AAPG/SPE/SEG HEDBERG CONFERENCE
"ENHANCED GEOTHERMAL SYSTEMS"
MARCH 14-18, 2011 – NAPA, CALIFORNIA

Prediction of Open Fractures in Granite Basement: A Proven Successful Geo-Mechanical Approach

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Geothermal energy from hot dry rocks often depends on he presence of open fractures in granitic basement rock. In order to drill efficient wells, these should be deviated and oriented perpendicular to the strike of the open fractures. Clearly, the location and orientation of such fractures needs to be known. Often the maximum depth to which fractures can be found open is also required.

This abstract describes a geo-mechanical method for the prediction of the location and orientation of open fractures in granitic basement. A successful case history is included to provide realistic data and proven results.

Standard fracture prediction methods rely on either curvature analysis or on statistical methods. Curvature does not apply to granite plutons and for statistical methods a fracture population needs to be available to serve as a basis for extrapolation. For granites in the subsurface a reliable fracture system analogue is mostly not available.

In order to predict open fractures, their location orientation and depth to which they can be open, requires a different approach. If it is possible to determine the state of stress in the various stages of the deformation history of the granite, the state of stress that would result in the formation of open tension fractures can be reconstructed. This approach requires a palaeo stress analysis, based on the tectonic history of the greater region in which the target granite is situated.

There are three states of stress that can result in the formation of open tension fractures:

1. hydraulic fracturing due to high fluid pressures;
2. tension fracturing due to regional extension;
3. tensionfracturing due to outer arc extension.

Given a common starting situation, hydraulic fracturing has the highest probability of creating an open tension fracture. The reason is that the whole stress circle in a Mohr-Coulomb stress circle plot, moves towards the failure envelope because the increased fluid pressure equally affects the effective stresses in all directions.

Tension fracturing due to regional extension, results from a decrease in the minimum horizontal stress (σ_h) whereas the vertical stress (σ_V=depth) remains constant. The result is an increasing stress circle of which the maximum stress point (σ_V) remains constant because the depth of the extended rock remais constant, but the minimum horizontal stress (σ_h) decreases as a result of the regional extension. For a strong rock at relatively shallow depth this will result in the formation of tension fractures (or joints). Due the increase in circle size, it is less likely that an open tension fracture can form than in the case of hydraulic fracturing where the circle size is constant.

Tension fracturing due to outer arc extension, commonly in a compressional anticline, is associated with a decrease in the maximum horizontal stress and as a result is associated with an increase in the size of the stress circle.

Outer arc extension can also be the result of drape, in which case the effect on the stress circle is similar to that of regional extension.

For the granite in the case history that serves as an example, regional extension resulting from rifting in Yemen formed the tectonic framework for the fracture analysis. It will be demonstrated that the formation of open fractures in the granite basement was associated with a rifting phase and with the faulting/fracturing in the corresponding stress regime. An important rock property that controls the orientation of failure planes (tension fractures or shear fractures) is the internal friction angle ψ. This parameter is often listed as a constant rock property, however, it varies with depth. With shallow depths, strong rocks such as granites will fail in tension rather than in shear mode and will form steep open tension fractures (also called joints if very large). As the depth increases, the internal friction angle ψ decreases and the failure zone gradually rotates from steep to shallow dipping and finally closes (Fig.1). This variation in failure with depth results in curved failure zones in strong rocks such as granites (or any rock with a high cohesion). It was the listric shape of a fault in the granite seen on seismic that triggered the search for a mechanism that would produce curved faults in granites (Fig. 2).

Using this relatively simple geo-mechanical approach, it was possible to predict the location and orientation of open fractures in the basement granite. They were expected to be associated with the listric faults that were recognised on seismic and that formed part of the same rift event during which the granite was at a shallow depth.

An exploration well proved the method to be correct and resulted in the most successful oil exploration well in Yemen in 2007, followed by a series of equally successful development wells.

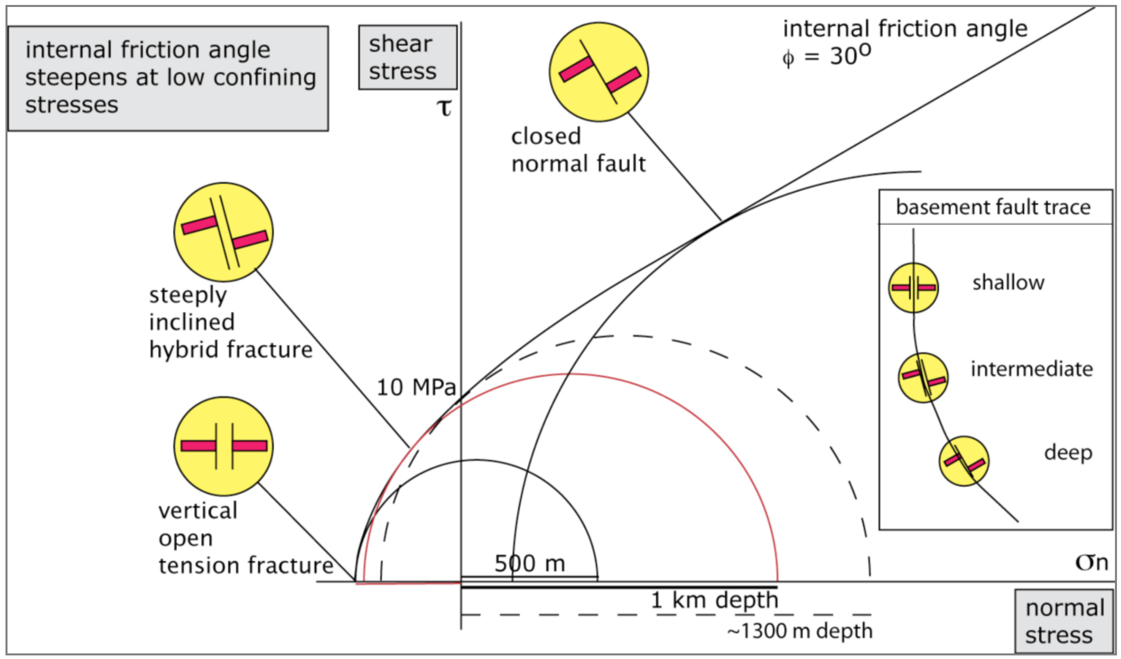

Fig. 1. Formation of a curved fault trajectory in a granite, with open tension fracture mode at shallow depth and gradually closing and flattening with increasing depth.

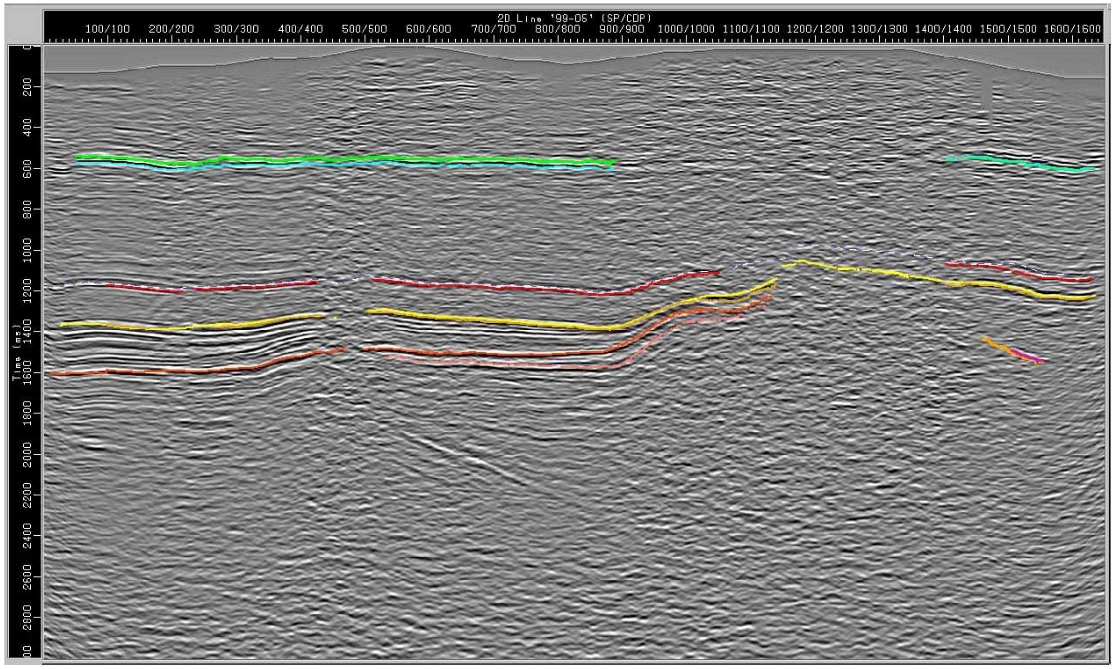

Fig. 2. 2D seismic line with wedge shaped (syn-rift) sedimentation patterns, an indication of syn-tectonic sedimentation along a listric fault.