FRACTURES, SHALE GAS AND THE ENVIRONMENT: THE APPLICATION OF DISCRETE FRACTURE NETWORK MODELLING TO ENVIRONMENTAL RISK MANAGEMENT FOR UNCONVENTIONAL HYDROCARBONS

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ABSTRACT

In Europe, the Americas, and elsewhere in the world, the development of Unconventional Oil and Gas (UCOG) resources as a viable energy source and industrial feed stock offers the possibility of energy security to areas which have traditionally been heavily reliant on oil and gas imports from Russia and or the Middle East. In North America, shale gas and tight oil fields have been operational for a number of years. However the industry is currently still in an early stage of development in Europe, with the majority of operations still at the exploration stage. The key feature of UCOG operations has been the application of hydraulic fracturing to enhance the permeability of strata that do not have the natural permeability to allow significant gas or oil flow to the wellbore. It is arguably the technique of hydraulic fracturing that has made the exploitation of UCOG plays technically and economically feasible. Although there are potential social and economic benefits from UCOG development, its introduction in certain areas, in particular to the European Union, has been met with some notable political and public opposition. This opposition has a number of components but is in part due to apprehension over the perceived impact of hydraulic fracturing on the environment, and the perceived risk to shallow aquifers and to human health. During the hydraulic stimulation process, the extent and path of hydraulic fracturing has traditionally been difficult to predict due to the complex interaction of the induced fractures with the natural fracturing of surrounding formations. It is this uncertainty which has led to concern that hydraulic fracturing may create preferential pathways for fluid migration to conductive faults and aquifers, and in turn generate unforeseen seismic activity.

An approach for mitigating the risks posed to subsurface entities, such as faults and aquifers, resulting from an incomplete understanding of the natural fracture systems of shale reservoirs and hydraulic fracture, is described through the application of Discrete Fracture Network (DFN) analysis of naturally fractured reservoirs. DFN modelling provides a state-of-the-art tool for predicting hydraulic fracture patterns and thus the potential interaction with the identified geohazards. The potential application of DFN analysis in managing and mitigating the risks identified with hydraulic fracture propagation is discussed, together with the benefits that such analysis can provide in managing the environmental risk associated with UCOG exploration and production operations.

Digges La Touche, G. 2014. Fractures, shale gas and the environment: the application of discrete fracture network modelling to environmental risk management for unconventional hydrocarbons.
Pp. 105-109 in Hunger, E. and Brown, T.J. (Eds.)
Proceedings of the 18th Extractive Industry Geology Conference 2014 and technical meeting 2015, EIG Conferences Ltd, 250pp.
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INTRODUCTION

The exploration and development of Unconventional Oil and Gas (UCOG) resources, shale gas and oil in particular, from self sourced reservoirs as an economically viable source of fuel and petrochemical feedstock in the United Kingdom, Europe, the Americas and in many other regions offers the opportunity of energy security to regions which have traditionally been heavily reliant on oil and gas imports. The development of these self-sourced reservoirs has turned some regions from net importers of hydrocarbon fuel to net exporters. While the UCOG sector has been operating for a number of years in the United States, the industry is currently nascent in Europe, with the majority of operations at the exploration stage of the development cycle.

It has been the use of hydraulic fracturing to increase the permeability of strata that do not have a high enough natural permeability to allow significant gas flow to the wellbore, that, combined with horizontal drilling, has increased the economic viability of these self-sourced reservoirs, be it for shale gas or shale oil. The prospect of UCOG development, despite the potential economic gains, has in some areas, in particular to the European Union and Western Europe, been met with both public and political opposition (House of Commons, 2011). Opposition has arisen for many reasons including apprehension over the perceived potential impact of the hydraulic fracturing on the surface and shallow environment, including seismicity, and fears over the risks of contamination of groundwater aquifers used for the supply of drinking water and thus the consequential risks to public health (The Royal Society, 2012).

The extent of hydraulic fracturing during reservoir stimulation has, in the past, been considered difficult to predict due to the complex interaction of the induced fractures with the natural fracturing of surrounding formations (Rogers et al, 2010). As a consequence of such uncertainties, concerns have been raised in some quarters that hydraulic fracturing may create preferential fluid migration pathways to conductive faults and shallow aquifers through hundreds of metres of overlying strata, and also generate earthquakes, both with associated environmental risks. The propagation of hydraulic fractures and their interaction with pre-existing natural fractures and geological features can readily be modelled using a Discrete Fracture Network (DFN) approach (Dershowitz et al, 2011a). The use of DFN analysis for self-sourced reservoirs, which are naturally fractured, provides a methodology for predicting the nature and extent of hydraulic fractures and consequentially their interaction with identified geohazards. The DFN method can be used to better understand the risks of UCOG exploration and production operations and thus better understand and manage any identified environmental risks.

ENVIRONMENTAL RISK ASSESSMENT AND HYDRAULIC FRACTURING

Claims of groundwater contamination (Helman, 2012) have been the subject of conflicting academic studies (e.g. Osborn et al, 2011; Molofsky et al, 2013; and Darrah et al, 2014) with the balance of evidence indicating that elevated methane concentrations in groundwater in areas of shale gas operations have not been caused by hydraulic fracturing (Warner et al, 2013), but rather by either pre-existing natural background methane concentrations or by historic poor well completions. The hypothesis that hydraulic fracturing can create pathways to shallow aquifers may readily be demonstrated to be incompatible with any realistic geological model and also with natural analogues. Data presented in Davies et al, 2012 demonstrate that the probability of an artificially induced hydraulic fracture propagating more than 350m is less than 1% and that the longest natural hydraulic fractures, which form under very different conditions are approximately 1000m with the majority being less than 350m (Davies et al, 2012).

Given the ongoing debate and natural public concern, it is clear that UCOG operations, like any oil and gas operation, should be undertaken in a manner that is conservative with regard to the mitigation of possible environmental risks.

Hydraulic fracturing

The stimulation of low permeability self-sourced reservoirs through hydraulic fracturing typically comprises the pumping of a relatively large volume of fluid (typically ~4,000m^3/stage (New Brunswick, 2014)) and proppants into the target reservoir at the selected target horizon. The injected fluid is pumped to a pressure such that the minimum in-situ stress is exceeded resulting in the stimulation (i.e. opening) of the existing unproductive natural fracture network and the generation of new hydraulic fractures. The proppant serves to prop open the stimulated fractures maintaining permeability for fluid (gas) flow back to the well bore.

By design, the zone stimulated during a hydraulic fracturing operation is kept within the target formation. Over stimulation of the formation, that is causing fractures to propagate beyond the target horizon, is economically and technically detrimental due to unnecessary and unwanted fluid production (Zoback et al, 2010) and also due to the increased volume of fracture fluid necessary. Hydraulic fracture stimulation beyond the target reservoir formation could in theory, dependent of the extent of the induced fracturing, potentially connect to aquifers and faults with potential negative environmental impacts, hence stimulations are designed to avoid this theoretical scenario.

Risk assessment and geohazards

For the purpose of this discussion a geohazard is considered as a geological state that has the potential to result in a situation that causes damage or an uncontrolled environmental risk (International Centre for Geohazards, 2010). The two geohazards that are of particular relevance to hydraulic fracture stimulation are:

- The propagation of hydraulic fractures from the reservoir formation to an aquifer allowing fracture fluid and hydrocarbon migration resulting in the consequential contamination of groundwater resources; and
- Hydraulic fracture propagation to faults capable of transmitting fluid, allowing fluid and hydrocarbon migration to an aquifer or to the surface elevation or possibly inducing seismic activity detectable at surface.

The risk of a hydraulic fracture propagating to an aquifer or fault is related not only to the specific geological setting, but also to distance (Zoback, 2010). Following seismic activity associated with a hydraulic fracture treatment in Lancashire, UK, a study by Baisch and Vörös (2011) concluded that faults within approximately 300m of the location of hydraulic stimulation could be at risk of connecting with propagating fractures due to the proximity of major faulting to the well and, indirectly, a highly variable in situ stress field. Subsequent analysis of seismic data and source mechanism data (Clarke et al, 2014) supports this analysis.

Appropriate and sufficient identification of the nature and extent of natural fractures and the nature, extent and direction of stimulated hydraulic fractures is of considerable importance when considering such higher risk scenarios and in such situations numerical analysis using DFN modelling is considered a critical tool for environmental risk management.

THE DISCRETE FRACTURE NETWORK (DFN) METHOD

The properties of individual, or discrete, fracture features are explicitly included in a Discrete Fracture Network (DFN) model to facilitate the analysis of flow and material (e.g. proppant) transport (Dershowitz et al, 2011a and Cottrell, 2012). This approach is based on the principles of fluid flow in fractured media. A typical DFN model is shown in Figure 1.

A DFN model of a hydraulic fracture stimulation must include a characterisation of the geometric, hydrological and geomechanical properties of the three dimensional natural fracture network around the treatment zone and any potential geohazard as well as the characteristics of the well (orientation, geometry), fracture treatment (injection rate, duration), rock matrix mechanical properties and in-situ stress conditions. Inclusion of existing natural fractures is important as natural fractures are known to have a primary influence hydraulic stimulation (e.g. Olson 2010).

In simple terms, a hydraulic fracture propagates when the effective stress is greater than the tensile strength of the surrounding rock. This occurs together with the reactivation of the natural fracture network as fluid flows into and through the existing fractures. The direction of hydraulic fracture propagation is controlled by the local fracture normal stress condition, the minimum principal stress orientation and pore pressure, as hydraulic fracturing occurs predominantly in tension (Dershowitz et al, 2011a), with the vertical extent being controlled by quenching layers of reduced elasticity and the horizontal extent by the fluid mass balance (Dershowitz et al, 2011b).

ANALYSIS OF HYDRAULIC FRACTURING FOR RISK ASSESSMENT

Following the construction and validation of a DFN model for a particular reservoir, the model can be used to investigate the potential impacts of hydraulic fracturing treatments. Model validation is typically achieved through calibration against existing well test data, data from previous reservoir stimulation treatments and analogues. On the assumption that the characteristics of the reservoir formation are well constrained this may be undertaken through variation of the injection fluid properties, rates and timing. Often stochastic simulations are undertaken to capture any uncertainty in the characteristics of the reservoir and fluid properties.

An example of the components of a DFN model of a shale gas reservoir, based on a confidential North American shale gas play, is presented in Figure 2. The geological data that characterises the natural fracture network in terms of fracture orientation, intensity, and size is presented in Figure 2(a) to (c). Two significant fault structures, Figure 2(d), derived from seismic data, are included in the full model (Figure 2(e)). Two potential hydraulic fracture treatment designs have been tested using the previously developed and validated DFN model, and the results are presented in Figure 3. The first potential hydraulic fracture treatment resulted in the development of a connection from the horizontal lateral of the well to the previously characterised fault structures (Figure 3(a)). The second hydraulic fracture treatment generates fractures that do not propagate as far as the two identified fault structures (Figure 3(b)). Note that in both examples the unstimulated natural fractures are for clarity not shown. The connection of the stimulated

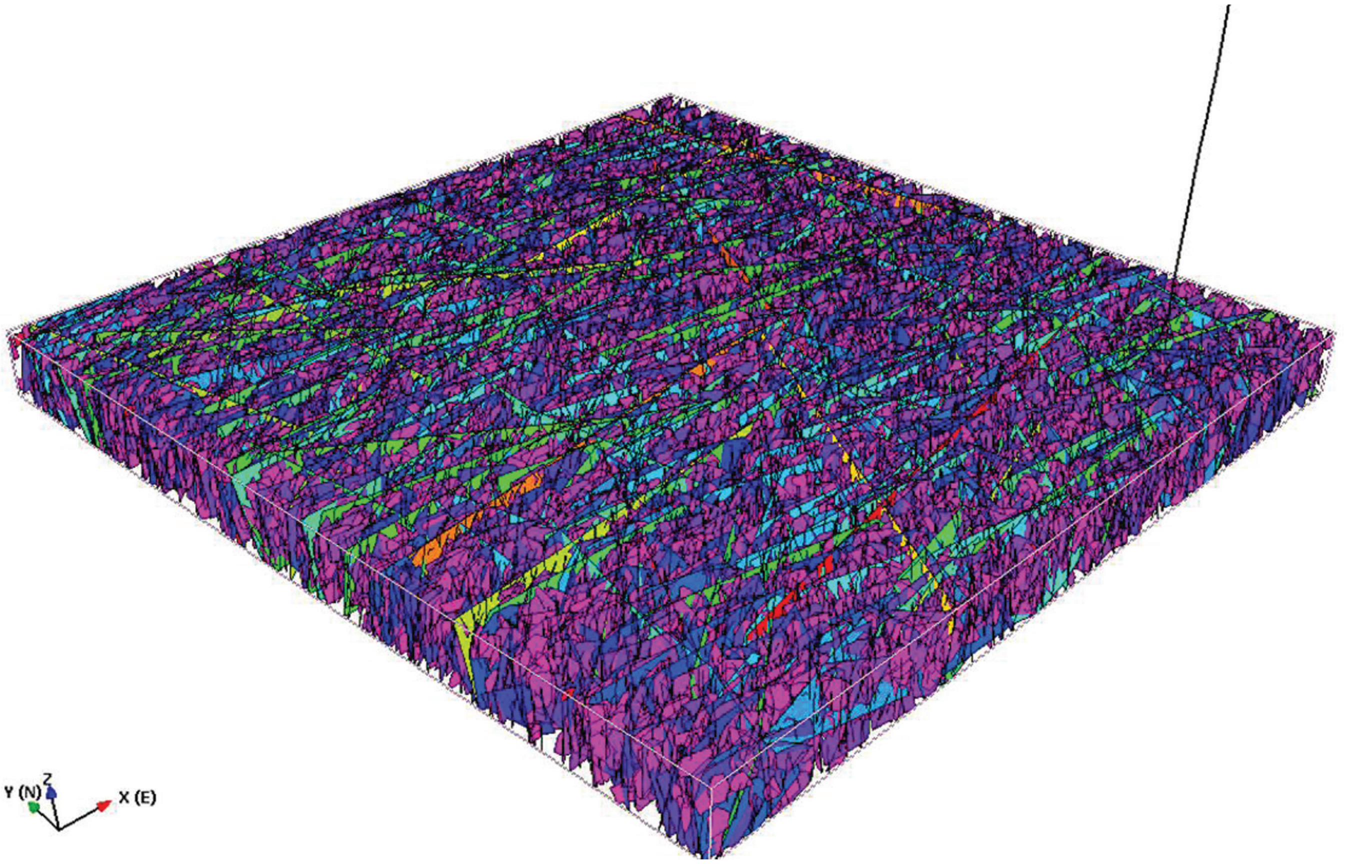
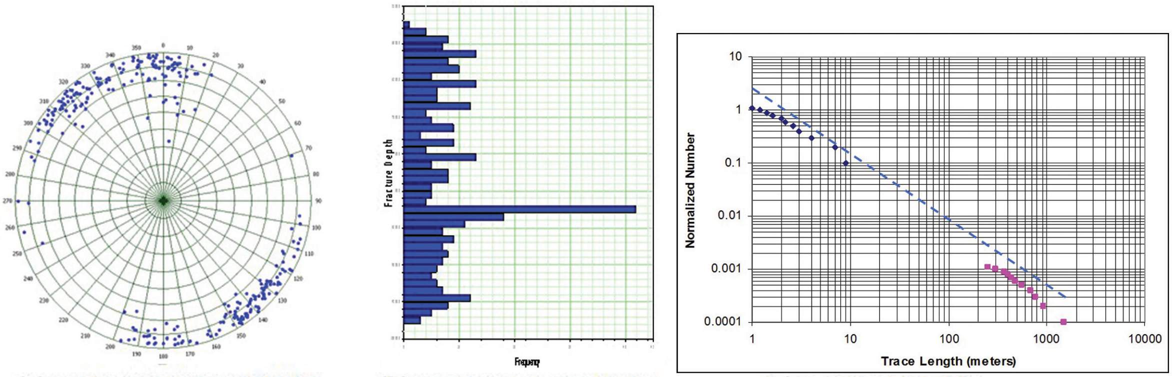
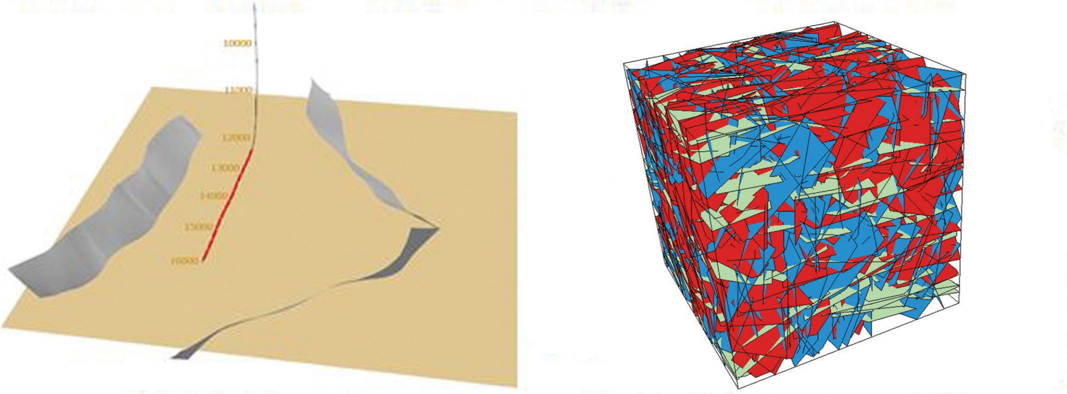


Figure 1. *Discrete Fracture Network model of a shale reservoir.*

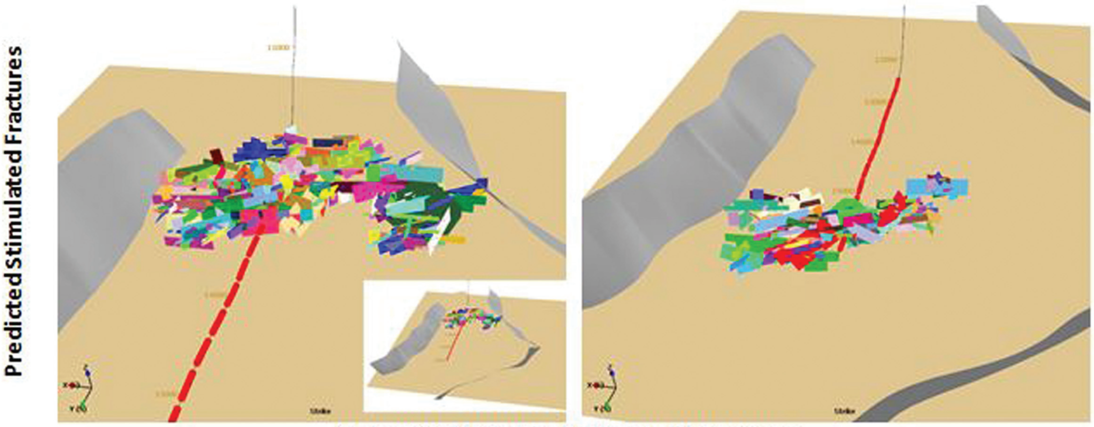


(a) Fracture Orientation Data (b) Fracture Intensity Data (c) Fracture Size Data

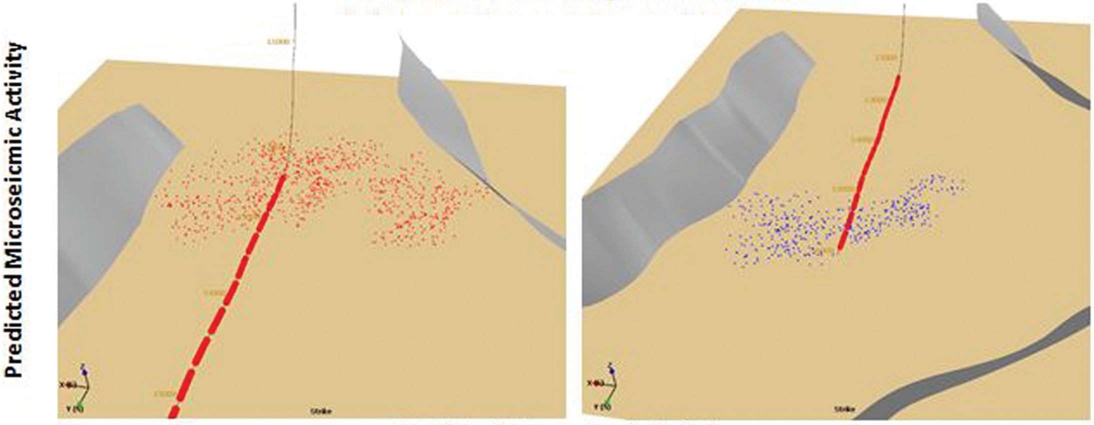


(d) Inserted Major Faults (e) Natural Fracturing of Target Stratum

Figure 2. *Natural fracturing and inserted faults for a Discrete Fracture Network (DFN) model.*



Connected Natural and Hydraulic Fractures



Predicted Microseismic Activity

(a) Poorly Controlled Hydraulic Stimulation (b) Well Controlled Hydraulic Stimulation

Figure 3. *Alternative hydraulic fracturing treatment examples in a Discrete Fracture Network (DFN) model, showing (a) a poorly controlled hydraulic fracturing stimulation, and (b) a well controlled hydraulic fracturing stimulation, near a fault system.*

fractures to the fault structure in the first scenario (Figure 3(a)), is the result of a fluid injection pressure that was maintained at too high a pressure over too long a period of time. In the second scenario both the fluid pressure and the injection period were reduced resulting in a smaller stimulated volume. The vertical extent of hydraulic fracturing is constrained in this example by a quenching layer immediately overlying the reservoir formation of interest.

DISCUSSION

Inadequately managed hydraulic fracture treatments typically result from poor characterisation of the in-situ stress field and a consequent lack of understanding of the direction and extent of fracture propagation and or the use of inappropriate fluid injection pressures and rates. The use of the toolbox of DFN hydraulic fracture analysis as part of the approach to the assessment of environmental risk resulting from a specific hydraulic stimulation treatment can significantly reduce the uncertainties in such a risk assessment and help constrain the design of appropriate hydraulic fracture treatments. The approach used makes use of typical exploration data, as well shallow, conventional environmental hydrogeological data, maximising the value of existing data and supporting not only the characterisation and estimation of the resource but also allowing the quantification of environmental risk.

CONCLUSIONS

Despite the potential economic benefits arising from the development of self-sourced reservoirs for shale gas, shale oil, coal bed methane and underground coal gasification, if the perceived environmental risks are not described, assessed and mitigated then public resistance may hinder the future expansion of the industry. The use of a Discrete Fracture Network (DFN) approach, combined with a holistic surface to reservoir approach, should be used as a key part of the environmental risk assessment toolbox to quantify and predict the behavior of hydraulically propagated fractures in response to fluid injection during hydraulic fracture treatments. Through the application of the DFN approach, operating companies and regulators can demonstrate to stakeholders that the perceived environmental risks have been appropriately characterised and can be managed and mitigated.

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