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Geomechanical modeling of induced seismicity due to fluid injection

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Summary

The paper addresses the effect of a layered lithological structure in the sedimentary infilling on the spatial variation in microseismicity. Numerical modeling is used and two natural cases are studied. The modeling approach simulates the depth variations of the tensile and shear failure criteria. It takes into account the strength, the stiffness rock properties and the in situ pore pressure. The stiffness variation, obtained from well data, induces a variation in the local state of stress as a function of the layering. We show that the depth distribution of recorded microseismic events is highly correlated to the variation of the failure criteria as imposed by the interplay of rock strength and stress concentration due to lithological layering. A high density of events is observed in layers that must fail in tension during the fluid injection indicating that the initiation of tensile fractures is a key mechanism. The layers that do not fail in tension are associated to a decrease in the number of events. Shearing may also be an important mechanism during the fluid injection and we highlight shear reactivation induced by the fluid injection.

Introduction

In hydraulic fracturing, a fluid is injected into a target formation in order to increase the inter-connected permeability. This process is applied to the recovery of oil and gas from low permeability rocks. The increase in permeability results from fracture nucleation and reactivation of pre-existing fractures that form a complex fracture network (Figure 1). Identifying the characteristics of the fracture network and the underlying parameters leads to improved understanding of well performance. These characteristics may be assessed by looking at the distribution of microseismic events that are induced by the fluid injection. In this work we analyze why the event distributions often display spatial variations by looking at the combined effect of the strength, the stiffness rock properties and the in situ pore pressure.

Theory and Method

The effect of the layering heterogeneity on fracture nucleation and propagation is a coupled effect involving both strength and stiffness variations [Roche et al., 2013c]. We use a similar discrete-element method to investigate how the heterogeneity of the rock affects the initiation and the development of fractures in the case of hydraulic fracturing [Roche et al., 2013a and b].

- The heterogeneity of the rock layering is expressed by the depth variation of the Young's modulus and the Poisson's ratio as calculated from density, and shear and compressional velocity logs (see example Figure 2a).

- The magnitudes of the effective remote regional stresses applied as boundary condition are calculated assuming a critical, frictional and cohesionless state of stress. The models take into account predefined background pore pressure within the rock prior to fluid injection including dry, hydrostatic and partially depleted conditions.
- The discrete element method computes the effective local stresses given the imposed regional stress field, pore pressure and mechanical properties.
- The local effective stresses after the injection are calculated from the difference in the pre-injection effective local principal stresses and the increase in pore pressure due to injection.
- We use failure criteria calculated from the local effective stresses after injection for analyzing the likelihood of initiation of shear and tensile fractures.
- Next we compare the depth variations of the failure criteria to the vertical distribution of the microseismic events recorded over the course of fluid injection.

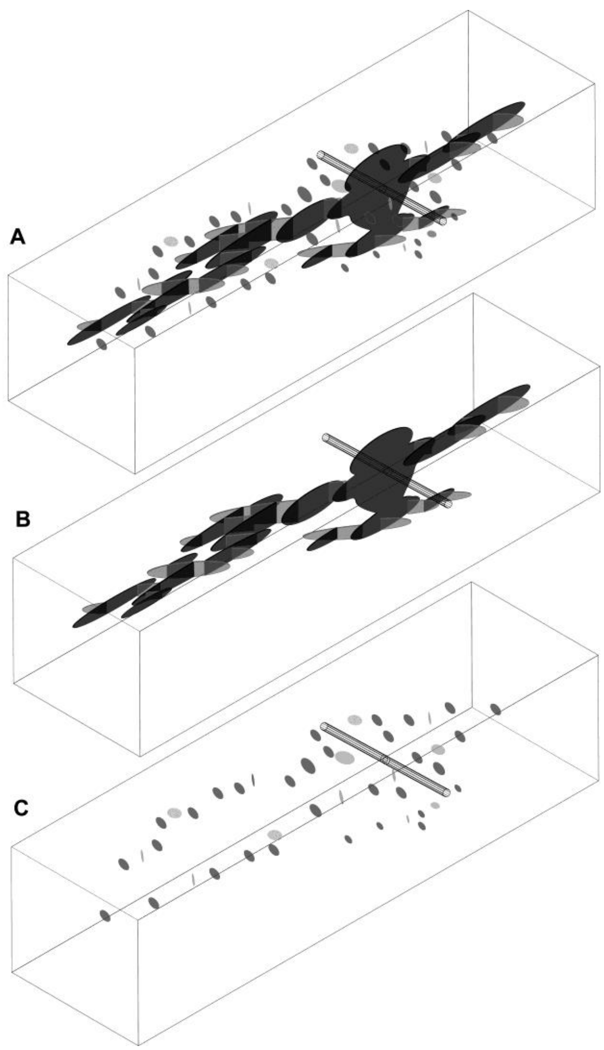

Figure 1: Simplified sketch of a hypothetical fracture network. The totality of fractures occurring during a fluid injection in a horizontal well is indicated in A. The fracture network comprises fractures hydraulically connected to the well (B), and secondary fractures not connected hydraulically to the well (C). In this example, the hydraulic fractures grow mainly in a horizontally plane with an asymmetric distribution. Vertical and downward propagation also results in horizontal extensions into other levels. Connected and unconnected fractures may have their major displacement as opening (dark grey fractures), or shearing (light grey). They also may result from initiation or reactivation of fractures not differenced here. For ease of illustration, all the fractures are assumed vertical but dipping or horizontal fracture are also likely to occur, depending on the local stress state.

Examples

Two naturally layered field examples are investigated. We present in this abstract results for the Carthage Cotton Valley field [Roche et al., 2013a and b; Rutledge and Phillips, 2003]. We use a normal-faulting stress regime. One set of models simulates initial dry conditions before fluid injection and a second set assumes an initial hydrostatic pore pressure.

Lithological layering has little effect on stress concentrations in the local vertical stresses. Conversely, the horizontal stresses change due to the layering because of the stiffness contrast that produces additional layer-parallel stresses. For the Cotton Valley case, the minimum principal stress is horizontal. It increases locally in the compliant layers because of the creation of an additional layer-parallel compressive stress which restrains these layers from further elongation. In return, the stiffer layers acquire locally an additional layer-parallel tensile stress due to the elongation imposed by the softer layers and the stress decrease in such layers (Figure 2b). The variation in the local stresses does not result in stress permutation within any layer and depends on the contrast in the Young's modulii between surrounding layers.

The variation in the local state of stress combined with the strength variations implies a depth variation in the failure criteria. The depth variation of the tensile failure criteria, obtained with initially hydrostatic in situ pore pressures, is shown in figure 2c. Although probably unrealistic, we assume a constant pore pressure increase due to injection within all layers, instead of solely inside the injection layer. Simulation results indicate that some layers reach the tensile failure threshold whereas others do no fail despite of the fluid injection.

Figure 2d shows that most of the events occur in the layers predicted to fail for the depicted scenario with initial hydrostatic pore pressures. Decreases in the number of events are also observed in layers that act as mechanical barriers. Finally, the simulated stresses are suitable for strike-slip reactivation of natural vertical fracture populations that have been identified in the area [Rutledge and Phillips, 2003]. This result provides a mechanical explanation of why shearing mechanisms have been identified in the area [Rutledge and Phillips, 2003].

Conclusions

The magnitude of the local stresses can be very different from the regional stress state due to lithological layering. Simplistic analyses based on the assumption that local stresses are equal to the regional ones will thus erroneously predict that the weakest layers will fail first, whereas in reality failure may initiate in the stronger layers if sandwiched between two compliant layers. Combination of stress concentration and variations in rock properties cause in reality that tensile or shear failures may occur in both the stronger and the weaker layers.
Microseismicity observed during hydraulic fracture treatments provides pertinent clues on the in situ stresses and rock properties. In this case, both the pre-injection local pore pressures and the injection pressures play a dominant role to ascertain failure. The location of the fluid injection forces the failure to occur in a specific interval of the rock formation during hydraulic fracturing. In layered sequences with contrasts in Young's moduli between strong and compliant rocks comprised between 1 and 2, like in the studied cases, stress concentration occurs in the stiffer rocks, but tensile or shear failures occurs in both the stronger and the weaker layers. Events are often also bound by mechanical barriers, either due to their strength, decreases in differential and absolute local stresses due to their compliance or absence of sufficiently high pore pressures. As a final conclusion, the significant increase in recorded microseismicity during fluid injection provide a powerful source of data and promise considerable improvements in understanding fracturing processes in a complementary way to analyses of outcrops or other geological analogues.

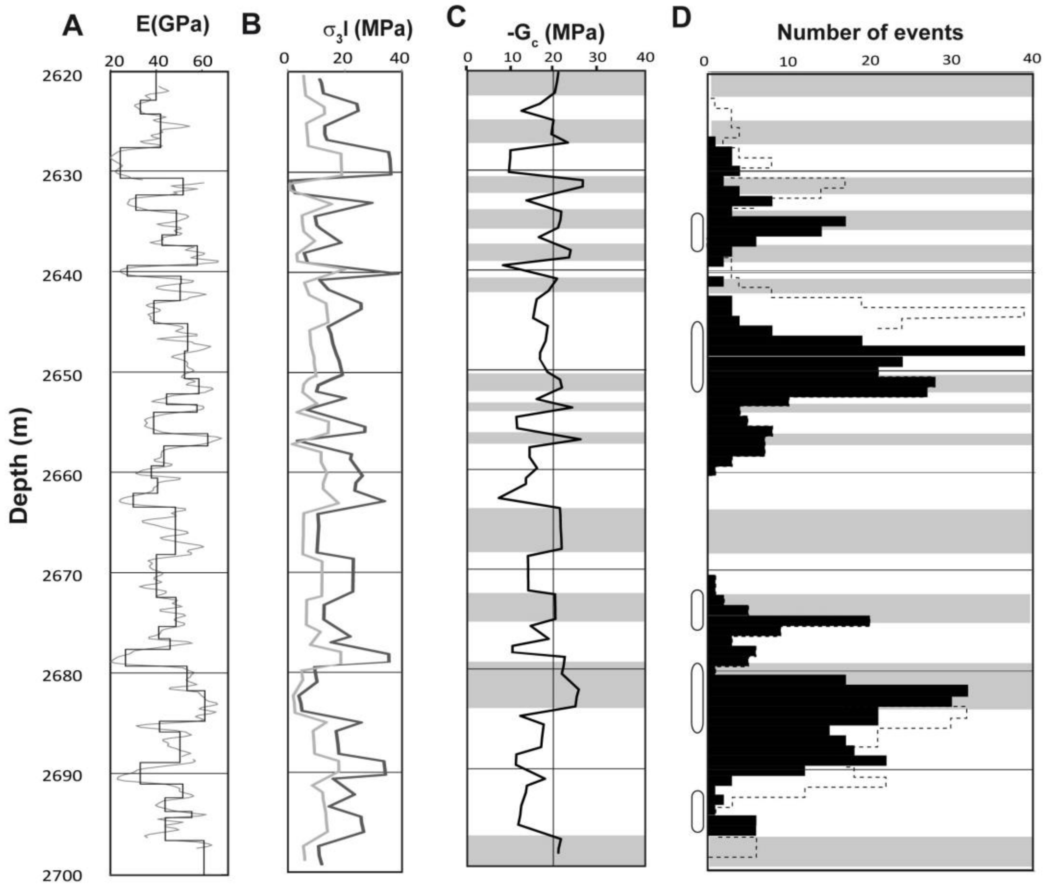

Figure 2: A: depth variation of the Young's Modulus used in the models and calculated from the variation of the density and velocities. B: depth variation of the minimal principal stresses before fluid injection. Dark grey: no fluids in the reservoir; light grey: hydrostatic pore pressure conditions. C: depth variation in the Griffith failure criteria for hydrostatic pore pressures condition. Failure criteria are shown such that positive values indicate failure. D: depth distribution of the number of events. Homogeneous grey bands: layers that fail in tension.

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