Geophysical Research Abstracts
Vol. 20, EGU2018-6483-1, 2018
EGU General Assembly 2018

Propagation paths of fluid-driven fractures

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Understanding and forecasting the propagation paths of rock fractures is of great importance in fields such as seismology (paths of earthquake ruptures), volcanology (propagation paths of dikes), enhanced geothermal systems (hydroshearing), and the hydrocarbon industry (conventional and unconventional hydraulic fracturing). With current knowledge it is not possible to forecast with any reliability the likely path of rock fractures. Here the focus is on fluid-driven mode I fractures, hydrofractures, which include natural fractures such as dikes, inclined sheets, sills, many mineral veins and joints, as well as human-made hydraulic fractures used in the hydrocarbon industry.

Many natural fractures such as dikes and mineral veins are deflected or arrested at contacts while others use suitable oriented joints or faults to form parts of their paths. Similarly, many human-made hydraulic fractures injected vertically (from sub-horizontal wells) into gas-rich shales become deflected into contacts between layers or (particularly low-dipping) faults before eventually becoming arrested – ideally at a certain minimum depth below any shallow aquifers.

To understand and forecast hydrofracture propagation paths, I combine analytical and numerical models. The analytical models derive from analytical mechanics and fracture mechanics and provide the general forecasts. These are then made more site-specific by adding local complexities, such as layering, mechanically weak contacts, and faults, and analysing the actual propagation fracture paths through numerical modelling. The results of analytical and numerical forecasts as to hydraulic fracture propagation are then compared with, and tested on, actual data of two types. (a) Seismic data on actual hydraulic fracture propagation paths, both for conventional and unconventional hydraulic fractures. (b) Field data on natural hydrofracture propagation paths in layered and faulted rocks, namely dikes, mineral veins, and joints.

The numerical results for fracture propagation in mechanically layered rocks show that the paths are complex. The local stress field predict common deflection along layer contacts (and lamina contacts in shale), in agreement with field and rock-physics data. The fracture propagation path is thus not entirely in pure mode I but rather partly in a mixed mode. The energy required to propagate the fracture is primarily the surface energy needed to rupture the rock, to form two new surfaces and move them apart as the fracture propagates. The energy available to drive the fracture is the elastic energy (the stored strain energy in the host rock and the potential energy due to loading). The selected path seeks to minimise the action (energy $\times$ time, unit Js; Hamilton's principle). Whether or not the hydrofracture uses existing discontinuities as part of its path depends on whether by doing so the action is minimised.

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