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Microfracturing during primary migration in shales

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ABSTRACT

In several geological environments, chemical reactions are coupled to rock deformation and the associated stresses induced locally interact with the far field loading. This is the case in immature shales that undergo burial and diagenesis, where the organic matter evolves with temperature into hydrocarbons which induces local volume expansion. At large scale, this mechanism is responsible for the transport of hydrocarbons from source to reservoir rocks, a process referred to as primary migration. However, how the interactions between local fluid production, microfracturing, and transport are coupled remain to be understood. Here, we analyze this coupling phenomenon by developing a discrete element model where the generation of local overpressures occurring in kerogen patches is simulated, while the surrounding rock is subjected to external loading. It is shown that, due to local fluid overpressure; microfracturing occurs and brings the fluids to migrate through the medium. The numerical results are confirmed by laboratory experiments where the network of microfractures induced in an immature Green River shale sample heated under small differential stress was imaged in three dimensions using X-ray microtomography. Moreover, the numerical simulations identify that the state of differential stress and the initial kerogen distribution constitute two key parameters that control the formation of the three-dimensional percolating microfracture network and could thus explain primary migration in shale rocks.

1. Introduction

The coupled response of chemical reactions and deformation in rocks can induce the development of localized damage in the form of connected microfractures or microporosity which facilitate the circulation of fluids. These phenomena are observed in various geological processes such as weathering and erosion of surface rocks (Røyne et al., 2008; Jamtveit and Hammer, 2012), hydration of the Earth's lower crust (Peacock, 1993; Jamtveit et al., 2000), dehydration of sediments in subduction zones (Ulmer and Trommsdorff, 1995; Saffer and Bekins, 1998; Brantut et al., 2012), alteration of monuments by salt precipitation (Noiriel et al., 2010), or the maturation of organic matter in source rock sediments (Snarsky, 1961; Tissot and Welte, 1978; England et al., 1987; Hunt, 1996; Lafargue et al., 1994, 1998; Vernik, 1994; Rudkiewicz et al., 1994; Kobchenko et al., 2011). For the latter, the coupling between maturation of the organic matter and creation of porosity by fracturing of the source rocks during burial may lead to hydrocarbon escape towards a more porous reservoir, a process called primary migration.

Shale rocks overlie or underlie most hydrocarbon-bearing reservoirs, forming cap rocks and source rocks. They prevent fluids from escaping due to their low permeability and by a capillary sealing mechanism controlled by the small pores (Horsrud et al., 1998). While the presence of fractures in shales in outcrops and from cores through unconventional reservoirs has been described (Gale et al., 2014), the presence of microfractures and microporosity at smaller scales, that may control the overall permeability, is debated because of scarce observations (Gale et al., 2014; Kalani et al., 2015, Ougier-Simonin et al., 2016). Sometimes, bitumen-filled microfractures with chemical characteristics similar to decomposed kerogen are observed (Lash and Engelder, 2005), in other cases the presence of sealed veins indicate that microfractures were open at depth (Kalani et al., 2015). Moreover, microfractures control the long-term sealing capacities of cap rocks, the expulsion of hydrocarbon during primary migration, and the potential increase in permeability when reactivated by hydraulic fracturing. More generally, the petrophysical properties of argillite rocks have

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fundamental implications, for example on their frictional behavior in faults (Brantut et al., 2008) and in controlling their permeability (Holland et al., 2006).

Kerogen maturation into oil and gas leads to a volume increase in the order of 10–20% at standard pressure and temperature conditions. In many cases maturation takes place within the internal porosity of kerogen flakes, which may indicate that expansion of the solid might be another cause of microfracturing. Such overpressure mechanisms have been proposed to be high enough to fracture the source rock (Pelet and Tissot, 1971; Vernik, 1994). When the overpressure reaches a critical stress, microfractures starts to nucleate and propagate (Hunt, 1996; Capuano, 1993; Vernik, 1994; Jin et al., 2010). Propagating microfractures may then coalesce and even get connected to pre-existing vertical fractures which would further facilitate hydrocarbon primary migration (Fan et al., 2012).

Here, we study the process of primary migration coupled to microfracture development by a combined experimental and numerical approach. The experimental component involves imaging in three dimensions (X-ray tomography) of Green River shale samples that were heated under small differential stress, in order to characterize the network of microfractures produced during the maturation of organic matter (Kobchenko et al., 2011; Panahi et al., 2013). The natural Green River shale rock contains kerogen organic matter which is present in the form of sub-millimeter elongated ellipsoids distributed in the rock matrix. These patches, when undergoing thermal maturation, act as local sources of overpressure due to the breakage of shorter molecules from the very long chained molecules constituting the polymerized kerogen. Such pressure variations can induce local microfracturing at the scale of the kerogen patches. These fractures then grow and ultimately connect to each other in three-dimensions, spanning the whole volume of the rock mass. In order to gain more insight into the process, we simulate numerically the formation and propagation of these microfractures at the scale of kerogen patches using a three dimensional model based on the discrete element method (Cundall and Strack, 1979, Donzé and Magnier, 1994). The conditions under which these microfractures become the preferred paths for fluid products and control primary migration are then discussed.

2. Materials and methods

2.1. Experiments of shale maturation

Two core samples of a Green River shale, that contains 5 wt.% type I kerogen, were heated to 390 °C in pressure vessels for 48 h to transform the kerogen into oil and gas. The rock is made of quartz, clays, pyrite, and carbonate minerals and has a low porosity, close to 5% as measured by helium gas adsorption method. This rock is an immature shale and previous experiments have shown that kerogen maturation at atmospheric pressure can be performed at temperatures in the range 300–400 °C (Kobchenko et al., 2011; Panahi et al., 2013). The samples, 25 mm diameter and height, were cored perpendicularly to bedding. The kerogen is organized into small elongated patches, 10–200 μm long and 2–5 μm thick, spread along preferential beds in the shale. The microstructure of the rock was imaged before heating using high resolution X-ray microtomography at beamline ID19 at the European Synchrotron Radiation Facility (Grenoble, France), at a voxel size of 0.16 μm, allowing identification of the 3D geometry of kerogen patches (Fig. 1).

A steel sample holder was custom-made to contain the sample and simulated a moderate confinement. Some holes were drilled into the

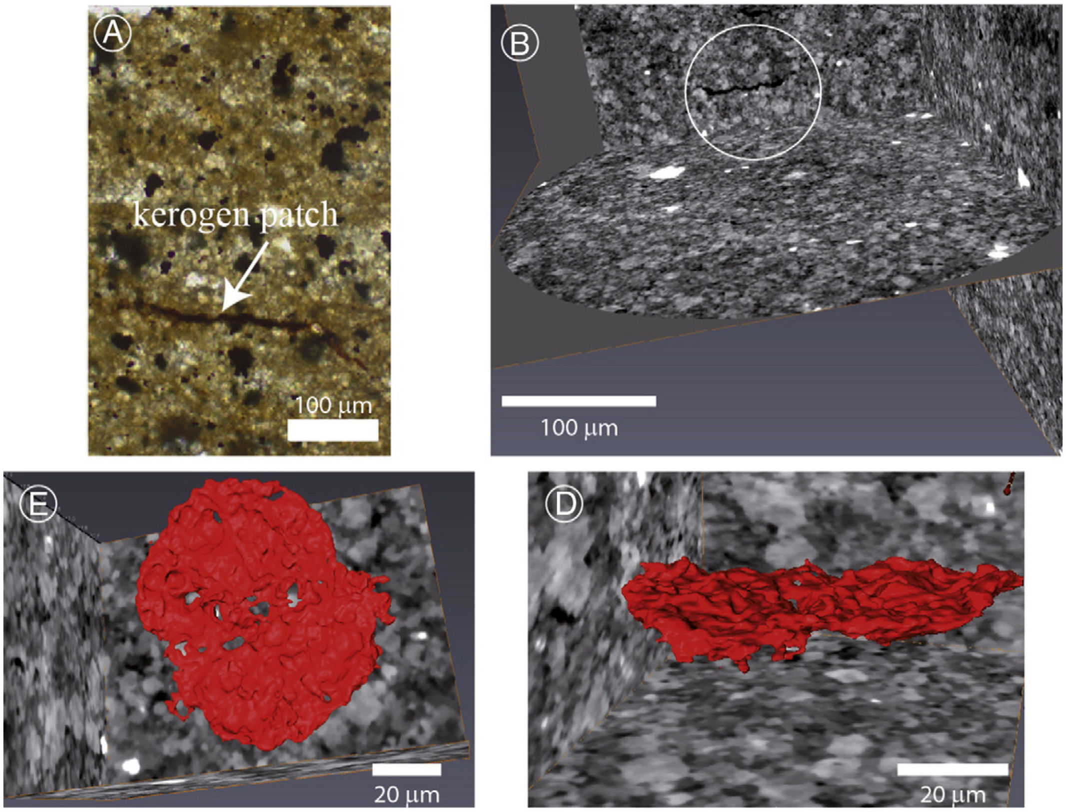

Fig. 1. Imaging of kerogen in a Green River shale sample. A) Optical microscopy showing a kerogen patch. B–D) X-ray microtomography imaging of a Green River shale sample at a voxel size of 0.16 μm showing the microstructure of the shale where the various gray scale levels underline the individual grains (for example pyrite minerals appear in white). A kerogen patch is parallel to bedding (white circle in B). C–D) Zooms on a patch of kerogen which forms an ellipsoid, 70 μm wide and 2–4 μm height. The outer surface of the bed parallel kerogen patch is colored in red.