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Large-scale mass transfers related to pressure solution creep-faulting interactions in mudstones: Driving processes and impact of lithification degree

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ABSTRACT

Where normal faulting is associated with PSC (Pressure Solution Creep), it generates evolutions in petrophysical properties of mudstones like chalk: decrease in reservoir qualities and transport properties in the deformed zones adjacent to the fault plane and increase (or no change) in reservoir qualities and transport properties in the outermost deformed zones. These modifications result from large-scale mass transfers linked to a transport of solutes through the pore space over distances of several grains within decimeter or larger zones (open systems at the grain scale). In the lithified mudstones, these large-scale mass transfers consist in a mass redistribution from the outermost deformed zones (mass and volume loss) to the deformed zones adjacent to the fault planes (mass gain). In the weakly lithified mudstones, the mass redistribution occurs in an opposite direction. A deeper understanding of these large-scale mass redistributions is essential because the PSC–faulting interactions and the associated petrophysical modifications can be a key topic in several geological applications (oil and gas migration and entrapment in mudstone reservoirs, anthropogenic waste storage, carbon dioxyde geosequestration). The results of two studies about mass transfers and volume changes induced by natural fault systems in "white chalk" allowed to point out that two driving processes control the large-scale mass transfers during PSC–faulting interactions: the advective mass transport related to pore fluid flows and the large-scale diffusive mass transport linked to chemical potential gradients. The present contribution also highlights that the lithification degree of the host material plays a key role in the large-scale mass transfers related to PSC–faulting interactions by controlling (1) the spatial distribution of voids induced by the deformation, (2) the particle displacement on the fault plane and in the adjacent zones and (3) the petrophysical properties of the host material in some zones.

1. Introduction

Understanding the impact of faulting on the petrophysical properties (particularly permeability and porosity) of mudstones is essential because (1) faults often play a significant role in oil and gas migration and entrapment in carbonate reservoirs (about 60% of world's oil and 40% of world's gas reserves are contained in carbonate reservoirs with an important part in mudstones) and (2) faults can affect the low-permeability mudstones employed as barriers in anthropogenic waste storage and carbon dioxyde geosequestration. In addition, the fluid flows and their control are a key subject in the studies of fault zones.

Previous contributions (Angelier et al., 2006; Carrio-Schaffhauser and Gaviglio, 1990; Gaviglio et al., 1993, 1997, 1999, 2009; Mimran, 1985; Richard, 2008; Richard and Sizun, 2011; Richard et al., 2002; Schroeder et al., 2006) have provided data about the petrophysical and petrographic modifications related to faulting in mudstones. By examining the driving processes that generate these modifications, these works highlighted the importance of PSC (Pressure Solution Creep) where it is spatially associated with faulting.

A small number of studies focussed on the mass transfers and volume changes (quantification, spatial distribution and driving processes at the grain scale) caused by the PSC–faulting interactions in mudstones. These contributions (Richard, 2008; Richard and Sizun, 2011) showed the interest of this approach to develop conceptual models of deformation mechanisms. They also pointed out that the fault systems are not closed at the grain scale during PSC–faulting interactions: large-scale mass transfers causing significant modifications in petrophysical properties (notably total porosity and permeability) and nannofacies (particle size and cementation, fabric, …) occur. These large-scale mass transfers result from a transport of solutes through the pore space over distances of several grains within decimeter or larger domains.

Large-scale mass transfers triggered by PSC–faulting interactions have been frequently observed in mudstones and as a rule in carbonate rocks (Carrio-Schaffhauser and Gaviglio, 1990; Gaviglio et al., 2009; Labaume et al., 2004; Matonti et al., 2012; Mimran, 1985). These mass transfers due to a transport of solutes through the pore space over distances of several grains are poorly documented (Gundersen et al., 2002; Hellmann et al., 2002b; Lehner, 1995) compared to the mass transfers

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that occur in closed systems at the grain scale (Baker et al., 1980; Croizé et al., 2010a,b; Hellmann et al., 2002a,b; Hu and Hueckel, 2007; Lydzba et al., 2007; Zhang and Spiers, 2005; Zhang et al., 2002, 2010; Zubtsov et al., 2005). By using the results of two studies about mass transfers and volume changes induced by the activity of natural fault systems in "white chalk" (Richard, 2008; Richard and Sizun, 2011), the aim of the present paper is (1) to determine the driving processes that trigger the large-scale mass transfers during PSC–faulting interactions and their evolutions through time, (2) to identify the factors that control the spatial distribution of mass and volume changes and the direction of large-scale mass transfers and (3) to clarify the influence of the lithification degree on large-scale mass transfers.

2. Geological setting

Two exhumed fault systems were studied:

- the Omey fault system, located in the eastern part of the Paris Basin near Omey (France, Fig. 1), shows an 11.4 m wide fractured zone with one normal fault and a network of tension gashes (Fig. 2). This system is linked to the Oligocene extension observed in the NW European Platform (Richard, 2008). It affected a Coniacian "white chalk" in an unconfined phreatic zone at a depth between −150 m and −250 m (Coulon and Frizon de Lamotte, 1988; Richard et al., 1999). At the time of activity of the Omey fault system, it is reasonable to consider that the host Coniacian chalk was lithified: in the Omey area (eastern part of the Paris basin, Champagne), (1) the undecompacted thickness of sedimentary deposits that overlaid the Coniacian chalk (Santonian and Campanian chalk essentially) reached a minimum of 250 m (Mégnien et al., 1980) and (2) the Paleogene continental paleoenvironment probably speeded up the compaction of the chalk by inducing a meteoric porewater input;
- the Mons fault system, located in the Mons Basin near Harmignies (Belgium, Fig. 1), shows one normal fault with two subsidiary branches (Fig. 3) which affects a "white chalk" in the Obourg Chalk (Late Campanian lithostratigraphic unit). This system is related to the Late Campanian NW-SE extension observed in the NW European Platform (Richard and Sizun, 2011). The normal faults linked to the Late Campanian NW-SE extension are only observed through the Late Campanian lithostratigraphic units, never in the Maastrichtian units (Vandycke et al., 1991). In the Harmignies area, the Late Campanian lithostratigraphic units overlaying the Obourg chalk (Nouvelles Chalk and Spiennes Chalk) are 40 m thick (undecompacted thickness, Robaszinski and Anciaux, 1996). It is therefore reasonable to consider that the Mons fault system affected a weakly lithified chalk in a near-surface environment. At the time of activity of the Mons fault system, this near-surface environment was an unconfined phreatic zone (Richard and Sizun, 2011).

The conditions of deformation, the deformed material and the diagenetic environment of Omey and Mons fault systems are similar (Fig. 4). In both systems, the PSC–faulting interactions result from the development of one normal fault that affect a "white chalk" (insoluble residue below 3%) in a saturated and unconfined near-surface environment. The major difference lies in the degree of lithification of the deformed material (Fig. 4). By considering the aim of the present paper, the difference in width of fractured zones does not make the comparison difficult between the Omey and Mons fault systems.

3. Sampling, methods and analytical techniques

3.1. Sampling

3.1.1. Omey fault system

Sixty samples were collected along a 100 m wide working face (Fig. 2A) in the Marson quarry. The working face crosscuts an 11.4 m wide fractured zone with one normal fault plane F and a network of subvertical tension gashes (Fig. 2A). Four fracture network types can be distinguished by using the aperture width and the spatial distribution of fractures (Fig. 2B). The fracture network type of the 60 sampling points is given in Fig. 2C.

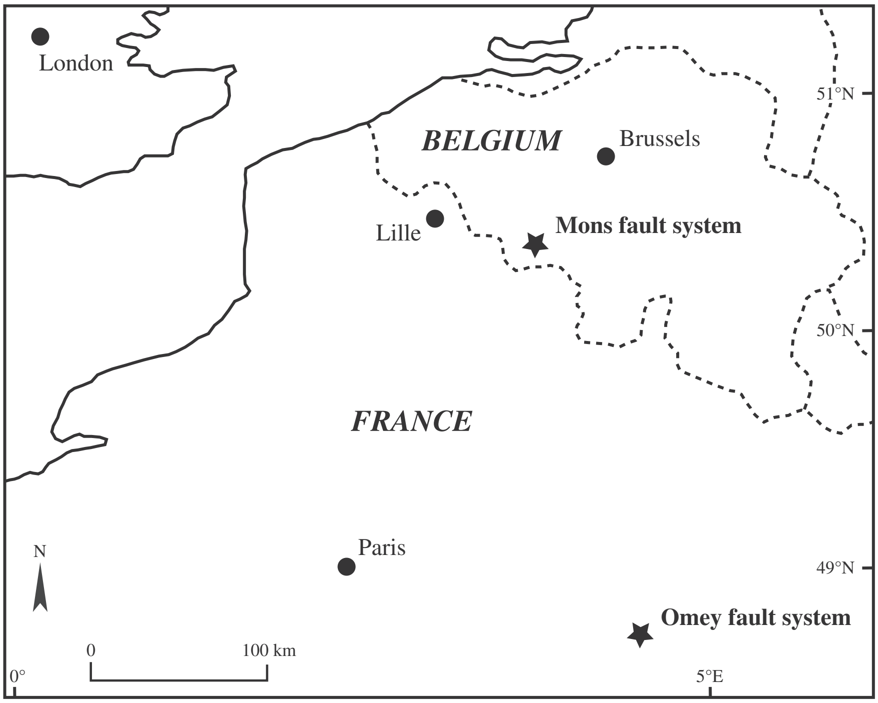

Fig. 1. Location of Omey and Mons fault systems. The Omey fault system is located in the eastern part of the Paris Basin near Omey (Marson quarry, France) and the Mons fault system is located in the southern part of the Mons Basin near Harmignies (Hainault-Sambre quarry, Belgium).