

Relationship between Porosity and Water Saturation: Methodology to Distinguish Mobile from Capillary Bound Water

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ABSTRACT

In 1965, Buckles proposed that porosity and irreducible water saturation are hyperbolically related:

$$\text{Porosity} \times \text{Irreducible Water Saturation} = \text{Constant}$$

The magnitude of the constant was shown to be related to rock type, and indirectly to permeability. The lower the value of the constant, the better the quality of the rock – higher porosity for any given value of porosity.

Extensive analysis of both core data and petrophysical estimates of porosity and irreducible water saturation, from all types of reservoirs worldwide, suggests that Buckles relationship is a unique solution to a more general equation:

$$\text{Porosity}^Q \times \text{Irreducible Water Saturation} = \text{Constant}$$

The value of the power function, Q , ranges from about 0.8 to about 1.3, with many reservoirs close to 1.0.

Values of Q and the constant are easily derived by plotting the log of porosity vs. log irreducible water saturation, resulting in a straight line of negative slope = Q . Projection of the straight line to a porosity of 1.0 gives the value of the constant.

The cross plot can be used to distinguish rock groupings with different values of Q and the constant. They also can be used to infer the presence of mobile water. Points that fall above the line suggest that the level is not at irreducible water saturation, or is of lower rock quality.

By comparing, with depth, theoretical irreducible water saturation with petrophysical calculated water saturation, it is possible to categorize changing rock quality and /or presence of mobile water. This can be very useful in deciding which intervals to complete, and to rationalize water production. Examples from a number of reservoirs are presented, both core data and petrophysical calculations of porosity and water saturation.

INTRODUCTION

Relationships between porosity and irreducible water saturation have been described by a number of authors (Buckles, 1965; Morris and Biggs, 1967; Chilingar et al 1972; Bond, 1978; Doveton, 1994). The generally accepted relation is hyperbolic:

$$\text{Porosity} \times \text{Irreducible Water Saturation} = \text{Constant}$$

Ranges of the constant are:

Sandstones 0.02 to 0.10
Intergranular Carbonates 0.01 to 0.06
Vuggy Carbonates 0.005 to 0.06

The relationship can be linearized to:

$$\text{Log}S_{wi} = \log C - \log \text{Phi}$$

Where:

S_{wi} = Irreducible water saturation
 C = Constant
 Phi = Porosity

When data are presented on a log-log graph, points should align on a slope of -1.

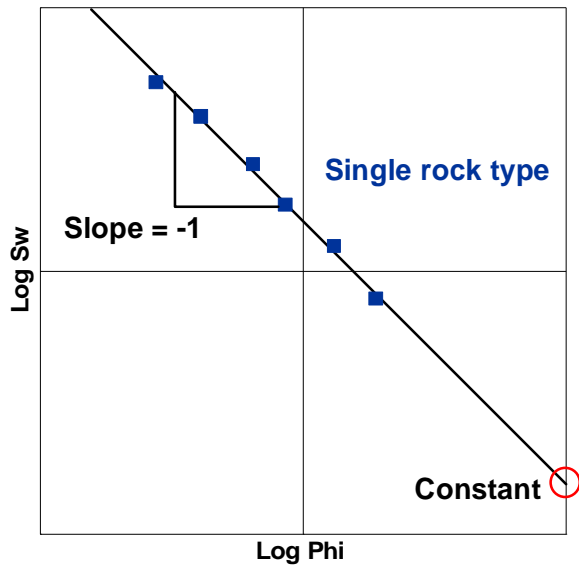


Figure 1

Theoretically, if more than one rock type exists, the different rock types should align on different trends, each with a slope of -1.

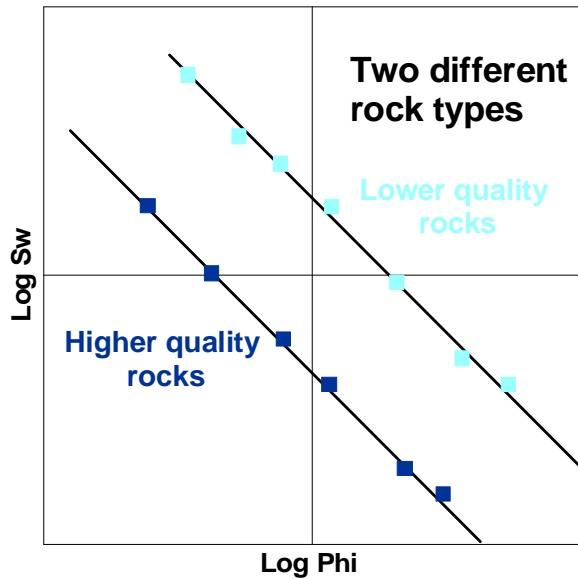


Figure 2

Higher quality rocks have higher permeability at any one porosity, as compared with lower quality rocks.

If data is included for rocks not at irreducible water saturation, the patterns become less distinct.

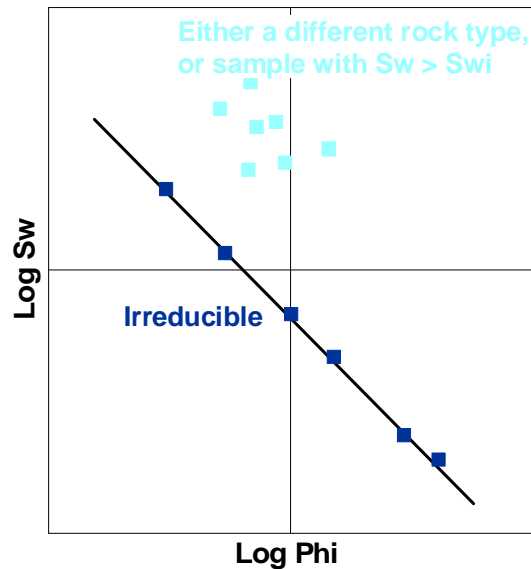


Figure 3

S_w = Water saturation

In this paper, we present both core and petrophysical data that suggest a closer relationship between Φ and S_{wi} is:

$$\Phi^Q \times S_{wi} = Constant$$

Where Q is the slope of the alignment on the $\log S_{wi}$ vs. $\log \Phi$ plot

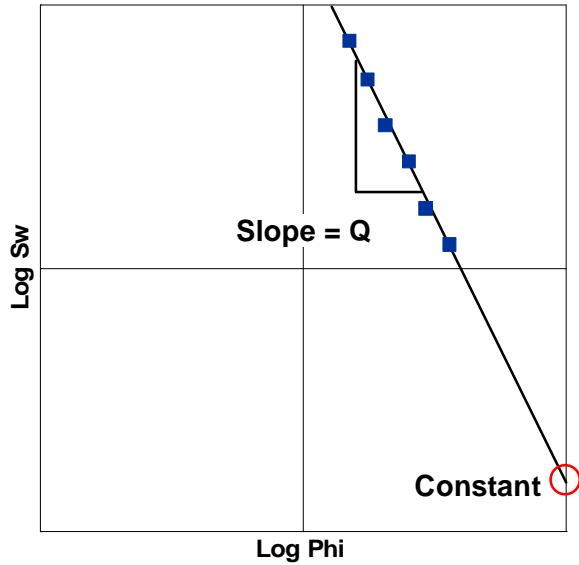


Figure 4

For petrophysical analysis, effective porosity is compared with effective water saturation.

$$\text{Effective Porosity} = \text{Total Porosity} - \text{Shale Contribution}$$

CORE DATA EXAMPLES – SHOWING VARIABLE ROCK QUALITY

Distinction of rock quality is shown on the log porosity vs. log water saturation plots, and equivalent data presented on the log permeability vs. linear porosity plot. In all cases, the higher quality rocks have a steeper slope on the log permeability vs. linear porosity plot than do the lower quality rocks. The distinction of rock quality helps explain data dispersion on porosity/permeability plots. Also, for wells with no core data, similar petrophysical porosity/water saturation cross plots can be used to group rocks with different porosity/permeability characteristics.

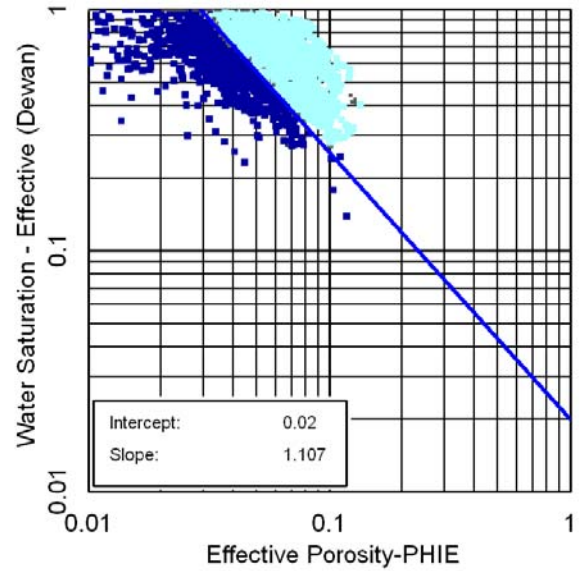


Figure 5a: Piceance Basin MWX-1

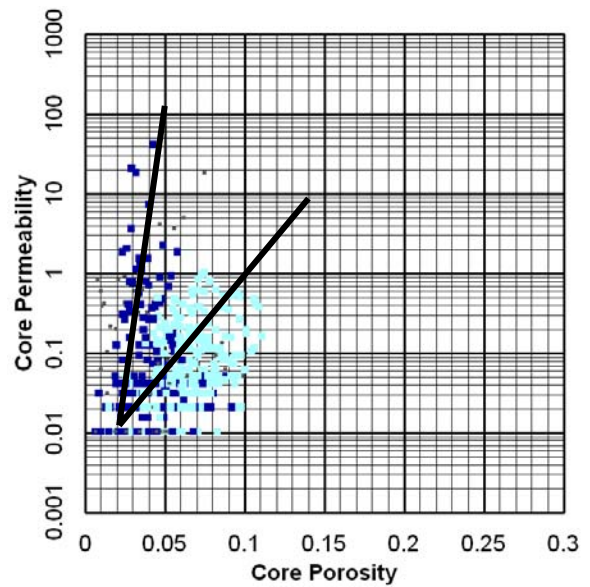


Figure 5b: Piceance Basin MWX-1

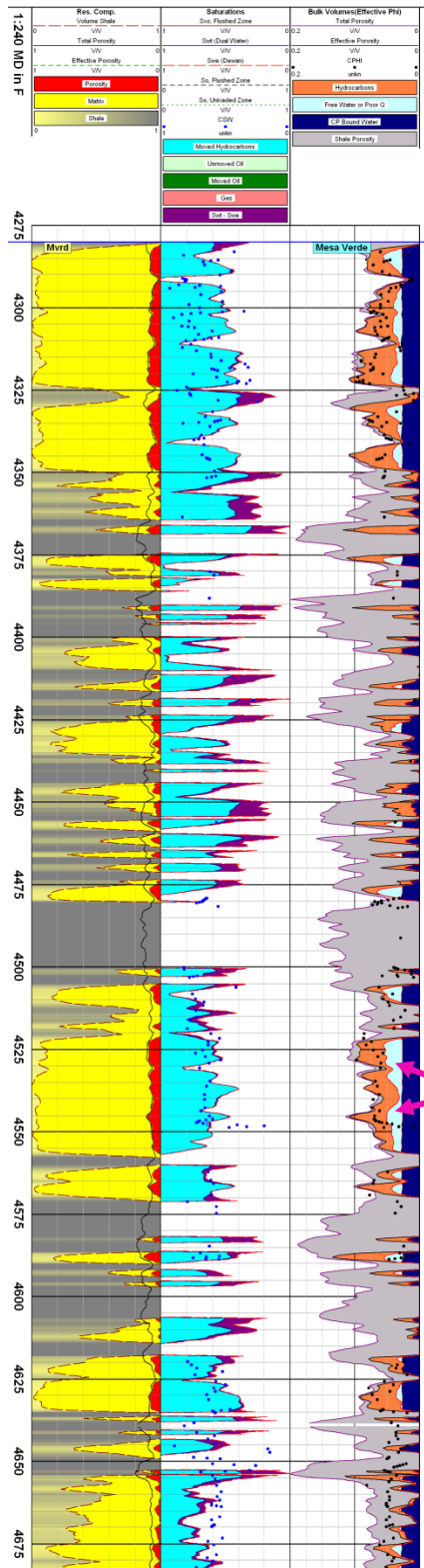


Figure 5c: Piceance Basin MWX-1 (4250-4700 ft)

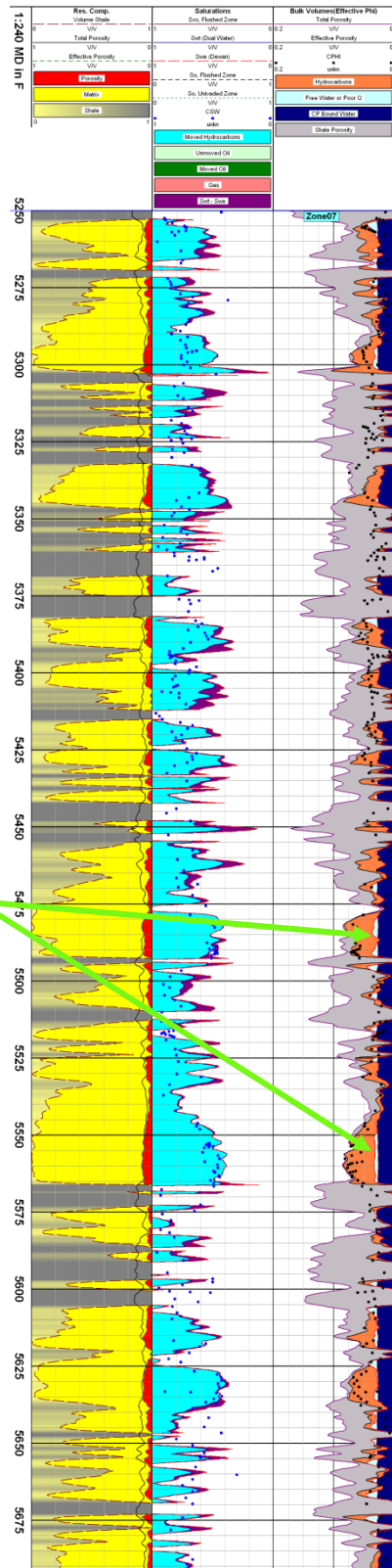


Figure 5d: Piceance Basin MWX-1 (5250-5700 ft)

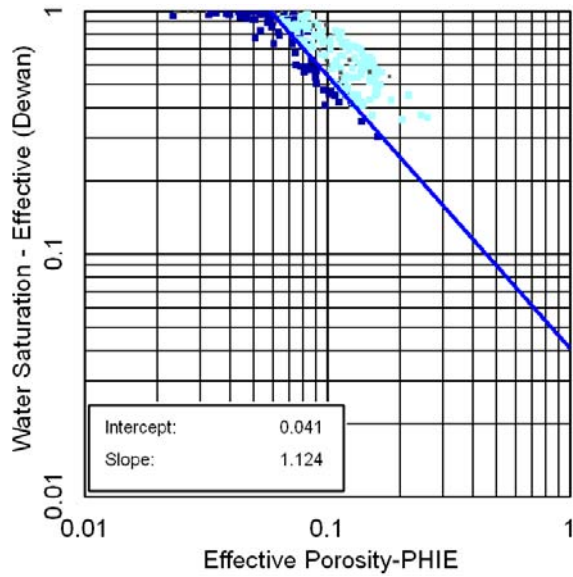


Figure 6a: Southern Wyoming Tight Gas Sand

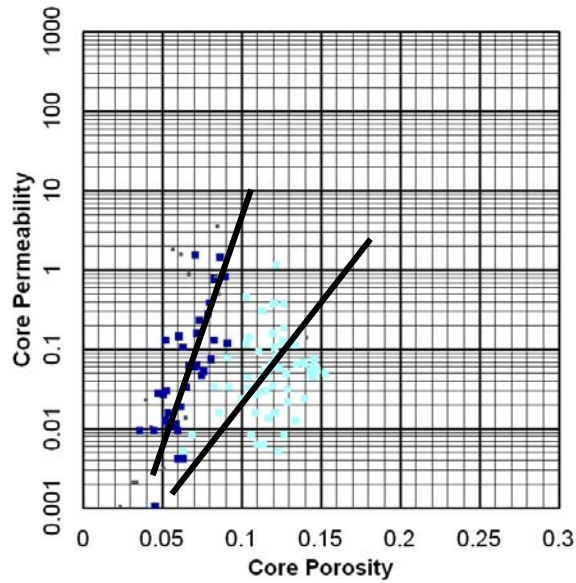


Figure 6b: Southern Wyoming Tight Gas Sand

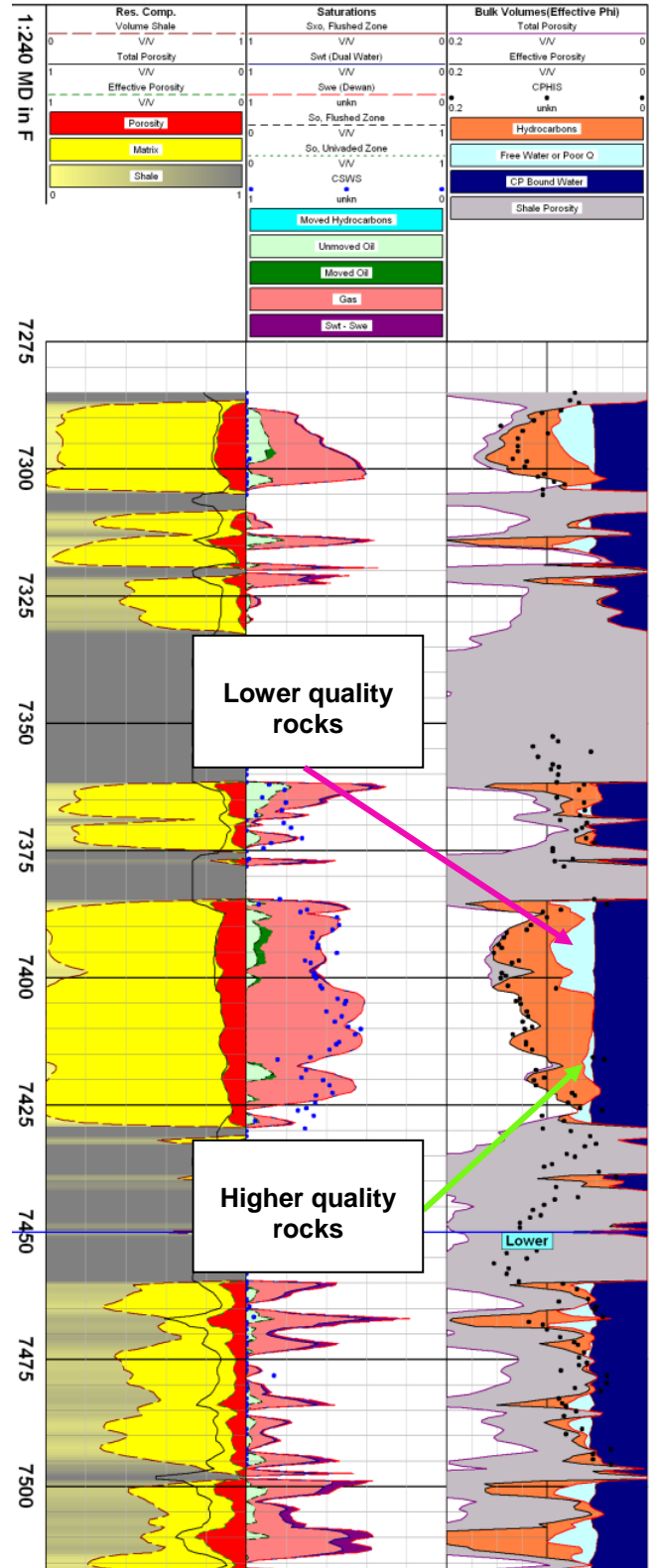


Figure 6c: Southern Wyoming Tight Gas Sand

EXAMPLES – LOG DATA

The first three examples are from the Piance Basin, Colorado. Example 1 is from well MWX-1. On the cross plot data of porosity vs. water saturation, data falling on or below the lower south-west line are interpreted to be at irreducible water saturation. The product $\Phi^{0.4} \times S_{wi}$ is coded as capillary bound water (shown in dark blue). Any data with S_w values higher than this minimal S_{wi} is coded as lower quality rock or potentially mobile water (shown in light blue).

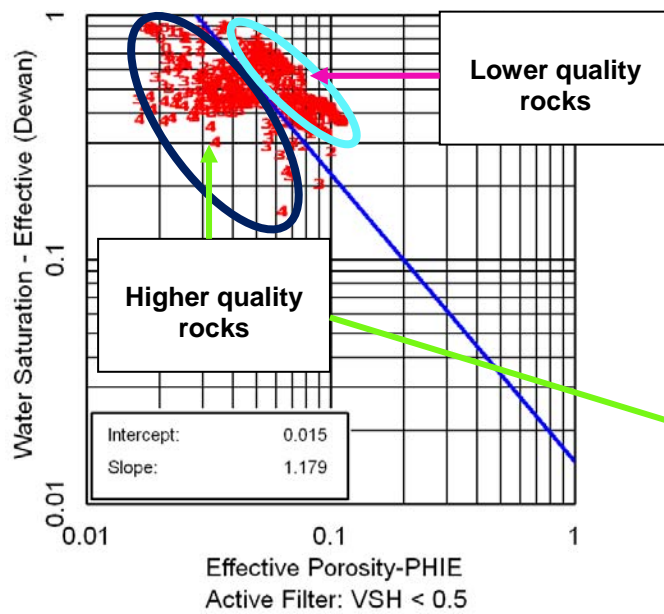


Figure 7a: Piceance Basin MWX-1

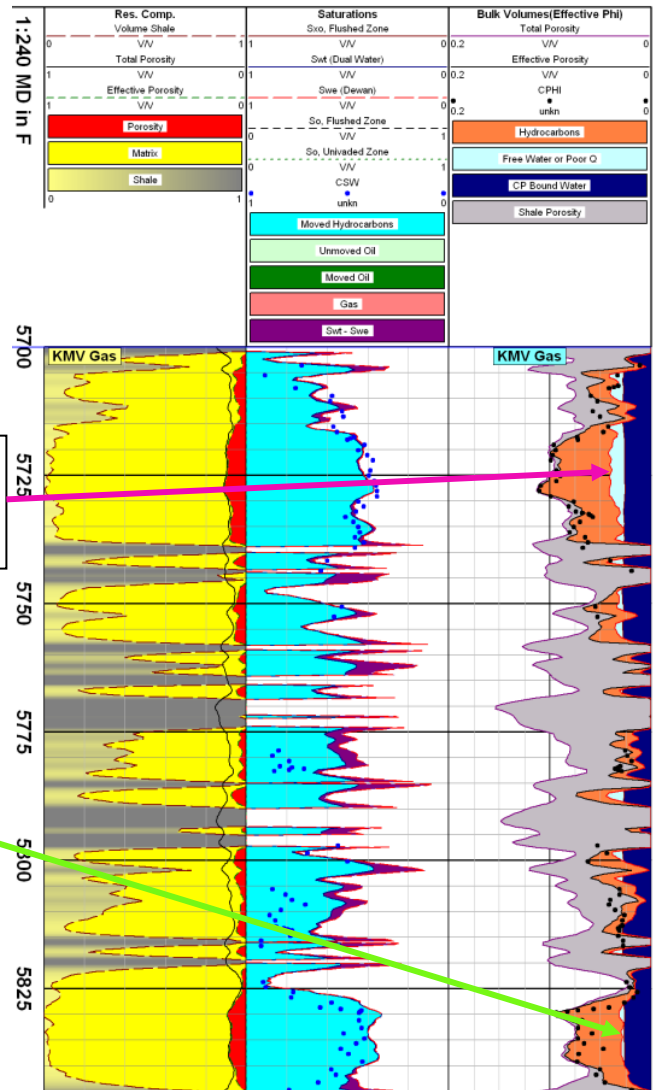


Figure 7b: Piceance Basin MWX-1

Example 2 is from a well that produces 60-80 barrels water per MMCFG. Many of the sands suggest poorer quality rocks and/or mobile water.

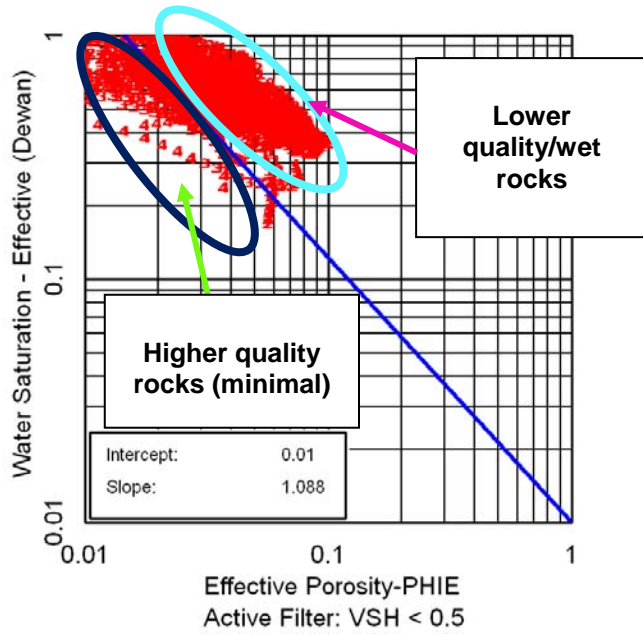


Figure 8a: Piceance Basin – example from well that produces water

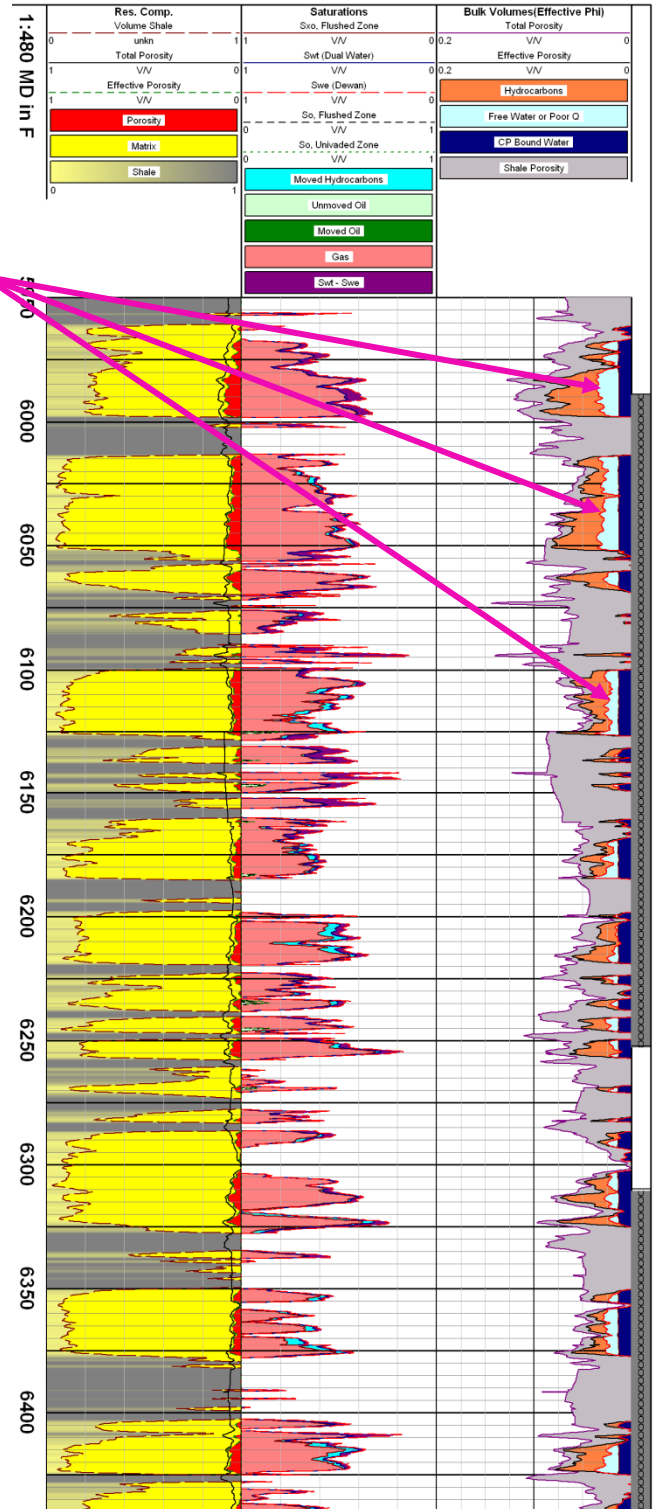


Figure 8b: Piceance Basin – example from well that produces water

Example 3 is from a Piceance Basin well that produces only 10 barrels water per MMCFG.

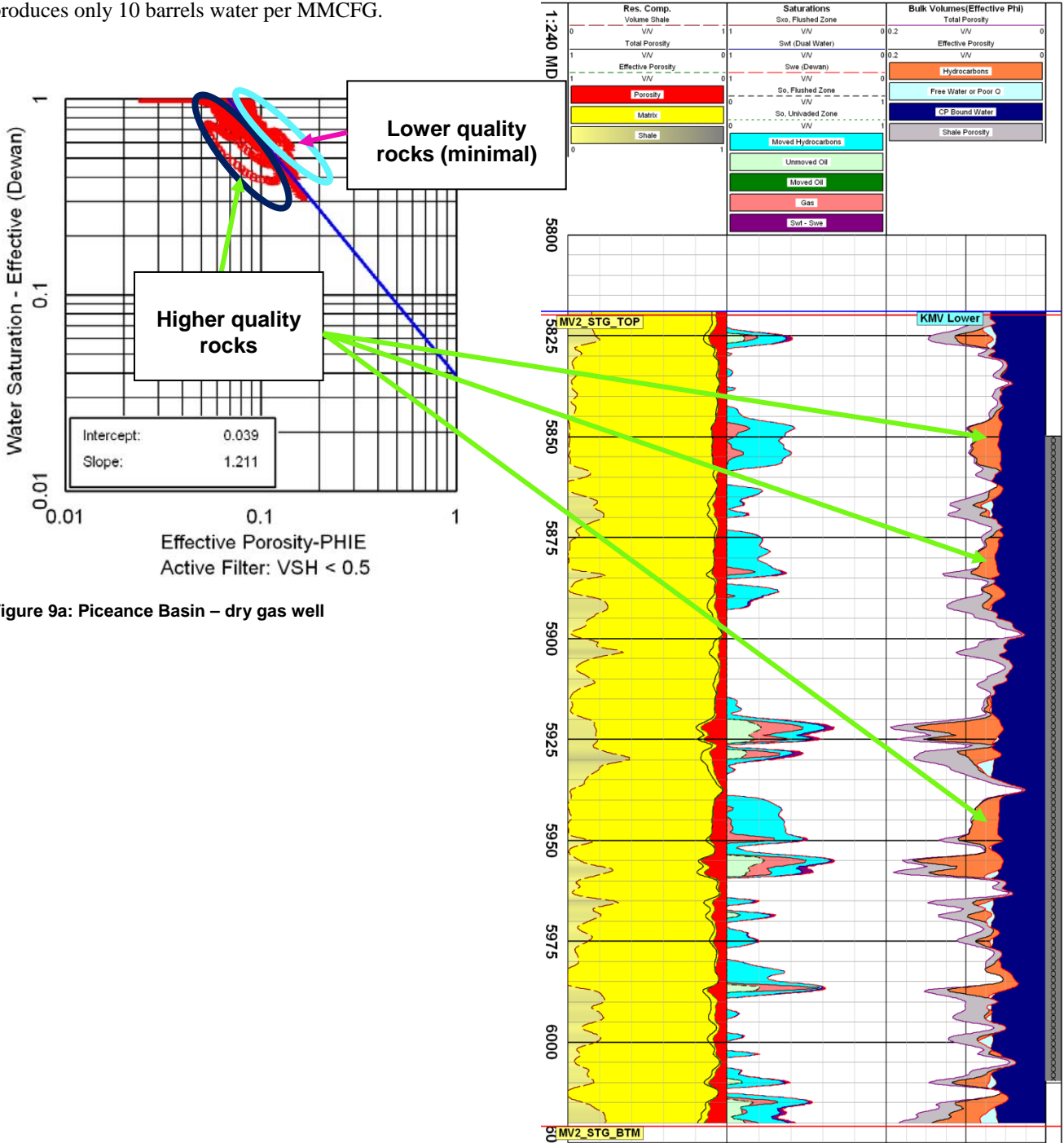


Figure 9a: Piceance Basin – dry gas well

Figure 9b: Piceance Basin – dry gas well

Example 4 is from the Travis Peak, East Texas.

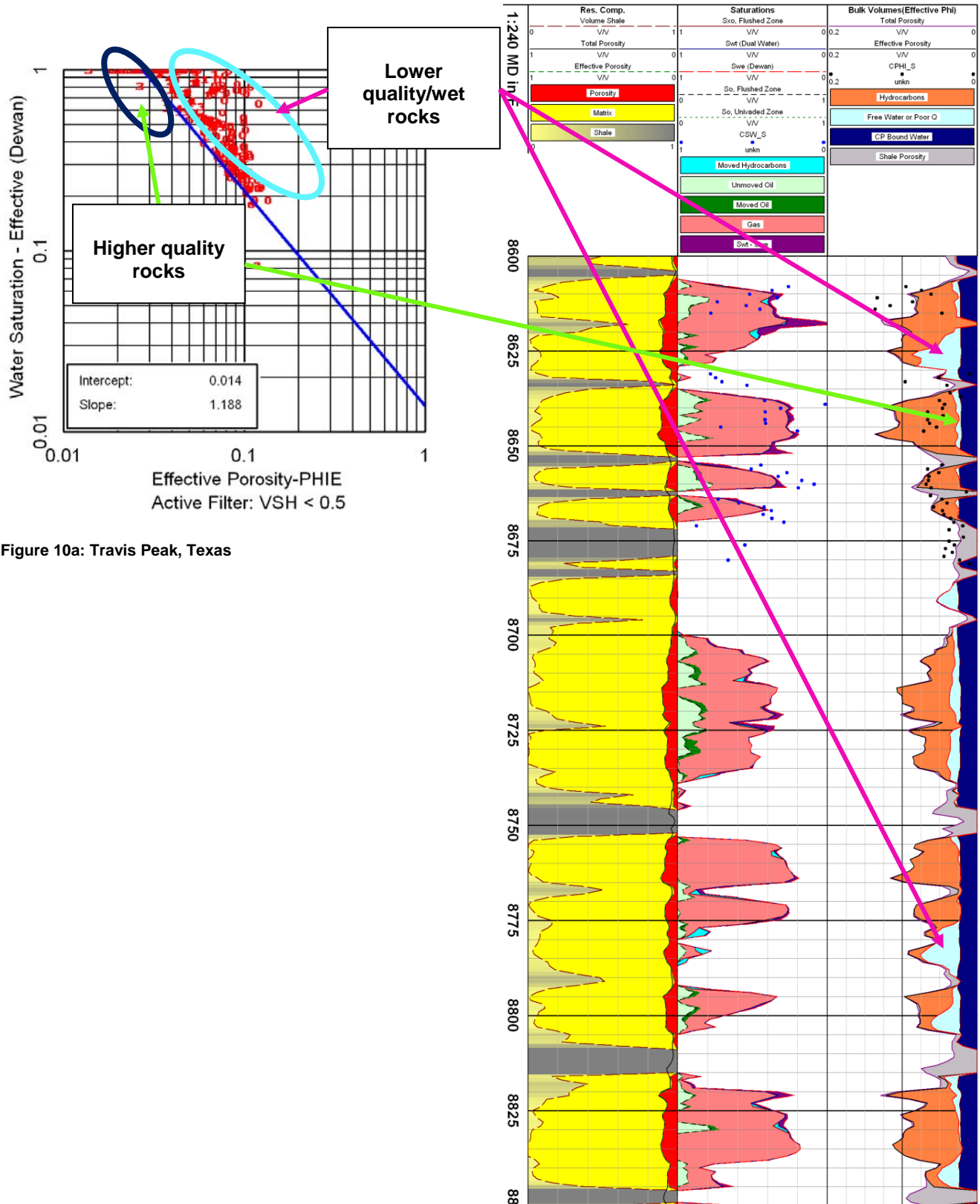


Figure 10a: Travis Peak, Texas

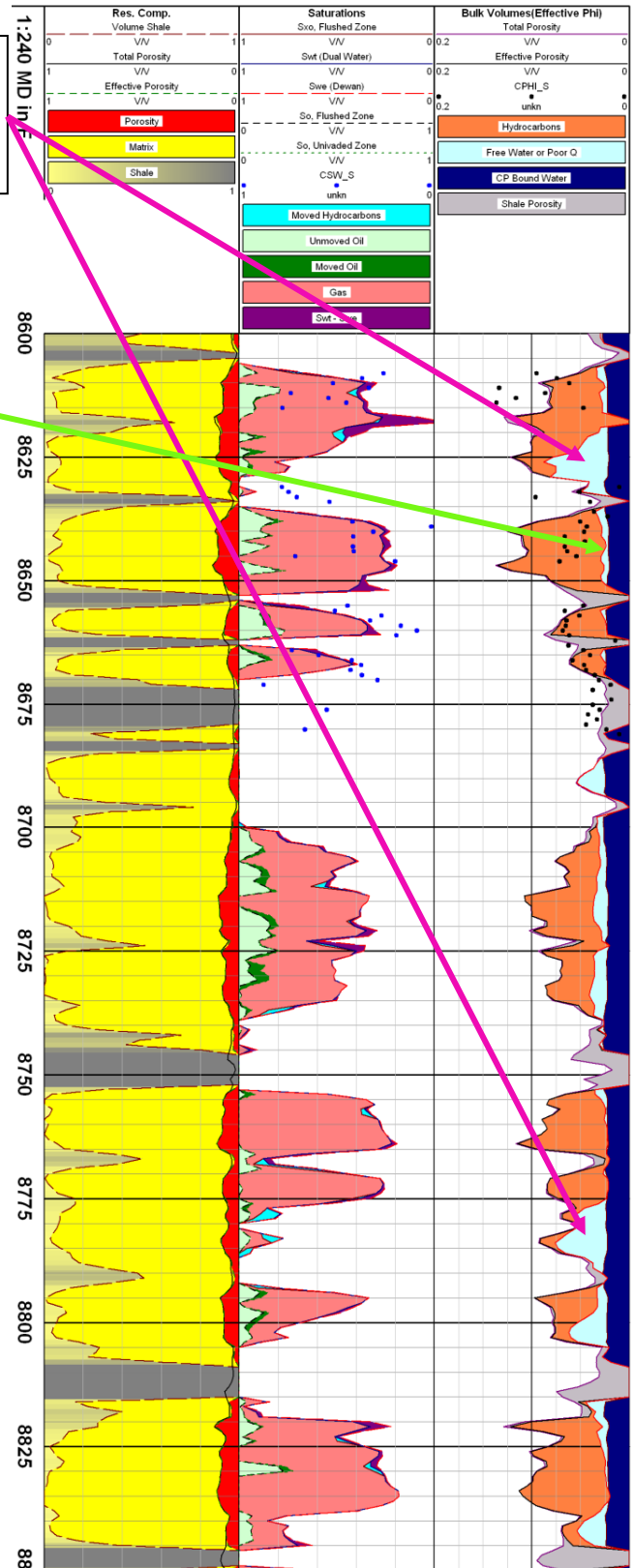


Figure 10b: Travis Peak, Texas

SUMMARY

Examination of relationships between porosity and irreducible water saturation, both from petrophysical analysis and core measurements, shows that an equation of the form:

$$\text{Porosity}^Q \times \text{Irreducible Saturation} = \text{Constant}$$

is appropriate.

Prior studies have assumed that the exponent is always unity. Data presented here suggests that the exponent is often greater than one, often in the range 1.1 to 1.3.

By presenting data on a log-log graph, it is simple to choose both the exponent and the constant. This is accomplished by interpreting data to the lower left of the plot to represent the best quality reservoir at irreducible water saturation. Data points that diverge (higher S_w at any one porosity) are then interpreted to be either poorer quality rock or to contain mobile water.

Comparisons of core porosity with core water saturation can be used to distinguish rocks with different porosity/permeability relations. Such distinction helps in understanding dispersion of data. Extrapolation to log data allows for application of different porosity/permeability transforms, as related to changing rock quality. Examples from 2 Rocky Mountain tight gas sands – show that porosity/permeability relations for the different rock quality categories are reservoir-specific.

For petrophysical applications, interpretational algorithms have been developed to distinguish between bulk volumes of water at irreducible water saturation (capillary bound water) and potential mobile water/poorer rock quality. Depth plots show these variations, level-by-level. By comparing porosity/water saturations from petrophysics with core data, it is possible to determine whether the core water saturations are at irreducible, or if they have increased due to invasion by mud filtrate.

Petrophysical examples were presented from two tight gas provinces – Piceance Basin, Colorado, and East Texas. Interpretations involve distinguishing between capillary bound water and potential mobile water/poorer quality rocks, and relating to reservoir production of water accompanying the gas.

ACKNOWLEDGEMENTS

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