How Porosity is Developed or Preserved in Unconventional Hemipelagic Carbonate Reservoir? Case Study in SE France (Provence, Durance Area)*

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Abstract

Understanding unconventional reservoirs with low porosity and permeability of the host rock is a major scientific and economic challenge with applications for the oil and gas industry, underground water management and industrial risk assessments. Hydrogeologists consider that tight rocks have high fracture permeability and negligible storage capacity, although deep unconventional tight reservoirs can produce significant quantities of oil and gas.

The key question addressed in this article is how fluid flows through the tight host rocks. This question is of prime importance for better understanding fluid flow both in the near surface aquifers and in the deeply buried sedimentary reservoirs.

We investigated the lower Cretaceous carbonates of the Durance area. From Berriasian to Valanginian the area of interest is positioned in the steeply slope-to-basin transition open towards the Vocontian Basin. In such context, deposits are represented by a mix of micritic and fine-grained sediments. This association is representative of a hemipelagic environment.

Observations

Present day observations of hemipelagic carbonate matrix allows comparing these rocks as analogues for unconventional reservoir with a host rock average permeability of 10^{-16} m^2 and porosity of 0-4%. Permeability in fracture zones, composed with a large variability of fracture

type and fracture size, reaches high values of 10^{-8} m^2 and allows the shallow aquifer drainage through a dozen of perennial springs with a significant annual flow of 1000 m^3/h. The question of the diffusivity in these rocks at depth is addressed through a pluri-disciplinary approach including: (1) a sedimentological analysis of upper Berriasian to lower Valanginian rocks based on outcrop observations and thin sections description; (2) micro-structural and geodynamic (burial history) analyses; and (3) petrophysical measurements, including helium, water and mercury porosimetry and p-wave measurements, on deep borehole core and on outcrops.

South-east basin geodynamics, for lower Cretaceous sediments, was investigated in terms of subsidence. Major hiatus (from lower Hauterivian to Maastrichtian) which occurs in the area of interest leads to combining datasets from the Durance region and from peripheral locations evolving in the same depositional environment framework. The obtained curve displays three main phases: first is a global subsidence reaching the depth of 1000 m, then a global and fractionated uplift (three main steps corresponding to pulses of compression), and finally lower Cretaceous rocks do not record significant subsidence.

The studied lithostratigraphic interval is represented by four sedimentary formations and nine depositional facies. These facies are linked to basinal environments and structured from low energetic to gravity/tractive processes. According to their dominant constitutions, sedimentary formations were grouped into two main lithologies: mud-dominated and grain-dominated. Host rock porosity reaches 0-4% in mud-dominated formations and 1% to more than 8% in grain-dominated formations. Fractures and stylolites affect both of the considered formations but in variable morphologies and frequencies.

Results

Results of this study show a high degree of heterogeneity of hemipelagic carbonates' porosity. This heterogeneity is due to differential evolution of the host rock during burial history depending on the ratio of grain-to-mud initial content of the sediments. Initial porosity was better preserved in grain-dominated formation where early micritic cements built bridges between grains generating a solid skeleton that supported the burial compaction effects. Indeed, no concavo-convex grain contacts and a very slight stylolitisation, mainly represented by diffuse microstylolites, were observed in such formation.

No such phenomena were observed in mud-dominated facies where micrite first diffuse within the rock matrix was progressively rearranged under stress (lead to coalescent and fuzzy micrite arrangement). The compaction effect in mud-dominated formation is well expressed by the amount of stylolites. A comparative microstructural study was performed in mud-dominated facies in order to determine a relative chronology between stylolitisation and fracturing regarding the burial history of lower Cretaceous rocks. Ten different microstructural items were described depending on their morphology, their filling and their size. The counting of more than 1000 contacts between the different stylolites types and between fractures and stylolites allows proposing a relative chronology of microstructural discontinuities development in lower Cretaceous mud-dominated formations. This chronology was then compared to the obtained subsidence curve. Horizontal stylolites were generated in the first phase of the burial history when the subsidence was continuous and reached its maximal. Thus, due to stress relaxation and the rapid poly-phased uplift, stylolites are partly open (mainly compaction bands). The last stage of burial history induced the reactivation of pre-existing fractures which play complex opposite roles on the porosity that are difficult to differentiate in this study.

This study then shows a differential response of compacted grain and mud-dominated facies to deviatoric stress characterised in the Durance area by regional 1 km uplift. Grain-dominated facies poorly responded to the tectonic stress. They appear relatively lightly fractured and a few deformations are observed at the grain scale. In the mud-dominated facies, a high density of fractures and the partial opening of the stylolithes generate double fracture-stylolite porosity. Grain content in hemipelagic facies is enough to induce such different porosity evolutions of sediments and the 0-8% actual matrix porosity (Figure 1).

The coupling of p-waves velocity and porosity measurements allows differentiation of a wide range of porosity for a restricted value of p-wave, and at the opposite a wide range of p-wave value for a single value of porosity in both mud- and grain-dominated formations. Opened stylolites occurrence explain the porosity variations and open cracks and fractures explain the seismic velocities variations. These interpretations are linked to the geometries and the contact point between stylolites walls compared to fracture walls. Indeed, cracks and fractures represent straight and continuous open space rather than stylolite which displays marbled contacts and discontinuous open space porosity. Finally, cracks and fractures poorly influence the porosity as compared to stylolites.

Conclusion

These results are of interest for the understanding of fluid trapping in basinal series that often are composed of alternate grain-dominated and mud-dominated facies with a more or less high carbonate-to-clay ratio. Indeed, due to early diagenesis, gas and oil generated at high burial depths may remain trapped in the grain-dominated facies, or they may migrate and store into mud-dominated layers thanks to the opening of the compaction features under stress inversions. This work allows proposing a global classification of unconventional reservoirs types in the location where they are described and compared to our case study.

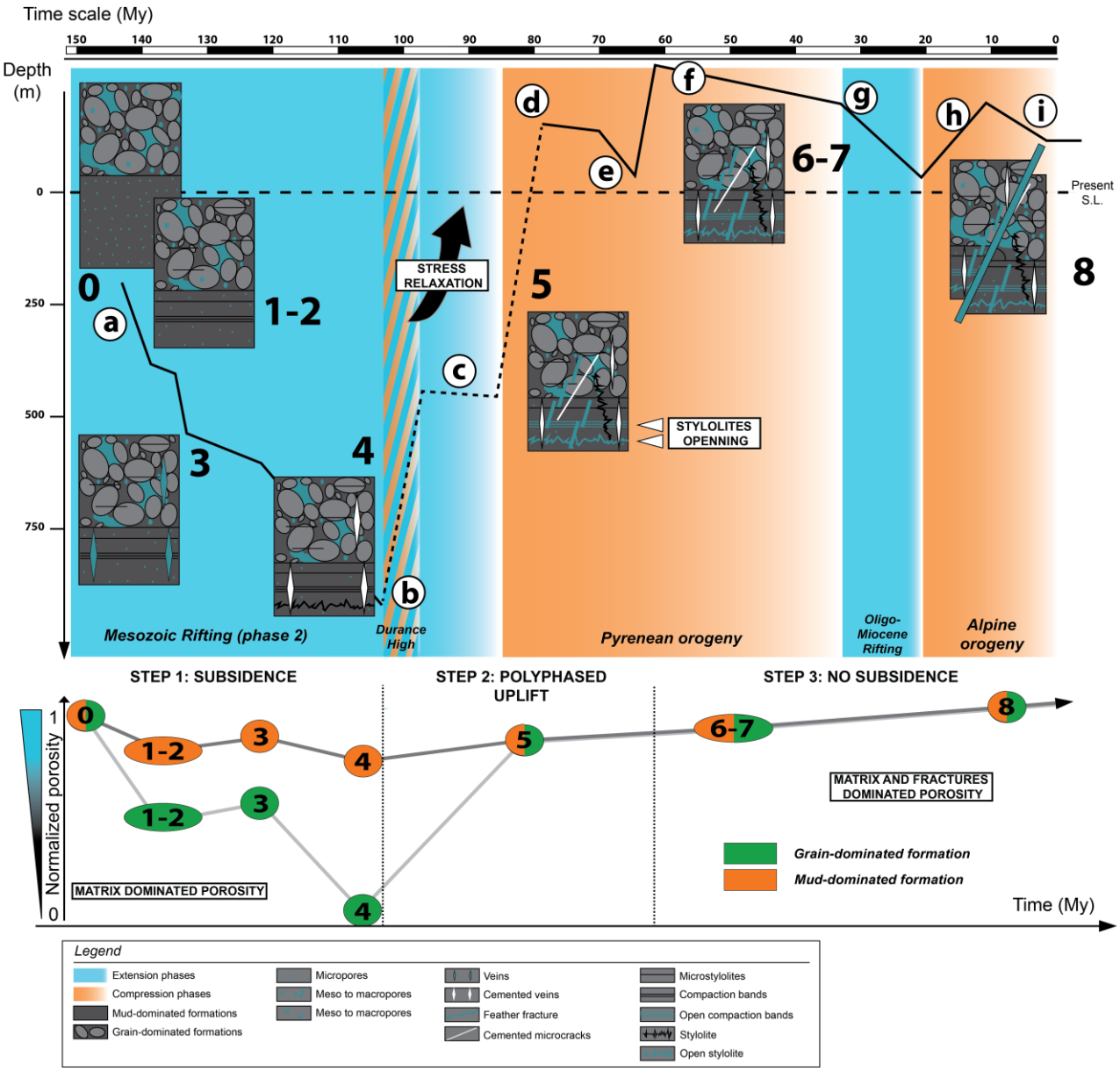

Figure 1. Porosity evolution in Lower Cretaceous deposits compared to the burial history.