Earth-Science Reviews 162 (2016) 198–226

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Microfracturing and microporosity in shales

Audrey Ougier-Simonin [a,b], François Renard [a,c,*], Claudine Boehm [d], Sandrine Vidal-Gilbert [d]

[a] Univ. Grenoble Alpes & CNRS, ISTerre, CS 4070, 38056 cedex 9 Grenoble, France
[b] British Geological Survey, Environmental Science Centre, Keyworth, Nottingham NG12 5GG, United Kingdom
[c] PGP, Department of Geosciences, University of Oslo, Norway
[d] Total, SA, France

ARTICLE INFO

Article history:
Received 22 February 2016
Received in revised form 7 September 2016
Accepted 8 September 2016
Available online 24 September 2016

Keywords:
Shale
Microfracture
Porosity
Mechanical properties
Transport properties

ABSTRACT

Shales are ubiquitous rocks in sedimentary basins, where their low permeability makes them efficient seals for conventional oil and gas reservoirs and underground waste storage repositories (waste waters, CO_2, nuclear fuels). Moreover, when they contain organic matter, they form source rocks for hydrocarbons that may escape towards a more porous reservoir during burial, a process referred to as primary migration. And when the hydrocarbons cannot escape, these rocks can be exploited as oil or shale gas reservoirs. While the presence of fractures at the outcrop scale has been described, the existence of fractures at smaller scales, their link with microporosity, the mechanisms that created them, their persistence over geological times, and their effect on the petrophysical properties of shales represent scientific challenges for which drillings in various sedimentary basins over the past decades may hold timely key data.

Here, we review and synthetize the current knowledge on how microfractures and micropores in shales can be imaged and characterized and how they control their anisotropic mechanical properties and permeability. One question is whether such microfractures, when observed in outcrops or in drilled core samples extracted from boreholes, are related to decompaction and do not exist at depth. Another question is whether veins observed in shales represent microfractures that were open long enough to have acted as flow paths across the formation. The mechanisms of microfracture development are described. Some have an internal origin (fracturing by maturation of organic matter, dehydration of clays) while others are caused by external factors (tectonic loading). Importantly, the amount of microfracturing in shales is shown to depend strongly on the content in 1) organic matter, and 2) strong minerals. The nucleation of microfractures depends on the existence of mechanical heterogeneities down to the nanometer scale. Their propagation and linkage to create a percolating network will depend on the presence of heterogeneities at the meso- to macro-scales. Such percolating microfracture networks could control both the long-term sealing capabilities of cap rocks and the further propagation of hydraulic fracturing cracks. Finally, possible areas of research for describing the mechanism of microfracture formation in greater detail and how this impacts the transport and mechanical properties of shales are also discussed.

Contents

---

* Corresponding author at: Univ. Grenoble Alpes & CNRS, ISTerre, CS 4070, 38056 cedex 9 Grenoble, France.
E-mail address: francois.renard@geo.uio.no (F. Renard).

http://dx.doi.org/10.1016/j.earscirev.2016.09.006
0012-8252/

1. Introduction

Shales make up between one-half and two-thirds of all sedimentary rocks in the Earth's shallow crust. They constitute about 80% of all drilled sections in oil- and gas-drilling operations, mainly because they overlie or underlie most hydrocarbon-bearing reservoirs (Sarout and Guéguen, 2008a), forming cap rocks and source rocks. In this context, shales have been considered as source rocks and seals for conventional petroleum and gas systems for many years (Hunt, 1996). However, the commercial production of shale gas and shale oil since the end of the 1990s has changed this idea. Accordingly mudrocks, and shales in particular, have received renewed attention in recent years because of their emergence as effective unconventional hydrocarbon reservoirs (Curtis, 2002; Montgomery et al., 2005; Jarvie et al., 2007; Pollastro et al., 2007; Loucks et al., 2009).

Today, shales are target rocks for crustal fluid resources such as groundwater and hydrocarbons, but also fields of interest for the storage of carbon dioxide and radioactive wastes. Shales can act either as source rocks for hydrocarbons or/and as cap rocks (top-seals) when located above reservoirs. 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). The new economic interest has triggered questions around their petrophysical and mechanical properties. However, their low permeability and sensitivity to the nature of contacting fluids make it difficult to handle them under laboratory conditions. In addition, recovery of shales from depth can cause stress-relief microfracturing and gaseous exsolution from pore fluids (Dewhurst et al., 2011), which overprint the natural microporous space geometry and fluid content. The transport properties of low-permeability rocks are fundamentally controlled by the structure of available transport pathways (Keller et al., 2011). Consequently, the identification of porosity and pore size distribution in shales, including microfractures, has become a high research priority as they are key parameters for the commercial evaluation of a potential shale (Ross and Bustin, 2008, 2009; Loucks et al., 2009). 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. These properties are particularly useful in the context of deep buried reservoirs, where dry boreholes are particularly costly. Here, we review the mechanisms by which microfractures have formed during the geological history of shales, synthetize our knowledge on their role on petrophysical properties of the rock and how interwoven they are with (micro)porosity.

Kranz (1983) wrote a first review article on microfractures in rock and emphasized their importance in controlling transport properties. Anders et al. (2014) updated the current knowledge on microfractures in rocks, discussing their mechanical origin and the modern imaging techniques used to characterize them. These two review studies were focused on all kinds of sedimentary and igneous rocks, with only a few examples concerning shales. Finally, Gale et al. (2014) proposed a comprehensive study of fractures in shales based on observations at the outcrop scale or in core samples extracted from boreholes. However, in these three studies, no comprehensive review was performed on the microfractures in shales. Several studies have been performed to address microfracturing in tight rocks. They focused on technologies related to underground nuclear waste disposal and, more recently, geological storage of CO_2 (e.g. Bolton et al., 2000; Yang. and Aplin, 2007; Sarout and Guéguen, 2008a; Ababou et al., 2011; Skurtveit et al., 2012; Ghayaza et al., 2013). In the present study, we intend to review current knowledge concerning microfractures in shales through a state-of-the-art literature survey. We address several questions in order to assess how natural microfractures are generated in shales and how they affect rock properties. In particular, the following questions represent key challenges that are not completely solved yet:

- How do cracks nucleate, propagate, stop and eventually heal in shales?
- How is it possible to discriminate between induced microfractures (due to drilling campaigns or rock exhumation) and natural microfractures present at depth?
- Is it possible to characterize “inherited” micro-cracking?
- What are the effects of clay mineralogy and organic matter content?
- When a microfracture has been generated, does it close or remain open? Over which time scale?
- What is the effect of fluid chemistry on crack propagation or healing/sealing?

1.1. What is a shale rock?

The term “shale” was first introduced by Hooson (1747) to describe an indurated, laminated, clayey rock; ‘shale’ is now the ubiquitous term that encompasses the entire class of fine-grained clayey sedimentary rocks, whether they are laminated or not. Beside the term shale, there is a plethora of names in the literature to describe fine-grained clayey sedimentary materials partly based in grain size – argillite, clay, claystone, mud, mudrock, mudstone, pelite, silt, siltstone, slate, or wacke. In the petroleum industry, the term shale is not precisely defined: it may range from weak and soft clay (named gumbo) to strongly cemented and shaly siltstones (Horsrud et al., 1998). Shales have in common that they all contain substantial amounts of clay minerals, which define their typical gray color, and (silty) quartz, carbonates, and smaller quantities of feldspars, iron oxides, organic matter, and, sometimes, fossils (Fig. 1). But shales differ from 1) mudstones in that they break into thin chips with roughly parallel tops and bottoms, whereas mudstones break into blocky pieces, and 2) from argillites and slates in that they are fissile but do not show distinctive layering nor true slaty cleavage or foliation (Blatt and Tracy, 1996; Merriman et al., 2003).

Shales generally form by settling from sediment suspension in very slow moving water such as in lakes, lagoons, deltas, floodplains, and in the offshore below wave-base. The fine particles composing them can remain suspended long after the larger and denser particles of sand have been deposited. Along with mudrocks, shales contain roughly 95% of the organic matter in all sedimentary rocks. However, this amounts to only several percent by mass in an average shale sample.