# Role of lithological layering on spatial variation of natural and induced fractures in hydraulic fracture stimulation

Vincent Roche *, Department of Physics, University of Alberta, Edmonton
roche@ualberta.ca
and
Mirko van der Baan, Department of Physics, University of Alberta, Edmonton

## Summary

Fluid-induced fractures used for the recovery of oil and gas from reservoir rocks may form a complex fracture network. The characteristics of such a fracture network are key parameters to improving well performance. Numerical modeling approaches are developed in order to address either the spatial or the temporal variation in the distribution of microseismic events. We use continuum-based modeling to study the spatial variation of microfracturation due to lithological layering. In particular we demonstrate that failure (and thus fracture nucleation) may not necessarily initiate in the mechanically weakest layers due to differential stress accumulation in surrounding, essentially load-bearing, stronger lithologies.

## Introduction

In hydraulic fracturing, fluid-induced fracture networks are created to increase the inter-connected permeability in low permeability rocks. This process is largely applied to the recovery of oil and gas from clay rich rocks. High-pressure fluid is injected in a portion of the well, which results in a decrease of the local state of stress. It leads to brittle failure of the host rock, which includes 3D fracture tip propagation, fracture nucleation, and fracture reactivation. These fractures may connect and interact together to form a complex fracture network.

Identifying the characteristics of fracture networks as well as the parameters behind these characteristics leads to improved understanding of the well performance. For instance, the productivity of the well depends on the lateral extent of the connected fracture network and on the internal arrangement of the fractures within the reservoir rock. Likewise, the vertical extent of the fractures is a key parameter for cap rock integrities or leak-off pressure processes.

The characteristics of an induced fracture network including its length, its time dependence, and its location within reservoir rocks may be assessed using the event distributions of the induced microseismicity obtained from monitoring surveys. Such experiments show that the distribution of microseismic events displays temporal and spatial variations (Fisher et al., 2008; Grob and Van der Baan, 2011). The spatial variation deals particularly with the layered structure of the sedimentary infilling, whereas the temporal variation is likely related to the dynamic characteristics of the fractures.

Numerical modeling approaches are developed in order to understand the mechanical processes and the key parameters behind the distribution of microseismic events.. We use 3D numerical modeling based on distinct element methods (Cundall, 1988) to investigate how the heterogeneity of the rock affects the initiation and development of fractures. We examine in particular the fracture nucleation, restriction and propagation.

## Fracture development related to lithological layering

The heterogeneity of the rock highly affects the development and the spatial distribution of fractures in layered systems. The following features are commonly observed in natural tectonic fractures in layered systems: refraction (*i.e.* dip change), segmentation of the faults as a function of the lithology, variation in the fracture density, relatively high ratio between the horizontal and vertical lengths of the fractures, and distribution of the displacement related to the layering (see Roche et al., 2012a and b).

The same features are observed in induced fractures despite that in this specific case we often force failure to occur in one particular layer. The vertical and horizontal extent of the microseismic cloud can be strongly influenced by the lithological layering. It may extend much further out horizontally than vary vertically. This is often desired; yet it is not always clear why microseismicity is limited to certain layers, and most importantly if fluid leak off occurs in any intermediate, 'silent' ones. The similarity between the characteristics of natural and induced fractures may indicate either that the induced fractures are formed by the reactivation of natural fractures or that the same mechanical processes are responsible for the creation of both fracture sets.

Two mechanisms related to layering may be responsible for natural and induced fracture development. Fractures may first locate preferentially in one lithology through a mechanism of preferential nucleation (Roche et al., 2012b). Then their vertical fracture propagation may be stopped at the edges of the sedimentary layers through a mechanism of restriction. The fractures may then not cross these surfaces. In other cases, fracture propagating continues in the some surrounding layers, while skipping intermediate ones with different geomechanic properties (e.g., if they are more ductile). Nucleation and restriction processes depend on several geomechanical attributes. It includes variation of the rock stiffness, the strength of the layering and the thickness of the individual layers (Roche et al., submitted; Welsh et al., 2009).

The fractures should localize first within the weaker layer and are less likely to propagate into adjacent stronger layers. In practice, failures occur first in those layers with a favorable state of stress such as high deviatory stresses or low minimal principal stresses for shear and tensile failure, respectively. In a similar way, a layer which is geomechanically weak or which is subjected to an unfavorable local state of stress could act as restrictors to fracture propagation initiated in adjacent stronger or more stressed layers (Roche et al., submitted; Welsh et al., 2009). In the next section we demonstrate this using geomechanical modeling.

## Modeling approach

The distinct element method (DEM, Cundall, 1988) enables the stresses and strains to be calculated inside discontinuous media such as fractured layered rock masses.

The layered section is built by dividing a cubic medium into horizontal blocks (Fig 1). The discontinuous medium was is then meshed into polyhedral elements. Material properties are assigned to each block. A first set of models is devoid of fractures and used to discuss the nucleation process (Fig 1.A). A second set includes a fracture bounded in the central layer and used to discuss the propagation and the restriction of the fractures (Fig 1.B). Various stress regimes including extension and compression are simulated.

Numerical modeling adopted here allows various combinations of rock properties and patterns of layering to be examined. The variations of the stiffness and the strength properties are taken into account. We consider multilayered systems composed of compliant and weak units alternating with stiff and strong units. The ranges of stiffness and strength properties have been calibrated to simulate most of the clay-rich rocks, limestones and sandstones.

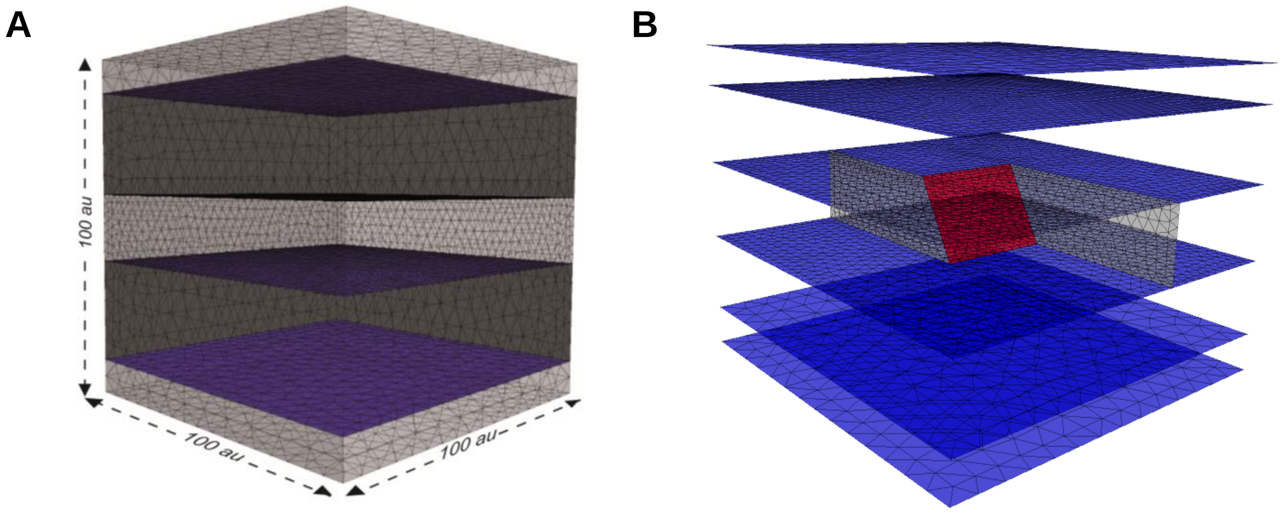


Figure 1. Illustrations of the model geometries. A and B: Example of an un-fractured (A) and fractured (B) layered block. The blocks are meshed in polyhedral elements. The blue and red discontinuities model the lithological interfaces and the bounded fracture, respectively. In B, the gray discontinuities are used to build the fractures and do not perturb the results of the models.

## Preliminary results for non-fractured layered rocks submitted to an extension regime

Our models suggest no stationary variation of stress with depth because of the variation of the mechanical properties induced by the layering despite the fixed spatially uniform extensional stress regime in the far field (Fig 2). The stiffness heterogeneity results in a change in the minimum horizontal principal stress with an increase in the compliant layer and a decrease in the stiff layer. These stress changes occur because the stiffness contrast produces additional layer-parallel stresses. The compliant layer acquires an additional layer-parallel compressive stress which restrains it from further elongation. In return, the stiffer layer acquires an additional layer-parallel tensile stress due to the elongation imposed by the softer layer. These results are in agreement with other modeling approaches.

The minimal principal stress and the maximum differential stress differ from one layer to another. Mohr-Coloumb failure criteria will thus predict that failure is more likely in the stronger layer, even if the coefficient of internal friction is lower in the more compliant layer. In a model with vertically varying stiffness but constant strength properties, the fracturing including fault or joint is therefore inhibited in the compliant layers and is promoted in the stiff layer. Fractures will therefore nucleate preferentially in the stiff layer. However, if the stiffness is constant in all the blocks and the strength properties vary through the layering, then the fracture is inhibited in the weakest layer (i.e., low cohesion, low tensile strength) or is promoted in the low internal friction layer. Therefore if competent and incompetent beds alternate with variable strength, the fractures may alternatively nucleate in one or another unit, depending on the characteristics of the system.

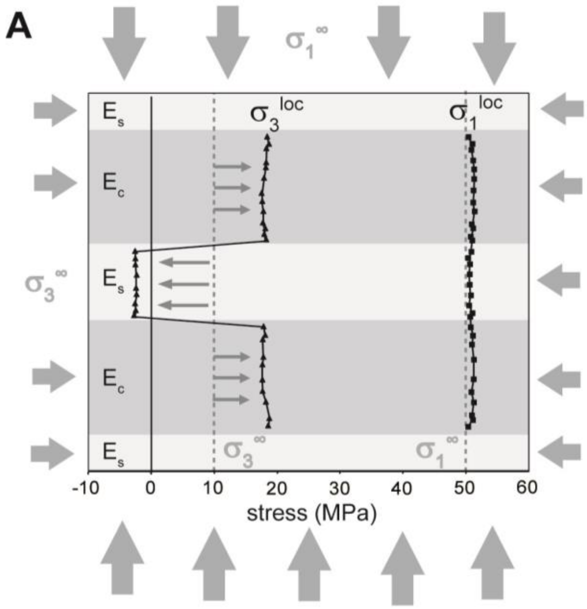


Figure 2. Example of modeling variations of the state of stress within the layering. The relatively stiff and compliant layers are in light grey and grey, respectively. The ratio of the stiff and compliant Young's modulii ($E_s/E_c$) was set to 2. The squares and the triangles indicate local maximum ($\sigma_1^{loc}$) and minimum ($\sigma_3^{loc}$) principal stresses, respectively along the vertical axis (*Z*) through the layered section. The dotted lines represent the maximum ($\sigma_1^{\infty}$) and minimum remote principal stresses ($\sigma_3^{\infty}$) applied on the blocks. The contrast in Young's modulus produces modification of the minimum principal stresses represented with the small grey arrows.

## Conclusions

In some cases it has been observed that microseismic events seem to be restricted to specific lithologies, where little to no seismicity is observed in intermediate more compliant layers (Pettitt et al., 2009). This raises the question if and how fluids traversed such intermediate layers if no brittle failure seems to occur here. In other instances, seismicity can happen in surrounding layers even if it is certain that no fluids leaked into these formations. The numerical simulations show that differential stress concentration in stronger layers is likely to contribute to fracture nucleation, propagation and restriction in all but homogenous half-spaces. It is thus important to take lithological layering and pre-existing in situ stress fields into account when interpreting microseismic event clouds in terms of interconnected fracture

## Acknowledgements

The authors thank the sponsors of the Microseismic Industry Consortium for financial support, and Itasca for providing a license to their 3DEC software.

#### References

Bourne, S.J. (2003), Contrast of elastic properties between rock layers as a mechanism for the initiation and orientation of tensile failure under uniform remote compression, Journal of Geophysical Research, 108.

Cundall, P.A. (1988), Formulation of a three dimensional distinct element model: Part I. A scheme to detect and represent contacts in a system composed of many polyhedral blocks, Int. J. Rock Mech. Min. Sci. Geomech., Abstr. 25, 107–116.

Fischer, T., Hainzl, S., Eisner, L., Shapiro, S. A., and J. Le Calvez, (2008), Microseismic signatures of hydraulic fracture growth in sediment formations: Observations and modeling, Journal of Geophysical Research, 113.

Grob, M., and Vand Der Baan, M., (2011), Inferring in-situ stress changes by statistical analysis of microseismic event characteristics, Canada, Artic Technology.

Pettitt, W., J. Reyes-montes, B. Hemmings, E. Hughes, and R. P. Young, 2009, Using Continuous Microseismic Records for Hydrofracture Diagnostics and Mechanics: SEG Expanded Abstract, 28, 1542–1546.

Roche, V., Homberg, C., and M. Rocher (2012a), Architecture and growth of fault zones in multilayer systems: a 3D field analysis in South-Eastern Basin, France, Journal of Structural Geology, 37, 19-35.

Roche, V., Homberg, C., and M. Rocher (2012b), Fault displacement profiles in multilayer systems: from fault restriction to fault propagation, Terra Nova, 24, 499-504.

Roche, V., Homberg, C., Rocher, M., Fault nucleation, restriction and aspect ratio in layered sections: quantification of the strength and stiffness roles using a 3D modeling. submitted to Journal of Geophysical Research.

Welch, M.J., Davies, R.K., Knipe, R.J., and C. Tueckmantel (2009), A dynamic model for fault nucleation and propagation in a mechanically layered section, Tectonophysics, 474, 473-492.