PS Defining Mechanical and Compositional Heterogeneity of Highly Siliceous Mudstones: Upper Monterey Formation, Belridge Oil Field, San Joaquin Basin, California*

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Abstract

Highly siliceous mudstones of the Upper Monterey Formation exhibit a complex range of physical and mechanical properties at a fine spatial resolution. Unlike argillaceous mudstones, highly siliceous mudstones undergo a stepwise diagenetic transformation from opal-A to opal-CT to quartz phase silica with dramatic reductions in porosity and concurrent increases in brittleness. Increased clay-rich detritus in the initial sediment also reduces total porosity but with an associated decrease in brittleness. Prior studies of mechanical stratigraphy in the Monterey Formation focused on the heterogeneity of natural fracture patterns in outcrop. This study examines 40 cores from different burial depths to quantify the relationship between composition, porosity, diagenetic stage and hardness in subsurface rocks.

XRF scanning and Leeb hardness testing (HLD) were performed at a 1 cm resolution. Hardness by a Proceq Bambino rebound hammer, is used to quantify mechanical heterogeneity. Results indicate that porosity is the principle influence on hardness, while the HLD deviation from this trend is strongly influenced by silica-detritus ratios. The greatest shift in hardness occurs with the opal-A to opal-CT diagenetic transition (+55% HLD) where porosity reduction by fluid expulsion and matrix compaction was greatest. The conversion from opal-CT to quartz phase silica produced a smaller reduction in porosity and lesser shift in hardness (+12% HLD). Within opal-CT and quartz phase rocks, silica-detritus ratios have the greatest influence on hardness properties. In quartz phase rocks, doubling burial depth significantly increases hardness (+20% HLD) without further silica diagenesis. Data suggests that hardness increase and porosity loss in the deeply buried quartz-phase rocks was accomplished by silica enrichment via pore-filling cementation. These data can be used to model the mechanical stratigraphy of thin-bedded mudrocks. For example, in a diagenetically stratified opal-A to opal-CT transition zone, high porosity opal-A strata intercalated with highly-fracturable opal-CT strata may be exploited as a play with great mixed reservoir potential. The study also reveals the distinct properties of the very deeply buried siliceous rocks rarely encountered in outcrop or conventional drilling in California. Our findings emphasize that the processes responsible for porosity reduction are critical to understanding the strength and brittleness of siliceous mudstones.

Defining Mechanical and Compositional Heterogeneity of Highly Siliceous Mudstones

Upper Monterey Formation, Belridge Oil Field, San Joaquin Basin, California

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BACKGROUND

In the San Joaquin Basin, siliceous mudstones of the upper Monterey Formation (UMF), exhibit a complex range of physical and mechanical heterogeneity at a fine spatial resolution. The UMF is primarily composed of biogenic silica and clay-rich detritus which may be thinly interbedded. Minor calcite, dolomite, ash, and sand also exist. Relatively abrupt diagenetic steps separate the UMF into three bulk intervals with contrasting properties (opal-A, opal-CT, and quartz-phase; Figure 1, 2, & 6). The upper Monterey Formation and related sediments are key elements of multiple prolific petroleum systems from which several billion barrels of oil haven been produced in Central and Southern California.

PROBLEM

The controls on rock mechanics in the upper Monterey Formation are intrinsically complex and have not been well quantified. UMF rock properties are dissimilar to argillaceous mudstones. Highly siliceous mudstones experience dramatic and stepwise diagenetic transformations of in situ grain dissolution and mineral precipitation that reduces porosity and increases brittleness. Clay-rich detritus in the initial sediment also reduces total porosity but decreases rock strength and brittleness. Where composition and diagenesis is heterogeneous, standard wireline logs may not capture or differentiate these conflicting trends. Prior studies have developed a strong relationship of composition and natural fracture patterns in outcrop. Few other studies capture the attributes of very deeply buried quartz-phase rocks.

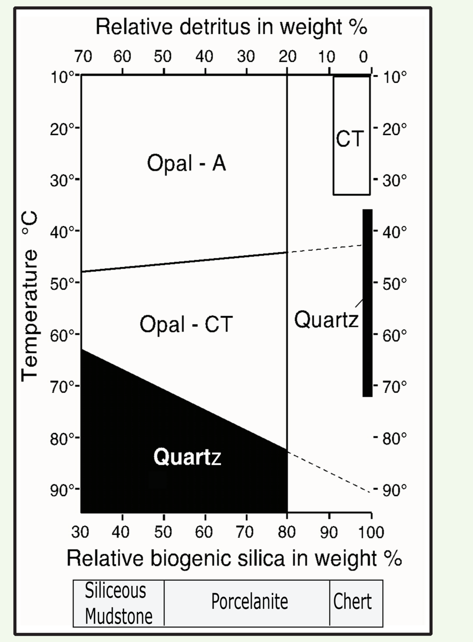


FIGURE 1: Three phase silica diagenesis with regard to temperature and compositional controls. Note that detrital % influences burial temperature (depth) for conversions.
(Behl, 1999)

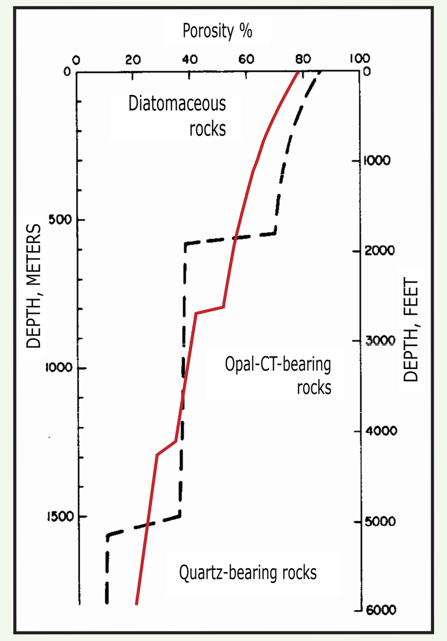
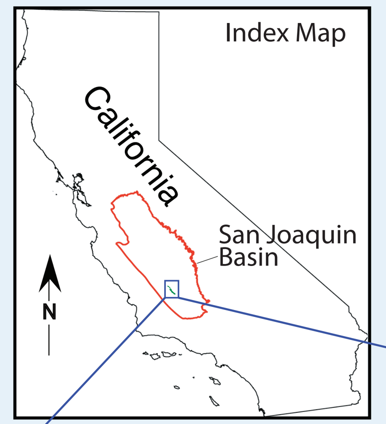


FIGURE 2: Porosity reduction in diatomaceous rocks. The red line represents low-silica (detrital clay-rich) rocks, the dashed line represents high-silica rocks. (modified from Isaacs, 1981)

LOCATION and METHODS



The Belridge oil field is located 50 miles W-NW of Bakersfield, CA in the SW San Joaquin Basin. It is one of many oilfields where the UMF is a source, seal, and reservoir in different capacities. Similar stratigraphic horizons were targeted across the Belridge anticline to test heterogeneous compositions different burial depths and diagenetic stages.

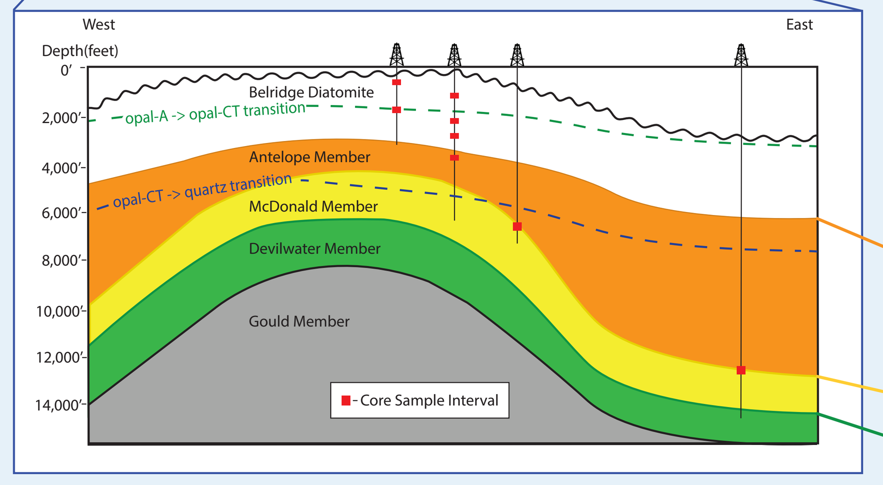


FIGURE 3: (Top) Regional map with Belridge Oilfield. (Bottom) Generalized cross-section of Belridge Anticline and core samples stratigraphically correlated within Monterey Formation Members where possible.

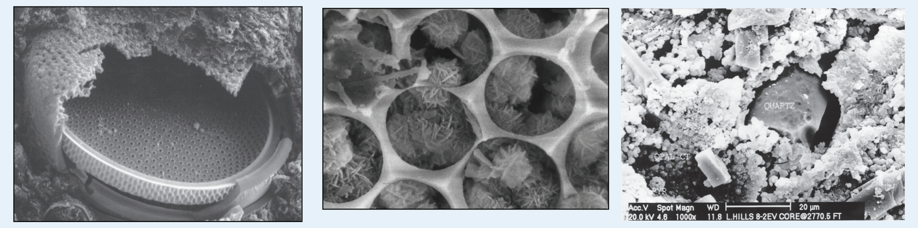


FIGURE (Left) SEM of opal-A diatom frustule; (Middle) Partial diatom dissolution w/ early opal-CT lepisphere growth (Right) Opal-CT porcelanite with quartz precipitation.

XRF GEOCHEMISTRY and LEEB HARDNESS

Over 120 ft of core samples were selected from wireline logs. XRF elemental scanning at 1 cm (0.4") steps measured elements Al through Fe. Si/(Al+K+Ti) ratios are used as a proxy for silica vs. detrital content, high Ca samples associated with carbonates were removed.

Leeb hardness (HLD), used as the resistance to permanent deformation, is determined from a 5 point average of over 1,800 locations at 1 cm increments (Fig 5).

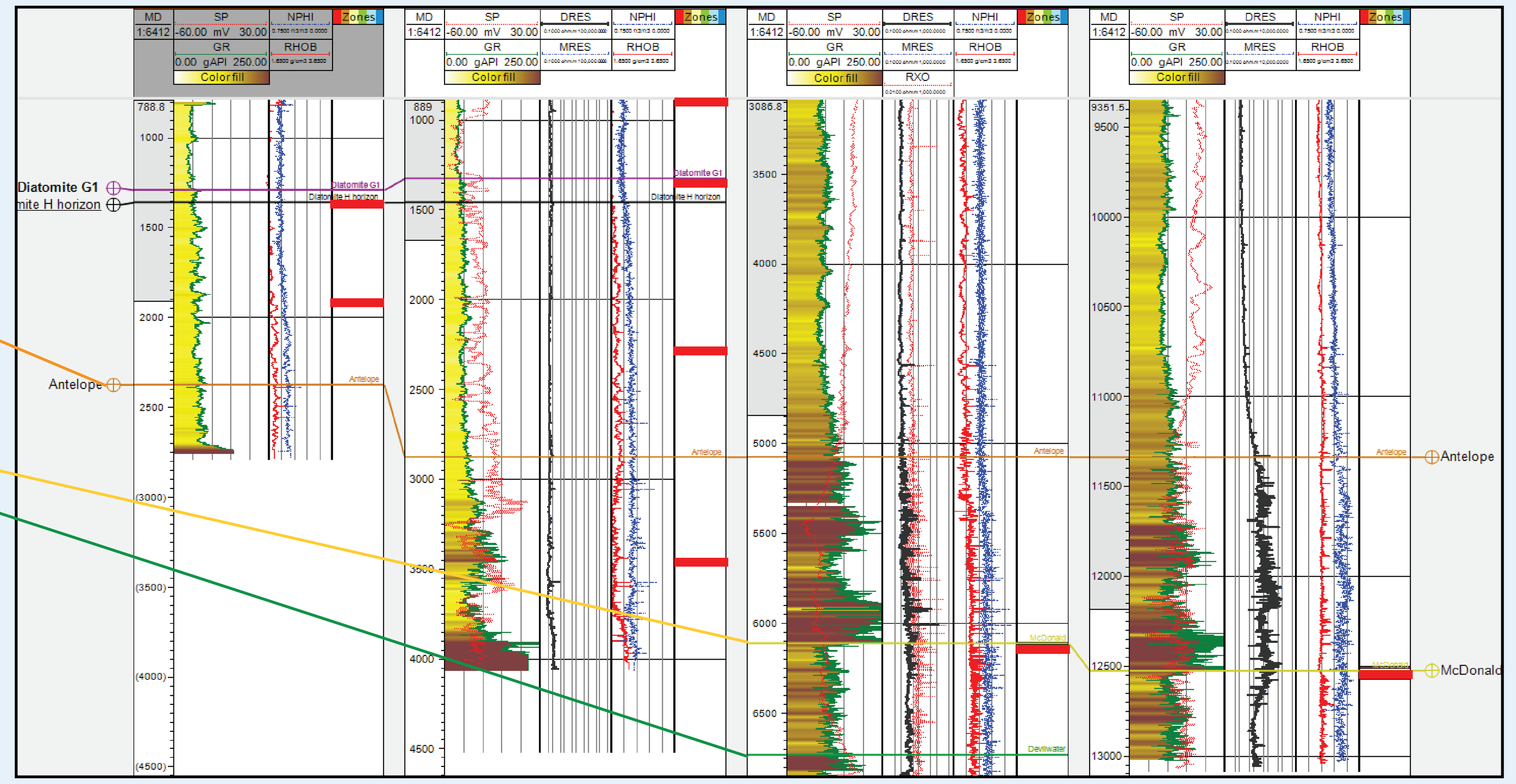
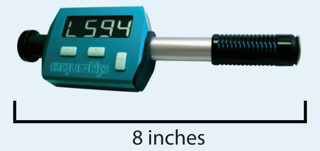


FIGURE 4: Core selection (in red) from wells target correlative yet heterogeneous intervals from each silica phase.

FIGURE 5: (Above) Avatech XRF Core Scanner with 2/3 slab measured elements Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, and Rh at 1cm steps. (Below) Proceq Bambino 2 Leeb Hardness Tester



MECHANICAL STRATIGRAPHY

Previous studies have characterize the Monterey Formation as prone to having a complex mechanical stratigraphy. Strain style from equal stress is strongly influenced by the mineralogy of individual beds. Brittle lithologies tend to fail by jointing while more ductile lithologies fail by faulting. Composition, bed thickness, and structural position are closely related to fracture style, spacing, and length (Figure 6 & 7).

Brittleness relationships of UMF lithologies are generalized but thresholds are poorly defined. (Fig 6)

- How much more brittle is an opal-CT porcelanite than a quartz-phase porcelanite? (Fig 16)
- Is porosity or composition a stronger influence on brittleness? (Fig 22)

Partial diagenesis of compositionally heterogeneous interbeds amplifies the contrasts of a mechanically stratified succession (Figure 8). In any phase, clay-rich beds can be mechanical boundaries, preventing fracture propagation. Quantifying mechanical properties will improve the prediction of fractured reservoir behaviors.

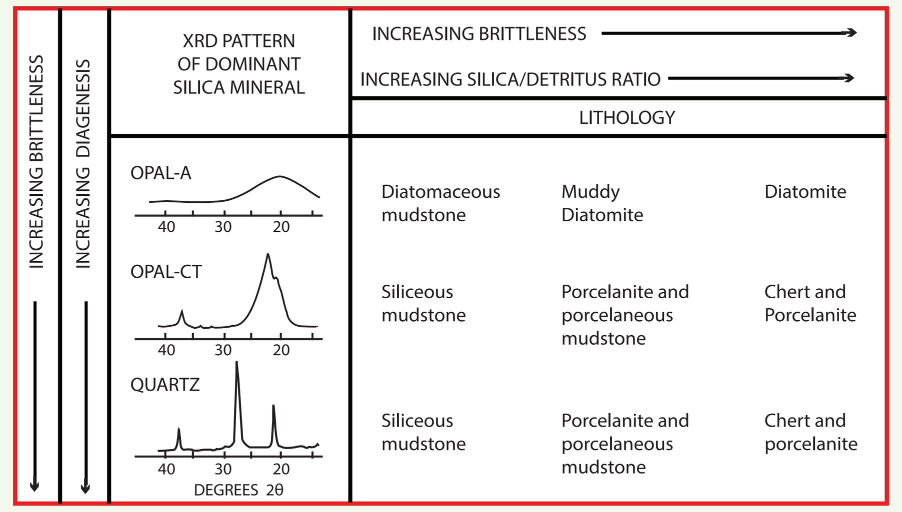
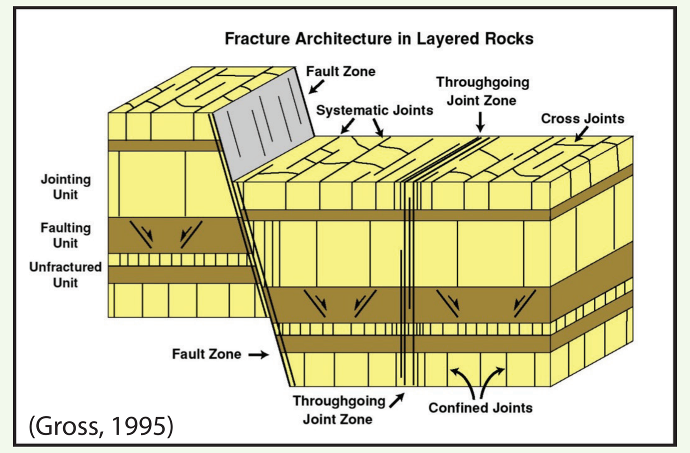


FIGURE 6: First-order approximation of relative ductility. Brittleness increases with greater crystalline mineralization (silica phase identified by XRD) and increasing silica/detritus ratios.
Modified from Snyder et al. (1983) and Pisciotto and Garrison (1981)



(Gross, 1995)

FIGURE 7: Fracture mode, style, density, and connectivity is dependent on composition, bedding thickness, and structural position.

FIGURE 8: Brittle opal-CT lithologies readily fracture providing enhanced permeability whereas detritus rich opal-A diatomaceous mudstones and sandy mudstones are unfractured with high effective porosity. White specks are wind-blown beach sand. Paradise Cove Coastline, Malibu, CA

RESULTS

Results confirm our initial hypothesis of a moderate to strong correlation of hardness to diagenetic grade and silica/detritus ratios. The most significant step of hardening is observed from the opal-A to opal-CT transition, with less from opal-CT to quartz (Figure 10).

Clay-rich lithologies have lower hardness than clay-poor rocks in every diagenetic phase and track well when plotted with high resolution line scans (Figure 9). Quartz-phase rocks continue to harden without a change in silica phase.

Detritus proxy defined as combined XRF counts Al+K+Ti

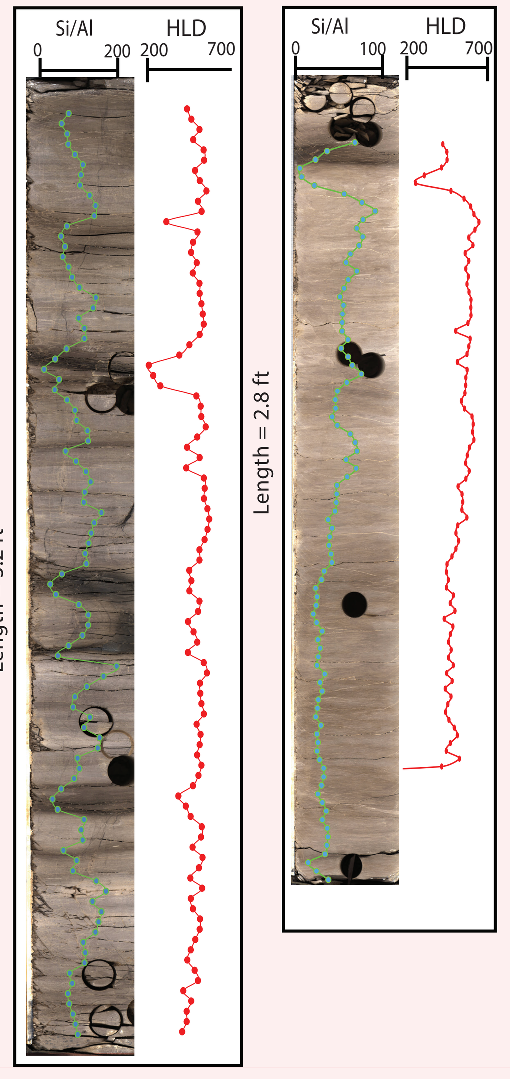


FIGURE 9: (Above) Line scan of two opal-CT core sections show a good agreement between Si/Al (green) and average hardness (HLD) (red) at a 1 cm resolution.

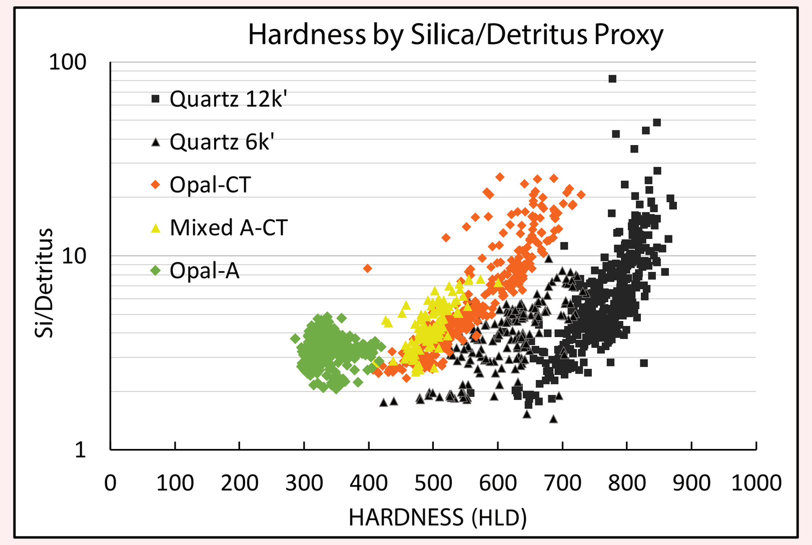


FIGURE 10: Hardness increases with higher silica/detritus ratios (less clay) and with increasing steps of diagenesis from biogenic opal-A to more crystalline opal-CT and eventually quartz.

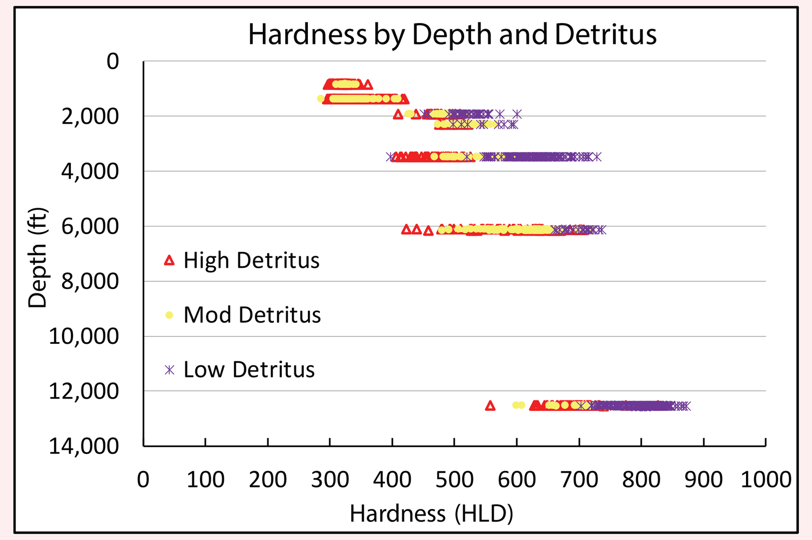


FIGURE 11: Hardness increases stepwise with silica phase change. The largest increase is from opal-A (800ft) to opal-CT (>2000ft). Higher Si/detritus ratios (less clay or less detritus) result in greater hardness within any single silica phase.

SYNTHESIS

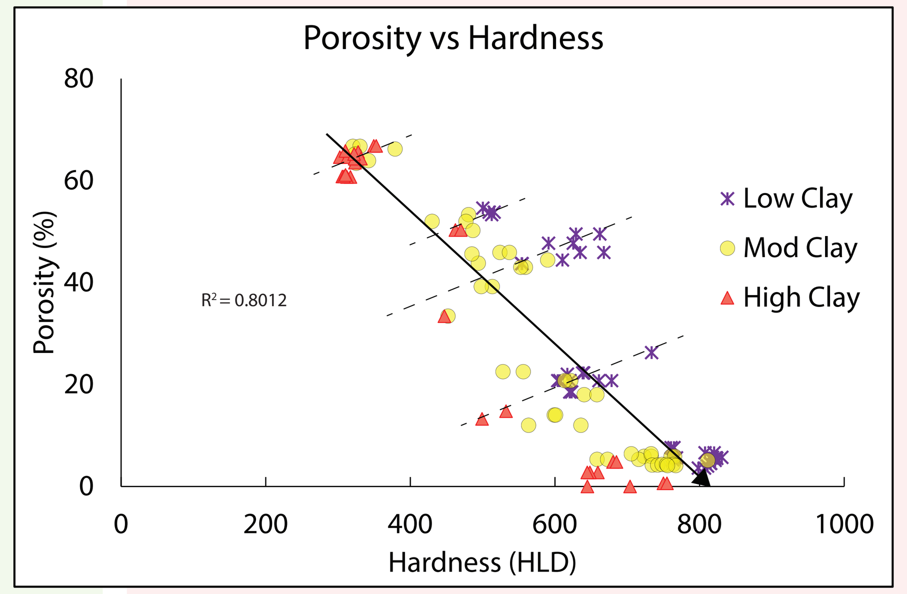


FIGURE 12: Stepwise diagenetic porosity loss has a first-order influence on hardness (solid trendline). Although within any diagenetic phase, composition becomes the primary attribute that is key to identifying rock strength. High-clay rocks have slightly lower porosity and lower hardness (dashed trends). No low-clay opal-A rocks were tested.

Our findings demonstrate that it is important to consider the geologic process of porosity reduction in predicting rock strength of siliceous mudstones. Hardness increases where intergranular contacts of siliceous components increases due to pore collapse in silica diagenesis. Low porosity due to clay mineral content has a negative effect on hardness and rock strength. This compositional trend must be a key consideration in geomechnical models of UMF rocks.

ROCK STRENGTH

Unconfined compressive strength (UCS) is a useful metric to determine the failure point of rock samples. An established calibration from Lee et al. (2014) was used to correlate HLD to UCS (Figures 13 & 14).

Lab derived UCS data (with average HLD values) from Monterey Formation cores outside of this study are added to show reasonable agreement for the application to this study.

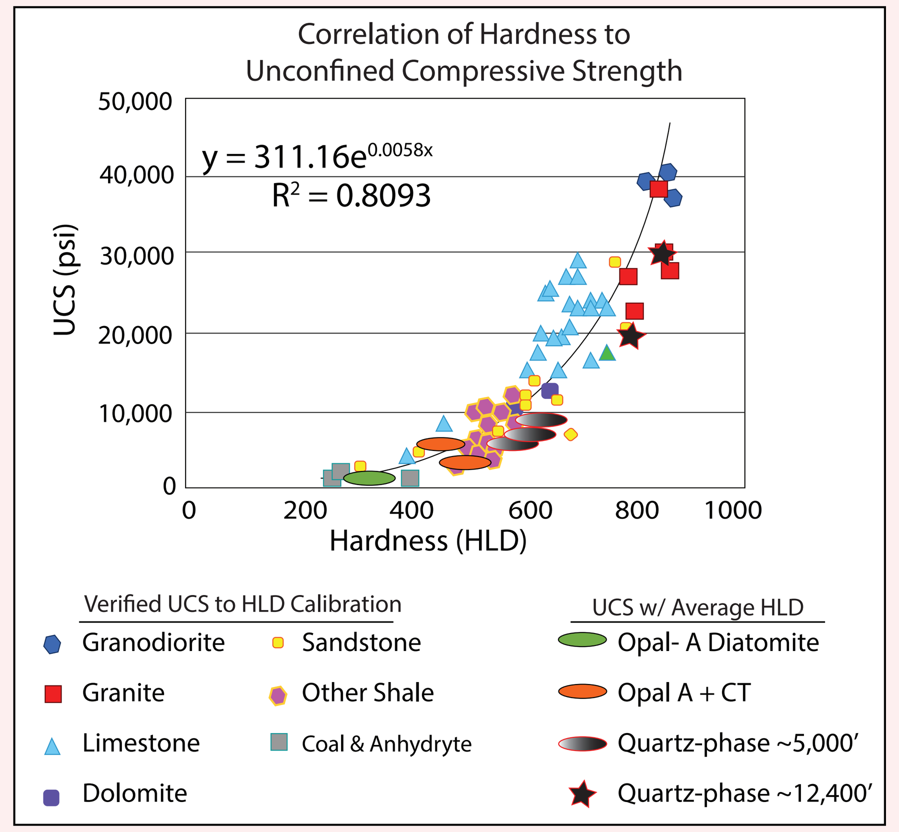


FIGURE 13: HLD to UCS conversion modified from Lee et al. (2014)

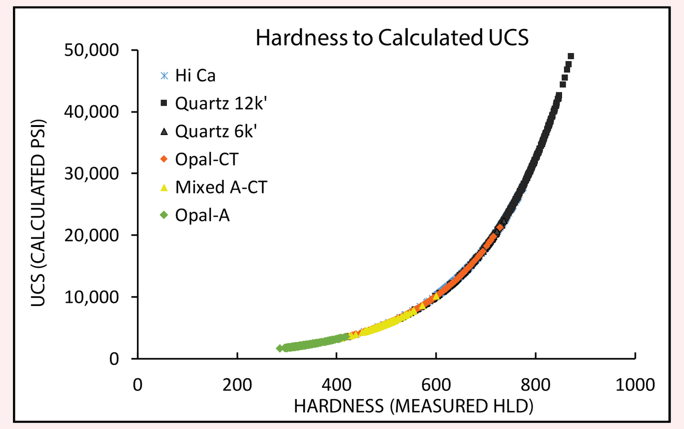


FIGURE 14: An incredibly wide range of calculated UCS values are comparable to a succession of mixed sedimentary and igneous rocks within a reservoir (Figure 13).

- Tremendous range of UCS values in deeply buried quartz-phase rocks
- A significant strength increase between opal-CT and 6,000' quartz-phase rock strengths occurs in rocks of different detritus groups.
- Multiple factors including compaction, cementation, organic maturation, and clay diagenesis influence deep hardening. (Fig 22)
- Steps of hardening are greatest between opal-A and opal-CT, while within opal-CT rocks there is a resisance to burial compacation and hardening.
- Low Detritus opal-CT and quartz porcelanites have contrasting hardnesses and which should effect fracture development. (Fig 16)

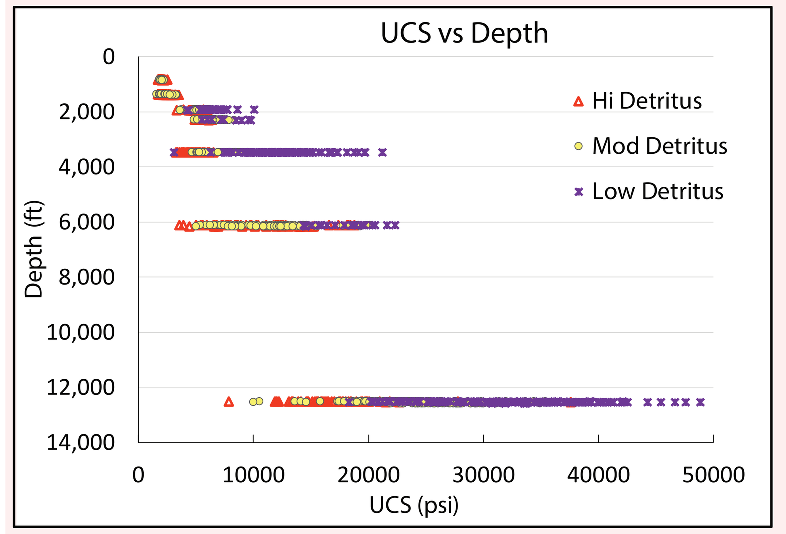


FIGURE 15: UCS plotted in depth, demonstrates a compositionally controlled range and with stepped increases due to diagenesis.

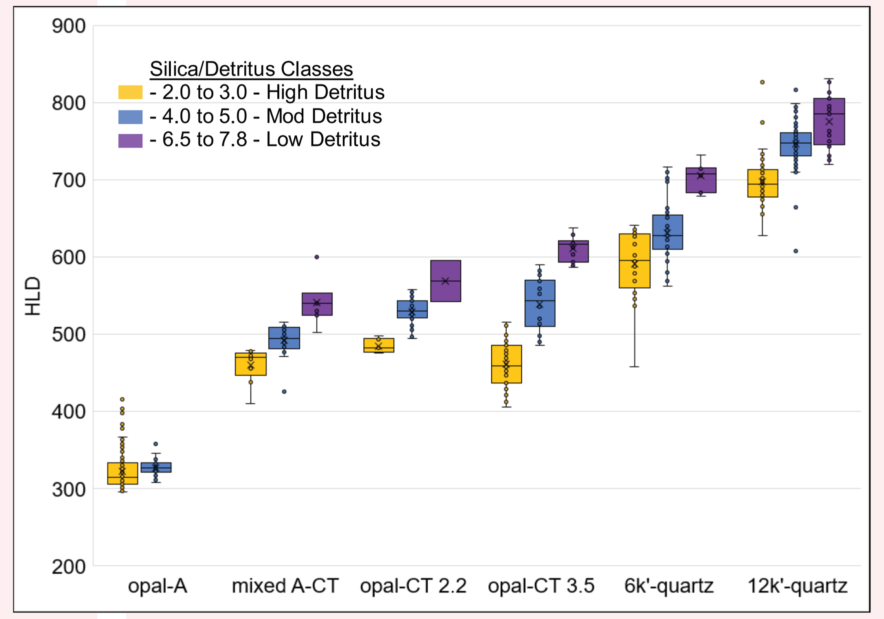


FIGURE 16: Hardness of three discrete classes of detritus groups through multiple burial depths and diagenetic stages show how clay-rich and clay-poor rocks increase in hardness at different rates.

Mechanical Attributes of Highly Siliceous Mudstone

Drilling Deeper: Hardness, Geochemistry, and Petroleum Applications

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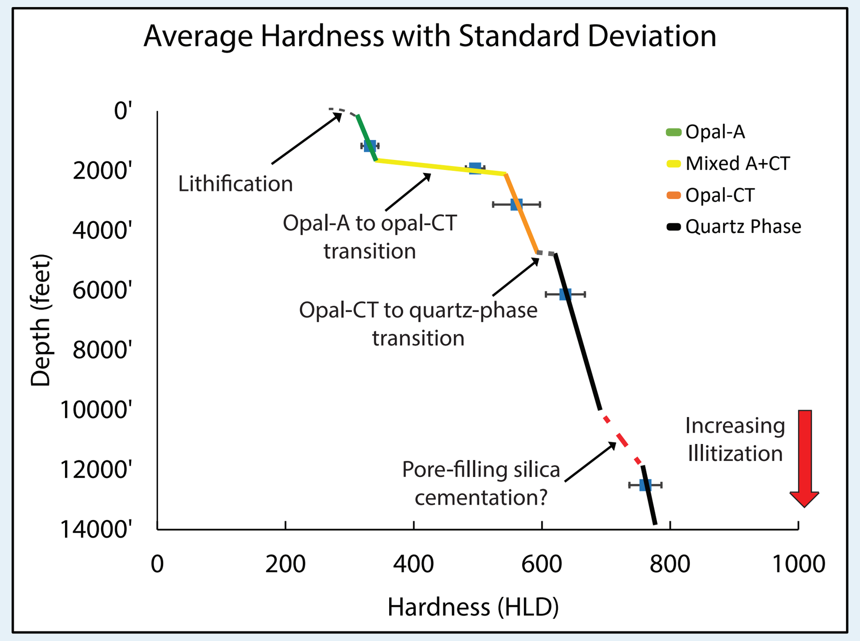
Is porosity and hardness driven by just burial compaction?

No. Although the trend of hardness and depth appears to be simply exponential (Figure 18), we know that the grain-to-grain contacts of diatom frustules and/or crystalline silica are relatively stiff and resist compaction until diagenetic dissolution, fluid expulsion, and physical collapse at transition boundaries (Figures 2 & 17). Stepwise porosity loss is linked to diagenetic shifts not gradual compaction (Isaacs, 1981). A third increase in hardness occurs without further opal to quartz diagenesis (Figure 17). This shift is associated with an increase in silica/detritus ratios (Figure 22) and is suggested to be related to the advanced conversion of illite to smectite where there is an expulsion of water, dispersion of silica, and reduction of porosity (increased grain contact interactions).



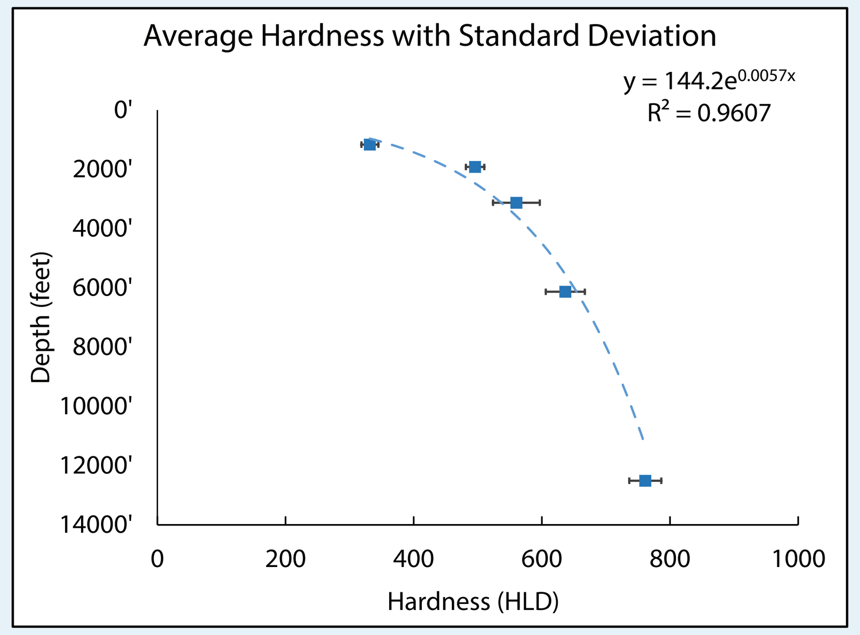


Figure 17: (Top) Stepwise porosity loss equates to stepwise hardness increase. Deep quartz lithologies are subjected to pore-filling silica cementation.
Figure 18: (Bottom) Exponential regression with 0.96 R^2 value appears to be burial compaction but is geologically incorrect.

How is this related to porosity?

Silica diagenesis is by far the largest influence on porosity. Within any phase, there are significant trends (dashed lines) in decreasing porosity and increasing clay content. However in deeply buried quartz phase rocks the trend is lost as Si/Detritus increases. We believe this to be evidence of porosity reduction due to pore-filling silica cementation of previously high porosity rocks.

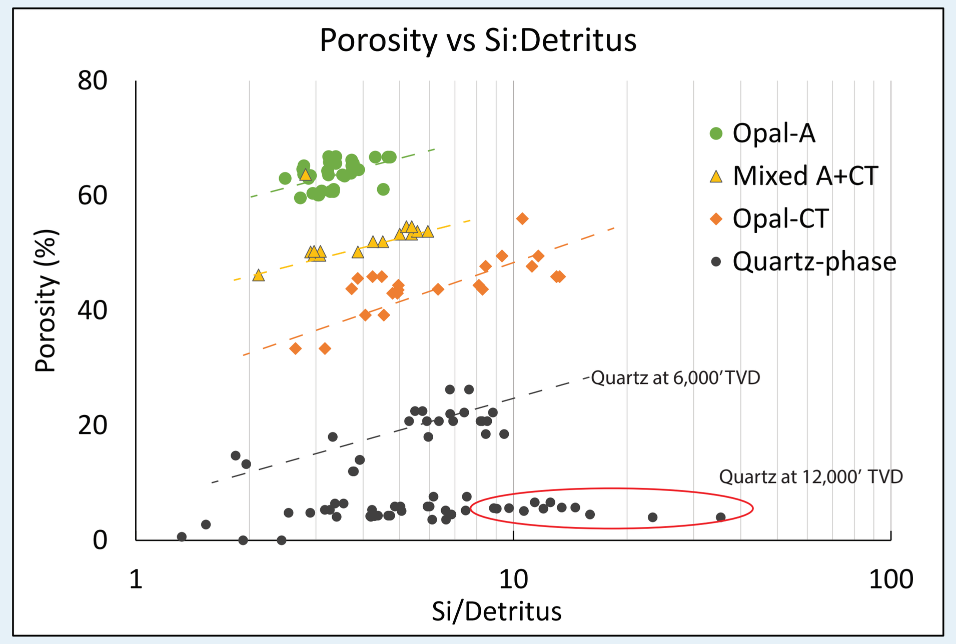


Figure 22: Core plug porosity plots follows compositional trends within each diagenetic phase. The trend is flattened >12,000' where the most porous rocks are cemented with additional silica.

Calibration of XRF Elemental Ratios

Ratios are useful for transforming XRF scanning results (reported in counts) into normalized relationships. To correlate XRF counts into a mineralogical components, 36 samples were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) and correlated to a normalized fraction of XRF Si counts.

Further analysis may better define elemental detritus in the San Joaquin Basin.

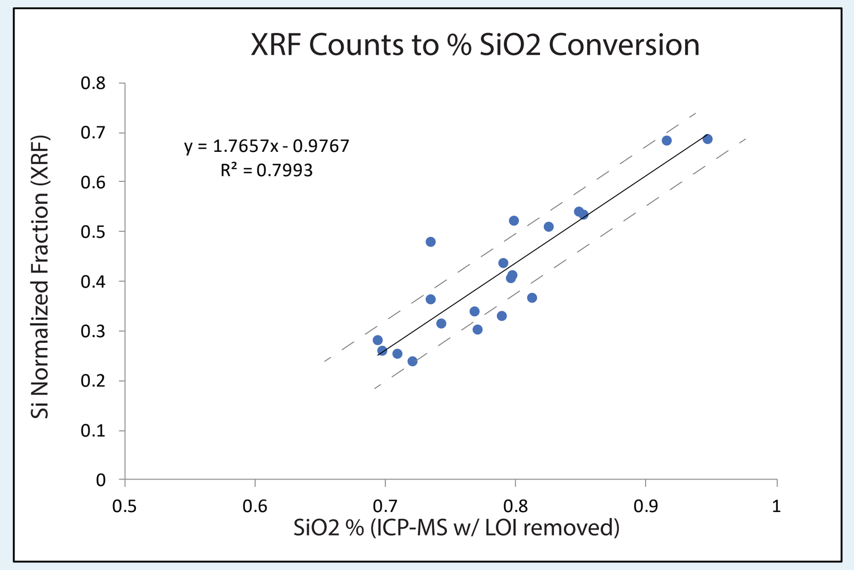


FIGURE 23: A regression analysis between XRF and ICP-MS data allows for the transformation of XRF data into the 1 cm resolution of % SiO_2 ± 3.3% or 1 standard deviation (grey dashed lines).

Targeting extremely heterogeneous successions.

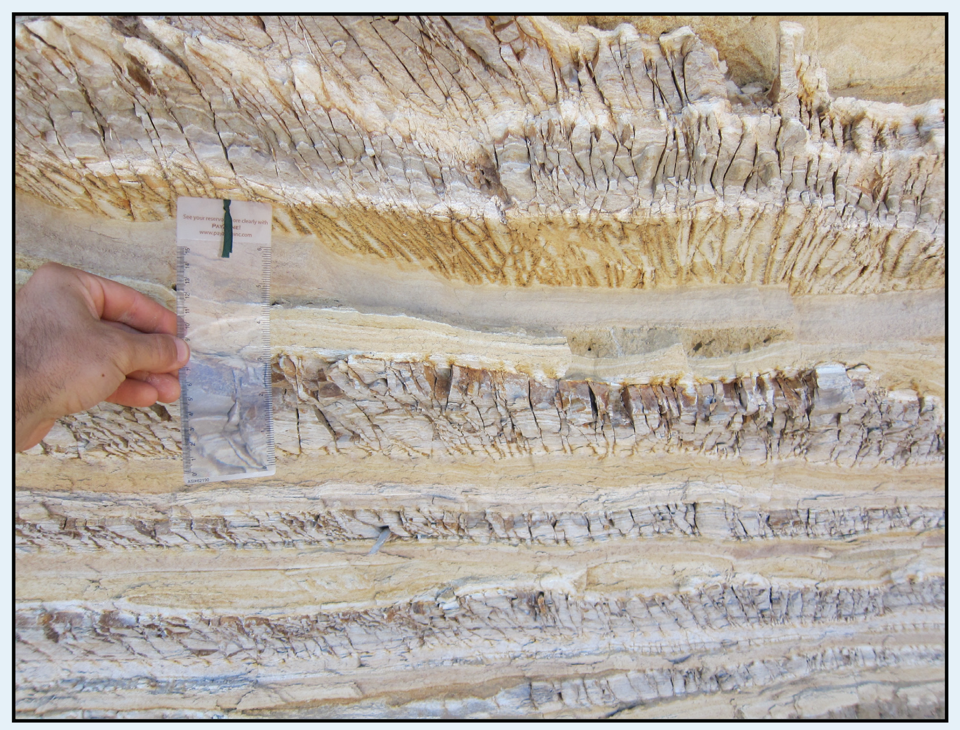


FIGURE 19: Brittle opal-CT lithologies readily fracture providing enhanced permeability whereas opal-A diatomaceous mudstones retain high porosity (>50%) and are unfractured.
Paradise Cove Coastline, Malibu, CA.

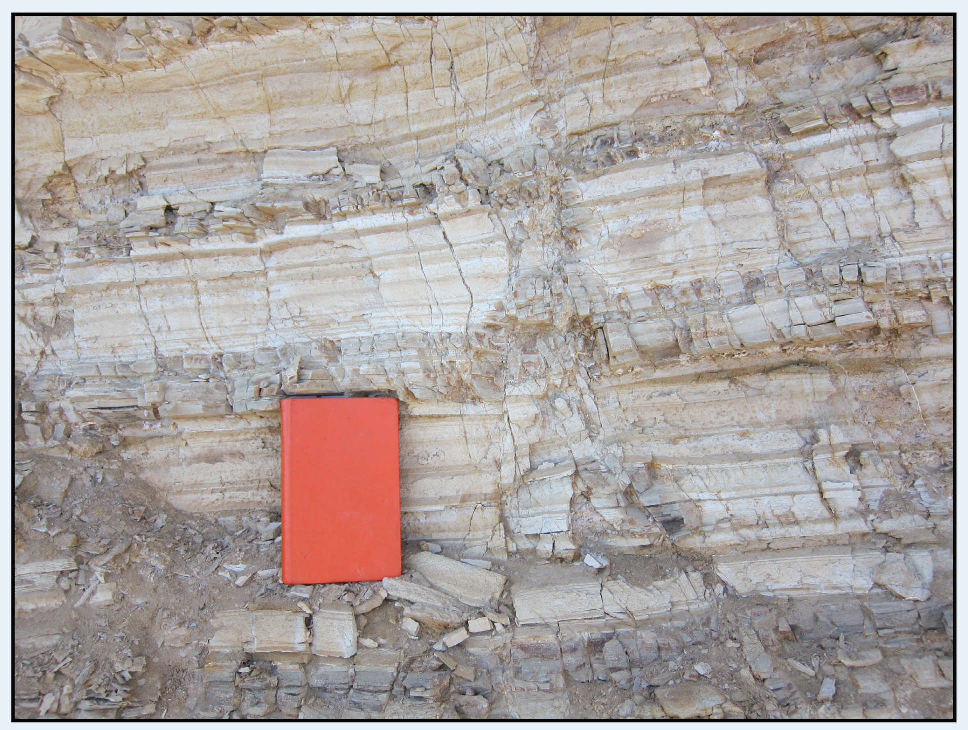


FIGURE 20: Cyclic interbedded of heterogeneous compositions leading to complex fracture stratigraphy important to reservoir performance.
Arroyo Burro Beach, CA.

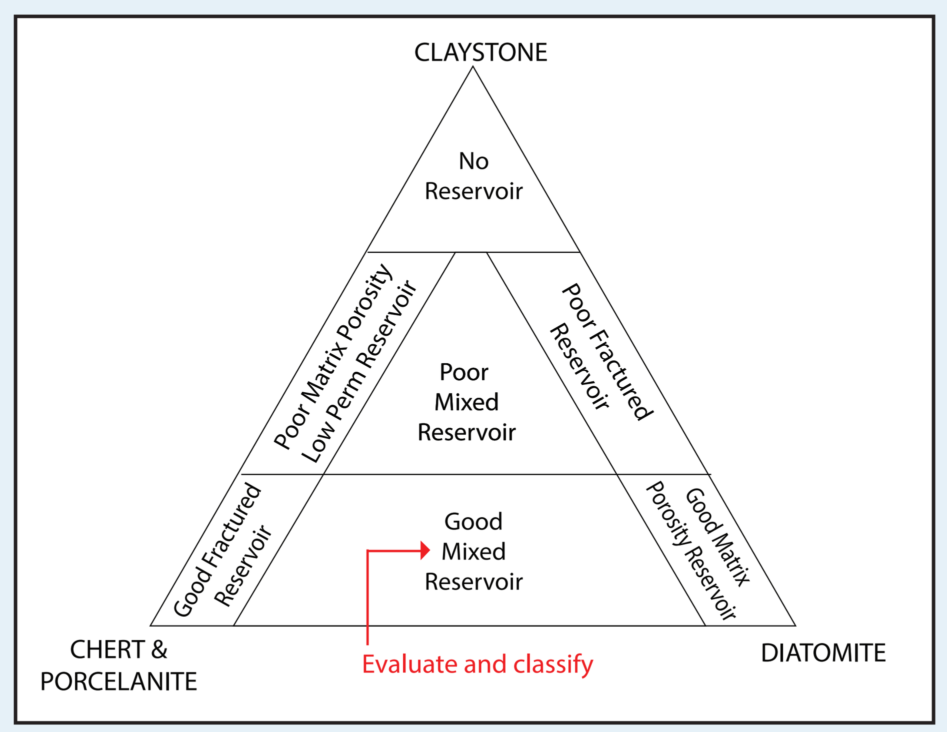
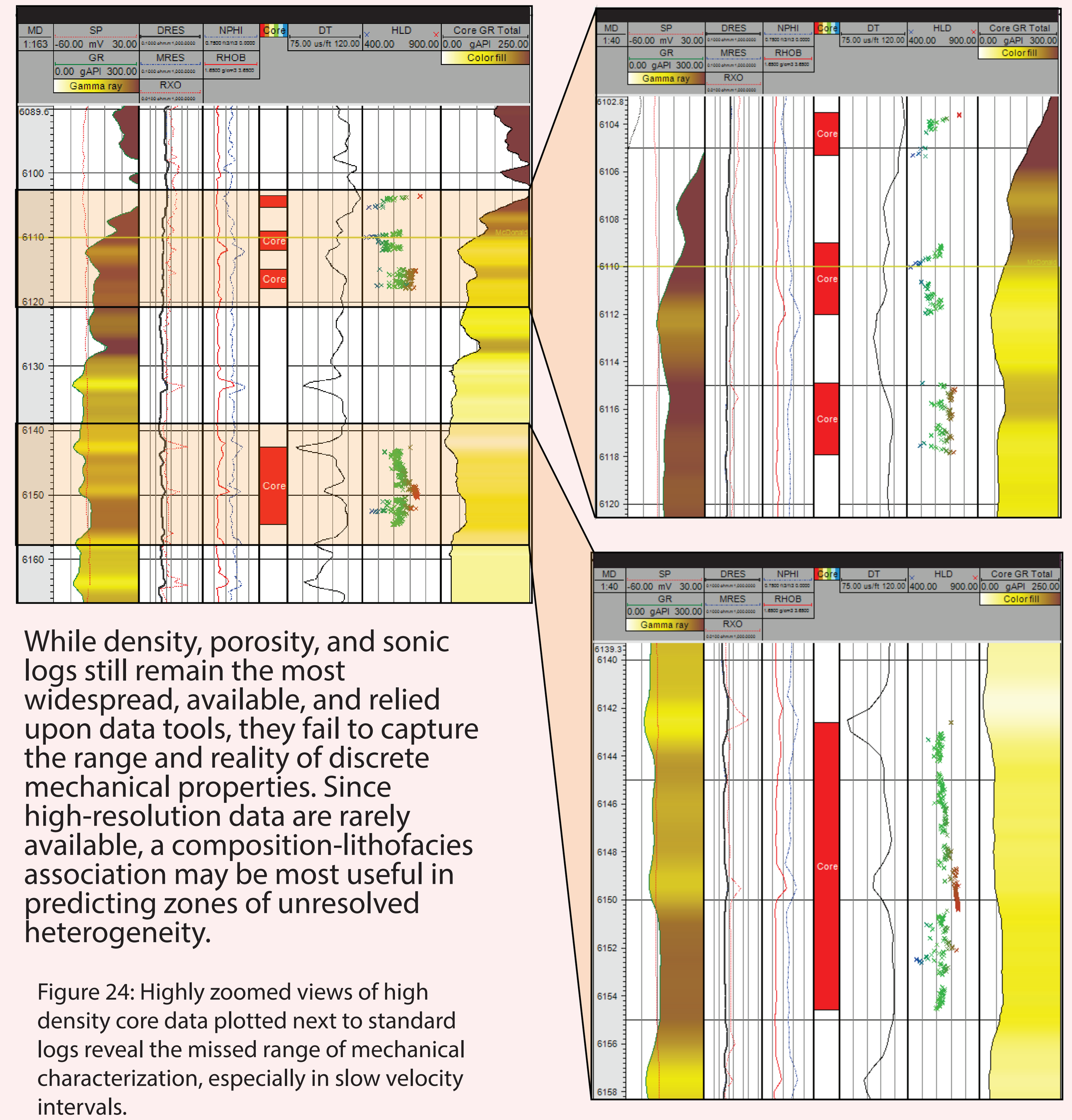


FIGURE 21: Conceptualized ternary diagram of reservoir potential in unaltered and embrittled lithologies.
Modified from Williams (1988).

WELL LOG COMPARISON



While density, porosity, and sonic logs still remain the most widespread, available, and relied upon data tools, they fail to capture the range and reality of discrete mechanical properties. Since high-resolution data are rarely available, a composition-lithofacies association may be most useful in predicting zones of unresolved heterogeneity.

Figure 24: Highly zoomed views of high density core data plotted next to standard logs reveal the missed range of mechanical characterization, especially in slow velocity intervals.

WELL LOG DISCUSSION

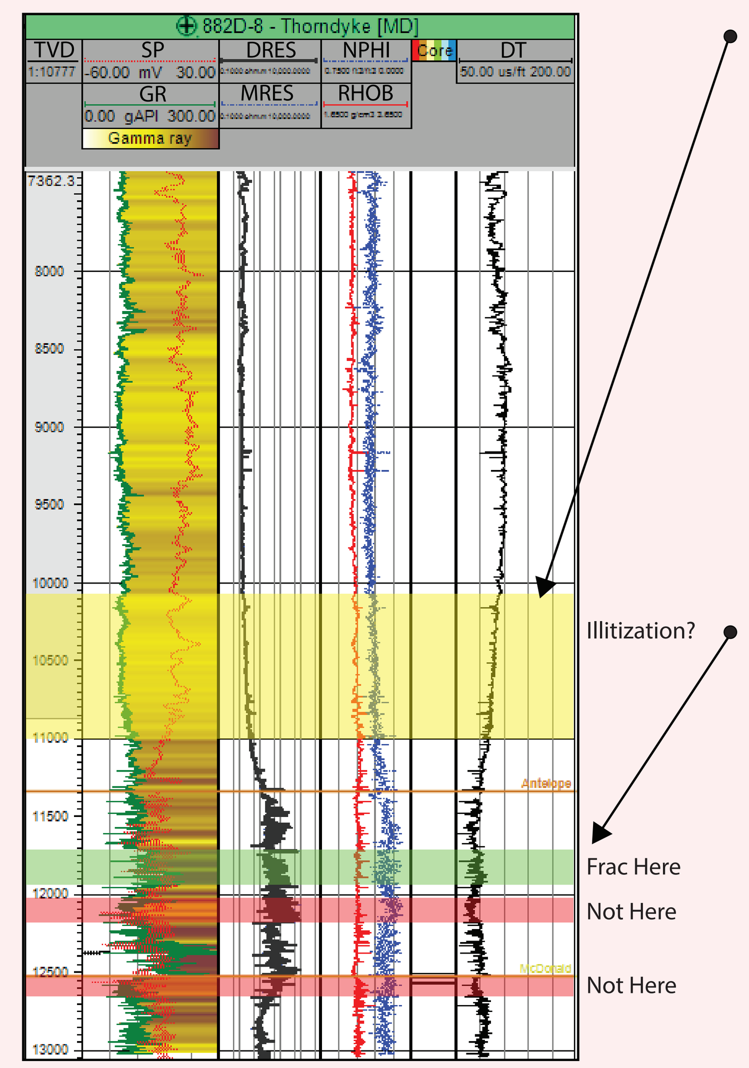


Figure 25: A standard log suite from one of the few wells that probe the potential of the Monterey Formation as a self-sourced reservoir rock the San Joaquin Basin. A shift from 10,000' - 11,300' (yellow) matches estimated depths for advanced illitization along with trends for harder and more silica-rich rocks (Figures 17 & 22). Green and red intervals consider sonic travel time as a measure of rock strength and fracturability related to gamma highs and lows.

- The onset of a shift in density, porosity, and sonic travel time generally agree with predicted illite/smectite transformations in the San Joaquin Basin. This shift precedes the transition to higher gamma ray and is evidence for the third step in diagenetic hardening as opposed to gradual compaction.
- Although quartz is considered a favorable factor in brittleness, excessive quartz in deeply buried siliceous mudstones may have extremely high strengths that resist mechanical failure.
  - Even moderately clayey UMF mudstones have enough quartz to brittlely fracture. Fractures will propagate into lower strength rock, while pure quartz is presently too strong.
  - However such zones might be naturally fractured from a consistent geologic history of being brittle.

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SUMMARY

- Composition and mechanical properties are well correlated in opal-CT and quartz-phase lithologies of the upper Monterey Formation (UMF). (Fig 10 & 16)
- Mechanical properties are calculated with a much wider variance than core-plug lab results suggest. Fracture propagation may be significantly inhibited by the common occurrence of thin intervals not represented in core-plug or well log data.
- Illitization at depth may promote a hardening related to pore-filling silica cementation that is often miss-attributed to compaction.
- Opal-A (diatomaceous) lithologies have no clear results in mechanical correlation with composition. The rebound hammer methods are ineffective in differentiating strength in very high porosity rocks.
- Exceedingly high silica (quartz) content may over-strengthen deeply buried UMF siliceous mudstones making them fracturable.

FUTURE WORK

- Further analysis of XRF geochemical data to better define the elemental detritus definition and hardness variance from specific clay types.
- Correlate and calibrate HLD relationships to Poisson's Ratio, Young's Modulus in the UMF.
- Compare the illite/smecite transition and hydrocarbon maturity to other shale plays to determine deep diagenesis and unconventional potential.
- Modeling scenarios of bedding composition, thickness, and spacing for maximum fracture access in a mechanically stratified sequence (Figure 21).
- Analyze anomalies in production data from opal-A to opal-CT transition zones to identify and further study mixed-reservoir behavior in siliceous mudstones.
- Predict a mixed-reservoir play fairway by mapping thin and heterogeneous compositions at the opal-A to opal-CT transition zone.

ACKNOWLEDGMENTS

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