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# Fracture propagation in sandstone and slate – Laboratory experiments, acoustic emissions and fracture mechanics

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ABSTRACT

Fracturing of highly anisotropic rocks is a problem often encountered in the stimulation of unconventional hydrocarbon or geothermal reservoirs by hydraulic fracturing. Fracture propagation in isotropic material is well understood but strictly isotropic rocks are rarely found in nature. This study aims at the examination of fracture initiation and propagation processes in a highly anisotropic rock, specifically slate. We performed a series of tensile fracturing laboratory experiments under uniaxial as well as triaxial loading. Cubic specimens with edge lengths of 150 mm and a central borehole with a diameter of 13 mm were prepared from Fredeburg slate. An experiment using the rather isotropic Bebertal sandstone as a rather isotropic rock was also performed for comparison. Tensile fractures were generated using the sleeve fracturing technique, in which a polymer tube placed inside the borehole is pressurized to generate tensile fractures emanating from the borehole. In the uniaxial test series, the loading was varied in order to observe the transition from strength-dominated fracture propagation at low loading magnitudes to stress-dominated fracture propagation at high loading magnitudes.

## 1. Introduction

### 1.1. Hydraulic fracturing laboratory experiments

Hydraulic fracturing is the generation of fractures by injecting fluid into a borehole at pressures sufficient to induce failure in the surrounding rock mass. It is used in a vast field of applications, e.g. increasing productivity from hydrocarbon or geothermal reservoirs, stress measurements, stress relief for tunneling or subsurface mining techniques like block caving. In these applications we are confronted with a wide range of lithologies, stress magnitudes and desired fracture dimensions.

The process of hydraulic fracturing is well understood for homogenous and isotropic media (Valkó and Economides, 1995), but the problem gets much more complex if the mechanical properties of the surrounding rock deviate from being isotropic. Basically all rocks in-situ exhibit a certain degree of anisotropy due to bedding, cleavage or preexisting discontinuities such as joints or faults. This anisotropy might have a strong influence on the fracture propagation direction, the overall fracture geometry and the injection pressures (Warpinski and Teufel, 1987). Such anisotropy often includes a directional dependency of the material's strength. Therefore, one single strength parameter is usually not sufficient for the prediction of failure and fracture geometries in anisotropic materials.

Hydraulic fractures are basically tensile fractures that are propagated by a pressure inside the fracture. To generate such hydraulic fractures under confining pressure in the laboratory, two different experimental setups are most commonly used. One uses core specimens with a central injection borehole that are loaded isostatically by a Hoek-Cell (Haimson and Fairhurst, 1970; Lockner and Byerlee, 1977; Rummel, 1987; Brenne et al., 2013). A fluid is then injected into the borehole until the specimen is split into two parts. The second setup makes use of cubic or cuboid specimens that are loaded independently in three directions to induce a true triaxial stress field more similar to in-situ conditions (Haimson and Avasthi, 1975; Zoback et al., 1977; van Dam et al., 2000; Ishida et al., 2004; Frash et al., 2013). The recording of acoustic emissions (AEs) is a useful tool to gain insights into fracturing processes (Stanchits et al., 2014). Due to typical specimen dimensions in laboratory experiments, with specimen's outer dimensions being only several times the borehole diameter, such experiments are mainly suitable for the examination of mechanical processes near the borehole (fracture length in the order of few borehole diameters) like fracture initiation or borehole failure.

To simplify the boundary conditions in the experiments and to exclude complex poroelastic and leakoff effects, a polymer tube can be pressurized inside the borehole instead of injecting fluid directly

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into an open borehole (Clifton et al., 1976; Abou-Sayed et al., 1978; Schmitt and Zoback, 1992). This also brings the positive side-effect that quasi-static fracture propagation can be achieved and fracture processes can be investigated at very low velocities. A similar technique, sleeve fracturing, is also used in-situ for stress measurements (Stephansson, 1983; Serata and Kikuchi, 1986).

### 1.2. Continuum models

Basic continuum mechanics models are commonly used to predict the pressure at which an internally pressurized borehole will fail in isotropic and homogeneous rock mass. In the classic model for non-poroelastic rock (Hubbert and Willis, 1957), the initiation of hydraulic fracture propagation is only controlled by the orientation and magnitude of the external stress field as well as the strength of the rock. The borehole breakdown pressure $P_b$ can be calculated as

$$P_b = 3\sigma_3 - \sigma_1 + T - P_0 \tag{1}$$

where $\sigma_3$ and $\sigma_1$ are the minimum and maximum horizontal far field stresses, respectively; $T$ is the tensile strength of the rock; and $P_0$ is the pore pressure.

When the rock near the wellbore is assumed to be poroelastic, the Poisson's ratio $\nu$ and the Biot poroelastic parameter $\alpha$ ($\alpha = 1 - C_r/C_b$, where $C_r$ is the rock matrix compressibility, and $C_b$ is the material bulk compressibility) are introduced as additional parameters into this equation (Haimson and Fairhurst, 1967):

$$P_b = \frac{3\sigma_3 - \sigma_1 + T}{2 - \alpha(1 - 2\nu)/(1 - \nu)} - P_0 \tag{2}$$

For the impermeable case ($\alpha = 0$, $P_0 = 0$), instead of reducing to the equation of Hubbert and Willis (1957), this equation gives

$$P_b = (3\sigma_3 - \sigma_1 + T)/2 \tag{3}$$

From this discrepancy, it follows that the correlation between far field stress $\sigma = (\sigma_1 + \sigma_3)/2$ and breakdown pressure for an impermeable medium could be either $P_b \propto \sigma$ or $P_b \propto 2\sigma$. Furthermore, laboratory experiments indicate that small specimen dimensions as well as high pressurization rates and fluid viscosity increase the breakdown pressure (Haimson and Zhao, 1991; Schmitt and Zoback, 1992). However, such effects are not covered by the continuum models mentioned above.

### 1.3. Linear elastic fracture mechanics

The classical approaches for calculating breakdown pressures are only valid for a homogenous, defect free continuum. These assumptions are not met by most rocks, at least when a hydraulic fracture is present. To overcome these shortcomings, the principles of fracture mechanics have been successfully applied in the evaluation of hydraulic fracturing experiments (Abou-Sayed et al., 1978; Rummel, 1987; Haimson and Zhao, 1991; Detournay and Carbonell, 1997; Stoeckhert et al., 2014).

Linear elastic fracture mechanics deal explicitly with the stress distribution around fractures and the conditions under which fractures propagate. The magnitude of the stress field at the tip of a sharp fracture can be characterized by one single parameter—the stress intensity factor $K$ (Irwin, 1957). The stress intensity factor is dependent on the stress acting on the fracture as well as the fracture length. For the simple case of a fracture of the length $a$ in an infinite plate that is loaded by a tensile stress $\sigma$ perpendicular to the fracture, the stress intensity factor $K_I$ (the subscript "I" refers to tensile fracturing mode) is given by

$$K_I = \sigma\sqrt{a\pi} \tag{4}$$

Accordingly, a corresponding material parameter called fracture toughness $K_C$ (or $K_{IC}$ for tensile fracturing) can be defined, at which the fracture propagates:

$$K = K_C \tag{5}$$

This parameter can be determined by standardized laboratory tests like the chevron notched three-point bending test (Ouchterlony, 1988). Typical fracture toughness values for the rocks used in our experiments can be found in Table 1.

For a hydraulic fracture emanating from a borehole in an infinite isotropic medium, the stress intensity factors can be calculated by superposition of known solutions for simple problems (Rummel, 1987). However, the influence of the specimen geometry should be taken into account, as the distance between borehole and outer walls is quite small. The calculation of stress intensity factors for such complex geometries can be done numerically. Stress intensity factors can be calculated from finite element method (FEM) simulations using the J-integral (Parks, 1977) which requires the mesh to be adjusted at the fracture tip for good solutions. Another approach is the extended finite element method (XFEM) where the fracture path is independent of the mesh. These numerical methods also facilitate the incorporation of anisotropic material failure models by using an anisotropic fracture toughness.

As the fracture grows, parameters such as the hydraulic properties of the injection fluid and the surrounding rock have an increasing influence on the further propagation. This case is not considered in our models as we only want to examine near-borehole process and exclude all hydraulic effects by the sleeve fracturing technique.

## 2. Methods

### 2.1. Experimental setup and specimen preparation

Within this work, two series of hydraulic fracturing experiments on cube specimens (edge length = 150 mm) were carried out using the sleeve fracturing technique. Fig. 1 shows the true triaxial loading frame construction. Loading is maintained by four servo-controlled pressure intensifiers simultaneously controlled by an MTS Teststar IIm system. Principal stresses $\sigma_2$ and $\sigma_3$ are applied by super flat cylinders with a maximum capacity of 525 kN. The maximum principal stress ($\sigma_1$) is applied via a hydraulic ram with a

**Table 1**
Rock mechanical parameters (cohesion $c$, internal friction angle $\phi$, Young's modulus $E$, tensile strength $T$, fracture toughness $K_{IC}$, ultra-sonic wave velocity $V_P$) of Bebertal sandstone and Fredeburg slate perpendicular ($\perp$) as well as parallel (//) to bedding/cleavage.

| Lithology | $c$ (MPa) | $\phi$ (°) | $E$ (GPa) | $T$ (MPa) | $K_{IC}$ (MPa m$^{1/2}$) | $V_P$ (km/s) |
|---|---|---|---|---|---|---|
| Bebertal sandstone | 26 | 48 | 19 ± 1.3 | 5.5 ± 0.5 | 1.21 ± 0.27 | //3.98 ± 0.24<br>$\perp$4.10 ± 0.19 |
| Fredeburg slate | 8.6–34.1 | 21.7–37.6 | 14.5–35.5 | 3.5<br>21.1 | 0.3 (assumed)<br>2.5 (determined) | //5.92 ± 0.13<br>$\perp$2.69 ± 0.14 |