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Geomechanical implications of dissolution of mineralized natural fractures in shale formations

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ABSTRACT

Organic shale reservoirs accommodate large amounts of hydrocarbons in extremely tight rock matrix. Slick water hydraulic fracturing and proppant placement is the most spread stimulating technology for this type of reservoirs. Some shale formations contain a fair amount of easily-dissolvable carbonates, which prompts shale acidizing as a potential method to increase reservoir permeability. Carbonates in shale formations can be present as a part of rock matrix or can be localized in natural fractures — so-called mineral veins. Previous studies investigated the effects of chemical dissolution within the matrix, implying that acidizing can etch the rock, open new conduits for flow, and increase fracture permeability after closure. This study rather focuses on the reservoir-scale geomechanical implications of chemical dissolution of mineral filling in natural fractures. We use a combination of elasto-plastic analytical methods, analogous thermo-elastic numerical solutions, and experimental results to elucidate the impact of veins dissolution on in-situ stresses. Analytical, numerical, and experimental results indicate that mineral dissolution of localized carbonate fractures leads to changes of local in-situ stresses. The direction of stress relaxation strongly depends on the orientation of mineralized fractures. Dissolution of near-vertical mineralized fractures contributes the most to decreases of effective horizontal stress and reduce stress shadow effects in multistage hydraulic fracture completions. Mineral dissolution, similar to pore pressure depletion or thermal cooling/heating, can increase stress anisotropy, which can reactivate critically-oriented natural fractures. In-situ stress chemical manipulation can be used advantageously to enlarge the stimulated reservoir volume.

1. Introduction

Hydrocarbon-bearing shale formations can extend over large areas and contain vast amounts of oil and gas. However, they are distinguished by extremely low permeability and low recovery factors (Sandrea, 2012). Not all shale plays are equally productive (Petrie, 2014). Sweetspots, places exhibiting high production rates, usually contain a fair amount of natural fractures, among other features (Gale and Holder, 2010). Hydraulic fracturing, the primary stimulation technology in shales, has been known to significantly increase production rates. In shales, in particular, hydraulic fracturing provides access to the systems of natural fractures and substantially increases the drainage area connected to the wellbore, commonly referred to as stimulated reservoir volume (Fisher et al., 2005). Furthermore, natural fracture networks can promote hydraulic fracture "branching", enhance their complexity, and allow hydrocarbons in the shale matrix to reach the wellbore more easily through both propped and un-propped fractures (Fisher et al., 2005, Suarez-Rivera et al., 2013, Lee et al., 2015, Sharma et al., 2015, Espinoza et al., 2016). Production from hydraulically fractured shale reservoirs, however, suffers from rapid production declines (Patzek et al., 2013). One of the reasons of these declines is the closure of natural fractures caused by the depletion-induced increase in effective stresses (Cui et al., 2016). Therefore, both extending fracture network and reducing the closure of natural fractures are desirable to increase and maintain reservoir fracture permeability.

Acidizing is the oldest stimulation technology applied in oil and gas reservoirs (Portier et al., 2007). Acid treatments fall into three categories: wellbore acidizing used to clean the wellbore surface, matrix acidizing used to reduce near-wellbore formation damage, and acid fracturing (Samiha Morsy et al., 2013, Al-Otaibi et al., 2006). Carbonate rocks are the most common targets for acidizing with hydrochloric acid (HCl) in 5–15% solution, which may result in formation of wormholes, highly localized channels for reactive fluid flow (Hoefner and Fogler, 1988, Gdanski, 1999). Acid fracturing in carbonates seeks to etch fracture

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surfaces so that they remain conductive after closure (Settari et al., 1993).

Carbonates, however, are not the only type of rocks featuring high carbonate content: some organic-rich shales may contain a substantial amount of carbonates either in matrix (Fig. 1a) or localized in natural fractures (Fig. 1b). The matrix of some organic-rich shales, such as Barnett, Haynesville, and Eagle Ford, may contain as well over 50% of carbonates (Loucks and Ruppel, 2007, Sone and Zoback, 2013). Barnett, Wolfcamp, and Haynesville shale formations also feature multiple systems of natural fractures, some of which are filled with calcite (Gale et al., 2007, Hart, 2014, Wickard et al., 2016). For example, the aperture of mineral-filled natural fractures in the Barnett Shale varies from 0.05 mm to 2.7 mm and their height – in field cores – has been documented as high as 80 cm (Gale et al., 2007). These fractures are usually found in en-échelon arrays. The same study shows that the strike of the calcite-filled veins in the Barnett shale is predominantly oriented in northwest direction, which is perpendicular to the present-day maximum horizontal stress. In addition to thin mineralized veins, organic-rich shales (e.g. Vaca Muerta, Haynesville) may contain relatively thick (up to 10 cm) mostly bedding-parallel fibrous calcite veins ("beef") (Rodrigues et al., 2009, Al Duhailan et al., 2015). Owing to this calcareous nature of same hydrocarbon-bearing shales, it results appealing to perform hydraulic fracturing combined with acidizing as an enhanced stimulation technique in calcareous shales. A recent study suggests that shale acidizing can create a network of openings from 10 to 100 μm in natural fractures due to non-uniform etching, resulting in channels that could increase the transmissibility of fractures and improve the productivity of acidized completions (Wu et al., 2015). Vein-dissolution extent and reach may also be enhanced by carbonate localization. When a propagating open-mode fracture encounters a mineralized natural fracture (i.e. mineralized vein), it can turn into the direction of the vein (Fig. 1c) or even split the vein in half (Lee et al., 2015). Hence, shale acidizing combined with hydraulic fracturing could enhance fracture network complexity and mineral dissolution effectiveness since acid solutions would preferentially flow through localized carbonate interfaces.

The objective of this work is to explore the consequences of localized carbonate dissolution on the state of stresses of hydrocarbon-bearing shale formations imposed by shale acidizing. We propose acidizing of carbonate-rich shales as a means of improving production of hydrocarbons. In this study we put emphasis on stress reorientation and the potential enhancement of the size and permeability of the stimulated reservoir volume. Rather than looking at the effects of acidizing on shale matrix, we assess the effect of dissolution on change of local stress state and, therefore, on permeability enhanced by shear fracture reactivation and stress relaxation. We use linear elasticity and Mohr-Coulomb shear failure criterion to explore the influence of geometric characteristics of mineralized fractures, such as volume fraction and orientation, on changes of stresses imposed by localized mineral dissolution. Triaxial experiments conducted on a fractured shale seek to confirm expectations from analytical results. Reservoir-scale effects and implications of acidizing are simulated with the Finite Element Method by means of a thermo-elastic analogy.

2. Analytical model of stress relaxation induced by localized mineral dissolution

Consider an idealized shale formation with Young's modulus E and Poisson's ratio ν (Fig. 2), subjected to in-situ stresses as follows: total vertical stress S_V, maximum total horizontal stress S_H, and minimum total horizontal stress S_h. The shale has continuous mineralized fractures of thickness h, spaced by a distance L, dipping at an angle α, and striking at an angle β (counterclockwise from the direction of S_h). As discussed above, natural fractures are frequently present in a systematic fashion, so that strike and dip of mineralized veins are consistent on a reservoir scale in a given formation. We additionally assume abundant non-mineralized natural fractures, some of which are critically-oriented with respect to the in-situ stresses.

Let us find an upper-bound solution in which we assume that carbonates are homogeneously dissolved along the fracture faces (net reduction in vein thickness). The assumption is reasonable for small areas considering rapid reaction rates with HCl, the fact that calcite veins are highly localized, and the shale matrix has an extremely low permeability, so that mineralized fractures would act as preferential fluid flow paths. Part of the dissolved minerals are assumed to precipitate in the shale matrix after leak-off.

Total vertical stress remains constant assuming that the overburden does not change with time and no overarching stresses develop. The dissolution zone is assumed to be much larger than the representative elementary volume (REV) so that a perfect lateral containment condition applies (no lateral displacements). As dissolution progresses, the thickness of the veins decreases, and shale matrix expands laterally due to Poisson's effect. The following two subsections explore the parameters governing stress relaxation and required volume fraction needed for shear reactivation of critically-oriented fractures within the shale. Both stress relaxation and shear reactivation contribute to increases of permeability of the stimulated reservoir volume. We use the term "stress relaxation" to refer to reduction of compressive stress caused by the removal of the dissolved material rather than visco-elastic effects.

2.1. Dissolution of a single vein

Geometrical analysis of Fig. 2 permits finding strains $\Delta\varepsilon_{xx}$ and $\Delta\varepsilon_{yy}$ on

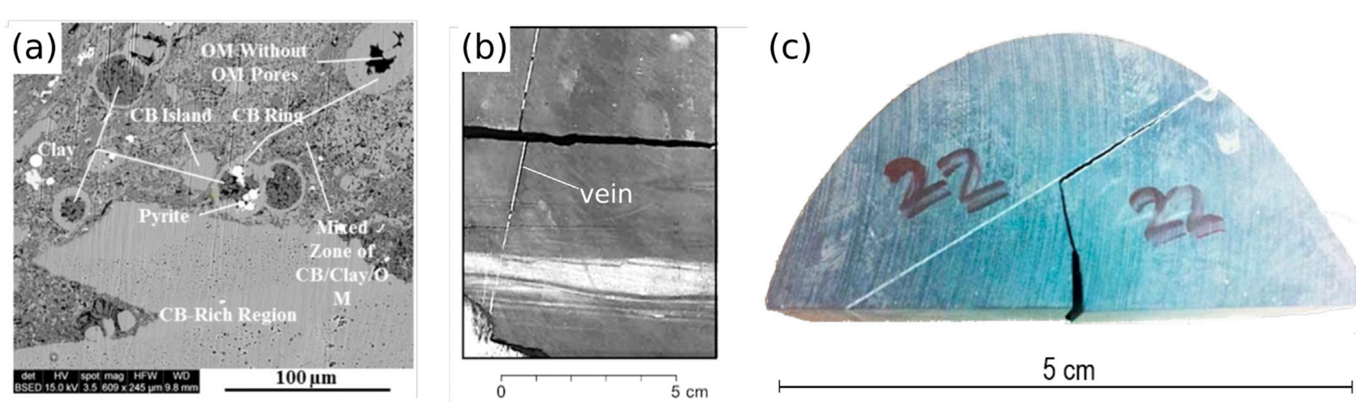

Fig. 1. Different modes of calcite occurrence in shales. (a) Carbonates (CB) in the matrix (after (Wu et al., 2015)). In the lower half of the image one can see a substantial area occupied by carbonates. Carbonates can also localize in the matrix forming rings and islands. They can share mixed regions with organic matter (OM) and clays. (b) Calcite in the form of veins (after (Gale et al., 2007)). (c) Interaction of a open-mode fracture with a mineralized vein (after (Lee et al., 2015)). When hitting a natural fracture, an open-mode fracture may deviate and start propagating in the direction of the vein.