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Structural and petrophysical characterization of mixed conduit/seal fault zones in carbonates: Example from the Castellas fault (SE France)

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The Castellas fault in SE France affects carbonate rocks with a plurimeter scale offset along 1.5 km of outcrop. In order to decipher the structural control on fault petrophysical and hydraulic character, we performed high resolution field structural mapping, laboratory porosity-Vp measurements, and thin sections analysis of deformations and diagenesis. Field mapping shows that the fault zone architecture displays strong lateral variations at the hectometer scale characterized by core thicknesses of 0–5 m, one or several slip planes, and varying fracture patterns within the damage zone. The fault zone heterogeneity may be related to the magnitude of the throw, the position along the fault and the affected rock facies. Laboratory measurements revealed a strong porosity reduction correlated to a Vp increase, related to the cementation of pore volumes within a decameter area around the fault plane. This fault-sealing occurred mainly through a chemical diagenesis related to fluid circulation within fault-zone heterogeneities. A 3D conceptual model of a mixed conduit/seal fault zone is proposed, characterized by sealed impermeable fault tips and more or less permeable units within which flow can occur either perpendicular or parallel to the fault strike.

1. Introduction

Fault-zone petrophysical characterization is a crucial issue in reservoir exploitation, because fault zones can behave either as hydraulic seal or as conduit. In the first case, fault zones lead to compartmentalizing of the reservoir (Caine et al., 1996); in the second case, they connect porous volumes and drain fluids along high-permeability corridors (Moretti, 1998; Géraud et al., 2006). In addition, combining petrophysical analyses with fault-zone structural characterization is a challenge, because faults may display a number of different hydraulic properties, depending on the presence of an impermeable core, the fault-zone width and complexity, and the diffusivity of the fracture pattern (density, connectivity, and strike).

Faults are discontinuities in rock mass associated with a slip along the fault plane. Strain not only affects the fault plane but also extends into the rock volume, the fault zone. The volume of rock included in a fault zone is commonly divided into three structural parts accommodating increased strain toward the fault plane (Chester and Logan, 1987): (1) the fault core, a centimeter-to-meter-wide area wherein the strain is mainly accommodated, characterized by fault rocks, and pervasive deformation that obliterates the initial rock facies; (2) the damage zone, a plurimeter-to-hectometer scale wide area containing numerous fractures related to the fault genesis, where fracture density and length decrease with the distance from the fault (e.g Micarelli et al., 2006b; Blenkinsop, 2008; Mitchell and Faulkner, 2009); (3) the protolith zone, the surrounding undamaged host rock not affected by the fault-related strain. These structural compartments have variable width, depending on fault properties such as the throw, the position along the fault, the rock type and its mechanical properties. In addition, the strain pattern on fault flanks is rarely symmetric (Billi et al., 2003; Micarelli et al., 2006a).

In carbonates, the initial rock-physical properties are highly variable, depending on the depositional facies, and are controlled by biological and sedimentary processes as well as by early diagenesis (e.g. Tiab and Donaldson, 1996; Lucia, 1999). Moreover, carbonates are more sensitive to diagenetic processes than siliciclastic rocks (e.g. Anselmetti and Eberli, 1993; Fournier and Borgomano, 2009). Thus, carbonates tend to easily acquire new rock-physical properties (over time and with burial depth) that are quite different from their initial properties. This phenomenon is particularly true along faults, especially where they experience polyphased deformations. Fault-zone properties can drastically change even with respect to shallowly buried (<1 km) and small throw faults. Thus, it is of major importance to couple structural

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and deformation approaches with diagenetic and petrophysical measurements, in order to accurately characterize the petrophysical properties within a fault zone and their evolution over time.

More generally, studying field analogs is necessary for hydraulic characterization of faulted reservoirs, in that field analogs enable investigators to reach the less-than-meter resolution that cannot be realized with classical seismic methods. In addition, field investigations allow to characterize the fault zone in three-dimensions and to investigate its property variations along the strike, which is not possible with borehole data. Consequently, this paper is focused on answering the questions: what genetic link exists between rock-physical and architectural properties in a carbonate fault zone? How does a fault zone acquire its petrophysical and hydraulic properties, spatially and over the time? To answer these questions, we characterized and quantified the Castellas fault zone (SE France) architecture and its variations along its strike with meter-scale resolution. We performed a very-high-resolution structural mapping and physical characterization of the fault-zone rock in the region, and finally attempted to determine whether the fault was a potential conduit or seal.

2. Geological settings

2.1. Regional geology

The Castellas fault is located in SE France, in Provence, near Marseille (Fig. 1A). This region is marked by successive tectonic events since early Cretaceous times (Fig. 1B). During early Cretaceous times, southern Provence was affected by an extensional tectonic context favorable for shallow-platform carbonate deposition. During the mid-Cretaceous, a regional uplift (Durance Uplift) led to the emersion and partial erosion of the early Cretaceous carbonates (Masse and Philip, 1975; Guyonnet-Benaize et al., 2010). The late Cretaceous era shows the return to an extensional tectonic and platform conditions in Provence, leading to the deposition of Late Cretaceous carbonates. From the Late Cretaceous, the tectonic context turned to compressional while the basin was located in the foreland of the Pyrénéo-Provencale orogeny. North-verging shortening caused a rise in E–W folds and thrust faults (Fig. 1A). During the Oligocene and Miocene, the tectonic context is extensional, due to West European rifting (Gattacceca, 2001), with a back-arc basin extension due to the Alpine subduction. From that time, the Alpine orogeny maintained a compressional regime that reactivated earlier Pyrenean folds and thrusts (Leleu, 2005).

2.2. Structural and kinematic context of the fault

The Castellas fault is located on the southern dipping limb of the E–W-striking La Fare ramp anticline. The fold limb is affected by a fault network running mostly parallel to the fold axis, among which is the Castellas fault (Roche, 2008). The fault strikes N060 to N070 (Fig. 2E) and dips 40–80° to the north. Its present-day vertical throw is metric and ranges between 1.5 and more than 5 m (at least) from west to east. We performed a detailed structural analysis of the polyphased kinematics in the field, as well as on samples and thin sections in the laboratory. The kinematic indicators on the fault plane indicate at least two slip episodes (Fig. 2D), the first due to extension, associated with normal dip-slip striations, and the second due to a strike-slip event associated with a strike-slip slickenside (pitch between 2 and 14°E). This latter episode is likely sinistral (Fig. 2E), considering the slickensides. The fault timing was deduced from cross-cutting relationships as well, using calcite veins, stylolithes, breccia, open fractures, and overall bed tilting (Fig. 3A–F).

Combining these observations led to the following scenario of fault-zone development. First, the fault formed, affecting the host rock while the bedding was horizontal, which produced a dark breccia (Breccia 1) in the fault core (Fig. 3A) and tension gashes mainly running parallel to the fault plane and present on both sides of the fault plane. The breccia contains angular clasts, laminated and micritic dark matrix, and pendular calcite cements located under and at the clast contacts. These markers suggest that voids opened in the rocks that were subsequently filled by sedimentary matrix during an extensional tectonic context. Second, the host rock is affected by a second breccia (Breccia 2), which cuts through the first breccia (Fig. 3B and C). This breccia is made of smoother clasts surrounded by an orange matrix or by calcite cement. It is affected by numerous randomly distributed stylolithes, especially in the first meter closest to the fault plane. Observing the thin sections, we can see that stylolithes are emphasized by a dark orange border, likely composed of insoluble clay residues. Rounded breccia clasts are often derived from a thrust or strike-slip fault movement. Thus, these strain markers are associated with

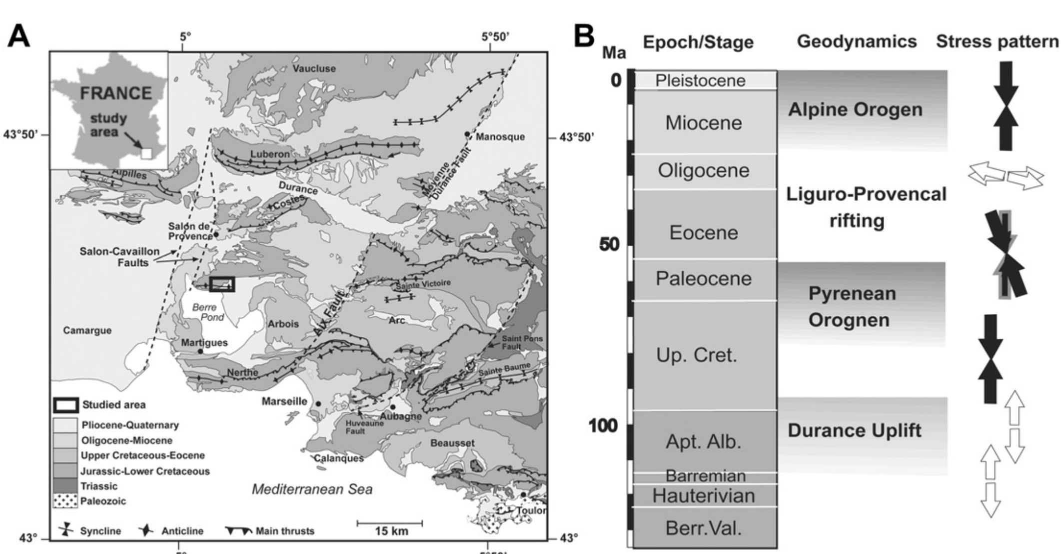

Fig. 1. A. Structural map of south Provence (from Lavenu et al. (in preparation) modified from Lamarche et al. (2010)). B. Tectonic phases and stress regime since Mesozoïc (modified from Lamarche et al. (in press)).