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**An Algorithm for Estimating Gas-Production Potential  
Using Digital Wire-line Log Data  
(Cretaceous of Northern Montana)**  
On-Line Edition

by

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## Introduction

Cretaceous sandstones of northern Montana are recognized as a major source of natural gas. Current production, however, is associated with structural features, and not well established in other areas. Lack of development is partly due to difficulties in recognizing potential pay in these highly shaly beds, where clay volume makes conventional formation evaluation ineffective. Under these conditions, the “gas effect” itself can be an effective exploration tool (Hester, 1999d).

The “gas effect” is a geophysical-tool response to gas in a formation. On well logs, the gas effect is most often manifested as a visual “crossover” of neutron-porosity and density-porosity curves, which serves an important role in gas exploration. However, as clay volume and associated bound water increase, the neutron-porosity and density-porosity curves separate until the crossover no longer occurs. The gas effect, though still present, is no longer detectable on well logs. A more effective method for detecting the gas effect in this situation is a crossplot (fig. 1) of neutron porosity minus density porosity (y-axis) versus gamma-ray intensity (x-axis). The crossplot acts to separate porosity due to the gas effect, from that due to clay and associated bound water. In this way, the gas effect is revealed on the crossplot without regard to clay content (Hester, 1999a).

The magnitude of the gas effect is closely related to the bulk volume of gas present in the formation surrounding the borehole. Thus, the gas effect is an indirect measure of gas-charged porosity and may substitute for water-saturation determinations as a qualitative measure of gas concentration, and as an indicator of production potential. An index system, which is part of the crossplot (fig. 1), measures and scales the gas effect into 12 levels of magnitude (Hester, 1999a). The index, referred to here as the gas-production index (GPI), is linked to actual gas production (fig. 2). In this way, the GPI provides an estimate of gas-production potential for a broad range of reservoir conditions. Figure 3 shows the age and stratigraphic locations of the producing formations indicated in figure 2. The index is a robust indicator of gas-production potential, specifically calibrated for shallow gas sandstone reservoirs of the Northern Great Plains (Hester, 1999a).

An index map (fig. 4) shows the geographic area in which the method for determining the GPI was applied, and the locations of 39 wells used for calibration, as well as major structural features. The wells are identified in table 1. Figure 5 shows the locations of 84 additional wells that have the necessary log suite (compensated density and neutron porosity, and gamma-ray intensity) to calculate the GPI. These wells are identified in table 2, and include 13 others located outside the study area. Although the study area is relatively small (5 counties), the method is believed to be applicable to the Northern Great Plains in general. The crossplot and GPI are discussed in detail in Hester (1999a).

Application of the GPI system has an advantage over conventional log analysis in areas where clay volume tends to hide the gas effect on well logs, and makes conventional water-saturation determinations unreliable (for example, Cretaceous rocks of northern Montana). An additional advantage that is emphasized here, is that the GPI is numerical and, therefore, easily adaptable for computer applications. GPI may be

calculated directly from the digital log curves, eliminating the crossplot altogether. Being numerical also maximizes the utility of the gas effect as an exploration tool by allowing thousands of continuous log feet to be analyzed at once. For every logged interval where neutron, density, and gamma-ray intensity curves are recorded, a continuous GPI can be displayed as a log curve such as shown in figures 6 through 8 for 3 selected gas-producing wells. These 3 wells reflect typical log responses for the Cretaceous formations in the study area, and illustrate the utility of the GPI as a log curve and as a visual indicator of gas-production potential. Particularly noticeable are the numerous intervals with production potential not marked by crossover of the neutron-porosity and density-porosity curves.

This paper describes the algorithm used to generate the GPI and explains its implementation in two different computer applications—Geographix’s Prizm, a log-analysis program specifically designed for digital well-log files, and Microsoft’s Excel spreadsheet software. Each computer application requires a slightly different version of the algorithm, and therefore is discussed separately. The descriptions include enough detail to give the user the flexibility to modify the algorithm, if necessary, for use in other similar software programs. Appendices that explain how to enter the algorithm directly into either Prizm or Excel are also included.

### Using the Algorithm in Prizm

The algorithm consists of multiple parts (Appendix 1). Each part consists of a brief description (excluded from Prizm calculations by the insertion of a semicolon at the beginning of the line) and an equation or equivalence. The algorithm retrieves data from digital logs already loaded into Prizm, formats the data, and defines and creates other log curves used in subsequent equations.

The algorithm then calculates the GPI by defining an area on the crossplot for each index level (fig. 1) using a series of Boolean (If-Then-Else) statements. The boundaries for each index level are the line segments shown in figure 1, and are represented in the algorithm by their unique equations. The following paragraphs describe how the digital data, the equations for the lines, and the If-Then-Else statements are used to generate the GPI.

Three curves are used by Prizm to calculate the GPI: density porosity, neutron porosity, and gamma-ray intensity. Density porosity values may be taken directly from the density-porosity curve, or calculated from bulk density using the equation,

$$\phi_{\text{density}} = (\rho_{\text{ma}} - \rho_{\text{b}}) / (\rho_{\text{ma}} - \rho_{\text{f}}) \quad (1)$$

where  $\phi_{\text{density}}$  is density porosity (decimal percent),  $\rho_{\text{ma}}$  is matrix density (grams per cubic centimeter; g/cc),  $\rho_{\text{b}}$  is bulk density (g/cc), and  $\rho_{\text{f}}$  is fluid density (g/cc). Despite the source, density porosity should be converted to porosity units for consistency with the porosity display in this application (fig. 1, y-axis) using the equation,

$$\phi_{\text{D}} = \phi_{\text{density}} * 100 \quad (2)$$

where  $\phi_D$  is density porosity in porosity units. Similarly, neutron porosity recorded as decimal percent should also be converted to porosity units.

$$\phi_N = \phi_{\text{neutron}} * 100 \quad (3)$$

Density porosity is then subtracted from neutron porosity to yield a single “neutron-minus density-porosity” variable ( $\phi_{ND}$ ).

$$\phi_{ND} = \phi_N - \phi_D \quad (4)$$

The linear equations for the line segments are of the form,

$$y = mx + b \quad (5)$$

where y is the variable “neutron porosity minus density porosity” ( $\phi_{ND}$ , y-axis, fig.1), x is the variable “gamma-ray intensity” (GRI, x-axis, fig. 1), m is the slope of the line segment, and b is the y intercept at x = 0. For this application, all lines are parallel, thus each has the same slope (0.425); the y intercept is different for each line. The values for the variable  $\phi_{ND}$  are generated from the digitized neutron- and density-porosity curves (eq. 1-3); GRI comes directly from the digitized gamma-ray curve.

Now the algorithm can be written for the equations for the lines on the left side of the crossplot (where GRI < 80 API) based on If-Then-Else statements and the equations for the lines on the left side of figure 1. The If-Then-Else statements are written here using the general form,

$$\text{If } (y > (m * x) + b) \text{ Then } X_n = X_{n-1} \text{ Else } X_n = n \quad (6)$$

Where X is a variable representing the value of GPI (with a range of n=1 to n=12) for the left side of the chart. (Note: in the first line where n=1,  $X_{n-1}$  ( $X_0$ ) is set equal to zero.) The actual syntax used for the algorithm in Prizm is shown in [Appendix 1](#).

```

If ( $\phi_{ND} > (0.425 * \text{GRI}) - 5.0$ ) Then  $X_1=0$  Else  $X_1=1$ 
If ( $\phi_{ND} > (0.425 * \text{GRI}) - 8.0$ ) Then  $X_2=X_1$  Else  $X_2=2$ 
If ( $\phi_{ND} > (0.425 * \text{GRI}) - 11.0$ ) Then  $X_3=X_2$  Else  $X_3=3$ 
If ( $\phi_{ND} > (0.425 * \text{GRI}) - 14.0$ ) Then  $X_4=X_3$  Else  $X_4=4$ 
If ( $\phi_{ND} > (0.425 * \text{GRI}) - 17.0$ ) Then  $X_5=X_4$  Else  $X_5=5$ 
If ( $\phi_{ND} > (0.425 * \text{GRI}) - 20.0$ ) Then  $X_6=X_5$  Else  $X_6=6$ 
If ( $\phi_{ND} > (0.425 * \text{GRI}) - 23.0$ ) Then  $X_7=X_6$  Else  $X_7=7$ 

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If ( $\Phi_{ND} > (0.425 * GRI) - 26.0$ ) Then  $X_8=X_7$  Else  $X_8=8$   
 If ( $\Phi_{ND} > (0.425 * GRI) - 29.0$ ) Then  $X_9=X_8$  Else  $X_9=9$   
 If ( $\Phi_{ND} > (0.425 * GRI) - 32.0$ ) Then  $X_{10}=X_9$  Else  $X_{10}=10$   
 If ( $\Phi_{ND} > (0.425 * GRI) - 35.0$ ) Then  $X_{11}=X_{10}$  Else  $X_{11}=11$   
 If ( $\Phi_{ND} > (0.425 * GRI) - 38.0$ ) Then  $X_{12}=X_{11}$  Else  $X_{12}=12$

Now the algorithm can be written for the equations for the lines on the right side of the crossplot (where  $GRI > 80$  API), again based on If-Then-Else statements and the equations for the lines on the right side of [figure 1](#). The general form is the same as equation 5 except that the lines on the right side have zero slope ( $m = 0$ ), and therefore  $y = b$ . The general form (eq. 6) is now simplified to the following statement:

$$\text{If } (y > b) \text{ Then } Y_n = Y_{n-1} \text{ Else } Y_n = n \quad (7)$$

Where Y is a variable representing the value of GPI (with a range of  $n=1$  to  $n=12$ ) for the right side of the chart. (Note: in the first line where  $n=1$ ,  $Y_{n-1}$  ( $Y_0$ ) is set equal to zero.) The actual syntax used for the algorithm in Prizm is shown in [Appendix 1](#).

If ( $\Phi_{ND} > 29$ ) Then  $Y_1=0$  Else  $Y_1=1$   
 If ( $\Phi_{ND} > 26$ ) Then  $Y_2=Y_1$  Else  $Y_2=2$   
 If ( $\Phi_{ND} > 23$ ) Then  $Y_3=Y_2$  Else  $Y_3=3$   
 If ( $\Phi_{ND} > 20$ ) Then  $Y_4=Y_3$  Else  $Y_4=4$   
 If ( $\Phi_{ND} > 17$ ) Then  $Y_5=Y_4$  Else  $Y_5=5$   
 If ( $\Phi_{ND} > 14$ ) Then  $Y_6=Y_5$  Else  $Y_6=6$   
 If ( $\Phi_{ND} > 11$ ) Then  $Y_7=Y_6$  Else  $Y_7=7$   
 If ( $\Phi_{ND} > 8$ ) Then  $Y_8=Y_7$  Else  $Y_8=8$   
 If ( $\Phi_{ND} > 5$ ) Then  $Y_9=Y_8$  Else  $Y_9=9$   
 If ( $\Phi_{ND} > 2$ ) Then  $Y_{10}=Y_9$  Else  $Y_{10}=10$   
 If ( $\Phi_{ND} > -1$ ) Then  $Y_{11}=Y_{10}$  Else  $Y_{11}=11$   
 If ( $\Phi_{ND} > -4$ ) Then  $Y_{12}=Y_{11}$  Else  $Y_{12}=12$

Now the left and right sides of the chart are combined using the following statement:

$$\text{If } (GRI < 80) \text{ Then } Z=X_{12} \text{ Else } Z=Y_{12}$$

A “discriminator” statement is now added to create a “GPI = zero” line that passes through both sides of the chart (**fig. 1, heavy diagonal line**). This line is established empirically (using gas-production data) and defines a boundary, above which commercial volumes of gas are not likely to be produced (Hester, 1999a).

$$\text{If } (\phi_{\text{ND}} > (0.425 * \text{GRI}) - 14.0) \text{ Then GPI}=0 \text{ Else GPI}=Z$$

Other parameters may be added to this statement to further discriminate using minimum or maximum values. Examples might include some of the following: 1) eliminating from the calculations all porosities below 8 percent using the density-porosity curve, 2) creating “zoned” parameters that can change matrix densities for certain stratigraphic intervals, or 3) eliminating shaly zones from the calculations using the gamma-ray curve. Appendix 1 shows examples of additional discriminators that were used in evaluating gas wells in north-central Montana (Hester, 1999c,d). **Appendix 1** will generate the GPI when typed directly as presented into Prizm’s “User-Defined Equations” window.

### Using the Algorithm in EXCEL

The algorithm is used in EXCEL by applying a series of “nested” If-Then-Else statements. The statements and the values for neutron and density porosities, and gamma-ray intensity, are written into cells in specific columns. Each row constitutes a single data point (record). Raw data can be entered by hand or copied from the digitized-log files once the header data and unnecessary curve data are removed (please, save a copy of the original file).

One caveat of using this method is that EXCEL (Office 97) only allows for a maximum of 8 If-Then-Else statements in a single cell. Because there are 12 levels of GPI (each requiring an If-Then-Else statement) the equations for both left and right sides of the chart (12 statements each; **fig. 1**) must be separated into multiple columns to do the calculations, and then re-combined.

The procedure requires that the statements representing the equations for the lines on the left side of the crossplot be split into two groups, “top” and “bottom”. The calculations for each group are completed, then the groups are re-combined to put the GPI values for the left side of the chart into a single column. The equations for the right side of the chart are handled in the same way. Finally, the GPI values for the left and right sides of the chart are combined (final GPI).

**Appendix 2** explains the procedure for inserting the formulae and data. **Figure 9** is an example of an Excel spreadsheet with 34 records of well data (columns A and B) and interval data (columns C, and D). Completed calculations (or “answers”) are shown in the cells of columns E through K.

## References

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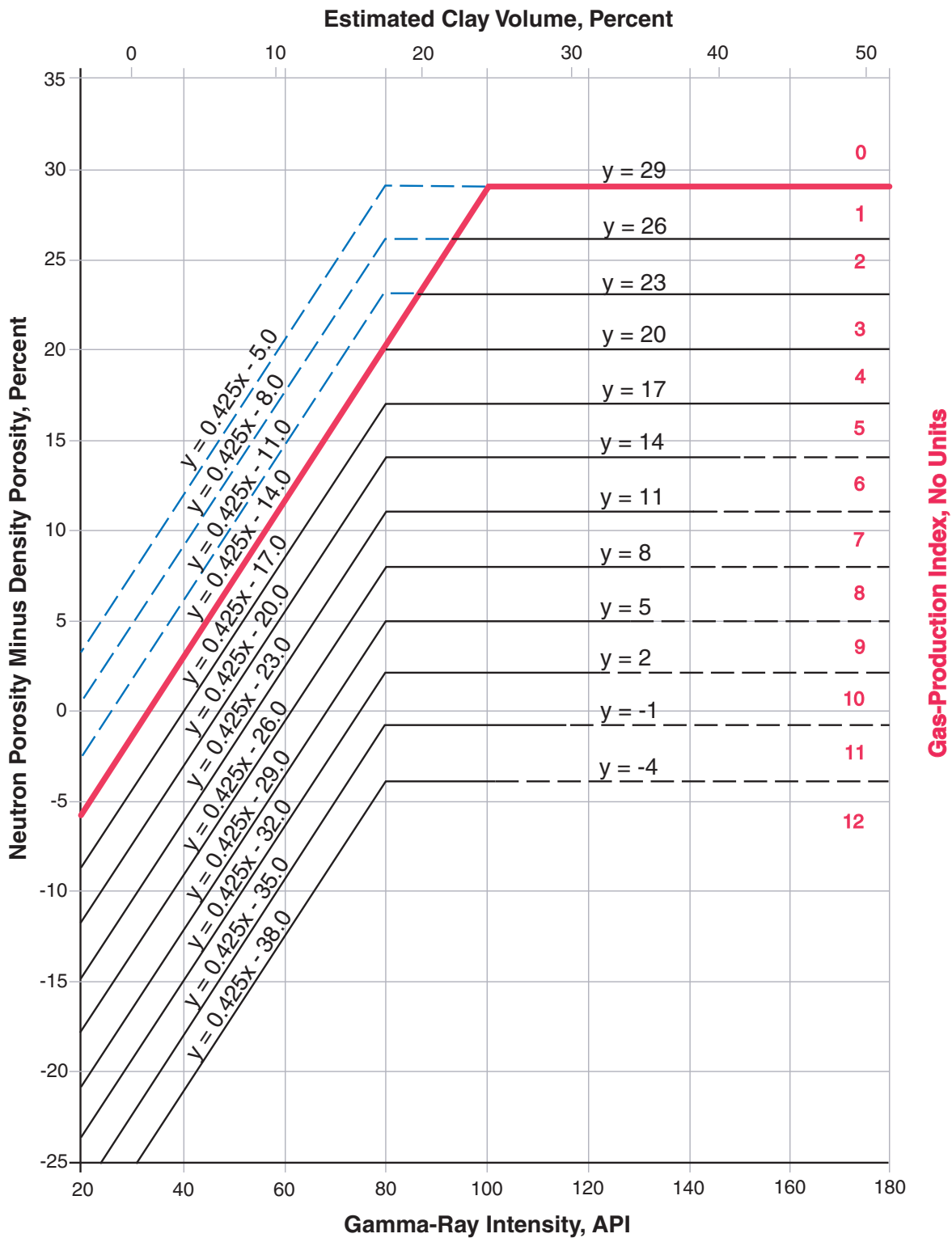


Figure 1. Neutron porosity minus density porosity versus gamma-ray intensity crossplot showing equations for line segments that make up the gas-production index. Thin, solid lines show 12 indexed levels of gas-production potential. Level one has the least potential for gas production; level 12 has the greatest potential. Bold line is an empirically-determined "cut-off", above which commercial volumes of gas are unlikely. Dashed lines are inferred.

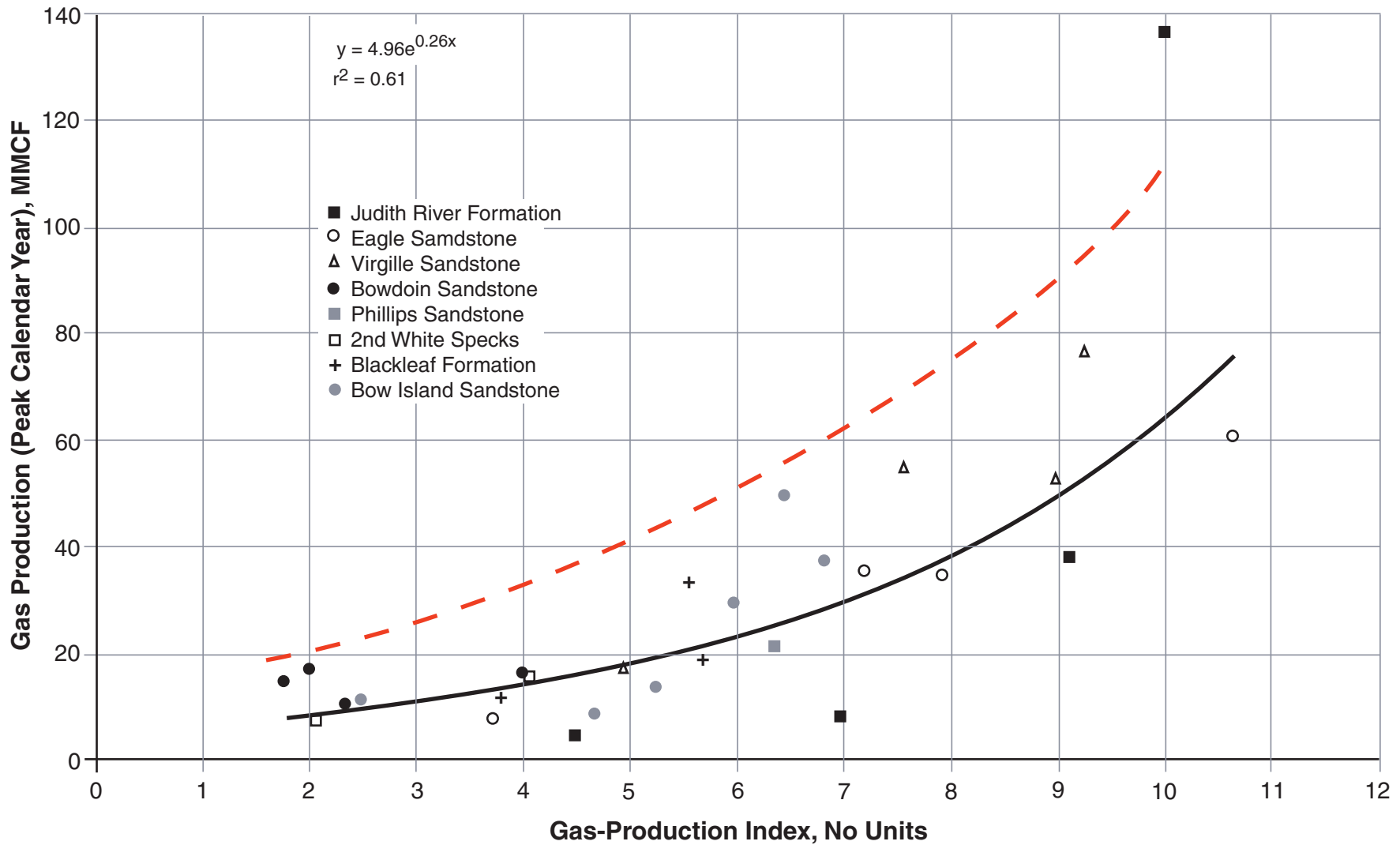


Figure 2. Gas production (peak calendar year) vs gas-production index (GPI; fig.1) for 28 gas-producing wells in north-central Montana (fig. 3; table 1). Dashed line indicates approximate production potential associated with a given index level. Equation and sample coefficient of determination ( $r^2$ ) for regression line (heavy, solid line) are shown in upper left. GPI for each well is averaged using log data from perforated intervals, plotted using figure 1.

SERIES	GROUP or FORMATION		
Tertiary			
Upper Cretaceous	Montana Group	Hell Creek Formation	
		Fox Hills Sandstone	
		Bearpaw Shale	
		Judith River Formation*	
		Clagget Shale	
		Eagle Sandstone*	
		Virgelle Sandstone*	
		Telegraph Creek Formation	
	Colorado Group	Niobrara Formation	
		Carlile Shale	Bowdoin ss.*
		Greenhorn Formation*	2nd White Specks*
		Belle Fourche Shale	Mosby Ss. Mbr.   Phillips ss.*
		Blackleaf* Formation	Mowry Shale
			Muddy Sandstone
Skull Creek Shale			
Lower Cretaceous	Fall River Sandstone		
	Kootenai Formation		
Jurassic			

\* Gas producing horizons represented in the data of this report.

Figure 3. Generalized stratigraphic column showing Cretaceous formations in northern Montana (based on Rice, 1981).

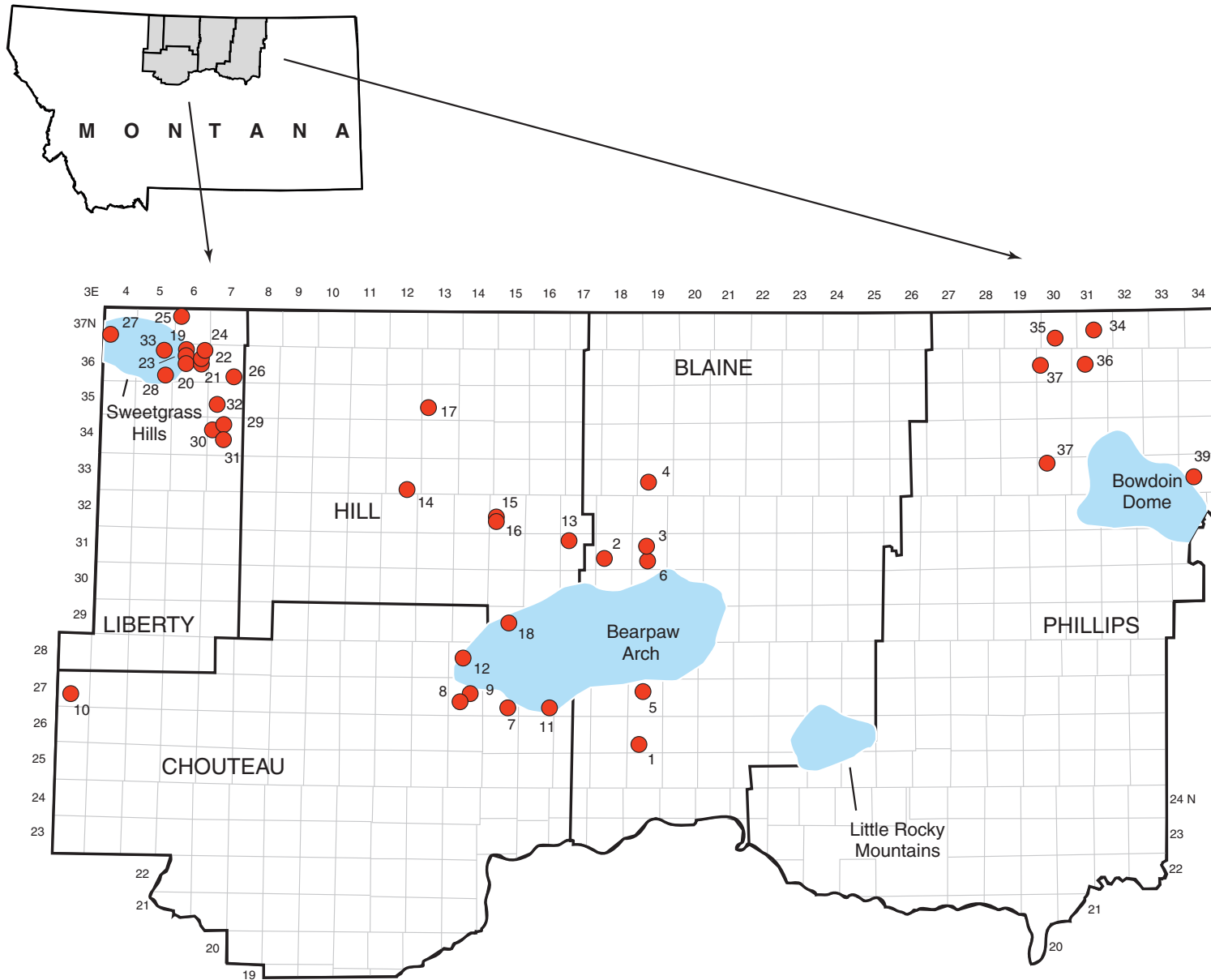


Figure 4. Index map showing major structural features, and locations of 39 wells used for calibrating the gas-production index (GPI). These wells have the necessary log suite (neutron and density porosity, and gamma-ray intensity) for calculating the GPI. Well numbers refer to table 1.

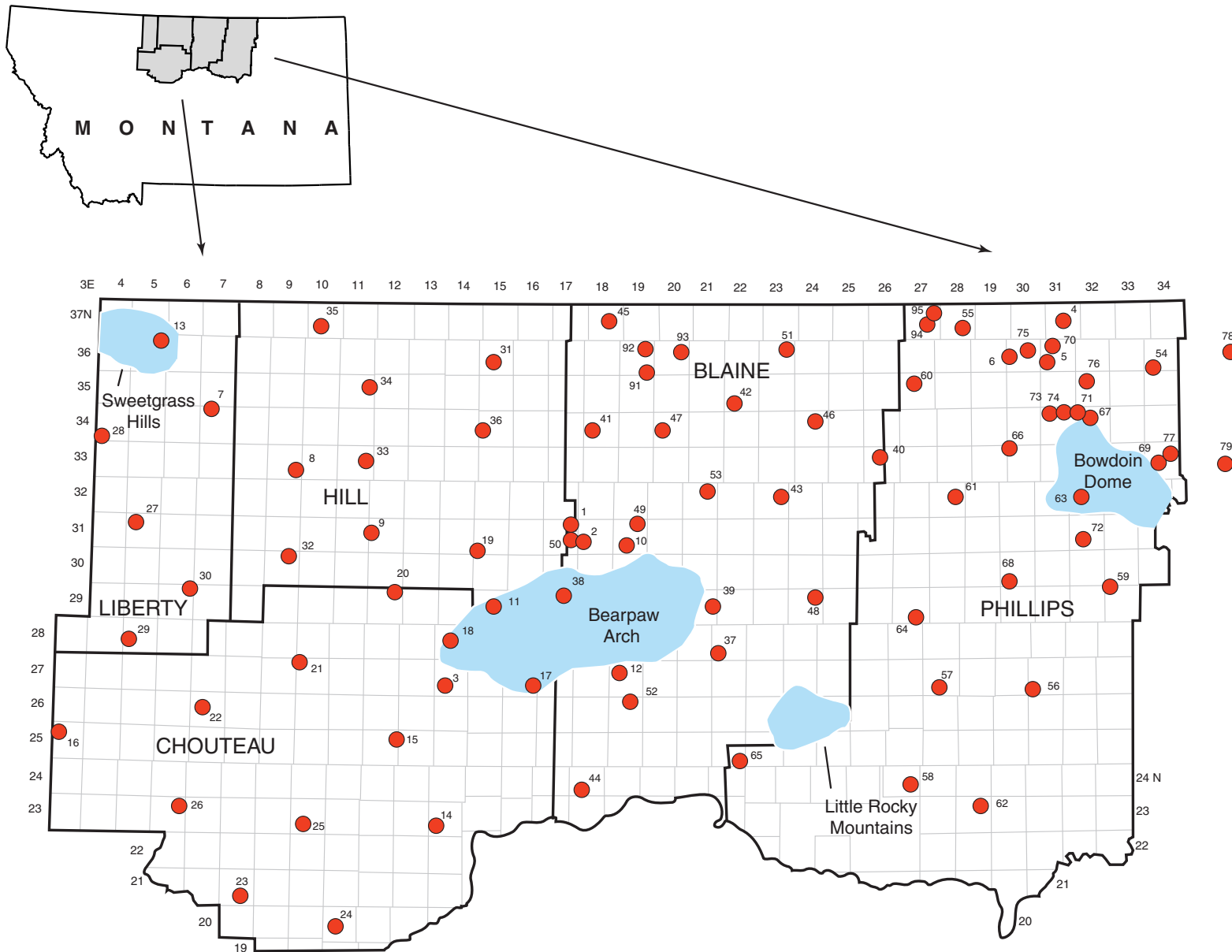


Figure 5. Index map showing major structural features, and locations of 84 wells that have the necessary log suite (neutron and density porosity, and gamma-ray intensity) for calculating the gas-production index. Well numbers refer to table 2.

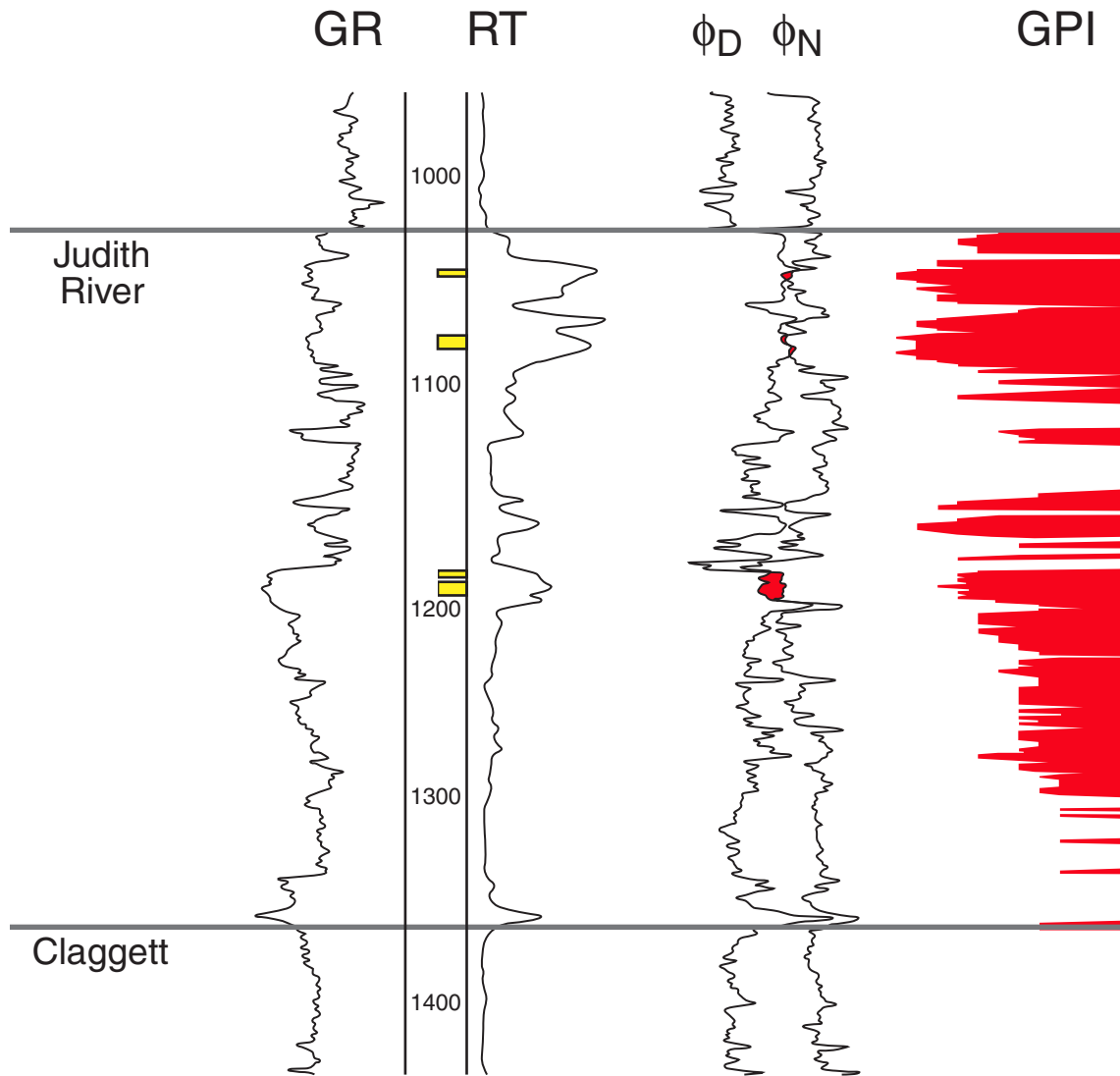


Figure 6. Well no. 2 (table 1; fig. 4) showing typical log responses and calculated GPI curve for Cretaceous Judith River Formation, north-central Montana. This well produced 37.9 MMCF gas in its best year of production. Perforated intervals are shown in depth track.

Roberts 28-4  
28-31N-19E

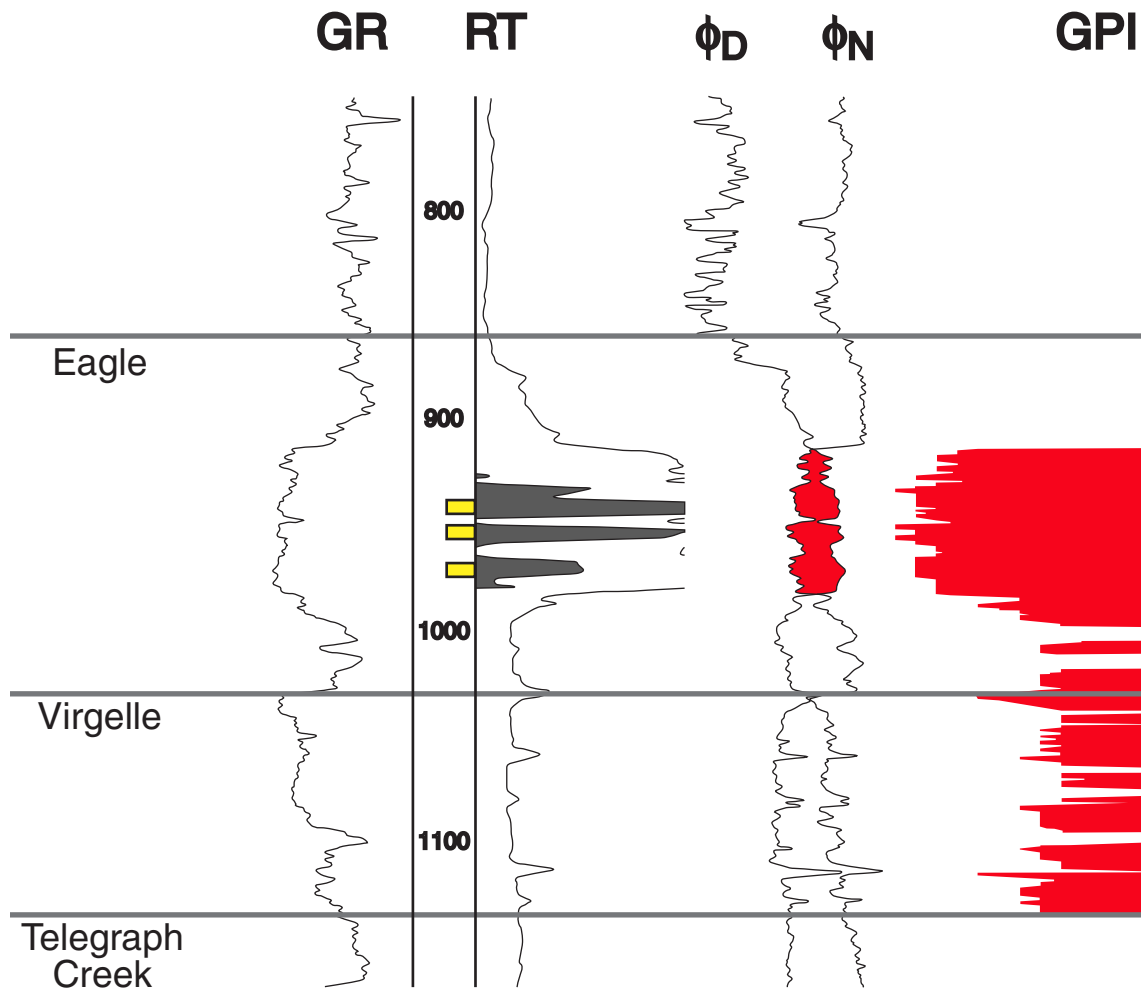


Figure 7. Well no. 6 (table 1; fig. 4) showing typical log responses and calculated GPI curve for Cretaceous Eagle Sandstone, north-central Montana. This well produced 60.3 MMCF gas in its best year of production. Perforated intervals are shown in depth track.

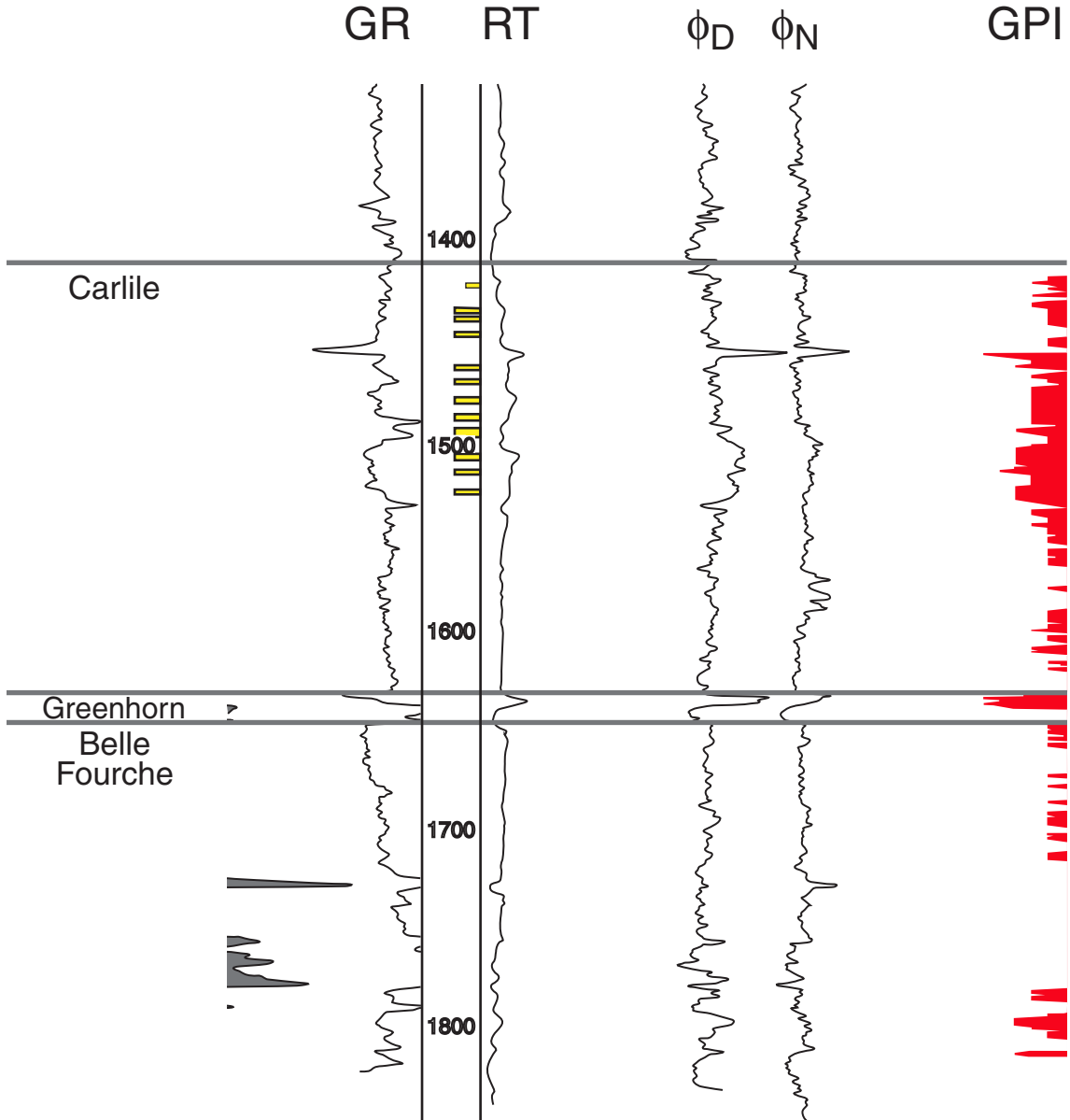


Figure 8. Well no. 34 (table 1; fig. 4) showing typical log responses and calculated GPI curve for Cretaceous Carlile Shale (Bowdoin ss), Greenhorn Formation (2nd White Specks), and Belle Fourche Shale (Phillips ss), north-

	A	B	C	D	E	F	G	H	I	J	K
1	Well #	Int #	Gr	N-D	Left Top	Left Bot	Right Top	Right Bot	Left GPI	Right GPI	Final GPI
2	1	1	45	-6.2	7	-999.25	FALSE	12	7	12	7
3	2	1	42	-0.2	5	-999.25	FALSE	10	5	10	5
4	2	2	52	5.7	4	-999.25	FALSE	8	4	8	4
5	4	1	81	-2.6	FALSE	11	FALSE	11	11	11	11
6	4	2	79	-1.1	10	-999.25	FALSE	11	10	11	10
7	4	3	49	-5.5	8	-999.25	FALSE	12	8	12	8
8	6	1	61	-4.5	9	-999.25	FALSE	12	9	12	9
9	6	2	70	-4.9	10	-999.25	FALSE	12	10	12	10
10	6	3	68	-3.6	10	-999.25	FALSE	11	10	11	10
11	6	4	70	-2.8	10	-999.25	FALSE	11	10	11	10
12	6	5	75	-3.6	FALSE	11	FALSE	11	11	11	11
13	8	1	63	-4.8	9	-999.25	FALSE	12	9	12	9
14	8	2	64	3.8	7	-999.25	FALSE	9	7	9	7
15	8	3	66	-3.6	9	-999.25	FALSE	11	9	11	9
16	8	4	57	1.7	6	-999.25	FALSE	10	6	10	6
17	8	5	56	-1.6	7	-999.25	FALSE	11	7	11	7
18	8	6	55	3.1	6	-999.25	FALSE	9	6	9	6
19	8	7	56	-2.5	8	-999.25	FALSE	11	8	11	8
20	9	1	63	-7	10	-999.25	FALSE	12	10	12	10
21	9	2	52	-20.2	FALSE	12	FALSE	12	12	12	12
22	9	3	60	0.7	7	-999.25	FALSE	10	7	10	7
23	10	1	56	-5.7	9	-999.25	FALSE	12	9	12	9
24	11	1	55	4.1	5	-999.25	FALSE	9	5	9	5
25	11	2	54	3.2	5	-999.25	FALSE	9	5	9	5
26	12	1	124	28.5	7	-999.25	1	-999.25	7	1	1
27	12	2	120	27.5	7	-999.25	1	-999.25	7	1	1
28	12	3	117	27.7	6	-999.25	1	-999.25	6	1	1
29	12	4	122	25.1	8	-999.25	2	-999.25	8	2	2
30	12	5	116	24.3	7	-999.25	2	-999.25	7	2	2
31	12	6	135	25.1	10	-999.25	2	-999.25	10	2	2
32	12	7	108	22.2	7	-999.25	3	-999.25	7	3	3
33	12	8	113	23.4	7	-999.25	2	-999.25	7	2	2
34	12	9	100	17.9	7	-999.25	4	-999.25	7	4	4
35	12	10	107	28.7	4	-999.25	1	-999.25	4	1	1
36											
37	Figure 9. Example of Excel spreadsheet with 34 records of well data (columns A and B) and interval										
38	data (columns C and D). Completed calculations (or "answers") are shown in the cells of columns E										
39	through K. Procedure for inserting formulae and data is shown in Appendix 2.										
40											

**Table 1.** Identification of 39 gas-producing wells in north-central Montana with neutron- and density-porosity, and gamma-ray intensity logs. Well numbers refer to figure 4. (API numbers not available.)

Well	Operator	Lease Name and No.	Location	Producing Unit	County
1	Tricentrol USA	O'Connell 29-4	29-26N-19E	Judith River	Blaine
2*	Tricentrol USA	Ramberg 19-5	19-31N-18E	Judith River	Blaine
3*	Montana Power	Sprinkle 9-9	09-31N-19E	Judith River	Blaine
4	Probe Oil	Putnam 1	20-33N-19E	Judith River	Blaine
5	Roland Bond	Elizabeth Campbell 2-9	09-27N-19E	Eagle	Blaine
6*	High Crest Oil	Roberts 28-4	28-31N-19E	Eagle	Blaine
7*	Montana Power	IX Ranch B9-26	26-27N-15E	Judith River	Chouteau
8*	Montana Power	State 5-20	20-27N-14E	Virgelle	Chouteau
9*	Viking Res	State 2-15	15-27N-14E	Virgelle	Chouteau
10*	Monterrey Pet	Sada Woods 1-21	21-27N-03E	Bow Island	Chouteau
11*	Montana Power	Weaver 4-25	25-27N-16E	Eagle	Chouteau
12*	Montana Power	State 6	16-28N-14E	Eagle	Chouteau
13*	Norfolk Energy	Clark 1-14	01-31N-17E	Judith River	Hill
14	Concept Res	Givan 3-34	34-33N-12E	Judith River	Hill
15*	Montana Power	Runkel 16-19	19-32N-15E	Virgelle	Hill
16*	Montana Power	Runkel 13-19	19-32N-15E	Virgelle	Hill
17	Oil Res Inc	Larson 19-4	19-35N-13E	2nd Wt Spks	Hill
18*	Roland Bond	Rocky Boy 1-15	15-29N-15E	Eagle	Hill
19*	Montana Power	Bingham-Anderson 1-4	04-36N-06E	2nd Wt Spks	Liberty
20	Montana Power	State 1-16	16-36N-06E	Blackleaf	Liberty
21*	Montana Power	Johns 7-15	15-36N-06E	Blackleaf	Liberty
22*	Montana Power	Gunderson 7-10	10-36N-06E	Blackleaf	Liberty
23	Lawrence McCarthy	Gunderson 1-9	09-36N-06E	Blackleaf	Liberty
24	Montana Power	E Gunderson 14-2	02-36N-06E	Blackleaf	Liberty
25	Kenneth Luff	Federal 1-6	06-37N-06E	Blackleaf	Liberty
26*	Lawrence McCarthy	Hodges 1-34	34-36N-07E	2nd Wt Spks	Liberty
27*	Croft Petroleum	Brown 1	30-37N-04E	Bow Island	Liberty
28*	JB Appling	Federal 7A-25	25-36N-05E	Bow Island	Liberty
29*	Grace Petroleum	Milnar 4-7X	04-34N-07E	Bow Island	Liberty
30*	Grace Petroleum	Graff 8-15	08-34N-07E	Bow Island	Liberty
31*	Grace Petroleum	State 16-7	16-34N-07E	Bow Island	Liberty
32	Montana Power	Joy 9-20-35-7	20-35N-07E	Bow Island	Liberty
33*	Cardinal Petroleum	Jensen 11-1	01-36N-05E	Blackleaf	Liberty
34*	Midlands Gas	State 1671-1	16-37N-31E	Bowdoin	Phillips
35*	Midlands Gas	Fee 2970-1	29-37N-30E	Bowdoin	Phillips
36*	Midlands Gas	Federal 1761-2	17-36N-31E	Bowdoin	Phillips
37	Midlands Gas	Federal 0530-1	05-33N-30E	Phillips	Phillips
38*	Southland Royalty	Federal 1860-1	18-36N-30E	Bowdoin	Phillips
39*	Falcon-Colo Expl	Federal 2-21	21-33N-34E	Phillips	Phillips

\* Indicates wells with at least 2-yr production history (from Fig. 2, all others initial production only).

**Table 2.** Identification of 97 wells in north-central Montana with neutron- and density-porosity, and gamma-ray intensity logs. Well numbers refer to figure 5. (\* Indicates wells outside study area not mapped.)

Well No.	Operator	Lease Name and Number	Location	County	API No.
1	Norfolk Energy	Clark 1-14	01-31N-17E	Hill	25-041-22410
2	Tricentrol USA	Ramberg 19-5	19-31N-18E	Blaine	25-005-22322
3	Montana Power	State 5-20	20-27N-14E	Chouteau	25-015-21646
4	Midlands Gas	State 1671-1	16-37N-31E	Phillips	25-071-21485
5	Midlands Gas	Federal 1761-2	17-36N-31E	Phillips	25-071-21864
6	Southland Royalty	Federal 1860-1	18-36N-30E	Phillips	25-071-21746
7	Grace Petroleum	Milnar 4-7X	04-34N-07E	Liberty	25-051-21477
8	Smoky Hill Expl	Voss 2-23	23-33N-09E	Hill	25-041-22233
9	Louisiana Land	State 12-1	18-31N-12E	Hill	25-041-22358
10	High Crest Oil	Roberts 28-4	28-31N-19E	Blaine	25-005-21597
11	Roland Bond	Rocky Boy 1-15	15-29N-15E	Hill	25-041-21384
12	Roland Bond	Elizabeth Campbell 2-9	09-27N-19E	Blaine	25-005-22402
13	Cardinal Petroleum	Jensen 11-1	01-36N-05E	Liberty	25-051-21202
14	Balcron Oil	Trunk 1-29	29-23N-14E	Chouteau	25-015-21622
15	Balcron Oil	Trunk 2-12	12-25N-12E	Chouteau	25-015-21621
16	S & J Operating	Rossmiller 1-8	08-25N-03E	Chouteau	25-015-21648
17	Montana Power	Weaver 4-25	25-27N-16E	Chouteau	25-015-21633
18	Montana Power	State 6	16-28N-14E	Chouteau	25-015-21613
19	Tricentrol USA	Herron 31-16	31-31N-15E	Hill	25-041-22199
20	Louisiana Land	Federal 14-2	02-29N-12E	Chouteau	25-015-21630
21	Beard Oil	Richard 1	06-27N-10E	Chouteau	25-015-21499
22	Richard Thompson	State of Mt 1	16-26N-07E	Chouteau	25-015-21636
23	Webb Resources	Harris Land & Cattle	27-21N-08E	Chouteau	25-015-21296
24	Webb Resources	Leroy Strand 21-13	21-20N-11E	Chouteau	25-015-21180
25	Webb Resources	State-Webb 21-16	21-23N-10E	Chouteau	25-015-21197
26	Webb Resources	Mosier 11-16	11-23N-06E	Chouteau	25-015-21205
27	Mapco Inc	Eveland 1-9	09-31N-05E	Liberty	25-051-21471
28	Montana Power	Smith 13-31	31-34N-04E	Liberty	25-051-21666
29	Montana Power	Stewart Ranch 13-20-28-5	20-28N-05E	Liberty	25-051-21391
30	Elenburg Expl	Meissner 10-1	01-29N-06E	Liberty	25-051-21604
31	Fuel Resources Dev	Federal L21-36-15N	21-36N-15E	Hill	25-041-22256
32	Louisiana Land & Expl	Anderson 12-2	02-30N-09E	Hill	25-041-22339
33	Montana Power	Murr-Lacasse 9-14	14-33N-11E	Hill	25-041-22345
34	Pet Q Inc	Wise 12-13	13-35N-11E	Hill	25-041-22250
35	Salmon Resources	Schaller 1	20-37N-10E	Hill	25-041-22095
36	Grace Petroleum	Valadon 19-9	19-34N-15E	Hill	25-041-22130
37	Energetics Inc	Spencer 41-31	31-28N-22E	Blaine	25-005-21894
38	Western Natural Gas	Brown 1-3	03-29N-17E	Blaine	25-005-21571
39	Industrial Energy Corp	Kuhr 34-24	24-29N-21E	Blaine	25-005-21733
40	Beartooth Oil & Gas	Stout 1	17-33N-26E	Blaine	25-005-22205
41	Benson Mineral Group	Williams 1-20	20-34N-18E	Blaine	25-005-22055
42	Flare Energy	Wood Coulee 2-32	32-35N-22E	Blaine	25-005-22286
43	Pinion Petroleum Corp	State 1-13	13-32N-23E	Blaine	25-005-21840

**Table 2.** Continued.

Well No.	Operator	Lease Name and Number	Location	County	API No.
44	Fuel Resources Dev	Sanford J33 24-18N	33-24N-18E	Blaine	25-005-22190
45	John J Lyon	Williamson 4-15	15-37N-18E	Blaine	25-005-21921
46	LYTM Co Inc	Modic 11-15	15-34N-24E	Blaine	25-005-22422
47	LYTM Co Inc	Grover 1	20-34N-20E	Blaine	25-005-22456
48	Montana Power	Tribal 8-11-29-24	11-29N-24E	Blaine	25-005-21833
49	Texaco Inc	Bowes-Sawtooth Unit D-502	02-31N-19E	Blaine	25-005-21622
50	Tricentrol USA	Ramberg 24-8	24-31N-17E	Blaine	25-005-22320
51	Universal Gas	Rasmussen 11-36-23	11-36N-23E	Blaine	25-005-22072
52	Tricentrol USA	Williamson 3-10	03-26N-19E	Blaine	25-005-22283
53	True Oil	Gorman 24-10	10-32N-21E	Blaine	25-005-21617
54	Terra Resources	Morgan Ranch Etal 1	29-36N-34E	Phillips	25-071-21233
55	Beartooth Oil & Gas	Federal 22-13	22-37N-28E	Phillips	25-071-21759
56	Elenburg Expl	French 31-27-31	31-27N-31E	Phillips	25-071-21454
57	Lear Petroleum	Fee-Taylor 1	28-27N-28E	Phillips	25-071-21731
58	Montana-Dakota Utilities	Federal 22-23	23-24N-27E	Phillips	25-071-21545
59	Phoenix Resources	Federal 44-5	05-29N-33E	Phillips	25-071-21674
60	Statex Petroleum	Federal 9-1	09-35N-27E	Phillips	25-071-21806
61	Tenneco Oil	Olsen 1	15-32N-28E	Phillips	25-071-21505
62	Tenneco Oil	Stapp-Federal 1	10-23N-29E	Phillips	25-071-21507
63	Amarex Inc	State 1-16	16-32N-32E	Phillips	25-071-21129
64	Bobcat Oil	Milk River Land 1	27-29N-27E	Phillips	25-071-21130
65	Bridger Petroleum	State 1-36	36-25N-22E	Phillips	25-071-21515
66	Miami Oil Producers	Sergeant 6-1	06-33N-30E	Phillips	25-071-21174
67	Miami Oil Producers	State 614-16-1	16-34N-32E	Phillips	25-071-21141
68	Webb Resources	State-Magill 32-15	32-30N-30E	Phillips	25-071-21140
69	Falcon-Colorado Expl	Federal 2-21	21-33N-34E	Phillips	25-071-21751
70	FMP Operating Co	Loring Unit 0861-3	08-36N-31E	Phillips	25-071-21946
71	FMP Operating Co	Whitewater Unit 0642-3	06-34N-32E	Phillips	25-071-21944
72	Midlands Gas	Federal 2-2112	21-31N-32E	Phillips	25-071-21887
73	Freeport Etal	Federal 241-4	02-34N-31E	Phillips	25-071-22007
74	Midlands Gas	Federal 0141-2	01-34N-31E	Phillips	25-071-21863
75	Midlands Gas	Federal 1-0960	09-36N-30E	Phillips	25-071-21646
76	Meridan oil	Loring 3-0952	09-35N-32E	Phillips	25-071-22156
77	Falcon-Colorado Expl	State 1-22	22-33N-34E	Phillips	25-071-21718
78	PanCanadian Petroleum	Federal 1	20-36N-36E	Valley	25-105-21087
79	Terra Resources	State 1	36-33N-36E	Valley	25-105-21094
80*	Atlantic Richfield	Van Winkle 1-17	17-24N-37E	Valley	25-105-21221
81*	Montana Power	Federal 10-32	32-21N-34E	Garfield	25-033-21029
82*	Montana Power	State 8-36	36-19N-32E	Garfield	25-033-21032
83*	Montana Power	Federal 9-8	08-17N-31E	Garfield	25-033-21030
84*	Montana Power	State 2-16	16-19N-36E	Garfield	25-033-21028
85*	Louisiana Land	Kasten 1	10-17N-44E	McCone	25-055-21092
86*	American Hunter	Crow Rock 1	21-15N-45E	Prairie	25-079-21031

**Table 2.** Continued.

Well No.	Operator	Lease Name and Number	Location	County	API No.
87*	Sun-Texas	BN 29-1	29-12N-53E	Prairie	25-079-21026
88*	Burlington Northern	State 44-36	36-08N-56E	Fallon	25-025-21064
89*	CIG Expl	BN 1	21-06N-58E	Fallon	25-025-21143
90*	Integrity Oil and Gas	BN 17-6-26	17-06N-26E	Musselshell	25-065-21497
91	Xeno Inc.	Battle 16-35	35-36N-19E	Blaine	25-005-22430
92	John J Lyon	Malsam 14-12	12-36N-19E	Blaine	25-005-21927
93	John J Lyon	Battle Creek 2	14-36N-20E	Blaine	25-005-21913
94	General Well Service	Hutton 1-22	22-37N-27E	Phillips	25-071-21754
95	Tenneco Oil	Nolte-Federal 1	12-37N-27E	Phillips	25-071-21512
96*	Mont-Dakota Utilities	BN 414	27-07N-60E	Fallon	25-025-21190
97*	Mont-Dakota Utilities	BN 448	27-06N-60E	Fallon	25-025-21331

## Appendix 1: Plug-in Algorithm for Calculating GPI, Using PRIZM

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;          Density Porosity from Bulk Density (decimal)
PHID[] = (RhoM - RHOB[]) / (RhoM - RhoF)

;          Convert Decimal Porosity to Porosity Units (density and neutron porosity)
D[]=PHID[] * 100
N[]=NPHI[] * 100

;          Neutron Porosity minus Density Porosity (Porosity Units)
ND[] = N[] - D[]

;          Gas Detection Chart (left side)
If (ND[] > (0.425 * GR[]) - 5.0) Then X1[]=0 Else X1[]=1
If (ND[] > (0.425 * GR[]) - 8.0) Then X2[]=X1[] Else X2[]=2
If (ND[] > (0.425 * GR[]) - 11.0) Then X3[]=X2[] Else X3[]=3
If (ND[] > (0.425 * GR[]) - 14.0) Then X4[]=X3[] Else X4[]=4
If (ND[] > (0.425 * GR[]) - 17.0) Then X5[]=X4[] Else X5[]=5
If (ND[] > (0.425 * GR[]) - 20.0) Then X6[]=X5[] Else X6[]=6
If (ND[] > (0.425 * GR[]) - 23.0) Then X7[]=X6[] Else X7[]=7
If (ND[] > (0.425 * GR[]) - 26.0) Then X8[]=X7[] Else X8[]=8
If (ND[] > (0.425 * GR[]) - 29.0) Then X9[]=X8[] Else X9[]=9
If (ND[] > (0.425 * GR[]) - 32.0) Then X10[]=X9[] Else X10[]=10
If (ND[] > (0.425 * GR[]) - 35.0) Then X11[]=X10[] Else X11[]=11
If (ND[] > (0.425 * GR[]) - 38.0) Then X12[]=X11[] Else X12[]=12

;          Gas Detection Chart (right side)
If (ND[] > 29.0) Then Y1[]=0 Else Y1[]=1
If (ND[] > 26.0) Then Y2[]=Y1[] Else Y2[]=2
If (ND[] > 23.0) Then Y3[]=Y2[] Else Y3[]=3
If (ND[] > 20.0) Then Y4[]=Y3[] Else Y4[]=4
If (ND[] > 17.0) Then Y5[]=Y4[] Else Y5[]=5
If (ND[] > 14.0) Then Y6[]=Y5[] Else Y6[]=6
If (ND[] > 11.0) Then Y7[]=Y6[] Else Y7[]=7
If (ND[] > 8.0) Then Y8[]=Y7[] Else Y8[]=8
If (ND[] > 5.0) Then Y9[]=Y8[] Else Y9[]=9
If (ND[] > 2.0) Then Y10[]=Y9[] Else Y10[]=10
If (ND[] > -1) Then Y11[]=Y10[] Else Y11[]=11
If (ND[] > -4) Then Y12[]=Y11[] Else Y12[]=12

;          Gas Detection Chart (combination)

If (GR[] < 80) Then Z[]=X12[] Else Z[]=Y12[]

;          Neutron plus Density (Discriminator curve)

NDplus[]=NPHI[] + PHID[]

;          Discriminator Curve for Gas Detection
; (Restivity curve eliminates values less than 5 ohm-m; Sum of neutron and density porosity curves (decimal)
; eliminates values greater than 0.75; Neutron porosity curve (decimal) eliminates values greater than 0.50; Density
; porosity curve (decimal) eliminates values less than 0.08; GRI inserted as a “zoned” parameter for gamma-ray
; curve; neutron minus density “GPI = 0” curve)

If (RT[] < 5.0 or NDplus[] > 0.75 or NPHI[] > 0.50 or PHID[] < 0.08 or GR[] > GRI or ND[] > (0.425 * GR[]) -
14.0) Then GPI[]=0 Else GPI[]=Z[]

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