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Fault Tips as Favorable Drilling Targets for Geothermal Prospecting – a Fracture Mechanical Perspective

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ABSTRACT

The productivity from geothermal systems is often controlled by faults and fractures. Faults can have positive effects on fluid flow and heat transport, leading to drilling targets at fault zones. It is, however, under debate which part of the fault might be the most favorable site for drilling. The catalog of geothermal systems in the Great Basin, Nevada, demonstrates that not the center of fault planes is the setting for high geothermal activity. Instead, step-over regions, fault intersections and fault tips belong to the favorable structural settings of geothermal fields in the Great Basin. Our attempt aims to explain from a fracture mechanical perspective the cause and effect why faults tips may represent favorable targets for geothermal exploration.

1. INTRODUCTION

Fault and fracture zones serve as fluid conduit or barrier for fluid flow. The behavior of faults should therefore be studied and estimated before drilling.

Different concepts exist to qualitatively and numerically characterize fault and fracture zones from hydrogeologic, hydraulic (e.g. Agosta, 2007; Zhang et al., 2008; Bense et al., 2013) structural geological and tectonical (e.g. Johansen and Fossen, 2008; Ferrill et al., 2008) or mechanical analysis (e.g. Imber et al., 2008; Morris et al., 1996) to explain fluid flow patterns and behavior of faults in the present day stress field and under reservoir operational conditions.

Fracture mechanics may be another approach to characterize and understand the hydraulic behavior of fractures. Other than the frequently used empirical failure criteria fracture mechanics is physically based. Fracture mechanics is the study of stress and displacement fields near a crack tip leading to fracture propagation. Fractures in solid materials determine the strength of the material. Inglis (1913) and in particular Griffith (1921), were the first to recognize the importance of pre-existing discontinuities as precursors to failure of solid materials. Today, fracture mechanics is mainly employed to recognize pre-failure rock mass behavior that may result in predicting or averting the potential for geotechnical and geological failure (Szwedzicki, 2003).

Fracture mechanics can also be employed to understand the emplacement of geothermal resources in fault controlled geologic systems. In this article we contribute to answering the question why geothermal resources develop predominantly at fault tips instead of in the central part of a fault zone.

2. GEOLOGICAL EVIDENCE

One of the first attempts to systematically catalogue the inventory of structural settings of geothermal systems was conducted by Faulds et al. (2012) for the Great Basin region in the western USA. The Great Basin is part of the Basin and Range Province, which is one the regions with the largest extension rates worldwide.

Most faults are normal, transtensional or strike-slip faults. Significantly, most of the catalogued geothermal systems in the Great Basin are located on discrete fault steps or relay ramps followed by fault tips and fault terminations. Also fault intersections play a dominating role for the placement of geothermal systems while major faults or pull-apart basins belong to subordinate locations of geothermal resources in fault-controlled systems (Faulds et al., 2012).

Delineating the causes for this observation it seems reasonable that geothermal systems emplace in dilational zones of normal fault relay ramps, or the in the highly fractured zone of a fault intersection. However, the emplacement of geothermal commodities on fault terminations does obviously not follow a reasonable concept to explain favorable drilling targets at fault tips.

3. FRACTURE MECHANICS FRAMEWORK

Linear fracture mechanics provides the tools to estimate the stress and displacement fields around the tip of a fracture. Fractures are usually subdivided into three basic types, namely Mode I, Mode II and Mode III, according to the fracture surface displacement (Lawn, 1993; Figure 1). In Mode I, the tensile mode, the fracture tip is subject to displacements perpendicular to the fracture plane; no record of shear displacement is visible. In Mode II the relative movement of the fracture faces is perpendicular to the front in the plane of the fracture. Shear traction parallels the plane of the fracture. In Mode III, shear traction and displacement are parallel to the fracture front in the plane of the fracture and can therefore only be handled by three-dimensional analysis. Any combination of the three basic modes is referred to as mixed mode. The principle of superposition is sufficient to describe the most general case of fracture tip deformation (Whittaker et al., 1992).

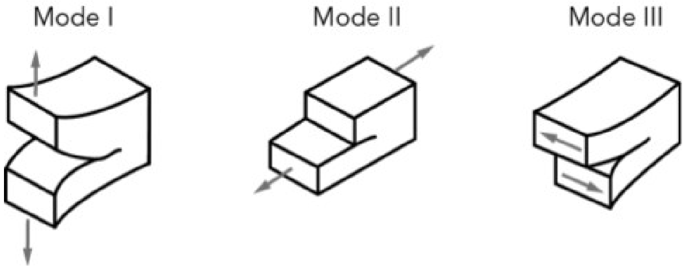

Figure 1. Basic modes of fracturing. Any combination of these is referred to as mixed mode. The principle of superposition is applicable (modified from Hudson & Harrison, 1997).

Any loading of a fracture will result in an alteration of the stresses at the fracture tip. The stresses around the fracture tip (Figure 2) are given by Westergaard (1939) and Irwin (1958) as

$$\sigma_{ij} = K_k \cdot \frac{1}{\sqrt{2\pi \cdot r}} \cdot f_{ij}(\theta) \qquad (1)$$

where r is the distance from the fracture tip, S_{ij} is a general component of the stress tensor in Cartesian coordinates, f_{ij} is a geometric factor depending solely on angle θ, and K_k is a stress intensity factor depending on the outer boundary conditions, i.e. the applied loading and geometry (Figure 2). The subscript k refers to the corresponding mode.

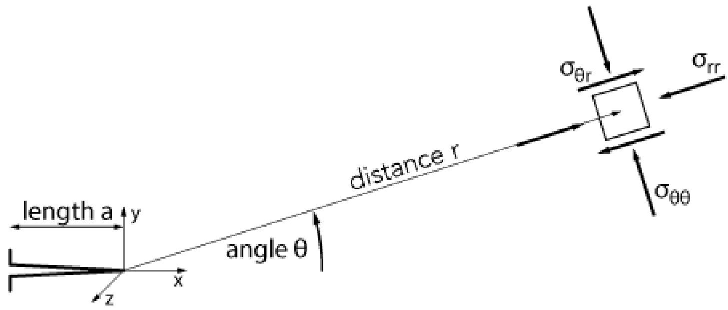

Figure 2. Notations within polar coordinate system for stress tensor.

Mode I stress redistribution

In pure Mode I, the radial and tangential stresses (represented as stress factors here) are symmetric about the plane of the fracture (Figure 3). Both stresses are tensional. The tangential stress shows its maximum in direction of the fracture tip (θ = 0°), whereas the radial stress shows a lokal minimum at θ = 0° and its maxima at about θ ≈ 77° and -77°. The shear stress shows point symmetry about the fracture tip, indicating a change of shear sense from one side of the fracture to the other.

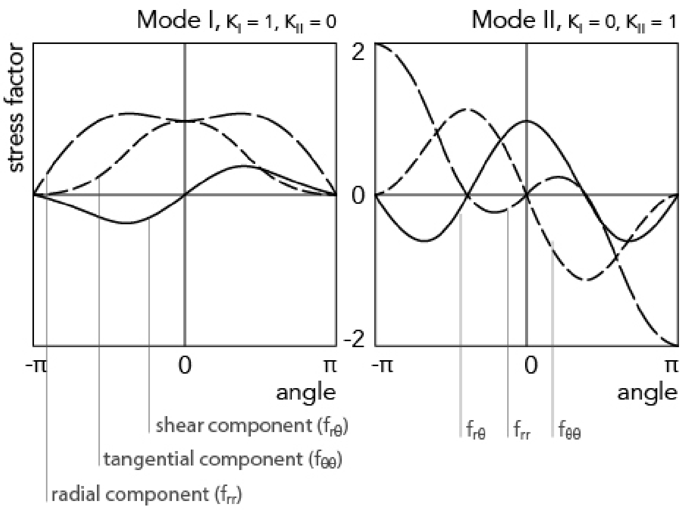

Figure 3. Stress distribution in terms of stress factor f_{ij} around crack tip for different pure modes of loading. Each of the modes possesses specific stress symmetry properties near the crack edge (Broberg, 1999). Notations according to Figure 2. Note: positive stress factor as indicative of tension.

<u>Mode II stress redistribution</u>

Under pure Mode II loading the shear stress is symmetric with respect to the fracture plane. It has its maximum at θ = 0° and minima at about θ ≈ -120° and 120°. These minima show a shear sense opposite to the maximum.

Both the radial and tangental stress component are point symmetric to the fracture tip. The tangential stress is extensive at angles θ < 0° and compressive at θ > 0° with maximum and minimum values at roughly θ ≈ -72° and 72 respectively. The radial stress component shows very high tensile values at θ < -70°, and comparable high compressive stresses at θ > 70°; around the fracture tip a change from compression to tension is evident.

<u>Mode III stress redistribution</u>

As the analysis is confining itself to 2D cases, the Model III stress components are not discussed here but may be found elsewhere (e.g. Lawn 1993).

4. ANALYSIS AND INTERPRETATION

We assume a fracture subject to a compressive shear loading, i.e. K_I = -1 MPa√m and K_{II} = 1 MPa√m. The fault trace itself is therefore subject to compressive stress, hence is under compressive-shear load.

This leads to a stress redistribution around the fracture tips as plotted in Figure 4 in polar coordinates.

It becomes evident that there is at each tip a region, that is under extensive stress. From about -30° to -110° the tangential stress is tensile, whereas the radial stress, which is perpendicular to the tangential stress is compressive. Existing fractures in this region are subject to a biaxial stress field in the horizontal plane, that combines compressive and extensive components. It can be expected that depending on the orientation within the local stress field, the fractures have some shear and opening displacements. This can be expected to lead to increased permeabilities on those fractures.

From about -110° on, both the tangential and radial stress components are extensive. Most fractures in this sector irrespective of their orientation can be expected to be open and therefore showing some increased permeability.

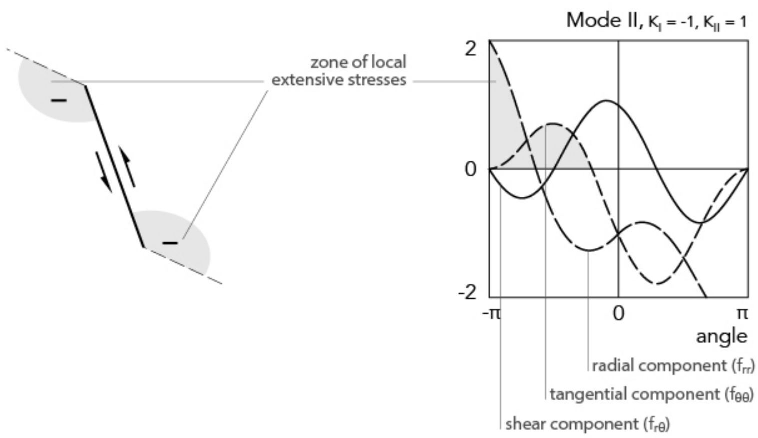

Figure 4. Stress distribution at a fault tip as resulting from a compressive-shear loading on a fault with a sinistral sense of shear. At the tip of the fracture a region of about 150° is subject to tensile stresses in tangential direction and super-positioned by radial tensile stresses in a region of about 70°.

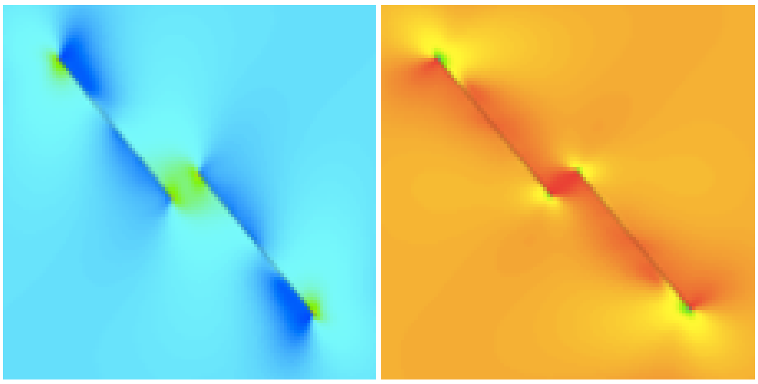

Figure 5. Stress field due to a compressive load (SH horizontal) of two overlapping fractures. Blue to red colors indicate high to low stresses. (left) maximum principal stress, and (right) minimum principal stress. The stresses are reduced in the overlapping area of the fractures, the minimum principal stress becomes tensile between the faults. See text for details on the model.

5. NUMERICAL EVIDENCE

The simulation software roxol^{TM} is designed to simulate fracture growth and related fracture network evolution in rock and rock mass. The development is based on fracture mechanics principles and employs the mathematical framework of XFEM (extended finite element method). The code may simulate linear elastic materials with existing fractures or fracture networks. These may propagate and coalesce during alteration of boundary conditions e.g. due to construction works. Application areas are hydraulic fracturing, wellbore stability or similar. Application examples may be found in Backers 2010, Backers et al. 2012, or Mischo and Backers 2012.

In the context of this study a simple 2D model was set up with two fractures that are inclined to the acting stress field. The two fractures show same orientation within the stress field and overlap at one of their ends. The fractures are modeled with a Coulomb friction ($\mu = 0.7$) and the stresses are SH = 35 MPa and Sh = 14 MPa. The rock material is modeled isotropic linear elastic

The simulation clearly shows reduced stresses in the area of the overlapping faults and at the distal tips of the faults. One of the principal stresses becomes tensile, which is an indication that the tip and overlap areas are favorable for geothermal exploration.

6. DISCUSSION AND CONCLUSIONS

The analysis has shown that there are good arguments from a fracture mechanics perspective, that there are regions close to fault tips where extensive stresses dominate and hence can be expected to show enhanced permeabilities.

Geothermal exploration should therefore analyze the stress fields and the stress perturbations around existing faults. A good interactive structural geological and geomechanical site analysis should be an integral part of the early exploration phase.

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