Structural and Petrophysical Characterization of Mixed Drain/Barrier Fault Zones in Carbonates: Example from the Castellas Fault (SE France)*

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Abstract

Carbonate rocks are highly heterogeneous and complex, as they are induced from superimposed biological, chemical and mechanical processes. Few studies have been dedicated to the characterization of their petrophysical heterogeneity at a meso-scale, i.e. above the laboratory scale and below the common seismic resolution. In this article, petrophysics, geophysics and geostatistics are combined at outcrop scale to characterize the relationships between heterogeneities and the spatial distribution of petrophysical properties. Thus, three decimetre-scale outcrops (Cassis, Calissane and Grignantes outcrops) presenting contrasted faciologic, structural and sedimentary heterogeneities were chosen to support this analysis. For each outcrop, the following workflow is proposed:

1) Mapping of geological and mechanical structures (stylolithes, joints, fractures, karst, etc.); characterized by morphological and qualitative attributes as fracture aperture, strike and dip, and karstification level.

2) Geophysical and petrophysical measurements at infra-meter scale (Vp on outcrop surface and porosity on plugs). P-wave velocities were measured on the field with a portative device (Pundit7 CNS Farnell Ltd.) composed of two piezoelectric transducers. A step by step iterative and directional method was used. At each measurement step, the emitter is placed on the previous receiver location along the horizontal and vertical directions. Finally, Vp values were artificially attributed to the centre of the emitter/receptor segment along horizontal or vertical transects.

3) Statistical and geostatistical analyses of the measured petrophysical and geophysical properties. Histogram statistics as well as aerial variograms (8 directions) were calculated on Vp values. The variogram analysis was performed using Gringarten et al. (1999) methodology.

Outcrop Observations

Wide differences were noticed between the three outcrops concerning the nature and the spatial repartitions of the geological and mechanical structures. The Cassis outcrop is composed of lower Barremian tight grainstone from inner platform facies. It presents a high fracture density and a karstified area on its eastern part. Two fracture sets affect the rock mass, striking around N030 and N090 respectively. The N090 striking set shows evidence of reactivation associated with a principal stress striking N030. Fracture aperture measurements show an increasing trend toward the eastern part of the outcrop. This may result from the fracture reactivation or the dissolution of fracture walls by water circulation.

The Calissane outcrop is composed of Barremian Rudstone of outer platform facies with “high” porosity values (around 10% to 20%) and large granulometry variations at the decimetre scale. It is related to the occurrence of sedimentary structure as dune/mega ripple of metric scale. A few fractures with large aperture (>1 cm) affect this outcrop.

Finally, the Grignantes outcrop presents tight carbonates of Berriasian ages with a high micrite content related to a hemipelagite mudstone to wackestone facies. This outcrop is affected by two horizontal compaction bands, corresponding to about 20 cm thick intervals of dense and porous stylolithes (Bruna et al., in prep.). The stylolithe density decreases gradually from the centre of a compaction band to its two sides.

Analysis and Results

A first comparison between geological structures and petrophysical and geophysical properties pointed out the signatures of the heterogeneities encountered on each site. On the Cassis outcrop, the zones presenting high Vp values (>6000 m/s, around the pure calcite theoretical velocity) correspond to locations containing numerous and large cemented fractures (Figure 1), hence completely closed. On the contrary, the zones characterized by low Vp (<2500 m/s) are affected by open fractures (aperture > 0.05 mm). These zones of relatively high fracture apertures are located at the intersection of two plurimetric fractures from the two fracture sets. The Vp value variations are then essentially related to the fracture aperture.

On the Calissane outcrop, the Vp variations have a two-fold origin. First, the few metric fractures presenting large aperture lead to narrow zones of very low Vp values. Second, the high frequency granulometry and porosity variation (decimetric scale) lead to small areas presenting contrasted Vp between (3500 and 2500 m/s).

In the Grignantes outcrop, the Vp variations are controlled by the presence of the two compaction bands that make the Vp values decreases to <1500 m/s or even to not measurable velocity (i.e. P-waves are not transmitted through the compaction bands). Each stylolithe has an aperture about 0.05 to 0.1 mm wide. The zones presenting “intact” rock have an averaged Vp about 6000 m/s, i.e. slightly under the intact rock on the cassis outcrop.

The geostatistical study consolidated previous interpretations but also provided information on the spatial organisation of the petrophysical heterogeneities and their relationships with the observed structural, diagenetic and sedimentologic heterogeneities. In the Cassis case study the highly fractured rock mass induced a near isotropic variogram ellipsoid. The modelled variograms are spherical and the data variance is reached.

In the Grignantes outcrop a strong horizontal anisotropy of variograms [max range (horiz)=100 cm, min range (vert)=30 cm] is obviously observed. Moreover, hole-effect behaviours are observable on vertical and oblique variograms (Figure 2). The period of the hole effect corresponds to the observed interval between the two compaction bands.

In the Calissane outcrop, a slight horizontal anisotropy (Rmax=42 cm, Rmin=34 cm) is noticed. However, once removing from the dataset the extreme values associated with the metric open fractures, variograms show an oblique anisotropy (30°) with a maximum range of 64 cm and a minimum of 42 cm. Moreover, experimental variograms are best fitted using an exponential variogram type, suggesting high frequency variation of Vp in this site. Several studies have shown that foreset direction of sedimentary structures can cause variographical anisotropy (Huysmans et al., 2009) and difference in matrix and K measured on outcrops (Hartkamp et al., 1993).

Conclusions

Finally, beyond the aim to quantify the impact of depicted superimposed geological structures on petrophysical heterogeneity, this work represents the basis for providing petrophysical high-resolution analogues at outcrop scale and is tentative to quantify the impact of the depicted geological structures on petrophysical heterogeneity. More fundamentally, this work may provide an insight into the processes of genesis of heterogeneities in carbonate rocks (fracture reactivation, poronecrose in tight interval, pressure/solution processes…)

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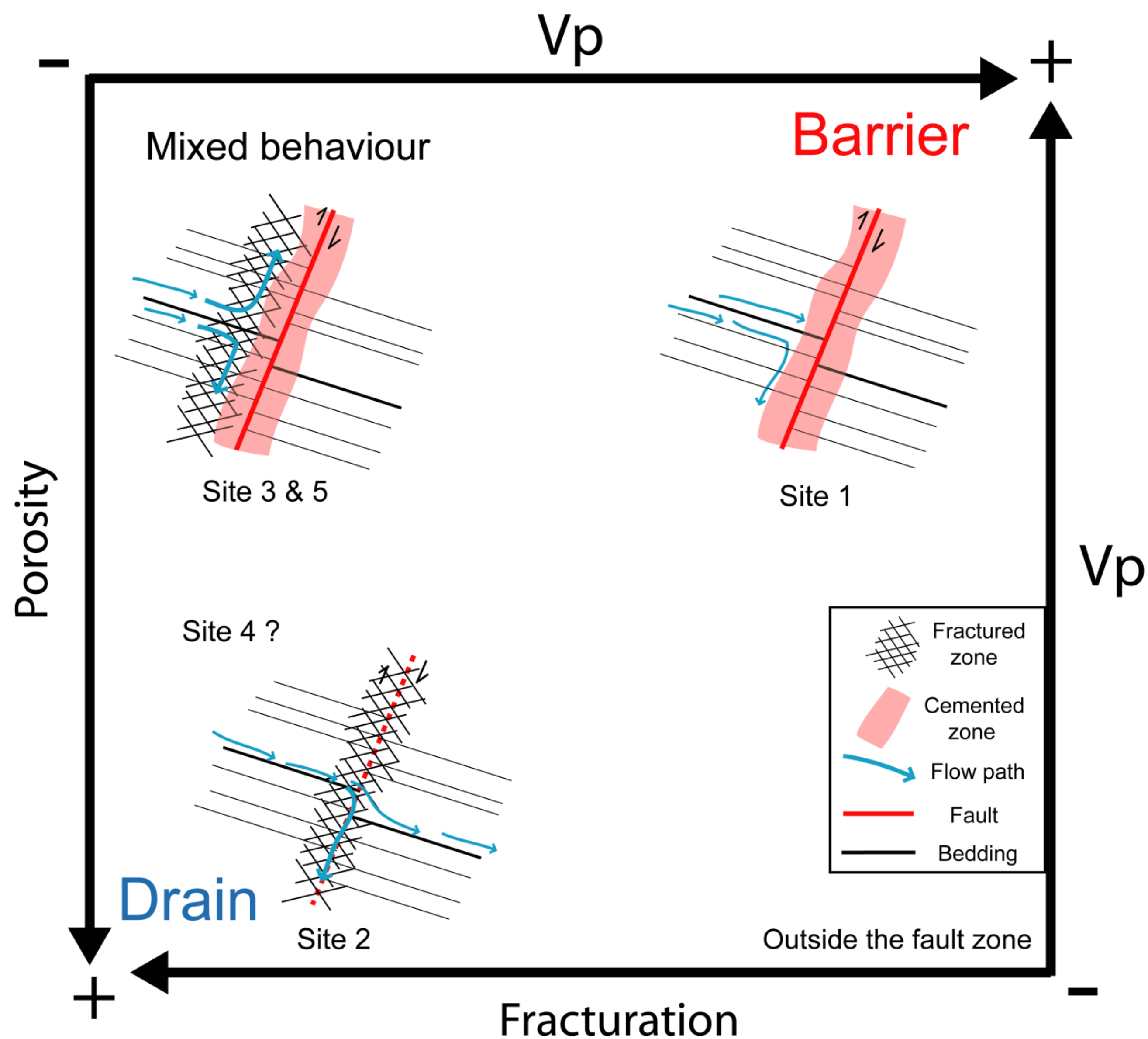

Figure 1. Conceptual scheme of the three hydraulic types along the fault zone, depending on cementation and fracturation.

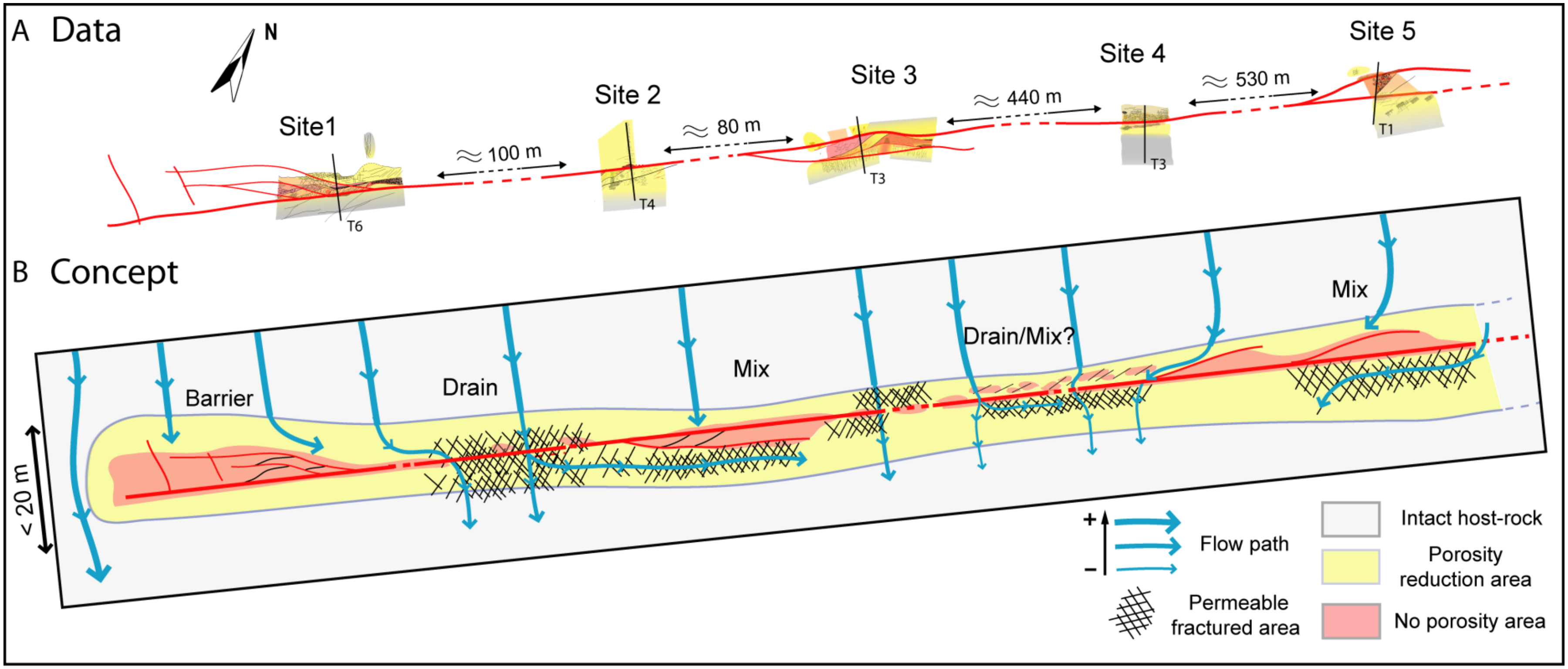

Figure 2. Conceptual model of the fault hydraulic behavior lateral variations. (A) Structural maps of the entire fault. (B) Conceptual model.