Journal of Geodynamics 101 (2016) 5–29

Contents lists available at ScienceDirect

Journal of Geodynamics

journal homepage: http://www.elsevier.com/locate/jog

Diagenetic effects of compaction on reservoir properties: The case of early callovian "Dalle Nacrée" formation (Paris basin, France)

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ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form 7 May 2016
Accepted 26 May 2016
Available online 2 June 2016

Keywords:
Jurassic
Oolitic reservoirs
Burial diagenesis
Stylolites
Porosity plugging
Oxygen isotopes
Fluid flow

ABSTRACT

The impact of compaction diagenesis on reservoir properties is addressed by means of observations made on five boreholes with different burial histories of the Early Callovian "Dalle Nacrée" Formation in the Paris Basin. Petrographic analyses were carried out in order to investigate the rock-texture, pore space type and volume, micro-fabrics, and cement phases. Based on the acquired data, a chronologically ordered sequence of diagenetic events (paragenesis) for each borehole was reconstructed taking the burial history into account. Point counting and a segmentation algorithm (Matlab) were used to quantify porosity, as well as the amounts of grain constituents and cement phases on scanned images of studied thin sections. In addition, four key samples were analyzed by 3D imaging using microfocus X-ray computer tomography.

Basin margin grainstones display a different burial diagenesis when compared to basin centre grainstones and wackestones. The former have been affected by considerable cementation (especially by blocky calcite) prior to effective burial, in contrast to the basin centre lithologies where burial and compaction prevailed with relatively less cementation. Fracturing and bed-parallel stylolitization, observed especially in basinal wackestone facies also invoke higher levels of mechanical and chemical compaction than observed in basin marginal equivalents. Compaction fluids may have migrated at the time of burial from the basin centre towards its margins, affecting hence the reservoir properties of similar rock textures and facies and resulting in cross-basin spatial diagenetic heterogeneities.

1. Introduction

Carbonate rocks account for about half the world oil and gas reservoirs (Warren, 2000). Carbonate reservoirs are complex and their characterization is often difficult irrespective of the scale of the investigation, because they dominantly originate from heterogeneous sedimentary systems in shallow marine or continental lacustrine environments. Due to their high chemical reactivity, these sedimentary rocks undergo physical or chemical changes just after deposition till their exhumation (*e.g.* dissolution, cementation, neomorphism; Scholle and Ulmer-Scholle, 2003; Morad et al., 2012; Nader, 2015). Such sedimentary and diagenetic heterogeneities increase the complexity to understand the evolution of the petrophysical properties of these rocks. One main process responsible for the change of the pore network through time is compaction (Heydari, 2000). In fact, due to the increasing lithostatic pressure, the pore volume is expected to decrease with depth (Moore, 2001; and reference therein). This is not so easy to predict in carbonate rocks due to diagenesis, which could change the mechanical properties of the rocks, controlling their response to compaction (Blaise, 2012). Log signatures of carbonates are therefore not straightforward to interpret and show a wide range of values due to the influence of diagenesis, specially the commonly used sonic wave propagation velocities (Eberli et al., 2003; for Jurassic limestones of the Paris Basin see Brigaud et al., 2010; Casteleyn et al., 2011; Regnet et al., 2015). Hence, additional research on the compaction and associated processes occurring during burial diagenesis remains crucial and needed.

Key sedimentological, petrographic, and diagenetic data related to the Middle Jurassic carbonate rocks of the Paris Basin are provided by Floquet et al. (1989), Javaux (1992), Granier (1994, 1995) Granier and Staffelbach (2009), Garcia and Dromart (1997), Gaumet (1997), Guillocheau et al. (2000), Buschaert et al. (2004), Brigaud et al. (2009a, b), Delmas et al. (2010), Brosse et al. (2010) and Carpentier et al. (2014), among others. This paper aims to investigate the diagenetic influence of burial compaction on the reservoir

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http://dx.doi.org/10.1016/j.jog.2016.05.010
0264-3707/

Table 1
List of the investigated wells, including well code, current and estimated total burial depths, and thickness of the "Dalle Nacrée" Formation. The "Maximal estimated burial depth" represents the present-day burial depth in addition to the thickness eroded series.

Well	Code	Current top burial depth (in meters)	Current base burial depth (in meters)	Thickness of DN (in meters)	Maximal estimated burial depth (in meters)
Arrentières	ART1	520.0	539.0	19.0	990.0
Saint-Martin-de-Bossenay	SMB18	1363.0	1384.0	21.0	1460.0
Gisly-les-Nobles	GN1	1437.5	1455.0	17.5	1600.0
Avon-la-Pèze	AP2	1504.0	1526.0	22.0	1622.0
Grange-le-Bocage	GLB1	1596.0	1609.0	13.0	1714.0

properties (porosity and permeability) of these carbonate rocks to provide eventually constraints for numerical modelling tools and workflows (*e.g.* Gonçalvès et al., 2004; Blaise, 2012). For this purpose the "Dalle Nacrée" Formation (Early Callovian) deposited in the Paris Basin was selected as a case study. This "oobioclastic" rock succession forms a characteristic limestone reservoir that has been intercepted by subsurface boreholes at burial depths ranging approximately between 1000 and 1700 m in the study area.

1.1. Geological setting

The Paris Basin is a classical example of an intracratonic basin that is characterized by decreasing thermal subsidence in an extensional setting since its genesis (Pomerol, 1989; Guillocheau et al., 2000; Le Solleuz et al., 2004). Superimposed, successive lithospheric processes are believed to have shaped the history of this sedimentary basin (e.g. Loup and Wildi, 1994). Guillocheau et al. (2000) demonstrated that the overall subsidence history of the Paris Basin, which started upon Permo-Triassic rifting, influenced the nature, geometry and hierarchy of the stratigraphic cycles constituting the basin infill. Since Middle Jurassic times, subsidence rates and accommodation spaces varied considerably together with the type of the sedimentary filling (*e.g.* carbonates and silici-clastics). Though, the Early Cretaceous was characterized by a compression regime, the major compression and uplift occurred after the Turonian, with three main folding events (Late Cretaceous/Senonian, Lutetian-Early Oligocene, and Burdigalian-Late Miocene). These major tectonic events are inherently associated with the geodynamic evolution of the Paris Basin (Blès et al., 1989), and they resulted in significant fracturing phases which provided conduits for basinal fluids and the drivers for diagenesis.

Lacombe et al. (1990, 1994) and Rocher et al. (2004) managed to reconstruct the intraplate paleostresses that prevailed in the Paris Basin and its south and eastern margins, indicating NNE-SSW extension in the late Mesozoic, N-S compression and strike-slip phases striking successively NNW and NNE during the Tertiary Pyrenean orogenesis followed by WNW extension in the Oligocene, and WNW-ESE compression attributed to the Alpine Late Miocene collision. Furthermore, Andre et al. (2010) used microtectonics and stable oxygen and carbon isotopic analyses to demonstrate that late Jurassic to early Cretaceous extension started with a WNW–ESE direction but changed to E-W. In the Eocene, Pyrenean convergence, compression prevailed with NNE-SSW to NE-SW and finally ENE-WSW directions; while the Oligocene transition from Pyrenean to Alpine convergence, was marked by major changes in orientations and radial extension. Andre et al. (2010) pointed out strong reactivations of bedding stylolitisation at this time. They also suggested that the Alpine convergence (since the late Miocene), witnessed a change in the directions of shortening from WNW-ESE to NNW-SSE.

Bourgeois et al. (2007) associated the recent, Alpine orogeny with intraplate deformation affecting the Paris Basin, namely the "buckling" of its margins due to long-waevlength lithospheric folds striking NE. They have even postulated considerable rock uplift resulting from such folds (ca. 1000m). Hence, the Paris Basin developed by stretching and thermal subsidence (Triassic and Jurassic depocentres) followed by several episodes of lithospheric folding (as of the Cretaceous times) that led to uplifted margins and erosion – *e.g.* Vosges and Black Forest areas (Guillocheau et al., 2000; Bourgeois et al., 2007). The amount and timing of such erosions remain debatable, yet, based on stratigraphic corrleations and geomorphology, up to 500 m of Late Cretaceous carbonates have been eroded along the southeastern margins of the basin (*e.g.* Le Roux, 1980; Fizaine, 2012). Taking into account of such eroded rock series is crucial for estimating properly the maximal burial of the "Dalle Nacrée" Formation across the Paris Basin (Table 1).

An epicontinental sea covered the Paris Basin during Bathonian-Callovian times, which developed whithin subtropical latitudes (25–30° N) (Fig. 1; Enay and Mangold, 1980; Thierry and Barrier, 2000; Brigaud et al., 2009b). Overlying an aggradational Bathonian carbonate platform, consisting of ooids and bioclastic shoals (Oolithe Blanche) and carbonate muds (Calcaire de Comblanchien), shallow marine bioclastic and oolitic sands prevailed. These facies mark the end of a transgressive succession; they are overlain by the Middle Callovian maximum flooding surface (Guillocheau et al., 2000). During the latest Bathonian-Early Callovian, the Paris Basin was, subsequently, characterized by oobioclastic ramp settings (Garcia et al., 1996; Gaumet, 1997; Brigaud et al., 2009a,b). The Callovian witnessed a major carbonate productivity crisis at the Bathonian/Callovian boundary, in relation to the break-up of the Pangea supercontinent as well as global warming and associated transgression.

The study area concerns the Early Callovian oobioclastic facies and is located in the southeastern part of the Paris Basin (Yonne, Aube, and Haute-Marne; France). It comprises fives boreholes (Table 1): *i.e.* the Arrentières (ART) borehole situated towards the southeastern margin of the basin contrary to the Saint-Martin-de-Bossenay (SMB), Gisy-les-Nobles (GN), Grange-le-Bocage (GLB) and Avon-la-Pèze boreholes (AP) which are located in the deeper central part of the basin, to the west (Fig. 2). These boreholes intercept the Early Callovian "Dalle Nacrée" Formation with thicknesses varying between 13 and 22 m (GLB and AP, respectively; Table 1). The thicknesses recorded in the marginal Arrentières (ART) borehole and the further basinward Saint-Martin-de-Bossenay (SMB) borehole are very similar (19 and 21m, respectively). The maximum thickness of this formation reaches some 30 m in the Villeperdue oilfield (toward the centre of the Paris Basin; Fig. 3).

The term "Dalle Nacrée" is an old name that was given to a rock succession (mainly reservoirs) representing two sequences that are refered to as "Pierre de Dijon-Corton" and "Pierre de Ladoix", from bottom to top (Floquet et al., 1989 Javaux, 1992; Garcia et al., 1996; Thierry et al., 2006). The two latter rock units are sometimes termed together as "Calcaires d'Etrochey" (Purser, 1989; Gaumet, 1997). Stratigraphically, this formation is attributed to the upper part of the Middle Jurassic – Late Bathonian to/or Early Callovian (Thierry et al., 1980; Gaumet et al., 1996; ca. between 166.1-163.5 Ma; Gradstein et al., 2012). It is underlain by the Late Bathonian "Comblanchien", and overlain by the Middle Callovian "Marnes de Massingy". The latter, marl deposits make a relatively thick seal-