Petroleum Open File Report POF 9-88

Evaluation of the Daly Field Bakken Formation, Southwestern Manitoba

By M. Arbez

Manitoba
Energy and Mines
Petroleum

1988

Petroleum Open File Report POF 9-88

Evaluation of the Daly Field Bakken Formation, Southwestern Manitoba

By M. Arbez

Manitoba
Energy and Mines
Petroleum

1988

Manitoba
Energy and Mines
Petroleum

Petroleum Open File Report POF 9-88

Evaluation of the Daly Field Bakken Formation, Southwestern Manitoba

By M. Arbez

Winnipeg, 1988

Energy and Mines

Hon. Harold J. Neufeld
Minister

Charles S. Kang
Deputy Minister

Energy Division

H. Clare Moster
Assistant Deputy Minister

Petroleum Branch
L.R. Dubreuil
Director

TABLE OF CONTENTS

FIGURES

TABLE

Abstract

This study is a petrophysical evaluation of the Bakken sand in the study area (Figure 1). The study includes a description of the methods used to evaluate the Bakken formation as well as the results from these methods.

Log analysis techniques have been developed to obtain Bakken porosities and water saturations. Quick-look porosity estimates are obtained directly from porosity logs. A modified Archie equation gives fairly reliable water saturation estimates.

Introduction

The Bakken formation underlies the Mississippian Lodgepole and unconformably overlies the Devonian Lyleton or Three Forks Formation. For more detailed information on the geology of the Bakken sand, please refer to the Petroleum Open File Report POF 8-88. The Bakken is productive elsewhere in the Williston Basin, notably at Rocanville in southeastern Saskatchewan.

In 1985, Newscope Resources Limited discovered the Daly Bakken 'A' Pool by completing the well 13-21-10-29 WPM. Further development and exploratory drilling has resulted in the discovery of a number of Bakken pools in the Daly Field. The location of these pools and the study area are shown on Figure 1.

The Bakken is a clay-bearing sand. Because of this, conventional log analysis techniques often result in misleading or erroneous porosity and water saturation calculations. This study presents a reliable and effective Bakken formation evaluation method, using production, core and open-hole log data.

Methodology

a) Bakken Sand Lithology

i) Mineralogy

The Bakken formation is a very fine-grained quartz sandstone. The most abundant intergranular mineral is dolomite in the form of microcrystalline fines and/or cement. Dolomite cement helps lithify the rock but reduces formation porosity. Feldspars (potassium feldspar and plagioclase) and illite clay are also present in the Bakken sand. Illite generally occurs as a low relief clay which binds dolomite fines to larger grains and bridges and infills intergranular pore space.

ii) Log Lithology Model

The LDT or litho-density tool is a relatively new and expanded version of the compensated density log. In addition to measuring the formation bulk density, the LDT also records the formation photoelectric absorption cross-section index, Pe[(6)*]. Because Pe primarily reflects mineralogy, the LDT is a good lithology indicator.

Quantitative Bakken clay volumes were obtained from special core analyses of samples from the well 9-14-10-29 WPM. These clay volumes were matched with gamma ray log readings to

* reference listed at end of report

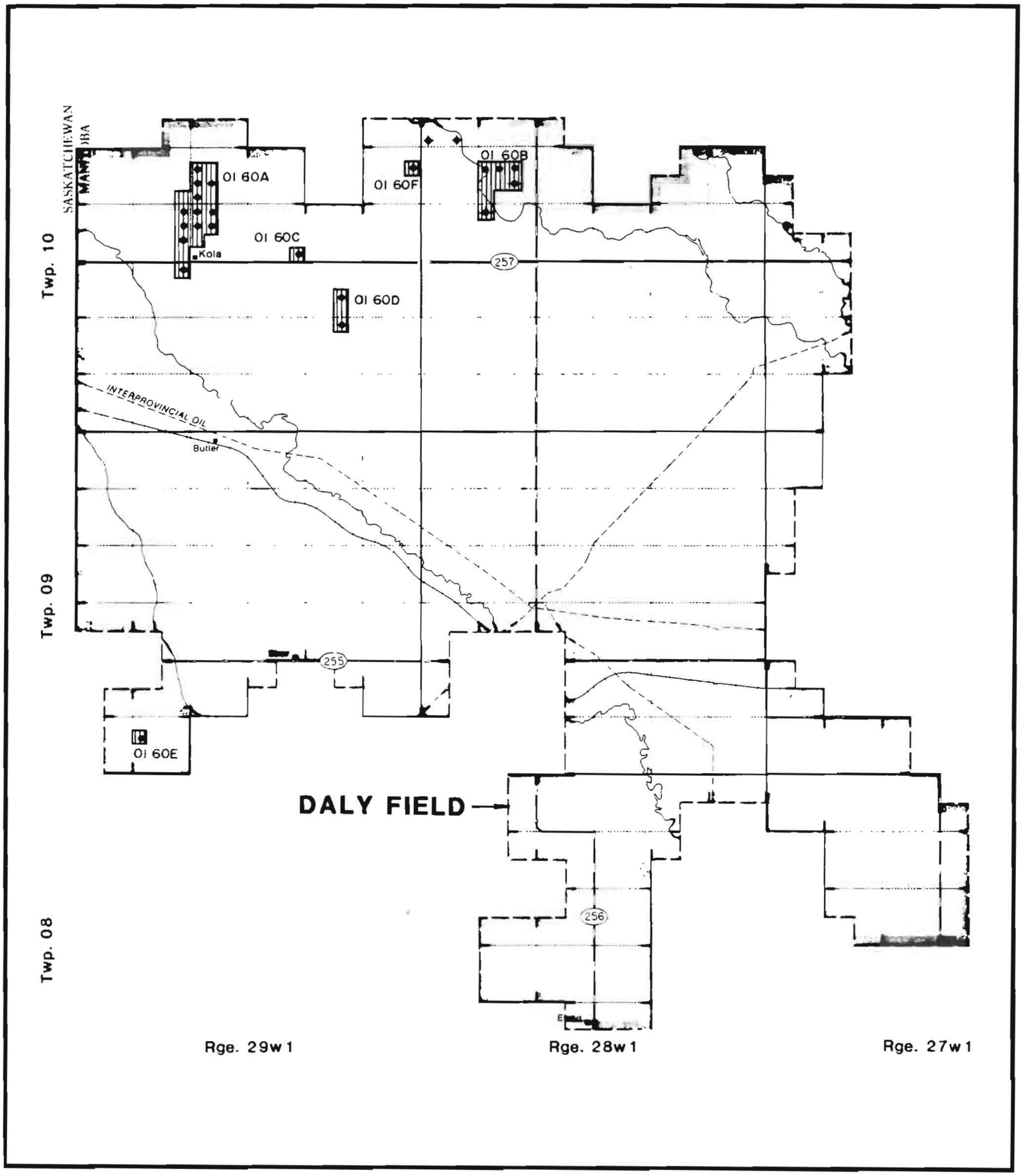


Figure 1: Bakken Pools and Wells

derive a clay volume to radioactivity correlaton (see Appendix A). This correlation is applied throughout the study to calculate illite clay volumes for the Bakken formation.

Figure 2 shows a Matrix Identification (MID) plot. The MID plot is used to identify lithology from LDT data. The apparent matrix density (ρmaa) is plotted along the Y axis. The apparent matrix volumetric cross-section (Umaa) is plotted along the X axis. Both ρmaa and Umaa are derived from the bulk density and photoelectric absorption index from the LDT log (see Appendix B).

Uma and ρma data for some common minerals can be obtained from the literature[3]. The table below lists Uma and ρma values for three of the four minerals from the Bakken lithology model:

Mineral	Uma	ρma
quartz	4.78	2.64
dolomite	9.00	2.88
illite	11.80	3.06

Because the fourth component of the model is a complex feldspar mineral assemblage, its Uma and ρma values are not readily available from the literature. By combining special core analysis data with simple material balance, the Uma and ρma parameters for feldspar were estimated to be 15.06 and 2.65, respectively (see Appendix B).

The MID plot in Figure 2 can be used to estimate the percentages of quartz, dolomite and feldspar for the Bakken sand. The procedure is as follows:

1) obtain V_{clay} (clay volume) from gamma ray log (see Appendix A);
2) calculate ρmaa, Umaa (see Appendix B);
3) locate point on MID plot;
4) apply V_{clay} correction along a line joining illite clay point and point of interest;
5) read quartz, dolomite and feldspar percentages at clay-corrected point.

The MID plot should only be used to obtain rough estimates of mineral percentages for the Bakken sand. Many factors can affect the accuracy of the MID plot. For example, radioactive feldspars increase the gamma ray response. Consequently, calculated clay volumes are too high and the clay correction to the MID plot is too severe. The Bakken sand contains potassium feldspars which can adversely affect MID plot results.

b) Total Porosity

All Bakken core samples in the study area have been dried in conventional ovens before porosity determination. Clay-bound water is evaporated under the quick-drying conditions of a conventional oven. Because the Bakken is a clay-bearing sand, all available core-measured porosities are equivalent to total porosities Φ_T. To obtain effective porosities, core samples must be dried in humidity-controlled ovens which do not drive off clay-bound water.

By depth-adjusting Bakken core data to log traces, the following core bulk density ($\rho_{b\ core}$) to log bulk density ($\rho_{b\ log}$) correlation is obtained:

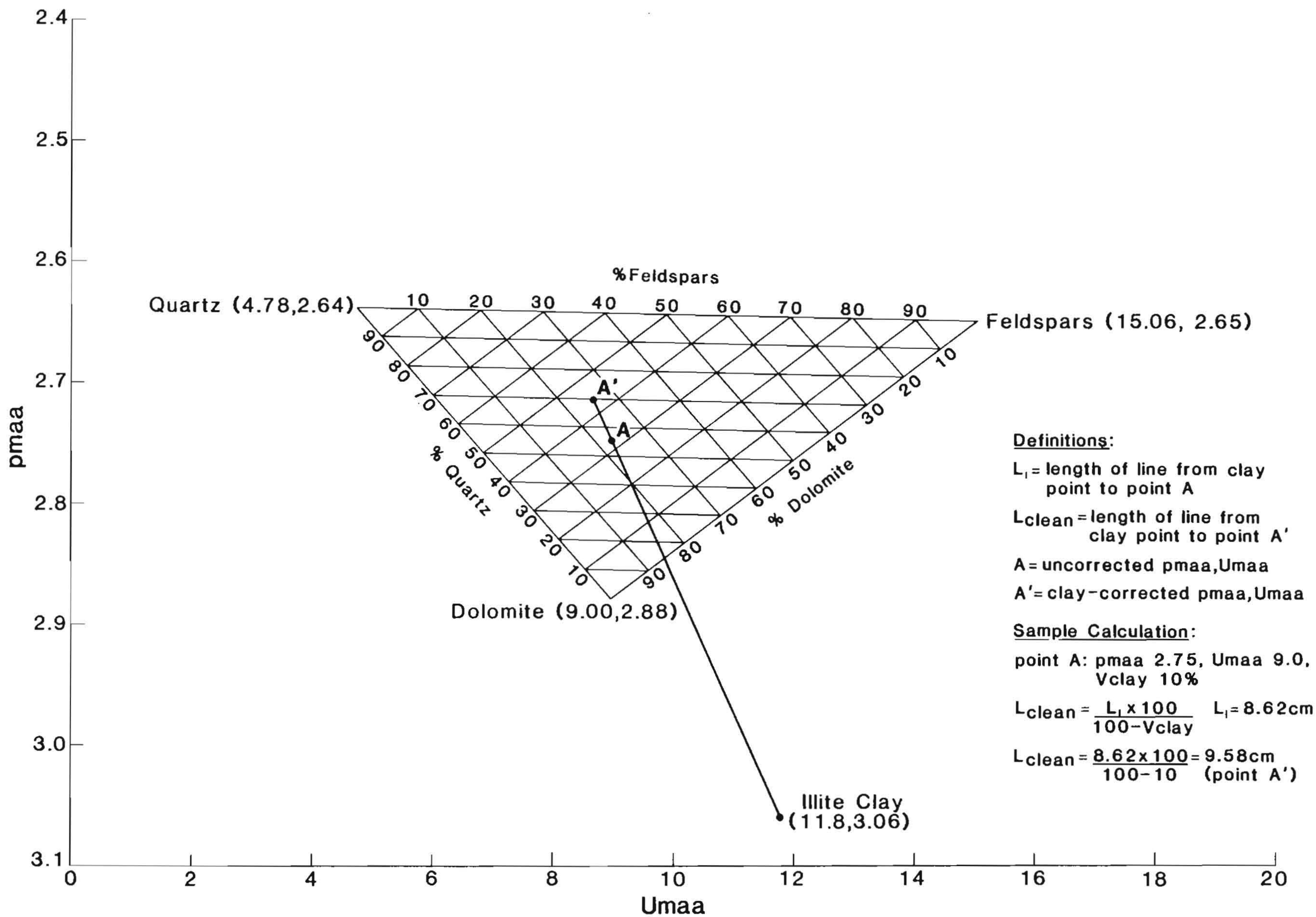


Figure 2: MID Plot

(1) $\rho_{b\ core} = \dfrac{(\rho_{b\ log} + 0.252)}{1.111}$ ρ in gm/cm^3

The log bulk density is a function of the (density) porosity as shown in the equation:

(2) $\rho_{b\ log} = \Phi_D + (1-\Phi_D) \times 2.71$ Φ_D in fraction, limestone scale [6]

rearranging (2), we get a corrected density porosity:

(3) $\Phi_{D\ corr} = \dfrac{(2.71 - \rho_{b\ core})}{1.71}$ $\Phi_{D\ corr}$ in fraction, limestone scale

Figure 3 is a Φ_D corr versus Φ_N crossplot for the Bakken sand in the study area. The following procedure was used to develop this crossplot:

1) depth-adjust core porosities to log porosity traces;
2) plot $\Phi_{D\ corr}$ and Φ_N (point A);
3) locate Φ_{core} or Φ_T along diagonal or clean sand line (point A');
4) join A to A';
5) calculate slope of line in (4) ($\Phi_{D\ corr}/\Phi_N$ or total porosity slope).

These steps were followed for a number of core intervals. A total porosity to log porosity correlation was derived:

(4) $\Phi_T = \dfrac{(\Phi_{D\ corr} + (0.095 \times \Phi_N))}{1.095}$ Φ in percentage, limestone scale.

c) Water Saturations

i) Choice of Water Saturation Models

The Waxman-Smits shaly sand model[1] has been selected to calculate water saturations for the Bakken formation. A modified version of the Archie equation is also used to calculate saturations. The empirical Archie equation, with $a=1$ and $m=2$, is not well suited to clay-bearing sands like the Bakken.

The Waxman-Smits model assumes that an electrical current through a clay-bearing sand will flow along a parallel conductance path. Part of the current flows through the brine solution within the pore system. The remainder of the current flows through a cation-rich layer of water bound to the clay.

The Waxman-Smits model was developed on the premise that the suppression of resistivity by water-bearing clays is a function of the cation exchange capacity (CEC) of the clays. Different clay types have different CEC's. Special core analyses on clay-rich samples usually yield reliable CEC values. No such analyses are available for the Bakken sand. The literature[1] offers lists of typical CEC values associated with different clay types.

The Bakken contains illite clay. The CEC for illite usually ranges from 0.2 to 0.3 meg/g. A CEC of 0.25 is used in this study.

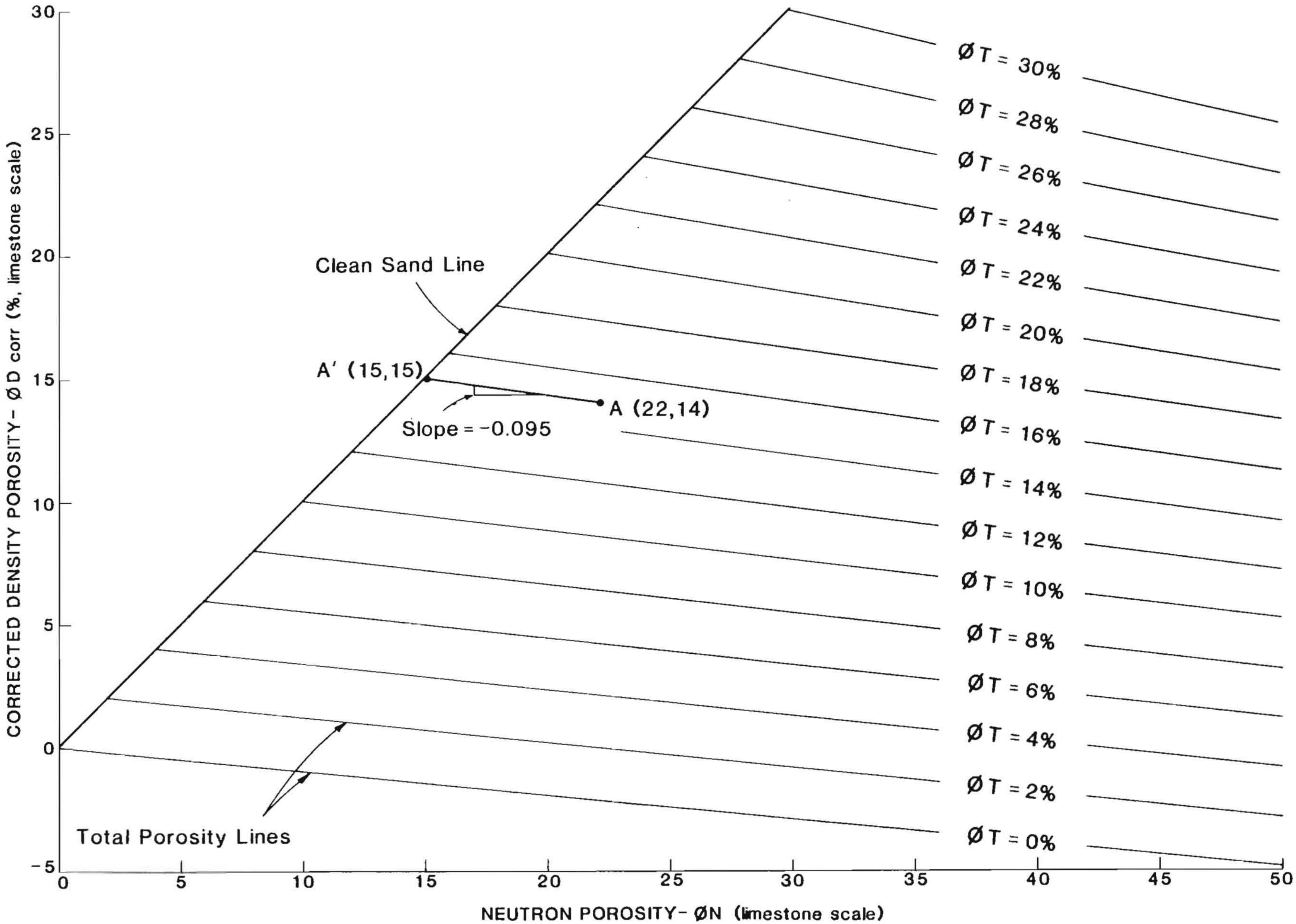


Figure 3: Neutron-Density Porosity Crossplot

ii) S_{wt} from Waxman-Smits Model

The Waxman-Smits equation can be written in the form:

$$5)\ C_t = \frac{C_{wt}{}^{n}}{F^*} + \frac{BQ_vS_{wt}{}^{n-1}}{F^*}$$

where: C_t is the formation conductivity

C_w is the formation water conductivity

B is the conductance of the clay exchange cations

Q_v is the cation concentration per unit volume of fluid in pore space

F^* is the Waxman-Smits formation factor

S_{wt} is the total water saturation, including clay-bound water.

$C_t = \frac{1}{R_t}$; R_t from deep resistivity log trace

$C_w = \frac{1}{R_w} = \frac{1}{0.05} = 20$ ohm-meters;

$R_w = 0.05$ ohm-meters, from produced Bakken water at $t = 31^\circ C$

$$B = \frac{-1.28 + .225t - .0004059t^2}{1 + R_w{}^{1.23}(0.045\ t - .27)} = 5.16$$

$$Q_v = \frac{CEC\ (1-\Phi_T)\ \rho ma}{\Phi_T} = \frac{0.25\ (1-\Phi_T)\ \rho ma}{\Phi_T}$$

$F^* = F\ (1 + R_wBQ_v)$

To obtain F, plot $F = R_o/R_w$ versus Φ_T (log-log plot), for wet Bakken sand intervals (see Figure 4).

If $n=2$ in equation (5), the Waxman-Smits equation can be solved as a simple quadratic:

$$(6)\ X = \frac{-b \pm (b^2 - 4ac)^{.5}}{2a} \quad (1)$$

where $X = S_{wt}$

$a = C_w/F^*$

$b = B\ Q_v/F^*$

$c = -C_t$

iii) S_{wt} from Archie Equation

From Figure 4, $\log_{10}F = 0.0098743 - 1.74 \log_{10} \Phi_T$; the slope "m" = -1.74 and "a" or the y-intercept = 1.023 (Φ_T = 100%). The parameters "a" and "m" are used in the Archie water saturation equation.

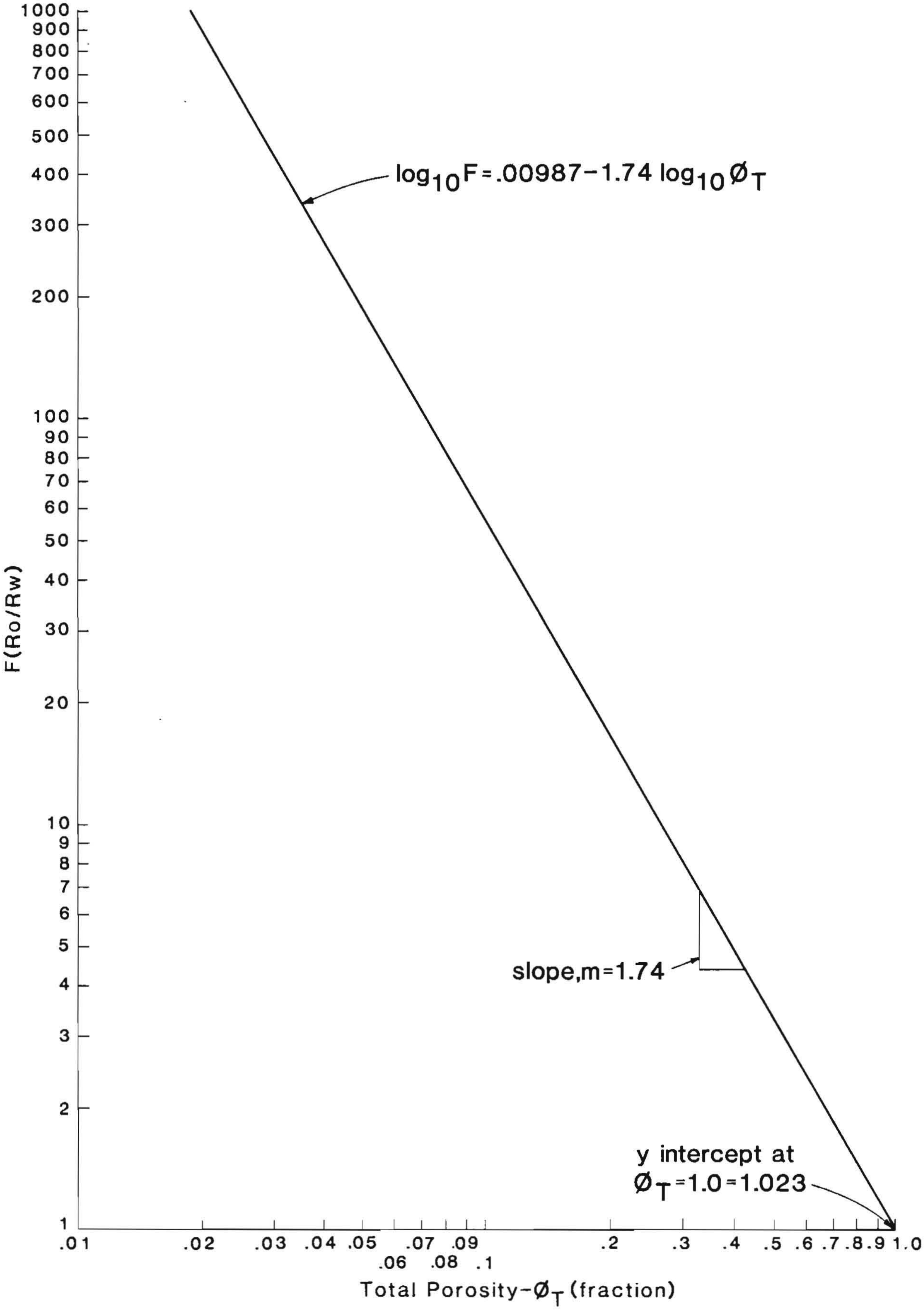


Figure 4: F versus $Φ_T$ Crossplot

The Archie equation for the Bakken sand in the study area can be written as:

$$(7)\ S_{wt}{}^{n} = \frac{a\,R_w}{\Phi_T{}^m R_t};$$

where $n = 2.0$

$a = 1.023$

$m = 1.74$

$R_w = 0.05$

Archie water saturations were calculated for the Daly Bakken sand.

A modifed version of equation (7) yields accurate quick-look results:

$$(8)\ S_{wt} = \frac{(aR_w/\Phi_D{}^m\ R_t)^{0.5}}{1.32}$$

Daly Bakken Pool Descriptions

Each of the designated Bakken pools have been analysed in detail for lithology, porosity, water saturation, original oil-in-place per unit area and estimated primary recovery. Calculations were made on well data available to September 1, 1988. Appendix C lists these results.

a) Lithology

MID plot calculations consistently show that the Bakken in the study area is a feldspathic, dolomitic clay-bearing sandstone. Core descriptions confer with these log-derived results. The litho-density log is a reliable lithology indicator for the Bakken sand.

b) Total Porosity (see Figure 5)

'A' Pool: Porosities range from 13 to 23% and average 17%. The best porosity development is in the central portion of the pool at the locations: 16-20, 13-21, 2-28, 3-28, 4-28 all in Township 10, Range 29 WPM. Porosities drop off rapidly to the west, away from the centre of the pool.

'B' Pool (includes 'F' Pool): Porosities range from 13 to 19% and average 16%. Because of their narrow range, porosities were not contoured.

'D' Pool: Porosities range from 9 to 21% and average 18%. The highest porosities occur near the eastern edge of the pool (12-13, 9-14 and 16-14, Township 10, Range 29 WPM). Porosities decrease quickly to the west. Lack of data at the east side of the pool limits contouring of porosity data.

c) Total Water Saturation (see Figure 6)

'A' Pool: The average water saturation is 45%. Saturations consistently range from 30 to 40% in the middle of the pool and increase to the west which is downdip from the centre of the pool.

'B' Pool (includes 'F' Pool): Water saturations do not vary appreciably. The average saturation is 54%.

'D' Pool: The average water saturation at the eastern edge of the pool is 33%. Saturations increase sharply on the west side of the pool.

d) Original Oil-in-Place per Unit Area (see Figure 7)

Table 1 lists reservoir properties for the Daly Bakken 'A', 'B' and 'D' Pools. The shrinkage factor (1/Boi) was obtained from a PVT analysis on the well 3-28-10-29 WPM.

'A' Pool: The total oil-in-place for this pool is calculated to be 1 123 180 m^3. Most oil appears to be trapped in the geographic centre of the pool. The west side of the pool is probably limited by a downdip water zone. The north, south and east sides of the pool exhibit rapid decreases in net pay thickness. There appears to be a limited amount of future drilling potential.

'B' Pool (includes 'F' Pool): The oil-in-place for this pool is calculated to be 492 043 m^3. The edge of the pool is difficult to define because of the lack of data to the north and south.

'D' Pool: The oil-in-place for this pool is calculated to be 231 000 m^3. The edge of the pool is loosely defined.

e) Production Decline and Recovery Factor

The lower economic limit for oil production is assumed to be 0.5 m^3 per day per well for all three Bakken pools (see Appendix D).

'A' Pool: A primary recovery factor of 7.1% was estimated from an annual production decline of 20%. The decline was obtained over a period of time when the pool was not being actively developed (Dec/86 - June/87) (see Figure 8). The ultimate recoverable reserves are 80 631 m^3 oil.

'B' Pool (includes 'F' Pool): A very low primary recovery factor of 1.0% was calculated for this pool. 'B' Pool oil production is very erratic with time. Overall, production from the pool is declining quite rapidly. Assuming an annual decline of 42% (based on production from 12-29), the ultimate recoverable reserves are 4 174 m^3 oil. Many of the wells in this pool have been recompleted to the overlying Lodgepole formation because of uneconomic Bakken production.

'D' Pool: A recovery factor of 11% was calculated, based on an annual decline of 24% for the well 15-11-10-29 WPM. A decline rate could not be estimated for the pool as a whole because of active development throughout its production history. The ultimate recoverable reserves are 25 742 m^3 oil.

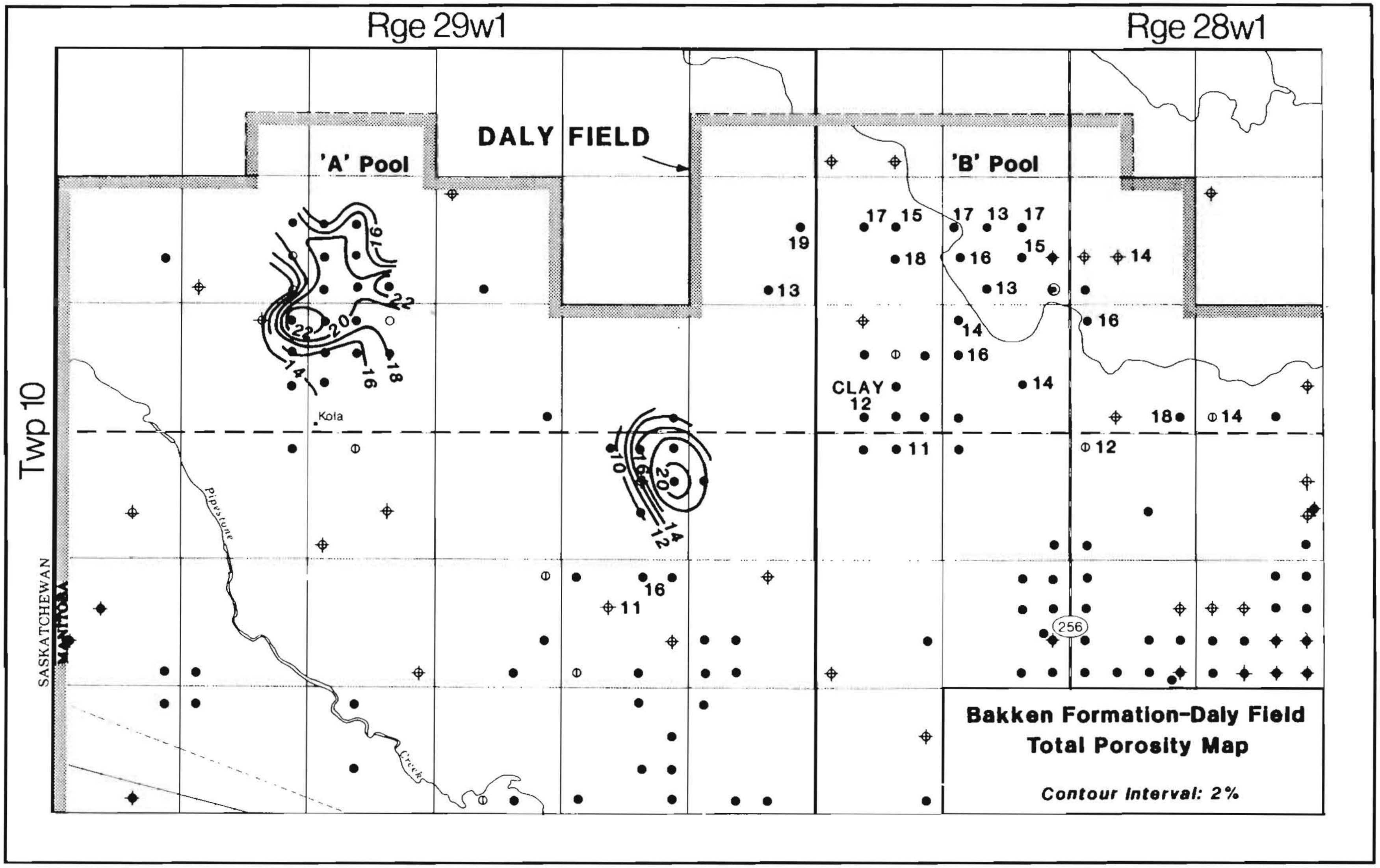


Figure 5: Bakken Formation - Daly Field Total Porosity Map

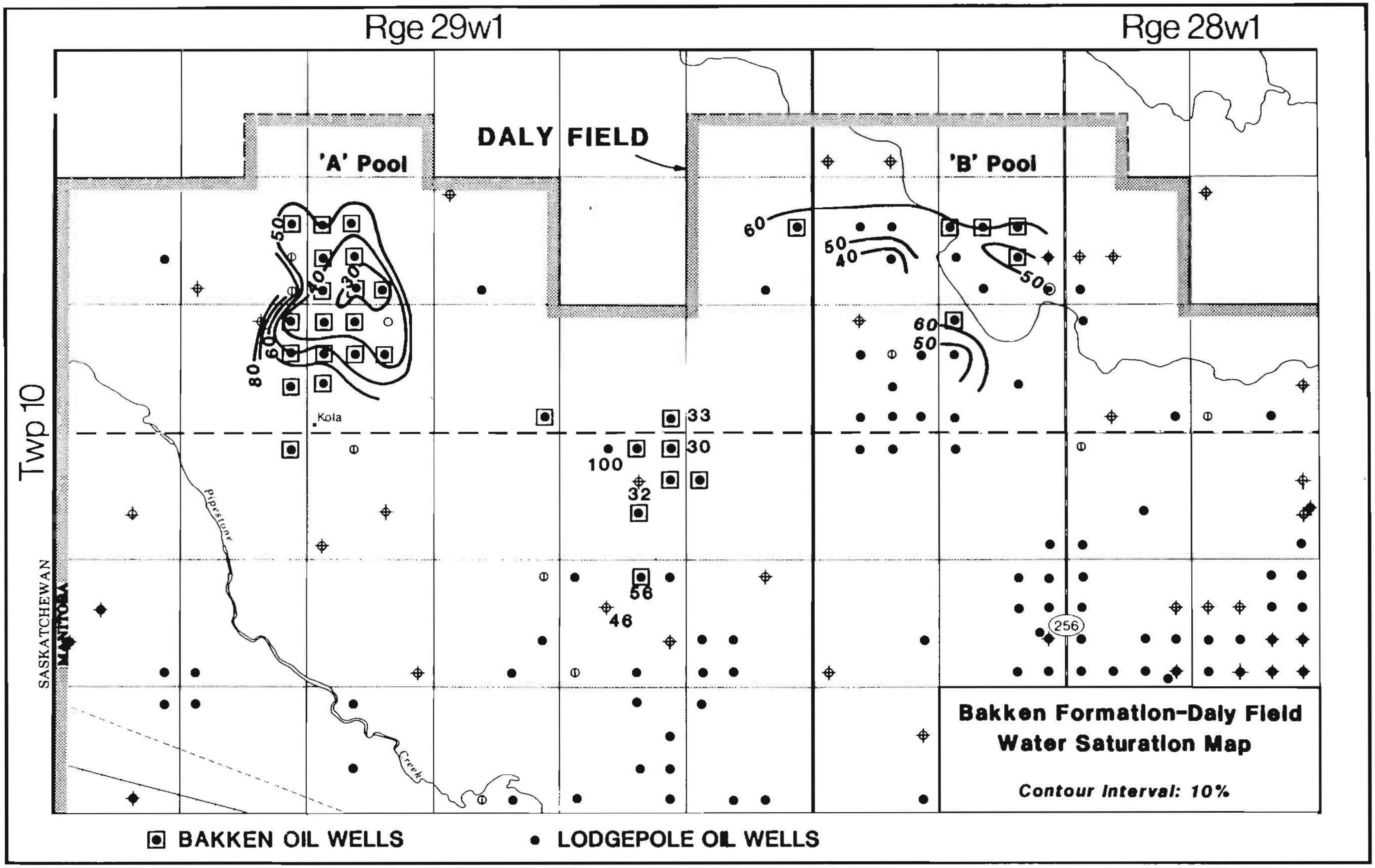


Figure 6: Bakken Formation - Daly Field Water Saturation Map

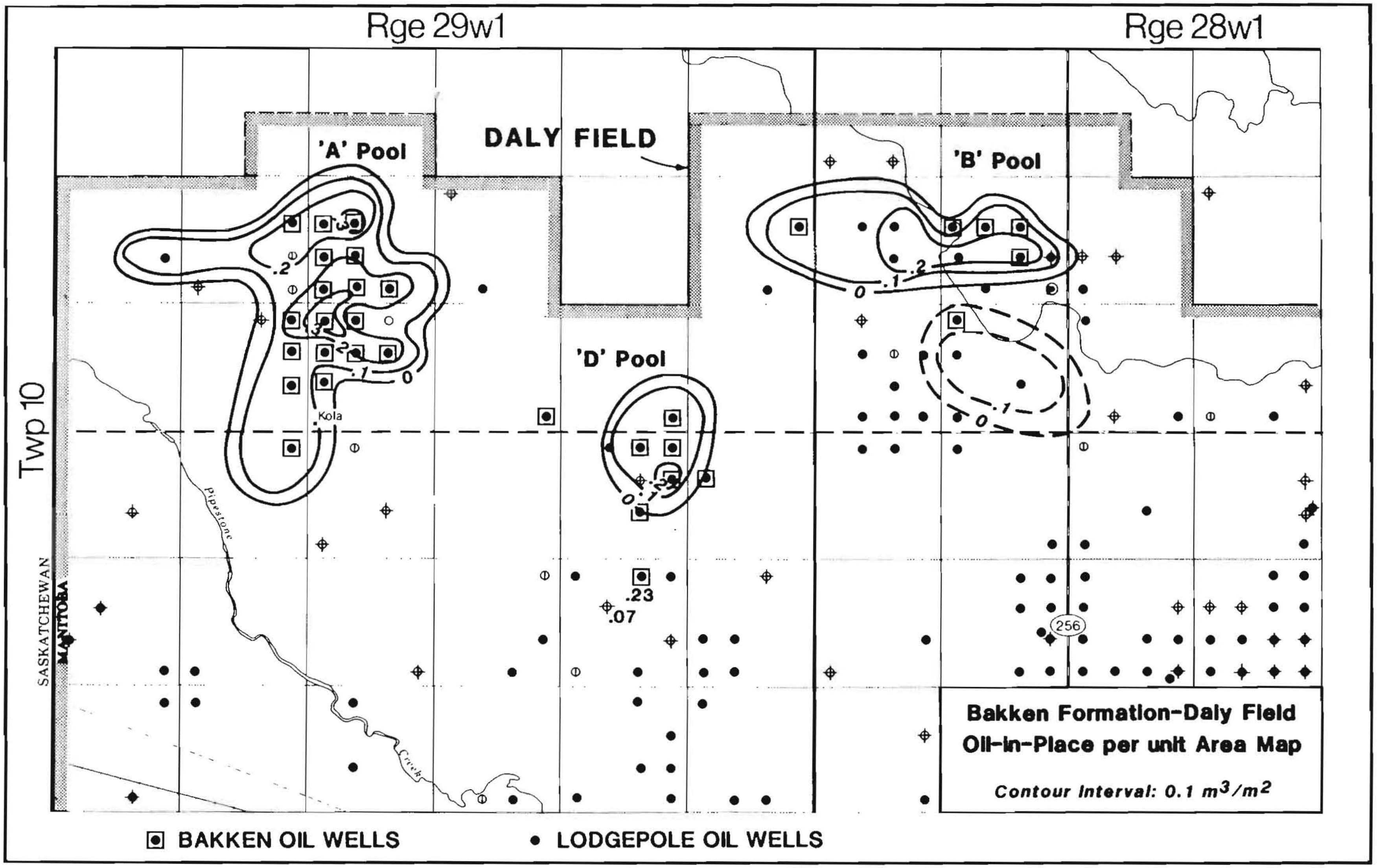


Figure 7: Bakken Formation - Daly Field Oil-in-Place per Unit Area Map

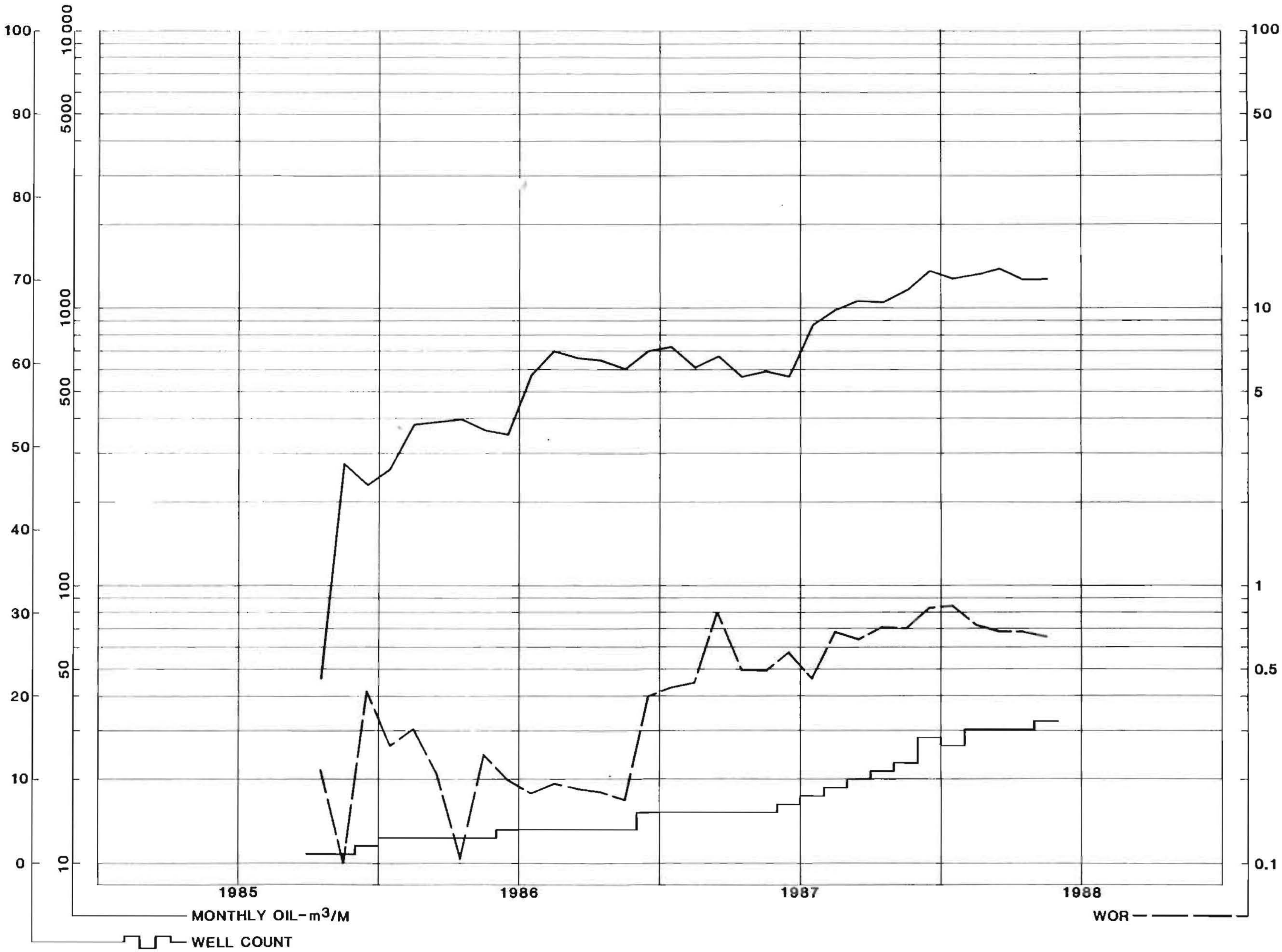


Figure 8: Daly Bakken "A" Pool History Plot

POOL	BAKKEN "A"	BAKKEN "B"	BAKKEN "D"
General Information			
1. Year of Discovery	1985	1986	1986
2. Number of wells a) capable of oil production	19	6	7
b) produced first half of '88	17	6	7
c) previous producers	0	0	0
3. Spacing	16 ha	16 ha	16 ha
4. Average Depth of Producing Zone	-340 m(subsea elev.)	N/A	N/A
5. Crude Oil Quality a) density	776.4 kg/m^3	776.4 kg/m^3	776.4 kg/m^3
b) sulphur content	0.13%	--	–
6. Initial Pressure (at datum)	8 500 kPa	7 716 kPa	7 900 kPa (3)
7. Current Pressure (at datum)	4 000 - 6 000 kPa	N/A	N/A
8. Recovery Mechanism	--------------------------- low energy natural water drive ------------------------		
Reserves Information			
1. Production Area	853 ha	424 ha	196 ha
2. Net Pay	1.6 m	1.8 m	1.1 m
3. Porosity (ϕ_T)	17.0%	16.0%	18.0%
4. Connate Water Saturation (S_{wT})	45.0%	54.0%	33.0%
5. Shrinking Factor (1/Boi)	0.893	0.893	0.893
6. Original oil-in-place	1 125 180 m^3	492 043 m^3	231 000 m^3
7. Recovery Factor	7.1% (1)	1.0% (2)	11.0% (4)
8. Ultimate Recoverable Reserves	80 631 m^3	4 174 m^3	25 742 m^3
9. Cummulative Production (to Sept 30, 1988)	27 539 m^3	4 216 m^3	5 759 m^3
10. Remaining Recoverable Reserves (Sept 30, 1988)	53 092 m^3	-	19 983 m^3

(1) 20% annual production decline for pool
(2) 42% annual production decline from 12-29-10-28 (WPM)
(3) DST's show dramatic pressure drop
(4) 24% annual production decline from the well 15-11-10-29 (WPM)

Trap Type: (For all pools)

1. Primarily stratigraphic (related to the lateral pinch-out of the Middle Member)
2. Secondary structural (related to minor structural elevation on top of the Middle Member)

Table 1: Reservoir Engineering Properties of the Bakken Formation

Conclusions

1) The Waxman-Smits equation has been successfully used to derive total water saturations for the Bakken sand in the Daly area. This approach involves a number of complex empirical and derived equations and cannot be used as a quick-look method of calculating total water saturations.

2) A modified form of the Archie equation using log density porosities [equation (8)] yields total water saturations which almost mimic those obtained from the Waxman-Smits equation.

   This provides a simple way of calculating the total water saturation for the Bakken formation. If the calculation is done on a Bakken interval in Daly, $R_w = 0.05$ ohm-meters. When evaluating the Bakken outside the study area, R_w should be obtained from temperature-corrected water analyses on produced water.

3) Many Daly wells produce at extremely low water cuts yet their total water saturations are fairly high (>30%). These apparently high irreduceable saturations along with relatively low log resistivity measurements indicate that the Bakken is strongly water-wet. A strongly water-wet rock produces more efficiently under waterflood conditions than does an oil-wet rock.

4) Based on petrophysical data, it appears that there are some limited future development possibilities within existing Bakken Pools of the Daly Field. Development locations proposed within these pools are listed below:

   'A' Pool: 1-20-10-29 WPM, 5-29-10-29 WPM

   'B' Pool: 12-30-10-28 WPM, 5-30-10-28 WPM, 6-30-10-28 WPM

   'D' Pool: 2-23-10-29 WPM

Recommendations

a) Pressure Maintenance

Reservoir pressure and production data indicates that the Daly Bakken formation is being effected by a very low energy recovery mechanism. Over a production period of two years, there has been a substantial drop in the production rate, reflecting a decline in reservoir pressures in the Bakken 'A' Pool. Due to the lack of data, the pressure drop has not been quantified for other Bakken pools. All Bakken pools have shown rapid production declines.

It is evident that a pressure maintenance scheme, such as waterflooding, is necessary to maximize the economically recoverable reserves in the Bakken. However, illite and dolomite fines are abundant in the Bakken sand. Migrating illite and dolomite fines can clog pore throats between sand grains and reduce permeability. If water injection pressures are too high or if fluids are produced at unrestricted rates, a fines migration problem can be initiated. Some of the dolomite fines appear to be lodged within the illite clays. If these clays are disolved by injection water, an even greater migration problem can develop. Water compatibility tests would indicate which fluids dissolve illite clay and/or react with dolomite. Laboratory tests should be conducted in order to establish the benefits of dissolving illite clays to increase permeability, taking into account the increased fine migration problem associated with clay dissolution.

b) Data Collection

The following "shopping list" could lead to a more accurate and meaningful formation evaluation of the Bakken sand:

1) Conduct humidity-controlled and conventionally-dried core analyses on a Bakken core. Effective porosities are obtained from humidity-dried core; total porosities are obtained from conventionally-dried core. Data from both types of analyses can also be used to estimate formation cation exchange capacity (CEC).
2) More special core analysis work would result in a more reliable clay volume to gamma ray correlation for the Bakken (i.e. X-Ray diffraction and Scanning Electron Microscopy).
3) Meaningful Bakken formation water resistivities (R_w) can be measured from samples of produced water. Drill stem test water samples are often contaminated by drilling mud filtrate which has invaded the formation.

References:

1) Berry, W.R.
1983: Modern Shaly Sand Log Analysis.

2) Core Laboratories, Inc.
1988: Petrographic Analysis for The Manitoba Oil and Gas Corporation, MOGC Daly 9-14-10-29 WPM.

3) Core Laboratories, Inc.
1982: Special Core Analysis, p. v-17.

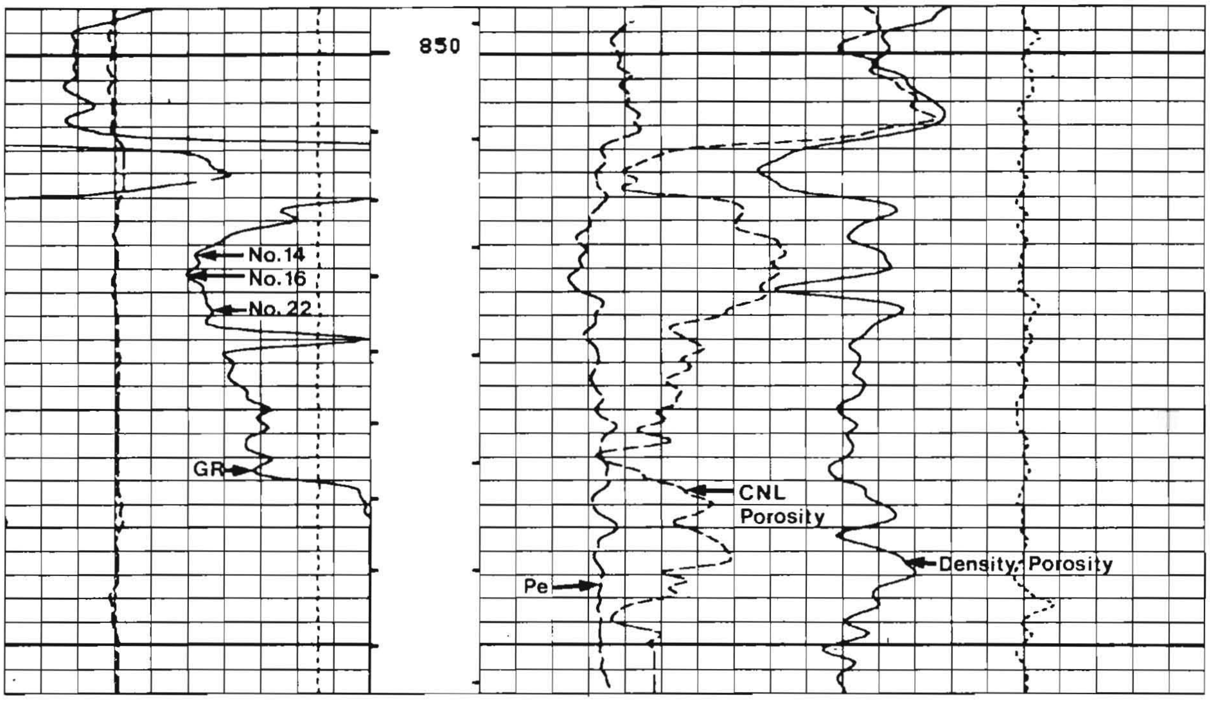
4)Dowell Schlumberger Canada
1986: Formation Analysis Report for Newscope Resources Limited, 4-28-10-29 WPM and 1-29-10-29 WPM, Bakken Formation.

5) Helander, D.P.
1971: Oil and Gas Consultants International, Inc. Formation Evaluation Manual.

6) Schlumberger Educational Services
1987: Schlumberger Log Interpretation Principles/Applications.

Appendix A

Clay Volume from Gamma Ray Response



Compensated Neutron-Lithodensity Log for 9-14-10-29 WPM

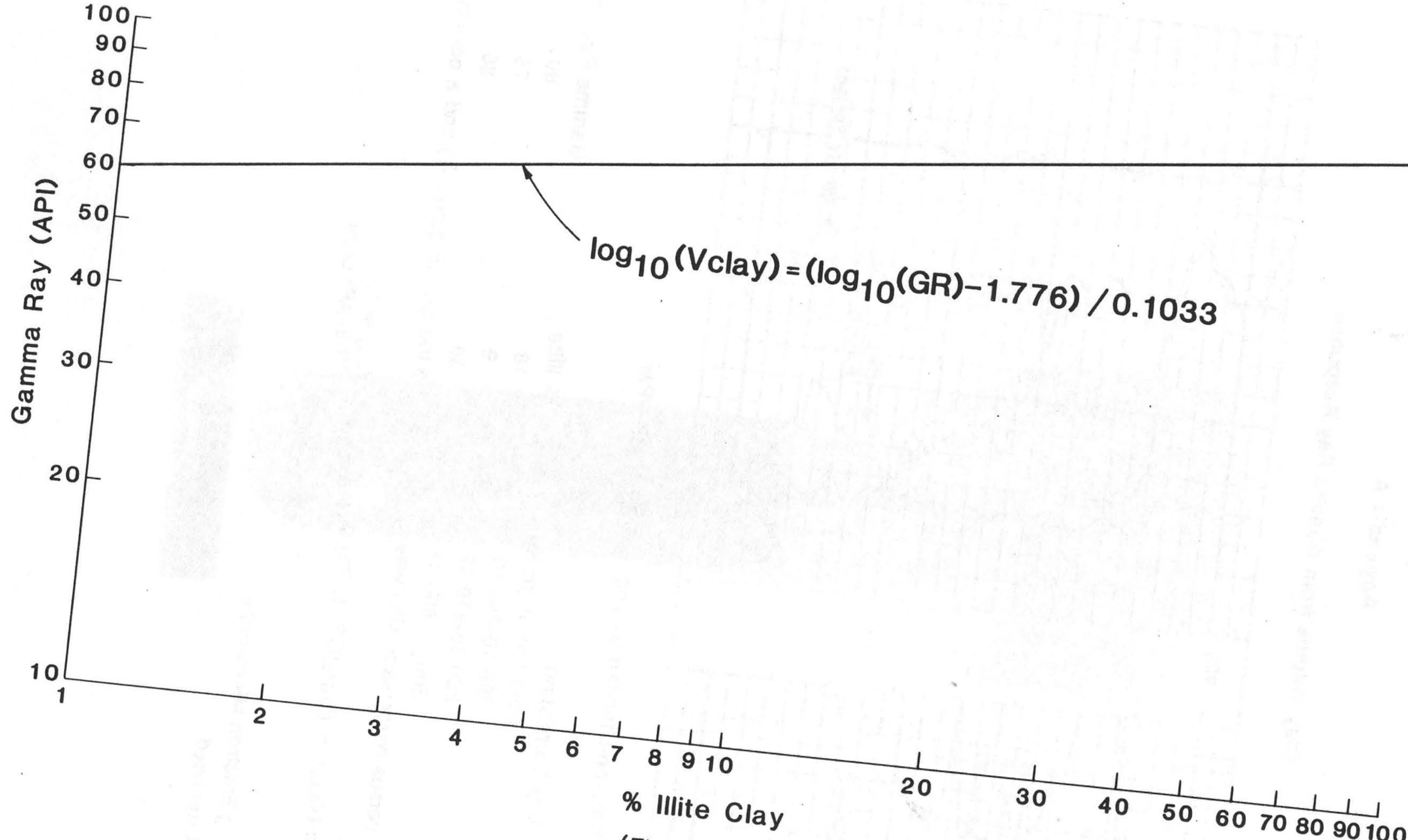
From SEM[1] - Log Correlation:

Sample No.	core depth (m Kb)	% illite	Gamma Ray (API)[2]
14	859.10-859.19	18	80
16	859.30-859.42	9	75
22	860.31-860.41	30	85

Gamma ray versus percentage illite was plotted on a log-log grid (Figure A-1) and a correlation was established:

$\log_{10}(V_{clay}) = (\log_{10}(GR)-1.776)/0.1033$; V_{clay} in %
GR in API units

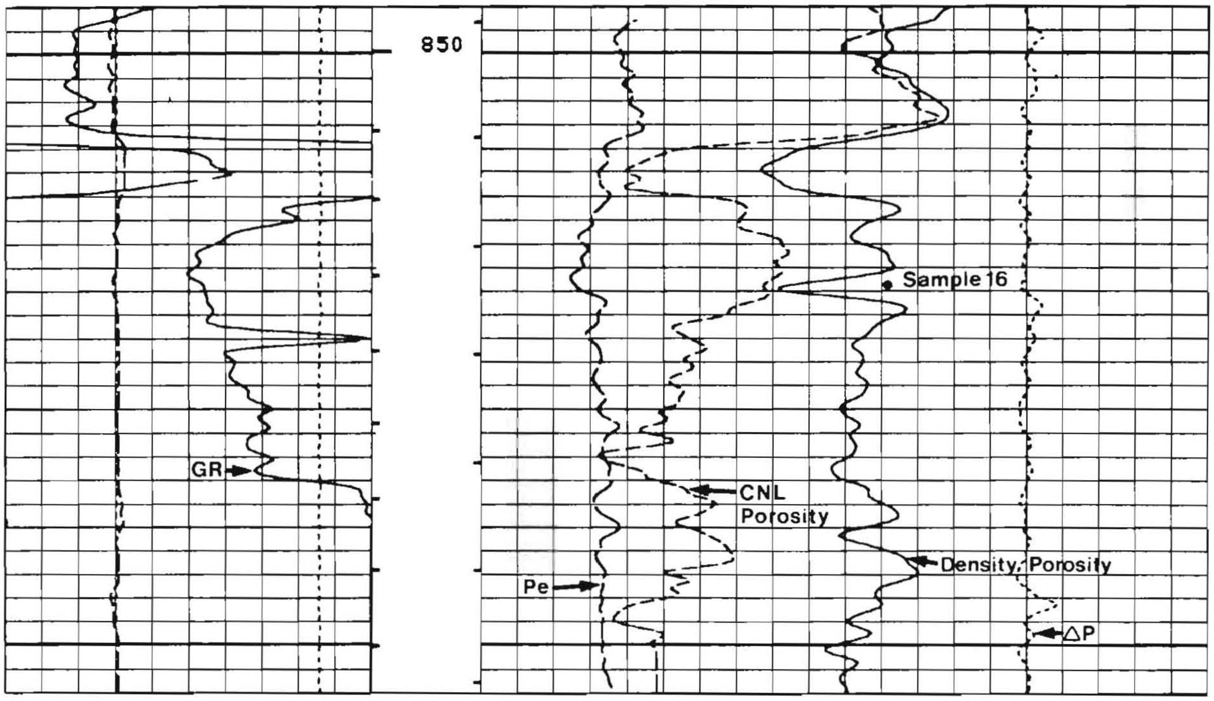
(1) Scanning Electron Microscope
(2) Repeat run used


Gamma Ray (API)
100
90
80
70
60
50
40
30
20
10
$\log_{10}(Vclay) = (\log_{10}(GR) - 1.776) / 0.1033$
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
% Illite Clay

(Figure A-1)

Appendix B

MID Plot Construction



Compensated Neutron-Lithodensity Log for 9-14-10-29 WPM

X-Ray Diffraction Results for Sample No. 16, 9-14-10-29 WPM:

core porosity: 21.3%

mineral percentages: quartz = 64%
K-feldspar = 10%
plagioclase = 4%
dolomite = 13%
illite = 9%

Log Response at Sample No. 16:

Pe = 2.5 barns/electron
Φ_N = 21.5% (limestone scale)
Φ_D = 20.5% (limestone scale)

$$\rho_{b\ log} = \Phi_D + (1-\Phi_D) \times 2.71$$
$$= .205 + (1-.205) \times 2.71$$
$$= 2.36$$

$$\rho_{b\ core} = (\rho_b \log + .252)/1.111$$
$$= (2.36 + .252)/1.111$$
$$= 2.35$$

$$\Phi_{D\,corr} = (2.71 - \rho_{b\,core})/1.71$$
$$= (2.71 - 2.35)/1.71$$
$$= 0.211$$

$$\Phi_T = [\Phi_{D}\ corr + (.095 \times \rho_N)]/1.095$$
$$= [0.211 + (0.95 \times 0.215)]/1.095$$
$$= 0.211 \text{ (porosity from Core Labs } = 0.213)$$

$$\rho_{maa} = \frac{\rho_{b\,core} - \Phi_T\rho_{FL}}{(1 - \Phi_T)} = \frac{2.35 - (0.211 \times 1.0)}{(1\text{-}0.211)} = 2.71$$

$$\rho e = \frac{\rho_{b\,core} + 0.1883}{1.0704} = \frac{(2.35 + 0.1883)}{1.0704} = 2.37$$

$$U_{maa} = \frac{Pe\rho_e - \Phi_T U_{FL}}{(1\text{-}\Phi_T)} = \frac{(2.5 \times 2.37) - (0.211 \times .398)}{(1\text{-}0.211)} = 7.40$$

$$\rho maa = \rho_q P_q + \rho_d P_d + \rho_i P_i + \rho_F P_F$$

where:

ρ = matrix density
P = fraction
q = quartz
d = dolomite
i = illite
F = feldspar

$2.71 = (2.64 \times 0.64) + (2.88 \times 0.13) + (3.06 \times 0.09) + (\rho_F \times 0.14)$
$\rho_F = 2.65$

$$U_{maa} = U_q P_q + U_d P_d + U_i P_i + U_F P_F$$

where:

U = matrix volumetric cross section
P = fraction

$7.40 = (4.78 \times 0.64) + (9.00 \times 0.13) + (11.80 \times 0.09) + (U_F \times 0.14)$
$U_F = 15.06$

We now have the three MID plot points for our Bakken quartz-dolomite-feldspar (+ illite) model:

Mineral	ρma	Uma	
quartz	2.64	4.78	(known)
dolomite	2.88	9.00	(known)
feldspar	2.65	15.06	
illite	3.06	11.80	(known)

MID plot shown in Figure 2 of study

Appendix C

Formation Evaluation Results

Location	Top Depth (m,ft)	Bottom Depth (m,ft)	Total Porosity (frac.)	Volume of Clay (frac.)	Quartz (frac.)	Dolomite (frac.)	Other (frac.)	Waxman -Smits Swt (fr)	Modified Archie Swt (fr)
7-30-10-28	814.00	816.00	0.18	0.12	0.65	0.11	0.12	0.38	0.40
10-30-10-28	815.00	818.50	0.15	0.09	0.55	0.17	0.19	0.55	0.56
11-30-10-28	815.40	817.00	0.17	0.27				0.52	0.52
5-2-10-29	877.00	878.80	0.09	0.05				1.00	1.00
	880.20	881.80	0.15	0.03				0.48	0.49
11-11-10-29	862.50	864.00	0.07	1.00				1.00	1.00
	865.20	866.30	0.11	0.05	0.40	0.24	0.32	0.46	0.55
9-20-10-29	883.00	885.00	0.11	0.19	0.53	0.02	0.25	0.97	0.96
	887.00	889.30	0.16	0.04	0.50	0.27	0.19	0.50	0.51
10-21-10-29	869.40	871.30	0.10	0.01	0.36	0.33	0.30	0.93	0.94
	874.00	876.00	0.18	0.01	0.55	0.30	0.15	0.38	0.40
11-21-10-29	873.50	875.00	0.12	0.31				0.84	0.80
	877.50	880.00	0.15	0.05	0.45	0.26	0.24	0.45	0.48
12-21-10-29	875.00	877.00	0.10	0.09				1.00	1.00
	880.00	882.00	0.15	0.05				0.58	0.57
13-21-10-29	875.00	876.00	0.12	0.09	0.44	0.18	0.29	0.74	0.73
	878.00	880.50	0.22	0.03	0.48	0.27	0.22	0.31	0.33
14-21-10-29	867.00	868.70	0.10	0.04	0.37	0.29	0.30	0.92	0.94
	871.00	872.20	0.19	0.04	0.38	0.27	0.32	0.35	0.38
1-22-10-29	859.80	861.50	0.09	0.34				1.00	1.00
	863.00	864.00	0.15	0.09	0.35	0.17	0.39	0.58	0.57
1-23-10-29	850.00	853.00	0.12	0.53				0.73	0.70
	853.00	855.20	0.14	0.02	0.47	0.25	0.25	0.33	0.40
9-25-10-29	819.00	821.00	0.19	0.48				0.54	0.52
	822.00	823.00	0.11	0.09	0.47	0.24	0.21	1.00	1.00
2-28-10-29	860.70	862.60	0.12	0.05	0.40	0.28	0.28	0.83	0.83
	864.00	865.60	0.23	0.01	0.49	0.31	0.19	0.30	0.32
3-28-10-29	867.60	869.60	0.10	0.05	0.41	0.27	0.27	0.84	0.88
	871.00	873.10	0.20	0.00	0.42	0.31	0.27	0.29	0.33
4-28-10-29	874.00	875.00	0.10	0.07	0.39	0.24	0.30	0.99	1.00
	877.00	879.00	0.21	0.01	0.50	0.31	0.18	0.32	0.34
5-28-10-29	869.00	870.00	0.10	0.05	0.34	0.25	0.36	0.95	0.94
	872.80	874.00	0.21	0.03	0.49	0.27	0.21	0.46	0.44
6-28-10-29	864.00	865.50	0.11	0.09	0.47	0.19	0.26	0.80	0.80
	867.50	869.00	0.19	0.00	0.46	0.29	0.24	0.31	0.34
7-28-10-29	859.00	860.60	0.12	0.13	0.49	0.12	0.25	0.80	0.80
	862.40	864.00	0.13	0.01	0.44	0.32	0.24	0.55	0.58
11-28-10-29	860.60	862.50	0.11	0.01	0.44	0.33	0.22	0.85	0.83
	864.50	867.50	0.19	0.01	0.42	0.30	0.26	0.44	0.44
1-29-10-29	879.50	881.00	0.10	0.24				0.93	0.94
	883.00	885.20	0.14	0.04	0.45	0.27	0.24	0.63	0.63
8-29-10-29	869.50	872.00	0.10	0.09	0.44	0.19	0.28	0.91	0.93
	873.50	876.00	0.18	0.09	0.49	0.16	0.26	0.47	0.46
9-29-10-29	864.00	866.00	0.12	0.09	0.46	0.19	0.25	0.80	0.80
	868.00	870.00	0.19	0.05	0.47	0.26	0.23	0.46	0.46
8-30-10-29	881.00	882.50	0.11	0.09	0.43	0.20	0.28	0.87	0.89
	884.00	886.00	0.17	0.02	0.43	0.29	0.26	0.47	0.47

Location	Top Depth (m,ft)	Bottom Depth (m,ft)	Total Porosity (frac.)	Volume of Clay (frac.)	Quartz (frac.)	Dolomite (frac.)	Other (frac.)	Waxman -Smits Swt (fr)	Modified Archie Swt (fr)
13-6-9-27	828.60	830.20	0.16	0.05				0.59	0.58
7-30-9-27	860.00	862.30	0.10	0.17	0.47	0.05	0.31	0.83	0.87
13-31-9-27	808.00	810.50	0.12	0.00				0.87	0.86
2-2-9-28	851.60	855.00	0.11	0.19	0.48	0.01	0.32	0.77	0.78
	856.00	858.00	0.12	0.01	0.39	0.36	0.24	0.97	0.94
14-13-9-28 dual lat.	815.00	816.20	0.11	0.53				0.78	0.78
4-18-9-28	903.70	906.00	0.09	0.53				1.00	1.00
	907.00	908.00	0.12	0.06				0.80	0.80
2-23-9-28	830.00	831.50	0.11	0.53				0.84	0.88
	831.50	833.00	0.13	0.09				0.69	0.69
13-26-9-28	818.80	822.00	0.15	0.09				0.56	0.55
5-36-9-28	809.40	812.70	0.12	1.00				0.80	0.80
12-5-9-29	954.00	955.50	0.12	0.31				0.54	0.60
	957.80	959.70	0.16	0.09	0.55	0.21	0.15	0.37	0.42
5-15-9-29	919.00	920.00	0.15	0.06	0.44	0.23	0.27	0.41	0.46
1-16-9-29	922.00	924.50	0.15	0.09				0.56	0.57
	930.00	931.00	0.13	0.01				0.63	0.67
10-16-9-29	920.50	923.00	0.13	0.17	0.33	0.06	0.44	0.57	0.62
	926.00	927.20	0.13	0.01	0.27	0.36	0.36	0.55	0.61
1-21-9-29	915.60	916.50	0.12	1.00				0.79	0.80
	921.00	922.00	0.15	0.01	0.43	0.32	0.24	0.49	0.52
8-29-9-29	909.00	910.50	0.11	0.17	0.50	0.05	0.28	0.72	0.77
	915.50	917.00	0.14	0.02	0.41	0.34	0.23	0.49	0.54
6-33-9-29	900.40	903.50	0.10	0.22				0.91	0.94
	905.00	906.00	0.12	0.09				0.71	0.78
11-35-9-29	882.00	883.80	0.11	0.09	0.43	0.20	0.28	0.82	0.84
	885.00	886.00	0.15	0.06	0.50	0.22	0.22	0.59	0.58
10-7-10-27	2588.00	2594.00	0.02	1.00					
7-18-10-27 dual lat.	2558.00	2564.00	0.16	0.07				0.47	0.49
	2568.00	2572.00	0.22	0.31				0.24	0.27
11-19-10-27	2576.00	2583.00		1.00					
12-9-10-28	929.60	831.00	0.09	1.00				1.00	1.00
	832.00	833.70	0.15	0.09				0.59	0.58
10a-12-10-28	2544.00	2554.00	0.10	0.31				0.95	0.97
13-16-10-28	818.80	820.10	0.12	1.00				0.74	0.73
15-18-10-28	830.00	831.00	0.11	1.00				0.81	0.83
13-20-10-28	807.80	809.00	0.10	0.73				0.76	0.82
	811.00	812.00	0.14	0.05	0.46	0.24	0.24	0.62	0.62
1-21-10-28	815.30	817.70	0.10	1.00				0.79	0.82
	818.00	819.00	0.18	0.31				0.38	0.41
4-22-10-28	810.50	812.00	0.10	0.05	0.23	0.21	0.51	0.93	0.90
	815.50	817.00	0.14	0.04	0.48	0.27	0.21	0.43	0.48
5-29-10-28	809.00	812.00	0.16	0.05	0.46	0.24	0.25	0.56	0.55
7-29-10-28	809.50	812.20	0.15	0.09	0.56	0.17	0.17	0.48	0.51
10-29-10-28	811.60	812.60	0.17	1.00				0.55	0.53
	813.20	815.00	0.15	0.22	0.52	0.06	0.32	0.60	0.58
11-29-10-28	813.00	816.70	0.13	0.31				0.69	0.67
12-29-10-28	813.00	815.00	0.16	0.34				0.52	0.52
	815.00	816.00	0.18	0.31				0.56	0.53

Location	Top Depth (m,ft)	Bottom Depth (m,ft)	Total Porosity (frac.)	Volume of Clay (frac.)	Quartz (frac.)	Dolomite (frac.)	Other (frac.)	Waxman -Smits Swt (fr)	Modified Archie Swt (fr)
1-20-9-28	865.00	866.60	0.10	0.53				0.81	0.87
15-12-9-29	908.00	909.20	0.09	0.01	0.43	0.35	0.21	0.89	0.99
	902.60	904.00	0.09	0.53				1.00	1.00
3-13-9-29	902.00	903.20	0.07	0.00	0.35	0.32	0.33	1.04	1.00
	905.30	906.70	0.12	0.01	0.30	0.33	0.36	0.52	0.60
3-31-9-29	917.50	919.00	0.12	0.15	0.44	0.09	0.31	0.79	0.80
	920.00	922.00	0.13	0.05	0.45	0.27	0.23	0.63	0.64
3-34-9-29	892.00	893.80	0.08	0.12	0.36	0.12	0.40	0.78	0.95
11-9-10-28	831.00	832.40	0.13	0.00	0.32	0.33	0.35	0.74	0.71
	833.00	834.80	0.14	0.07	0.33	0.18	0.42	0.52	0.54
3-19-10-28	827.00	828.60	0.12	1.00				0.82	0.82
7-20-10-28	810.00	813.50	0.14	0.22				0.67	0.65
12-20-10-28	812.00	814.00	0.16	0.05	0.47	0.23	0.25	0.45	0.47
13-21-10-28 dual lat.	804.00	807.30	0.16	0.02	0.51	0.28	0.18	0.52	0.52
6-28-10-28	813.50	817.00	0.14	0.04	0.45	0.27	0.24	0.65	0.64
3-29-10-28	808.80	811.80	0.13	0.99				0.71	0.70
4-2-10-29	878.00	879.50	0.09	0.00	0.30	0.35	0.35	0.93	1.00
	881.00	882.00	0.13	0.12	0.52	0.12	0.24	0.58	0.61
15-11-10-29	858.50	861.90	0.16	0.10	0.51	0.14	0.25	0.56	0.55
12-13-10-29	859.50	861.00	0.18	1.00				0.34	0.37
7-14-10-29	855.60	860.00	0.10	1.00				0.96	1.00
9-14-10-29	856.00	857.00	0.15	0.17	0.57	0.05	0.22	0.59	0.58
	859.00	860.30	0.21	0.01	0.55	0.27	0.17	0.39	0.39
14-14-10-29	851.00	852.50	0.09	0.13	0.37	0.12	0.38	1.00	1.00
15-14-10-29	856.00	857.30	0.17	0.22				0.41	0.42
16-14-10-29	861.00	862.00	0.15	1.00				0.58	0.58
	862.00	863.30	0.19	0.09	0.58	0.15	0.18	0.30	0.34
7-16-10-29	882.80	884.60	0.10	0.09	0.37	0.18	0.36	0.75	0.83
	886.00	887.00	0.13	0.08	0.54	0.18	0.20	0.61	0.62
14-16-10-29	883.50	885.00	0.07	0.48				1.00	1.00
	886.50	887.30	0.15	0.09	0.51	0.15	0.26	0.46	0.48
16-17-10-29	906.00	908.20	0.15	0.09	0.49	0.17	0.25	0.69	0.65
	911.00	913.00	0.18	0.02	0.52	0.29	0.17	0.49	0.48
8-20-10-29	884.80	886.60	0.10	0.08	0.48	0.22	0.22	0.95	0.96
	889.00	891.00	0.13	0.01	0.45	0.31	0.24	0.48	0.53
15-20-10-29	879.00	880.30	0.11	0.53				0.57	0.67
	882.00	883.00	0.13	0.27				0.83	0.82
16-20-10-29	878.00	880.00	0.11	0.06	0.41	0.23	0.30	0.83	0.82
	881.50	883.40	0.23	0.01	0.50	0.31	0.17	0.37	0.37
5-21-10-29	874.00	876.00	0.11	0.04	0.34	0.29	0.33	0.92	0.92
	884.00	885.00	0.15	0.05	0.43	0.24	0.27	0.57	0.56
16-21-10-29	861.00	863.80	0.11	0.05	0.39	0.26	0.30	0.80	0.80
	865.00	866.60	0.15	0.01	0.46	0.32	0.21	0.57	0.57
2-25-10-29	828.00	829.30	0.09	0.00	0.32	0.35	0.34	0.90	0.99
	831.00	832.00	0.13	0.53				0.71	0.69
3-27-10-29	857.50	859.50	0.11	0.09	0.37	0.17	0.37	0.82	0.80
	861.00	862.30	0.16	0.03	0.29	0.26	0.42	0.48	0.49
12-28-10-29	864.00	865.00	0.11	0.04	0.41	0.27	0.28	0.81	0.80
	868.00	871.00	0.16	0.03	0.45	0.26	0.25	0.51	0.51

Location	Top Depth (m,ft)	Bottom Depth (m,ft)	Total Porosity (frac.)	Volume of Clay (frac.)	Quartz (frac.)	Dolomite (frac.)	Other (frac.)	Waxman -Smits Swt (fr)	Modified Archie Swt (fr)
4-29-10-29	882.00	884.00	0.07	0.17	0.45	0.07	0.30	1.00	1.00
	883.50	885.00	0.14	0.04	0.44	0.29	0.23	0.73	0.70
	885.00	886.00	0.12	0.09	0.46	0.20	0.25	0.95	0.92

Appendix D

Economic Production Limit

To obtain the economic production limit for an average Daly Bakken producer, set the monthly revenue = monthly expenses as shown:

(1) $P \times D \times WHP = (R \times WHP \times P \times D) + O$

where:

P = daily economic production limit
D = number of days in one month = 30.4
WHP = wellhead price = \$103.00/m^3 (August/88)
R = royalties = 15% (0.15)
O = monthly operating cost = \$1300.00

equation (1) becomes:

$P \times 30.4 \times 103.00 = (0.15 \times 103.00 \times P \times 30.4) + 1300.00$

$P = 0.5\ m^3/\text{day oil}$