U.S. DEPARTMENT OF THE INTERIOR

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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 ,7 and 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,

$$\phi_{density} = (\rho_{ma} - \rho_b) / (\rho_{ma} - \rho_f) \qquad (1)$$

where $\phi_{density}$ is density porosity (decimal percent), $\rho_{ma}$ is matrix density (grams per cubic centimeter; g/cc), $\rho_b$ is bulk density (g/cc), and $\rho_f$ 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,

$$\phi_D = \phi_{density} * 100 \qquad (2)$$

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

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

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

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

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

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

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,

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

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.

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 5.0) \text{ Then } X_1=0 \text{ Else } X_1=1$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 8.0) \text{ Then } X_2=X_1 \text{ Else } X_2=2$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 11.0) \text{ Then } X_3=X_2 \text{ Else } X_3=3$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 14.0) \text{ Then } X_4=X_3 \text{ Else } X_4=4$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 17.0) \text{ Then } X_5=X_4 \text{ Else } X_5=5$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 20.0) \text{ Then } X_6=X_5 \text{ Else } X_6=6$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 23.0) \text{ Then } X_7=X_6 \text{ Else } X_7=7$$

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$$\text{If } (\phi_{ND} > (0.425 * GRI) - 26.0) \text{ Then } X_8 = X_7 \text{ Else } X_8 = 8$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 29.0) \text{ Then } X_9 = X_8 \text{ Else } X_9 = 9$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 32.0) \text{ Then } X_{10} = X_9 \text{ Else } X_{10} = 10$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 35.0) \text{ Then } X_{11} = X_{10} \text{ Else } X_{11} = 11$$

$$\text{If } (\phi_{ND} > (0.425 * GRI) - 38.0) \text{ Then } X_{12} = X_{11} \text{ Else } X_{12} = 12$$

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:

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

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.

$$\text{If } (\phi_{ND} > 29) \text{ Then } Y_1 = 0 \text{ Else } Y_1 = 1$$

$$\text{If } (\phi_{ND} > 26) \text{ Then } Y_2 = Y_1 \text{ Else } Y_2 = 2$$

$$\text{If } (\phi_{ND} > 23) \text{ Then } Y_3 = Y_2 \text{ Else } Y_3 = 3$$

$$\text{If } (\phi_{ND} > 20) \text{ Then } Y_4 = Y_3 \text{ Else } Y_4 = 4$$

$$\text{If } (\phi_{ND} > 17) \text{ Then } Y_5 = Y_4 \text{ Else } Y_5 = 5$$

$$\text{If } (\phi_{ND} > 14) \text{ Then } Y_6 = Y_5 \text{ Else } Y_6 = 6$$

$$\text{If } (\phi_{ND} > 11) \text{ Then } Y_7 = Y_6 \text{ Else } Y_7 = 7$$

$$\text{If } (\phi_{ND} > 8) \text{ Then } Y_8 = Y_7 \text{ Else } Y_8 = 8$$

$$\text{If } (\phi_{ND} > 5) \text{ Then } Y_9 = Y_8 \text{ Else } Y_9 = 9$$

$$\text{If } (\phi_{ND} > 2) \text{ Then } Y_{10} = Y_9 \text{ Else } Y_{10} = 10$$

$$\text{If } (\phi_{ND} > -1) \text{ Then } Y_{11} = Y_{10} \text{ Else } Y_{11} = 11$$

$$\text{If } (\phi_{ND} > -4) \text{ Then } Y_{12} = Y_{11} \text{ Else } Y_{12} = 12$$

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).

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

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 porosites, 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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_____, Condon, S.M., Anna, L.O., Hester, T.C., Rowan, E.L., Cook, Troy, and Lillis, P.G., 1999, Re-examination of Cretaceous shallow biogenic gas resources, Northern Great Plains, Montana—A multidisciplinary approach [abs.]: AAPG Rocky Mountain Section Meeting, Program with Abstracts, p. A9.

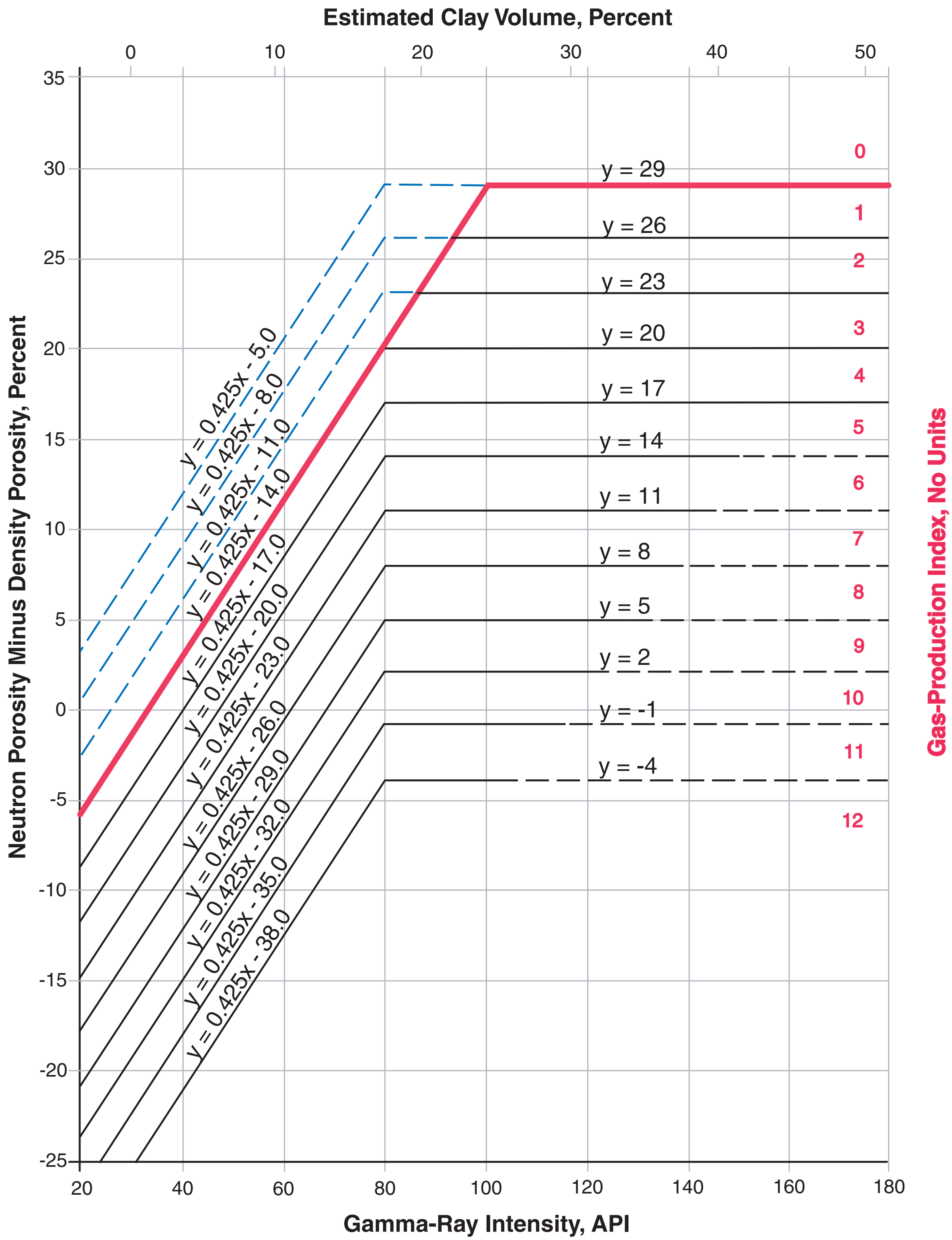


Figure 1. Neutron porosity minus density porosity versus gamma-ray intensity crossplot showing equations for line segments that make up the gas-production index. Thin, solid lines show 12 indexed levels of gas-production potential. Level one has the least potential for gas production; level 12 has the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

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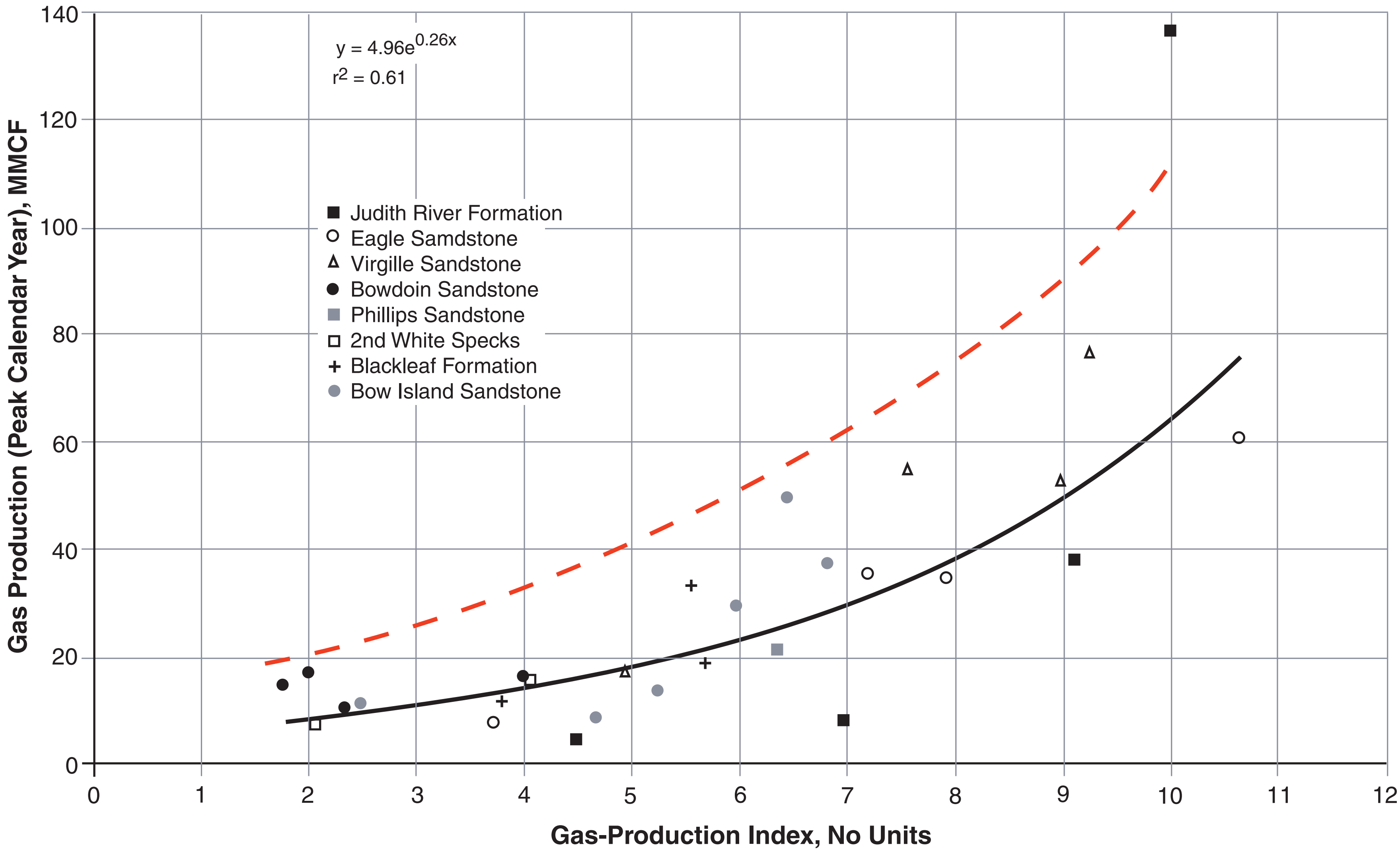


Figure 2. Gas production (peak calendar year) vs gas-production index (GPI; fig.1) for 28 gas-producing wells in north-central Montana (fig. 3; table 1). Dashed line indicates approximate production potential associated with a given index level. Equation and sample coefficient of determination (r2) for 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 | | |
| Upper Cretaceous | Montana Group | | Fox Hills Sandstone | | |
| Upper Cretaceous | Montana Group | | Bearpaw Shale | | |
| Upper Cretaceous | Montana Group | | Judith River Formation* | | |
| Upper Cretaceous | Montana Group | | Clagget Shale | | |
| Upper Cretaceous | Montana Group | | Eagle Sandstone* | | |
| Upper Cretaceous | Montana Group | | Virgelle Sandstone* | | |
| Upper Cretaceous | Montana Group | | Telegraph Creek Formation | | |
| Upper Cretaceous | Colorado Group | | Niobrara Formation | | |
| Upper Cretaceous | Colorado Group | | Carlile Shale | Bowdoin ss.* | |
| Upper Cretaceous | Colorado Group | | Greenhorn Formation* | 2nd White Specks* | |
| Upper Cretaceous | Colorado Group | | Belle Fourche Shale | Mosby Ss. Mbr. | Phillips ss.* |
| Upper Cretaceous | Colorado Group | Blackleaf Formation* | Mowry Shale | | |
| Lower Cretaceous | Colorado Group | Blackleaf Formation* | Muddy Sandstone | Bow Island Fm.* | Viking Fm. |
| Lower Cretaceous | Colorado Group | Blackleaf Formation* | Skull Creek Shale | | |
| Lower Cretaceous | Colorado Group | Blackleaf Formation* | Fall River Sandstone | | |
| Lower Cretaceous | 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).

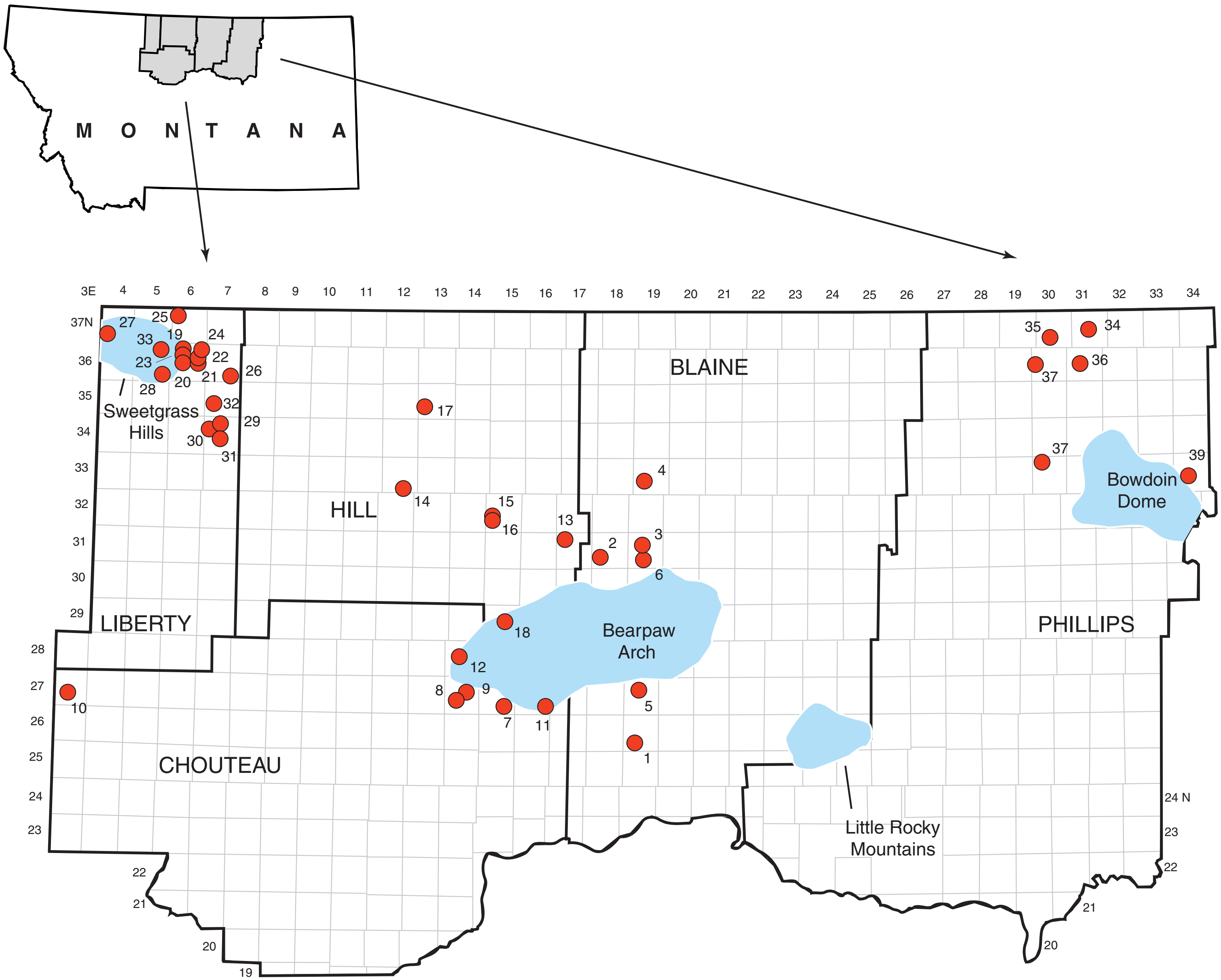


Figure 4. Index map showing major structural features, and locations of 39 wells used for calibrating the gas-production index (GPI). These wells have the necessary log suite (neutron and density porosity, and gamma-ray intensity) for calculating the GPI. Well numbers refer to table 1.

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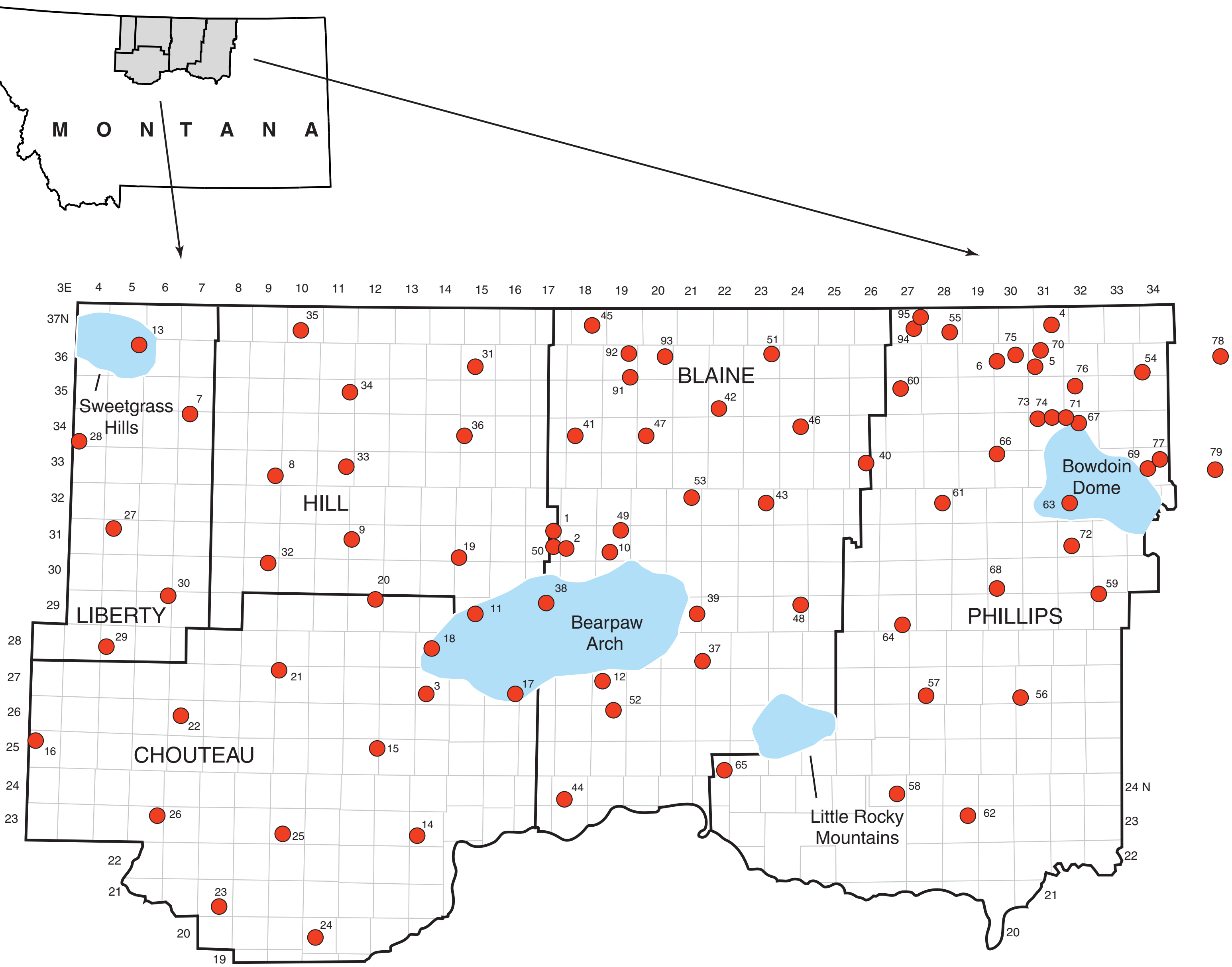


Figure 5. Index map showing major structural features, and locations of 84 wells that have the necessary log suite (neutron and density porosity, and gamma-ray intensity) for calculating the gas-production index. Well numbers refer to table 2.

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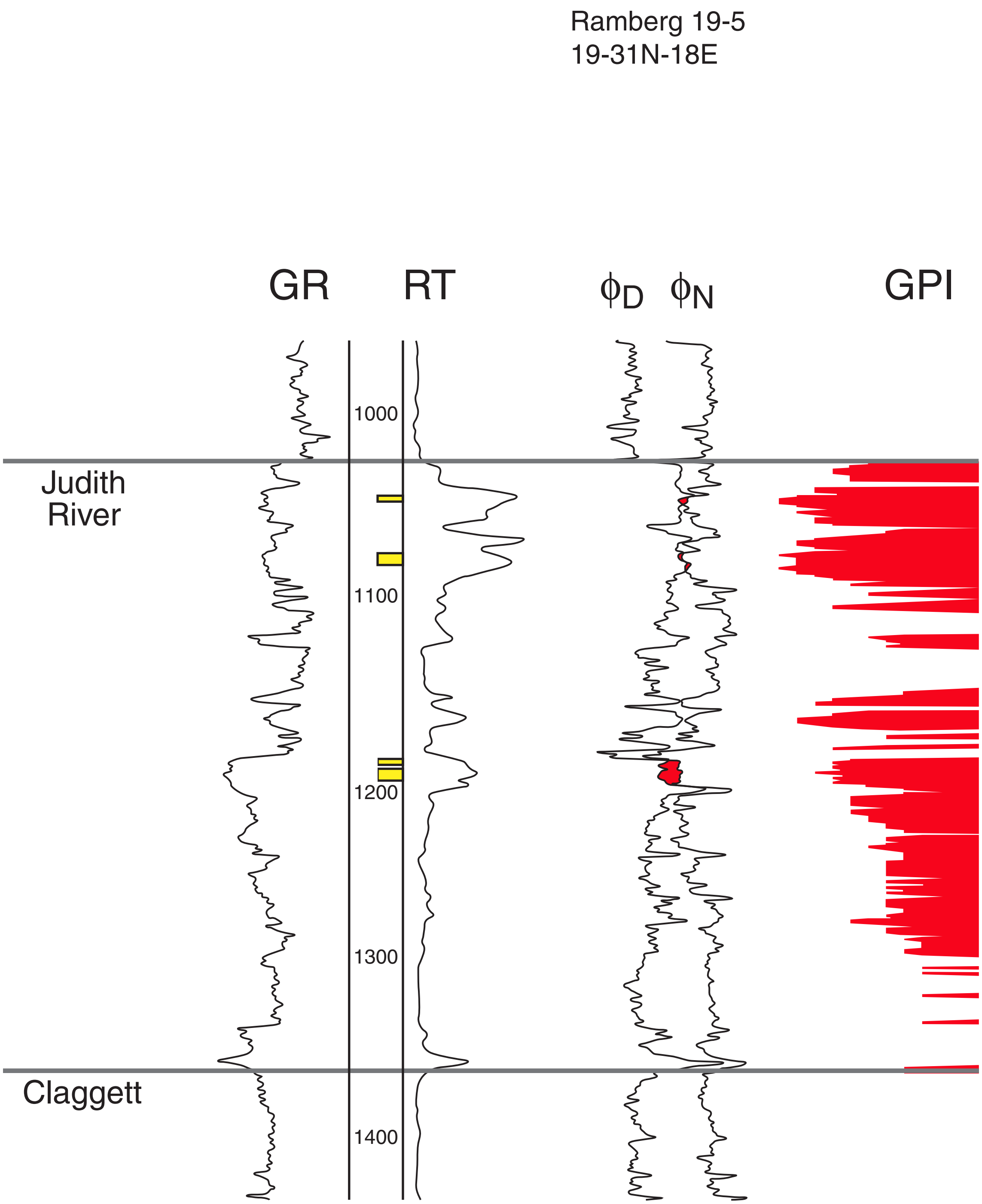


Figure 6. Well no. 2 (table 1; fig. 4) showing typical log responses and calculated GPI curve for Cretaceous Judith River Formation, north-central Montana. This well produced 37.9 MMCF gas in its best year of production. Perforated intervals are shown in depth track.

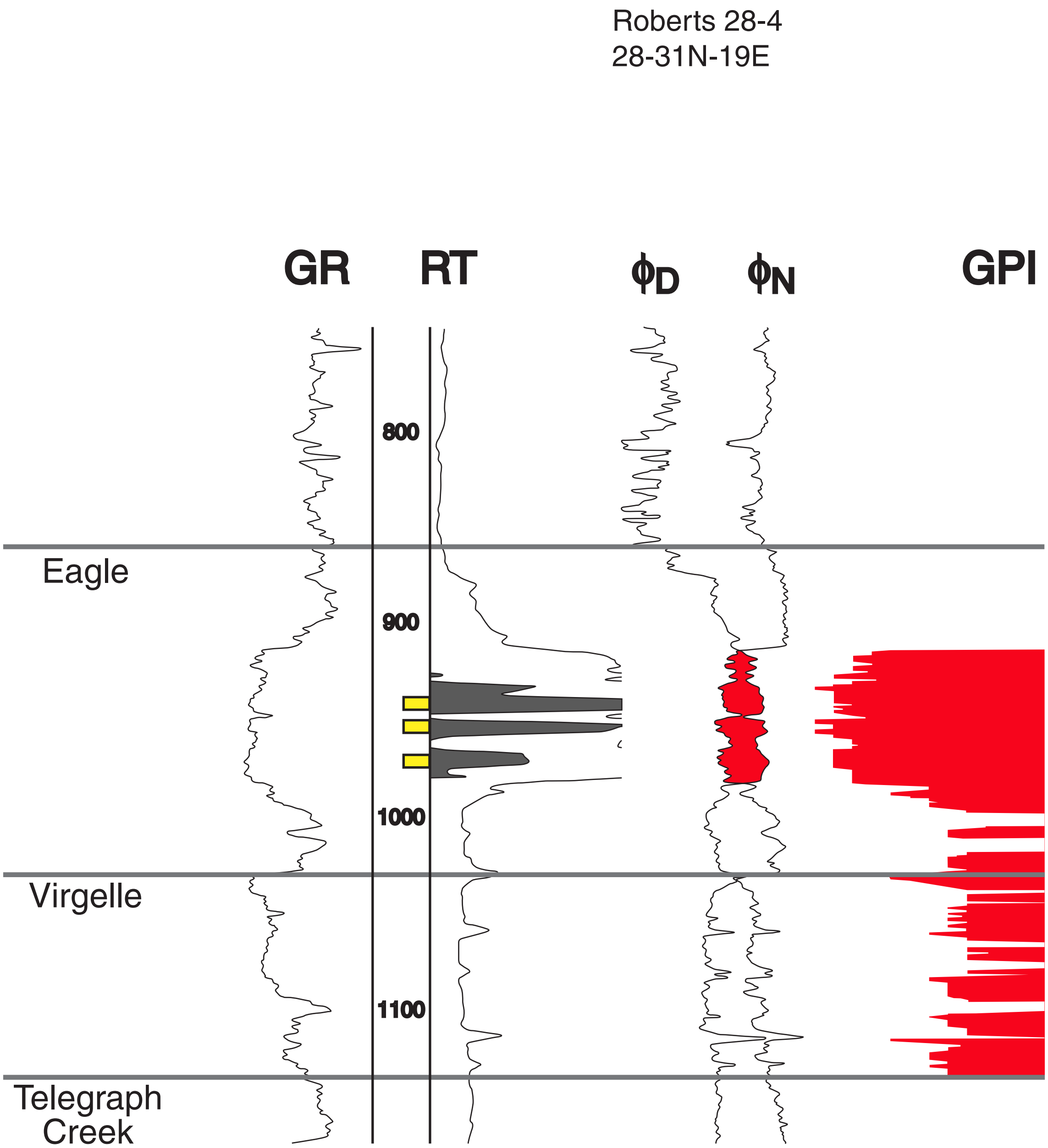


Figure 7. Well no. 6 (table 1; fig. 4) showing typical log responses and calculated GPI curve for Cretaceous Eagle Sandstone, north-central Montana. This well produced 60.3 MMCF gas in its best year of production. Perforated intervals are shown in depth track.

State 1671-1
16-37N-31E

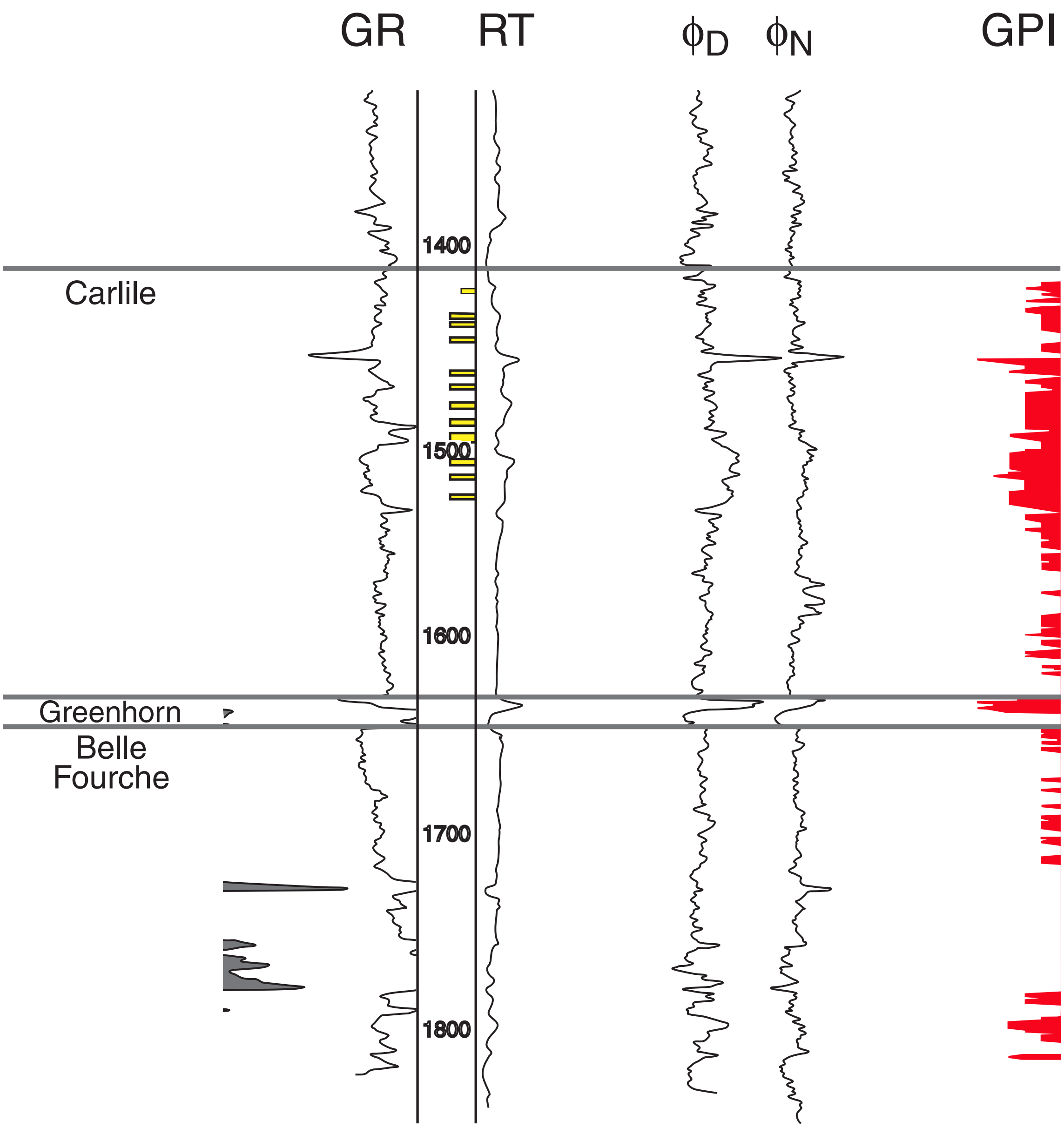


Figure 8. Well no. 34 (table 1; fig. 4) showing typical log responses and calculated GPI curve for Cretaceous Carlile Shale (Bowdoin ss), Greenhorn Formatiion (2nd White Specks), and Belle Fourche Shale (Phillips ss), north-

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| | 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 Cand 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).

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**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 |

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**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

```
;                    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 (Descriminator 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[]
```

| | 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 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 3 | | | | | | | | | | | |
| 4 | | | | | | | | | | | |
| 5 | | | | | | | | | | | |

Example spreadsheet

## Appendix 2. Four Steps to Calculating Gas-Production Index, Using EXCEL

**First:** Insert data or formulae into row 2 of spreadsheet as indicated by the numbers 1 thru 11

1) Well number (optional)
2) Interval number (optional)
3) Gamma-ray intensity
4) Neutron porosity minus density porosity
5) Insert formula:

=IF(D2>(0.425*C2)-14,"0",IF(D2>(0.425*C2)-17,"4",IF(D2>(0.425*C2)-20,"5",IF(D2>(0.425*C2)-23,"6",IF(D2>(0.425*C2)-26,"7",IF(D2>(0.425*C2)-29,"8",IF(D2>(0.425*C2)-32,"9",IF(D2>(0.425*C2)-35,"10"))))))))

6) Insert formula:

=IF(D2>(0.425*C2)-35,"-999.25",IF(D2>(0.425*C2)-38,"11","12"))

7) Insert formula:

=IF(D2>(0.425*C2)-14,"0",IF(D2<(0.425*C2)-14,IF(D2>29,"0",IF(D2>26,"1",IF(D2>23,"2",IF(D2>20,"3",IF(D2>17,"4",IF(D2>14,"5"))))))))

8) Insert formula:

=IF(D2>14,"-999.25",IF(D2>11,"6",IF(D2>8,"7",IF(D2>5,"8",IF(D2>2,"9",IF(D2>-1,"10",IF(D2>-4,"11","12")))))))

9) Insert formula: =IF(E2=FALSE,F2,E2)

10) Insert formula: =IF(G2=FALSE,H2,G2)

11) Insert formula: =IF(C2<80,I2,J2)

**Second:** Enter all data into columns A through D.
**Third:** Copy formula 5 into each cell of column E. (To do this, select cell E2, position curser on bottom right corner (until the curser becomes a black plus sign) and drag downward to the end of data set.
**Fourth:** Repeat this procedure for each formula (6 through 11).

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