Mudrock Diagenesis with Depth and Thermal Maturity and How it Impacts Petrophysical and Mechanical Properties in the Upper Cretaceous Eagle Ford Group

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Summary (All headings should be Arial 12pt bold)

The Upper Cretaceous Eagle Ford Group (EF) is composed of massive, laminated, and/or burrowed limestones, marls, and mudstones deposited on the drowned south Texas shelf below storm-wave base. Numerous volcanic ash layers were blown to the shelf, directly deposited or being reworked into the EF Group. An investigation of diagenesis with burial using seven cored wells from shallow to deep burial (depth ranges from 3,270 to 13,670 ft; BHT from 126 to 285°F) and from east (near the San Marcos Arch) to west (Maverick Basin) delineated a complex diagenetic history as a result of changes in water chemistry, redox condition, and burial history. The study sheds lights on how variable the diagenesis could be and how they can potentially affect reservoir quality, petrophysical, and geomechanical properties of mudrocks. This study focuses especially in the organic-rich Lower Eagle Ford (LEF) member deposited largely under anoxic-euxinic conditions. At deposition, porosity was as high as 70 to 80% but with burial porosity dropped to less than 10% because of diagenesis. The EF followed a diagenetic pathway from the deeper marine environment directly into the burial environment and was not affected by meteoric diagenesis. Compaction was the major porosity lost mechanism followed by cementation. Cementation of authigenic quartz and the coccolith hash by calcite with burial were major

processes forming a rigid and lithified brittle framework. The texture and fabric of these cements increase mechanical strength of the EF mudrocks significantly. Near seafloor sulfate-reduction, Fe-reduction, and methanogenesis processes produces calcite cementation (some as nodules and concretions). Feldspar diagenesis included the transformation of K-feldspar to clay minerals and albite with depth. Also, authigenic albite was deposited as grains with volcanic ashes. The shallow, immature EF limestones and marls have abundant interparticle pores, high porosity, permeability, and water saturation. With thermal maturation, bitumen conversion increases oil wetness of the rock. Clay mineral diagenesis is complex with smectite transforming to mixed layered clay with thermal maturation; however, illitization trend was not observed in the EF marls. Authigenic kaolinite and chlorite form in biota tests and matrix, and smectite forms during alteration of volcanic ashes and was then eroded, reworked and/or incorporated into the matrix. These clay minerals precipitate in the original interparticle pores, further reduce porosity, and impact permeability, fluid saturation, and capillary pressure. Diagenesis also implies changes in redox conditions. Some limestone beds are rich in ankerite (Fe-calcite) implying iron being incorporated in the calcite during relatively oxic conditions. These ankerite-rich limestones were found in OAE-II and MCE intervals in the LEF.

Theory / Method / Workflow

Eagle Ford (EF) samples from eight subsurface cored wells, mostly southwest of San Marcos Arch, were selected based on integrated lithofacies and chemostratigraphy. The majority of the subsurface samples were selected in the lower Eagle Ford (LEF) subgroup as this interval has been a major target for hydrocarbon production using horizontal drilling and hydraulic fracturing. Wireline logs and high-resolution (2-inch interval) XRF data are available on all seven cores (Harbor, 2011; Fry, 2015; Ko et al., 2017; Alnahwi, 2018; Alnahwi et al., 2018; Alnahwi and

Loucks, 2019). These data help identify the boundary between upper and lower Eagle Ford. The cores were described and sampled for thin-section and SEM petrography work based on the review of high-resolution XRF data. Polished thin sections were used to examine lithofacies variation, small-scale sedimentary features, biota, and bioturbation. Aliquot samples were selected on the basis of different lithofacies for Ar-ion milling and high-resolution FE-SEM imaging for diagenesis and pore type/pore-system characterization. A total of 47 Ar-ion milled samples were prepared for SEM micropetrography.

To estimate the thermal maturation of these cores, samples were analyzed using the LECO instrument, Rock-Eval II and/or HAWK pyrolysis to access the total organic carbon (TOC) content, types of kerogen, and thermal maturity.

Two cores (one in the Maverick Basin and the other in the Karnes trough) was selected for a very detailed and quantitative mineralogy on bulk rock and clay minerals.

Results, Observations, Conclusions

Figure 1 shows the diagenetic processes and likely paragenetic sequences in Eagle Ford mudrocks. Cementation and compaction are the two most important diagenetic processes in OM-rich mudrocks. This study shows how diagenetic processes varied from shallow to deep burial and how they might have changed the fluid and rock properties in the Eagle Ford.

The immature Eagle Ford marl and limestone show relatively low resistivity wireline-log response and abundant interconnected interparticle pores, permeability, and water saturation. From both extracted bitumen and petrographic studies, early bitumen conversion and migration with depth in the OM-rich marls was confirmed. Limestone pores were not completely cemented and form reservoirs or carrier beds for oil migration. We have also noted the abundance of K-feldspar in these shallow Eagle Ford samples. Formation of pyrite framboids and cementation by calcite, kaolinite, and quartz (opal-A transformation) occurred probably at shallow burial. These cements can inhibit compaction-related porosity loss and preserve interparticle pore spaces.

At deeper burial depth, the amount of K-feldspar decreases and the amount of kaolinite increases. During oil window diagenesis, smectite begins to dissolve and transformed to illite (less expandable), with an intermediate stage of mixed-layer illite-smectite and kaolinite started to be replaced by chlorite. OM pore development is closely related to changes in oil composition related to steps of hydrocarbon generation and migration. Increased amount of clay mineral precipitation with depth, causing further porosity reduction. When increased amount of clay clogs the interparticle pores, capillary pressure increases and permeability decreases as a result of decreasing pore-throat size. Clay minerals can also affect fluid properties and affect thermal cracking of organic matter. We have also documented that chloritization and dolomitization becomes more intensive at deeper burial depth.

We did not find a trend showing gradual transformation of smectite to increasing replacement of illite in R1 I/S. Extra smectite and kaolinite were formed from the alteration of volcanic glass. We suspect the alteration of glass forming smectite might cause smectite without a preferred orientation and retard the illitization reaction, similar as what Aplin et al. (2010) suggested. Further QXRD analyses will be made to prove the hypothesis.

Novel/Additive Information

This study summarizes the complete diagenetic and paragenetic sequences in an Upper Cretaceous calcareous mudrock system and links certain diagenetic processes to redox state of the paleodepositional environment.

Acknowledgements

Authors would like to thank Patrick Smith for the preparation of some Ar-ion milled samples, Dr. Priyanka Periwal for her help imaging some samples, and Dr. Ahmed Alnawhi for the sample selection in L1 and L3 wells. Authors would also like to thank Dr. Xun Sun for the solvent extraction work using Soxhlet. Also, we thank Evan Sivil for scanning and calibrating the XRF in all the cores. We thank Marathon Oil Company provides us access to the K1 and K2 cores and Talisman/Repsol provides us access to the L3 core. Dr. Steve Ruppel and Dr. Kitty Milliken provided insightful discussions, suggestions, and inspiration during the manuscript preparation.

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