A Deterministic Lithology Model for the Green River-Upper Wasatch Interval of the Uinta Basin*

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Abstract

Log evaluation of the clastic and carbonate lithologies in the Green River and upper Wasatch formations of the Uinta basin is complicated by the complex mineralogy and thin interbedding of diverse rock types. Simple zoned models smooth out the differences to yield porosities and saturations that may on average be correct, but misleading on a bed-by-bed basis. Probabilistic or stochastic approaches have been advocated for this area, but suffer from a lack of transparency, require specialized software and expert users, and require advanced logging measurements such as elemental capture spectroscopy logs to solve the problem. Although appropriate for an operator with a large formation evaluation budget and full access to all logging data run in a well, probabilistic methods do not work as well with public domain data or for mapping large areas with incomplete competitor data. We present a simple, deterministic 4-mineral solution consisting of quartz, calcite, dolomite, and "mixed clay" without attempting to derive the minor mineral components or individual clay species. The solution only requires the four basic logging measurements that are widely available: gamma ray, density, neutron porosity, and Pe. The solution does require one significant simplifying assumption: there is no dolomite in the shaly fraction of the interval; it only exists in the clean formation fraction. We then solve two triangles in apparent matrix density (RHOMAA) – apparent photoelectric cross-section (UMAA) space: 1) for clean (non-shaly) rocks the quartz-calcite-dolomite triangle; and 2) for shaly rocks, the quartz-calcite-clay triangle. These are solved using a gamma ray filter to separate clean from shaly formation solutions followed by a matrix inversion approach of 3 linear equations for each branch. The results are re-normalized to sum to 1 without any negative components, and are filtered for bad hole or other adverse logging conditions. The proposed approach yields lithology solutions very similar to logging vendor supplied multi-mineral solutions in terms of bulk mineralogy. Mineral endpoints are easily adjusted by the user as the "quartz point" drifts in rocks with high feldspar contents, or if the clay point drifts regionally. Organic matter and in many cases pyrite can also be determined in a subsequent step. The method can be implemented in a general-purpose software package (e.g. Petra, GeoGraphix) or in Excel.

Introduction

The Green River and upper Wasatch formations of the central Uinta basin consist of over 1000 feet of interbedded lithologically complex fluvial, deltaic and lacustrine sediments. While the Wasatch is primarily siliciclastic, the Green River contains both limestone and dolostone in

addition to sandstone and shale. The heterogeneous nature of this succession complicates petrophysical evaluation because the beds are too thin and numerous to be treated individually, but the entire section is too variable to be treated as a single entity. In order to calculate an accurate porosity in such successions, it is essential to first determine the lithology on a foot-by-foot basis. Some companies have solved this problem using probabilistic or stochastic models but these require specialty logs not available for most wells, and specialized software.

We present a simple, deterministic 4-mineral solution consisting of quartz, calcite, dolomite, and "mixed clay" without attempting to derive the minor mineral components or individual clay species. The solution only requires the four basic logging measurements that are widely available: gamma ray, density, neutron porosity, and Pe. By restricting the required inputs to only four basic log measurements, we simultaneously increase the pool of available wells and decrease the amount of work required to vet the log quality prior to running the model. Due to its transparency, the operator knows exactly how the lithology is calculated and can alter the method to fit different lithologic regimes.

Method

While there are numerous mineral identification crossplot techniques available, the RHOMAA (apparent matrix density) vs. UMAA (apparent matrix photoelectric cross-section) crossplot is the most diagnostic. RHOMAA and UMAA are calculated by Equations 1 and 2, respectively:

$$\text{RHOMAA} = \frac{\rho_b - (\phi_{ND} * \rho_{fl})}{1 - \phi_{ND}} \tag{1}$$

$$\text{UMAA} = \frac{(Pe * \rho_b) - (\phi_{ND} * U_{fl})}{1 - \phi_{ND}} \tag{2}$$

where:

ρ_b = bulk density (log)
ϕ_{ND} = neutron-density crossplot porosity
ρ_{fl} = fluid density
Pe = photoelectric absorption (log)
U_{fl} = photoelectric absorption of fluid

The RHOMAA-UMAA mineral identification plot determines the relative abundance of three mineral components through a ternary diagram with endpoints defined by the RHOMAA and UMAA values of the three minerals (Figure 1). Traditionally, the end point minerals are quartz, calcite, and dolomite; however, the technique may in fact be used to determine the mixture of almost any three minerals that can be plotted on the RHOMAA-UMAA plot. The mineral endpoints can be easily adjusted by the user if, for example, the "quartz point" drifts in rocks with high feldspar contents, or if the clay point drifts regionally.

Core observation and x-ray diffraction (XRD) data have indicated that the main mineral phases present in the Green River and upper Wasatch formations are quartz, calcite, dolomite, and clay (illite-smectite-mica mixture). Because a ternary diagram, by definition, provides the relative abundance of only three components, we introduce a branch point in the workflow to determine which of two ternary diagrams will be solved in order to gain the fourth mineral component. The branching is determined by gamma ray (GR). For clean intervals (GR < 70 API), we solve the quartz-calcite-dolomite ternary diagram typically illustrated in logging company chart books (Figure 1). For shaly formations (GR > 70 API) we assume there is no dolomite and solve the quartz-calcite-"mixed clay" ternary diagram (Figure 2). The "mixed clay" point is determined by the location of the data cloud in RHOMAA-UMAA space and by calibrating the calculated mineral abundances to those measured by XRD.

After determining the appropriate ternary diagram to solve, we use the deterministic matrix inversion approach described by Doveton (1994) for solving a three-component system. The result is a set of three linear equations for each of the two ternary diagrams that calculate the relative abundance, in volume %, of each of the minerals. The calculated volumes are trapped between 0 and 1 then renormalized to sum to 1. Points that fall outside of the ternary diagram are projected back onto the nearest face of the triangle resulting in a two-mineral solution for those points (Figure 3). The mineralogic outputs of the model consist of volume of quartz (VQUARTZ), volume of calcite (VCALCITE), volume of dolomite (VDOLOMITE), and volume of clay (VCLAY). Unfortunately, it is not possible to solve the four-component quartz-calcite-dolomite-clay system directly by matrix inversion because the dolomite point lies on the line between quartz and clay, thus uniquely separating dolomite from a quartz-clay mixture requires at least one additional measurement. For example, we could add a fourth equation relating the gamma ray to VCLAY instead of only using it to separate clean formation from shaly formation, but this assumes there are no radioactive components in the clean formation such as potassium feldspars or radioactive dolomites.

Once the mineral volumes have been calculated they are corrected for Vshale then used to compute a matrix-corrected grain density and finally a matrix-corrected density porosity. All of the aforementioned steps are carried out at each log depth, resulting in variable grain density and variable density porosity curves over the entire study interval. This method can be easily implemented in a general purpose geosciences software package (e.g. Petra, GeoGraphix) or in Excel. The entire workflow is illustrated in Figure 4.

As with any petrophysical evaluation, the validity of the results is highly dependent on the quality of the input data. Particular attention should be paid to the density logs, which are sensitive to hole rugosity, and to the Pe logs which can be affected by mud additives such as barite. The use of normalized logs is recommended whenever possible.

Results

A comparison to an ELAN lithology interpretation is provided in Figure 5. Overall, the two interpretations compare quite favorably, in both gross lithology and relative abundance of individual minerals. In clean intervals, both sandstone and carbonate solutions show strong similarities with the exception of Vshale, which, in the opinion of the authors, is too high in the ELAN interpretation. In shaly intervals, the primary difference is the presence of dolomite. The ELAN interpretation, which is supported by XRD data, indicates small to moderate amounts of dolomite in the shales while our method allows dolomite only in clean formations. A comparison of total carbonate in these intervals, however, shows notably similar results. There does appear to be a systematic disparity between the two interpretations in the non-

carbonate fraction of shaly intervals, and it is likely attributed to the way quartz from silt is allocated. Our method places much of this quartz in the VCLAY component, while the ELAN interpretation places it in the Quartz component, perhaps making the formation appear cleaner than it really is.

One of the main uses of the mineral solution is to compute a continuously variable grain density as a function of the mineralogy. We found this substantially improves the density porosity solution and in some cases identified high porosity pay zones that otherwise would be overlooked. Additionally, the model outputs can be summed or averaged and mapped, allowing more detailed stratigraphic and depositional interpretations of this complex section. Because the model requires a minimum log suite to implement, it can be applied to nearly all the well control in the area with publically released data. This is a significant advantage over more complex solutions that require neutron spectroscopy or other advanced logging measurements.

Conclusion

The simple, deterministic approach proposed here utilizes no exotic or specialty logs and yet yields lithology solutions very similar to logging vendor supplied multi-mineral solutions in terms of bulk mineralogy. Furthermore, the method is entirely transparent and requires no specialized software. This method has been shown effective in a wide range of geologic settings in addition to the example provided in this report.

Reference Cited

Doveton, J.H., 1994, Compositional Analysis of Lithologies from Wireline Logs, in Geological Log Analysis using Computer Methods: AAPG Computer Applications in Geology No. 2, Tulsa, OK, p. 47-64.

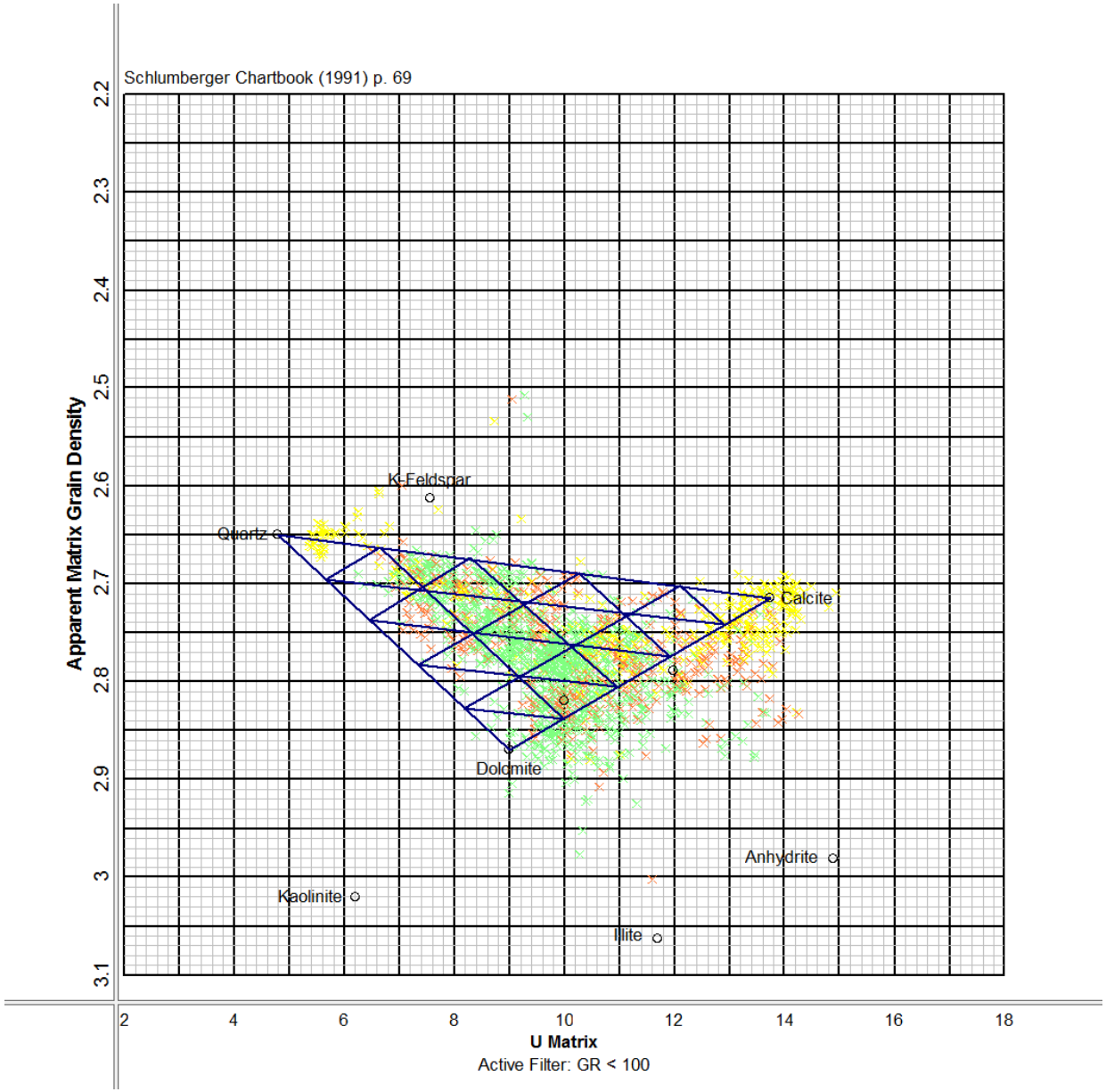

Figure 1. RHOMAA-UMAA crossplot showing the quartz-calcite-dolomite ternary diagram utilized for clean formations. In clean formations, properly calibrated data should plot primarily within the triangle. The points plotting just southeast of the dolomite-calcite mixing line indicate a small amount of clay.

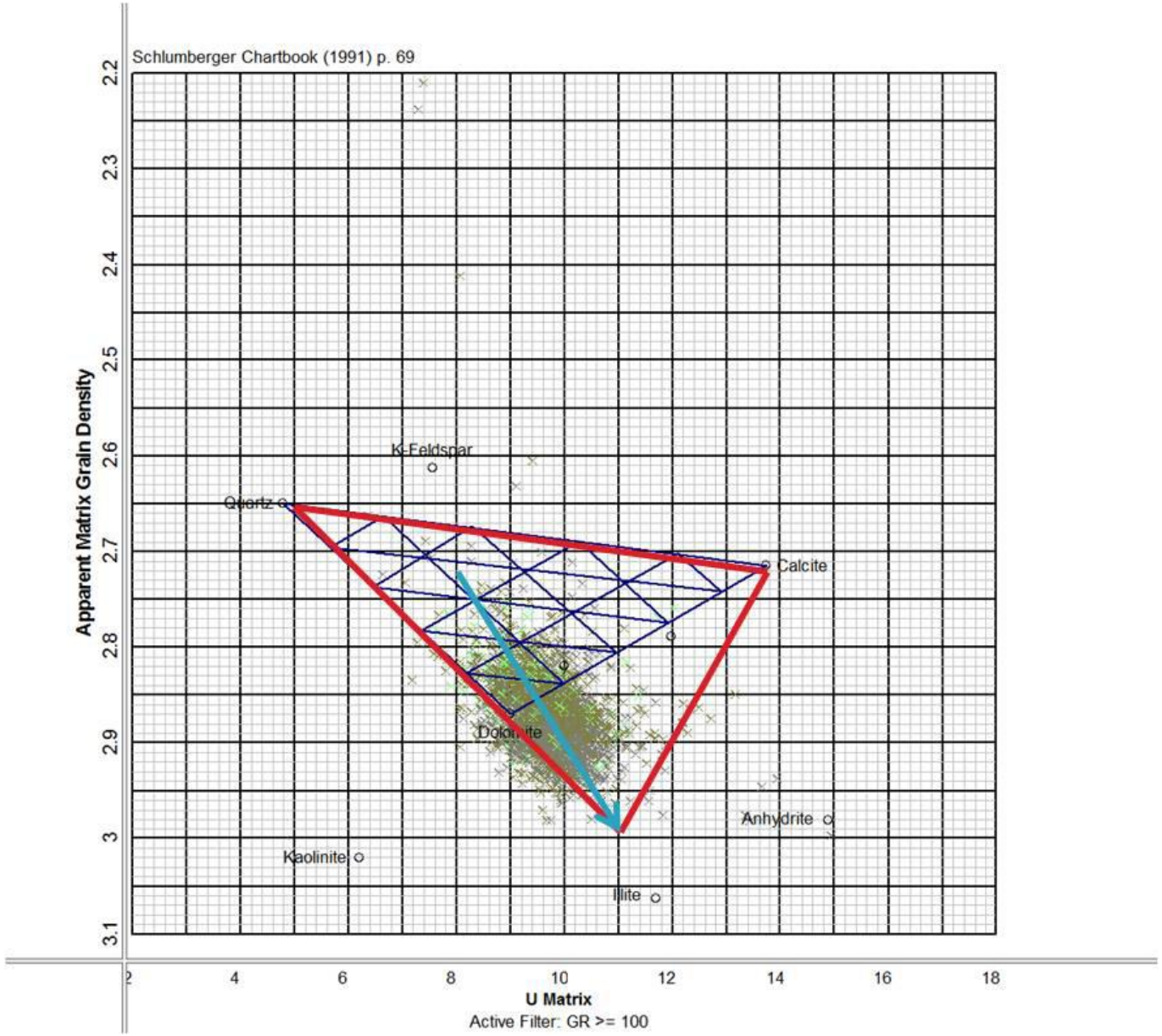

Figure 2. RHOMAA-UMAA crossplot showing the quartz-calcite-"mixed clay" ternary diagram utilized for shaly formations (red triangle). The increased illite-smectite-mica clay content in shaly formations causes a southeastward shift in the data cloud (blue arrow). Note that the data cloud from this shale example is nearly centered on the dolomite point, but is actually a slightly calcitic quartz-clay mixture.

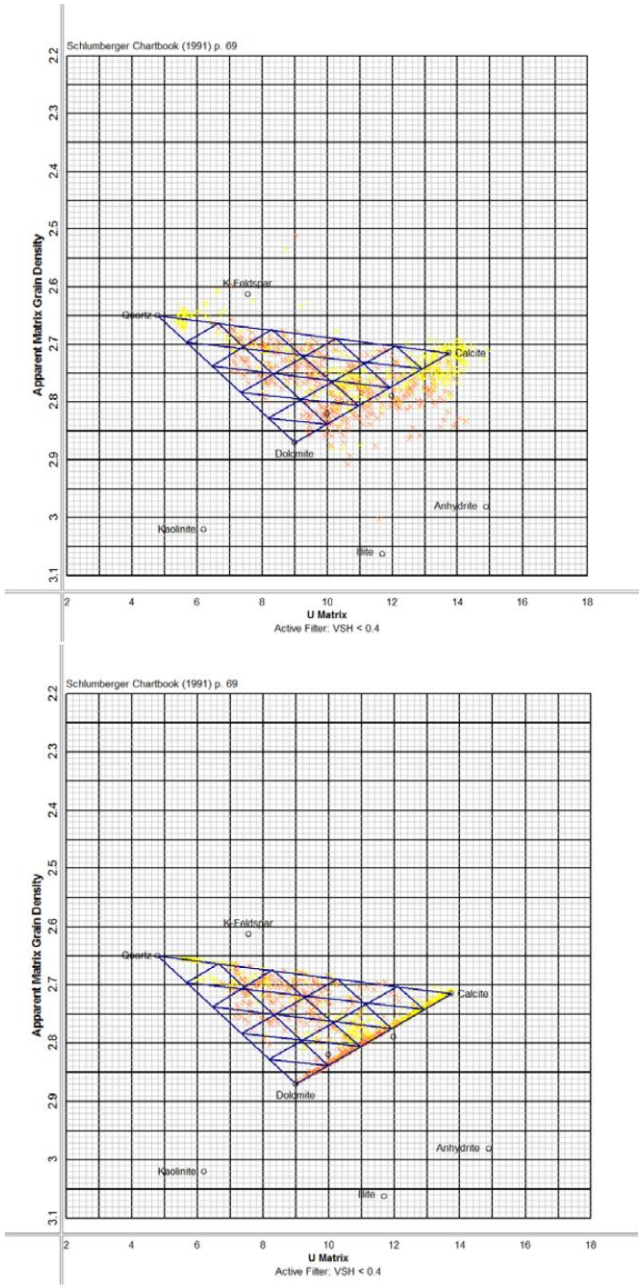

Figure 3. Before (top) and after (bottom) renormalization.

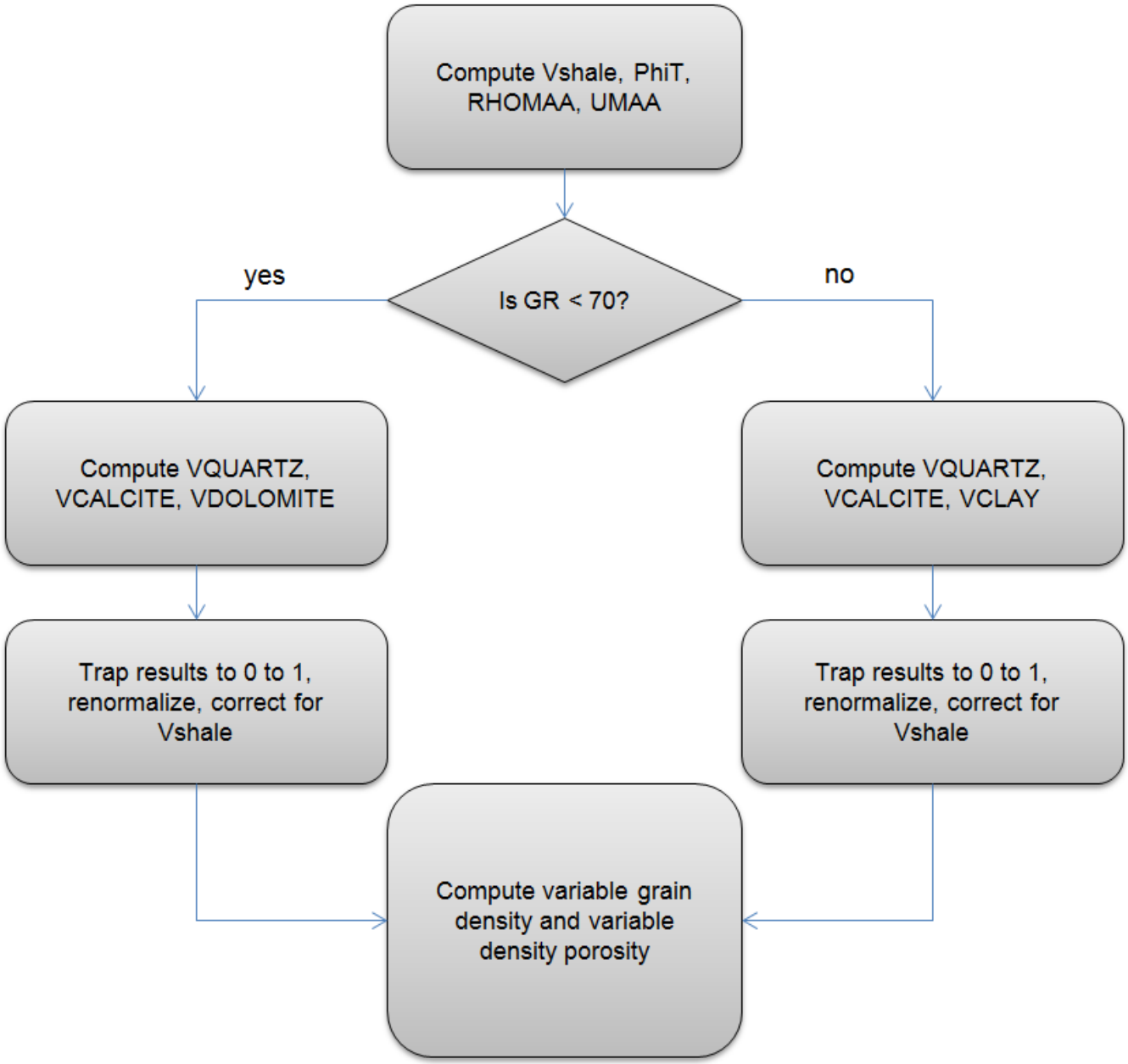

Figure 4. Flow chart for calculating lithology, variable grain density and variable density porosity.

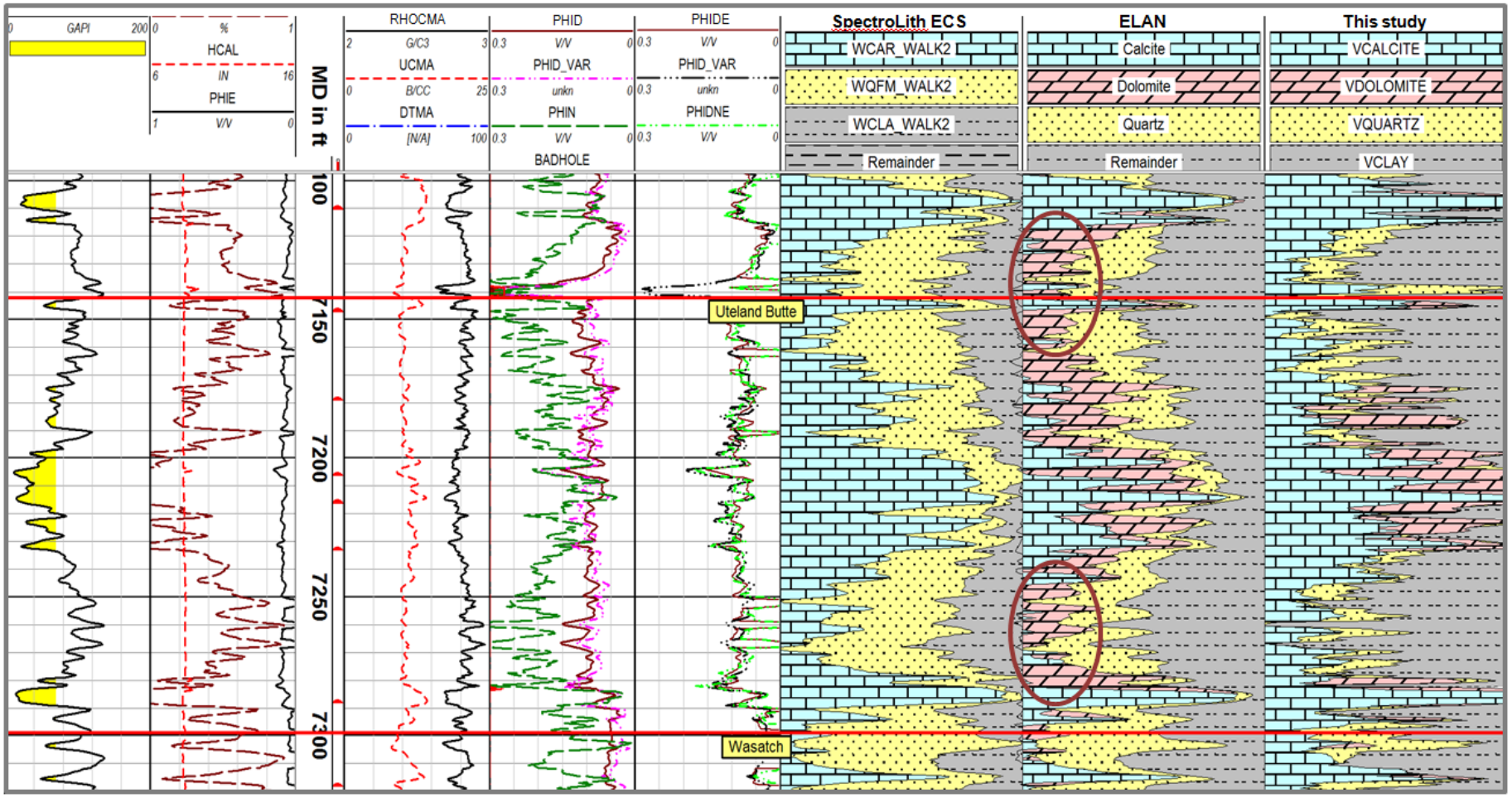

Figure 5. Log plot showing an ELAN interpretation (track 7) and our simple 4-mineral deterministic interpretation (track 8). While the carbonate type differs in shaly intervals (circled), the amount of total carbonate is comparable.