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**A Whole-Rock Geochemical Approach for Rapidly Assessing Reservoir Quality
and Fracture Openness in Sandstones**

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The whole-rock, inorganic geochemical composition of a sandstone is a function of 1) the initial detrital composition (mineralogy) of the sediment, and 2) the mineralogical transformations, additions, and subtractions that occur in the rock mass during diagenesis. In most sandstones and mudstones, the initial detrital composition is the primary control on whole-rock geochemistry, with diagenetic processes exerting a variable but generally subordinate influence. This is particularly true with regard to elements that are widely regarded as immobile in the diagenetic realm (e.g., Ti, Zr, Hf, most of the REE), at least on the scale of a few centimeters, and that can be sensitive indicators of sediment provenance. The robustness of this provenance signal is the key factor that allows the practical application of chemostratigraphy, the delineation and correlation of rock units based on elemental geochemical characteristics.

Can whole-rock geochemical data also be of use in quickly assessing sandstone reservoir quality, an attribute of prime interest in the production of hydrocarbons? Are there measurable geochemical signatures of higher or lower reservoir quality over a given spatial domain (e.g., 30-meter thick reservoir interval at a given depth range within an oil field or basin)? Can reservoir quality, as defined by porosity and permeability values in conventional reservoirs, be directly correlated with the abundance of certain easily-measured and mineralogically-controlled elements or elemental ratios? If so, can this approach then be extended to naturally-fractured sandstone reservoirs, where there may be geochemical signatures for sealed versus open fractures?

We have successfully tested this approach on a Mesozoic sandstone sequence from Africa (Craigie et al., in preparation). This interval is a conventional hydrocarbon reservoir that produces from rock-matrix porosity, and is not fractured. Whole-rock elemental analysis by ICP spectrometry was performed on sample plugs from a cored interval, and calibrated to previously-collected porosity and permeability data from petrographic and routine core analyses of the same plugs. Several simple and robust relationships between certain elemental values and both porosity and permeability were readily apparent, and could be used to reasonably predict reservoir quality in samples from an adjacent well. This data was still proprietary at the time this abstract was prepared.

Unlike the conventional example from Africa, a number of sandstone reservoirs cannot produce hydrocarbons economically from rock-matrix porosity alone. These reservoirs require open or at least partially open natural fractures in order to enhance fluid flow. Recognizing the presence of fractures, and being able to assess their openness in the subsurface, is a critical aspect of reservoir development in these cases. Historically, adequate characterization of the macroscopic fractures that have the greatest

impact on fluid flow has been a difficult task. Techniques attempting to directly assess the attributes of macrofractures (e.g. visual inspection of cores, analysis of various downhole petrophysical imaging logs) are limited in their usefulness, as the wellbore samples only a very small fraction of the reservoir rock mass. This sample may not be representative, and the important macrofractures are often not adequately sampled.

Laubach (2003) has recently shown, however, that the obstacle of representivity can be overcome with careful analysis of common small samples (e.g., core plugs or sidewall cores) using combined optical and SEM-CL microscopic techniques. Documentation of the timing and volume of late-stage diagenetic phases, which occlude (degrade) both microfracture porosity and remnant rock-matrix porosity, can provide a surrogate for actual observations of macrofractures. These late-stage cements precipitate after fractures have ceased to open; they are “post-kinematic cement” with respect to the fracture set. They also generally precipitate after rock-matrix porosity has been reduced by compaction and earlier cementation to less than about 10 vol%. Laubach (2003) has devised a “fracture degradation index” (D_g , ranging from 0 to 100%) that provides a quantitative, predictive estimate of fracture openness based on combined thin-section and SEM-CL analyses. At one extreme, a D_g value of zero indicates that no post-kinematic cements have formed in remnant fracture or rock-matrix porosity; this would predict that macrofractures in the given interval in the subsurface would be open. Conversely, a D_g value of 100% means that all remnant porosity in the fractures and the rock matrix have been sealed (degraded) by post-kinematic cement; this would predict macrofractures that are cemented closed for the given interval in the subsurface.

In Laubach’s (2003) study, the presence and relative abundance of post-kinematic ferroan carbonate cements, particularly ankerite, was the most important factor in determining the degree to which macrofractures will be sealed (degraded) in the subsurface. This relationship was recognized in three fractured-sandstone gas reservoirs of various ages in different basins in the United States.

We speculate that the whole-rock geochemical approach that proved successful on the conventional sandstone reservoir from Africa could be extended to fractured-sandstone reservoirs, if calibrated against high-quality petrographic fracture-degradation data (D_g values). We performed an initial test of this hypothesis on a subset of Laubach’s (2003) samples from the Cretaceous Travis Peak Formation from the East Texas basin, United States. We reasoned that the geochemical signature of post-kinematic carbonate cements (e.g., differences in CaO, MgO, Fe₂O₃, MnO, and possibly Sr, Zn, Ba) should be recognizable in sandstones of relatively simple initial composition, even if these cements occur in amounts of only a few volume percent. We analyzed 40 Travis Peak samples by inductively-coupled plasma atomic-emission spectroscopy (ICP-AES), giving whole-rock data for about 30 elements. The samples for ICP-AES were collected from cores archived at the Core Research Center of the Bureau of Economic Geology in Austin, Texas. They were physically saw-cut from points immediately adjacent to those sampled for thin-section analysis in Laubach’s (2003) study.

As a first test of the geochemical approach, we restricted our samples to those with petrographically-determined detrital-clay matrix contents of less than 1 vol%, so that initial sandstone composition would be relatively simple (relatively clean, quartzo-feldspathic to quartzose). We also chose samples with a full range of both post-kinematic ankerite cement abundances (0 to 11.5 vol%) and fracture degradation values (D_g from 0 to 100%). Figures 1-2 show plots of this distribution. Note that low D_g values (< 40%) are always associated with low amounts of ankerite cement (0 to 2.3 vol%). Higher D_g values (> 40%), while generally associated with higher amounts of ankerite cement (0.5 to 11.5 vol%), show a more variable relationship.

Carbonate cements in the studied Travis Peak sandstones consist of both post-kinematic ankerite (0 to 11.5 vol%, average of 2.7 vol%) and an earlier generation of dolomite (0 to 9.3 vol%, average of 1.3 vol%). The results of our ICP analyses show that whole-rock abundances of CaO (0.03 to 4.06 wt%, average of 0.75 wt%), MgO (0.12 to 2.27 wt%, average of 0.49 wt%), and MnO (0.001 to 0.119 wt%, average of 0.021 wt%) are almost entirely controlled by these carbonate cement phases. This is demonstrated by the strong positive covariance of each of these oxides when plotted against one another, and by fairly well-defined positive covariances when each are plotted against petrographic values for total carbonate cement (0 to 19.6 vol%, average of 4.0 vol%). When plotted against D_g values, whole-rock CaO, MgO, MnO, and their sum (CaO + MgO + MnO; 0.17 to 5.93 wt%, average of 1.20 wt%) show distributions that can be used to reasonably predict the occurrence of poor-quality (degraded) fractures (Figures 3-6). For each of the oxides, there is a visually-determined abundance threshold above which fractures show significantly higher average degradation. These thresholds, in weight percent, are: CaO = 1.25, MgO = 0.65, MnO = 0.038, and (CaO + MgO + MnO) = 1.30, respectively. Below these thresholds, there is more variability in fracture degradation, although average D_g values are always lower than above the thresholds. This relationship should generally be useful for predicting a greater probability of better-quality, more open fractures.

Whole-rock Fe_2O_3T (0.16 to 1.97 wt%, average of 0.71 wt%) does not co-vary with values of petrographic carbonate cement, CaO, MgO, MnO, or D_g . It appears that Fe_2O_3T abundance is controlled by several mineral phases in addition to the carbonate cement, probably including fine-grained mica, heavy minerals, clays, and perhaps authigenic pyrite. Its signature in the post-kinematic ankerite is therefore obscured, and Fe_2O_3T is not useful for predicting D_g values and fracture quality.

Whole-rock Zn (3.5 to 20.1 ppm, average of 9.4 ppm), Sr (33 to 134 ppm, average of 78 ppm), and Ba (103 to 719 ppm, average of 390 ppm) show no relationship to D_g , nor any covariance with one another. However, when each of these elements are ratioed to CaO, a similar and interesting relationship is observed (Figures 7-9), based again on visually-determined threshold values. About 75% of the samples plot below the thresholds (Zn/CaO = 65 ppm/wt%, Sr/CaO = 500 ppm/wt%, Ba/CaO = 2200 ppm/wt%), with ratios that are relatively consistent and span the entire range of D_g values. We interpret these to represent "normal" whole-rock sandstone ratios for the Travis Peak Formation. Conversely, about 25% of the samples plot above the threshold, with values up to seven times greater than the actual threshold ratios. These enrichments in Zn, Sr, and Ba with respect to CaO are invariably associated with low D_g values (0 to 33%, average < 7%). While it is possible that these enrichments may represent an extreme diagenetic phase not recognized by optical or SEM-CL analyses, we believe it is much more likely they represent contamination of the core samples by drilling (coring) fluids. Ba and Sr enrichments are probably the result of infiltration by very fine-grained barite weighting agent, and the elevated Zn could be related to coring fluid formulation or to fluid contact with tubulars. In support of this interpretation is the fact that barite cement has not been reported in the Travis Peak sandstones (Dutton and Diggs 1992; Laubach 2003), at least not to our knowledge.

Even though the elevated Zn/CaO, Sr/CaO, and Ba/CaO values probably do not correspond to diagenetic signals, they may still be an indirect indicator of fracture quality. Since remnant rock-matrix porosity in the Travis Peak samples is low, and only samples with low D_g values displayed trace element enrichments, it is reasonable to assume that drilling fluid components accessed the rock through open microfractures, or possibly even macrofractures. Petrographic reexamination of the trace-element enriched samples should reveal some evidence of drilling-fluid solids if they are present.

The results of this study, while encouraging for predictive applications, also suggest potential limitations to the widespread application of our geochemical approach. These will need to be assessed with further work, and include:

- 1) Fractured-sandstone reservoirs amenable to this type of analysis may be limited to those of relatively simple initial texture and mineralogical composition. In particular, relatively well-sorted quartzose and quartzo-feldspathic sandstones with little or no detrital clay and silt matrix should prove to be the best candidates. The presence of even minor amounts of detrital lithic fragments, clay, mica, and heavy minerals will probably be enough to obscure the geochemical signature of many post-kinematic cements. Fortunately, there are a number of fractured sandstone reservoirs that fit the optimal compositional criteria.
- 2) Post-kinematic cements often have heterogeneous distributions, showing significant variation even on a bed-to-bed scale (Laubach 2003, p. 570). Despite this, Laubach (2003) has shown that well-characterized point samples from cores and sidewall cores can be very effective in predicting open versus degraded fractures. While we are optimistic, it remains to be seen how well the geochemical versus petrographic calibration can be extended from point samples to interval samples (cuttings).

The ultimate aim of our geochemical approach would be to develop a quick, reliable screening technique for both conventional reservoir quality and for fracture openness that would be available at wellsite. During the past three years, we have developed a rugged, portable, laser-induced breakdown spectroscopy (LIBS) instrument. This instrument, along with simplified sample preparation techniques and sophisticated spectral analysis software, now allows whole-rock geochemical analysis of cuttings samples to be performed at wellsite. We presently conduct these analyses during drilling operations for the purpose of chemostratigraphic correlation, so that wellbore position in the stratigraphic sequence can be better constrained. Whole-rock geochemical data for up to 40 elements can be generated by the LIBS instrument within 15-20 minutes of cuttings samples being collected at the shale shaker. Given typical LWD sensor arrays on the drillstring, drilling rates in well-lithified rocks, and lag times to return cuttings to the surface, LIBS geochemical data can sometimes be available at about the same time as LWD petrophysical data for any given point in the stratigraphy.

The key to the success of our geochemical approach will be to properly calibrate cuttings (interval samples) to core plugs and sidewall cores (point samples) for the given spatial domain. High-quality optical and SEM-CL petrographic data from point samples, using the approach of Laubach (2003), must be correlated to whole-rock elemental compositions in order to establish the key geochemical indicators of relatively high fracture degradation. If core-to-cuttings calibration is successful, the geochemical approach could be a valuable tool in quickly alerting the operator to intervals of poor-quality reservoir with mostly degraded fractures.

Relatively slow drilling rates in many fractured, quartzose-sandstone reservoirs will allow picked cuttings to provide a statistical sample of as little as one to three meters of section. This should provide adequate stratigraphic resolution of fracture openness in most cases, without calling for a slowdown in normal drilling operations. Our experience thus far in chemostratigraphic applications indicates that mixing of cuttings while traveling upward in the wellbore, which can potentially obscure a specific geochemical signal, is minimal or at least manageable under most drilling conditions.

The approach we suggest is applicable even if the rock texture in the cuttings is completely obliterated by the shearing action of fixed-cutter (PDC) drill bits now in common use. Despite this shearing, we

have usually observed that only minor contamination of cuttings by drilling fluids occur during chemostratigraphic applications; the geochemical signatures used to perform correlations easily survive. It should therefore be possible to recognize the geochemical signatures for varying degrees of fracture openness, at least for sandstones of relatively simple mineralogical composition. If the chemical signature of significant drilling fluid contamination is detected in a cuttings interval, it may be an indirect indication of open fractures, as we have interpreted for some of the samples in this study.

Acknowledgements

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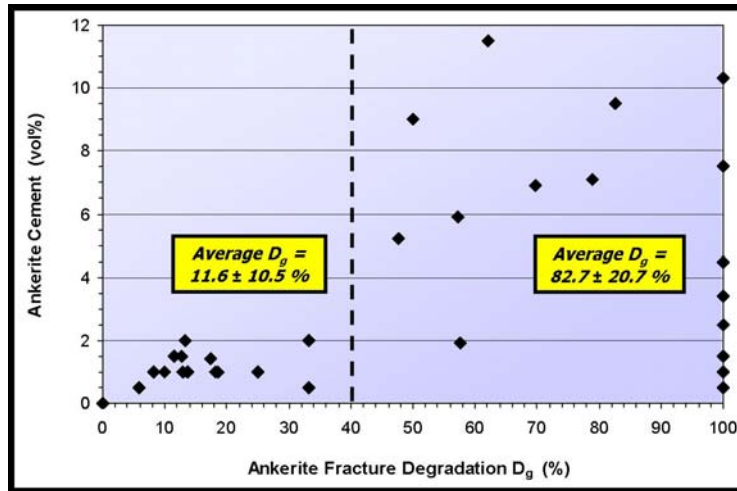


Figure 1. Plot of petrographic ankerite cement versus ankerite fracture degradation (D_g).

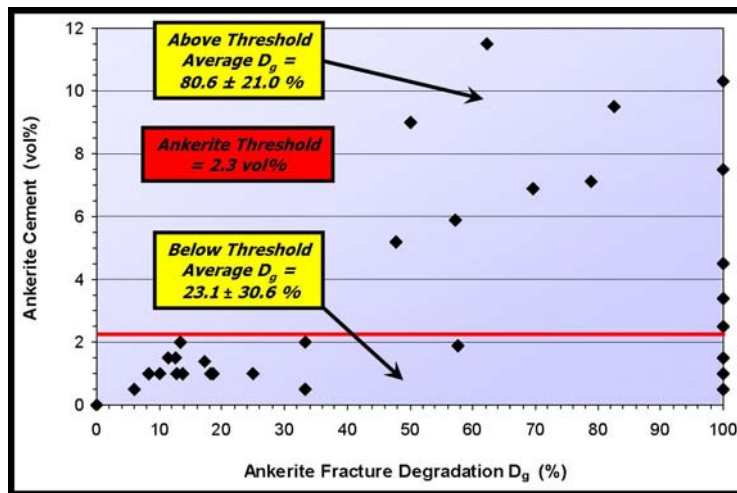


Figure 2. Same plot as Figure 1, showing critical ankerite cement threshold.

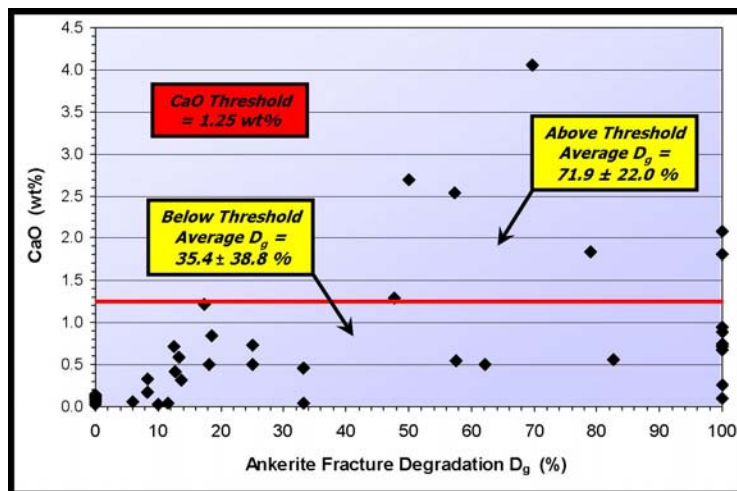


Figure 3. Plot of CaO versus ankerite fracture degradation (D_g).

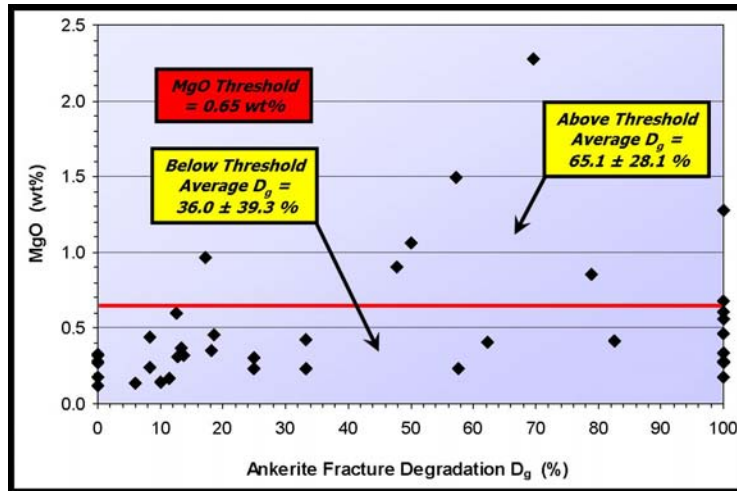


Figure 4. Plot of MgO versus ankerite fracture degradation (D_g).

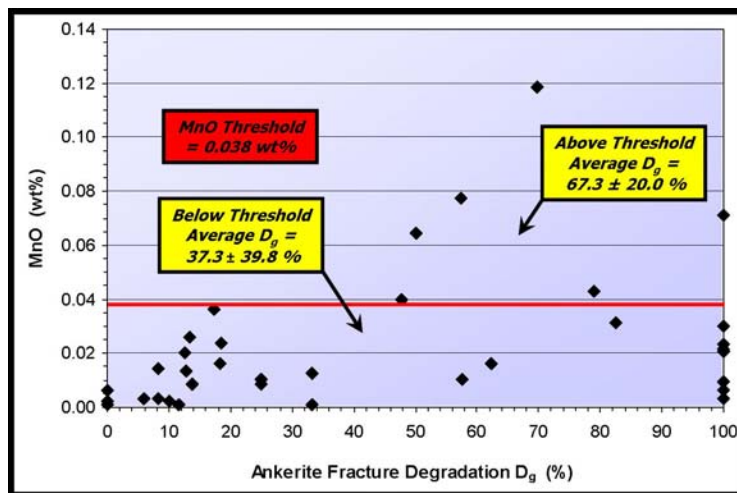


Figure 5. Plot of MnO versus ankerite fracture degradation (D_g).

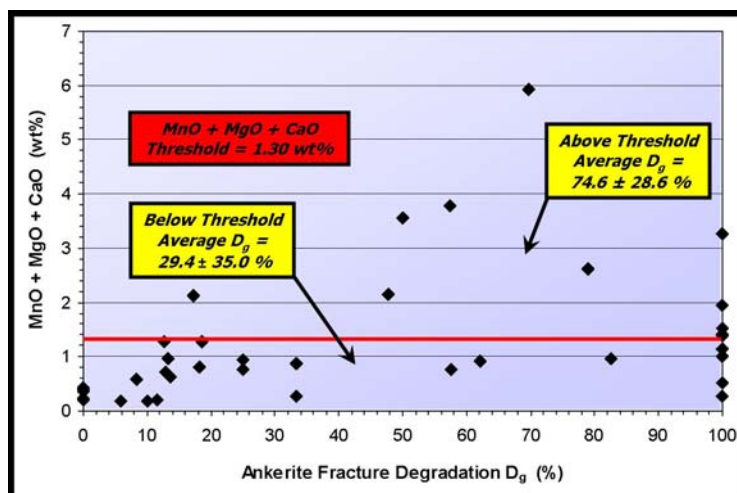


Figure 6. Plot of (CaO + MgO + MnO) versus ankerite fracture degradation (D_g).

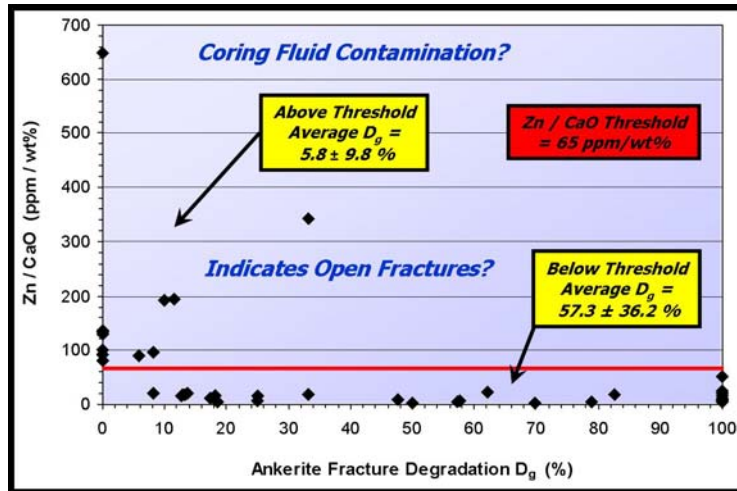


Figure 7. Plot of Zn/CaO versus ankerite fracture degradation (D_g).

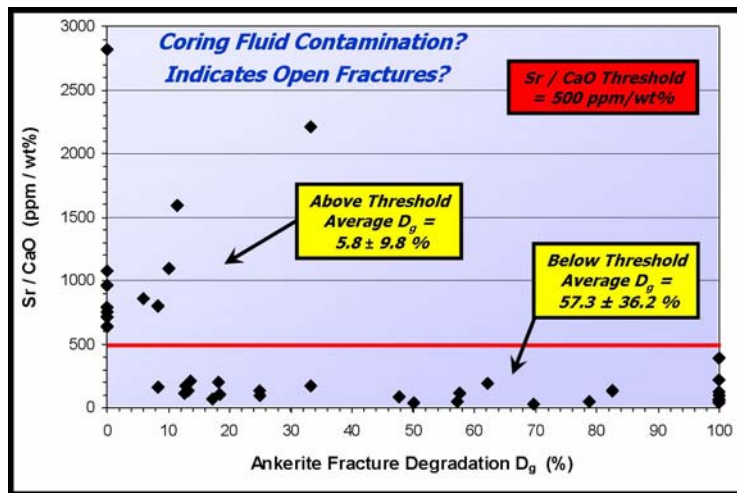


Figure 8. Plot of Sr/CaO versus ankerite fracture degradation (D_g).

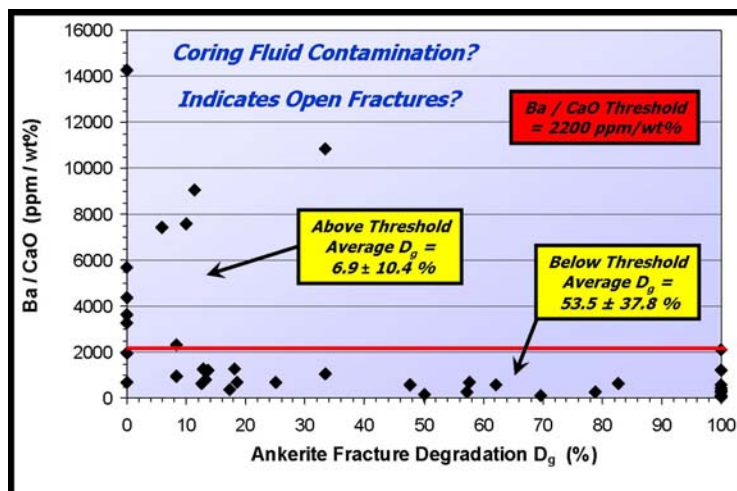


Figure 9. Plot of Ba/CaO versus ankerite fracture degradation (D_g).