Interpretation of Shaly Sands

Kenneth Heslop (LogX Inc.) and Alan Heslop (Anadarko Canada Corp.)

Shaly sands, as the name infers, are sands with a shale component. These shales are a very significant component of shaly sand reservoirs. Increased volumes of shale decrease the effective reservoir capacity. At the same time, the conductive shales reduce the formation resistivity, and, if not corrected for, the hydrocarbon volume calculated. A major task for the petrophysicist is to determine the effects of shale upon porosity, permeability and fluid saturations.

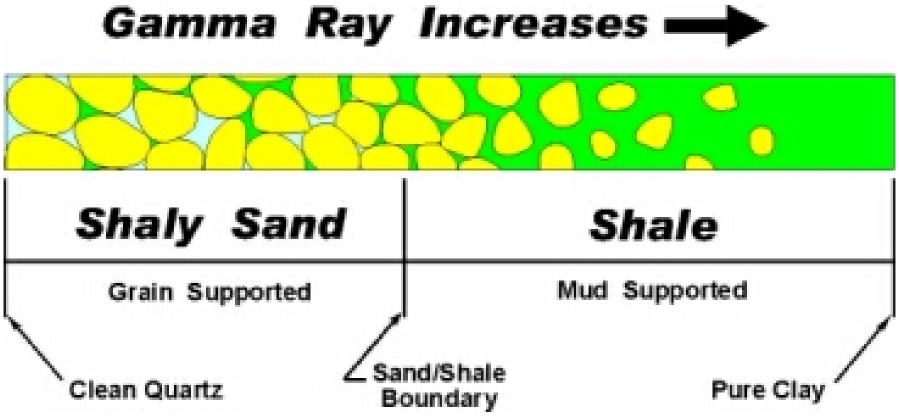

Figure #1: Sand/Shale Continuum

Consider a reservoir continuum from clean sand to pure clay. Such a continuum is illustrated in Figure #1. Moving from left (clean sand) to right (pure clay) the clay volume is increased until all of the available pore space has been filled. Up to this point the reservoir is grain supported. Moving further to the right, the addition of clay displaces sand grains. The formation is now mud supported with sand grains as inclusions. The boundary between grain supported and mud supported rock is the sand/shale boundary.

In the illustration above we are describing a dispersed clay within a sand matrix. Two other forms of shales exist in shaly sands: laminated and structural shales. A shale laminate within a sand will look just like a very shaly sand or a shale on the logs, and can be treated as such. Structural shales are shale grains within the sand matrix. Since these grains are part of the supporting matrix, they will function just as a sand grain, and will appear much like a sand except on the gamma ray log.

The gamma ray log is the most common shale volume indicator. This log responds to the changes in natural gamma radiation emitted by the formation. In shaly sands the level of gamma radiation emitted is generally a function of clay volume only. The gamma ray log does not measure the volume of silts or other inclusions within the shales. Although the gamma ray log is often the best shale indicator available, it is not definitive in identifying the sand-shale boundary by itself.

Above we said that gamma radiation was generally a function of clay volume only. One exception that should be kept in mind is the case of radioactive sands. In this case, the sands will appear shaly on the gamma ray, but will still respond as sands on the neutron and density logs. In western Canada, the Granite Wash and Gilwood formations are good examples where this occurs.

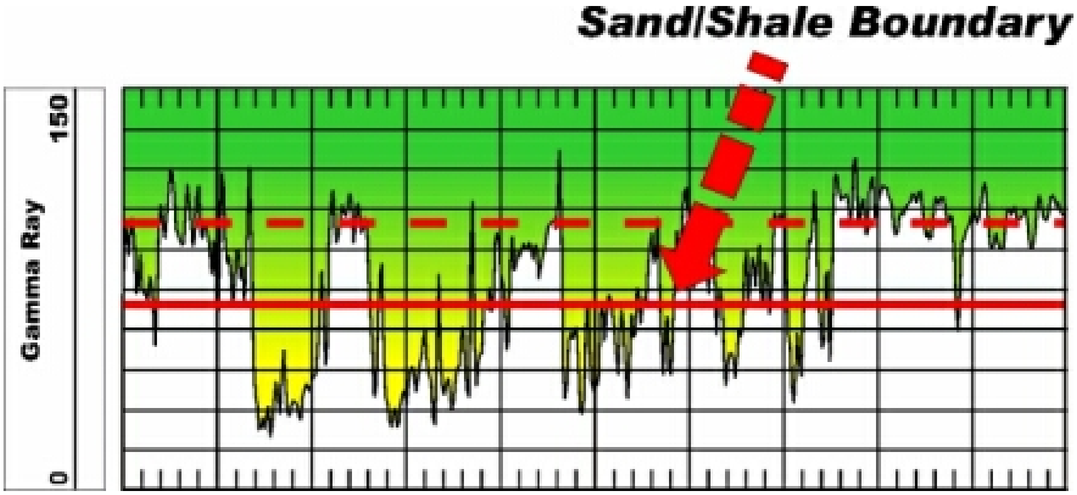

Figure #2: The Sand/Shale Boundary

It is common practice to use the maximum gamma-ray response as the shale point. However, it is known that shales can vary greatly in their composition. For example, kaolinite clays have a relatively low gamma ray response; yet can fill the available pore space. Sands with kaolinite clays will have a lower gamma ray sand-shale boundary response than other shaly sands. It is therefore more accurate to identify the gamma-ray response at the sand-shale boundary. (See Figure #2) Several log combinations may be used to determine the sand-shale boundary. Experience has shown that the neutron, density and resistivity logs used in combination with the gamma ray log are best suited for this purpose.

Each porosity log responds to shales and shaly sands in a different manner. A cross-plot technique is used to determine the porosity log responses for each shaly sand formation. Incorporated into this technique is an understanding of the physical principles behind the porosity log measurements.

The neutron log is measuring the hydrogen population of the formation. Therefore, it records a nearly constant response through sands (Figure #3) and increases in shales. Since the population of hydrogen is nearly the same in water, oil, and wet clay, the neutron log cannot distinguish between them.

In the shale portion of the shaly sand, the quartz fraction is not in grain-to-grain contact and the clays form the matrix. Hydrogen population is therefore no longer controlled by the pore distribution. The neutron log then measures increased hydrogen as the clay volume increases.

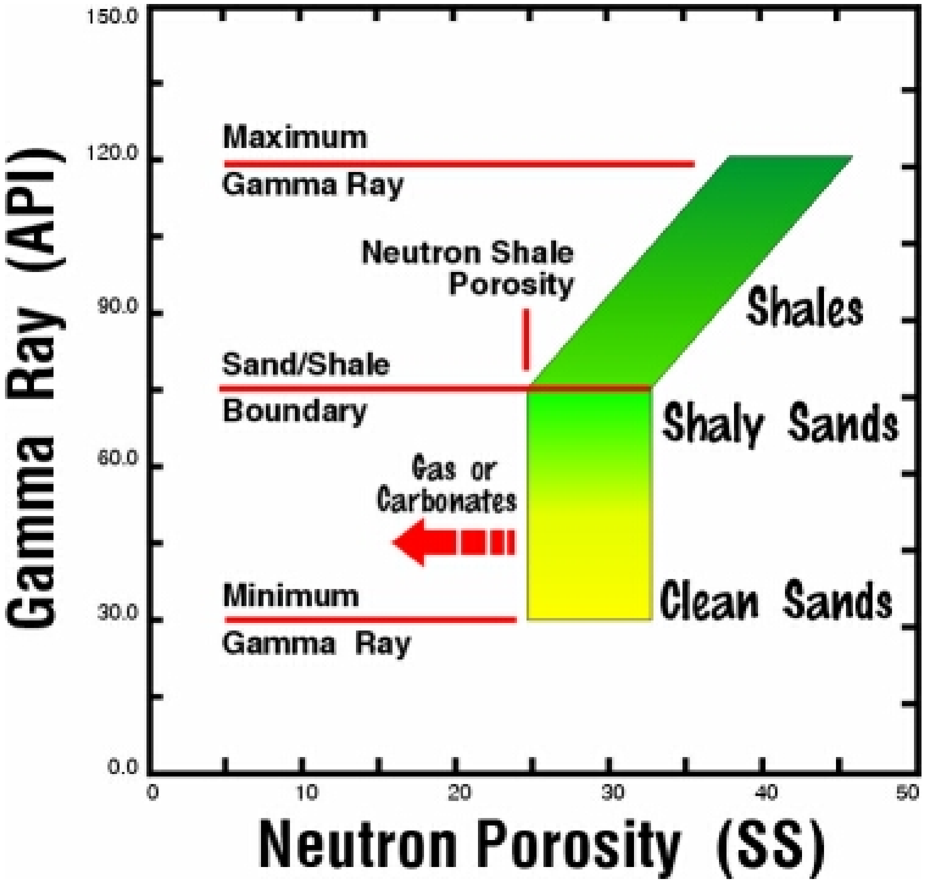

Figure #3: Neutron versus Gamma Ray Cross-Plot

As sand becomes increasingly shalier, fluids in the intergranular pore spaces are displaced by clay, and the bulk density increases as the gamma ray level increases. (See Figure #4) When the intergranular pore space is filled with a heavy mineral forming a cement, the density increases but the gamma ray response is constant. In shale, however, the bulk density remains nearly constant since an increase in the clay volume displaces quartz, which has a similar density.

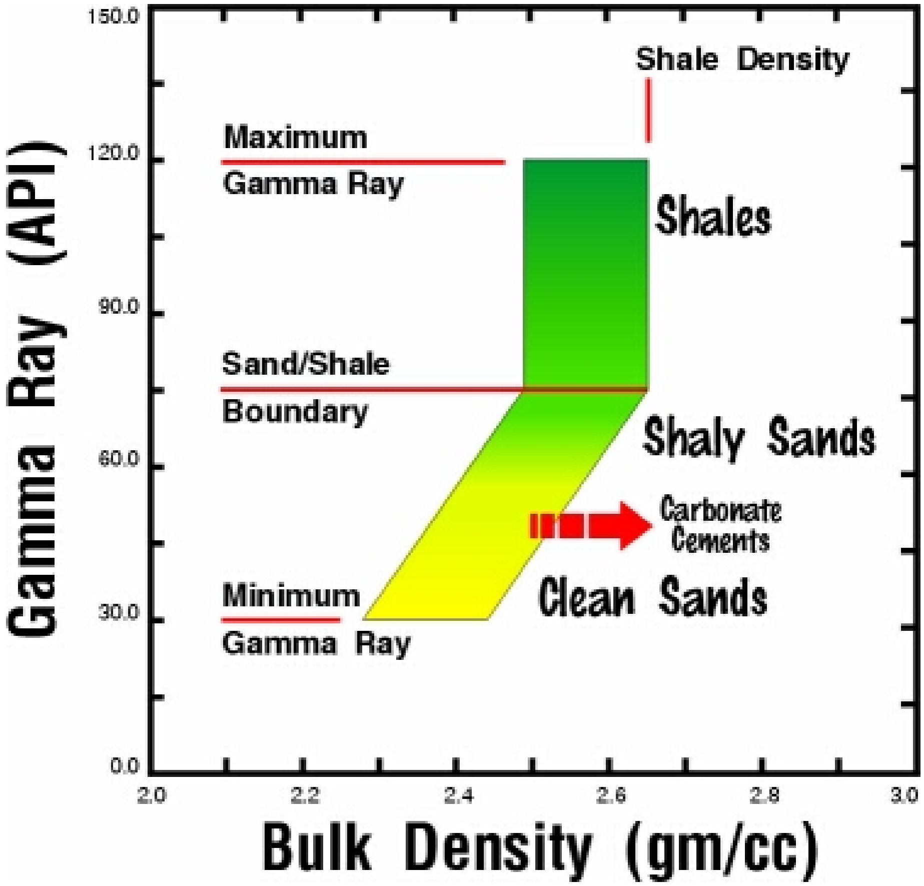

Figure #4: Density versus Gamma Ray Cross-Plot

The combined responses of the neutron and density logs clearly distinguish between sands and shales. On a cross-plot of neutron versus density (See Figure #5) three points can be defined: the Quartz Point which is at 0% porosity on a neutron sandstone scale, and the quartz grain density (which is usually taken to be 2.65 gm/cc); the Water Point defined by the neutron and density responses to formation water (typically 100% porosity and 1.0 gm/cc); and the Shale Point determined by the neutron and density shale responses selected from the previous cross-plots. The Clean Sand Line connects the Quartz Point and the Water Point. The Shale Line joins the Quartz Point and passes through the Shale Point. The typical shaly sand response will be a lobe of data vertically between the Shale Point and the Clean Sand Line, with the cleanest sands obviously nearer to the Clean Sand Line. The effect of gas or rough borehole will be to shift the data across the Clean Sand Line. Cementation will tend to shift the data to the left on the cross-plot. Shale data will form a lobe of data along the Shale Line to the right of the Shale Point.

Understanding the neutron and density responses, and their relationships as seen on the neutron / density cross-plot, is very helpful in cases where the sands are partially radioactive. In such cases, the correct sand/shale boundary responses can be determined from this cross-plot alone. Therefore, correct shale volumes can be determined even when the gamma ray log has been significantly affected by radioactivity.

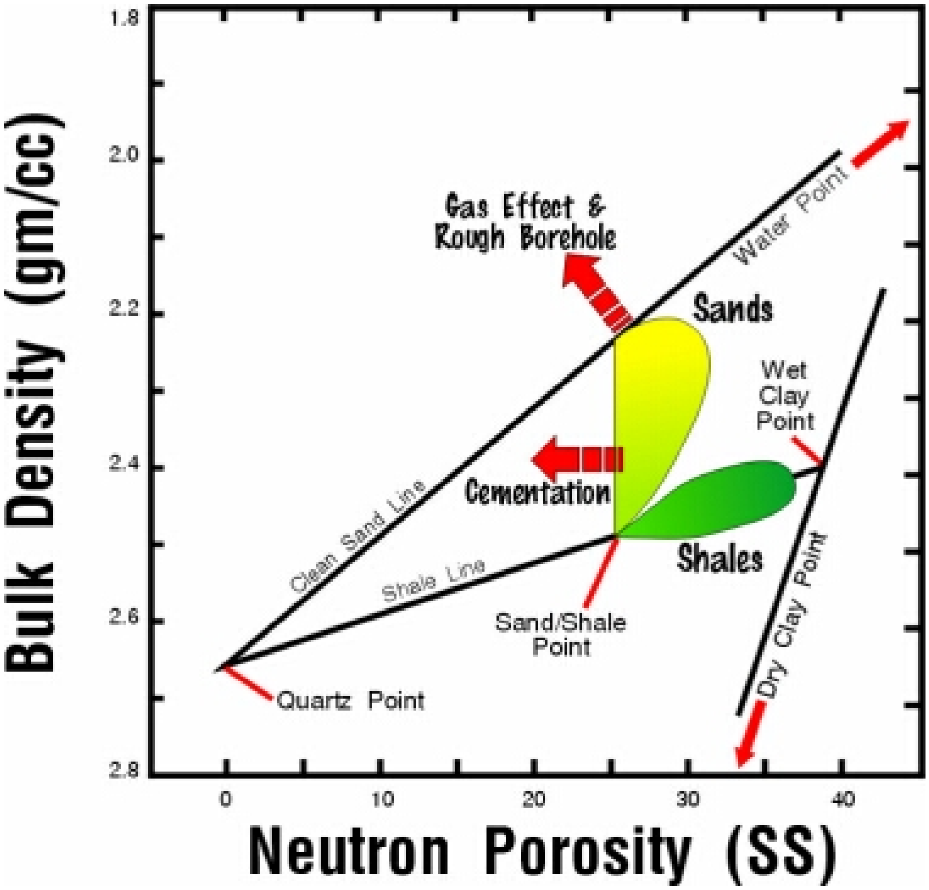

Figure #5: Neutron versus Density Cross-Plot

The acoustic transit time in sands and shales are often similar. See Figure #6. Therefore, it can be difficult to distinguish between the sand response and the shale response on the acoustic log. For this reason it is not possible to apply a model similar to that used for the neutron and density logs to the shale response characteristics of the acoustic log.

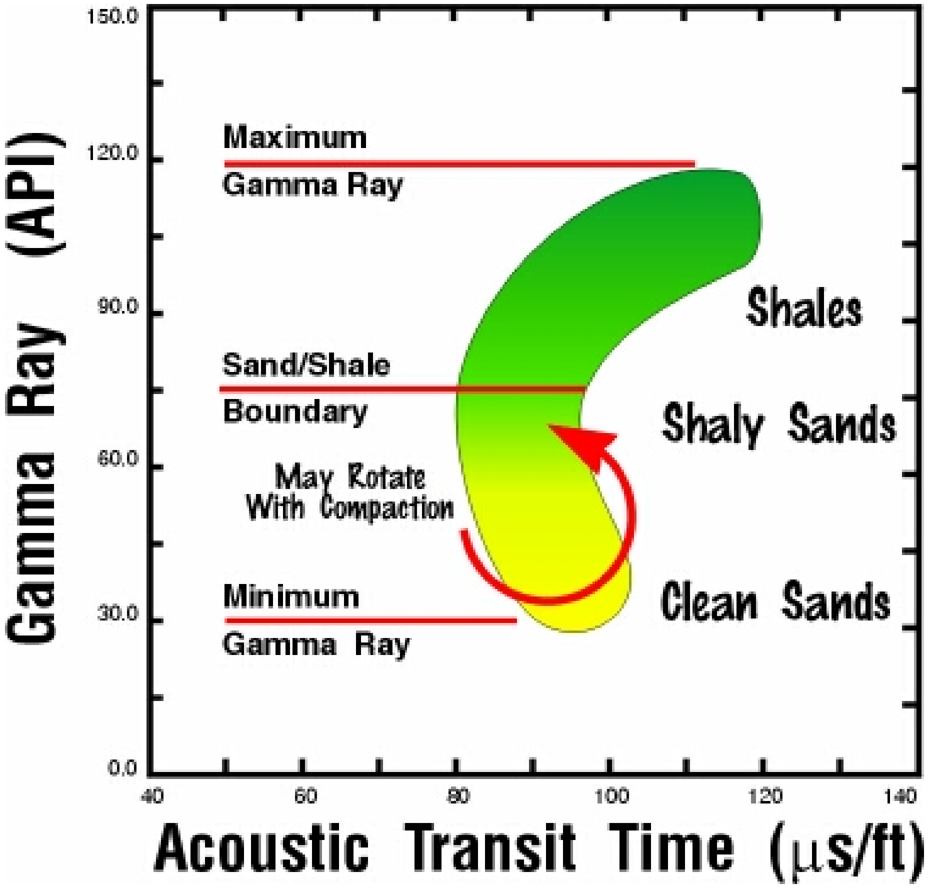

Figure #6: Acoustic versus Gamma Ray Cross-Plot

The resistivity response for shales of common depositional environment is generally constant. It is quite common to observe shales with varying clay contents, as identified by the gamma ray log, which have a constant resistivity response as seen in Figure #7. Shales are a clay matrix with quartz and other minerals as inclusions. These inclusions are much more resistive than the clay matrix. Based upon the electrical theory for parallel circuits it can be concluded that these high resistivity inclusions will have very little effect upon the total resistivity of the shale. Variations in the volumes of these inclusions will also have little effect upon the resistivity.

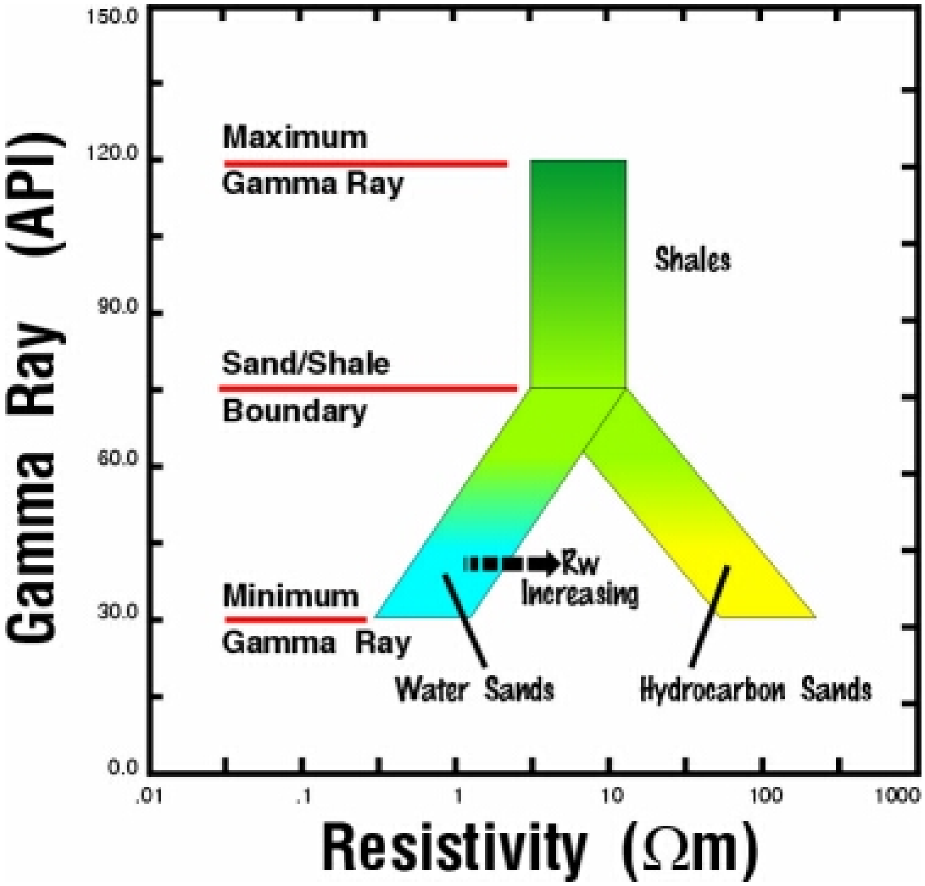

Figure #7: R_t versus Gamma Ray Cross-Plot

Understanding and comparing the responses from a suite of logs allows you to build a shaly sand model that correctly determines the shale content, and its effect upon porosity, permeability, and fluid saturations. In addition, you can build upon this model to handle cases where the shales either above or below the sand are different from that contained within the sand, or where other inclusions such as calcite cements are present.

Case Study – Canadian Arctic Example

The example we present here is from the Mackenzie Delta, in northern Canada. This was a discovery well, with gas tests in excess of 30 mmcf/d. Gas was tested in a number of sands, but in this paper we present just a few of those sands.

On a cross-plot of the bulk density versus gamma ray (Figure #8) we can identify the clean sands at approximately 2.40 gm/cc bulk density, and 45 API units gamma ray. Following the data trend, we find the density increasing as the sands become shalier, finally reaching the sand/shale boundary at a density of 2.59 gm/cc, and 85 API units on the gamma ray. There is a scattering of data towards the left side of the plot. This data represents the density tool response under bad hole conditions. Note also the data points trending to the right of the sand data. These represent calcite cements in the sands.

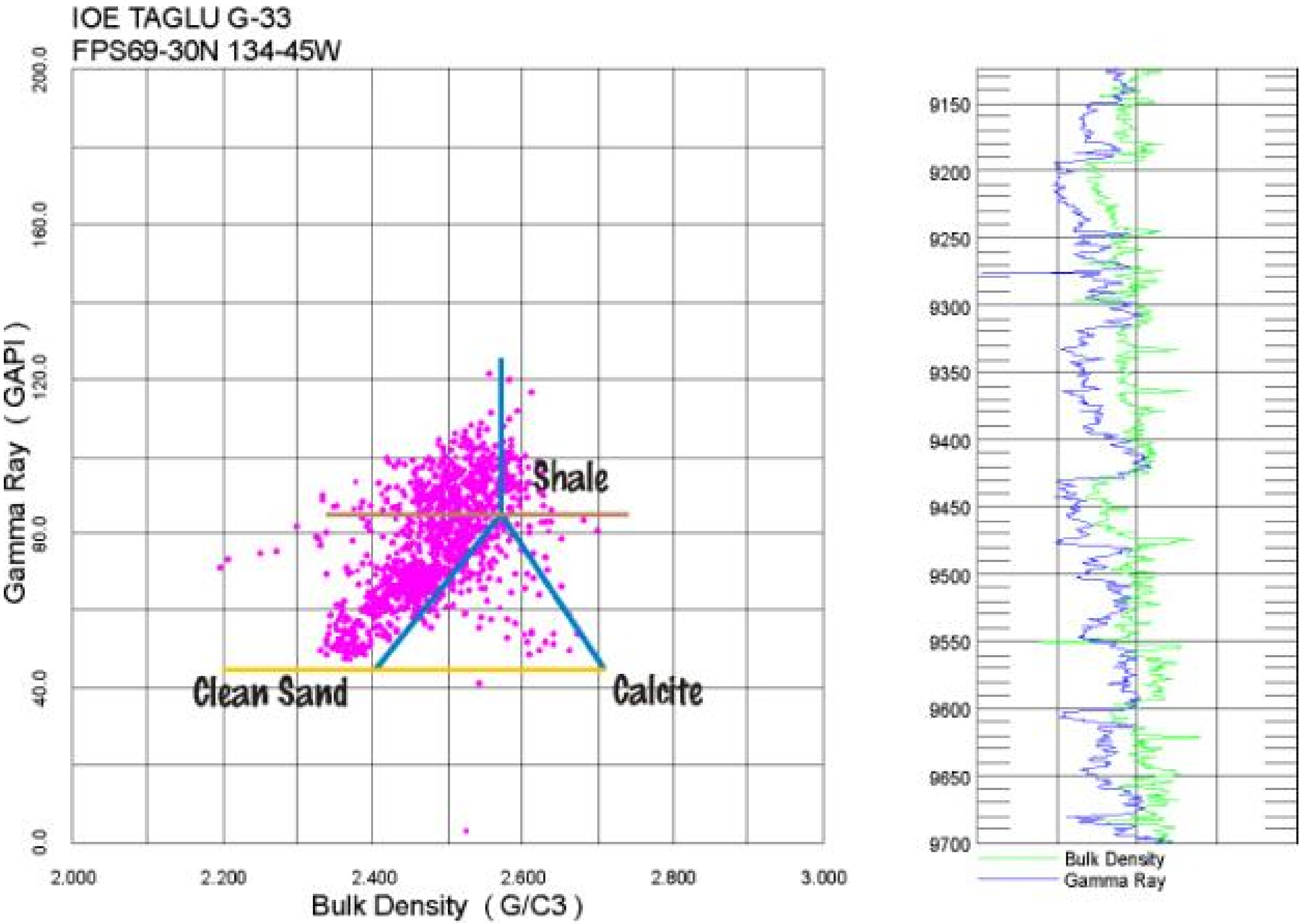

Figure #8: Bulk Density vs. Gamma Ray – Canadian Arctic Example

The data trend on the neutron versus gamma ray cross-plot (Figure #9) is a nearly constant neutron response of 15 percent porosity from the clean sands to the sand/shale boundary. The data points trending left to 5 percent porosity represent the sands with calcite cements.

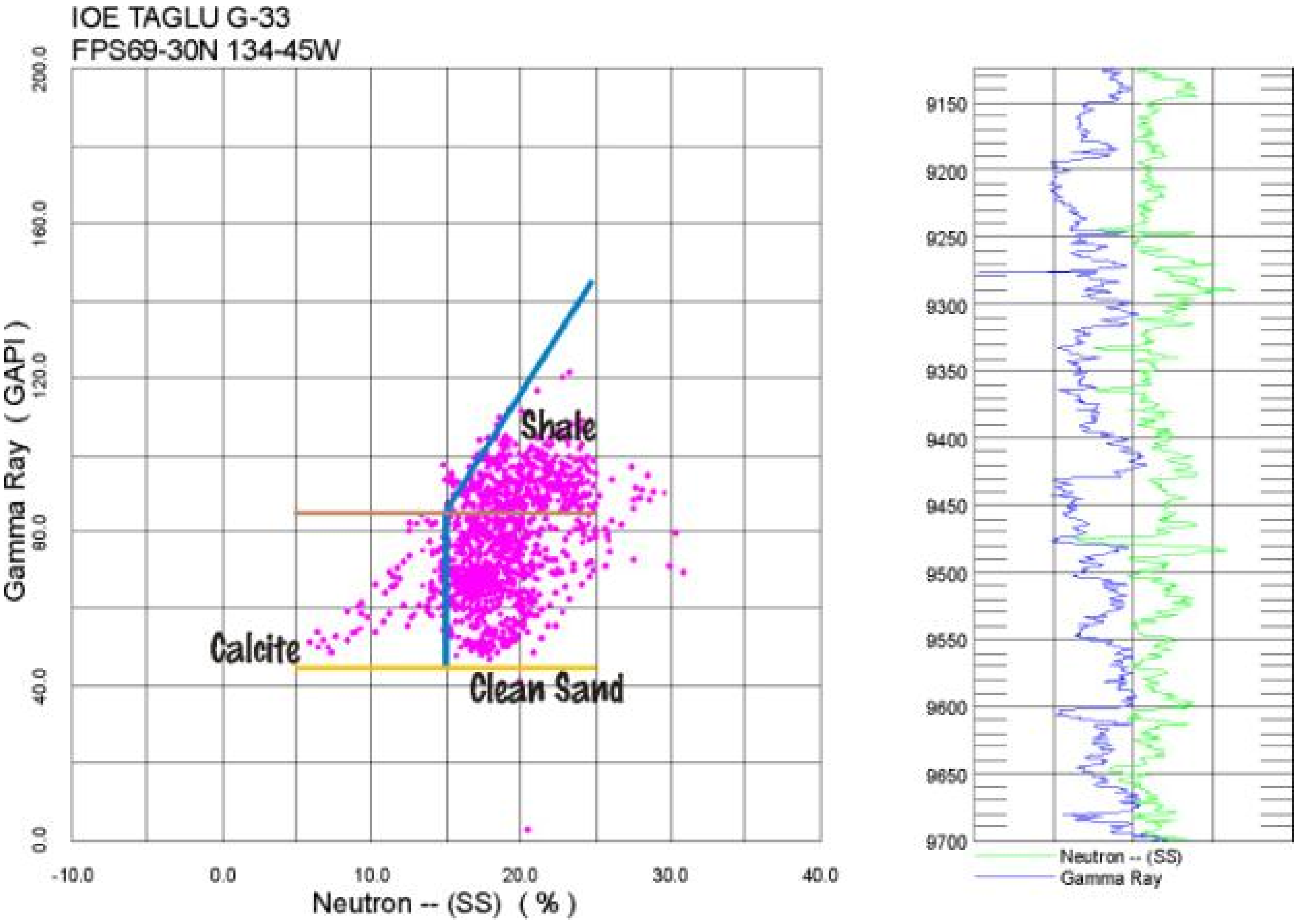

Figure #9: Neutron vs. Gamma Ray – Canadian Arctic Example

Combining the neutron and density responses into one cross-plot, we can see the sands and shales separating into two distinct trends. On the neutron versus bulk density cross-plot (Figure #10) the shales follow a trend of data to the right of the sand/shale boundary identified from the previous two cross-plots. The sands follow a trend straight up from the same point towards the clean sand line.

Different depositional environments will influence the radioactivity level observed on the gamma ray. Marine shale will have higher radioactivity than continental shale, due to the higher level of organics in the marine shale. But the sand/shale boundary can always be determined from these cross-plots, even though the base level of radioactivity changes.

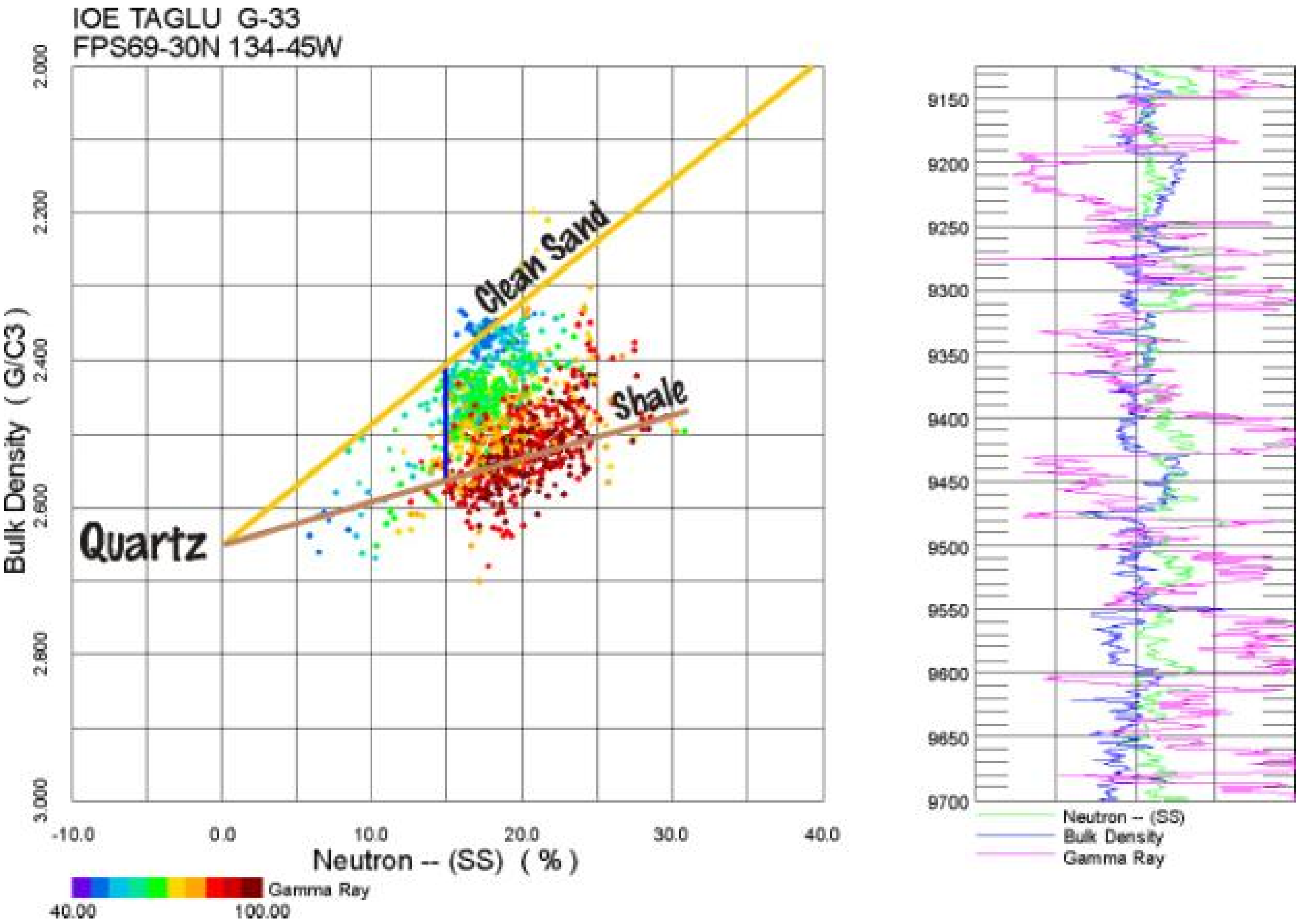

Figure #10: Bulk Density vs. Neutron – Canadian Arctic Example

Figure #11 is a plot of the analysis results obtained using this shaly sand model. This well was drilled in 1971, and numerous sands tested gas at substantial rates. The upper sand in this example (9190' to 9248') flowed nearly 10 mmcf/d on DST#6. The sand from 9317' to 9360' flowed approximately 6 mmcf/d on DST#5. Some of the up-hole sands tested even higher gas flow rates, with one sand testing over 30 mmcf/d of gas. However, the remote location, and distance from any gas pipeline, has meant this well remains shut-in to this day.

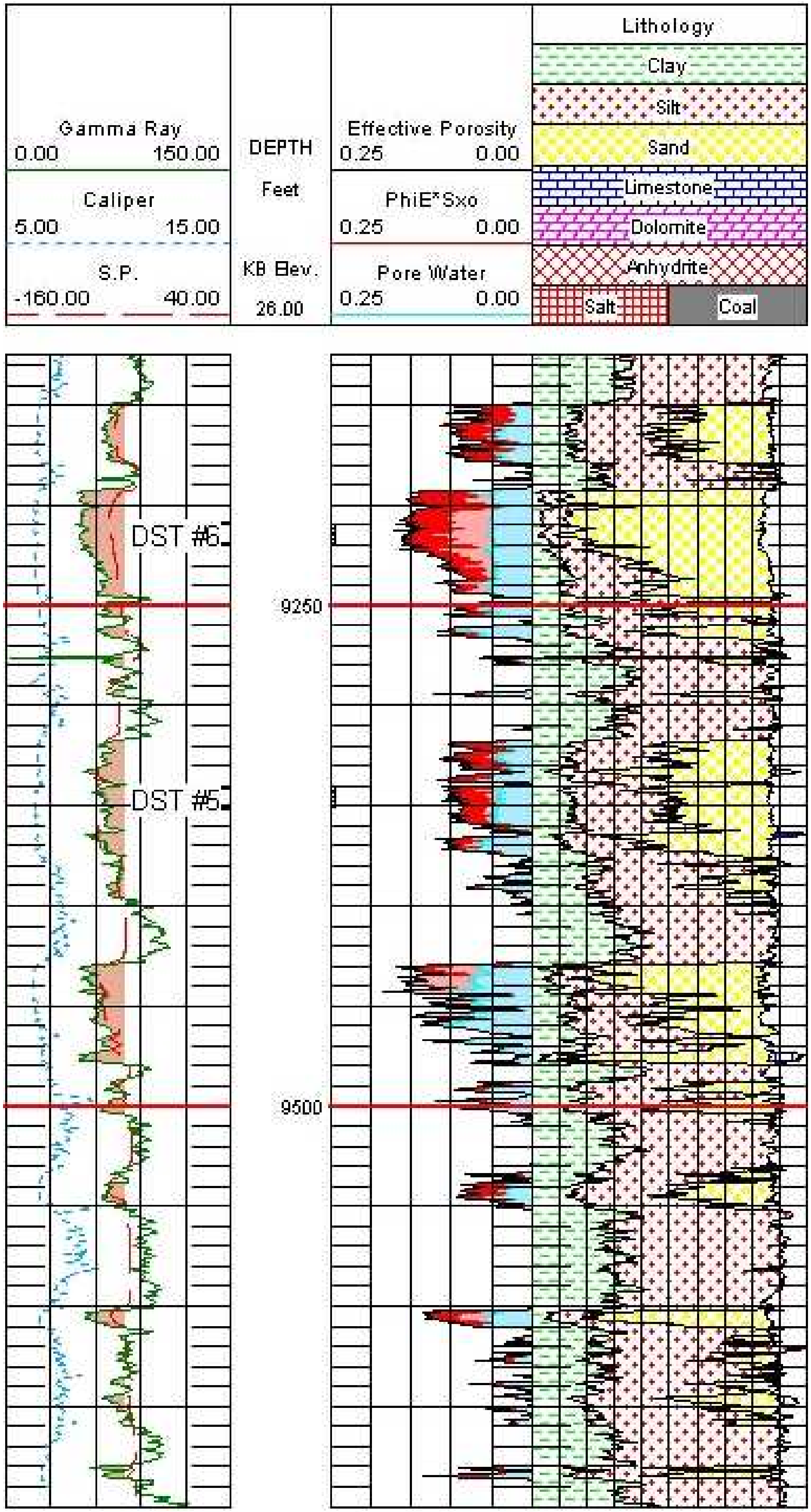

Figure #11: Shaly Sand Interpretation – Canadian Arctic Example

The data for this case study is available as a free download. Click here. The authors want to set an example of making the data used publicly available, allowing others to work with it on their own to verify their results. They believe that this should be an industry practice, especially when using the internet to publish reports.

Response to the Clay Point Challenge

In the June issue of Dialog we were given the challenge to identify the clay point in the following illustration.

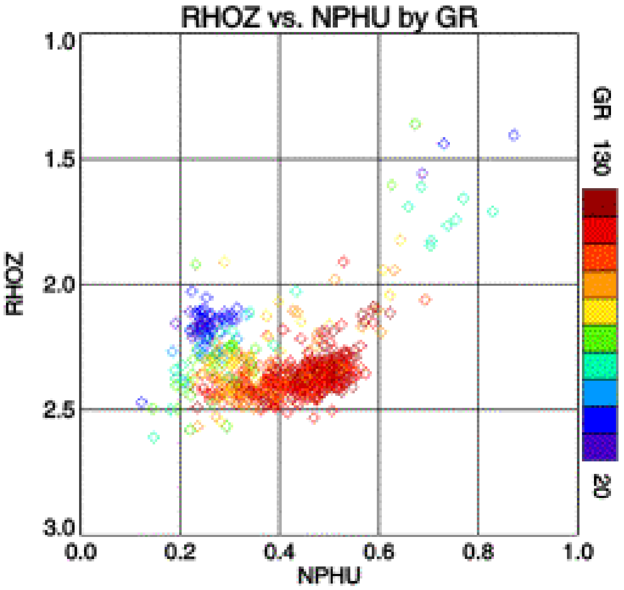

Figure #12: Clay Point Challenge

We note that the question posed left room for much conjecture and required assumptions on the part of the reader. Nothing stated that this was a shaly sand example, nor whether this data was presented in sandstone units. For those familiar with shaly sands, it was quite apparent that this example appeared to be data from a shaly sand. We have noted the confirmation that the data presented was in limestone units, as shown by the Sand point being placed at –3 percent porosity in the solution given in the September issue of DiaLog.

The greatest cause for conjecture in the question posed was this: which “clay point” was the author looking for? If he were looking for the log response of the naturally occurring clays, the “wet clay” point would be the answer. But, if it were the clay mineral response he had in mind, the “dry clay” point would be the solution requested.

In the September issue of DiaLog, the correct “clay point” was given as a bulk density of 2.35 gm/cc and a neutron porosity of 0.52. In explaining this solution, the following illustration (Figure #13) was given:

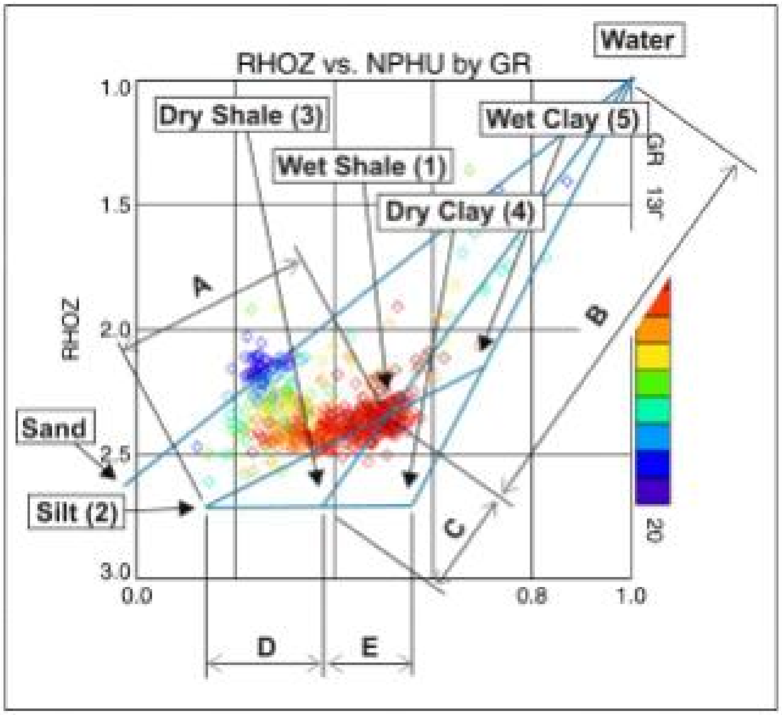

Figure #13: Clay Point Solution – DiaLog, September 2001

According to this illustration, and the text that was attached, 2.35/0.52 was not the correct answer, even though that is the answer declared correct. The author called that point the "Wet SHALE" point, not the "Clay Point" that was requested. Using his interpretation and nomenclature, the correct answer should have been 2.14/0.70. Alternately, if he had wanted the "Dry Clay" point, the answer should have been 2.70/0.57. Both answers would have satisfied the request to identify the Clay point. Either way, the answer deemed correct is shown to be incorrect by the author's interpretation and nomenclature.

However, in considering this example we should look deeper at the assumptions made. First, the entire solution hinged upon the selection of the “wet shale point”. (This is the point that was declared the correct “clay point”.) At this time we will not take issue with the selected “wet shale point”, because it may have been required in the model the author was using. There is no apparent reasoning for the selection of the point, other than perhaps the author’s intuition.

The next point in the described process was the identification of the “silt” point, defined by projecting back down the “silty shale” part of the boomerang to a grain density defined from core data. We will suggest that at this point considerable “interpretation” and potential error has already been introduced. Silt is a size classification defined as less than 62.5 microns and greater than 3.9 microns. In a shaly sand depositional environment, one would expect the sand-sized grains and the silt-sized grains to have a common geological source. What the author has described is a geological matrix consisting of quartz sand, a “silt” of unknown composition, but apparently heavier than quartz, and clays. But does this interpretation fit the data? Let us suggest that a better fit to the data could be obtained. Figure #14 is given by way of illustration.

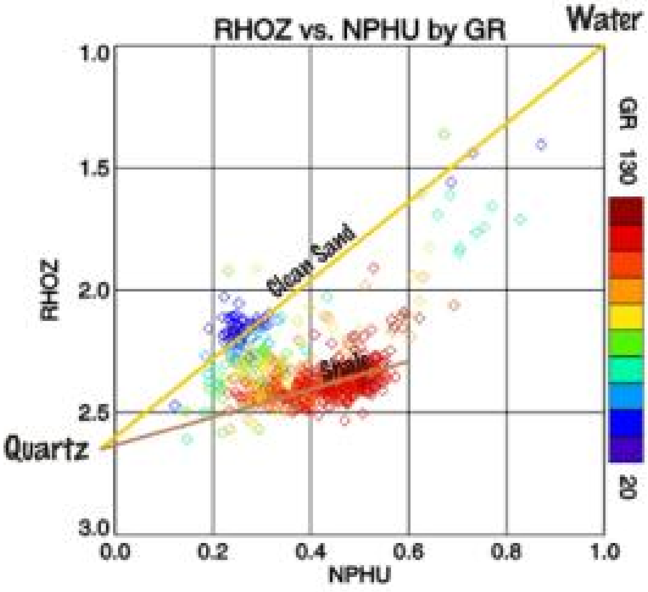

Figure #14: Another View of the Shale and Silt Response

Note that the “shale line” passes through the middle of the shale data. Keep in mind that shale is a mixture of clay minerals and rock particles of various sizes, but predominantly of silt size. Without reasonable cause to do so, it would be odd to assume a silt of different composition than the associated sand. Experience has shown that it is far more reasonable to assume that the silt-sized particles are of the same composition and source as the sand-sized particles. Therefore, it is entirely reasonable to expect the “silt point” would be the same as the “sand point”, which we would call the “quartz point”. The manner in which the “shale” line fits the shale data confirms this assumption.

As an aside, we suggest that the author of the Clay Point challenge consider whether the heavier density material in his core data may have been calcite or other carbonate cements.

We recognize that the author described the silt as “a hypothetical material” needed to get the correct grain density and porosity from his three-component model. Defining geological components according to the requirements of a mathematical model is an odd way to begin.

The interpretation process was further described such that the “dry shale” point was projected from the “silt point” by the amount of the total shale porosity, as interpreted from the NMR. This is a curious method. One might assume that the NMR would record the total porosity of wet shale, since that is how it occurs naturally. Why then should we define the “dry shale” point as having the density of silt and the hypothetical porosity silt plus the total porosity of wet shale? We know of no valid reason for this assumption. Nor, we might add, is there a valid reason to also conclude that the dry clay has the same density as silt.

Finally, the author connected the “dry clay” point to the “water” point, and defined the “wet clay” point as the intersection of the shale line with this new line. Having already noted our contention with the selected “dry clay” point, we do agree that the “wet clay” point is defined by the intersection of these two lines, as illustrated in Figure #15 below:

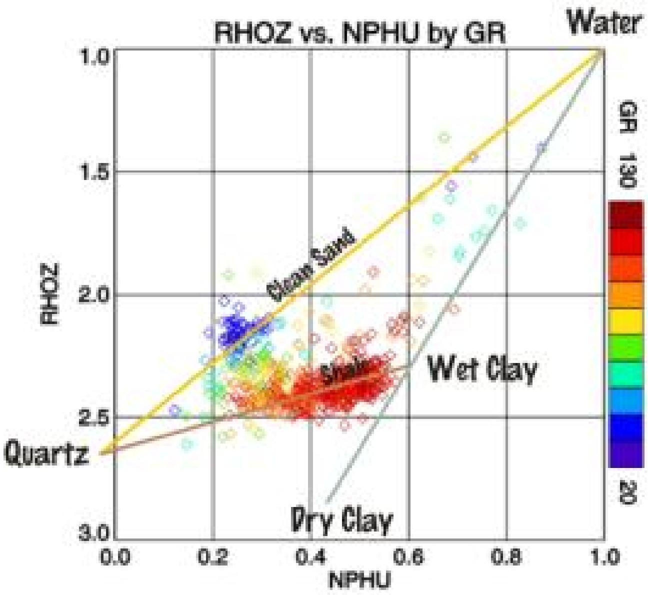

Figure #15: Dry and Wet Clay Points Defined

Given the variety of data the author had for this well, we wonder whether he considered identifying the clay types by their mineralogy, or through thin-sections. From the clay types one could define the “dry clay” point, based upon known clay mineral responses. If such data were not available, one could reasonably define a “dry clay” point as we have here, such that the “wet clay” point is just beyond the limits of the shale data.

We would encourage the author of the Clay Point Challenge to make the data for his example well available for further discussion of this important topic.

For further information or discussion, contact:

Kenneth Heslop, LogX Inc., Petrophysical Consultant kenneth.heslop@logx.ca

Alan Heslop, Anadarko Canada Corp., Petrophysical Advisor al_heslop@anadarko.com

top