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.
In the San Joaquin Basin, siliceous mudstones of the Upper Monterey Formation (UMF), exhibit a complex range of physical and mechanical heterogeneity. At a spatial scale, the UMF is primarily composed of clay, interbedded with silt, sand, and sandstone. Clay-rich layers may be thinly interbedded. Minor calcite, dolomite, quartz, and sandstone are also present. Framework analysis shows dramatic changes in composition over short distances.

Mechanical stratigraphy.

Previous studies have characterized the UMF lithofacies and their stratigraphic relationships. Strain style and stress depend on the properties of individual beds. Brittle lithologies tend to fail by joints and faults, whereas plastic beds fail by folding. Composition, bed thickness, and structural position are all related to fracture style, spacing, and length. (Figure 6 & 7)

Results confirm our initial hypothesis of a transitional rock response to pressure and temperature. Rock samples from the Upper Monterey Formation (UMF) were collected from the Belridge Oil Field in the San Joaquin Basin, California. The UMF is primarily composed of clay, interbedded with silt, sand, and sandstone. Clay-rich layers may be thinly interbedded. Minor calcite, dolomite, quartz, and sandstone are also present. Framework analysis shows dramatic changes in composition over short distances.

The mechanical heterogeneity of UMF lithologies is governed by their porosity and composition. Brittle lithologies tend to fail by joints and faults, whereas plastic beds fail by folding. Composition, bed thickness, and structural position are all related to fracture style, spacing, and length. (Figure 6 & 7)

Brittle lithologies have lower hardnesses than clay-rich rocks in every diagenetic phase and track well when plotted with clay content and diagenetic grade. Quartz-phase rocks continue to harden without a change in silica phase. Clay-rich lithologies have lower hardnesses that clay-rich rocks in every diagenetic phase and track well when plotted with clay content and diagenetic grade.

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Partial diagenesis of compositionally heterogeneous intervals amplifies the contrast in hardness. The interval's rock sample hardness (Figure 6) is a useful metric to determine the failure point of rock samples. An empirical relationship between hardness and porosity, diagenesis, and rock sample geometry was established. (Figure 6)

Synthesis.

Our findings demonstrate that it is important to consider the rock's composition in predicting its strength ofSiliconous mudstones continue to harden through silica maturation, and clay cementation, organic maturation, and diagenetic stages show how clay-rich lithologies. Brittle lithologies have lower hardnesses than clay-rich rocks in every diagenetic phase and track well when plotted with clay content and diagenetic grade. Quartz-phase rocks continue to harden without a change in silica phase. Clay-rich lithologies have lower hardnesses that clay-rich rocks in every diagenetic phase and track well when plotted with clay content and diagenetic grade.

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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 expusion, and physical collapse at transition boundaries (Figures 2 & 17). Stepwise porosity loss is linked to diagenetic stage, 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 filite to smectite where there is an expulsion of water, dispersion of silica, and reduction of porosity (increased grain contact interactions).

How is this related to porosity?

Silica diagenesis is far by 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 phreatic 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.

Targeting extremely heterogeneous successions.

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 diagenetic mechanisms. Since high resolution data is rarely available, a composition-lithofacies association may be most useful in predicting zones of unresolved heterogeneity. 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/smectite 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.

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REFERENCES