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Reactive transport modelling of carbonate cementation in a deep saline aquifer, the Middle Jurassic Oolithe Blanche Formation, Paris Basin, France

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ABSTRACT

The Oolithe Blanche Formation (Bathonian, Middle Jurassic) is one of the deep saline aquifers of the Paris Basin in France. The spatial distribution of its reservoir properties (porosity, permeability, tortuosity, etc.) is now better known with relatively homogeneous properties, except for some levels in the central part of the basin, where permeability exhibits higher values. This spatial distribution has been correlated with diagenetic events (variability of cementation) and palaeo-fluid flow circulation phases leading to variable cementation. In this paper, numerical simulations of reactive transport are performed. They provide a preliminary quantitative analysis of the Oolithe Blanche Formation, the type of fluids involved, the duration of fluid flow, and the time required to reduce the primary porosity of the Bathonian sediments by 10% due to cementation. Our results from the reactive transport simulations along a flow line, and a parameter sensitivity analysis suggest that diagenesis processes driven by meteoric water recharge do not exclusively cause the 10% decrease in porosity. Other geochemical and hydrogeologic processes must be involved.

1. Introduction

Long-term storage of CO_2 in deep geologic formations has been proposed to face the rising of atmospheric CO_2 concentrations due to fossils fuel consumption (Hitchon, 1996; Metz et al., 2005). In the Paris Basin potential target formations for aquifer storage (Bloomfield et al., 2003; Bonijoly et al., 2003) were porous, permeable, and saturated with saline groundwater, brines, hydrocarbons or a combination (Brosse et al., 2010; Vidal-Gilbert et al., 2009). The storage capacity of the Bathonian Oolithe Blanche Formation (saline aquifer/reservoir of the Paris Basin), estimated from its geometry, porosity, and a "storage efficiency" factor for suitable strata, is ca. 4Gt of CO_2 (Brosse et al., 2010). The Oolithe Blanche Formation is a deep saline aquifer with temperature between 55 and

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80 °C, confined above and below by two aquitards (very low permeability formations). Because of warm temperatures and favourable hydraulic properties in the centre of the basin, the Oolithe Blanche Formation also serves as an ideal reservoir for geothermal energy.

Carbonate reservoirs and deep reservoirs are ubiquitously known to be more or less heterogeneous (e.g., Davis et al., 2006; Dou et al., 2011; Lucia, 1999; Moore, 2001; Westphal et al., 2004). The degree of heterogeneity of carbonate formations is largely explained by the intrinsic complexity of lateral facies variations inherited from sedimentation (Ehrenberg et al., 2006). Furthermore, during burial, the chemical and physical processes of diagenesis of carbonate sediments (e.g., precipitation of cements, dissolution processes, and fracturing) can have a major impact on their geochemical, petrophysical and hydraulic properties (Palciauskas and Domenico, 1976; Rong et al., 2012; Wilson and Evans, 2002).

Porosity and permeability have a fundamental control on modern patterns and rates of fluid migration, and exerted a major control on palaeo-flow fields throughout geological time. Therefore, constraining the diagenetic processes and fluid flow history of the Bathonian reservoir formations of the Paris Basin is fundamental to understand both modern geothermal resources and the impacts of carbon sequestration. Several concepts have been proposed for the cementation of the sediments in the Paris Basin, and one way to test these hypotheses is with mathematical models, through numerical codes. One other major step is to check, with process modelling, the robustness of the hypotheses, which differ from one author to another (e.g., André, 2003; Brigaud et al., 2009a, b; Carpentier et al., 2014; Gonçalvès et al., 2003, 2004a, 2010; Vincent et al., 2007; see Table 1 for synthesis). The aim of our approach is to explain the present-day petrophysical setting and to provide first quantitative elements of the diagenetic events involved within the Bathonian carbonate formation. Therefore, we investigate the impact on the evolution of petrophysical characteristics of physical processes, fluid nature and origin meteoric water recharge *versus* deep fluids, timing and duration of groundwater flow, precipitation/dissolution processes (i.e. at least a reduction of 10% of porosity as observed).

In this paper, we test one of the most classical hypotheses, i.e. the cementation of the oolitic limestone formation by deep lateral meteoric groundwater recharge. To achieve this goal, we perform numerical simulations of reactive transport, constrained by available data. These simulations have been performed at the scales of both the geological formation and the sedimentary basin.

2. Geological setting of the Paris Basin and Oolithe Blanche Formation

2.1. The Paris Basin

The present-day Paris Basin is a sub-circular intracratonic sag basin (Fig. 1) that covers a broad part of northern France. The structural origin and evolution of the basin was described in detail by Pomerol (1978), and more recently by Guillocheau et al. (2000). Its dimensions are roughly of 500 × 600 km and in geological section it has a bowl shape that reaches a depth of 3000 m. The Paris Basin is bounded on its edges by several uplifted massifs: the Armorican Massif to the west, the French Massif Central and Morvan to the south, the Vosges Mountains to the east, and the Ardennes to the northeast. The crystalline basement is comprised of Variscan granites and Palaeozoic formations. This basement structure and topology is strongly controlled by faults (e.g., the Bray, Seine, Sennely, Saint-Martin-de-Bossenay, and Vittel faults) that propagated into the sedimentary cover throughout the Meso-Cenozoic history of the basin. The Paris Basin was located on a subsiding crust from Middle Triassic (Bourquin and Guillocheau, 1993, 1996, Bourquin et al., 1997) to Late

Table 1
Conceptual models and hydrogeologic venues of the different phases of fluid circulation, compiled from the mentioned articles. The fluid flow circulation phases do not necessarily match between the different studies because it is time relative.

	Cretaceous fluid circulation						Tertiary fluid circulation		
	Age	1st phase origin	Recharge zone	Age	2nd phase origin	Recharge zone	Age	Origin	Recharge zone
Vincent (2001)	Early to Late Cretaceous		North						
André (2003)	Early Cretaceous	Meteoric					Cretaceous chalk erosion	Meteoric	East and Southeast
Gonçalvès et al. (2003)	Hauterivian (136 Myr)	Marine	Southeast	Aptian (112 to 121 Myr)	Meteoric	Northwest	K/Pg (65 to 50 Myr)	Meteoric	Northwest
Vincent et al. (2007)	Berriasian (LCU)	Meteoric	North	Aptian/Albian boundary (LAU)	Meteoric	North			
Brigaud et al. (2009b)	Berriasian (LCU)	Mixed fluids	North	Aptian/Albian boundary (LAU)	Mixed fluids	North	Oligocene (33 to 23 Myr)	Vertical migration of meteoric fluids	No recharge zone
Gonçalvès et al. (2010)							Eocene (50 Myr)	Mixing (meteoric + deep brine)	
Carpentier et al. (2014)	Berriasian (LCU)	Mixed fluids	Northwest	Aptian/Albian boundary (LAU)	Mixed fluids	Northwest	Late Cretaceous to Early Oligocene	Mixed fluids	No recharge zone

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