Flow Units in Carbonate Karstic Reservoirs: Insights from Outcrop Analogues (Urgonian Limestone and Upper Jurassic Dolostone, SE France)*

A. Fournillon[1], F. Fournier[1], B. Arfib[1], F. Gisquet[1], P. Léonide[1], and J. Borgomano[1]

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[1] Aix–Marseille Univ, CEREGE Centre Saint-Charles, Marseille, France (afournillon@gmail.com)

Abstract

Hydrocarbon accumulations in karstified carbonates are known worldwide (Loucks, 1999). They commonly exhibit high reservoir potential in hydrocarbon fields such as Kashagan Field in Kazakhstan (Ronchi et al., 2010) and are regarded as relevant exploration targets (e.g. in the Oriente Basin Ecuador, Lee and Castagna, 2007). Karst carbonate reservoirs are challenging for both exploration and production since heterogeneities occur at all scales, from millimeters to kilometers, and are generally below the resolution of seismic. The spatial distribution of karsts and paleokarsts is controlled by a vast number of factors. Among them, the nature of the initial carbonate sediments, and their subsequent eogenesis, and the impact of tectonic deformation on the base levels positions during the telogenesis are considered to have played a major role on karst development (Palmer, 1991).

The aim of this study is to characterize the influence of the petrophysical properties on the development of karsts and flow units in karstic reservoirs. This study is based on two karstified outcrops: Lower Cretaceous tight limestones and Upper Jurassic porous dolostones from Provence in southeast France. Both outcrops have undergone the same telogenic karstification phases since they belong to the same structural unit. The case studies are in present active aquifers. The characterization of the flow units are then based on the link between their static and dynamic properties. The static properties are inferred from thin-section analyses, petrophysics measurements from outcrops and cores, and from field studies (characterization of shape, size and distribution of paleokarstic features). The dynamic properties are derived from continuous monitoring of three spring's parameters: temperature, specific conductance and water head. These springs are the outlets of both studied aquifers. The spring's records are analyzed as time series in order to quantify the influence of karst on fluid flow.

The South Provence area is composed of a succession of several thousand meters of sedimentary rocks, including much limestone and dolostone, but also siliciclastic rocks and evaporites. These rocks represent a time interval ranging from the Permian to the end of the Cretaceous. Several karstification phases are known, and they are linked to tectonic phases. The first main phase of karstification occurred during the Mid-Cretaceous and generates an embryonic tower-karst associated with bauxite. The second karst phase is linked to the Pyrenean orogeny, which starts during the Campanian. During the Cenozoic, there are numerous karstification phases that are related to the Oligocene-Miocene rifting phase, to the Alpine orogeny and to eustatic variations. The main eustatic phase is the Messinian salinity crisis associated a sea level drop of 1500 m.

The Upper Jurassic dolostones result from 2 main processes: (1) early dolomitization of shallow-water limestones in evaporitic environments (stratabound dolomite bodies), and (2) fault related dolomitization (non-stratiform dolomite). The porosity of this formation ranges from 4% to 22% (Combes, 1976). Petrographic analysis of thin sections showed that the highly-porous sucrosic dolostone (Figure 1C) is characterized by a dense micro-fractures and micro-karst network, together with high intercrystalline porosity. Well-tests have been performed by water pumping in this formation: hydraulic conductivity values range from 10^{-3} m/s to 10^{-2} m/s, i.e. equivalent to permeability from 10 D to 100 D. Such high values have been observed in sucrosic dolostones from the Eocene Upper Floridan Aquifer (Maliva et al., 2011). At the outcrop scale, the paleokarst appears to be diffuse (Figure 1A). Caver’s surveys indicate that the enterable karst in such a formation can be divided into two groups. The first one is formed by well-developed and conductive karst, made of vertical shafts and branch-work networks. The second groups correspond to smaller cavities characterized by divagating shaft and sponge-work embryonic networks. The Gapeau Spring drains an Upper Jurassic aquifer. The time series analyses of its record, by cross-correlograms, exhibits high lags and low correlations (Figure 2). This hydrodynamic behavior is typical of porous reservoirs. The small correlation peaks at very early lags show a small contribution of karst features during high water events.

The Urgonian Limestone (Hauterivian to Barremian) consists of a tight limestone mainly made of micrite, peloids, benthic foraminifera and rudists. The porosity measured from outcrop plugs is very low, generally lower than 2%. The outcrops show very intense fracturation; fractures may be solution-enhanced. Petrographic observations on thin sections indicate that the solution-enhanced fractures are present even at the microscale (Figure 1D and Figure 1E). The paleokarst features are, at the outcrop scale, either solution-enhanced fractures or huge collapse conduits, which size varies from a few meters to several tens of meters (Figure 1B). Caver’s surveys have shown that karst in the Urgonian Limestone is mainly big vertical pits, up to 360 m deep, and huge horizontal conduits, up to 25 m wide. The time series analysis of the Bonnefont Spring, which aquifer is mainly located within the Urgonian Limestone, shows high correlation peaks at very small lags. These points are typical of a major contribution of karst in the fluid flow behavior (Figure 2).

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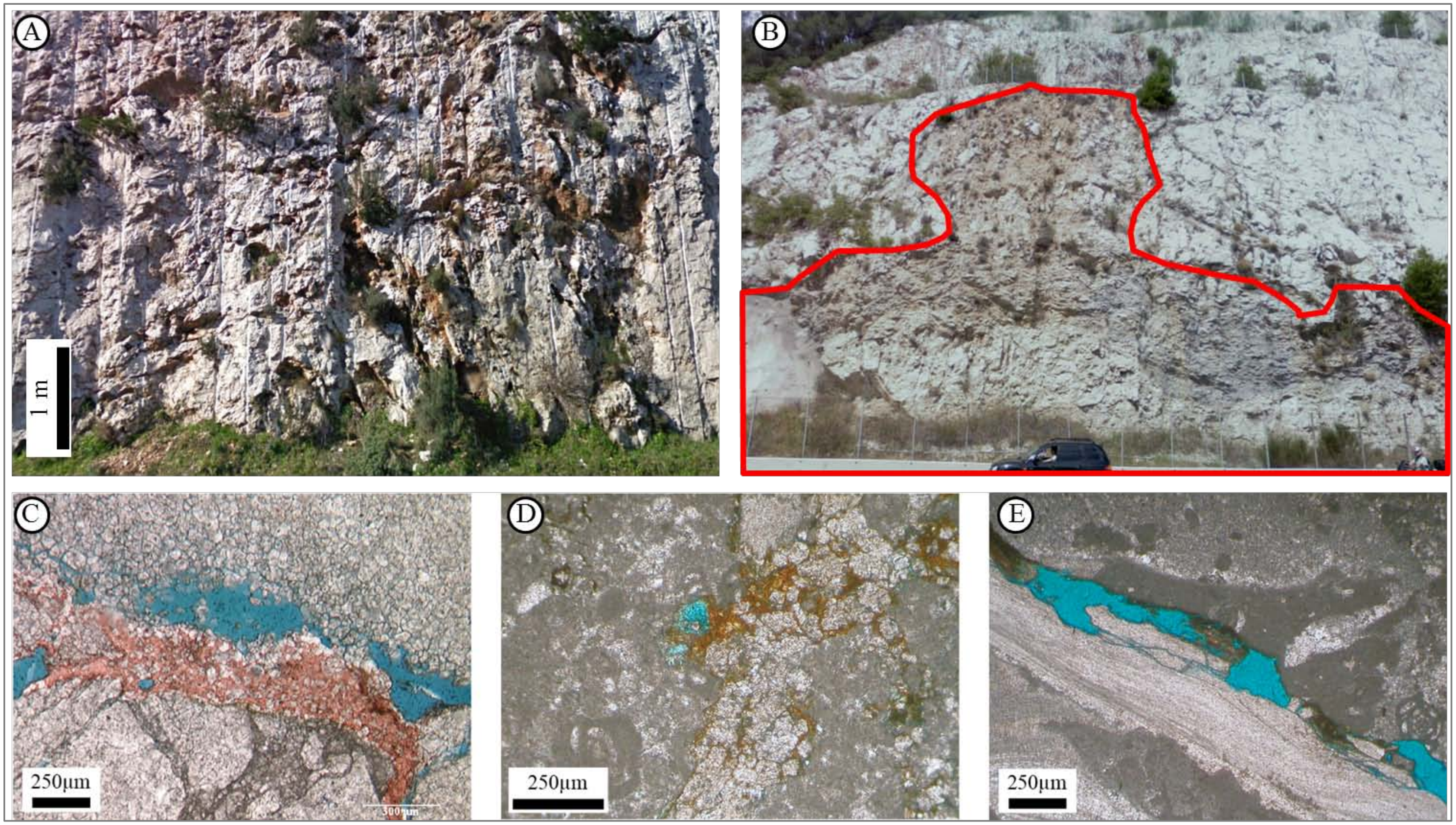

Figure 1. (A) Scattered paleokarsts in porous Upper Jurassic dolostone. (B) Karst conduit collapse (in red) in Barremian limestone, the car is for scale. (C) Thin-section of Upper Jurassic dolostone showing microkarst and fractures, and high intercrystalline porosity between dolomite rhombohedra. (D) Thin-section of Barremian limestone with urgonian facies, showing a karstified calcite-filled fracture in tight matrix. (E) Thin-section of Barremian limestone with urgonian facies, showing a karstified stylolite that affects a rudist shell.

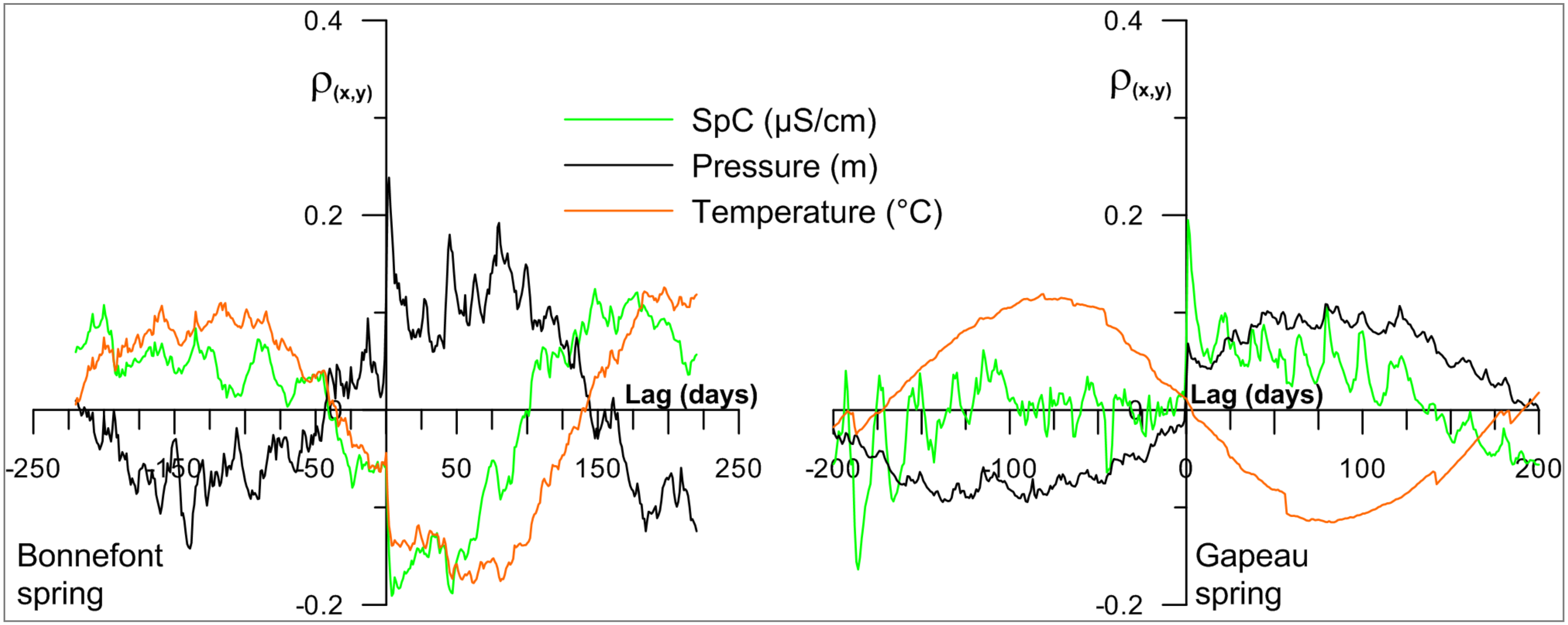

Figure 2. Cross-correlograms between rain and monitored parameters in springs.