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Fracture-fault Networks and Role of Nested Topology on the Mechanical Response and Connectivity for Tight Gas Extraction

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SUMMARY

Our aim is to quantify the role of intermediate length scale pre-existing faults and fractures on the critical loading of first order faults and on the potential for enhancement of fracture network.

The arrangement of smaller scale natural fractures relative to larger-scale faults is subject of our combined outcrop and numerical modelling study. In this study we perform finite element geomechanical simulation to quantify mechanical response in terms of loading and failure of complex network of pre-existing fault and fracture planes. The first and intermediate order faults and fractures are included in the mechanical models by means of Discrete Surface Networks. The structural configuration of the Dutch SE North Sea P6 block inspired the definition of the first order faults of our geologic input model for mechanical simulations. The analyses of first and smaller order fault patterns of the North Sea subsurface case were combined with the detailed fracture observations from our outcrop analogue. Differently from previous studies, this work addresses the length scales between larger scale tectonic models that account mainly for the horst-bounding faults and the detailed studies that address stresses at and around boreholes.

Introduction

The arrangement of small-scale natural fractures relative to larger-scale faults is subject of our combined outcrop and numerical modelling study. Apart from faults (Flt) being generally larger in order than fractures (Frc), they are understood as part of the continuous length-scale spectrum. The main difference is that faults exhibit substantial offsets while the offset of (shear) fractures is negligible. Evidently, the development of both fractures and faults follow brittle failure laws under given in-situ stress conditions. However, differences in rock failure mode, the degree of co-genetic natural evolution and spatial and length-scale variability determine to what extent fractures and neighbouring faults are linked.

Better understanding of the mechanical interaction between fracture network (10^{-1} - 10^2 m) and intermediate sized faults (10^2 - 10^4 m) has several applications for tight gas reservoirs. Firstly, it can help our predictions of the existing natural fracture network in relation to intermediate and larger scale faults. Secondly, understanding stress-deviations around faults down to the small-scale of local fracture networks can help new induced fracturing jobs to account for local, present-day, stress field variations.

The specific state of stress at smaller scale, down to that of boreholes, results from the interactions of the “regional” stress field and mechanical heterogeneities. Mechanical heterogeneities constitute of geological bodies with different mechanical properties and Flt-Frc surfaces. As a consequence, the effective state of stress of rocks between faults can differ significantly from the regional stress field and the degree of loading of faults and failure potential of pre-existing faults can be variable (in general, close to failure).

Influencing the natural in-situ stress conditions that may be close to the critical point of failure can result in i) hydraulic fracturing and enhancement of fracture network connectivity and, ii) the reactivation of pre-existing faults. The former can obviously be beneficial to gas extraction, the latter is a potential hazard to be mitigated. The degree to which gas extraction is improved very much depends on the characteristics of the pre-existing fracture network and its response to changes in effective stresses and leading to the activation of existing and formation of new fractures.

In this study we perform finite element (FE) geomechanical simulation to quantify mechanical response in terms of loading and failure of complex network of pre-existing Flt-Frc planes. This can be done to much greater detail by starting from a pre-existing network than by modelling the incipience of a new network. The characteristics of a pre-existing Flt-Frc network is best obtained from deterministic reservoir data combined with outcrop analogue studies. Deterministic Flt-Frc network descriptions are used where feasibly, otherwise network characterizations in terms of shape, directions, spacings, heights and lengths are used to describe the discontinuity surfaces.

The input model, mechanical model setup and simulation is inspired by current tight gas and anticipated shale gas challenges dealing with enhancing fracture permeability. Our study focusses on Posidonia shales and Rotliegend tight sands as target intervals for a subsurface case in the Dutch North Sea (P6 block). In addition, a detailed outcrop study from in thinly bedded lower Jurassic fine-grained intervals at the North Yorkshire coast gives insight in Flt-Frc relationships.

Methodology

Our aim is to quantify the role of intermediate length scale pre-existing faults (that are above the seismic resolution) and fractures (below seismic resolution) on the critical loading of first order faults and on the potential for (smaller scale) enhancement of fracture network. A innovation pursued by this study is the multi-scale character of our approach. Stress and strain studies have obviously been performed in the past but, typically, addressed either the very large scale structures or detailed studies at and around boreholes with little attention for bridging the two scales.

Differently from previous studies, we consider the presence of distributed fracturing in the rocks between larger-scale fractures and faults.

The first and intermediate order Flt-Frc systems are included in the mechanical models by means of Discrete Surface Networks (DSN). Fault patterns in the Rotliegend target interval (Figure 1a) were published by de Jager (2007) and fractures were studied from bore holes by Gauthier et al. (2000). The fault network is analysed using DigiFract geometric processing algorithms (Hardebol and Bertotti, 2013), not only in terms of orientation and length distributions, but also taking into account topological and hierarchical arrangements.

Similarly, geologic rules on the shape, spacing, orientation and abutment or intersection relationships of the smaller scale fractures (10^1 - 10^2 m) are established from outcrop analogue studies. Outcrop-based studies at Whitby (UK) Posidonia sections provide constraints on fracture distribution. Fracture stratigraphy and height are studied from vertical outcrops (van Laerhoven, 2013). Detailed study of the horizontal network arrangements were acquired from wave-cut pavement surfaces by using our new drone with bird-eye imaging and photogrammetry. The fracture network can be captured down to a cm resolution and a spatial coverage of a km. The digitized fracture network covers a 10^{-2} – 10^3 m length scale and turns such pavements into rich information sources on network arrangements that outweighs the limitation that outcrops exhibit as representative for subsurface characterisation.

The structural configuration of the Dutch SE North Sea P6 block inspired the definition of the first order faults of our geologic input model for mechanical simulations. The analyses on between first and smaller order fault patterns of the North Sea were integrated with the detailed fracture observations from our outcrop analogue. The synthesis on relationships between faults and fractures guide the translation of our outcrop analogue data to fitting discrete fracture network representations for our geological model. Discretizing the DFN representations for FE modelling

Figure 1 Fault-fracture network characterisation across multiple length scales to derive at input constraints for stochastic simulations of network arrangements and FE mechanical modelling. (a) Fault network in a Dutch offshore block at the northern edge of the Broad Fourteens Basin. (after de Jager, 2007) (b) A large-scale fracture network at the North Sea coast of North Yorkshire, Whitby. (c) Detailed pavement description of a fracture network. (d) Network topology and statistical input for stochastic simulation (e) stochastic simulation output of a three-tier fracture network.

(Figure 2e), instead of mechanical properties assigned to a voxel model, is important to properly account for mechanical failure criteria and for estimating failure potential along explicit surfaces. To this end we use the JewelSuite geomodeling software in combination with Abaqus for the FE mechanical simulations.

The benchmark model constitutes simplified shapes of the boundary faults of the horst and layering with thickness, tilting and offsets on faults inspired after the P6 block (Figure 2b and 2c). Mechanical simulations on this benchmark input model indicates how the stresses set at the boundary conditions propagate (and deviate) across the horst. Subsequent refinement of the input model comprises the mechanical heterogeneities, especially that intermediate order Flt-Frc planes. A series of scenarios are tested with variations in network configuration that address the implications of different degrees of network connectivity, size of the features and degree of confinement to the stratigraphic target intervals.

Results

The largest order, horst bounding faults trend NW-SE (Figure 1a) (Jager, 2007; Ziegler, 1990). Fracture order and network topology cannot be deciphered from bore hole data, although the presence of fracture sets in NW-SE, NE-SW, N-S and E-W directions (Gauthier et al., 2000) may indicate an intricate network in which the different orientations form a nested arrangement. The outcrop analogue in Yorkshire, next to the Sole Pitt Basin and subject to a similar tectonic evolution, points to possible development of such network hierarchy and topology in the arrangement of the different Flt-Frc subsets. The outcrop analogue case exhibits fracture networks that were formed most probably under a Tertiary N-S compression stress regime with fracture development both syn and post Tertiary

Figure 2 The case study located in the Broad Fourteens Basin as input to mechanical simulation. (a) geologic context of our study targets in the Posidonia shale and Rotliegend tight sand intervals. (b) cross-sections of the input models (c) map views of the first-order structure and (d) conceptual smaller scale fault network (e) and (f) geomodel discretization in JewelSuite and simulation results.

folding and faulting (Rawnsley et al, 1992). The similar larger tectonic evolution of the Yorkshire and Dutch offshore translation of these constraints for populating the input model with a perceivable smaller order fracture-fault network.

The role of various DSNs for models are compared and the impact of the different DSNs (variations in length-scale, intensity and orientation distributions) are addressed. This addresses the question whether small to intermediate scale fractures can be critically loaded to enhance effective permeabilities and how the critical loading of first order faults with the risk of seismic hazards can be mitigated. Testing for various DSN with different levels of detail points to the role of length-scales and help bridging to the physical rock deformation research executed by our academic partners.

Conclusions

The refined mechanical models that account both for the first-order faults and intermediate-sized Flt-Frc system help determine the degree of local stress deviations. The different Flt-Frc arrangements as series of input models indicate to what extent fractures may be critically stressed to our advantage (e.g. induced fracturing) and how critical loading of first order faults may be mitigated. This can contribute to questions on induced fracturing of tight sand (or shale) gas reservoirs in the follow ways:

- 1) Predict the spatially variable state of stress in target formations of sedimentary basins.
- 2) Predict the occurrence of fracturing in relevant parts of the basin and the geometric characteristics of the newly developed fractures.
- 3) Analyse the loading state of faults present in the basin and estimate their failure potential.

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