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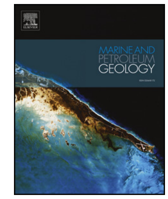

Research paper

Geological and mechanical study of argillaceous North Sea chalk: Implications for the characterisation of fractured reservoirs

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ABSTRACT

Argillaceous chalk intervals from the North Sea are characterised by matrix permeabilities lower than 0.2 mD and therefore they are defined as tight chalks. Hence, fracture networks within these chalks are of major importance to predict fluid flow and reservoir or seal behaviour. This study aims to understand the geological parameters controlling the chalk petrophysical and mechanical properties, using the outcrop analogue of the Cenomanian chalk at Cap-Blanc Nez (Northern France). Sedimentological, petrographic and petrophysical analyses were performed and show that the combination of the depositional environment and diagenetic imprint control the microtexture. Non carbonate content is ranging from 5 to 40% within the studied samples, and is critical for the diagenetic imprint. The fracture behaviour of the chalk was studied using a mechanical stratigraphy approach throughout the 70 m-thick succession, where a transition between lower Cenomanian argillaceous chalk and middle-upper Cenomanian pure chalk is exposed. Twenty-two mechanical units are distinguished and the amount of fractures crosscutting, initiating and terminating on mechanical interfaces quantified. Manual scanlines show that fracture spacing ranges from 17 to 232 cm. Mechanical interfaces are associated with lithological heterogeneities with strong microtextural contrasts, related to the non-carbonate content and/or degree of cementation. The mechanical units are thus defined either by deposition or diagenesis. The fracturing behaviour of about 10 m homogeneous pure chalk interval units, defined as DFZ (densely fractured zones) differs significantly from the rest of the succession. Large sigmoidal-shaped fractures are confined to those intervals, and a dense fracture network developed. Because of their plastic behaviour clay layers are able to accommodate part of the stress, whereas homogeneous pure chalk show a more brittle behaviour.

1. Introduction

Calcareous oozes have been deposited over large marine areas, from the Mesozoic till the present in sedimentary basins all over the world (Garrison, 1981). Chalk was deposited as such an ooze and is one of the most important carbonate rock types in NW Europe, playing a major economical role. Chalk is a major groundwater reservoir in NW Europe, yielding 8 million cubic metres daily (Downing et al., 2005) and a major hydrocarbon reservoir, especially in the North Sea. For example, estimates indicate that about 7 billion barrels of oil were originally in place in the Upper Cretaceous chalk of the Ekofisk Reservoir (North Sea) (Agarwal et al., 2000). Therefore, petrophysical properties and other rock characteristics of chalk reservoir intervals have been extensively studied and are fairly well known (e.g. Fabricius, 2007; Gommesen et al., 2007; Hardman, 1982; Scholle, 1977; Scholle et al., 1998; Vejbæk, 2002). Microporous chalk reservoirs are commonly characterised by high porosities (up to 50%) and low permeabilities (from 0.01 to 10 mD). However, only approximately 10% of the Upper Cretaceous/Lower Palaeocene Chalk Group in the central North Sea represents a conventional reservoir. The rest of the chalk was described as non-reservoir chalk (Damholt and Surlyk, 2004; Mallon and Swarbrick, 2002, 2008) or tight chalk (Faÿ-Gomord et al., 2016a; Lindgreen et al., 2012) which have permeability values lower than 0.2 mD (Bailey et al., 1999). Tight chalks have received relatively little attention since the discovery of chalk hydrocarbon reservoirs of the North Sea in the 1960s, despite forming the bulk of the chalk deposits. Recently there has been a growing interest in understanding the intrinsic properties of those low reservoir quality chalks that were

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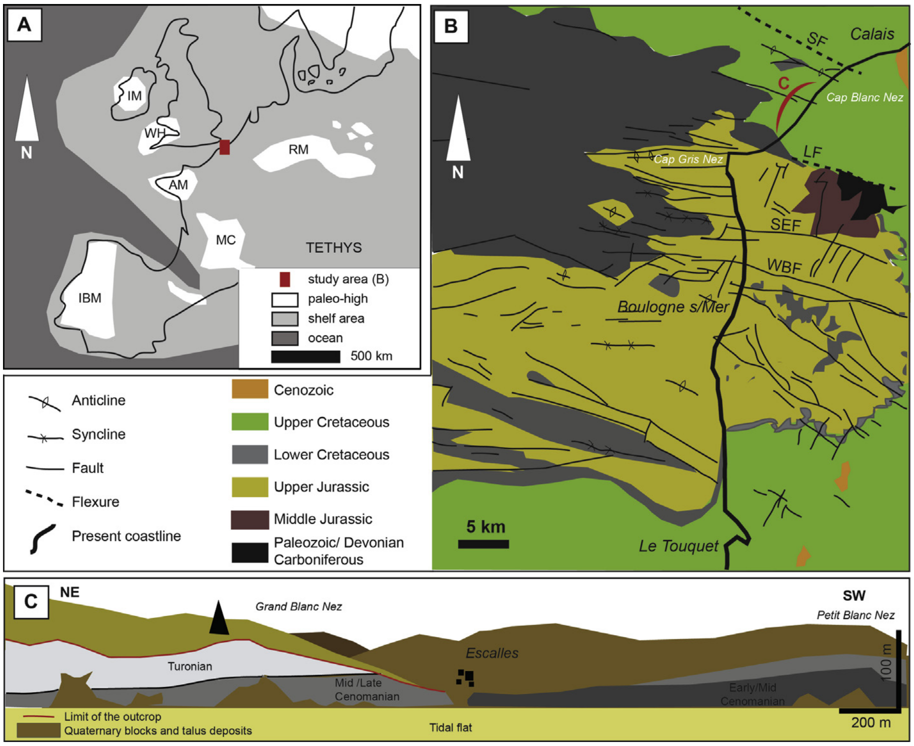

Fig. 1. (A) Palaeogeography map of western Europe during the middle Cenomanian (after Wendler et al., 2002); AM = Armorican Massive, WH = Wales High, IBM = Iberian Massive, IM = Irish Massive, MC = Massive Centrale, RM = Rheinish Massive. (B) Geological map of northern France, showing the extent of the Weald–Boulonnais Basin. (after Mansy et al., 2003) (C) Schematic profile of the cliffs along section C (after Amédro and Robaszynski, 2001).

previously identified as potential intrareservoir seals (Damholt and Surlyk, 2004; Fabricius, 2001; Gennaro et al., 2013; Hjuler and Fabricius, 2009; Jakobsen et al., 2004; Madsen, 2010; Røgen and Fabricius, 2002).

In such low permeability rocks, fractures are the primary pathway for fluid flow (Nelson, 1985), and the role of structural features as preferential flow pathways in chalk have been proven to be important in reservoir studies (e.g. Bear, 1993; Travis, 1984). In layered rocks it has been shown that the opening and the intensity of joint fracturing is controlled by stratigraphy. This was highlighted by Underwood et al. (2003) and Rustichelli et al. (2012), who defined a mechanical unit as a unit representing one or more sedimentary beds that fracture independently from other units. These mechanical units are bounded by mechanical interfaces, which are commonly related to sedimentary contrasts, although sedimentary boundaries do not always define mechanical interfaces. An example where the concept of mechanical stratigraphy has been applied to chalk are the deeply buried Austin chalks in Texas, where mechanical interfaces correspond to thick marl interlayers (Cooke et al., 2006).

In the subsurface, tight chalk intervals constrain fluid flow, acting as seals or as unconventional reservoirs depending on their fracture patterns. In order to accurately characterise their heterogeneity and to determine fundamental controls on fracturing behaviour of argillaceous chalks, outcrop analogue studies are essential. Thus, a multidisciplinary approach was used on the Cenomanian argillaceous chalk cliffs of Cap Blanc-Nez in Northern France. Deposits are characterised by a high non-carbonate content (up to 38%) resulting in very low permeabilities (as low as 0.04 mD) (Faÿ-Gomord et al., 2016a). Previous studies of this outcrop provide a detailed stratigraphical framework (Amédro and Robaszynski, 2001; Robaszynski and Amédro, 1986) and a detailed understanding of the clay fraction (Deconinck et al., 1989, 2005; Deconinck and Chamley, 1995). However, data on the petrographic, petrophysical and microtextural properties of the Cap Blanc-Nez chalk are limited to Doremus (1978), who described chalk microtextures based on SEM observations. This author highlighted the influence of porosity and clay content on mechanical properties, as well as the importance of grain contacts on the intrinsic cohesion of the rock. However, the relationship between the geological context, e.g. depositional and diagenetic history of the samples and their microtextural properties was not emphasized.

This study aims to better understand the geological history of Cap Blanc-Nez chalk, from depositional setting, through diagenesis and fracturing. Chalk porosity and permeability properties are assessed using sedimentological and petrographic analyses. In order to characterise the fracture network and define the mechanical interfaces, a mechanical stratigraphy study was performed. The latter provides essential information regarding fluid flow, since a proper characterisation of the dual permeability of pores and fractures is essential in order to accurately model fluid flow in aquifers, hydrocarbon reservoirs or apparent aquacludes and seals. The Cap Blanc-Nez outcrop allows an understanding of the behaviour of argillaceous chalk intervals in NW Europe and especially their equivalents in hydrocarbon fields of the North Sea. This study reveals the prominent impact of the variations in non-carbonate phases on the characteristic behaviour of a layered chalk succession, influencing both petrophysical and rock mechanical properties.

2. Geological settings

The field study focused on the 5 km long chalk cliffs of Cap Blanc-Nez (northern France), which is located in the Boulonnais area, in the NW part of the Paris Basin. The Paris Basin was part of the NW European Chalk Sea, which formed a large basin in western Europe known as the Anglo-Paris Basin. This intracratonic basin was mainly characterised by thermal subsidence, following Permian–Triassic tectonic extension (Brunet and Le Pichon, 1982; Le Solleuz et al., 2004). The basin is currently bounded by the Brabant Massif to the northeast which became flooded during the Late Cretaceous, the Central Massif to the south, and the Armorican Massif to the west (Fig. 1).

2.1. Sedimentological setting

The 70 m thick succession of Cap Blanc-Nez is the reference section for the Cenomanian in this part of the Anglo-Paris Basin (Robaszynski