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Review article

Hydraulic fractures: How far can they go?

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ABSTRACT

The maximum reported height of an upward propagating hydraulic fracture from several thousand fracturing operations in the Marcellus, Barnett, Woodford, Eagle Ford and Niobrara shale (USA) is ~588 m. Of the 1170 natural hydraulic fracture pipes imaged with three-dimensional seismic data offshore of West Africa and mid-Norway it is ~1106 m. Based on these empirical data, the probability of a stimulated and natural hydraulic fracture extending vertically >350 m is ~1% and ~33% respectively. Constraining the probability of stimulating unusually tall hydraulic fractures in sedimentary rocks is extremely important as an evidence base for decisions on the safe vertical separation between the depth of stimulation and rock strata not intended for penetration.

1. Introduction

Hydraulic fractures propagate when fluid pressure exceeds the least principal stress and the tensile strength of the host sediment (Hubbert and Willis, 1957). They continue to propagate until the stress-intensity at the fracture tip is lower than the critical stress-intensity of the rock being fractured (e.g. Savalli and Engelder, 2005). These conditions can occur naturally (e.g. Cosgrove, 1995) but they can also be stimulated to recover oil and gas (Simonson et al., 1978), or during injection of water into geothermal boreholes (e.g. Legarth et al., 2005; Julian et al., 2010) and unintentionally as the result of subsurface blowouts (e.g. Tingay et al., 2005).

Hydraulic fractures are commonly described in outcrops at centimetre to metre scale (e.g. Cosgrove, 1995 – Fig. 1ab). They can be up to ~50 m in height in the Devonian Marcellus shale (e.g. Engelder and Lash, 2008) and sand filled fractures (injectites) have been documented to extend hundreds of metres (Hurst et al., 2011). But three-dimensional (3D) seismic data now show that natural hydraulic fractures probably cluster, forming pipe-like features that often extend vertically for even greater distances than this (see Løseth et al., 2001; Zuhlsdorff and Spieß, 2004; Cartwright et al., 2007; Davies and Clarke, 2010).

Stimulation of hydraulic fractures as a technique for improved hydrocarbon production from low permeability reservoirs dates back to the late 1940s (Montgomery and Smith, 2010). Measurements of the microseismicity they cause (e.g. Maxwell et al., 2002) have shown that they can extend for several hundred metres upwards and downwards from the wellbore (Fisher and Warpinski, 2011). Multiple stages of hydraulic fracture stimulation on multiple wells are routine for the recovery of oil and gas from low permeability sedimentary reservoirs in shale gas provinces in the USA (e.g. King, 2010). Shale gas exploration is starting in many other countries with sediments from Neogene to Cambrian age being potential future targets. Therefore constraining the probability of stimulating unusually tall hydraulic fractures in sedimentary rocks is critically important, as it will help avoid the unintentional penetration of shallower rock strata (Fig. 2) that might be important aquifers or subsurface geological storage sites.

Mathematical methods for estimating hydraulic fracturing height are simplistic (Fisher and Warpinski, 2011) and it is generally accepted that we cannot yet accurately predict fracture propagation behaviour in detail, so to date much of what we know of how fractures will behave *in situ* conditions comes from operational experience (King et al., 2008). Future shale gas targets could be in a variety of different stress regimes and in rocks with varied mechanical properties and ages. Therefore at this stage our approach is to include a wide range of the tallest examples of hydraulic fractures that have different geometries, geological settings and trigger mechanisms.

Although hydraulic fractures are 3D, here we compile new and existing data on the extents of only the vertical component of both

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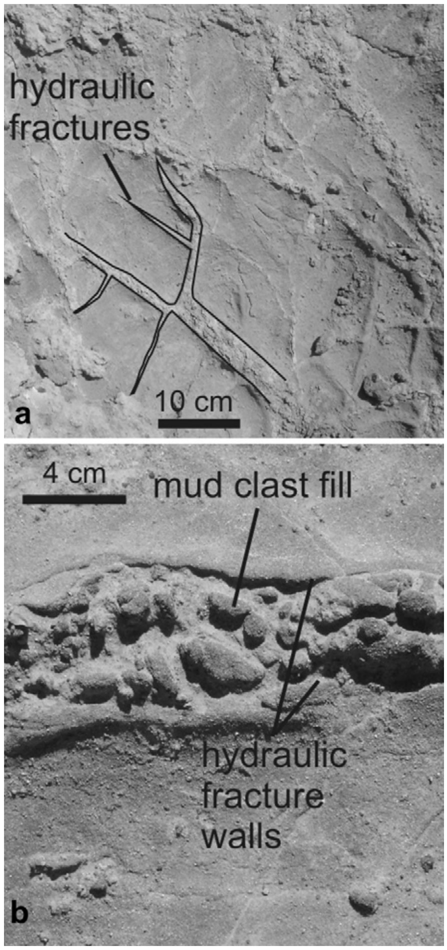

Figure 1. (a) Examples of natural hydraulic fractures in shale (b) close-up of a natural hydraulic fracture filled with shale clasts (both examples from onshore Azerbaijan).

natural and stimulated hydraulic fracture systems hosted in sediment from Neogene to Devonian in age from eight different locations (Fig. 3a). We briefly report on key statistics, compare them and consider which factors control the extent of upward fracture propagation.

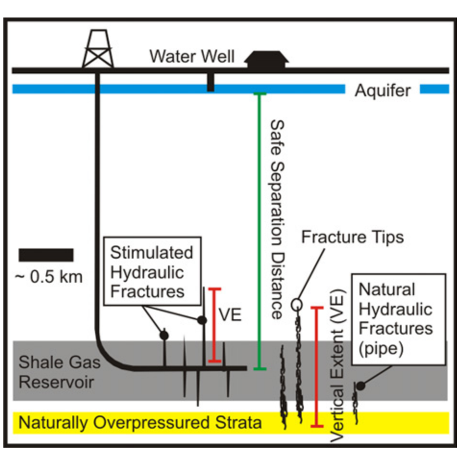

Figure 2. Schematic diagram showing stimulated hydraulic fractures within a shale gas reservoir, natural hydraulic fractures initiated at a naturally overpressured reservoir, the vertical extent (VE) of hydraulic fractures reported here and the safe separation between shale gas reservoir and shallower aquifer.

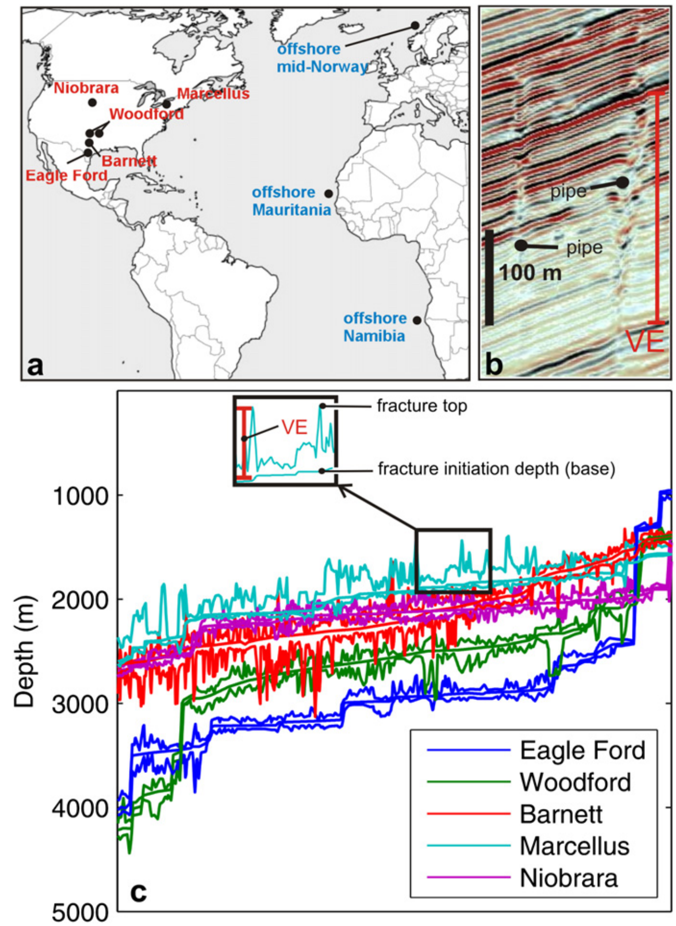

Figure 3. (a) Map of the globe showing location of the eight datasets. Red font – datasets for stimulated hydraulic fractures, blue font – datasets for natural hydraulic fractures (pipes). (b) Seismic line from offshore Mauritania showing a representative vertical pipe imaged on 3D seismic reflection data and its vertical extent (from Davies and Clarke, 2010). (c) Graph of stimulated hydraulic fractures in the Marcellus, Barnett, Woodford and Eagle Ford shales (after Fisher and Warpinski, 2011) and including unpublished data provided by Halliburton for the Niobrara shale. Inset – extract of the graph showing how the vertical extents of fractures were measured. All depths are in true vertical depth (TVD). Coloured spikes – separate hydraulic fractures propagating upwards and downwards from the fracture initiation depth.

1.1. Hydraulic fracturing

There are several types of natural hydraulic fracture: injectites (e.g. Hurst et al., 2011), igneous dikes (e.g. Polteau et al., 2008), veins (e.g. Cosgrove, 1995), coal cleats (e.g. Laubach et al., 1998), and joints (e.g. McConaughy and Engelder, 1999). They have been extensively studied. In the case of joints in the Devonian Marcellus Formation, USA, it is even possible to study how they grow on the basis of plume lines that occur at centimetre to metre scale (Savalli and Engelder, 2005). Marcellus shale fractures are thought to form due to gas diffusion and expansion within shale through multiple propagation events. In contrast the tallest examples of hydraulic fractures tend to cluster, are commonly termed chimneys, pipes or blowout pipes (herein we use the term 'pipe') and can extend vertically for hundreds of metres (e.g. Cartwright et al., 2007; Huuse et al., 2010). The origin of pipes is not certain, but they probably form due to critical pressurisation of aquifers and oil and gas accumulations (Zuhlsdorff and Spieß, 2004; Cartwright et al., 2007; Davies and Clarke, 2010). Pipe development may be followed by stoping, fluid-driven erosion and collapse of surrounding strata (Cartwright et al., 2007). Gases that have come out of solution and expand