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The ALBION Project: An Observatory in the Heart of a Carbonate Reservoir

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Abstract

The ALBION project applies a new and disruptive methodology of reservoir characterisation to the carbonate Urgonian Formation (South-East France) considered as the very best analogue of Mid Cretaceous reservoirs from Middle East. Thanks to numerous field sections and outcrops descriptions, to tens of wells drilled in the reservoir, to kilometres of cores, to monitoring of groundwater dynamics such as decades of hydraulic observations at pretty much the only natural outlet of a major groundwater reservoir (Fontaine-de-Vaucluse spring) and to a unique underground laboratory (LSBB, about four kilometers in the heart of the reservoir), a multi-scale model is being built for reservoir purpose. Different observation sites with wells whose spacing ranges from 2 to 20 meters contribute to the assessment of together the matrix, the fractures and the karst flow behaviours. Through the building of an observatory in the heart of a reservoir, the ALBION project is delivering advanced concepts and methodologies to apply to industrial projects in Middle East carbonate fields.

Introduction

In carbonate reservoirs, the huge diversity of types and scales of heterogeneity, together with the coexistence of embedded different media (porous matrix, fractures, vugs, karst, etc.), makes very complex and challenging both the evaluation of equivalent reservoir properties and their extrapolation for populating 3D reservoir models. In the same rock, several scales are successively involved as the volume of the data support increases. However, most of measurements are acquired at wells or between wells, for volumes strongly constrained by the radius of the wells and the spacing between wells. Unfortunately, there are only few data which investigate intermediate volumes: mostly pressure transient tests, interference tests, and 4D seismics can give information and data on flow properties at these intermediate scales. A proper management of the different scales of heterogeneity is consequently required to build reservoir models consistent with the main geological processes responsible for the 3D organisation of the heterogeneity and to evaluate equivalent properties at the gridblock scale. In order to enhance the evaluation of equivalent properties at missing scales that never can be assessed in oil & gas fields, a new and disruptive way of addressing the use of analogues in geosciences and reservoir has been developed through a multi-physics and multi-scales characterization of a analogue reservoir. The combination of data acquired on outcrops, in and between short spacing wells drilled in groundwater reservoirs enable to get measurements

in volumes never assessed in oil and gas fields. The detailed geological description of outcrops and cores combined with petrophysical data, high resolution geophysics, hydraulic data and hydromechanical measurements leads to an exhaustive reservoir characterisation and a comprehensive fluid flow response to heterogeneity. Geophysical and hydraulic inversions contribute to an iterative enhanced description of reservoir heterogeneity and equivalent properties at missing scales that usually can never be assessed. It gives drivers for a confident extrapolation of reservoir properties during modelling.

ALBION dynamic outcrop analogue: a disruptive methodology

For years, the oil industry and academics have cooperated by running studies on outcrops considered as field analogues. Geological data were collected and used for building conceptual and 3D static models. Those models were then used for fluid flow simulations and sensitivity studies of a hydraulic response to geological and petrophysical heterogeneity. Although quite advanced, this linear workflow did not integrate the dynamic information due to the lack of calibration data.

The new concept of dynamic outcrop analogue arose from the need for integration of hydrodynamics and geophysics in the process of characterization of the reservoir during the outcrop studies. Instead of single geological and petrophysical description of the reservoir before forecasting the seismic answer and the hydraulic behavior through numerical modelling, the analogue is assessed through multi-physics experiments. Very early in the workflow, the dynamic outcrop analogue allows measuring the hydrodynamic response to a well-known heterogeneity, in various locations places and at many scales.

The ALBION project benefits from a double access: i) to the observation of a geologic analogue of rudist-rich carbonate reservoirs of the Middle East, ii) to the in situ observation of fast and slow fluid flows in a major groundwater reservoir, the Fontaine-de-Vaucluse aquifer.

The Urgonian Formation

In terms of both chronostratigraphy and sedimentology, the carbonate Urgonian units outcropping in South-East France have been considered for a long time as closely analogous to Barremian – lower Aptian carbonates from the eastern Arabian Plate (Masse, 1992; Dercourt et al., 2000; Bastide et al., 2009; Arnaud et al., 2017) : the Kharaib and Shu'aiba Formations. These formations occur around the Bab Basin and constitute reservoirs in giant oilfields such as Al Huwaisah, Asab, Bab, Bu Hasa, Yibal, Dhulaima, Murban, Safah, Shaybah and Zakum (Borgomano et al., 2013). Both Urgonian and Kharaib/Shu'aiba formations are composed of rudist-rich grainstones and rudstones with moldic and intergranular porosity, with a typical chalky texture related to abundant microporosity Rock fabrics are similar at macro- and microscopic scales, and from thin section, it is not possible visually to distinguish the bioclastic grainstones from Provence from those from northern Oman (Borgomano et al., 2013). As a consequence, the two sets of grainstones show similar porosity and permeability trends (Borgomano et al., 2013). Such a similarity can be explained by the identical primary mineralogical composition of the carbonates, and by similar diagenetic modification comprising leaching and reprecipitation of calcite (Borgomano et al., 2013).

The Urgonian Formation belongs to the Early Cretaceous Group, and was deposited from the Upper Barremian to the Lower Aptian. During the Early Cretaceous, carbonate platforms developed on the passive margin of the Alpine (Tethyan) basin under a tropical to subtropical, warm and humid climate (Fig. 1). The platform system was up to 100 km wide and 1000 km long, and carbonate deposits were isolated from continental influences and siliciclastic input (Borgomano et al., 2013). Four main stages of growth and progradation of the platform (200-400 m thick) are recognized; they are separated by retrogradational events between mid-Valanginian and mid-Aptian. The end of platform development occurred during the early Aptian and was characterized by a reduction of the platform area. (Masse, 1993; Masse and Fenerci-Masse, 2011).

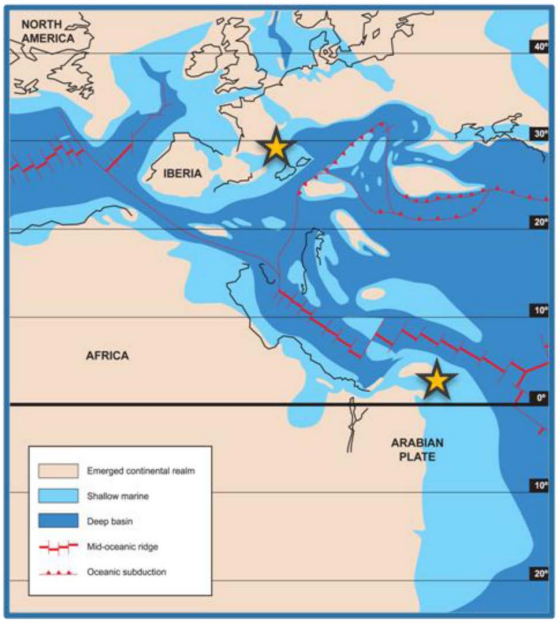

Figure 1—Provence and Middle East during Aptian Palaeogeography of Tethyan/ eastern Atlantic regions.*(map based on Masse et al., 2000; Skelton and Gili, 2012)*.

The Barremian and lower Aptian carbonates of Urgonian Fm. were deposited in high to moderate energy environments within an outer platform setting or on the distal part of an inner platform (Leonide et al., 2012). They comprise laterally extensive, cross-bedded carbonate sand bodies (sheets, channels and sand waves), characterised by a homogenous texture (100% grain-supported) and containing a significant content of sand-grade bioclasts; and rudist-bearing deposits with a high content of peloids (Masse and Fenerci-Masse, 2011). The diagenetic modification of these grainstones (Borgomano et al., 2013) generally includes the precipitation of phreatic calcite cements (marine and freshwater), micritisation and the leaching/replacement of unstable grains (aragonite and high magnesium calcite).

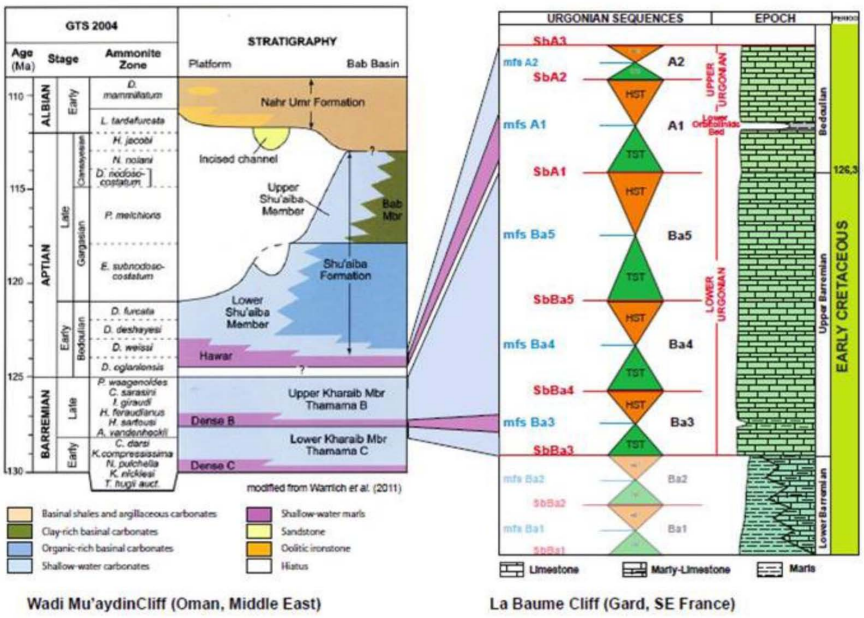

Figure 2—Correlations between Provence and Middle East during Barremian and Aptian times*(after Bastide, 2014)*.

The Fontaine de Vaucluse catchment area

The Fontaine-de-Vaucluse is one of the largest karst springs in the world, draining an area of about 1130 km^2 (Puig 1987) and delivering a considerable average flow of 20 m^3/s (Blavoux et al. 1992, Cognard-Plancq et al. 2006). The spring is located in the South-West side of the reservoir at an altitude of 84m. Exploration in the outlet vertical shaft evidenced the deepness of the hydrosystem that reaches at least -308 m from the surface, i.e. 224 m below the present sea level (Bayle and Graillot 1987; Audra et al. 2004). Above the spring, rock cover thickness is 800m in average and exceeds 1800 on top of Mont Ventoux. Indeed this aquifer belongs to a 1500m thick limestone series (Masse, 1968) between Necomanian marls and upper Aptian marls. Illustratively, Fleury et al. (2007) estimated that the volume of mobile water in the system could seasonally vary between 45.10^6 m^3 and 390.10^6 m^3 with a simple rainfall-discharge model.

The whole Vaucluse plateau is highly permeable with no surface water (Blavoux et al. 1992) while the water at lower elevation (below 400 m) is mostly captured by surface drainage on marl cover. More than 600 penetrable caves have been identified in the catchment area, mostly developed vertically with four caves being deeper than 500 m (e.g. Gaubert et Le Falher, 1990, 1995). One of the vertical caves, the Souffleur shaft, reaches the water table at a 750 m depth (Lefahler & Sanna 1990; Audra et al. 2004), indicating a low average hydraulic gradient (Blavoux et al. 1992). At the end of 2014, a well was drilled at almost 30km of the spring in the LSBB site to monitor water level variations. These variations range from an altitude of about 100m to more than 140m (sensor range exceeded) also indicating a low average hydraulic gradient, therefore a good connectivity. Variations of water level at the spring and in this well are highly correlated with a delay of almost 6 hours (r^2=0.9). In the other hand, natural tracers monitored in the spring water reveal the capacity of the system to store water for long time (e.g. Danquigny et al., 2010). Numerous perched aquifers also exist in the unsaturated zone that is able to delay infiltration (e.g. Emblanch et al. 2003, Carrière et al. 2016). Therefore the Fontaine-de-Vaucluse aquifer is not only a well-developped karst system but also a reservoir with huge capacitive compartments.

ALBION : Outstanding facilities and data

In this context, ALBION aims an exhaustive characterization of the reservoir at different scales (Fig. 3). For instance, numerous boreholes drilled and cored in a quarry in the South-West part of the reservoir allow studying the spatial variability of geological and petrophysical properties within a cell of a usual reservoir model. Such boreholes also provide data for enhancing knowledge about Provençal Urgonian platform stratigraphic and diagenetic evolution (Tendil et al. 2016, Lenteaume et al. 2016). In the central area (near Saint-Christol), where most caves have been inventoried, a specific study on karst genesis in such media has been carried out (Dal Soglio et al. 2016).

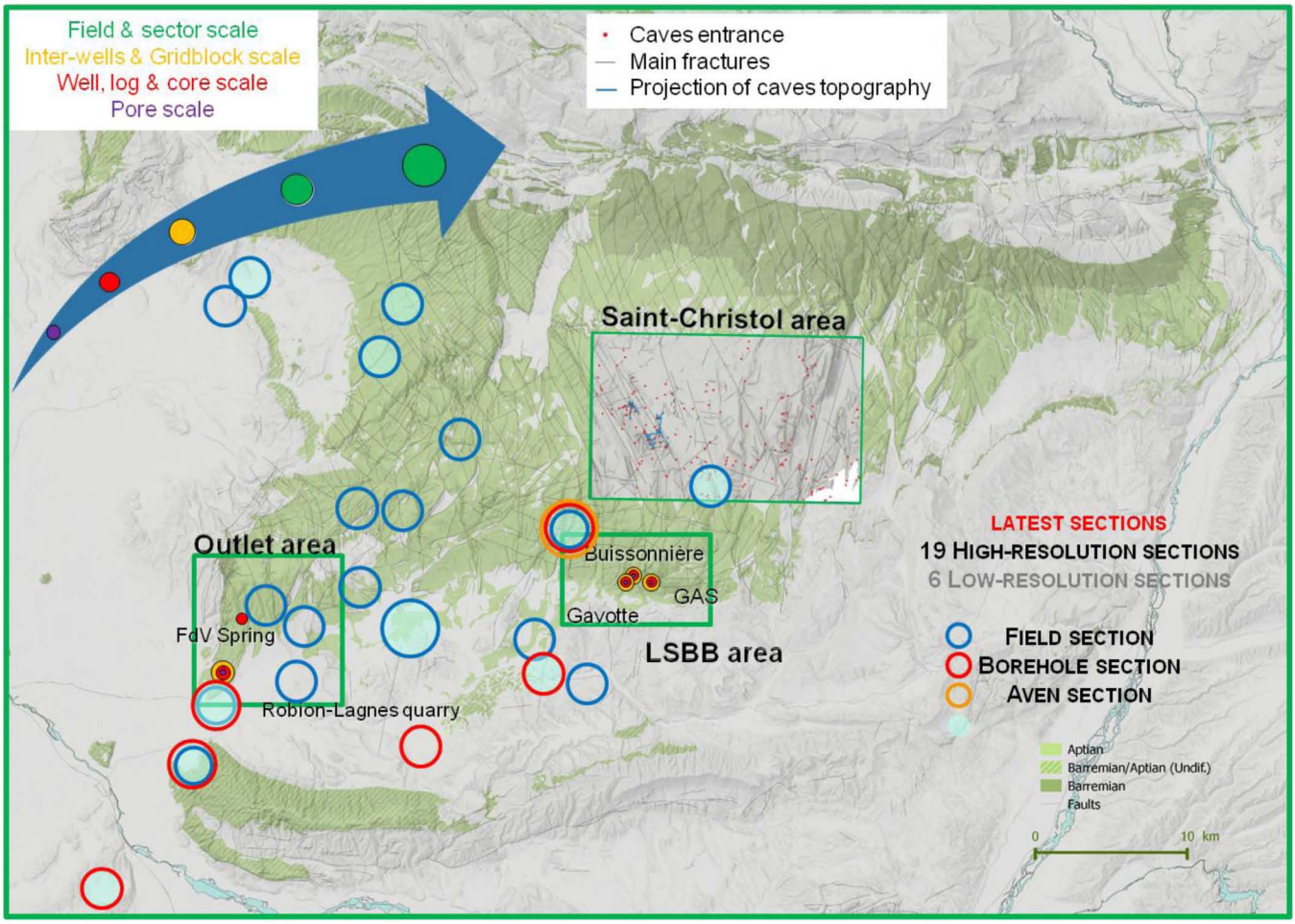

Figure 3—The multi-sites of the ALBION Project

But the main asset of this outcropping dynamic analogue is the LSBB (Laboratoire Souterrain à Bas Bruit, Low Noise Underground Research Laboratory, www.lsbb.eu) that provides 3.8 km of tunnels inside the carbonate reservoir and 54 ha outcropping. Initially built for a military purpose, the LSBB has become a "Mixed Service Unit" under the multiple guardianship of the University of Nice - Sophia- Antipolis (UNS), the University of Avignon and the Pays de Vaucluse (UAPV), the CNRS, the University of Aix-Marseille (AMU) and the Observatoire de la Côte d'Azur (OCA). The site has numerous (environmental, natural and preserved geological non-transferable and sustainable) qualities, and properties (an infrastructure inherited from a military site), making this Research and Development platform unique. The Low Noise Underground Laboratory is developing 3 key functions: (i) reception and accommodation of academic and industrial activities, (ii) accommodation and development of multidisciplinary observations within the framework of national and international observation networks, (iii) initiation and promotion of exploratory, interdisciplinary research projects.

The LSBB is excavated in the southern border of the Vaucluse plateau where monoclinic fractured limestone layers dip by 10 to 20° to the south (Jeanne et al. 2012; Sénéchal et al. 2013). Numerous faults and fractures present extensions from metric up to kilometric scale. Two main fault types are observed on the LSBB walls: normal and strike-slip faults oriented at N10-N40° and strike-slip fault oriented at N150-N170 which are also observed at the plateau scale. Both types of faults dip steeply between 80° and 90° (Gaffet et al. 2003). As LSBB tunnels penetrate arbitrarily the karst medium and the faults network, they intersect some flow paths through the unsaturated zone. Consequently, about fifty water flow points have been identified all over the laboratory at different depths from about 30m to about 440m (Garry et al.

2008; Barbel-Perineau et al. 2015; Ollivier et al. 2015). Monitored discharges rates and dissolved ions have revealed very contrasted behaviours, complementary to those observed in natural caves (Garry et al. 2008), that highlight the complexity of flows in such media.

Added to this natural flows study, one borehole platform was created in the laboratory at 280m depth. It consists of 5 cored boreholes of 21m depth and 146mm diameter very close from each other. Distance between these wells varies from 2 to 13m, allowing small scale experiments. For ALBION, this platform has been dedicated to diagenetic and geomechanical analysis of the fracturing, in-situ exploration of hydromechanical properties and geophysical characterization of anisotropy from core to grid cell scale. For ALBION purpose, two other platforms, called Gavotte and Buissonnière, have been created in the LSBB area. Each of them includes three boreholes forming an equilateral triangle of 18m side. In Buissonnière, boreholes are 50m deep and located around a shallow LSBB gallery in a capacitive zone where flows are slow and mostly occur in the matrix. There, specific study of these peculiar flows is based on coupling of long-term monitoring of natural response to precipitations, injection and pumping tests and geophysical monitoring. In contrast, the Gavotte platform investigate more variably karstified media and includes a 400m deep boreholes drilled across the entire Urgonian serie and partially through the saturated zone of the aquifer.

ALBION : multi-sites, multi-scales, multi-physics

The project addresses the study of the relationships between the hydraulic and mechanical properties of carbonates, and the geological processes and hydrogeophysical observations. The different sites are involved in this multi-scale investigation, for which laboratory and in-situ testing experiments have been elaborated through a wide range of protocols.

As an example, the program dedicated to the 5 boreholes platform and the unaltered rocks outcropping over 50 m along the gallery walls give the unique opportunity to study in great details the diagenetic sequence considering environment factors, rocks facies and fracturing, focusing on the characterization of the diagenetic cements both in the matrix and in the fractures (Fig. 4). A petrophysical approach has been conducted where (i) micro-to-macro pores shape attributes evolution is related to the diagenetic evolution and (ii) the influence of these multi-scale porosity variations on the carbonates mechanical and hydraulic properties is quantified.

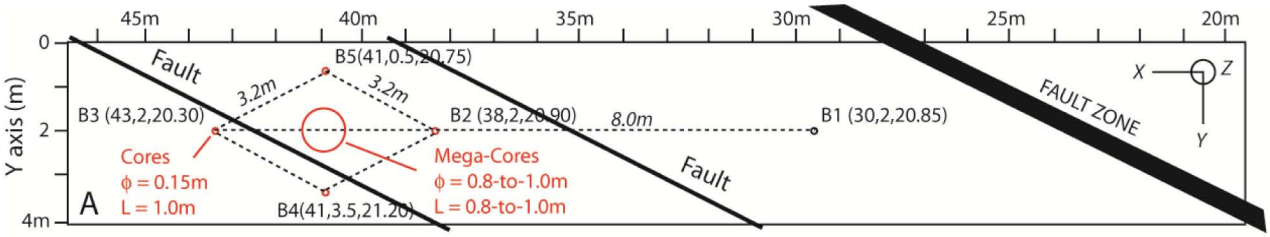

Figure 4—Schematic map of the *galerie anti-souffle* geology, with the five boreholes B1 to B5 (courtesy of Y. Guglielmi).

Together with field observation, laboratory measurements on samples from cored boreholes, borehole logging (borehole viewer images and water content variations relative to a reference value taken in the boreholes close to the surface), injection tests are performed between two inflatable packers at different depths in boreholes and analyzed with a hydraulic numerical code. The evolution of the mechanical properties is shown to be strongly influenced by the petrophysical properties.

A synthetic seismic modeling is on-going, using i) the acoustic velocity and impedance contrast models and ii) the wavelet type and frequency content of the source. Special focus addresses the impact of wavelet frequency on the seismic character of carbonate bodies. This study leads to a quantitative characterization of the diagenetic impact on the seismic expression of the carbonate reservoirs: features as transmission waves,

reflection amplitudes based on AVO analysis as well as reflection continuities based on seismic migration imaging techniques improve our capacity of reservoir description and reservoir body delineation.

The characterisation of the flow has been performed at different scales: i) at core scale, small pulse tests are reproduced in fully saturated conditions then used to calibrate the numerical models, ii) at borehole scale, the SIMFIP pulse data, both static and dynamic pressures and flowrate, have been analyzed to reconstruct the local permeability and storativity of the tested carbonate intervals, iii) at the LSBB site scale, the long duration injection will be reproduced through a numerical model.

In addition, the 5-boreholes site is a part of a larger volume, which is relatively well documented because the LSBB, as a national facility, has been hosting several research projects dedicated to the development of porous rocks geophysical and geomechanical imaging techniques. Data from these projects eventually added to the boreholes sedimentary, structural, diagenetic and petrophysical analyses will allow to build a three dimensional model of the rocks properties. The volume constitutes an analogue to quantify the effects of sedimentary facies, diagenesis and fault/fractures zones on the properties of carbonates at the reservoir scale. Interestingly, the geomodel data at a resolution of 1m will be compared to real data, taking the opportunity of a 5m-diameter- 200-m-long horizontal tunnel that has to be drilled through the volume in 2017.

Conclusions and Perspectives

ALBION is a ambitious R&D project which revisits the use of outcrops as analogues classically used in geology. Through a multi-sites, multi-physics and multi-scales assessment of the reservoir, ALBION allows to investigate the complex relations between the geological and petrophysical and the geophysical and hydraulic response to heterogeneity. Outstanding access in the heart of the Urgonian Formation and its flows provides key answers for the evaluation and the extrapolation of the properties in Kharaib and Shu’ aiba reservoirs.

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