Duration and Climate Effects on Meteoric Diagenesis: Non-Karstic Control on Distribution of Porosity and Permeability*

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Abstract

As porosity and permeability in carbonate reservoir systems are the products of both depositional history and diagenetic alteration, predictive models typically require an understanding of deposition and diagenesis. Improved understanding of carbonate depositional systems and sequence stratigraphy has led to models for prediction of depositional facies in the subsurface. Prediction of diagenetic effects on porosity and permeability, however, has been more challenging because of the complexity of geochemical and hydrologic processes, the relative inaccessibility of such systems for study, and the immense amount of geologic time involved. Fundamentally, part of the diagenetic history of a carbonate reservoir system can be predictable from its depositional and stratigraphic framework.

Introduction

This work, which is part of the ExxonMobil-sponsored Fundamental Controls on Flow in Carbonates academic alliance, presents results from a series of studies of Miocene carbonate strata from southeast Spain (Figure 1). The site is chosen because of its well-constrained sequence stratigraphic framework and preserved paleotopography, which allows evaluation of the diagenetic effects that are related to meteoric diagenesis associated with subaerial exposure along sequence boundaries (Figure 2). Furthermore, as these young strata have never been buried, the porosity and permeability result from deposition and early diagenesis alone, without the ambiguity of a later history of burial diagenesis. As both paleotopography and sequence boundaries can be either identified or reconstructed in the subsurface, this study adds to the understanding of how these parameters can be used as predictors of diagenetic alteration of porosity and permeability in carbonate reservoirs.

The results show that even with seven surfaces of subaerial exposure, each with associated meteoric diagenesis, significant diagenetic alteration was only associated with the uppermost one.

First Six Surfaces

Sequence boundaries on DS1A, DS2, DS3, and three of the first four sequences in the TCC all show petrographic evidence of subaerial diagenesis on the surface (Figure 3). Thin (less than a meter) zones below these surfaces contain caliche laminated crust, rhizoliths, and autoclastic breccia, all indicating periods of paleosol formation. Cement stratigraphic analysis above and below these surfaces shows only minor pendant and meniscus calcite cementation and such minor dissolution of aragonitic components, that it is barely recognizable. Cementation and moldic porosity associated with the first six surfaces is minor, apparently because of dominant calcitic mineralogy in DS1A on the first surface, and short duration of exposure and aridity on the next five.

Uppermost Surface – Dolomitization and Moldic Porosity

Diagenesis along the last (uppermost and seventh) surface, which has remained exposed since the end of the Miocene, had the greatest effect on porosity and permeability. Petrography shows that after deposition of the fourth and final sequence of the TCC, dolomitization was coeval with extensive moldic porosity (Figure 4). The process that developed this moldic porosity was the most important of the porosity-enhancing diagenetic processes. Immediately after this dissolution, grainstones, packstones, and microbialites had median porosity of approximately 28-30%, with common permeabilities near 1,000 md.

Dolomite decreases in abundance updip in proximal areas, shows isotopic trends indicative of mixing between fresh and evaporated seawater, and preserves fluid inclusions with salinities ranging from near fresh to 43 ppt (Figure 5). These observations indicate that during initial fall in sea level near the end of the Miocene, climate and hydrologic setting led to local meteoric recharge that mixed with evaporated seawater. It is mixing with this mesohaline end member that led to extensive dolomitization and moldic porosity. A distinctive climate, hydrologic setting, and sea-level position would be required during subaerial exposure to produce these conditions, and subsequent extensive alteration by mesohaline mixing.

Uppermost Surface – Calcite Cementation

During the Pliocene and Pleistocene, much of the upper surface remained exposed subaerially because of eustatic fall in sea level and regional uplift. The petrography shows that after moldic dissolution and dolomitization, calcite cementation was the dominant process. Symmetric fabrics indicate precipitation in a phreatic setting. The calcite contains fluid inclusions that yield Tm ice of 0.0ºC. The $\delta^{18}O$ values lie along a meteoric calcite line between -5 and -6‰ with $\delta^{13}C$ as negative as -8‰. These data indicate precipitation in a freshwater phreatic setting.

In cross section, distribution of calcite cements shows two laterally continuous zones where phreatic-zone calcite cement exists. An interval between the two zones lacks such calcite cement, although a minor amount of vadose calcite cement is present. Boundaries delineating these cemented and uncemented zones cut across stratigraphic surfaces. A plausible hypothesis is that each cemented zone coincides, to some degree, with a position near the top of a different paleo-water table. As the Pliocene-Pleistocene history is known to reflect regional incision of the topography during uplift, it is expected that the upper-cemented zone is the oldest one and the lower cemented zone is the youngest one.

The meteoric calcite cements had a profound effect on both porosity and permeability. Increases in calcite cementation led to predictable decreases in both porosity and permeability (Figure 6). The relationship between calcite cementation and porosity and permeability are lithofacies dependent. Such relationships are the most appropriate for application to subsurface models.

Application of Results

The La Molata, Spain example provides further support that surfaces of subaerial exposure are not consistent positive predictors of large-scale porosity. Most events of subaerial exposure generated no large-scale karstic porosity. For most subaerial exposure surfaces in the study area, meteoric diagenetic alteration was minor owing to calcite mineralogy of constituents in underlying strata, short time of subaerial exposure, or arid conditions. Thus, for most of the sequence boundaries studied, the results show that one should not casually predict porosity to be associated with subaerial exposure in updip areas without special conditions being met.

In the area studied, most moldic porosity was generated just at the end of Miocene, when climate conditions led to increased rainfall and meteoric recharge that coincided with slight evaporation of Mediterranean seawater. With the appropriate hydrogeology, the combination of meteoric recharge and evaporated seawater leads to mixing between meteoric water and mesohaline seawater, resulting in large-scale development of moldic porosity and dolomite. This short term and distinctive event was the most important porosity-enhancing process in the system. Prediction of such processes in subsurface analogs requires an understanding of the climate and hydrogeologic setting that would lead to such mesohaline mixing.

After dolomitization, strata were largely exposed subaerially for the approximately 5 million years following the Miocene. This time interval included multiple long-lived intervals of wet climate that led to significant meteoric recharge. Unlike predictions of common models, the meteoric diagenesis led to porosity and permeability reduction through calcite cementation rather than porosity enhancement. Relationships of reduction in both porosity and permeability are predictable based on depositional facies and can be incorporated into subsurface models. Simultaneous uplift and eustatic fall resulted in landscape incision, all of which caused meteoric water tables to successively drop through the succession, leading to heterogeneity reflecting two major cemented zones that cut across the stratigraphy. Modeling the distribution of meteoric cementation-associated heterogeneity is among the major challenges in predicting reservoir porosity in the subsurface.

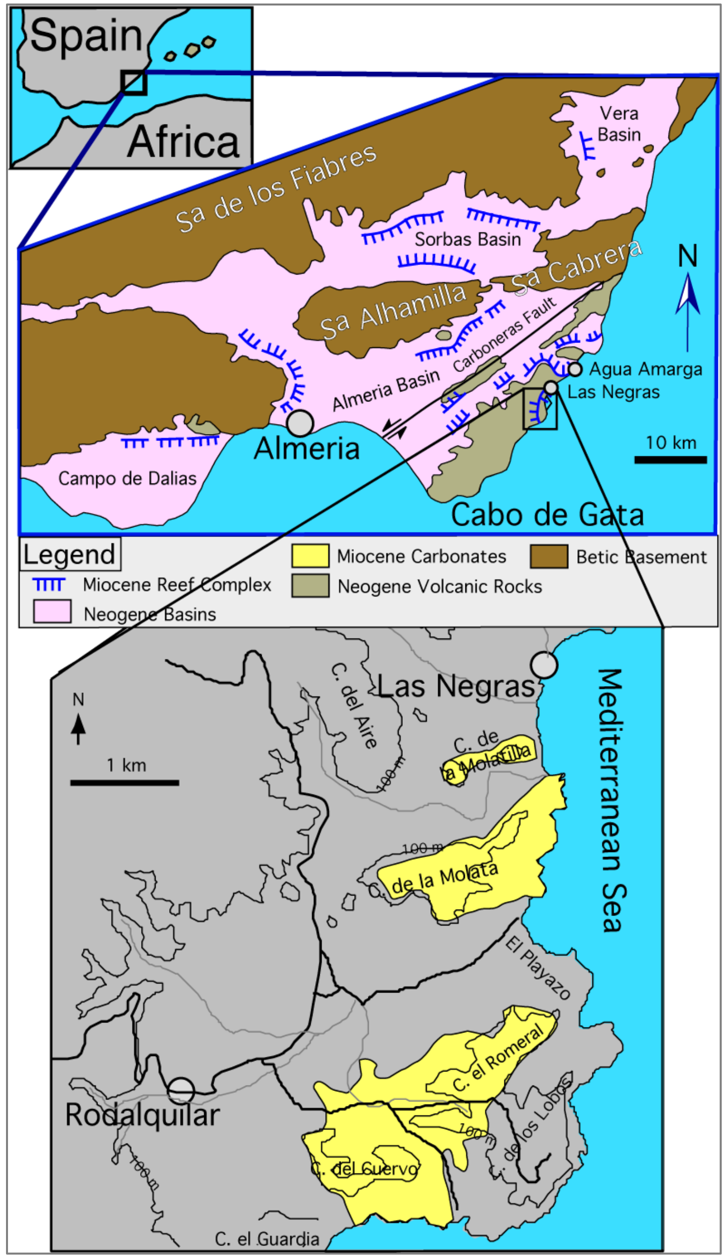


Figure 1. Location map of La Molata study area in southeast Spain.

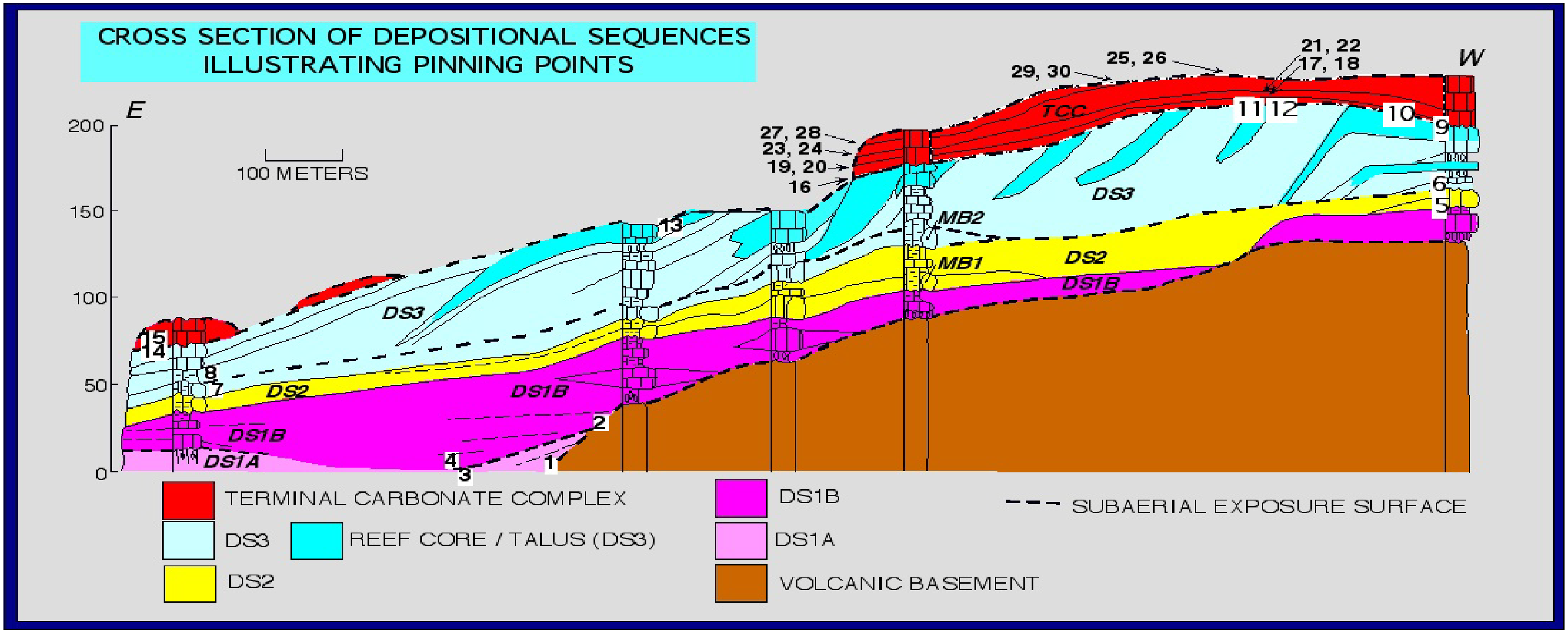


Figure 2. Schematic cross section of Miocene strata in southeast Spain illustrating pinning points used in conjunction with preserved paleotopography to evaluate sea level history.

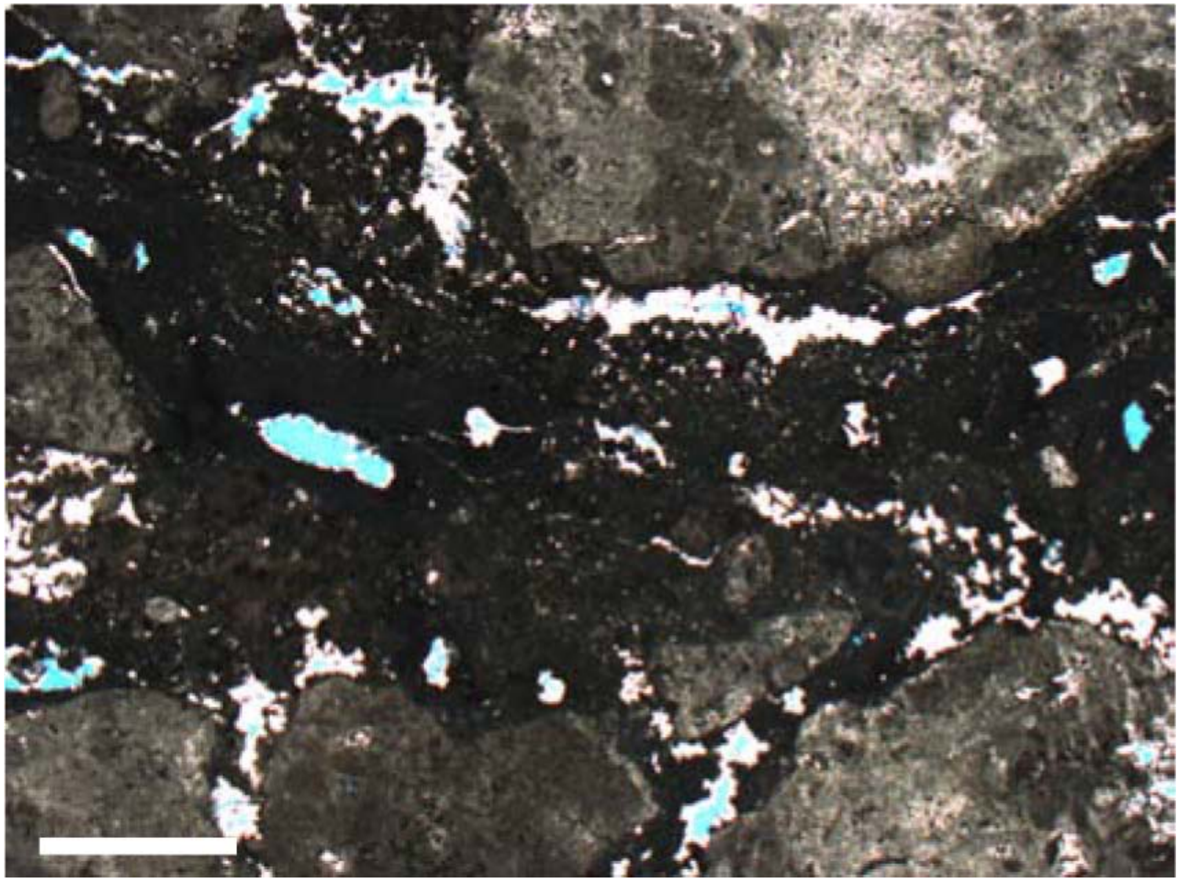


Figure 3. Transmitted light photomicrograph showing autoclastic breccia and rhizoliths. Scale is 1 mm.

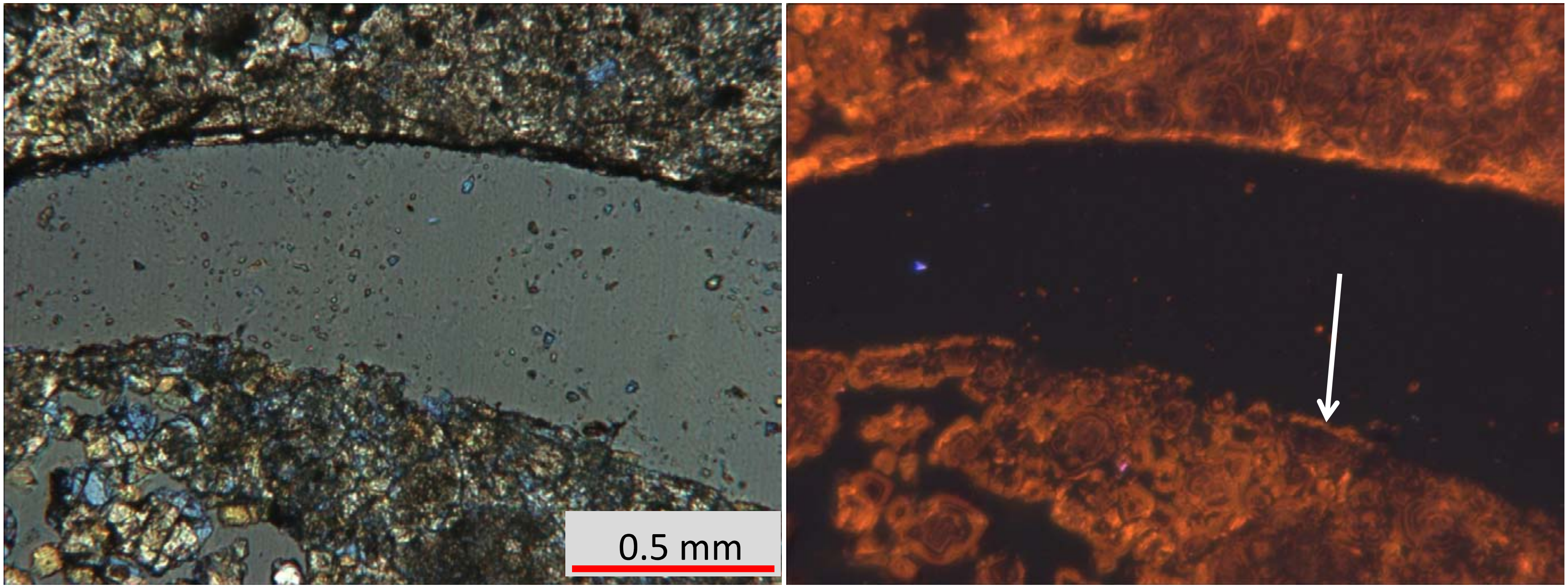
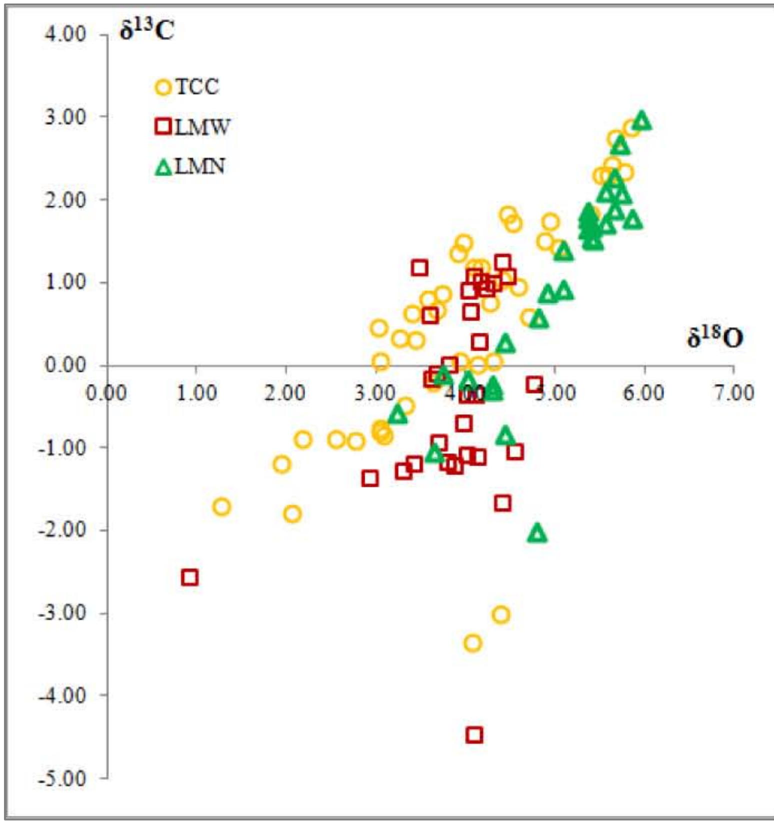


Figure 4. Paired transmitted light and cathodoluminescence photomicrograph illustrating moldic pore surrounded by cathodoluminescent-zoned dolomite. Later growth zones are present inside of mold (white arrow) whereas both earlier and later growth zones are present outside of mold. This indicates that dolomitization and moldic porosity were coeval.



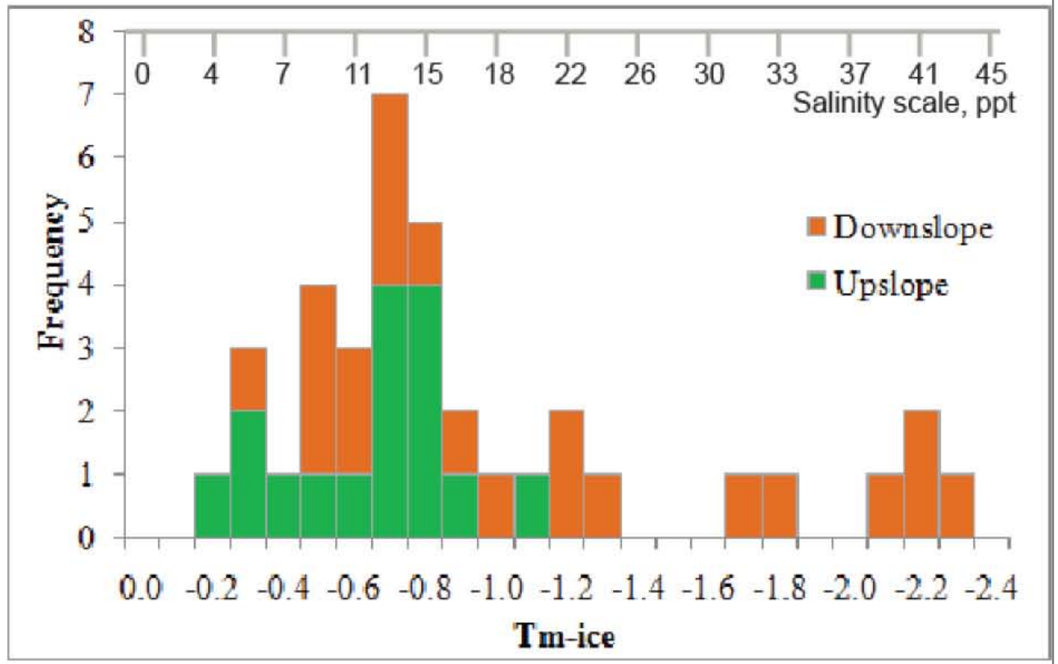


Figure 5. Stable isotope and fluid inclusion Tm ice data from dolomite, indicating mixing between fresh and evaporated marine (mesohaline) end members.

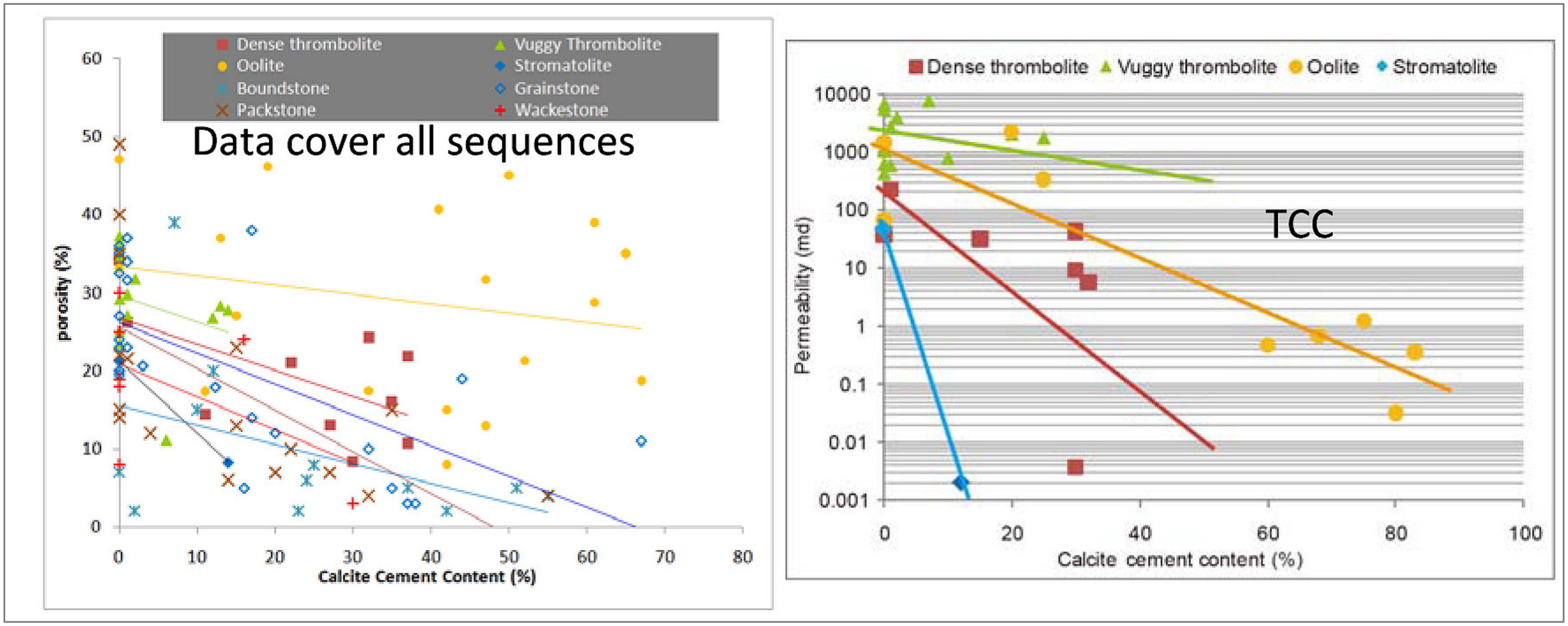


Figure 6. Lithology-dependent relationships between meteoric calcite cementation, porosity, and permeability.