BQv : | 0.509 |
| F* : | 36.63 |
| m* : | 2.01 |

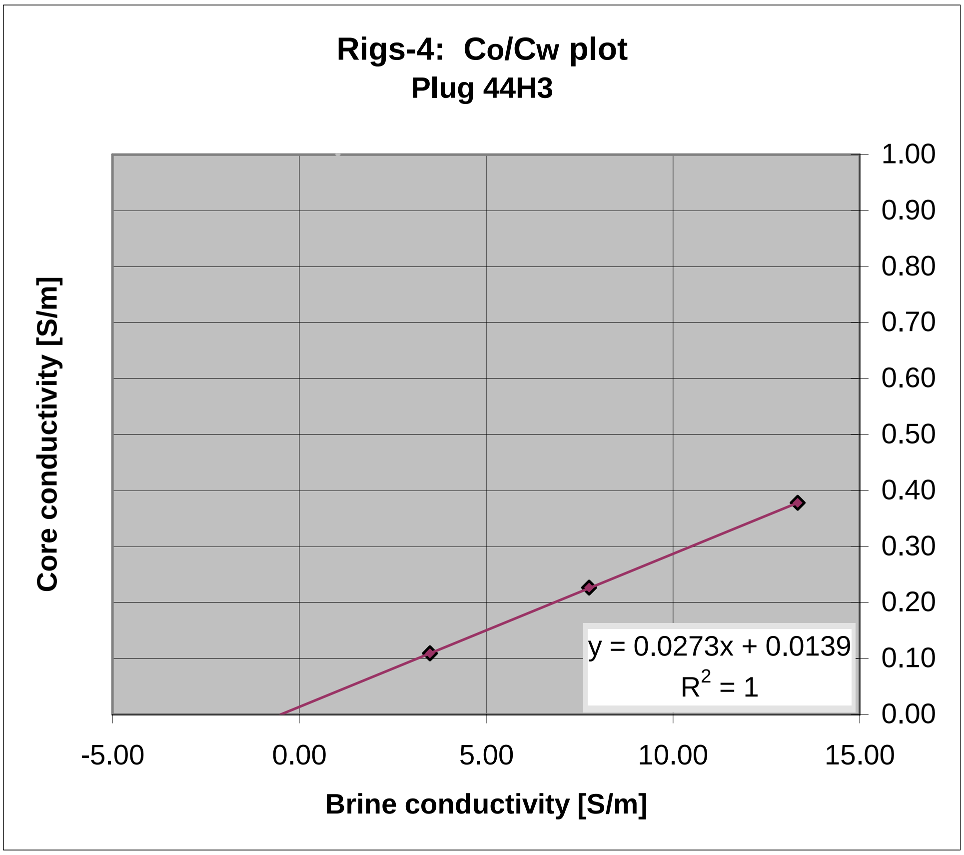


*Figure 5.8. Determination of F* and m* in Hod Fm chalk in the Rigs-4 well.*

| | |
|---|---|
| **Subject: Core conductivity measurements** | **Well: Rigs-4** |
| **@ overburden conditions (1200 psi)** | |
| **Company : Hess DK** | **GEUS Core Lab, 01.07.2010** |

| **Plug no. :** | **46H2** | **m* :** | **2.03** | **Conventional data** | |
|---|---|---|---|---|---|
| Depth [m]: | 2910.44 | | | $k_g$ [mD]: | 0.20 |
| Fm | Hod | | | $Ø_{i(He)}$ [%]: | 21.7 |

| **Brine concentration K [mg/L]** | **Brine conductivity Cw @ 25 °C [S/m]** | **Core conductivity Co @ 25 °C [S/m]** |
|---|---|---|
| 20,600 | 3.50 | 0.16 |
| 51,500 | 7.75 | 0.36 |
| 103,000 | 13.33 | 0.59 |

| | |
|---|---|
| $Ø_{1200\ psi}$ : | 0.214 |
| 1/F* : | 0.0437 |
| BQv : | 0.176 |
| F* : | 22.88 |
| m* : | 2.03 |

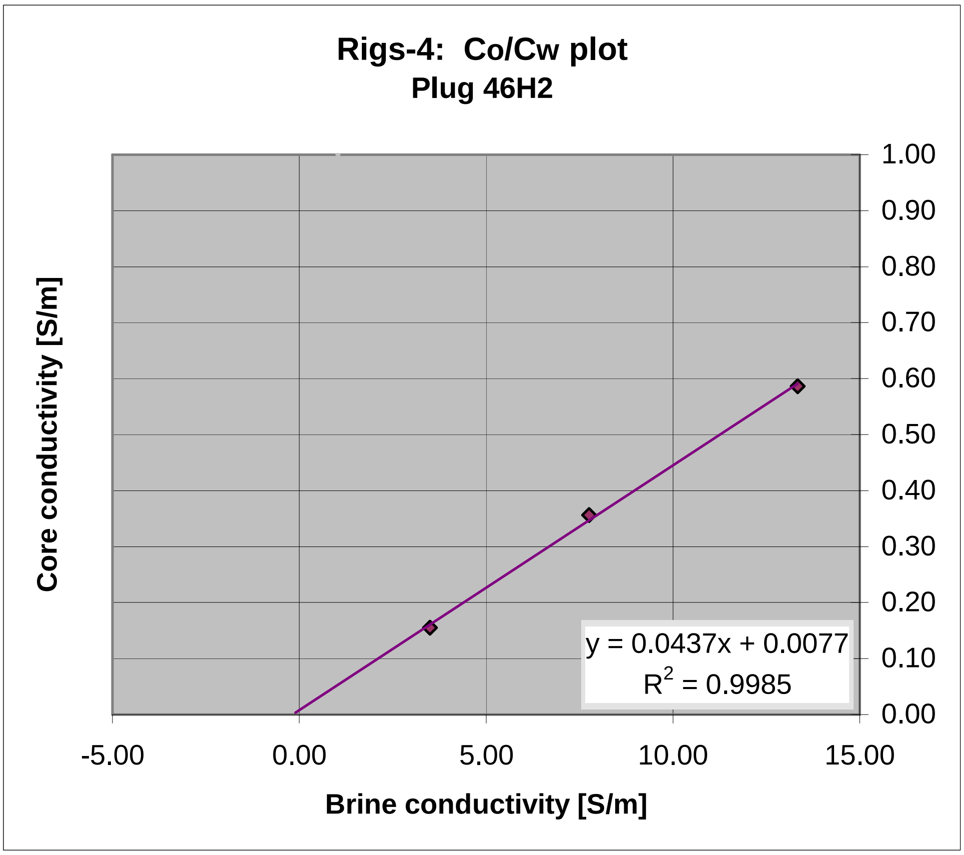


*Figure 5.9. Determination of F* and m* in Hod Fm chalk in the Rigs-4 well.*

| **Subject: Core conductivity measurements @ overburden conditions (1200 psi)** | **Well: Rigs-4** |
|---|---|
| **Company : Hess DK** | **GEUS Core Lab, 01.07.2010** |

| **Plug no. :** | **46H3** | **m* :** | **2.02** | **Conventional data** | |
|---|---|---|---|---|---|
| Depth [m]: | 2910.70 | | | $k_g$ [mD]: | 0.24 |
| Fm | Hod | | | $Ø_{i(He)}$ [%]: | 21.3 |

| Brine concentration<br>K [mg/L] | Brine conductivity<br>Cw @ 25 °C [S/m] | Core conductivity<br>Co @ 25 °C [S/m] |
|---|---|---|
| 20,600 | 3.50 | 0.16 |
| 51,500 | 7.75 | 0.35 |
| 103,000 | 13.33 | 0.58 |

| | |
|---|---|
| $Ø_{1200\ psi}$ : | 0.209 |
| 1/F* : | 0.0427 |
| BQv : | 0.279 |
| F* : | 23.42 |
| m* : | 2.02 |

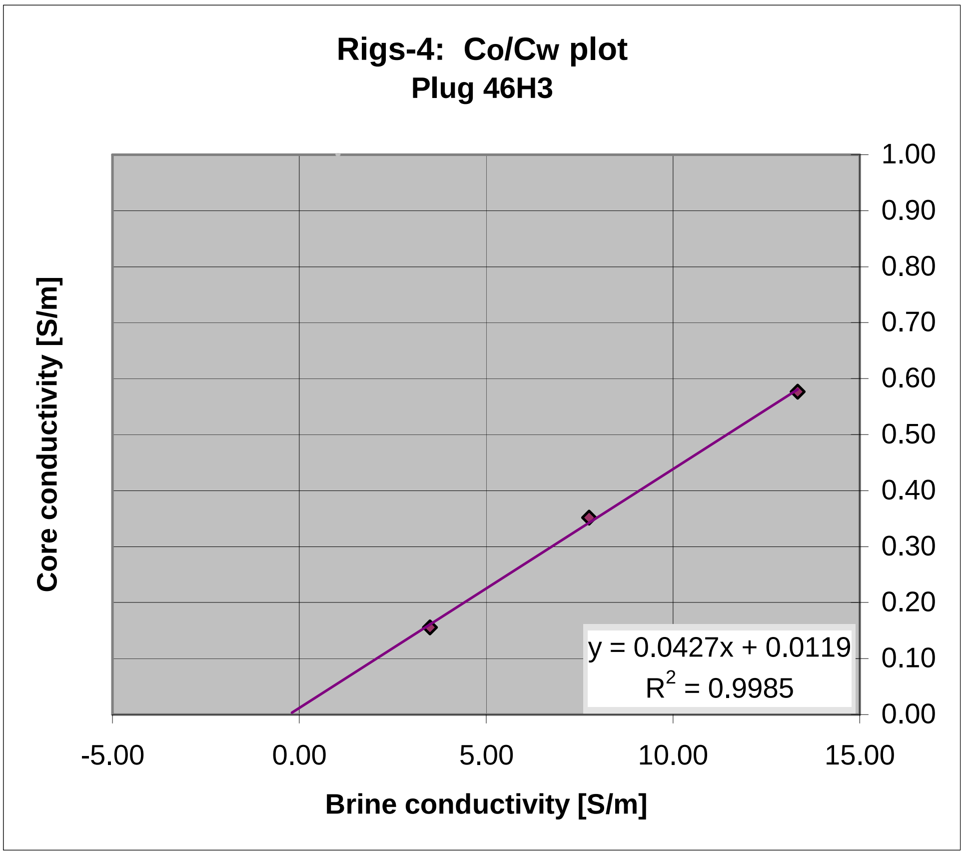


*Figure 5.10. Determination of F* and m* in Hod Fm chalk in the Rigs-4 well.*

| **Subject: Core conductivity measurements @ overburden conditions (1200 psi)** | **Well: Rigs-4** |
|---|---|
| **Company : Hess DK** | **GEUS Core Lab, 01.07.2010** |

| **Plug no. :** | **47H2** | **m* :** | **2.00** | **Conventional data** | |
|---|---|---|---|---|---|
| Depth [m]: | 2911.40 | | | $k_g$ [mD]: | 0.46 |
| Fm | Hod | | | $Ø_{i(He)}$ [%]: | 24.8 |

| **Brine concentration K [mg/L]** | **Brine conductivity Cw @ 25 °C [S/m]** | **Core conductivity Co @ 25 °C [S/m]** |
|---|---|---|
| 20,600 | 3.50 | 0.21 |
| 51,500 | 7.75 | 0.47 |
| 103,000 | 13.33 | 0.79 |

| | |
|---|---|
| $Ø_{1200\ psi}$ : | 0.242 |
| 1/F* : | 0.0582 |
| BQv : | 0.271 |
| F* : | 17.18 |
| m* : | 2.00 |

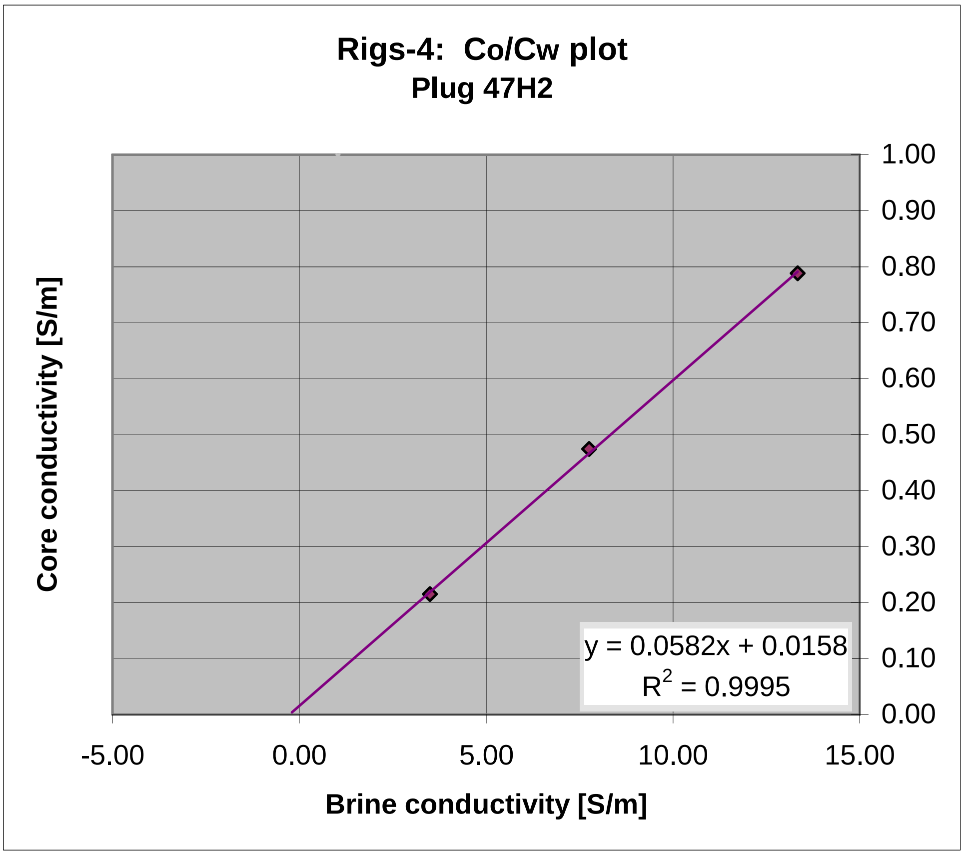


*Figure 5.11. Determination of F* and m* in Hod Fm chalk in the Rigs-4 well.*

| **Subject: Core conductivity measurements @ overburden conditions (1200 psi)** | **Well: Rigs-4** |
|---|---|
| **Company : Hess DK** | **GEUS Core Lab, 01.07.2010** |

| **Plug no. :** | **48H2** | **m* :** | **1.98** | **Conventional data** | |
|---|---|---|---|---|---|
| Depth [m]: | 2912.40 | | | $k_g$ [mD]: | 0.18 |
| Fm | Hod | | | $Ø_{i(He)}$ [%]: | 19.2 |

| **Brine concentration K [mg/L]** | **Brine conductivity Cw @ 25 °C [S/m]** | **Core conductivity Co @ 25 °C [S/m]** |
|---|---|---|
| 20,600 | 3.50 | 0.13 |
| 51,500 | 7.75 | 0.29 |
| 103,000 | 13.33 | 0.50 |

| | |
|---|---|
| $Ø_{1200\ psi}$ : | 0.190 |
| 1/F* : | 0.0371 |
| BQv : | 0.062 |
| F* : | 26.95 |
| m* : | 1.98 |

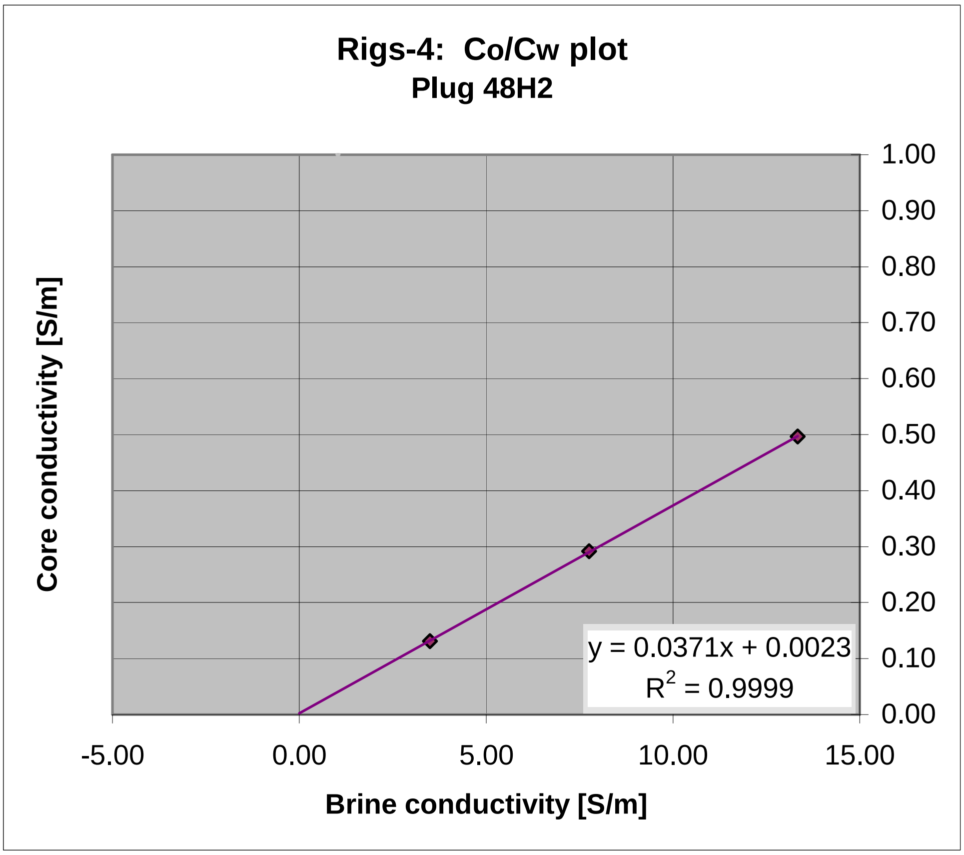


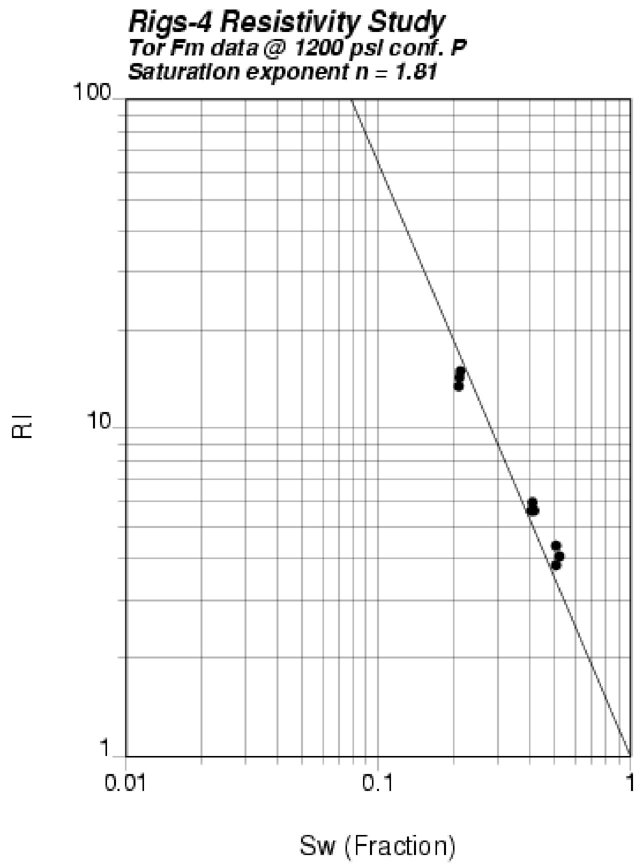
*Figure 5.12. Archie's saturation exponent 'n' for the Tor Fm chalk in the Rigs-4 well.*

| **Subject : Resistivity Index** | **Well: Rigs-4** |
|---|---|
| **Company : Hess DK** | |
| **Overburden RI data and saturation exponent 'n'** | **GEUS Core Lab, 01.03.2010** |

**Reservoir unit: Tor Fm** **Regression 'n' : 1.81**

| Well | Plug no. | Depth | Overburden data @ 1200 psi confining P | | | |
|---|---|---|---|---|---|---|
| | | [m] | Ø [%] | Sw [%] | RI | Archie 'n' |
| Rigs-4 | 1H2 | 2865.40 | 22.6 | 50.9 | 3.84 | 1.99 |
| | 1H3 | 2865.71 | 20.4 | 50.8 | 4.40 | 2.19 |
| | 3H2 | 2867.40 | 18.8 | 52.2 | 4.07 | 2.16 |
| Rigs-4 | 1H2 | 2865.40 | 22.6 | 40.7 | 5.64 | 1.93 |
| | 1H3 | 2865.71 | 20.4 | 40.8 | 5.94 | 1.99 |
| | 3H2 | 2867.40 | 18.8 | 41.6 | 5.63 | 1.97 |
| Rigs-4 | 1H2 | 2865.40 | 22.6 | 21.0 | 14.31 | 1.70 |
| | 1H3 | 2865.71 | 20.4 | 21.2 | 14.93 | 1.74 |
| | 3H2 | 2867.40 | 18.8 | 20.9 | 13.42 | 1.66 |

**Multi sample plot:**




| | |
|---|---|
| Number of data | 9 |
| Number plotted | 9 |
| X Variable: | |
| geom. mean | 0.354 |
| std. dev. | 1.461 |
| Y Variable: | |
| geom. mean | 6.937 |
| std. dev. | 1.694 |
| Correlation | -0.996 |
| Rank correlation | -0.900 |
| Regression: | |
| intercept | 1.00 |
| slope | -1.81 |

*Figure 5.13. Archie's saturation exponent 'n' for the Tor Fm chalk in the Rigs-4 well; single saturation step data demonstrating decreasing 'n' with $S_w$.*

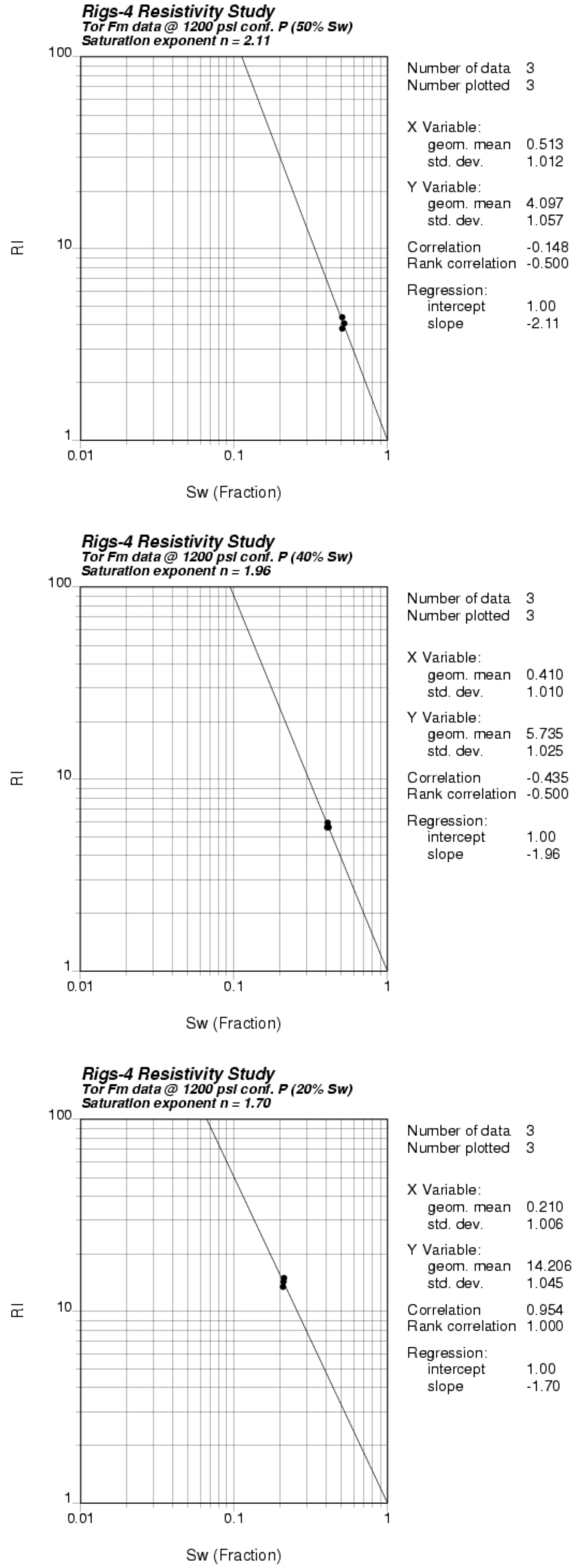


*Figure 5.14. Archie's saturation exponent 'n' for the Hod Fm chalk in the Rigs-4 well.*

| **Subject : Resistivity Index** | **Well: Rigs-4** |
|---|---|
| **Company : Hess DK** | |
| **Overburden RI data and saturation exponent 'n'** | **GEUS Core Lab, 07.01.2010** |

**Reservoir unit:** **Hod Fm** **Regression 'n' :** **1.80**

| Well | Plug no. | Depth | Overburden data @ 1200 psi confining P | | | |
|---|---|---|---|---|---|---|
| | | [m] | Ø [%] | Sw [%] | RI | Archie 'n' |
| **Rigs-4** | **46H2** | 2910.44 | 21.4 | 52.2 | 3.36 | 1.87 |
| | **46H3** | 2910.70 | 20.9 | 51.7 | 4.18 | 2.17 |
| | **47H2** | 2911.40 | 24.2 | 50.0 | 4.10 | 2.03 |
| | **48H2** | 2912.40 | 19.0 | 51.5 | 5.06 | 2.44 |
| **Rigs-4** | **46H2** | 2910.44 | 21.4 | 41.1 | 5.30 | 1.87 |
| | **46H3** | 2910.70 | 20.9 | 40.5 | 6.08 | 2.00 |
| | **47H2** | 2911.40 | 24.2 | 41.3 | 5.24 | 1.87 |
| | **48H2** | 2912.40 | 19.0 | 41.1 | 5.63 | 1.95 |
| **Rigs-4** | **46H2** | 2910.44 | 21.4 | 23.3 | 12.59 | 1.74 |
| | **46H3** | 2910.70 | 20.9 | 21.7 | 14.08 | 1.73 |
| | **47H2** | 2911.40 | 24.2 | 21.0 | 12.53 | 1.62 |
| | **48H2** | 2912.40 | 19.0 | 20.9 | 15.61 | 1.76 |

**Multi sample plot:**

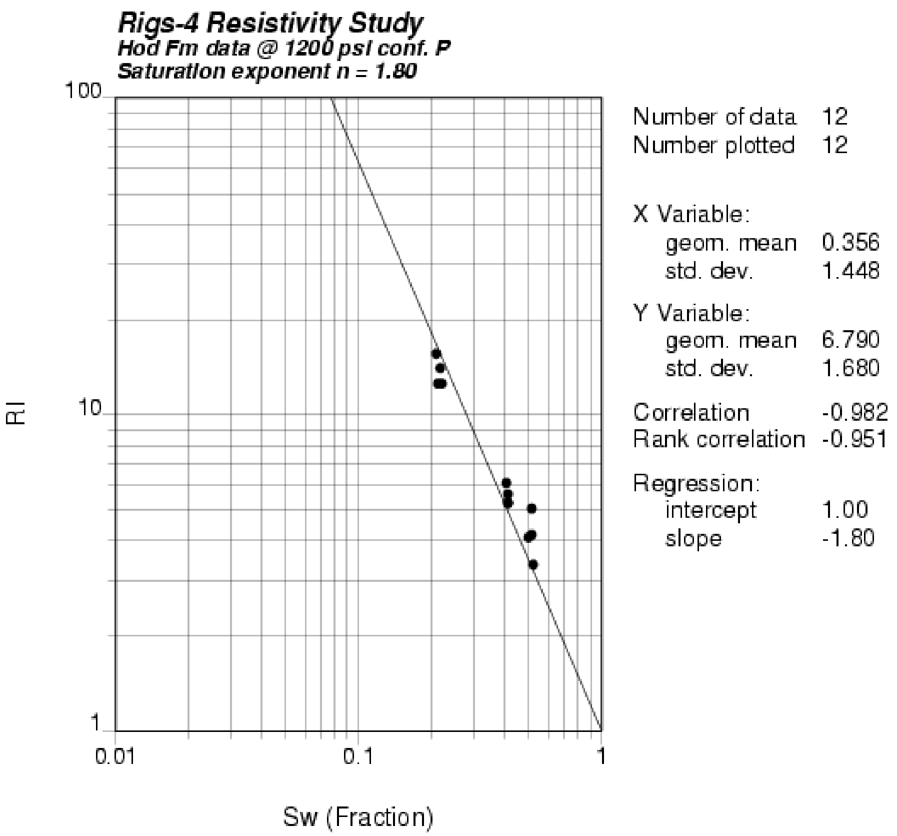
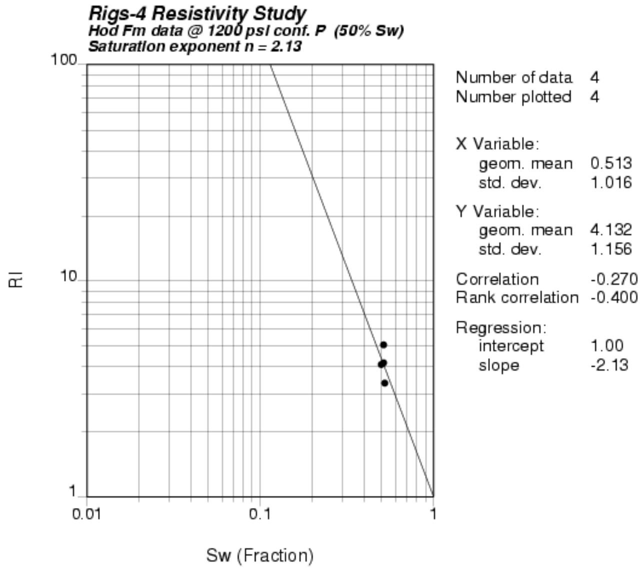
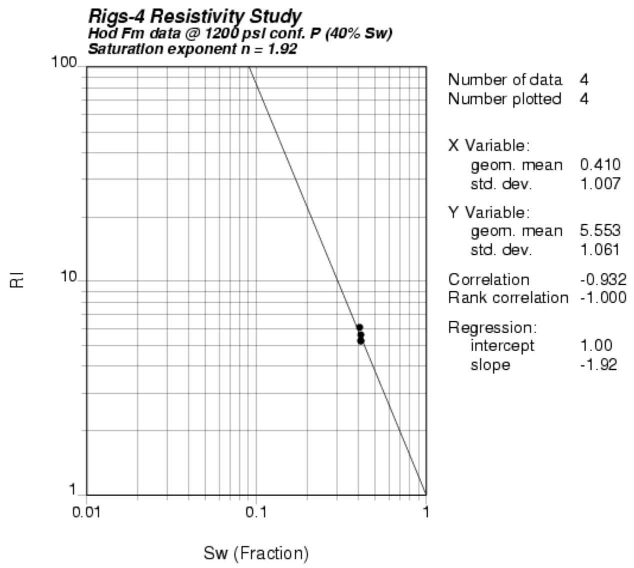
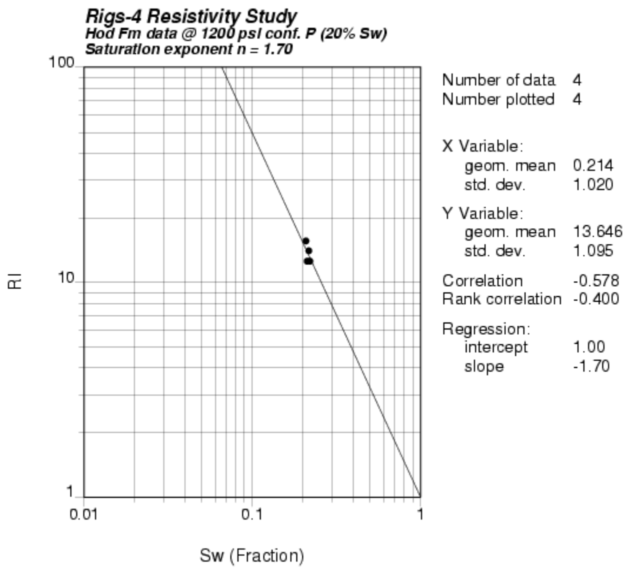


*Figure 5.15. Archie's saturation exponent 'n' for the Hod Fm chalk in the Rigs-4 well; single saturation step data demonstrating decreasing 'n' with $S_w$.*



# 6 References


1. Springer, Niels: Special Core Analysis for Amerada Hess Denmark. South Arne Field. Electrical properties.
   Geological Survey of Denmark and Greenland Report no. 24, 2005. Confidential.

2. Springer, Niels: Special Core Analysis for Amerada Hess Denmark. Well: Rigs-3, electrical properties and permeability at overburden stress conditions.
   Geological Survey of Denmark and Greenland Report no. 85, 2007. Confidential.

3. N. Springer, U. Korsbech, H.K. Aage: Resistivity Index Measurement without the Porous Plate: A Desaturation Technique Based on Evaporation Produces Uniform Water Saturation Profiles and More Reliable Results for Tight North Sea Chalk.
   Intl SCA Symp.,Pau, (September 2003), paper SCA 2003-38, p. 459-470.

4. SCA Guidelines for sample preparation and porosity measurement of electrical resistivity samples, part I-IV.
   The Log Analyst, **31**, 1 & 2, 1990.

5. Lindgren et al.: The structure and diagenetic transformation of illite-smectite and chlorite-smectite from North Sea Cretaceous-Tertiary chalk. Clays and Clay Minerals vol. **37**, 2002, 429-450.

6. Lindgren et al.: Clay mineralogy of the Central North Sea Upper Cretaceous-Tertiary chalk and the formation of clay-rich layers. Clays and Clay Minerals vol. **56**, 2008, 693-710.

7. Waxman, M.H. & Smits, L.J.M.: "Electrical conductivities in oil-bearing shaly sands". SPEJ, **8**, 1968, p. 107-122.

8. Worthington, P.F. & Pallatt, N.: " Effect of variable saturation exponent upon the evaluation of hydrocarbon saturation". Paper SPE 20538 presented at the 1990 SPE Annual Technical Conference and Exhibition held in New Orleans, LA, 23–26 September 1990.

9. Worthington, P.F et al..: "Influence of microporosity on the evaluation of hydrocarbon saturation". SPEFE, **4**, 1989, p. 203-209.

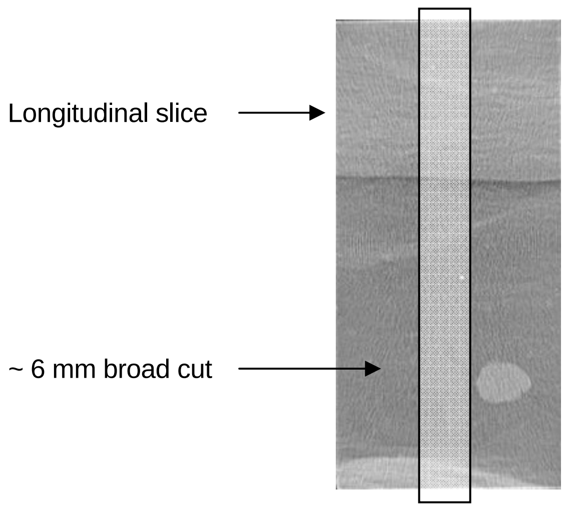
10. Worthington, P.F.: "Characterization of the intrinsic porosity exponent through dual-salinity measurements of electrical conductivity."
    Intl SCA Symp.,Pau, (September 2003), paper SCA 2003-30, p. 361-372.

# 7 Plug quality screening

### Scanning parameters

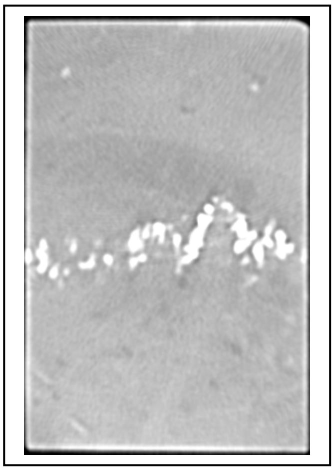
| | |
|---|---|
| Sellar-ear | Ultra High |
| 120 kV | 330 mAs |
| Time= | 2 s |
| Slice= | 4 mm |

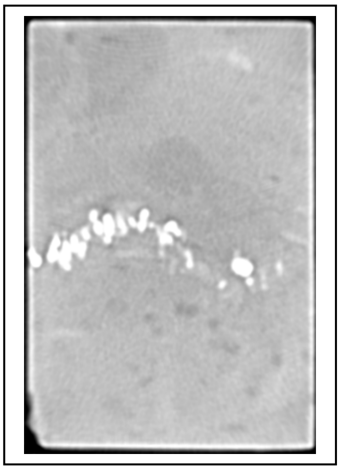
The images below are close to real plug size and represent 2 longitudinal slices perpendicular to each other through the plug sample. The thickness of each slice is 4 mm. To the right is shown the spectral (grey tone) distribution of an approx. 6 mm broad cut through each slice (cf. the figure below) to visualize the matrix homogeneity and structural elements. The distance axis corresponds to the length of the sample image, the grey scale is in CT units; -1000 represents air (100% porosity), +3000 is dense matrix (0% porosity). The average CT-number and standard deviation for the 2 longitudinal slices is given in the info box; this figure is proportional to the sample porosity. Typical CT-numbers for North Sea chalk are in the range 1200-2500. Homogeneous chalk samples have standard deviations < 80 CT-units on a pixel level (less than ± 1.5 porosity-% variation)

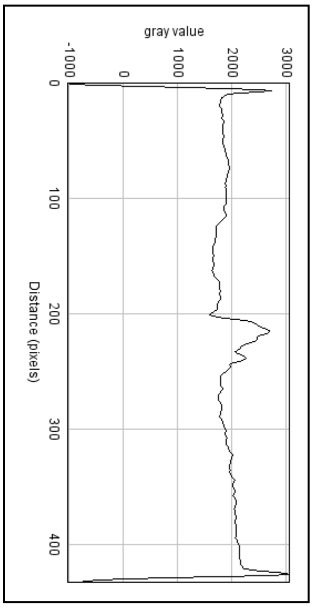


**Plug HS1, Depth : 2865.00 m**
2 perpendicular cuts,

Mean CT number : 1969
Sdev : 234
Porosity : 23.8 [%]
Comment : This (vertical) plug contains a stylolite seam filled with pyrite

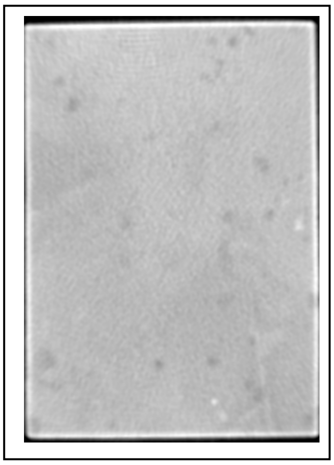


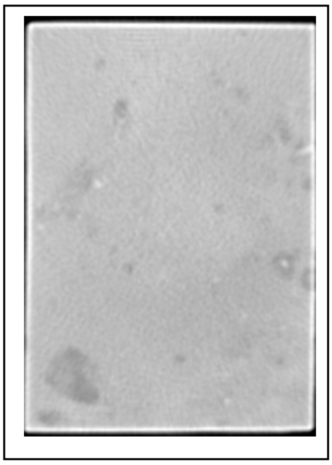


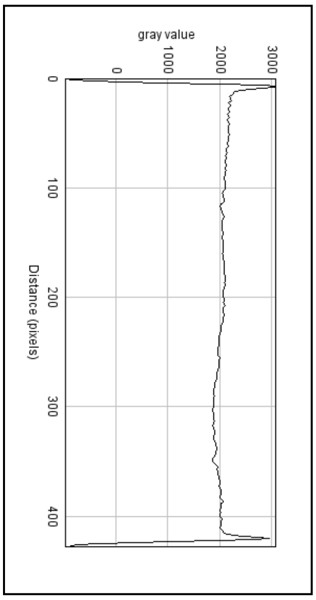



**Plug 1H2, Depth : 2865.40 m**
2 perpendicular cuts,

Mean CT number : 2015
Sdev : 124
Porosity : 23.0 [%]





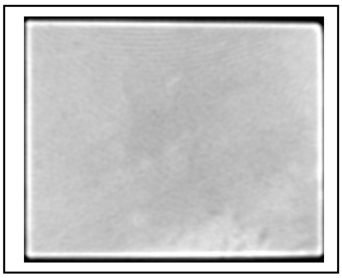


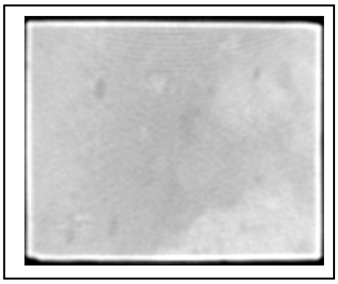
**Plug 1H3, Depth : 2865.71 m**

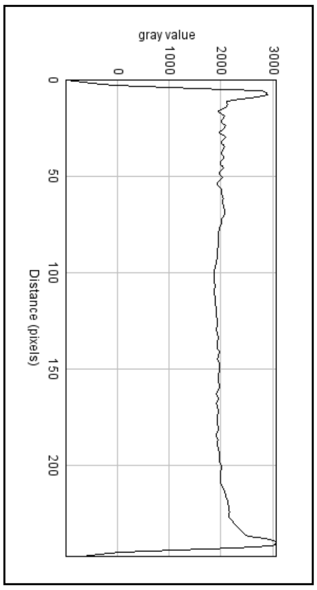


2 perpendicular cuts,

Mean CT number : 2024
Sdev : 149
Porosity : 20.6 [%]



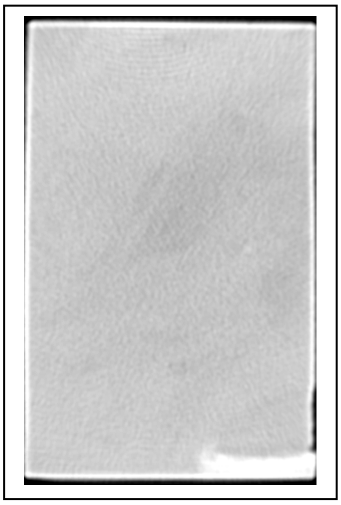


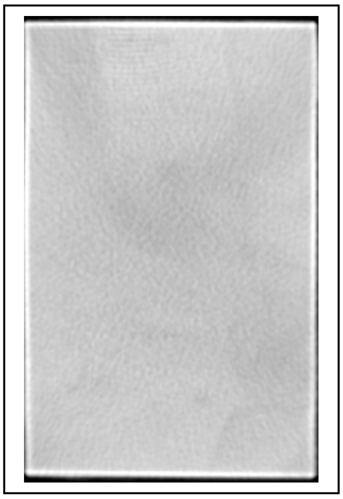


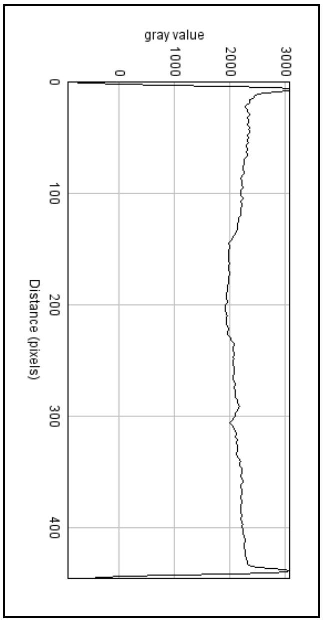

**Plug HS2, Depth: 2866.00 m**

2 perpendicular cuts,

Mean CT number : 2170
Sdev : 129
Porosity : 17.6 [%]

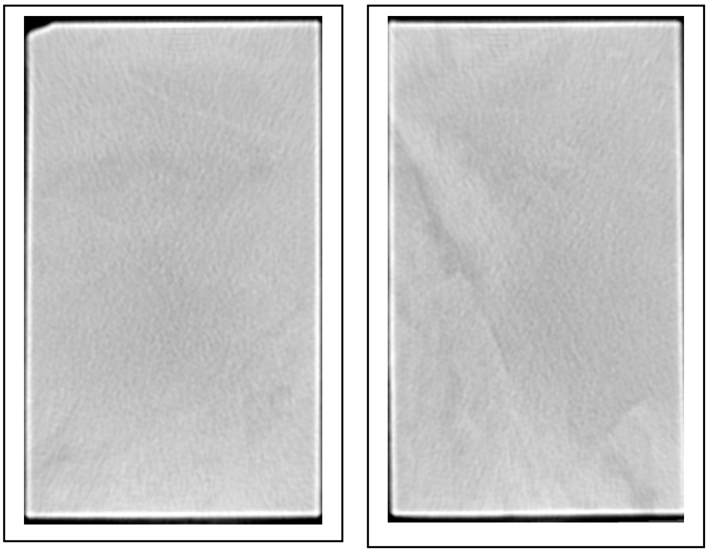


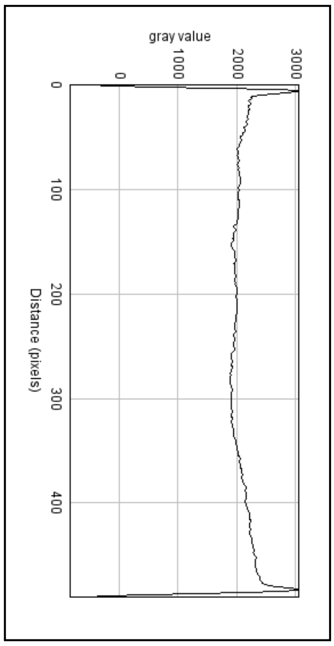




**Plug 2H2, Depth : 2866.40 m**
2 perpendicular cuts,

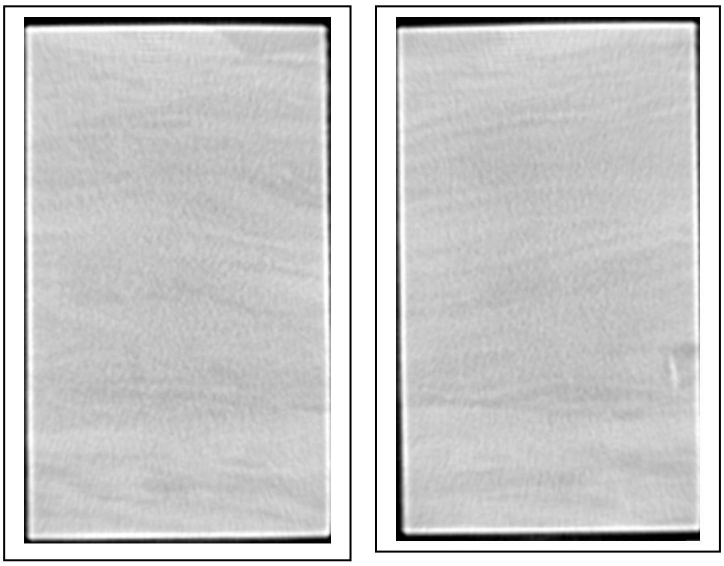
Mean CT number : 2088
Sdev : 124
Porosity : 19.1 [%]

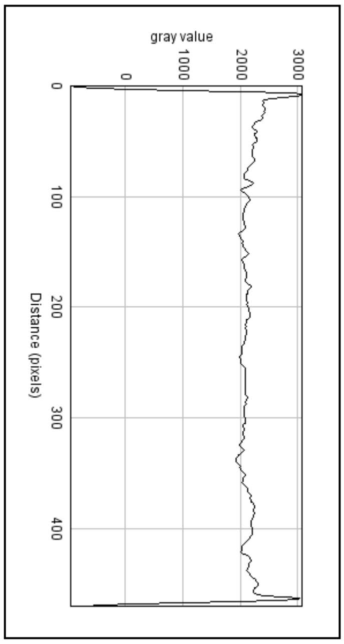





**Plug HS3, Depth: 2867.00 m**
2 perpendicular cuts,

Mean CT number : 2156
Sdev : 107
Porosity : 17.6 [%]



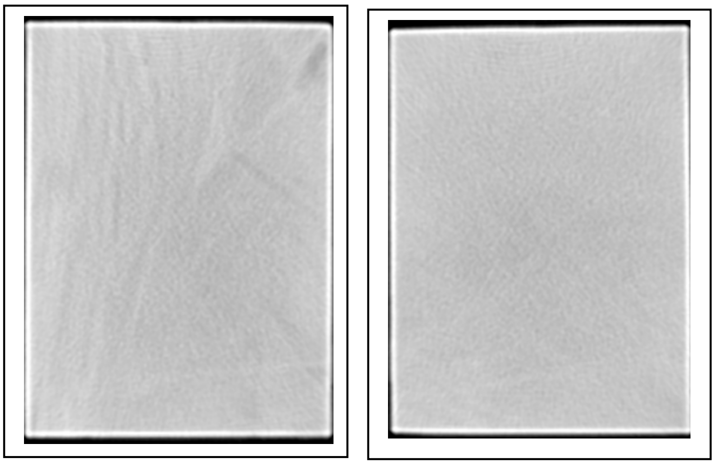


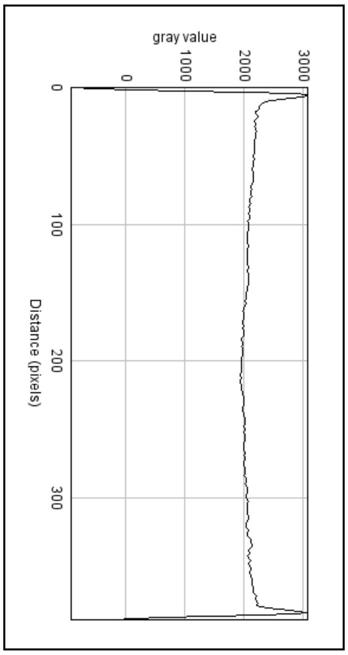
**Plug 3H2, Depth : 2867.40 m**



2 perpendicular cuts,

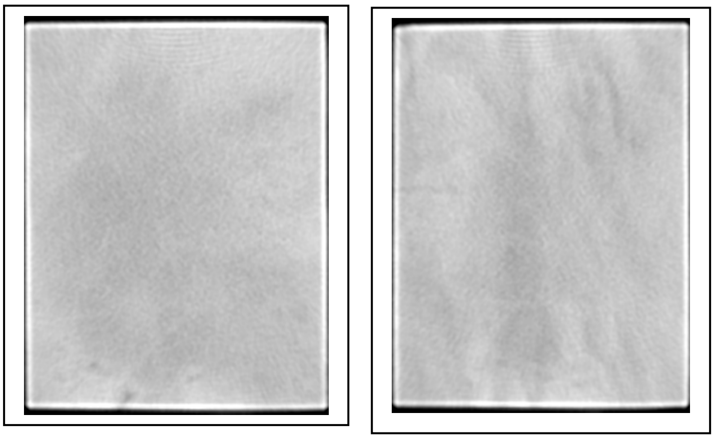
Mean CT number : 2122
Sdev : 99
Porosity : 19.1 [%]

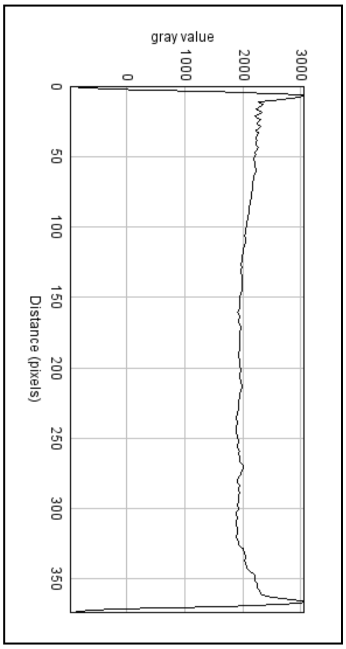





**Plug 3H3, Depth : 2867.67 m**
2 perpendicular cuts,

Mean CT number : 2091
Sdev : 141
Porosity : 19.7 [%]



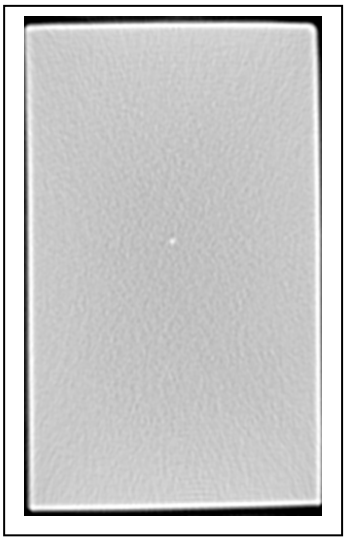


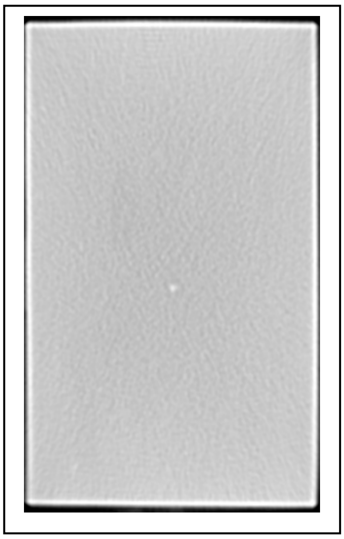
continue overleaf with the Hod Fm plugs

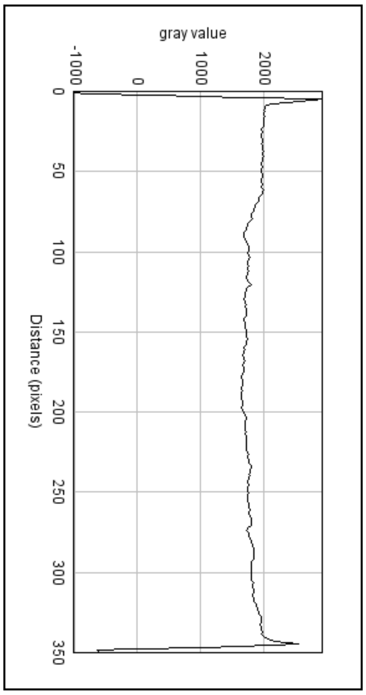
**Plug 44H3, Depth: 2908.74 m**
2 perpendicular cuts,

**Rigs-4, Hod Fm chalk**

Mean CT number : 2158
Sdev : 84
Porosity : 16.8 [%]

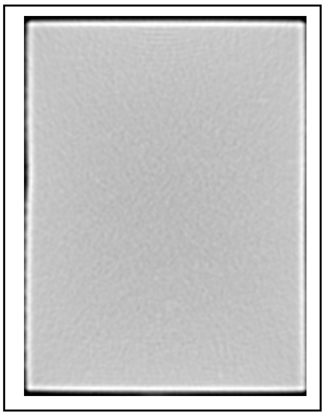


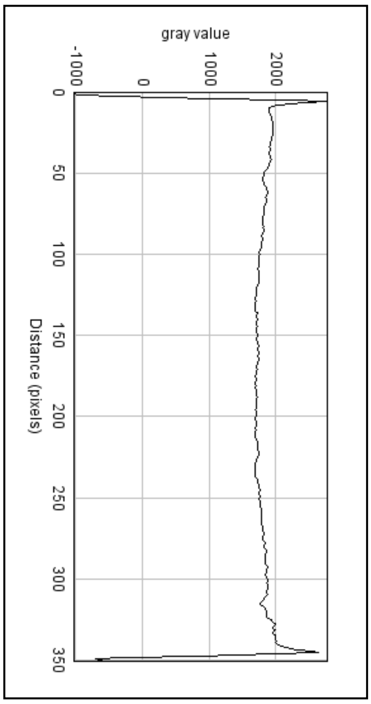





**Plug HS32, Depth: 2910.00 m**
2 perpendicular cuts,

Mean CT number : 2078
Sdev : 71
Porosity : 20.8 [%]



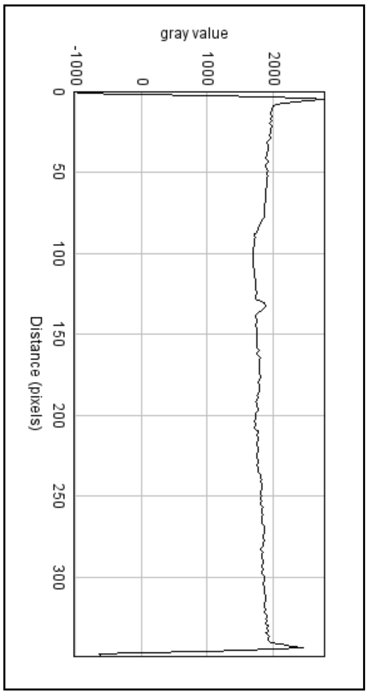


**Plug 46H2, Depth: 2910.44 m**
2 perpendicular cuts,

**Rigs-4, Hod Fm chalk**

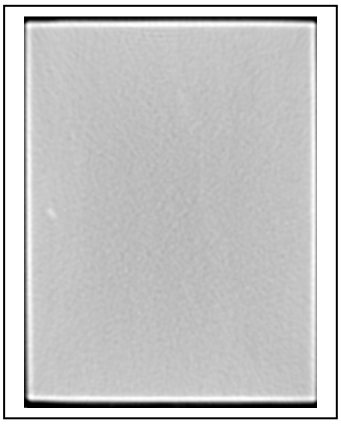
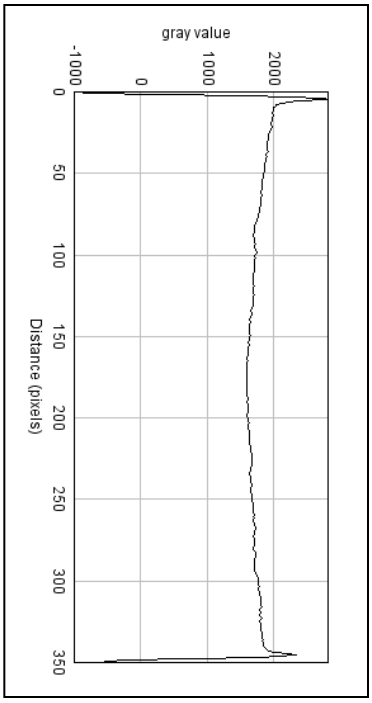
Mean CT number : 2029
Sdev : 79
Porosity : 21.4 [%]






**Plug 46H3, Depth: 2910.70 m**
2 perpendicular cuts,

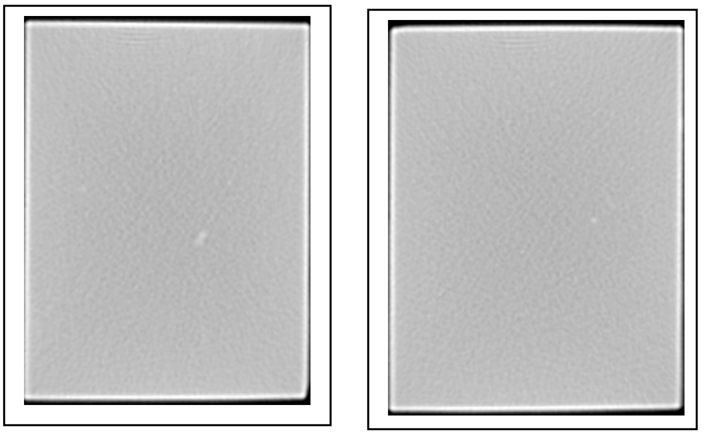
Mean CT number : 2069
Sdev : 72
Porosity : 20.9 [%]

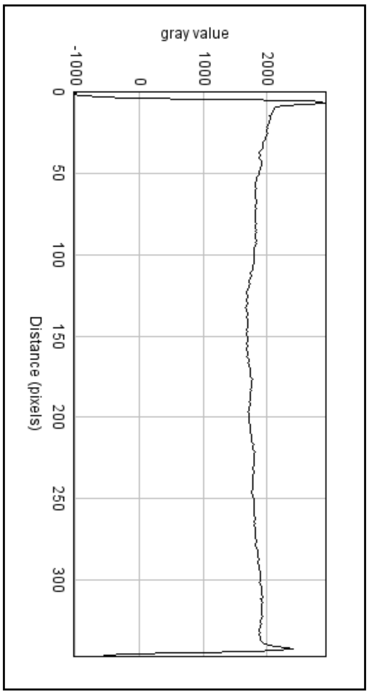




**Plug 46H4, Depth: 2910.94 m**
2 perpendicular cuts,

**Rigs-4, Hod Fm chalk**

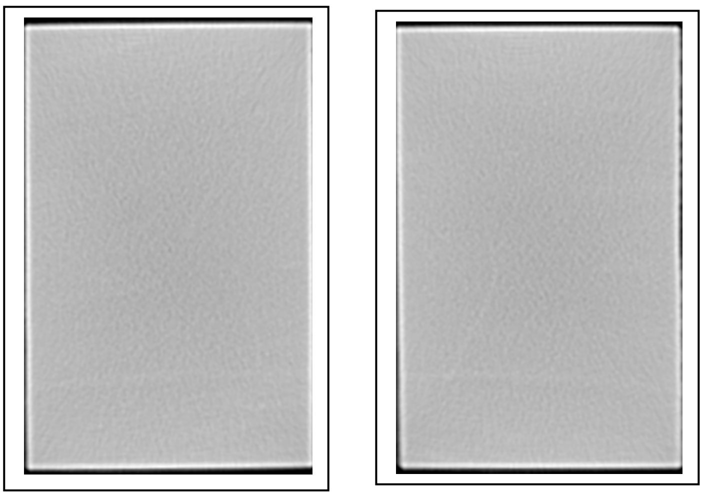
Mean CT number : 1995
Sdev : 69
Porosity : 23.2 [%]

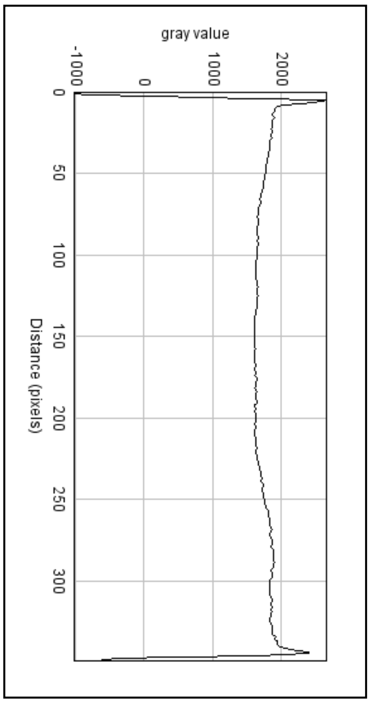





**Plug HS33, Depth: 2911.00 m**
2 perpendicular cuts,

Mean CT number : 1917
Sdev : 74
Porosity : 24.6 [%]

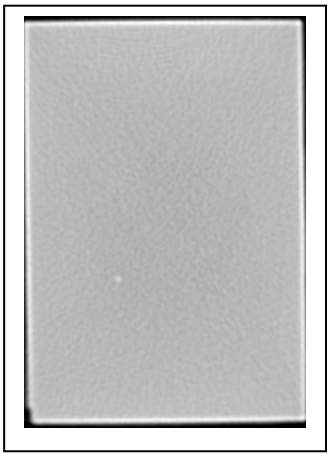


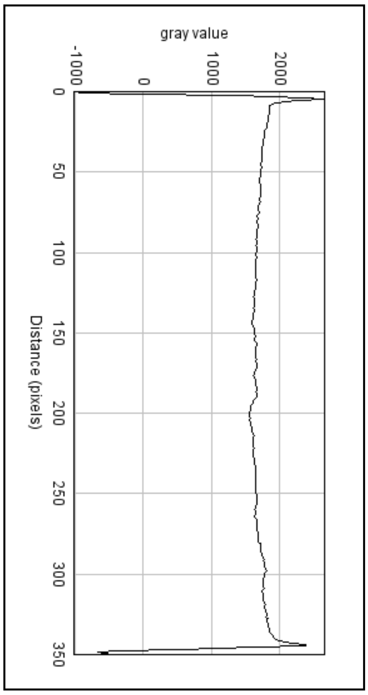


**Plug 47H2, Depth: 2911.40 m**
2 perpendicular cuts,

**Rigs-4, Hod Fm chalk**

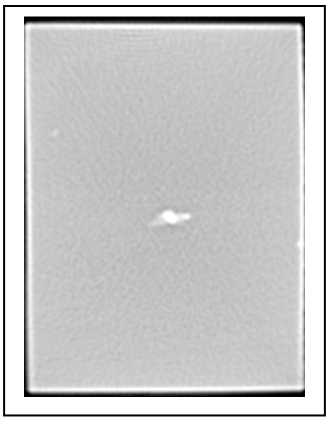
Mean CT number : 1931
Sdev : 72
Porosity : 24.4 [%]

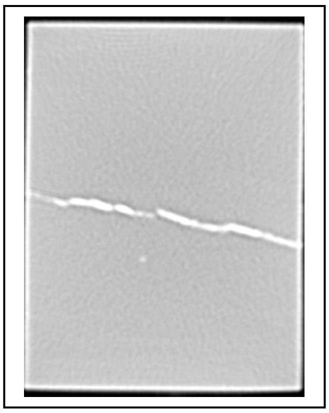


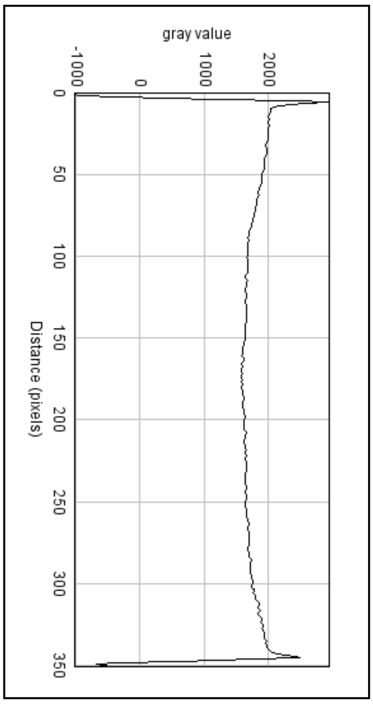



**Plug HS34, Depth: 2912.00 m**
2 perpendicular cuts,

Mean CT number : 2131
Sdev : 110
Porosity : 19.5 [%]

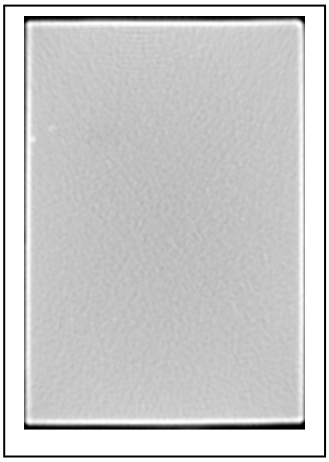


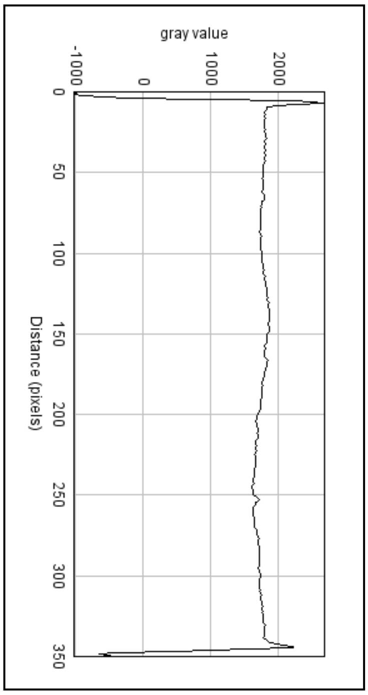




**Plug 48H2, Depth: 2912.40 m**
2 perpendicular cuts,

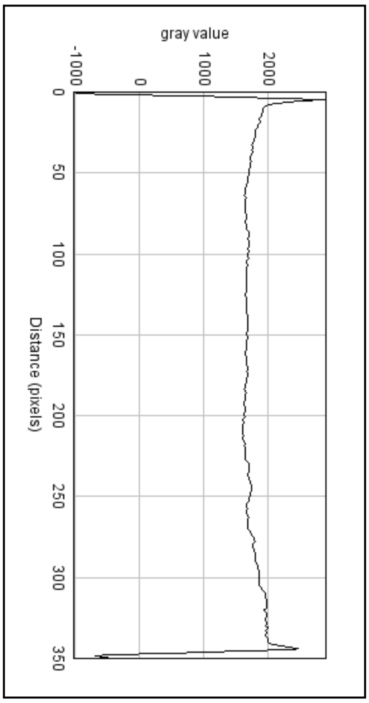
Mean CT number : 2125
Sdev : 74
Porosity : 19.0 [%]






**Plug 48H3, Depth: 2912.70 m**
2 perpendicular cuts,

Mean CT number : 2097
Sdev : 68
Porosity : 20.2 [%]

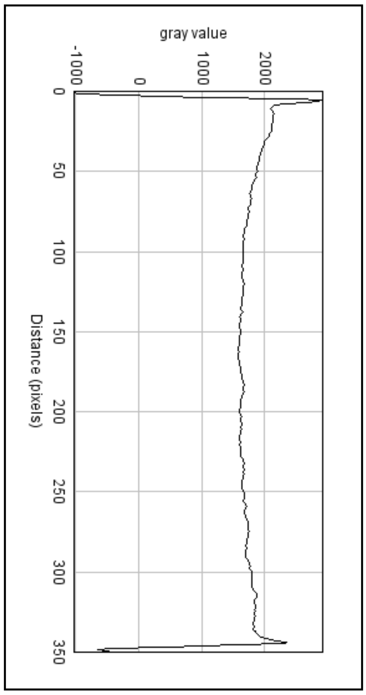


**Plug 49H3, Depth: 2913.70 m**
2 perpendicular cuts,

**Rigs-4, Hod Fm chalk**

Mean CT number : 2151
Sdev : 75
Porosity : 18.6 [%]






**Plug 50H2, Depth: 2914.42 m**
2 perpendicular cuts,

Mean CT number : 2165
Sdev : 74
Porosity : 18.0 [%]