GEUS
Report File no.
13181

RIGS-1

Rigs-1, Special core analysis. Capillary pressure and electrical properties at room and overburden conditions

Springer, N.

Copenhagen
01-09-1996

GEOLOGICAL SURVEY OF
DENMARK AND GREENLAND
REPORT 1996/26

Special Core Analysis for Amerada Hess Ltd.

Well: Rigs - 1
Capillary pressure and electrical properties at room and overburden conditions

Core Laboratory

By Niels Springer

GEUS
Geological Survey of
Denmark and Greenland

1. Introduction

By request of Amerada Hess Ltd., GEUS Core Laboratory has carried out a special core analysis programme on samples from the Rigs-1 well, Danish North Sea.

The analytical programme was agreed with Mr. Mads Sørensen, Amerada Hess London Office, and the contract - service order number S10886/NKM - was signed on 01.08.1995. This contract covers the following services:

- Mercury injection test
- Capillary pressure and resistivity index at room conditions
- Formation resistivity factor at overburden conditions

The mercury injection study has been completed earlier and the report forwarded to Amerada Hess Ltd. on 10.11.1995. The remaining part of the analytical programme is presented in this report.

2. Sampling and analytical procedure

The samples used in the special core analysis programme were selected from the routine plug set listed in the conventional core analysis report[1], ref. letter dated 30 May, 1995 from Mr. Mads Sørensen. Six samples were taken for the capillary pressure/resistivity index study, and 9 samples were included in the formation resistivity factor study. A list of samples and the measured conventional data is given in table 2.1 and 2.2. All plugs were horizontal with a diameter of 1½" and a nominal length of 2½".

2.1 Capillary pressure and resistivity index measurements

The oil-water capillary drainage curve was measured using the porous plate method at room conditions at the following 6 pressure steps: 3, 6, 12, 24, 40 and 90 psi. The cleaned and dried samples were vacuum saturated with simulated degassed formation brine in a desiccator for several days. An Archimedes test was carried out before the samples were finally placed in single sample capillary cells/core holders. Oil pressure was applied to the cells, and when brine production equilibrium had been obtained, or latest after 3 - 4 weeks, the plug electrical impedance was measured. At completion of the study, the Archie saturation exponent n was calculated for each plug, and the cementation exponent m was determined from multi sample plots, section 5. Fluid data are listed in table 2.3.

2.2 Formation resistivity factor measurements

The formation resistivity factor was measured at room temperature as a function of overburden pressure. Based on information supplied by Amerada Hess, the following 3 effective confining pressure steps were decided: 645, 1935 and 4113 psi. An additional pressure step of 161 psi was included to help define the liquid production curve. The cleaned and dried samples were vacuum saturated with simulated degassed formation brine in a desiccator for several days. An Archimedes test was carried out before the samples were finally placed in electrical, hydrostatic core holders. To secure complete saturation, the plugs were flushed in the core holders, and in some severe cases the sleeve pressure were cycled up and down during continued flushing. The samples were left to settle for at least 5 hours at each pressure step to obtain drainage equilibrium before the electrical impedance was measured. After completion of the study, the porosity reduction, the pore volume compressibility and the formation resistivity factor was calculated for each plug sample, and the Archie cementation exponent m was determined from multi sample plots, section 5.

1. Conventional core analysis for Amerada Hess (DK) A/S. Well: Rigs-1. DGU Service Report no. 17, 1995.

Table 2.1. Rigs-1/SCAL: List of plug samples analyzed in the capillary pressure study.

Well: Rigs-1 / P_C + RI plugs for room condition study				
Plug no.	**Depth in feet**	**Permeability mD**	**Porosity %**	**Grain density g/cc**
83	9176.32	1.37	34.27	2.709
119	9206.32	0.63	31.84	2.705
164	9244.05	0.75	30.98	2.708
214	9288.14	0.44	19.55	2.714
234	9305.31	4.96	36.78	2.715
259	9325.30	6.10	42.00	2.714

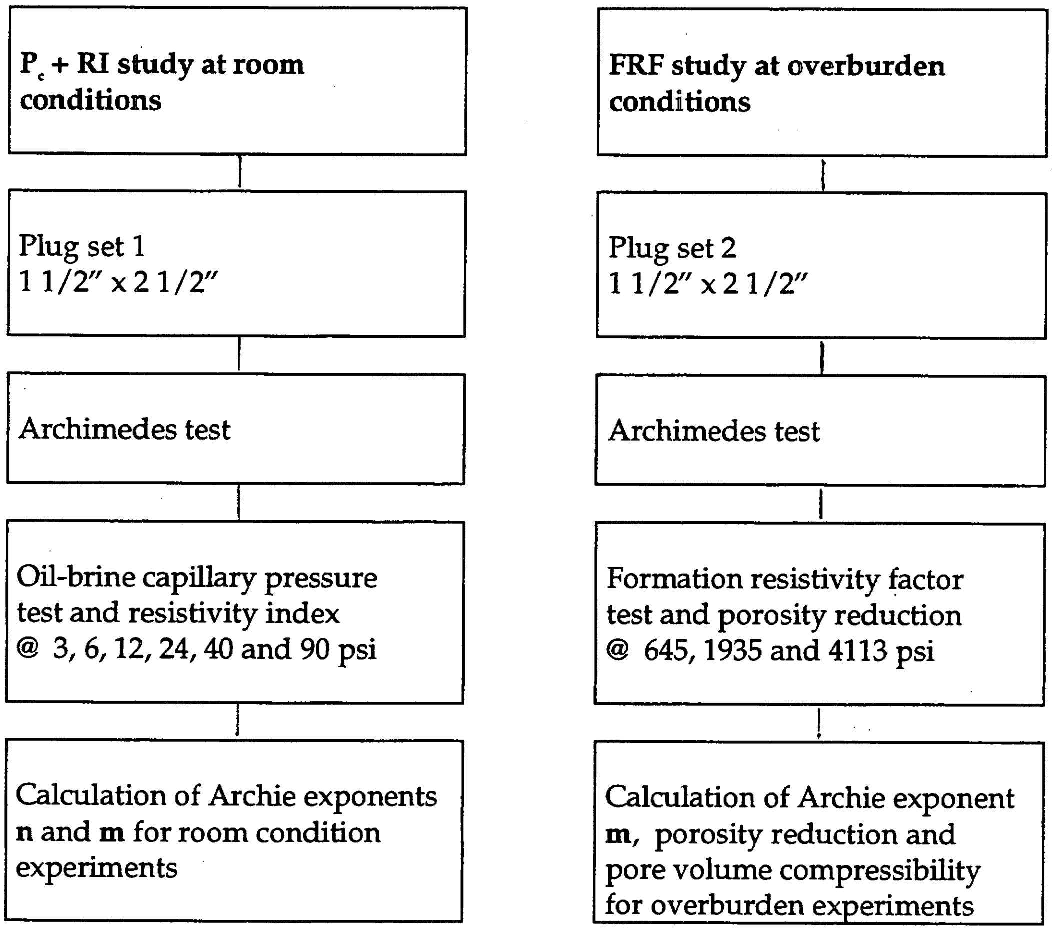
Table 2.2. Rigs-1/SCAL: List of plug samples analyzed in the formation factor study.

Well: Rigs-1 / FRF plugs for overburden pressure study				
Plug no.	**Depth in feet**	**Permeability mD**	**Porosity %**	**Grain density g/cc**
53	9152.31	0.46	25.32	2.700
89	9182.30	0.88	35.00	2.697
124	9211.31	0.57	31.94	2.697
151	9233.32	0.65	28.96	2.703
189	9266.32	0.12	15.88	2.704
212	9286.82	0.55	21.00	2.703
221	9294.32	2.82	33.79	2.706
259	9325.30	6.10	42.00	2.714
265	9329.49	3.85	39.21	2.707

Table 2.3. Rigs-1/SCAL: Fluid data.

Brine data:			
Chemical composition Element	**Conc. mg/l**	**Density @ 23 °C g/ml**	**Resistivity @ 23 °C ohm-m**
Na^{+}	32.500	1.075	0.0839
K^{+}	1.000		
Mg^{2+}	1.200		
Ca^{2+}	8.300		
Cl^{-}	68.950		
TDS	111.950		
Oil data:			
Type			
Exxon Chemical, Isopar-L		0.764	

3. Flow diagram of the analytical procedure



4. Analytical methods

For an explanation of the routine core analysis methods, please refer to the conventional core analysis report.

Room condition measurements

Room condition experiments is conducted at a constant temperature of 22 ° C. Deviations from this temperature is within ±1 ° C. Experimental conditions valid for the present study are described in section 2.

4.1 Archimedes porosity

Samples that are saturated to 100% with a liquid, can have their bulk volume determined by Archimedes test, i.e. by submersion in a jar containing the saturating liquid and weighing of the buoyancy. If the sample grain density is known, or can be estimated with good precision, the sample pore volume and porosity can be calculated.

4.2 Oil-brine capillary pressure (porous plate method)

The cleaned and dried plug is saturated to 100% using a suitable deaerated simulated formation brine and then placed at the saturated porous plate in a single sample pressure cell (ResLab cell), or the sample is mounted in a core holder. If a core holder is used, a moderate sleeve pressure of 100 psi is applied, and this is kept as an effective confining stress during the whole experiment. Care is taken to secure a good capillary contact between the plug and the porous plate especially when using the 15 bar plate. Oil pressure is applied to the pressure cell/core holder and the effluent from the cell is volumetrically read from a graduated collection tube. When a constant volume is achieved, the oil pressure is increased till the next pressure step without interrupting the experiment. After completion of the experiment a mass balance calculation is performed to secure consistency between volumetric and gravimetric readings (initial and final weight of the plug sample).

Normally 5 to 8 pressure steps in the range 0.5 - 90 psi are measured, and a curve displaying the relationship between fluid pressure P_c and brine saturation S_w is produced. This is the oil-brine capillary pressure curve for the plug sample.

Table 4.1. Conversion of laboratory measured capillary pressure data.
Capillary pressure can be measured using different fluid pairs. Conversion from one fluid pair P_{a1} to another pair P_{a2} can be roughly performed using the multipliers in the table below.

$$P_{a1} = P_{a2} * F$$

P_{a1}	P_{a2}	Multiplier F
brine-gas	brine-oil	1.7
brine-oil	brine-gas	0.6
brine-gas	gas-Hg	0.2
gas-Hg	brine-gas	5
brine-oil	gas-Hg	0.1
gas-Hg	brine-oil	9

Basic data[2]:

Fluid pair	Contact angle degrees	Surface tension dyn/cm
brine-gas	0	72
brine-oil	30	48
gas-Hg	140	480

4.3 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 should produce a straight line from which the saturation exponent n can be determined as the slope.

The measurement of RI involves desaturation in a porous plate cell, therefore the measurement of RI is conveniently combined with air/brine or oil/brine capillary pressure experiments. A pressure pot or a special resistivity cell/core holder is required for this measurement. The resistivity of the plug is measured at each pressure step. The two-electrode method is applied, and the resistivity measured as the impedance to an AC signal of 1 kHz frequency. Data logging is performed using a HP 4276A LCZ-meter controlled by a HP 85 desktop computer which allows fast data collection.

When the desaturation (capillary pressure measurement) is conducted in single sample cells, the advantage is that the experiment does not need to be interrupted to determine the water saturation, which is necessary in the traditional multi sample pressure pot experiment. The disadvantage is that the resistivity measurement will include the porous plate as well as the sample. The effect of the porous plate, which can be significant, must be corrected for. This is done by measuring the plug in a resistivity core holder 100% saturated before the experiment and again after the experiment when the plug is at S_{wir}. The data measured in the combined resistivity cell/core holder is then corrected according to these two measurements.

Overburden measurements

4.4 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, constantly monitored using an electronic Mettler balance connected to a HP 85 desktop computer. The final reading is taken when a stable level has been reached on the balance. The porosity reduction is calculated as the relative decrease in the initial porosity:

$$\emptyset_i = \frac{V_{pi}}{V_{bi}}$$

$$\emptyset_{i+\Delta p} = \frac{V_{pi} - \Delta V_p}{V_{bi} - \Delta V_p}$$

The porosity reduction is then given as:

$$\frac{\emptyset_{i+\Delta p}}{\emptyset_i}\cdot 100\% = \frac{V_{pi}-\Delta V_p}{V_{bi}-\Delta V_p}\cdot\frac{V_{bi}}{V_{pi}}\cdot 100\%$$

Where $\emptyset_i$ = initial porosity
V_{pi} = initial pore volume
V_{bi} = initial bulk volume
$\emptyset_{i+\Delta p}$ = new porosity induced by a certain change Δp in confining stress.
ΔV_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).

In this study the produced liquid was measured at effective confining stresses of 161, 645, 1935 and 4113 psi. From these measurements the liquid production curve was fitted manually because no simple mathematical function fitted the observed points.

4.5 Pore volume compressibility

The pore volume compressibility is calculated from the data recorded during the porosity reduction experiment as follows:

$$C_p = \frac{1}{V_p}\cdot\frac{dV_p}{dp_{eff}}$$

where:
C_p = Pore volume compressibility [vol/vol*psi]
V_p = Sample pore volume at a certain effective confining stress (ECS)
dV_p = Incremental change in pore volume resulting from an incremental change in ECS
dp_{eff} = Incremental change in ECS

The relationship dV_p/dp_{eff} is obtained by numerical or graphical differentiation of the liquid production curve.

Both the incremental change of pore volume and the pore volume compressibility has been calculated from the liquid production curve, section 5.

4.6 Formation resistivity factor

In a "clean" formation (non-shaly) the formation factor F is described by Archie's equation:

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

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:

$$\log F = -m \log \O + \log a$$

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. Therefor a set of regression constants are given for a regression line which has been biased through (1,1).

The measurement of F at overburden conditions is carried out in combination with the porosity reduction/pore volume compressibility test. The two electrode method is normally applied and the resistance measured as the impedance to an AC signal of 1 Khz frequency. The resistivity of the brine is measured in a specially designed standard cell. The standard cell is calibrated using a suitable conductivity standard solution delivered by a recognised chemical company. Data logging is performed using the HP 4276A LCZ-meter controlled by a HP 85 desktop computer which facilitates fast data collection.

The measurement of the formation resistivity factor was conducted after the plugs had reached drainage equilibrium at the subject stress level (in general 3-6 hours, some samples even longer).

4.7 Stress conversion in laboratory overburden tests

The stress conditions prevailing in a reservoir rock can be expressed by Terzaghi's equation:

$$\sigma_{eff} = \sigma_{tot} - \sigma_{res} \tag{1}$$

σ_{eff} : effective confining stress - ECS (= net overburden pressure).
σ_{tot} : total confining stress due to the overburden load.
σ_{res} : reservoir fluid pore pressure.

In petrophysical laboratory tests a hydrostatic core holder is normally used in overburden experiments. This core holder subjects the sample to an isotropic stress in the 3 main directions x, y, z. However, Geertsma[3] has shown that the compaction in a reservoir depends on the reservoir geometry, and that reservoirs with large lateral extension compared to their vertical thickness deform mainly in the vertical direction z. For equal pressures in hydrostatic and uniaxial loading the uniaxial strain is related to the bulk volume strain (hydrostatic volumetric strain) by the relation proposed by Teeuw[4]:

$$\varepsilon_z = \frac{1}{3}\left(\frac{1+\upsilon}{1-\upsilon}\right)\varepsilon_b \tag{2}$$

ε_z : vertical strain
ε_b : bulk volumetric strain
υ : Poissons ratio

Teeuw[4] demonstrated that for most rocks Poissons ratio υ falls in the range 0.25 - 0.35. Assuming a constant value of 0.3, equation (2) reduces to:

$$\varepsilon_z = 0.62\,\varepsilon_b \tag{3}$$

This means that the error in translation from hydrostatic to uniaxial compaction for most rocks will be in the order of +/- 10% for a constant $\upsilon = 0.3$.

Therefore in laboratory testing where hydrostatic confinement be used, the following translation should be applied to convert data to downhole uniaxial stress conditions:

$$\sigma_{lab} = 0.62\,\sigma_{eff} \tag{4}$$

σ_{lab} : laboratory applied hydrostatic pressure (HSP).

Teeuw[4] recommended the following procedure for laboratory compaction measurements on friable and consolidated rocks:

1. Hydrostatic compaction tests should be carried out on suites of samples systematically taken from the reservoir in question.

2. A limited number of samples should be measured in uniaxial compaction cells at K_o conditions ($\varepsilon_x = \varepsilon_y = 0$). This will enable a determination of Poissons ratio for the reservoir rock.

3. Based on the average Poissons ratio measured under #2, hydrostatic compaction data is translated to uniaxial compaction data using the relationship given in equation (2).

In this study effective confining stresses of 645, 1935 and 4113 psi have been applied. This translates to laboratory hydrostatic pressures of 400, 1200 and 2550 psi. The pressure steps were decided based on information from Amerada Hess of a reservoir total confining stress of ~ 8200 psi and reservoir pore pressure of 6280 psi.

2. Archer, J.S & Wall, C.G.: Petroleum Engineering, Principles and practice. Graham & Trotman, London (1986).
3. Geertsma, J.: Problems of rock mechanics in petroleum production engineering. Proc. 1st Int. Congr. Rock Mech., Lisbon (1966).
4. Teeuw, D.: Prediction of formation compaction from laboratory compressibility data. SPEJ, September, 1971, 263-271.

5. Results

At the time of printing it is uncertain where the division between the Ekofisk and Tor formation will be placed. Therefore samples 212 and 214 are included in both formations and they appear in both the Ekofisk and Tor diagrams in the following.

5.1 Room condition experiments

The results of the capillary pressure-resistivity index study are presented in tables and diagrams in section 5.3. An estimate of the capillary entry pressure P_e for the oil-brine - rock system is given in table 5.1.

Observations:

- The samples were very difficult to saturate completely. After installation in the capillary drainage cells it was observed that the samples **imbibed** small amounts of brine for a period of 3 weeks before steady state was obtained and the drainage experiment could be started.

- The Tor Fm plugs (214, 234, 259) were close to drainage equilibrium after 3 weeks at each pressure step, but the Ekofisk Fm plugs (83, 119, 164) never reached equilibrium within this period. This means that the true P_c curve for the Ekofisk plugs is displaced towards the left, i.e. towards lower water saturations, relative to the curves shown in the P_c diagrams. To obtain drainage equilibrium for Ekofisk material, several months is often required at each pressure step.

- In contrast to the capillary pressure data, the electrical measurements are not affected by disequilibrium conditions as long as the water saturation can be correctly determined simultaneous with the resistivity measurement. In the resistivity index diagram the data points will move up and down along the regression line, the slope of the line will not change however, which means that the saturation exponent n will be unaffected.

Table 5.1. Rigs-1/SCAL. Capillary entry pressures for the oil-brine-rock system estimated from the diagrams in section 5.3.

Plug no.	**Capillary Entry Pressure P_e, psi**	
	Interval	Best estimate
83	12-24	22
119	12-24	21
164	12-24	21
214	6-12	10
234	6-12	11
259	12-24	12

- Plug 259 started to drain when the pressure was raised to 24 psi, which means that P_e is placed in the interval 12 to 24 psi. This is a surprisingly high P_e for a Tor Fm sample of 42% porosity. No visible lithological structures in the plug could explain this result.

- A fairly high saturation exponent of 2.43 was measured for plug 164. With only 4 points measured and 3 points falling close to (1,1) a possible error in the last point measured at 90 psi capillary pressure will affect the slope of the regression line proportionally.

5.2 Overburden condition experiments

The results of the formation resistivity factor study are presented in tables and diagrams in section 5.4.

Observations:

- The plug weight before and after overburden test is an indication of the reservoir rock reaction to the testing conditions. Table 5.2 shows that most samples responded elastically to the applied hydrostatic pressure. It may be speculated if the high porosity samples 89, 259 and 265 suffered a slight compaction, but the recorded data are close to the error inherent in this check.

- The normal to low pore volume compressibility data recorded for the whole suite of samples could indicate that compaction is unlikely to occur even for the high porosity chalk.

Table 5.2. Rigs-1/SCAL. Plug weight before and efter overburden testing.

Plug no.	Porosity %	Pore volume ml	Weight before test g	Weight efter test g
53	25.32	18.19	163.95	164.28
89	35.00	20.98	127.88	127.54
124	31.94	22.74	155.05	154.85
151	28.96	19.17	147.70	147.50
189	15.88	11.43	175.76	175.74
212	21.00	15.03	168.80	168.76
221	33.79	14.83	94.41	94.52
259	42.00	18.88	90.88	90.62
265	39.21	26.93	141.88	141.57

5.3 Figures and tables (room condition study)

Rigs-1/SCAL: Capillary pressure and resistivity index study.

Room condition data.

Initial impedance Z_0 measured @ 1kHz in a resistivity core holder @ 100 psi confining pressure.

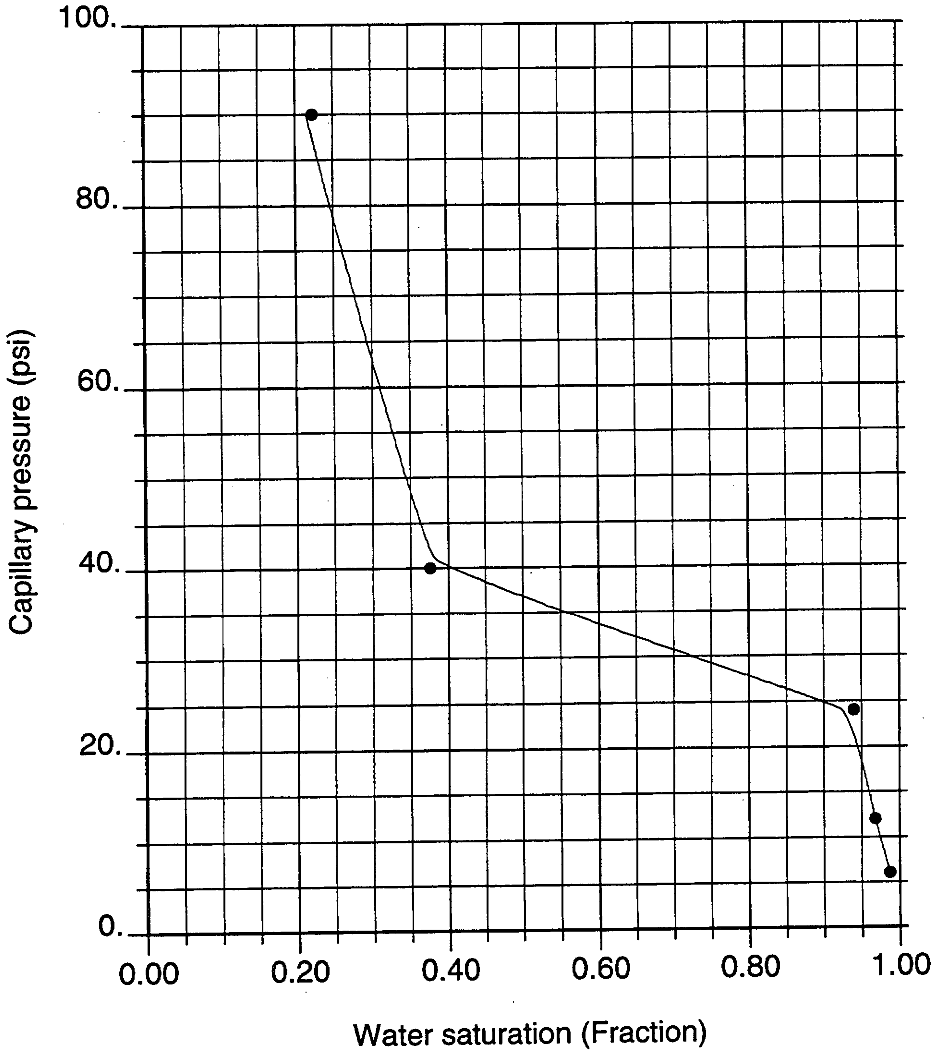
Well: Rigs-1	P_c + RI plugs		R_W : 0.0839 Ωm		T : 22±1 °C	
Plug no.	**Depth feet**	**Por. Ø**	**Z_0 @ 100 psi 100% S_W**	**Saturation Exponent n**	**Formation Resistivity Factor**	**Cementation Exponent m**
83	9176.32	34.27	38.0	2.11	10.47	**Ekofisk Fm.**
119	9206.32	31.84	38.7	2.00	11.33	**2.09**
164	9244.05	30.98	41.8	2.43	12.95	
214	9288.14	19.55	120.1	1.95	25.31	**Tor Fm.**
234	9305.31	36.78	30.5	2.01	6.40	**1.93**
259	9325.30	42.00	15.3	2.04	4.95	

Mean cementation exponent m: 2.04

Well: Rigs-1, Plug 83

Depth: 9176.3 f   Porosity: 34.3%

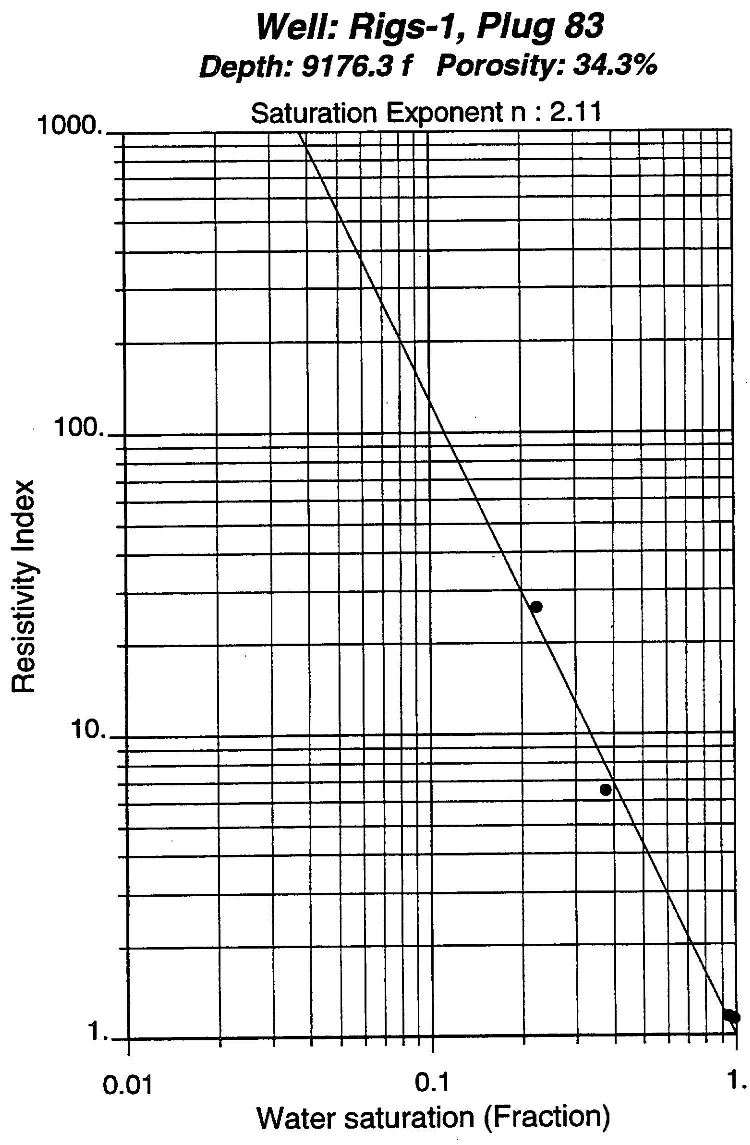
Oil/Water Capillary Pressure Curve



Porosity: 34.27 %

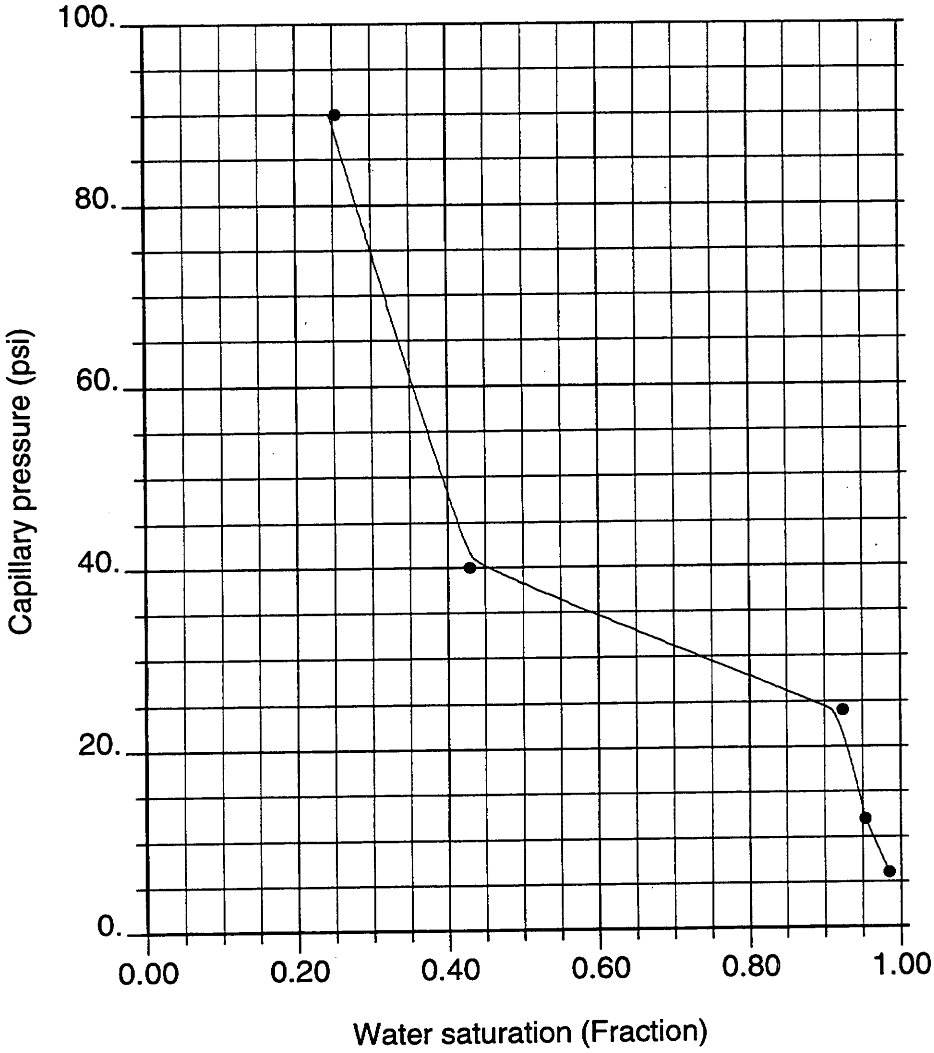
PV = 18.65 ml

Pressure psi	Sat.vol. ml	Dr.vol. ml	Diff ml	Sw %	Z ohm	RI
0	19.38	19.38	0.00	100.0	38.0	1.00
3	19.38	19.38	0.00	100.0	38.0	1.00
6	19.38	19.16	0.22	98.82	42.8	1.13
12	19.38	18.79	0.59	96.84	43.3	1.14
24	19.38	18.27	1.11	94.05	44.0	1.16
40	19.38	7.75	11.63	37.64	247	6.50
90	19.38	4.91	14.47	22.41	1000	26.3



Number of data	5
X variable mean	0.597
std. dev.	1.843
Y variable mean	3.030
std. dev.	3.572
Correlation	-0.996
Rank correlation	-1.000
Regression a	1.0
Regression b	-2.105

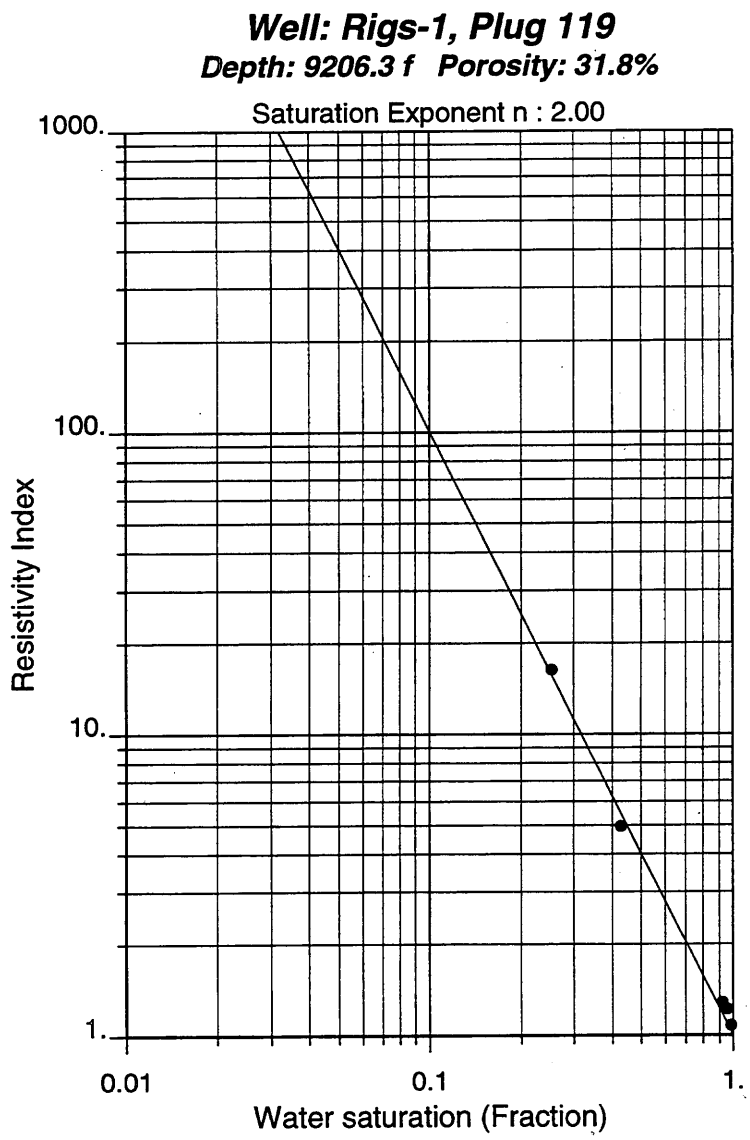
Well: Rigs-1, Plug 119
Depth: 9206.3 f   Porosity: 31.8%
Oil/Water Capillary Pressure Curve



Porosity: 31.84 %

PV = 16.39 ml

Pressure psi	Sat.vol. ml	Dr.vol. ml	Diff ml	Sw %	Z ohm	RI
0	14.14	14.14	0.00	100.0	38.7	1.00
3	14.14	14.14	0.00	100.0	38.7	1.00
6	14.14	13.90	0.24	98.54	41.7	1.08
12	14.14	13.38	0.76	95.36	47.1	1.22
24	14.14	12.89	1.25	92.37	49.5	1.28
40	14.14	4.79	9.35	42.95	191	4.94
90	14.14	1.91	12.23	25.38	630	16.3

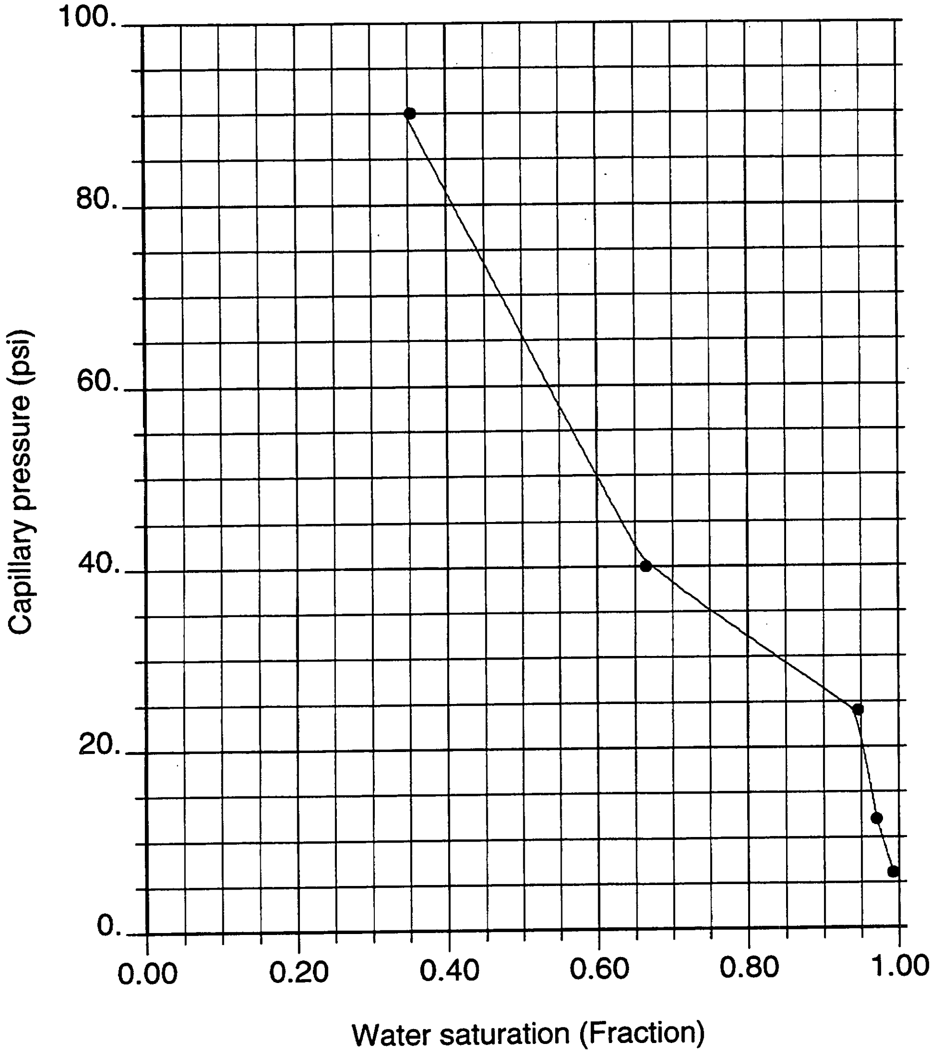


Number of data	5
X variable mean	0.624
std. dev.	1.726
Y variable mean	2.670
std. dev.	2.888
Correlation	-0.998
Rank correlation	-1.000
Regression a	1.0
Regression b	-2.002

Well: Rigs-1, Plug 164

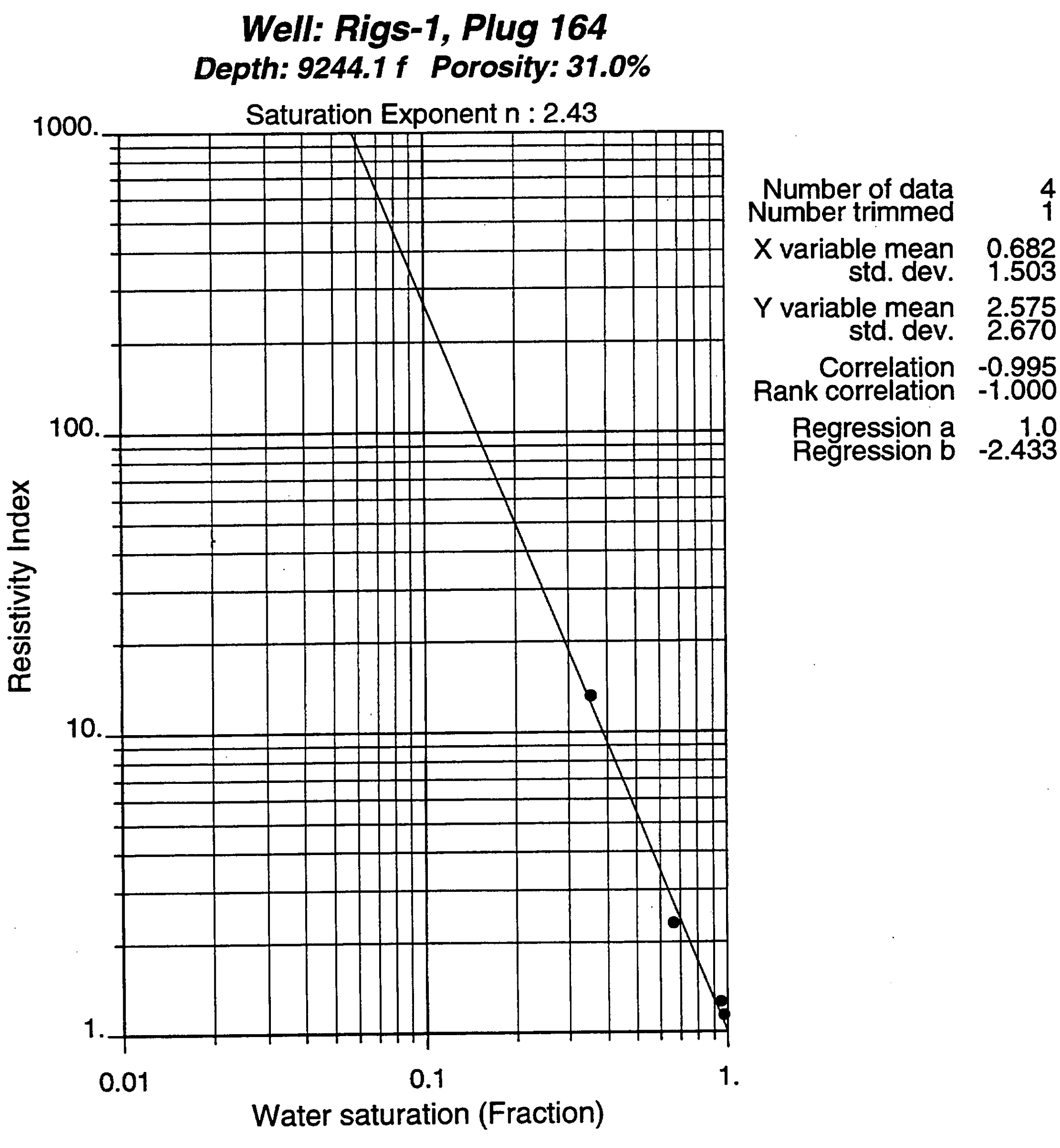
Depth: 9244.1 f Porosity: 31.0%

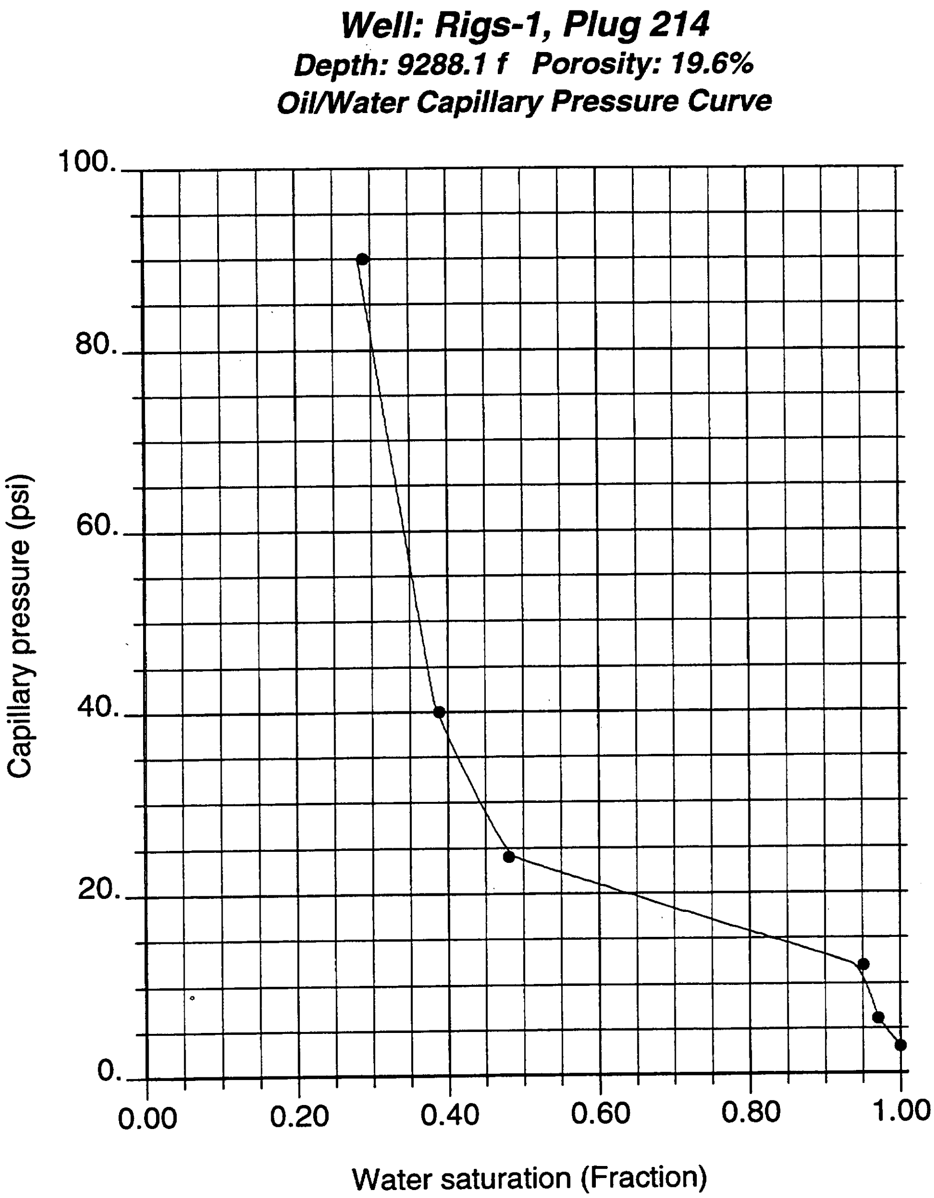
Oil/Water Capillary Pressure Curve



Porosity: 30.98 % **PV = 14.94 ml**

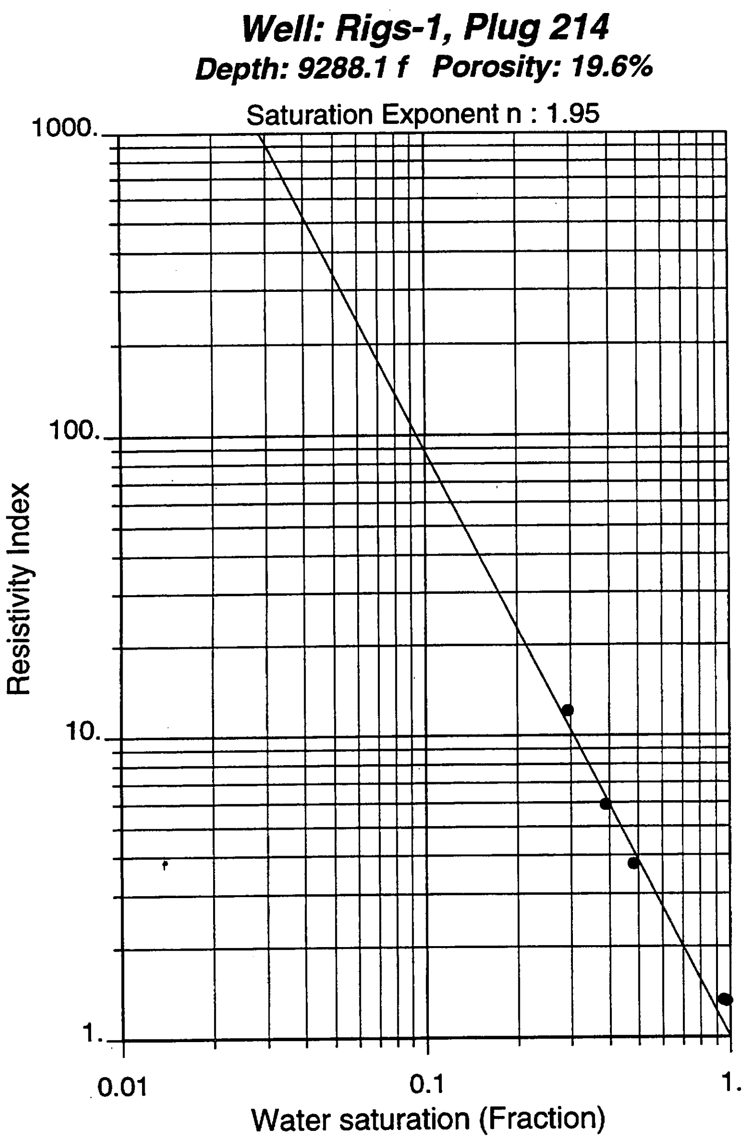
Pressure psi	Sat.vol. ml	Dr.vol. ml	Diff ml	Sw %	Z ohm	RI
0	14.16	14.16	0.00	100.0	41.8	1.00
3	14.16	14.16	0.00	100.0	41.8	1.00
6	14.16	14.05	0.11	99.26	41.8	1.00
12	14.16	13.73	0.43	97.12	47.8	1.14
24	14.16	13.36	0.80	94.65	52.7	1.26
40	14.16	9.14	5.02	66.40	97.0	2.32
90	14.16	4.51	9.65	35.41	550	13.2


Well: Rigs-1, Plug 164
Depth: 9244.1 f Porosity: 31.0%
Saturation Exponent n : 2.43
1000.
100.
10.
1.
Resistivity Index
0.01
0.1
1.
Water saturation (Fraction)
Number of data 4
Number trimmed 1
X variable mean 0.682
std. dev. 1.503
Y variable mean 2.575
std. dev. 2.670
Correlation -0.995
Rank correlation -1.000
Regression a 1.0
Regression b -2.433



Porosity: 19.55% **PV = 13.96ml**

Pressure psi	Sat.vol. ml	Dr.vol. ml	Diff ml	Sw %	Z ohm	RI
0	13.82	13.82	0.00	100.0	120.1	1.00
3	13.82	13.82	0.00	100.0	120.1	1.00
6	13.82	13.42	0.40	97.13	158.0	1.32
12	13.82	13.14	0.68	95.13	160.0	1.33
24	13.82	6.58	7.24	48.14	450	3.75
40	13.82	5.29	8.53	38.90	710	5.91
90	13.82	3.94	9.88	29.23	1450	12.1

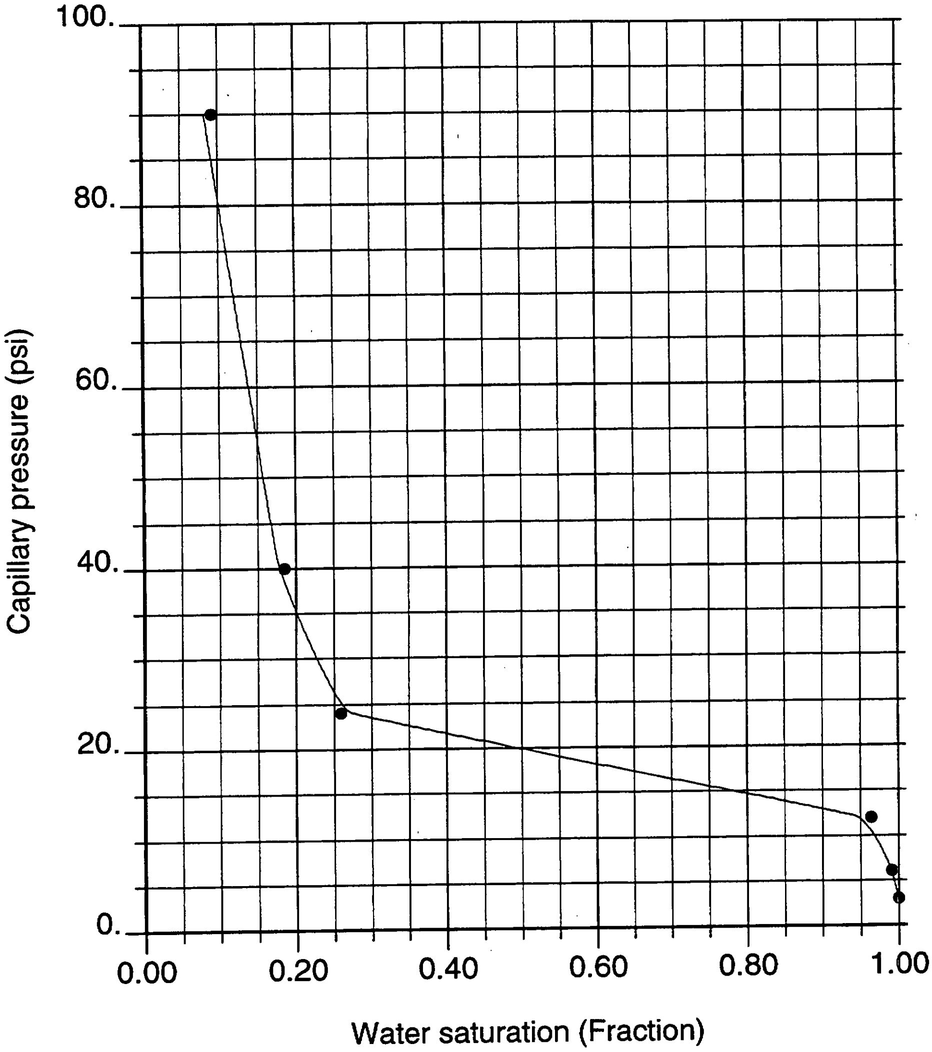


Number of data	5
X variable mean	0.550
std. dev.	1.619
Y variable mean	3.423
std. dev.	2.363
Correlation	-0.993
Rank correlation	-1.000
Regression a	1.0
Regression b	-1.946

Well: Rigs-1, Plug 234

Depth: 9305.3 f   Porosity: 36.8%

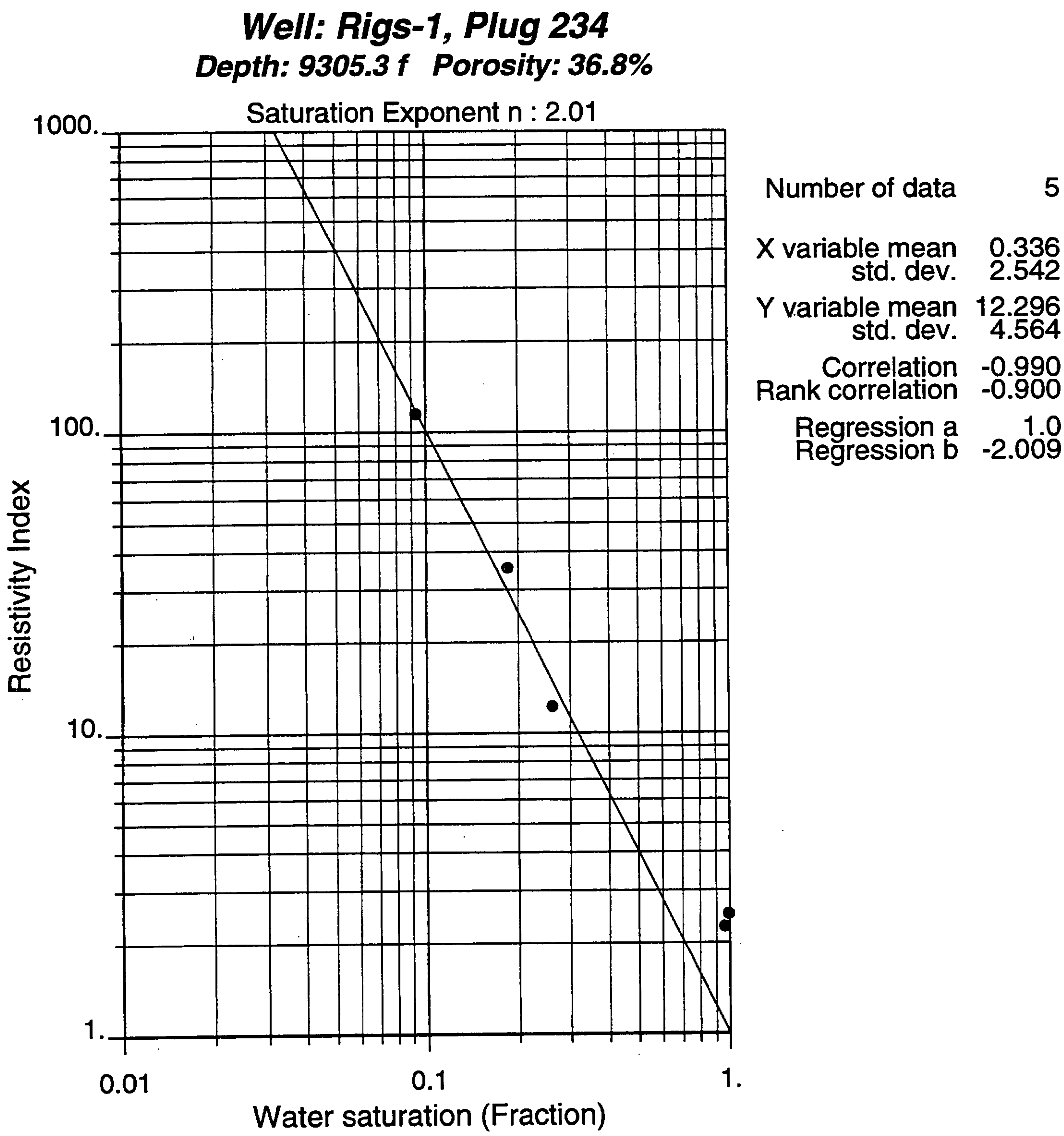
Oil/Water Capillary Pressure Curve



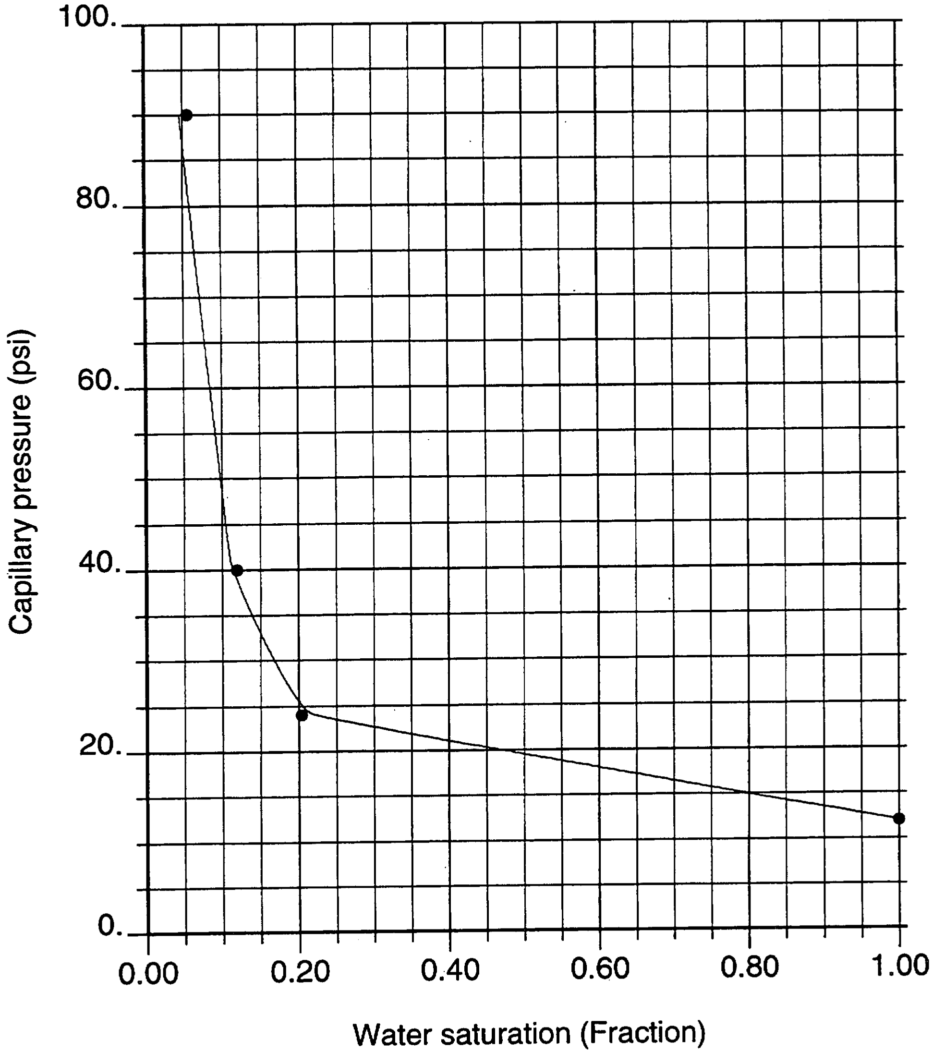
Porosity: 36.78%

PV = 26.32 ml

Pressure psi	Sat.vol. ml	Dr.vol. ml	Diff ml	Sw %	Z ohm	RI
0	27.70	27.70	0.00	100.0	30.5	1.00
3	27.70	27.70	0.00	100.0	30.5	1.00
6	27.70	27.45	0.25	99.05	76.0	2.49
12	27.70	26.75	0.95	96.39	69.0	2.26
24	27.70	8.23	19.47	26.03	375	12.3
40	27.70	6.24	21.46	18.47	1080	35.4
90	27.70	3.82	23.88	9.27	3500	115

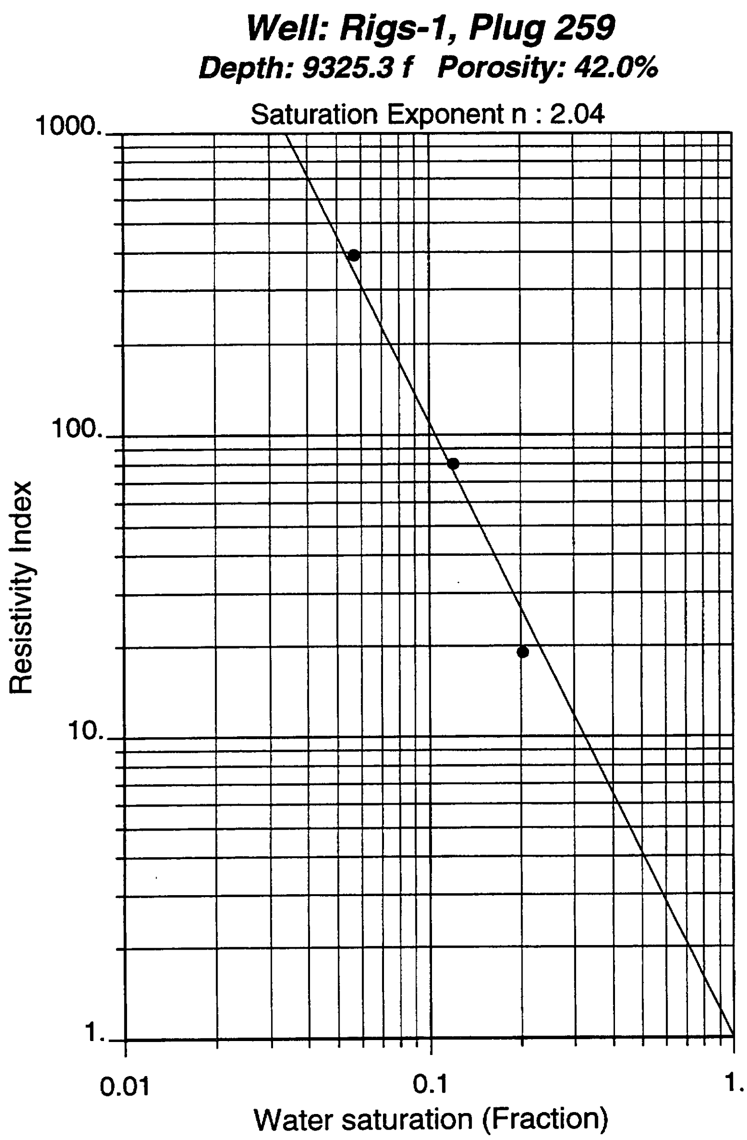

Well: Rigs-1, Plug 234
Depth: 9305.3 f Porosity: 36.8%
Saturation Exponent n : 2.01
1000.
100.
10.
1.
Resistivity Index
0.01
0.1
1.
Water saturation (Fraction)
Number of data 5
X variable mean 0.336
std. dev. 2.542
Y variable mean 12.296
std. dev. 4.564
Correlation -0.990
Rank correlation -0.900
Regression a 1.0
Regression b -2.009

Well: Rigs-1, Plug 259
Depth: 9325.3 f Porosity: 42.0%
Oil/Water Capillary Pressure Curve



Porosity: 42.00% **PV = 19.22 ml**

Pressure psi	Sat.vol. ml	Dr.vol. ml	Diff ml	Sw %	Z ohm	RI
0	24.09	24.09	0.00	100.0	15.3	1.00
3	24.09	24.09	0.00	100.0	15.3	1.00
6	24.09	24.09	0.00	100.0	15.3	1.00
12	24.09	24.09	0.00	100.0	15.3	1.00
24	24.09	8.79	15.30	20.40	290	19.0
40	24.09	7.18	16.91	12.02	1230	80.4
90	24.09	5.97	18.12	5.72	6000	392

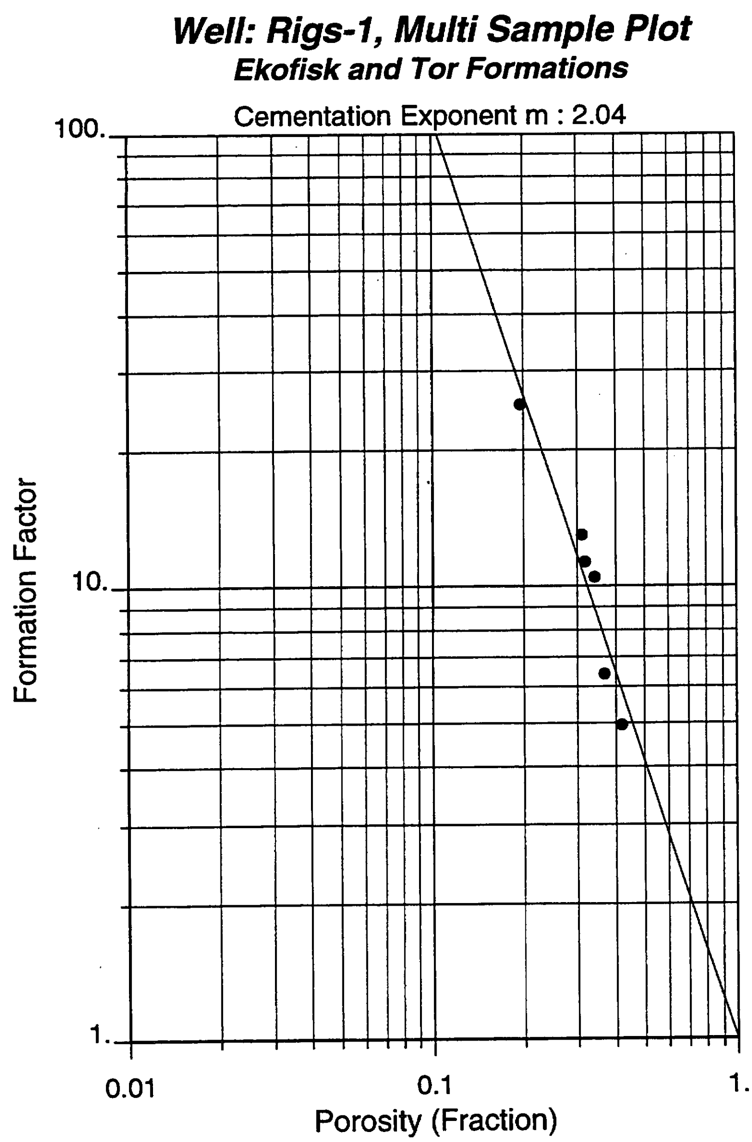


Number of data	3
Number trimmed	2
X variable mean	0.112
std. dev.	1.687
Y variable mean	84.288
std. dev.	3.442
Correlation	-0.998
Rank correlation	-1.000
Regression a	1.0
Regression b	-2.041

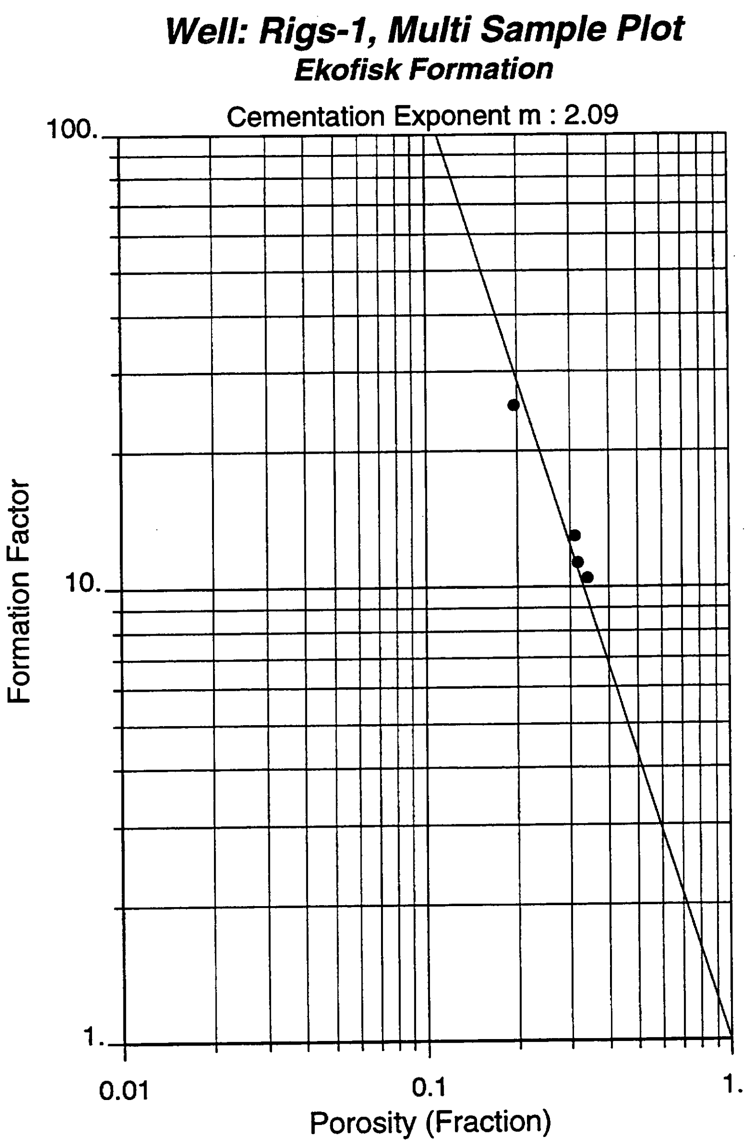
Rigs-1/SCAL: Capillary pressure and resistivity index study.

Room condition data.

Formation resistivity factor and cementation exponent from multi sample plots



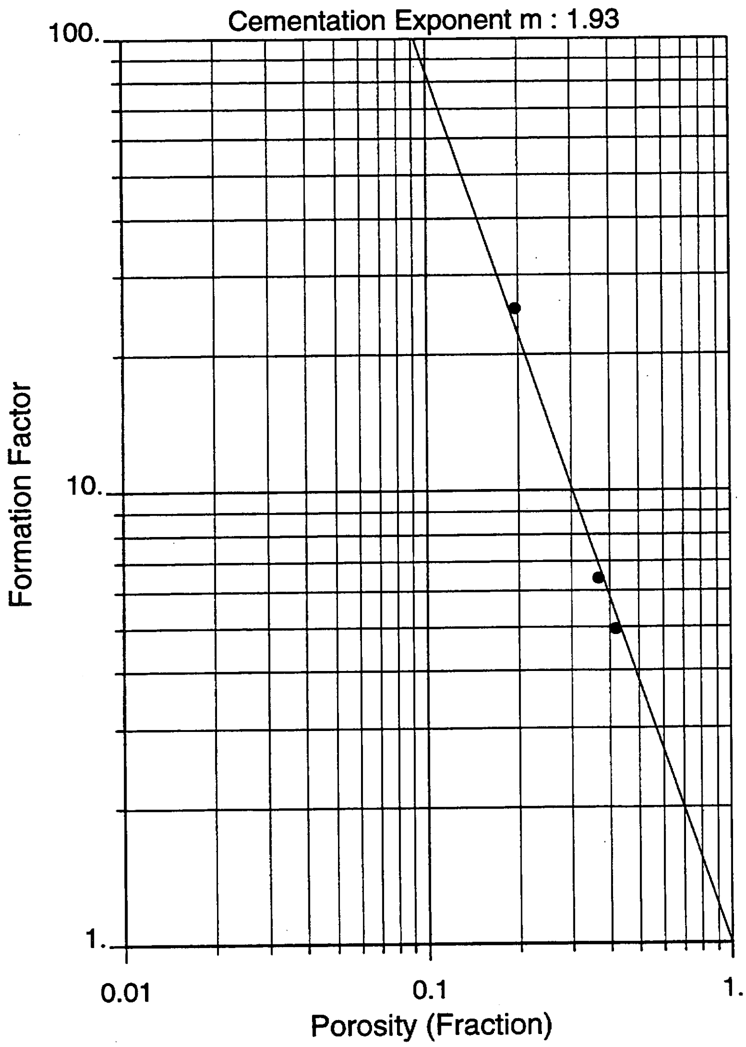
Number of data	6
X variable mean	0.317
std. dev.	1.269
Y variable mean	10.354
std. dev.	1.685
Correlation	-0.957
Rank correlation	-1.000
Regression a	1.0
Regression b	-2.039



Number of data	4
X variable mean	0.285
std. dev.	1.247
Y variable mean	14.042
std. dev.	1.417
Correlation	-0.996
Rank correlation	-1.000
Regression a	1.0
Regression b	-2.089

Well: Rigs-1, Multi Sample Plot

Tor Formation



Number of data	3
X variable mean	0.311
std. dev.	1.396
Y variable mean	9.290
std. dev.	2.047
Correlation	-1.000
Rank correlation	-1.000
Regression a	1.0
Regression b	-1.928

5.4 Figures and tables (overburden study)

Rigs-1/SCAL: Formation resistivity factor study

Overburden data.

Formation Resistivity Factor
Impedance @ 1kHz

Well: Rigs-1 / FRF plugs			R_w : 0.0839 Ωm		T : 22±1°C	
Plug no.	**Depth in feet**	**Porosity * %**	**Formation Resistivity Factor @ HSP/ECS in psi** @100/161	@400/645	@1200/1935	@2550/4113
53	9152.31	25.32		14.12	14.43	14.59
89	9182.30	35.00		8.03	8.22	8.26
124	9211.31	31.94		9.91	9.95	10.16
151	9233.32	28.96		10.89	10.92	10.98
189	9266.32	15.88		38.33	39.38	40.92
212	9286.82	21.00		26.36	27.06	27.57
221	9294.32	33.79		8.91	8.97	9.04
259	9325.30	42.00		5.48	5.67	5.91
265	9329.49	39.21		5.42	5.38	5.43
Cementation Exponent m				**1.98**	**1.98**	**1.99**

Pore volume compressibility data

Well: Rigs-1 / FRF plugs			Liquid production data				
Plug no.	**Porosity * %**	**Pore volume * ml**	**ΔPV in ml @ HSP/ECS in psi** 100/ 161**	400/ 645	1200/ 1935	2550/ 4113	**ΣPV ml**
53	25.32	18.19	0.009	0.023	0.040	0.068	0.140
89	35.00	20.98	0.025	0.084	0.079	0.124	0.312
124	31.94	22.74	0.055	0.111	0.093	0.108	0.367
151	28.96	19.17	0.020	0.033	0.051	0.081	0.185
189	15.88	11.43	0.015	0.030	0.036	0.055	0.136
212	21.00	15.03	0.035	0.066	0.066	0.071	0.238
221	33.79	14.83	0.070	0.143	0.095	0.090	0.398
259	42.00	18.88	0.040	0.104	0.130	0.165	0.439
265	39.21	26.93	0.072	0.116	0.169	0.202	0.559

* initial value from routine core analysis data.
** This column lists the ΔPV_0 values as determined from the liquid production curves.

Company	: Amerada Hess	Overburden measurements	
Well no.	: Rigs-1	Temperature:	22 ±1°C
Plug no.	: 53	Initial porosity:	25,32 %
Depth	: 9152,31 feet	Initial pore volume:	18,19 cc.

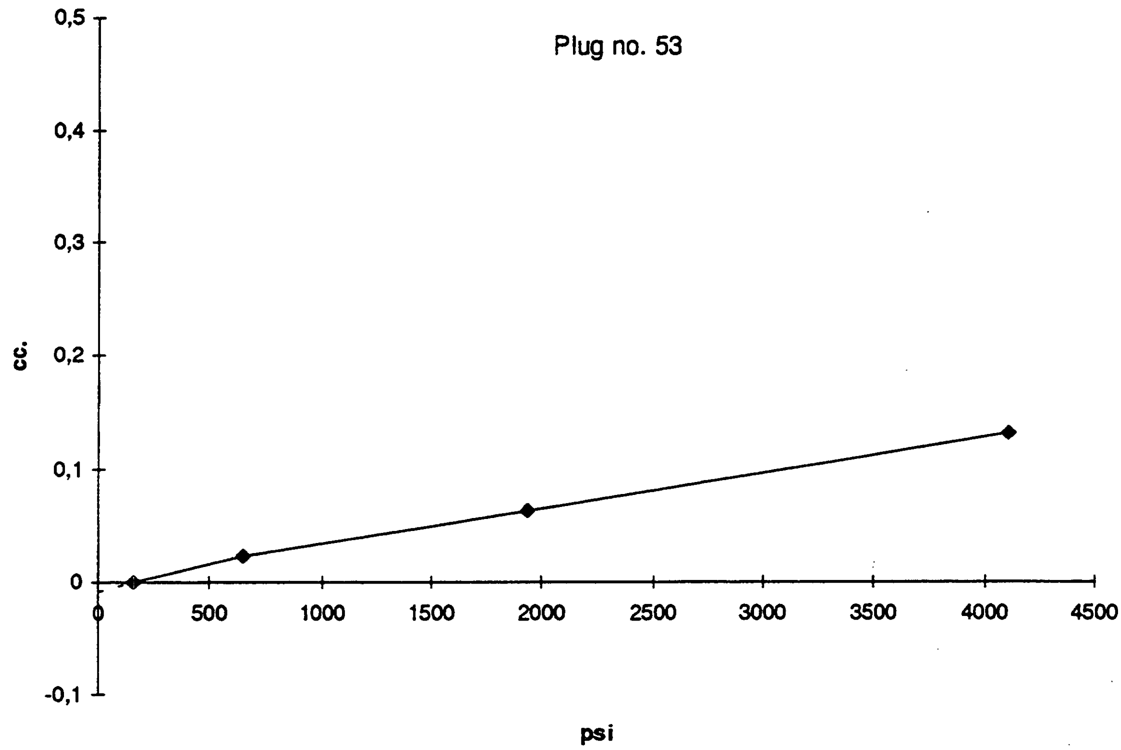


Diagram: Production of brine as a function of effective confining stress

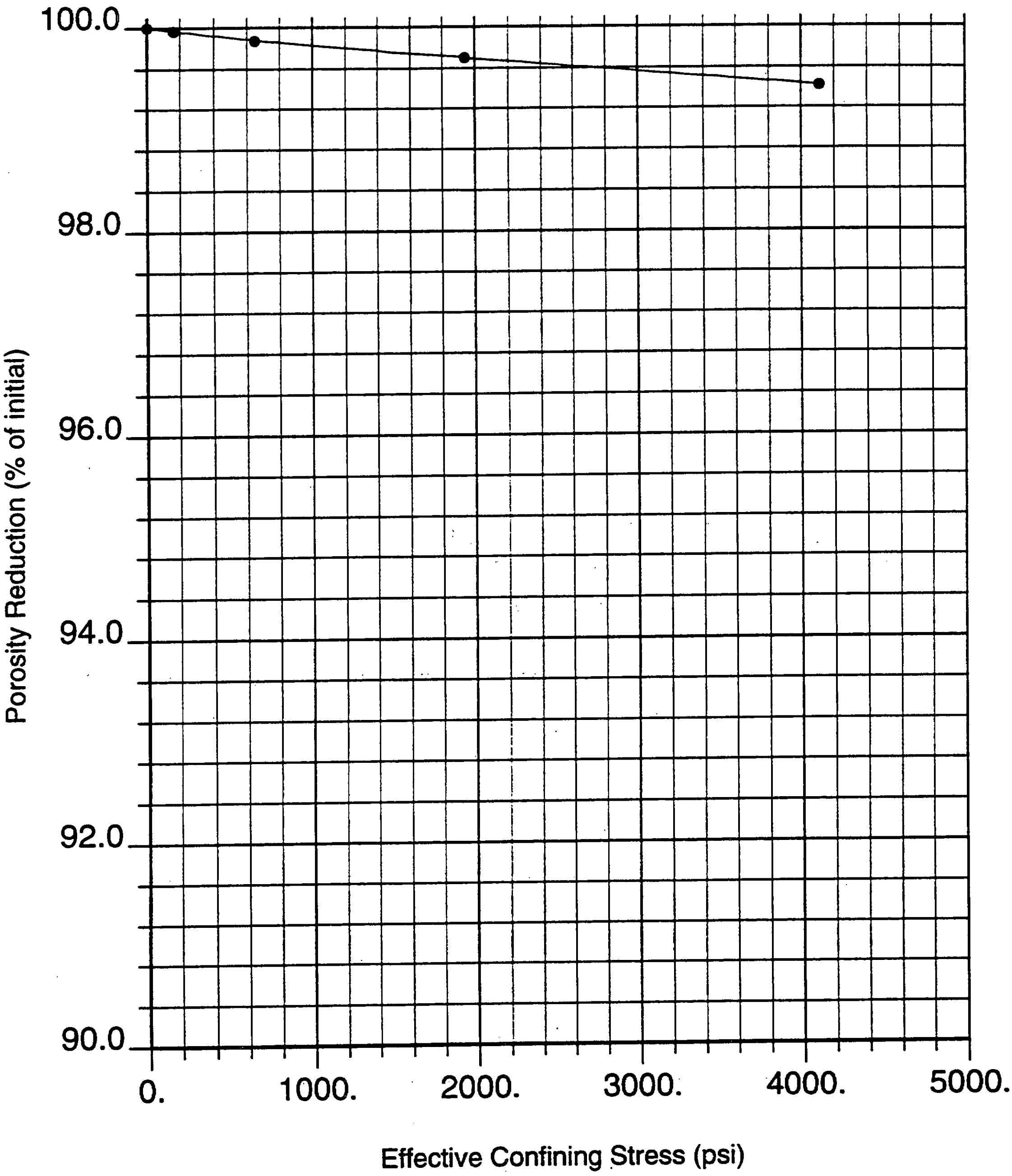
Table: Porosity reduction and pore volume compressibility

HSP psi	ECS psi	Σ Produced brine cc.	Measured porosity %	Porosity reduction %	Pore volume compressibility 10^{-6} psi^{-1}
0	0	0	25,32	100,00	-
100	161	0,009	25,31	99,96	2,8
400	645	0,032	25,29	99,87	2,4
1200	1935	0,072	25,25	99,70	1,7
2550	4113	0,140	25,17	99,42	1,4

Well: Rigs-1, Plug 53

Depth: 9152.3 f Porosity: 25.3%

Porosity Reduction vs. Effective Confining Stress



Company	: Amerada Hess	Overburden measurements	
Well no.	: Rigs-1	Temperature:	22 ±1°C
Plug no.	: 89	Initial porosity:	35,00 %
Depth	: 9182,30 feet	Initial pore volume:	20,98 cc.

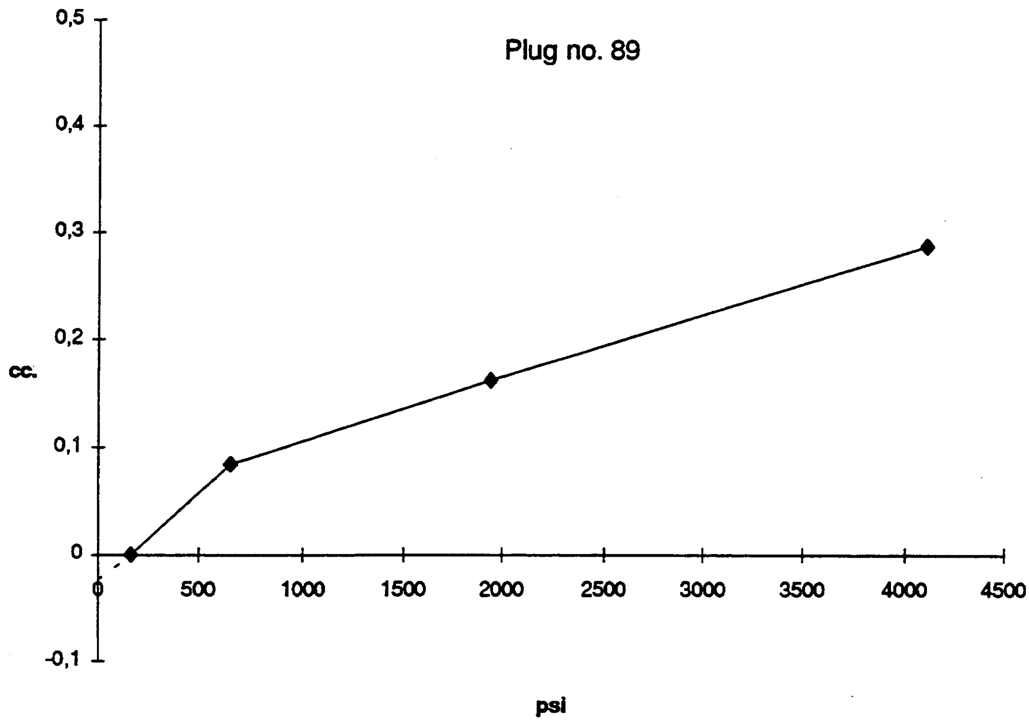
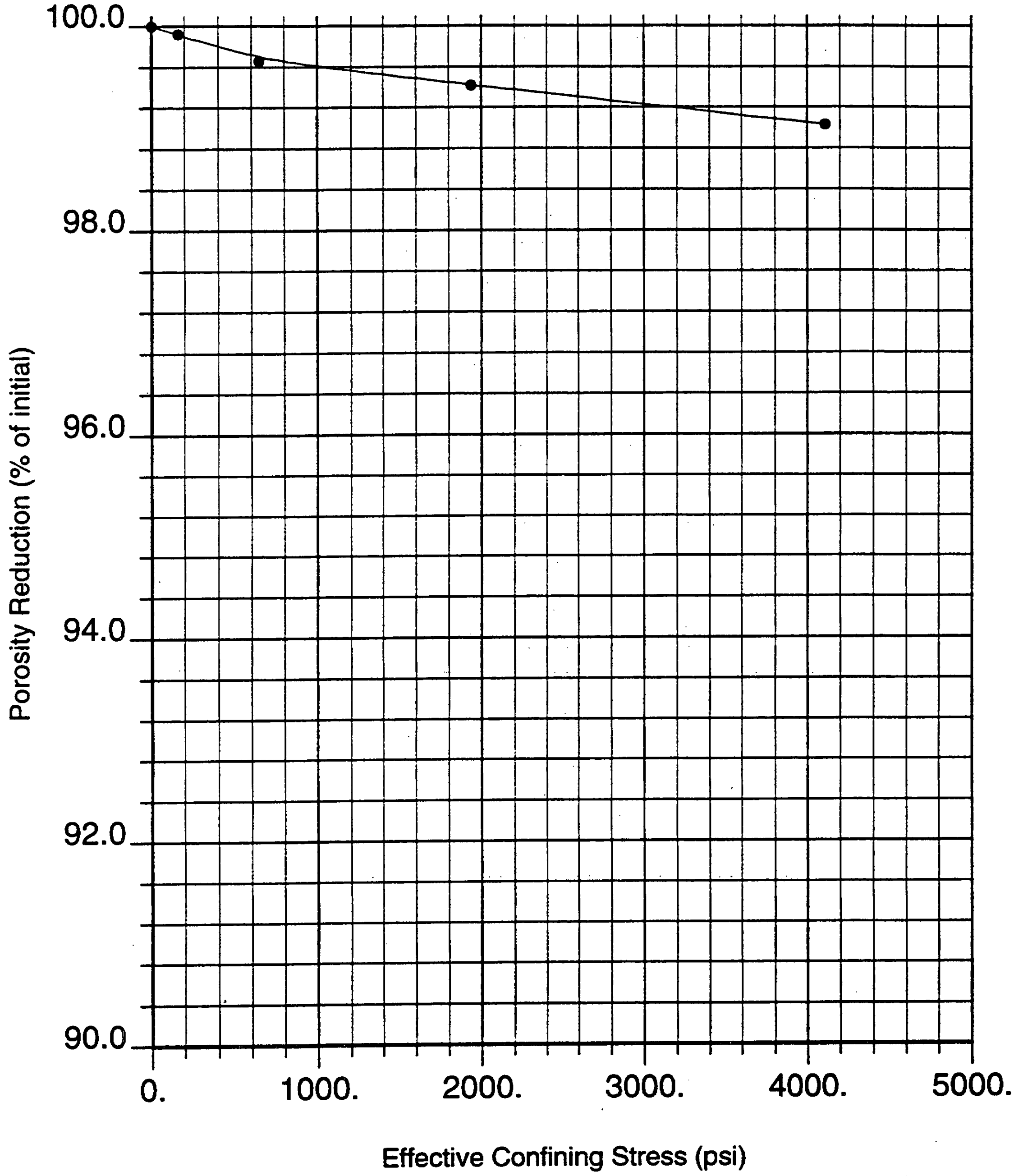


Diagram: Production of brine as a function of effective confining stress

Table: Porosity reduction and pore volume compressibility

HSP psi	ECS psi	Σ Produced brine cc.	Measured porosity %	Porosity reduction %	Pore volume compressibility 10^{-6} psi^{-1}
0	0	0	35,00	100,00	-
100	161	0,025	34,97	99,92	9,2
400	645	0,109	34,88	99,66	5,1
1200	1935	0,188	34,80	99,42	2,8
2550	4113	0,312	34,66	99,03	2,4

Well: Rigs-1, Plug 89
Depth: 9182.3 f Porosity: 35.0%
Porosity Reduction vs. Effective Confining Stress



Company	: Amerada Hess	Overburden measurements	
Well no.	: Rigs-1	Temperature:	22 ±1°C
Plug no.	: 124	Initial porosity:	31,94 %
Depth	: 9211,31 feet	Initial pore volume:	22,74 cc.

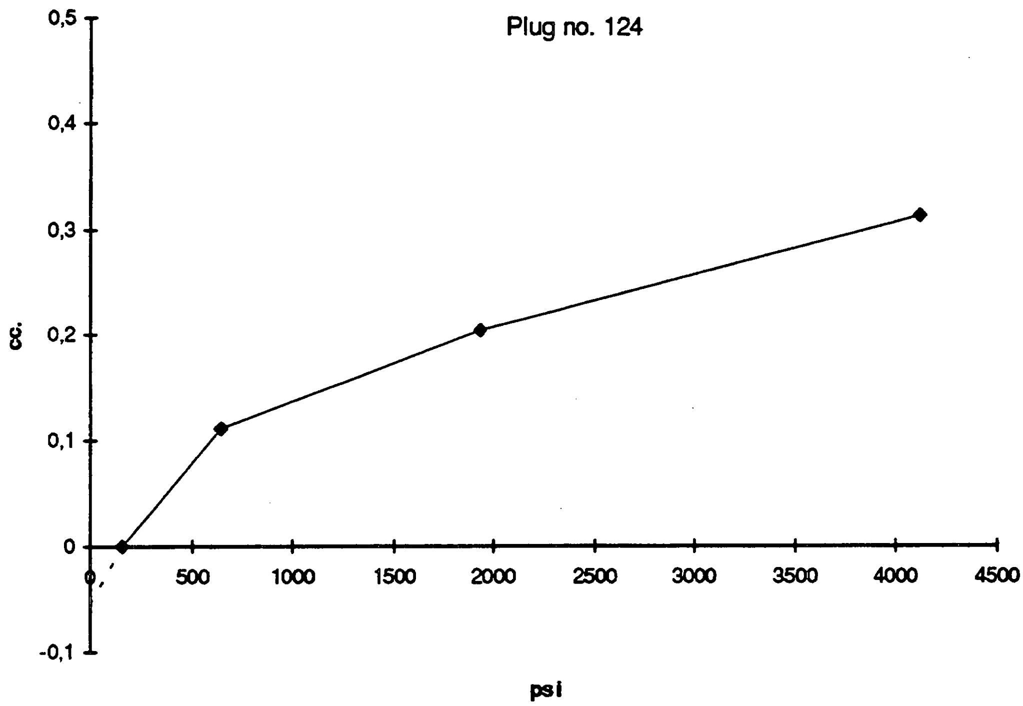
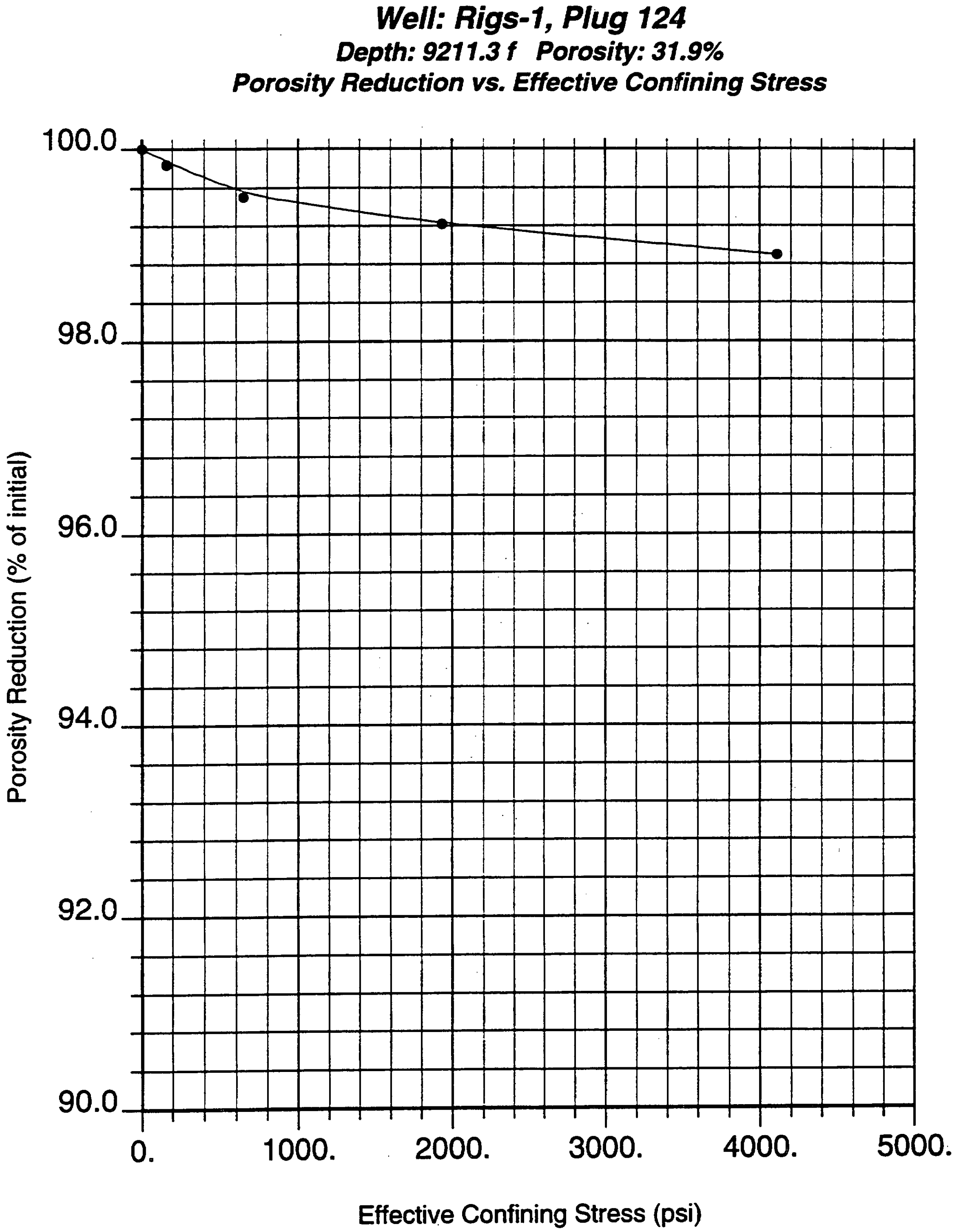


Diagram: Production of brine as a function of effective confining stress

Table: Porosity reduction and pore volume compressibility

HSP psi	ECS psi	Σ Produced brine cc.	Measured porosity %	Porosity reduction %	Pore volume compressibility 10^{-6} psi^{-1}
0	0	0	31,94	100,00	-
100	161	0,055	31,89	99,84	14,1
400	645	0,166	31,78	99,50	6,0
1200	1935	0,259	31,69	99,22	2,6
2550	4113	0,367	31,59	98,90	1,6


Well: Rigs-1, Plug 124
Depth: 9211.3 f Porosity: 31.9%
Porosity Reduction vs. Effective Confining Stress
100.0
98.0
96.0
94.0
92.0
90.0
Porosity Reduction (% of initial)
0.
1000.
2000.
3000.
4000.
5000.
Effective Confining Stress (psi)

Company	: Amerada Hess	Overburden measurements	
Well no.	: Rigs-1	Temperature:	22 ±1°C
Plug no.	: 151	Initial porosity:	28,96 %
Depth	: 9233,32 feet	Initial pore volume:	19,17 cc.

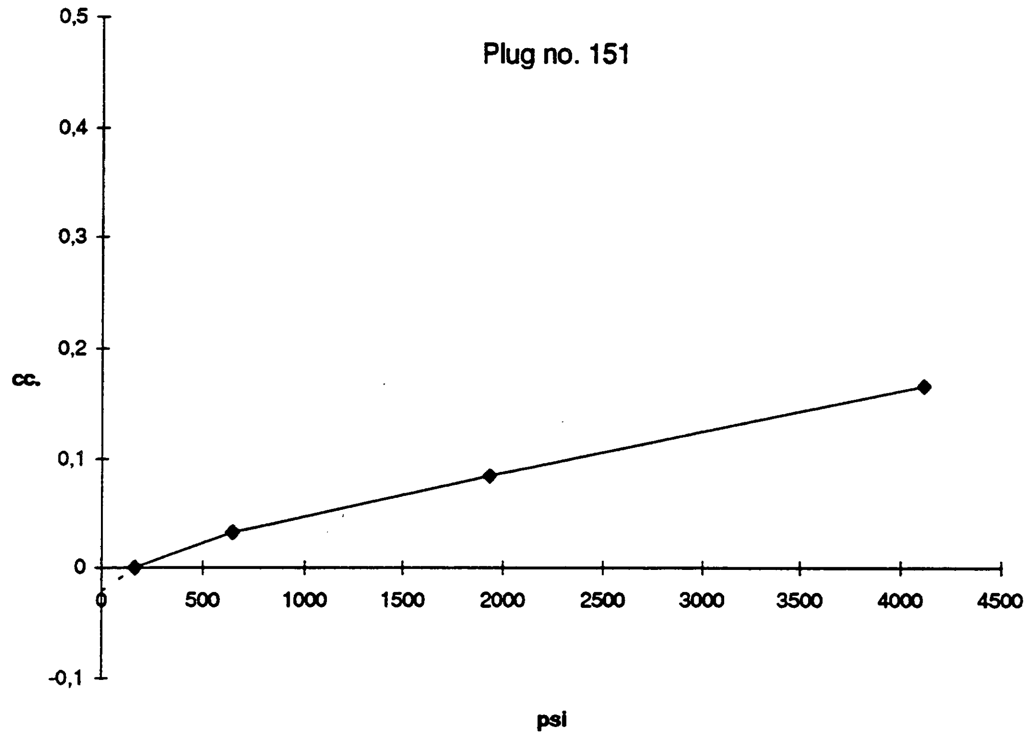


Diagram: Production of brine as a function of effective confining stress

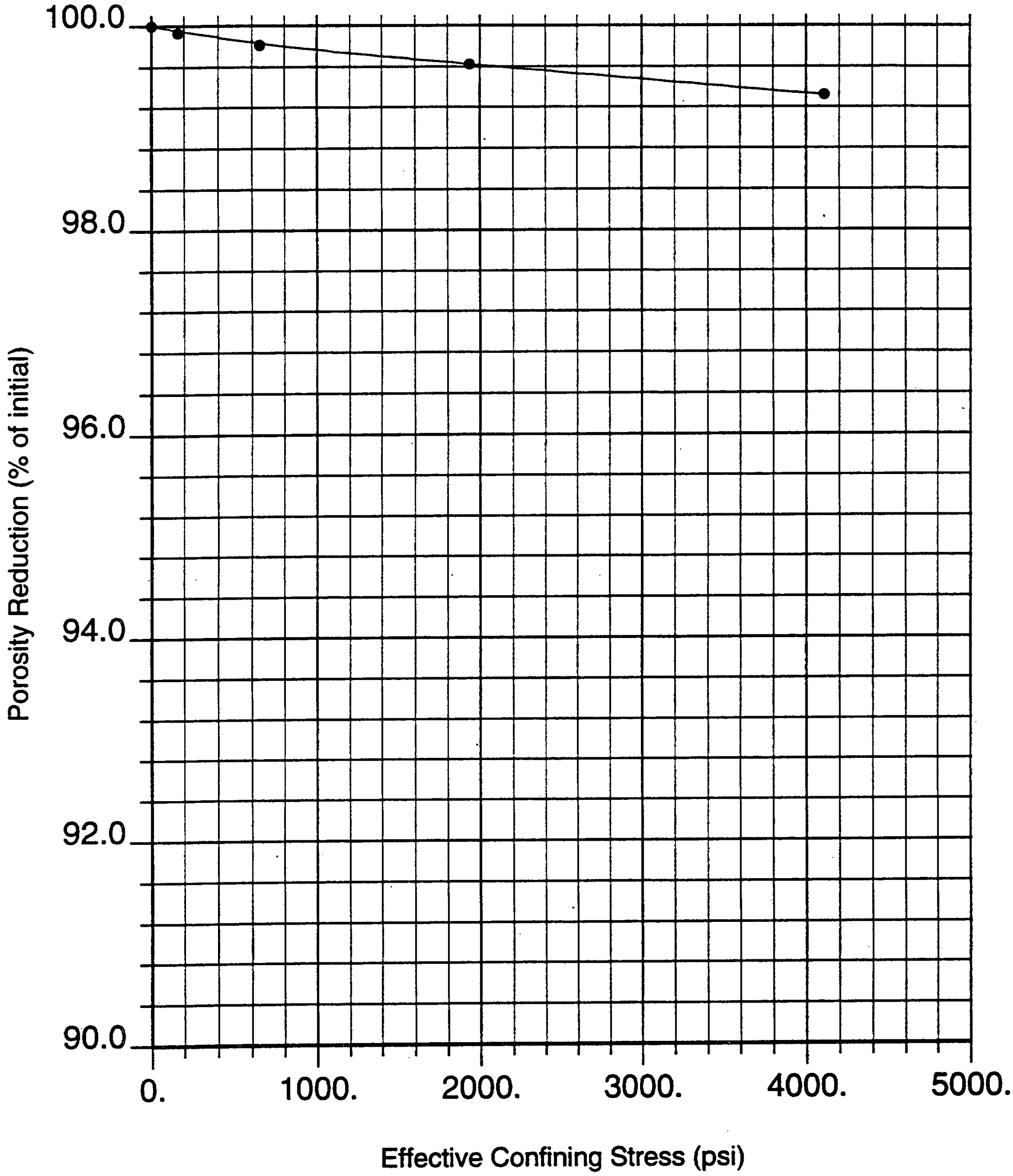
Table: Porosity reduction and pore volume compressibility

HSP psi	ECS psi	Σ Produced brine cc.	Measured porosity %	Porosity reduction %	Pore volume compressibility 10^{-6} psi^{-1}
0	0	0	28,96	100,00	-
100	161	0,02	28,94	99,93	4,9
400	645	0,053	28,91	99,81	3,0
1200	1935	0,104	28,85	99,62	1,9
2550	4113	0,185	28,76	99,32	1,6

Well: Rigs-1, Plug 151

Depth: 9233.3 f   Porosity: 29.0%

Porosity Reduction vs. Effective Confining Stress



Company	: Amerada Hess	Overburden measurements	
Well no.	: Rigs-1	Temperature:	22 ±1°C
Plug no.	: 189	Initial porosity:	15,88 %
Depth	: 9266,32 feet.	Initial pore volume:	11,43 cc.

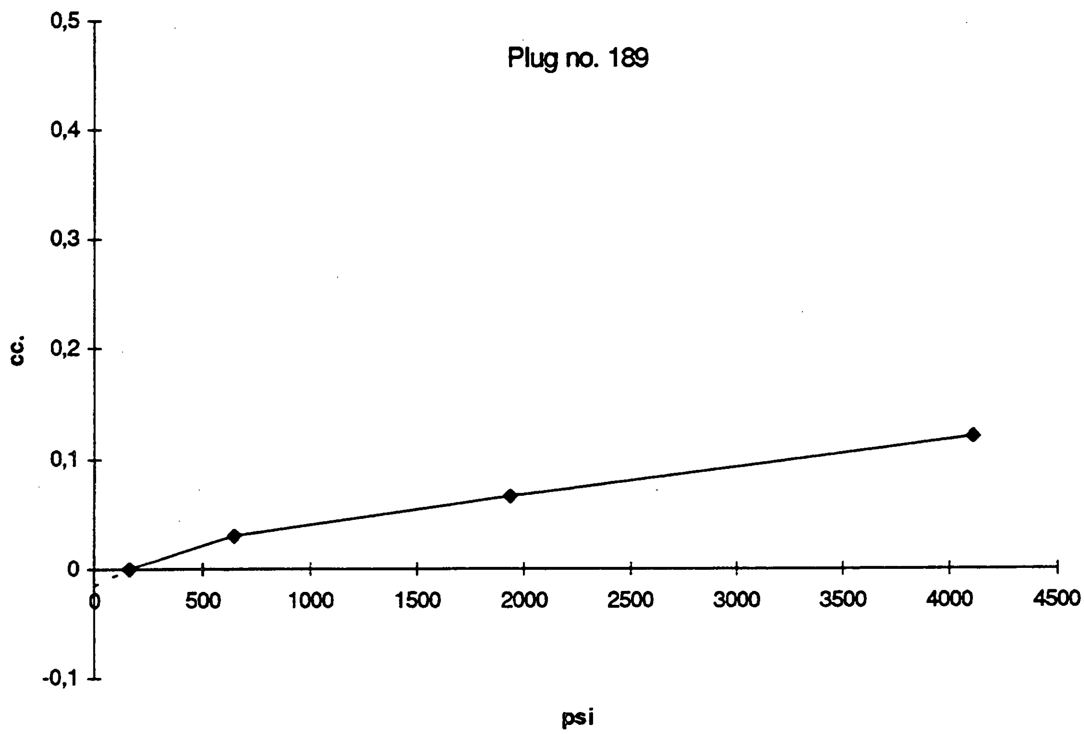
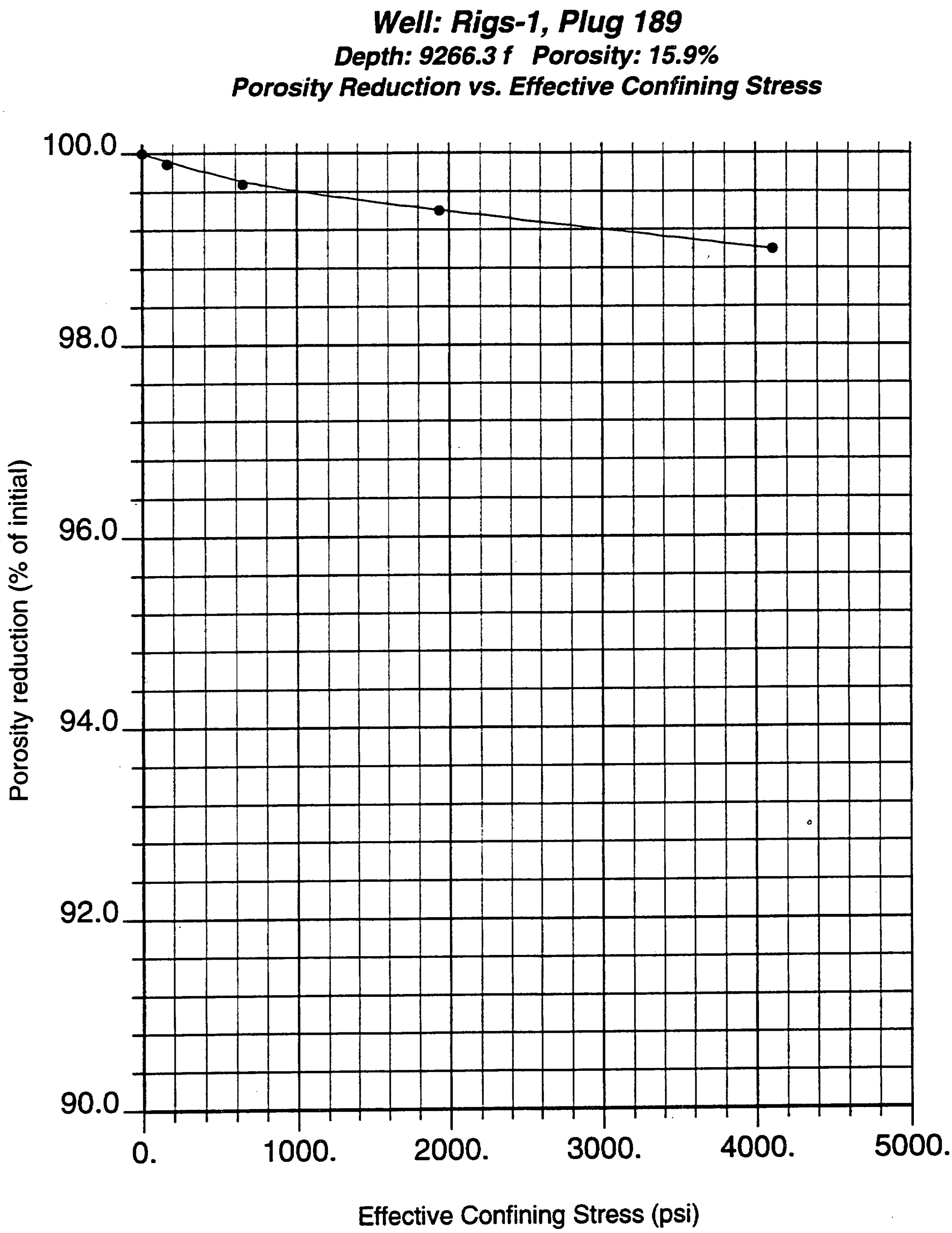


Diagram: Production of brine as a function of effective confining stress

Table: Porosity reduction and pore volume compressibility

HSP psi	ECS psi	Σ Produced brine cc.	Measured porosity %	Porosity reduction %	Pore volume compressibility 10^{-6} psi^{-1}
0	0	0	15,88	100,00	-
100	161	0,015	15,86	99,89	6,9
400	645	0,045	15,83	99,67	4,0
1200	1935	0,081	15,79	99,40	2,3
2550	4113	0,136	15,72	99,00	1,8


Well: Rigs-1, Plug 189
Depth: 9266.3 f Porosity: 15.9%
Porosity Reduction vs. Effective Confining Stress
100.0
98.0
96.0
94.0
92.0
90.0
Porosity reduction (% of initial)
0.
1000.
2000.
3000.
4000.
5000.
Effective Confining Stress (psi)

Company	: Amerada Hess	Overburden measurements	
Well no.	: Rigs-1	Temperature:	22 ±1°C
Plug no.	: 212	Initial porosity:	21,00 %
Depth	: 9286,82 feet.	Initial pore volume:	15,03 cc.

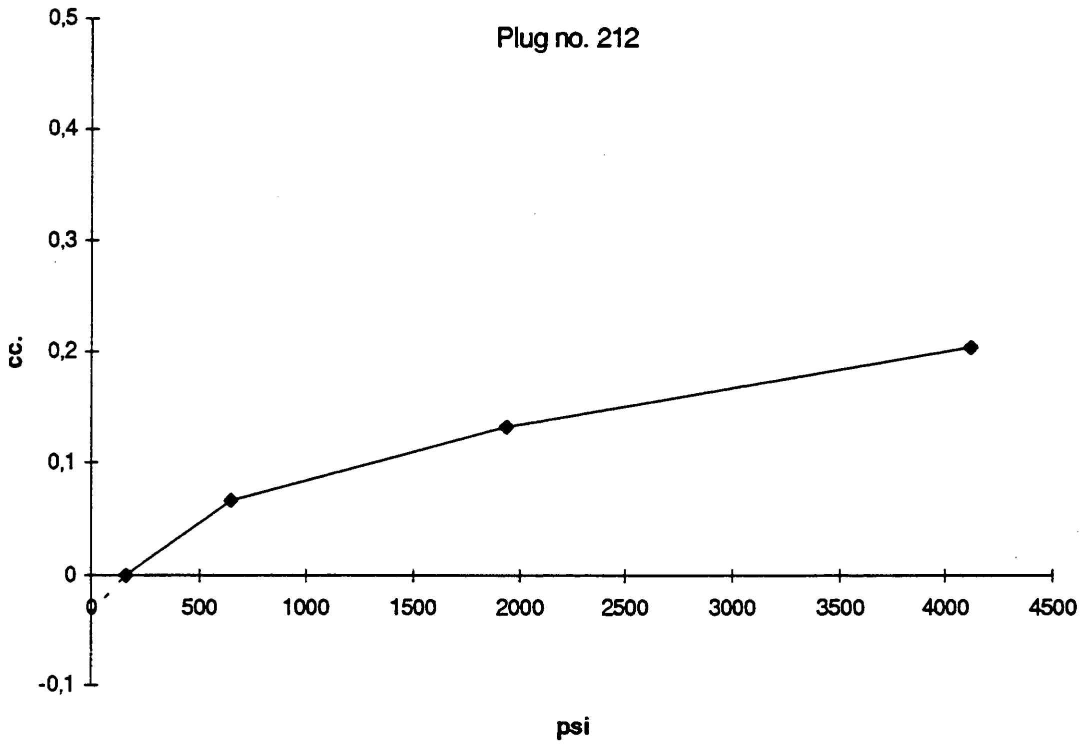
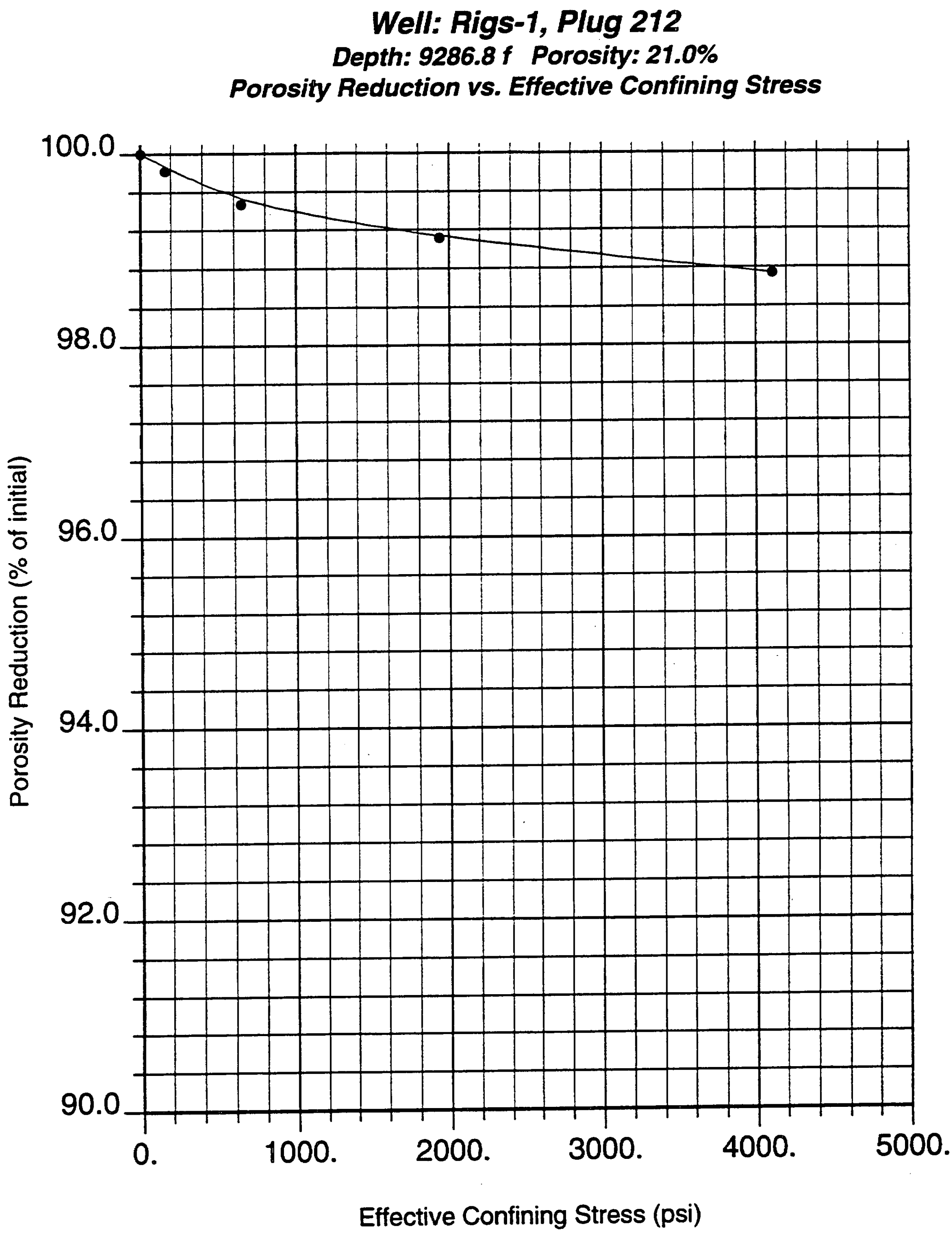


Diagram: Production of brine as a function of effective confining stress

Table: Porosity reduction and pore volume compressibility

HSP psi	ECS psi	Σ Produced brine cc.	Measured porosity %	Porosity reduction %	Pore volume compressibility 10^{-6} psi^{-1}
0	0	0	21,00	100,00	-
100	161	0,035	20,96	99,82	11,8
400	645	0,101	20,89	99,47	5,6
1200	1935	0,167	20,82	99,12	2,6
2550	4113	0,238	20,74	98,74	1,8


Well: Rigs-1, Plug 212
Depth: 9286.8 f Porosity: 21.0%
Porosity Reduction vs. Effective Confining Stress
100.0
98.0
96.0
94.0
92.0
90.0
Porosity Reduction (% of initial)
0.
1000.
2000.
3000.
4000.
5000.
Effective Confining Stress (psi)

Company : Amerada Hess
Well no. : Rigs-1
Plug no. : 221
Depth : 9294,32 feet.

Overburden measurements
Temperature: 22 ±1°C
Initial porosity: 33,79 %
Initial pore volume: 14,83 cc.

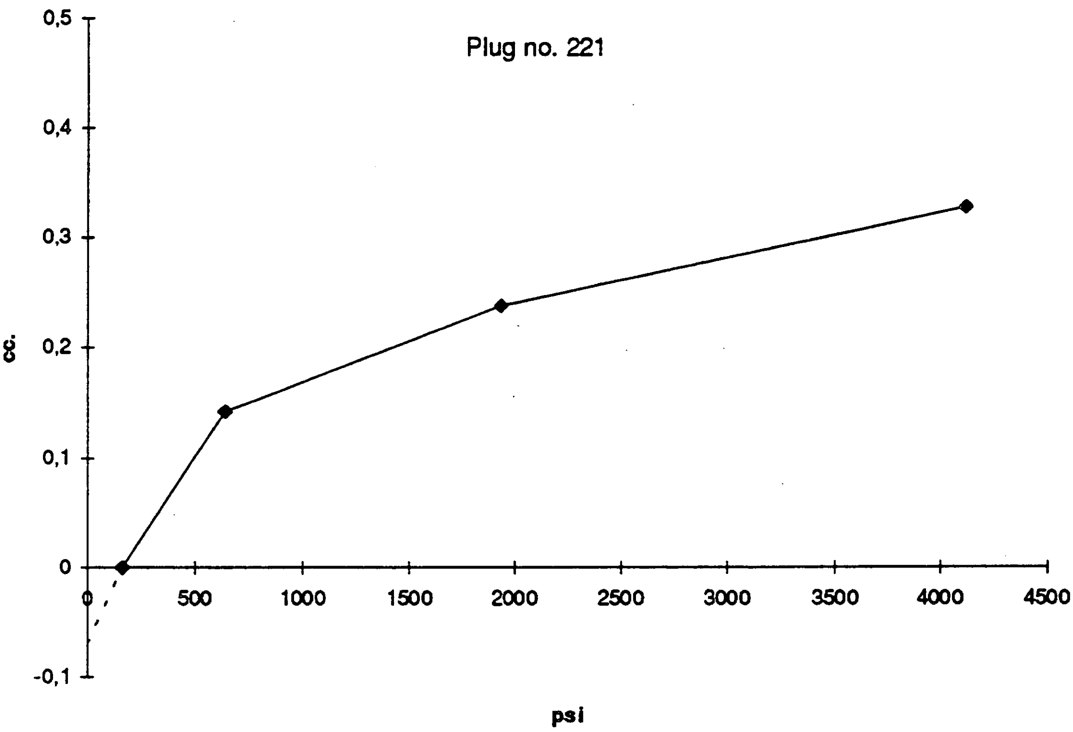
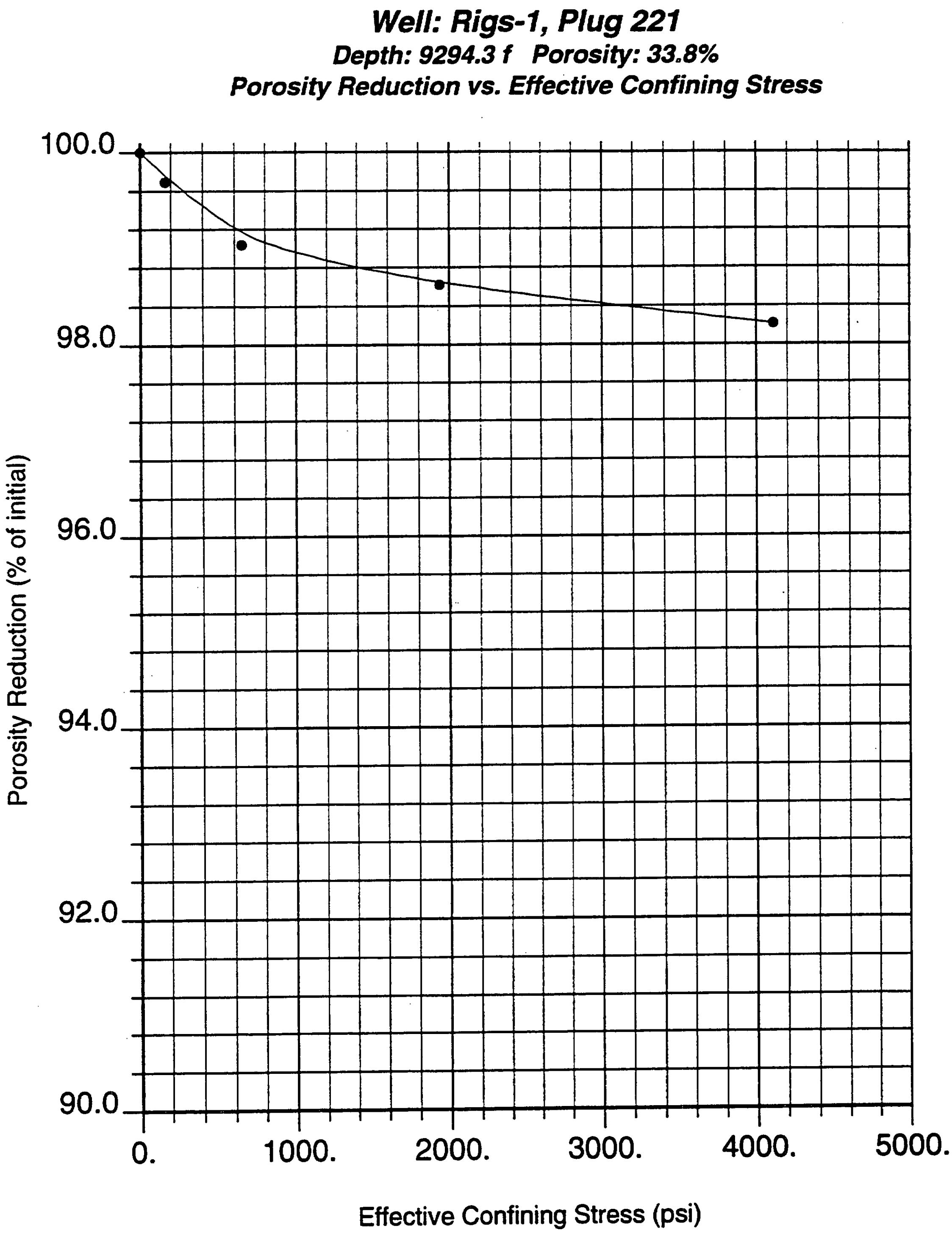


Diagram: Production of brine as a function of effective confining stress

Table: Porosity reduction and pore volume compressibility

HSP psi	ECS psi	Σ Produced brine cc.	Measured porosity %	Porosity reduction %	Pore volume compressibility 10^{-6} psi^{-1}
0	0	0	33,79	100,00	-
100	161	0,07	33,68	99,69	26
400	645	0,213	33,47	99,04	8,8
1200	1935	0,308	33,32	98,62	3,6
2550	4113	0,398	33,18	98,21	2,6



Well: Rigs-1, Plug 221
Depth: 9294.3 f Porosity: 33.8%
Porosity Reduction vs. Effective Confining Stress
100.0
98.0
96.0
94.0
92.0
90.0
Porosity Reduction (% of initial)
0.
1000.
2000.
3000.
4000.
5000.
Effective Confining Stress (psi)

Company : Amerada Hess
Well no. : Rigs-1
Plug no. : 259
Depth : 9325,30 feet.

Overburden measurements
Temperature: 22 ±1°C
Initial porosity: 42,00 %
Initial pore volume: 18,88 cc.

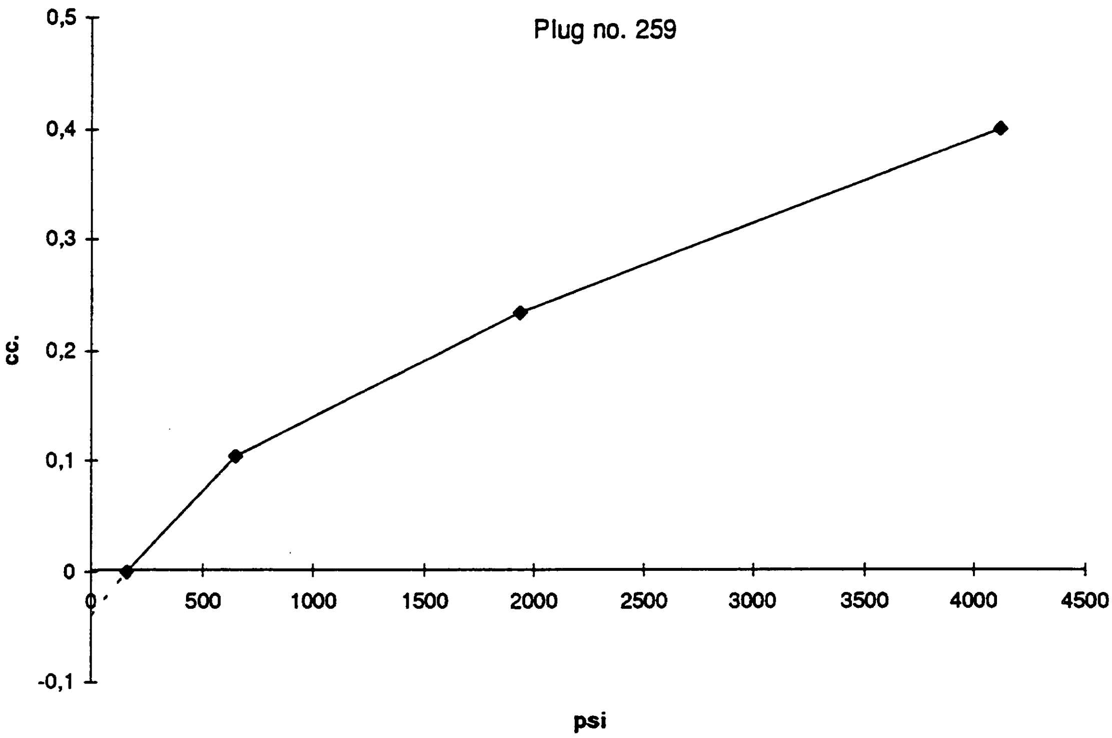
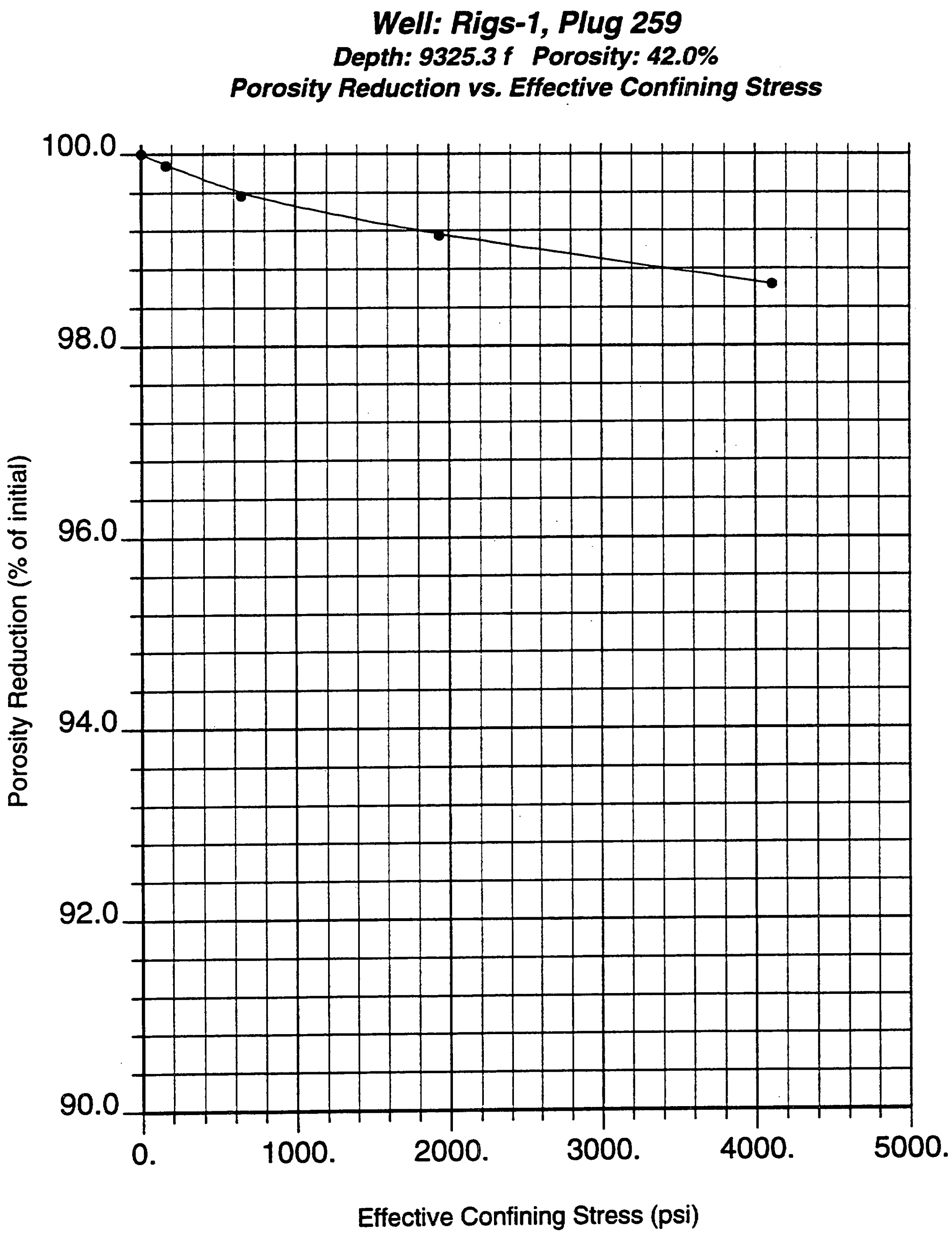


Diagram: Production of brine as a function of effective confining stress

Table: Porosity reduction and pore volume compressibility

HSP psi	ECS psi	Σ Produced brine cc.	Measured porosity %	Porosity reduction %	Pore volume compressibility 10^{-6} psi^{-1}
0	0	0	42,00	100,00	-
100	161	0,040	41,95	99,88	13,3
400	645	0,144	41,81	99,56	8,6
1200	1935	0,274	41,64	99,15	4,5
2550	4113	0,439	41,43	98,64	3,7



Well: Rigs-1, Plug 259
Depth: 9325.3 f Porosity: 42.0%
Porosity Reduction vs. Effective Confining Stress
100.0
98.0
96.0
94.0
92.0
90.0
Porosity Reduction (% of initial)
0.
1000.
2000.
3000.
4000.
5000.
Effective Confining Stress (psi)

Company	: Amerada Hess	Overburden measurements	
Well no.	: Rigs-1	Temperature:	22 ±1°C
Plug no.	: 265	Initial porosity:	39,21 %
Depth	: 9329,49 feet.	Initial pore volume:	26,93 cc.

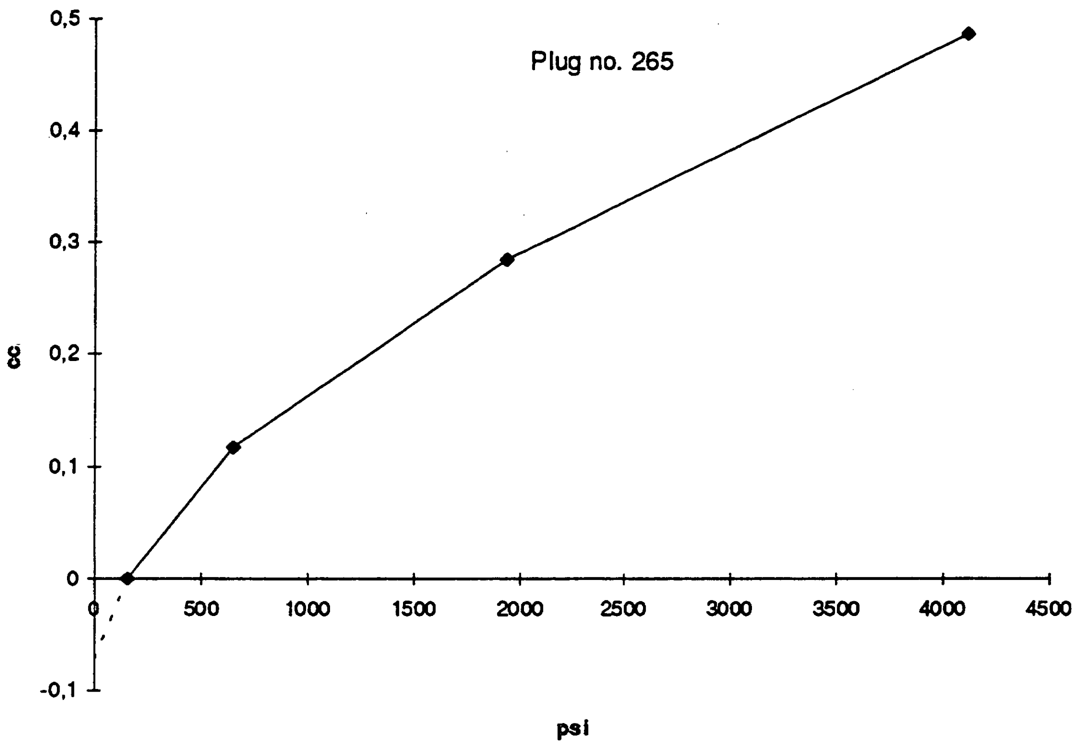
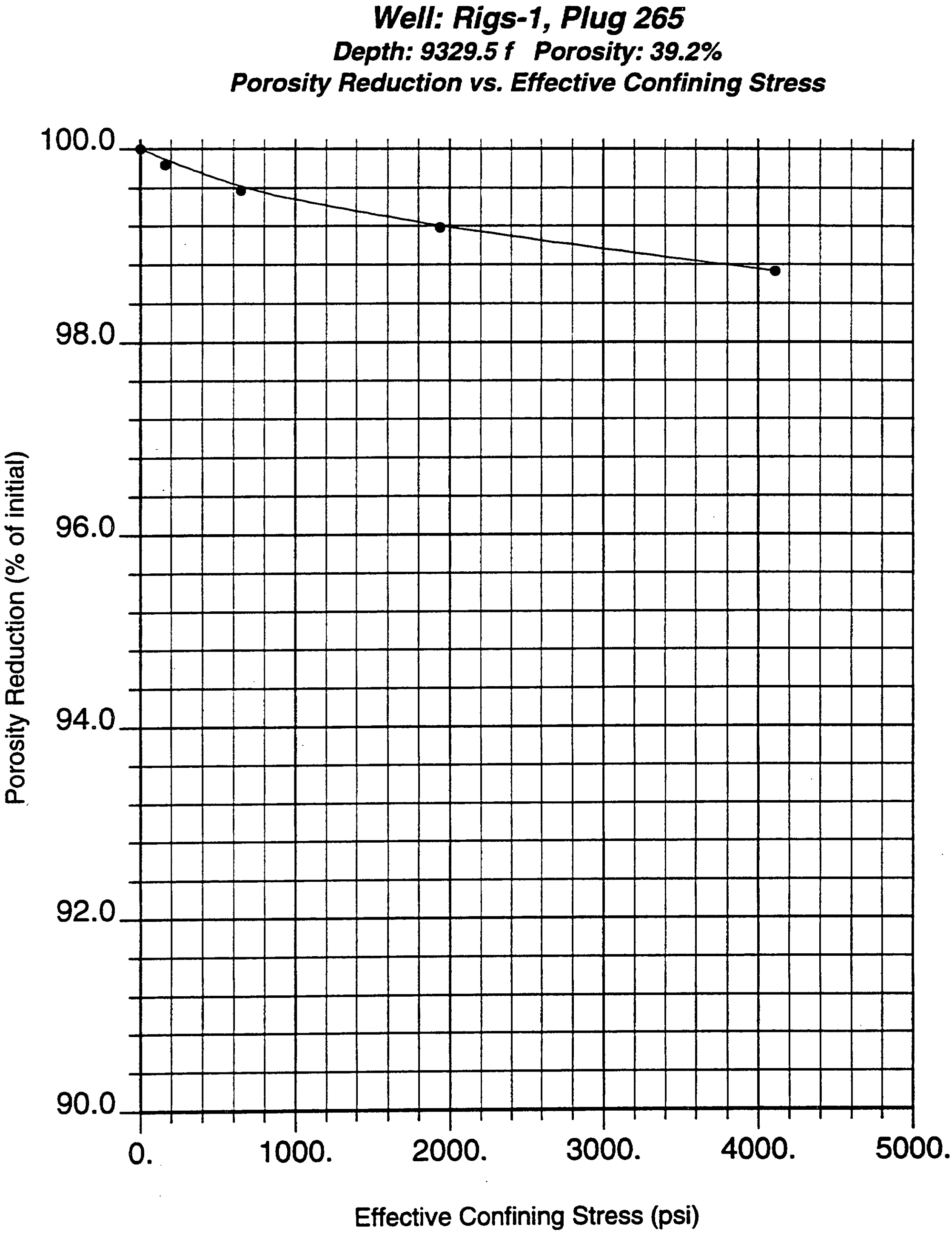


Diagram: Production of brine as a function of effective confining stress

Table: Porosity reduction and pore volume compressibility

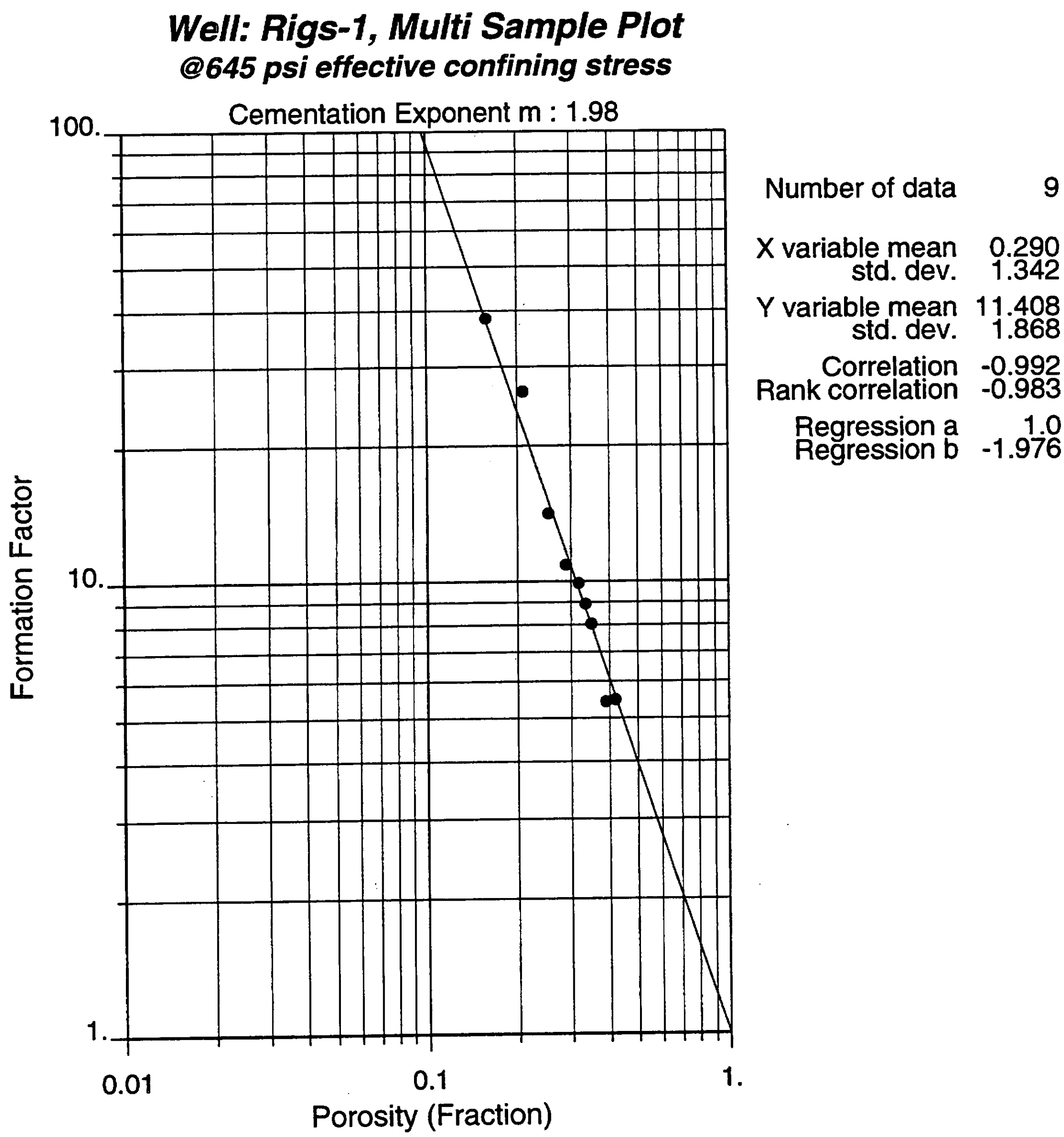
HSP psi	ECS psi	Σ Produced brine cc.	Measured porosity %	Porosity reduction %	Pore volume compressibility 10^{-6} psi^{-1}
0	0	0	39,21	100,00	-
100	161	0,072	39,15	99,84	12,7
400	645	0,188	39,04	99,57	6,4
1200	1935	0,357	38,89	99,19	3,8
2550	4113	0,559	38,71	98,73	3,8


Well: Rigs-1, Plug 265
Depth: 9329.5 f Porosity: 39.2%
Porosity Reduction vs. Effective Confining Stress
100.0
98.0
96.0
94.0
92.0
90.0
Porosity Reduction (% of initial)
0.
1000.
2000.
3000.
4000.
5000.
Effective Confining Stress (psi)

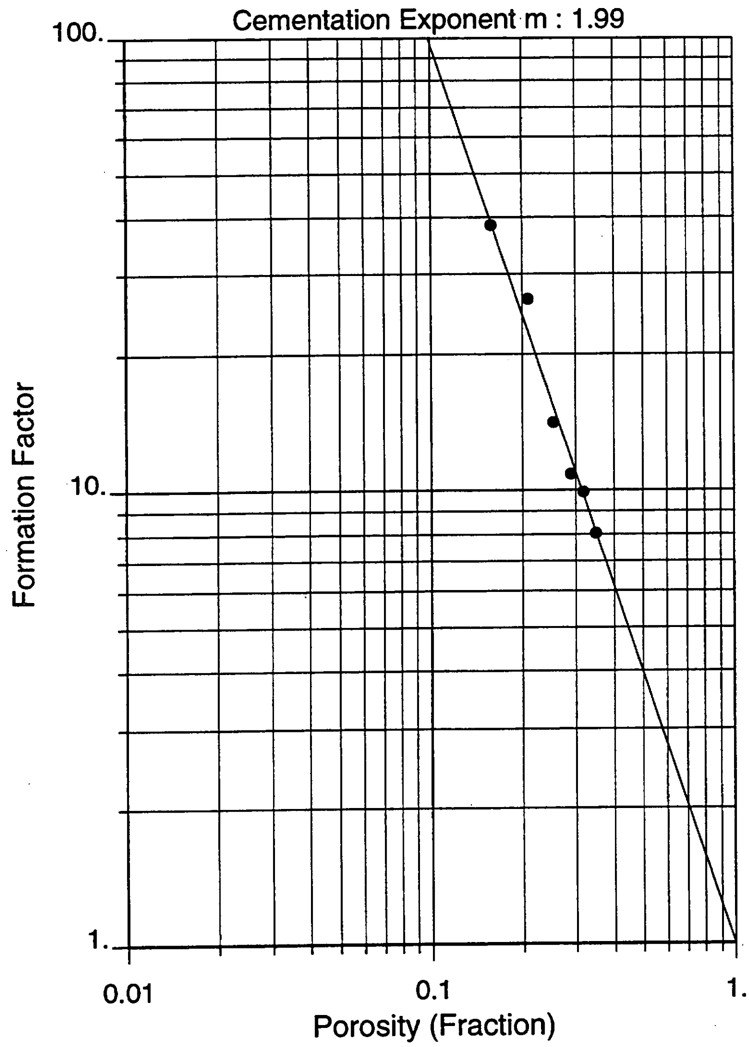
Rigs-1/SCAL: Formation resistivity factor study.

Overburden condition data.

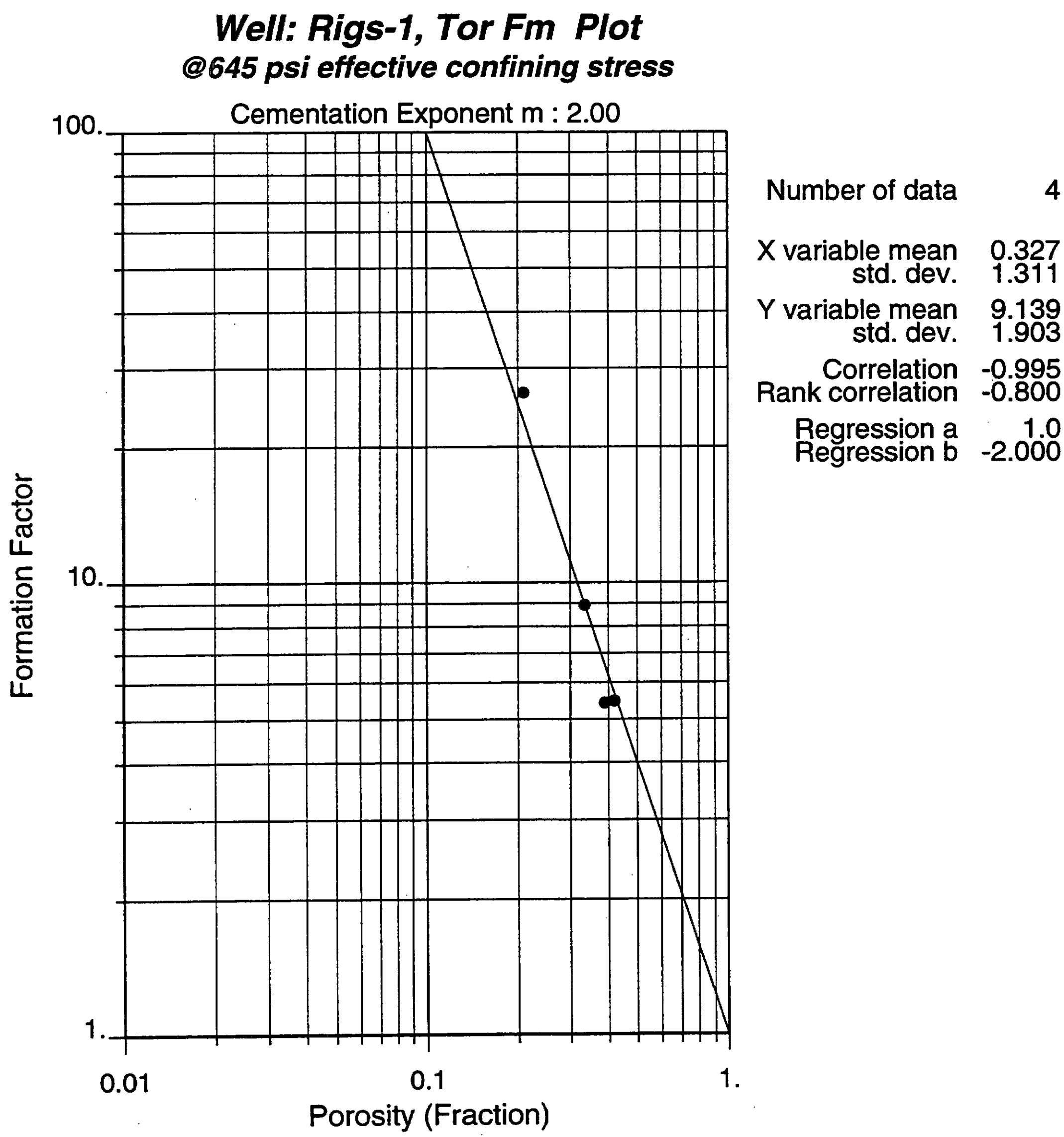
Formation resistivity factor and cementation exponent from multi sample plots.

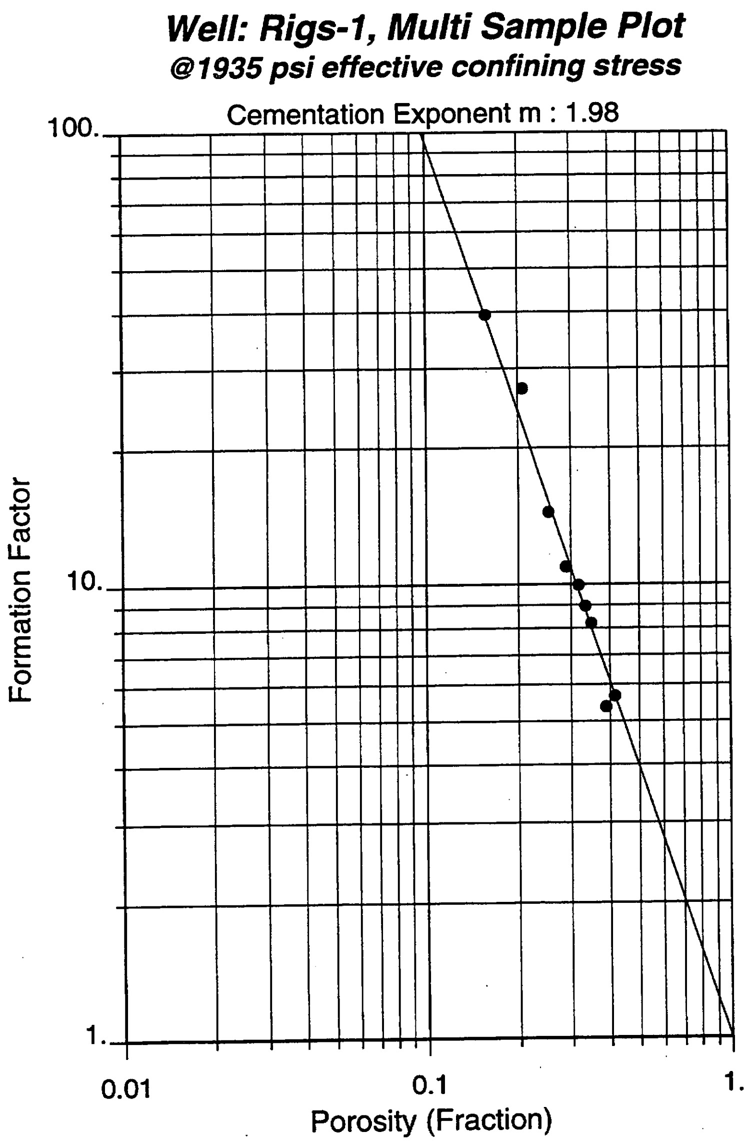

Well: Rigs-1, Multi Sample Plot
@645 psi effective confining stress
Cementation Exponent m : 1.98
100.
10.
1.
Formation Factor
0.01
0.1
1.
Porosity (Fraction)
Number of data 9
X variable mean 0.290
std. dev. 1.342
Y variable mean 11.408
std. dev. 1.868
Correlation -0.992
Rank correlation -0.983
Regression a 1.0
Regression b -1.976

Well: Rigs-1, Ekofisk Fm Plot
@645 psi effective confining stress

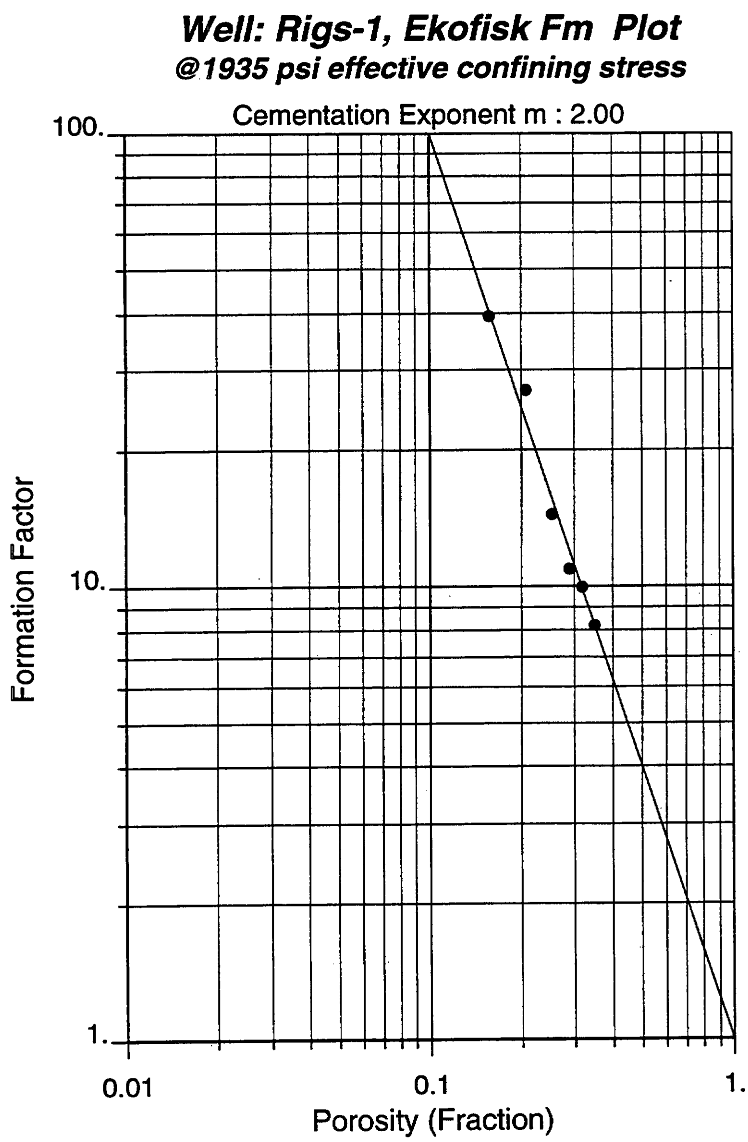


Number of data	6
X variable mean	0.254
std. dev.	1.307
Y variable mean	15.206
std. dev.	1.746
Correlation	-0.990
Rank correlation	-1.000
Regression a	1.0
Regression b	-1.988

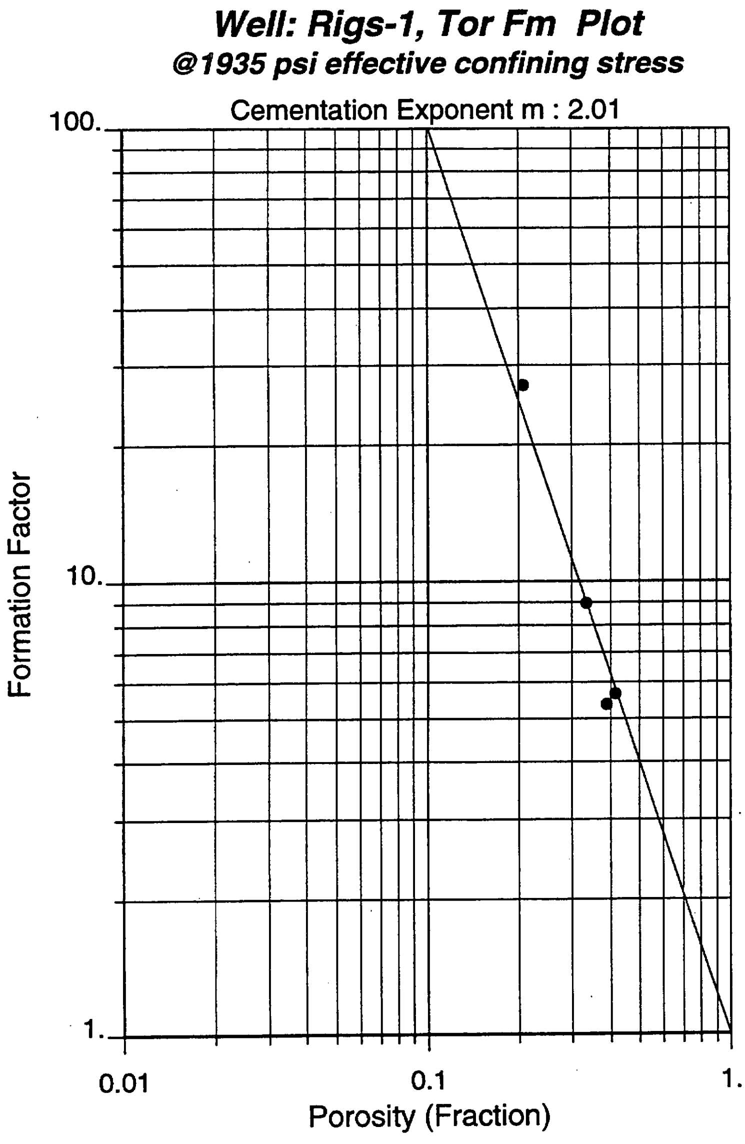

Well: Rigs-1, Tor Fm Plot
@645 psi effective confining stress
Cementation Exponent m : 2.00
100.
10.
1.
Formation Factor
0.01
0.1
1.
Porosity (Fraction)
Number of data 4
X variable mean 0.327
std. dev. 1.311
Y variable mean 9.139
std. dev. 1.903
Correlation -0.995
Rank correlation -0.800
Regression a 1.0
Regression b -2.000



Number of data	9
X variable mean	0.289
std. dev.	1.341
Y variable mean	11.585
std. dev.	1.878
Correlation	-0.991
Rank correlation	-0.983
Regression a	1.0
Regression b	-1.984

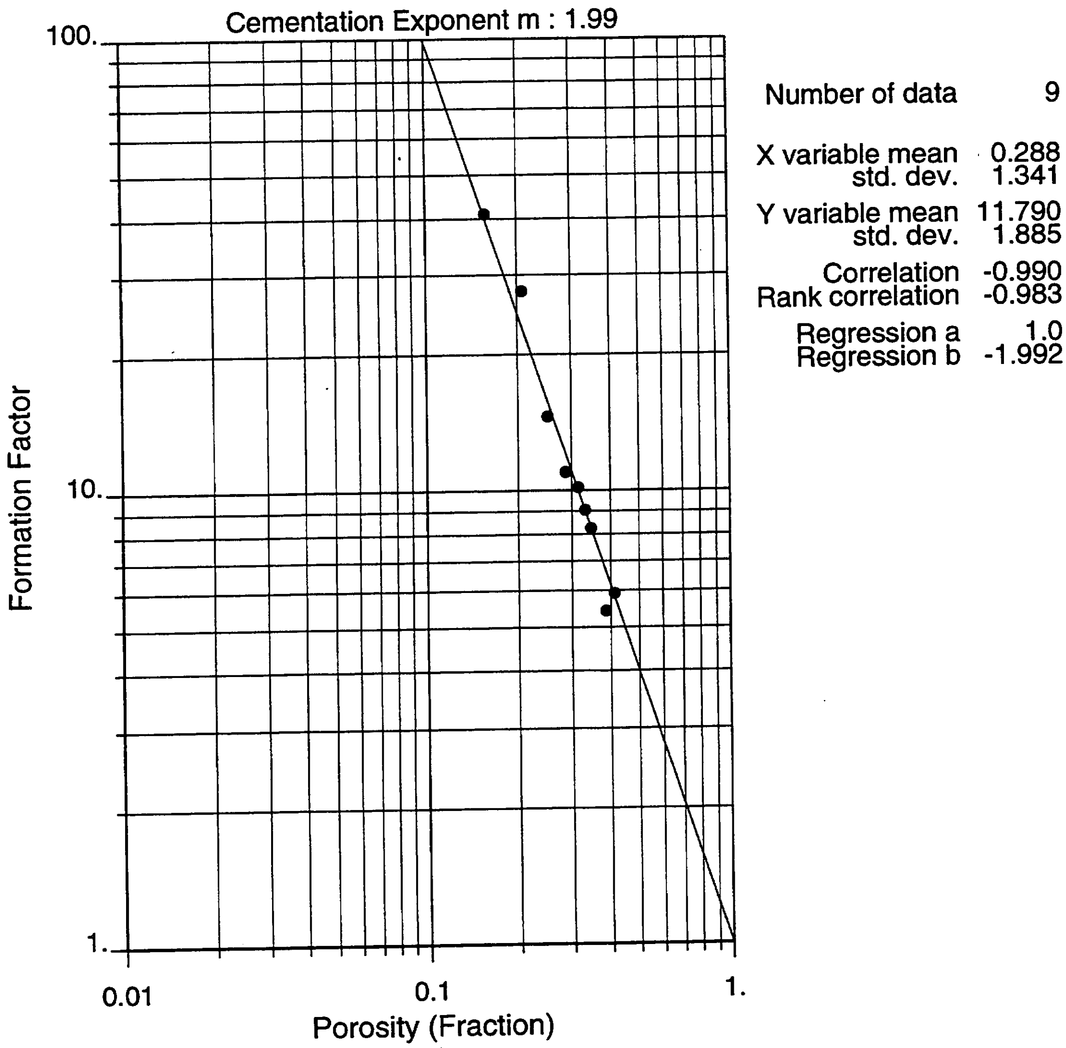


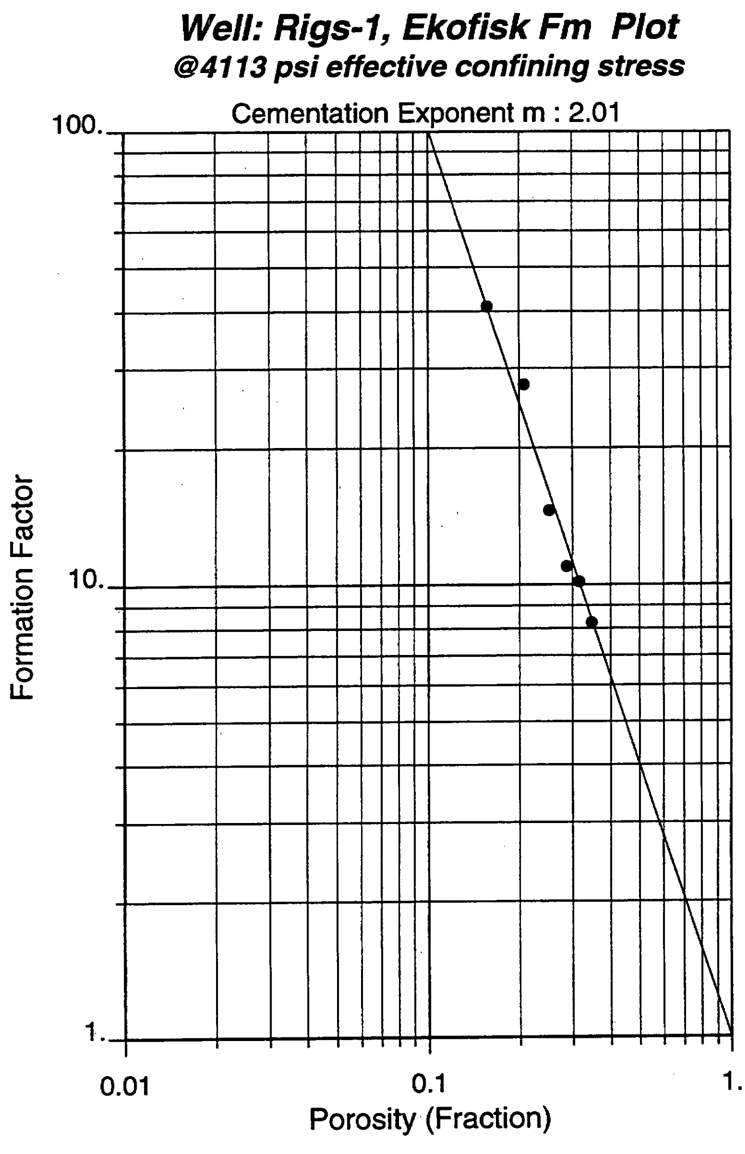
Number of data	6
X variable mean	0.253
std. dev.	1.307
Y variable mean	15.475
std. dev.	1.757
Correlation	-0.990
Rank correlation	-1.000
Regression a	1.0
Regression b	-1.998



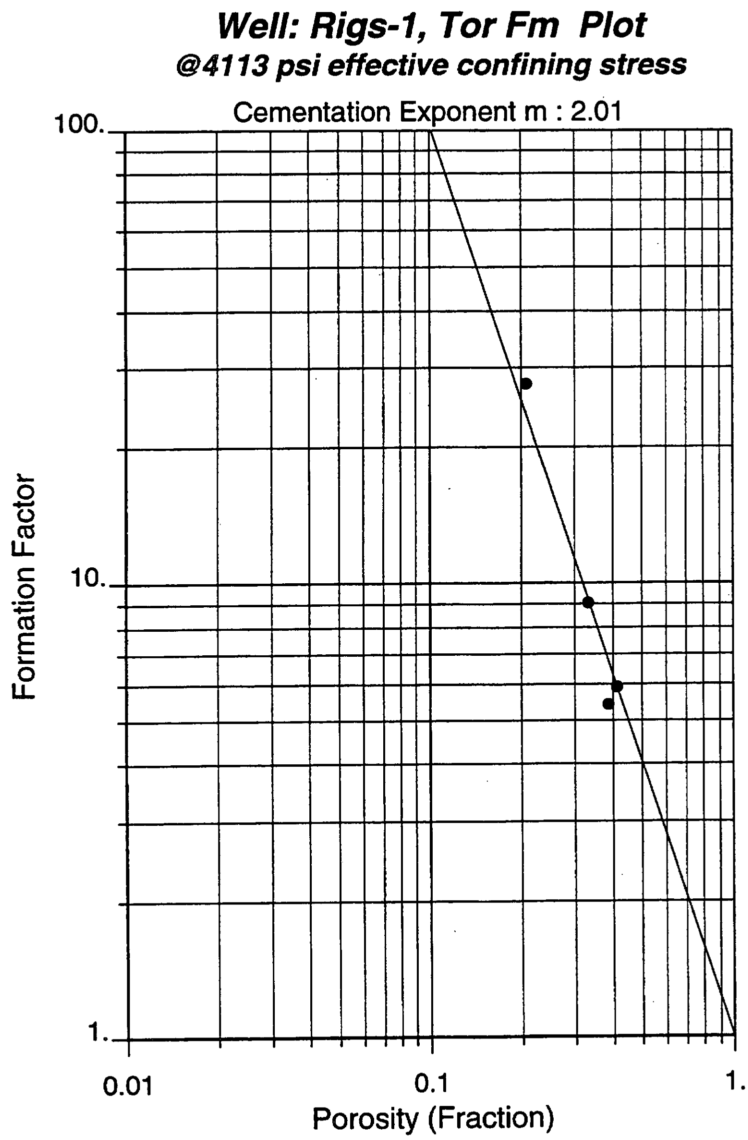
Number of data	4
X variable mean	0.326
std. dev.	1.311
Y variable mean	9.276
std. dev.	1.914
Correlation	-0.993
Rank correlation	-0.800
Regression a	1.0
Regression b	-2.007

Well: Rigs-1, Multi Sample Plot
@4113 psi effective confining stress





Number of data	6
X variable mean	0.252
std. dev.	1.307
Y variable mean	15.733
std. dev.	1.774
Correlation	-0.990
Rank correlation	-1.000
Regression a	1.0
Regression b	-2.006



Number of data	4
X variable mean	0.324
std. dev.	1.310
Y variable mean	9.457
std. dev.	1.910
Correlation	-0.991
Rank correlation	-0.800
Regression a	1.0
Regression b	-2.015