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The importance of fracture-healing on the deformation of fluid-filled layered systems

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Understanding the fracturing–healing–refracturing cycle is a fundamental part of studying the deformation dynamics and the permeability evolution of rock systems. Previous studies, however, have not examined the influence of healing i.e. fracture-closure through vein formation and the mechanical properties of the "healed" fractures (veins) on the rock deformation. We present results from a two-dimensional coupled hydro-mechanical model which simulates large time and spatial scale dynamic fracturing and healing of a porous medium under the influence of gravity, tectonic stretching and elevated fluid pressures. Our results show that healing decreases the local porosity, and that the veins' strength is more important than their elastic modulus in influencing the deformation and the evolving patterns. Hard veins make the aggregate progressively stronger, results in an overall healing of the system, limited fracturing and thus fluid flow, greater stresses and delayed fracture saturation. Weak veins make the system weaker in which refracturing of the healed bonds is the dominant process that creates more open fractures and thus increases the permeability. These results provide clues for the importance of the veins' mechanical properties and can enhance our understanding of the deformation dynamics and the permeability evolution of the rock systems.

1. Introduction

Fluids play an important role in a lot of processes in the Earth's crust. The circulation of fluids is primarily responsible for mass and energy transport, and the formation of hydrothermal ore deposits (Fyfe et al., 1978). Fluid has also been recognized as an important factor in triggering earthquakes, reactivation of faults and in influencing processes that control the deformation of rocks (Hubbert and Willis, 1957; Hubbert and Rubey, 1959; Putnis and Putnis, 2007; Putnis and Austrheim, 2010).Consequently, understanding fluid flow and the permeability evolution of the rock is crucial in many disciplines such as hydrocarbon and water supply exploration, waste disposal or mining. However, the dynamics of (hydraulic) fracturing, fracture closure through healing and refracturing of rocks are still poorly understood.

Local fluid overpressure within a rock suite can trigger fracturing. This process is known as hydrofracturing and can be either induced or natural. Induced hydrofracturing has been used as a well stimulation process to enhance the well productivity by fracturing the surrounding rock and induce fluid flow towards a well (Häring et al., 2008; Shapiro and Dinske, 2009; Caló et al., 2013; Shalev et al., 2013; Davies et al., 2013). Natural hydrofracturing is based on similar principles and occurs when the natural system has a local overpressure. The process is recognized as an important fracturing mechanism in rocks (Engelder and Lacazette, 1990; Hunt, 1990; Bruno and Nakagawa, 1991; Hurst et al., 2005; Rodrigues et al., 2009; Nermoen et al., 2010).

Fluid overpressure can be induced by a variety of processes and is generally linked to a local increase in fluid volume due to for example dewatering mechanisms, metamorphic reactions, thermal expansion of fluid, hydrocarbon generation or general density driven movement of fluid (Fyfe et al., 1978; Bethke, 1985; Oliver, 1986, 1996; Swarbrick et al., 2002; Cox, 2005; Vinningland et al.,

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2007; Johnsen et al., 2008a, 2008b). High pressure gradients that lead to fracturing are generally developing in heterogeneous systems, for example below or across seals or along fracture and fault systems. Pressure gradients induce seepage forces that can locally modify the principal stresses (Rice and Cleary, 1976; Mourgues and Cobbold, 2003; Cobbold and Rodrigues, 2007; Rozhko et al., 2007; Rozhko, 2010) especially in combination with anisotropies of the mechanical properties and heterogeneities in a rock (Cornet and Valette, 1984; Hu and Angelier, 2004).

The propagation of hydrofractures depends mainly on three factors, the (1) magnitude and orientation of fluid pressure gradients relative to tectonic and gravitational stresses, (2) mechanical properties of rocks involved and (3) discontinuities of a given system (Cook and Gordon, 1964; Cooke and Underwood, 2001; Smith et al., 2001; Brenner and Gudmundsson, 2004; Cooke et al., 2006; Gu and Siebrits, 2008; Ghani et al., 2013). When fracture propagation is favored, the fractures themselves provide pathways for fluids and therefore control fluid flow (Cox, 2005). In addition, fractures may close (heal) when material precipitates within them forming veins (Fig. 1), which decreases the permeability of the rock and limits the fluid flow again (Bons et al., 2012). Tenthorey et al. (2003) argue that healing of fractures and faults has two significant and competing effects on the system. First of all, it can strengthen the aggregate by increasing cementation and cohesion, which directly causes permeability decrease. At the same time, it weakens the system as the low permeability can result in elevated fluid pressure that in turn can cause further brittle failure.

Both the importance of hydrofracturing and the lack of detection of the process in nature have provoked the development of several numerical models (Tzshichholz et al., 1994; Dahm, 2000; McNamara et al., 2000; Flekkøy et al., 2002; Johnsen et al., 2006; Olson et al., 2009; Goren et al., 2010; Niebling et al., 2010a, 2010b; Goren et al., 2011; Wangen, 2011; Niebling et al., 2012; Aochi et al., 2013; Ghani et al., 2013). The different models face the same complexity as hydrofracturing involves (1) elastic deformation of the matrix triggered by fluid pressure, (2) fluid flow inside matrix and fracture and (3) fracture propagation (Adachi et al., 2007). Many numerical simulations demonstrated that the porosity and the mechanical failure of the media are crucial in the initiation and propagation of the hydrofractures (e.g. Flekkøy et al., 2002; Johnsen et al., 2006; Olson et al., 2009; Goren et al., 2010; Nermoen et al., 2010). However, most of these models lack the intimate coupling between the fluid diffusion and deformation, as well as real (scaled) values. Their spatial and temporal resolution is limited, they mostly deal with granular media and they do not consider healing of fractures. These limitations provided inspiration for further work in terms of numerical modeling.

This paper is a continuation of the work by Ghani et al. (2013) who presented a 2D coupled hydro-mechanical model through which the dynamics of layered porous systems were examined. In this contribution, we focus on the influence of the changing material properties (e.g. breaking strength and elastic modulus) on the development of fracture and vein patterns in single and multilayered systems under loading, tectonic stretching and high fluid pressures. We show that healing and vein properties play a crucial role in the dynamics of the rock system. Our large temporal and spatial scale simulations demonstrate how faults evolve that drain

a

b

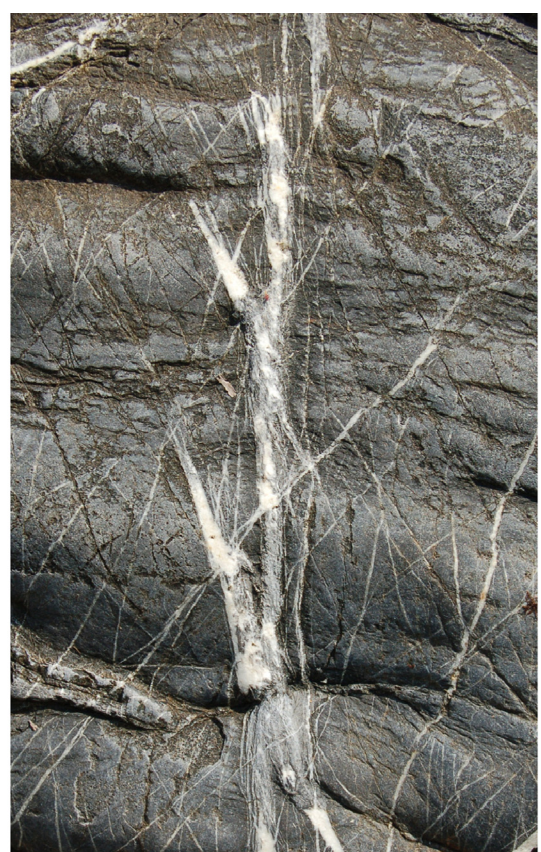

Fig. 1. Field examples of calcite veins in the Internal Ligurian Units near Sestri Levante, Italy. Intense veining is shown on (a), where the veins are relatively hard and the rock (shale) is weak. (b) Hard rock (sandstone) is cut by several weak veins along which multiple refracturing events can be observed.