Importance of stress information in Engineered Geothermal Systems: Which attributes of stress are the most important and a strategy for measuring them.

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Why measure stress anyway?

In principle, EGSs can be developed without explicit knowledge of the state of stress in the reservoir: e.g.

- First well drilled vertical and stimulated.
- Subsequent wells drilled to pass through the peripheral regions of the microseismic cloud.
- Sufficient pumping power mobilised to cope with any wellhead pressure required to deliver the design flow rate (stress-controlled).

However, in practice it will not be long before the discussion turns to the state of stress in the reservoir

Why is stress important?

One of the more important discoveries of crustal mechanics in the past 15 years is the realisation that the Earth's crust is generally close to failure, even in tectonically quiet areas (i.e. high levels of shear stress are the rule rather than the exception).

- This is the underlying reason why shear failure and attendant seismicity commonly result from fluid injection (i.e. the rock is weakened by the elevated fluid pressure).

- Since shearing represents the partial relaxation of the shear stress, and is the primary permeability creation mechanism, it follows that the natural Earth stresses supply most of the energy consumed in the hydraulic stimulation operation.
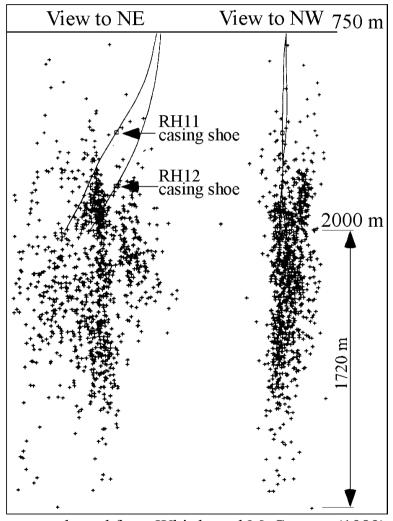
Rosemanowes, Cornwall

First stimulation of Phase 1 reservoir

Downward migration of seismicity:

During stimulation of the Phase 1 reservoir, microseismicity migrated *downwards* more than 1 km.

Explanation:

Pore pressure increase required to initiate failure decreases with increasing depth due to the stress gradients (i.e. stress state becomes more 'critical' with depth).

View to NE   View to NW 750 m

RH11 casing shoe
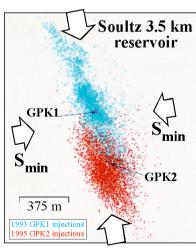
RH12 casing shoe

2000 m

1720 m

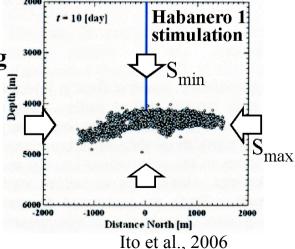adapted from Whittle and McCartney (1989)

What attributes of stress are the more important for reservoir creation?

- The *magnitude of the minimum principal stress* is the primary factor controlling stimulation pressure, and hence dictates the pumping power that must be mobilised.

- The *orientation of the minimum principal stress* is a primary factor in determining the geometry of the stimulation volume (i.e. the dimensions of the stimulated volume will tend to be smallest in a direction with 30° of normal to the minimum principal stress axis).

**Rhine Graben:
Normal-faulting
stress regime**

Soultz 3.5 km reservoir

GPK1

S_{min}

S_{min}

GPK2

375 m

1993 GPK1 injections
1995 GPK2 injections

**Cooper basin:
Thrust-faulting
stress regime**

$t = 10$ [day]

Habanero 1 stimulation

S_{min}

S_{max}

Ito et al., 2006

What attributes of stress are the more important for reservoir creation?

Any qualitative understanding of what is happening in the reservoir requires at least partial knowledge of the stress state, and full-reservoir modelling requires a full description.

Simplifying assumptions for characterising the state of stress in a reservoir?
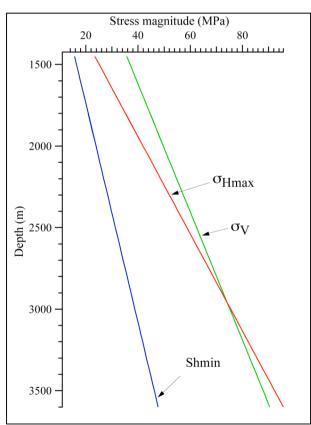
1) One principal stress is vertical
There can and usually are local deviations from verticality, but on the large scale (> 100 m) these tend to average out.

2) The magnitude of the vertical stress is equal to the integrated overburden
This follows from (1) and means that the vertical stress can be measured from integrated density logs.

3) Stress magnitudes are laterally uniform and increase linearly with depth within the reservoir.
First-order approximation that smoothes out the inevitable local variations that reflect **heterogeneity** of the stress field. Sudden step-increases in stress magnitude have been seen (e.g. Fenton Hill EGS) and so the assumptions should be treated with caution and established through measurement

Stress attributes that remain to be measured

1. Magnitude of minimum principal horizontal stress, S_{hmin}
2. Orientation of minimum principal horizontal stress, S_{hmin}-orient
3. Magnitude of maximum principal horizontal stress, S_{Hmax}

To completely define the profile of each of the above attributes will require a spot-value at some depth and a gradient (i.e at least one other value at a different depth). Thus there are six unknowns.

Some attributes of stress are more easy to estimate than others. The easiest are the magnitude and orientation of S_{hmin}. Usually the most difficult is the magnitude of S_{Hmax}.

Methods of stress estimation for EGS reservoirs - preliminary remarks

There are many different methods of measuring stresses in rock masses.

Few are direct measurements of stress. Most methods infer stress indirectly from observations of the consequences of stress. They are only as good as the robustness of the relation used to map the measurement(s) to the in-situ stress state.

Core-based methods invariably measure some property of the microcrack population and relate it to the stress existing at the core's location using some assumptions. Regardless of concerns as to the 'robustness' of these assumptions, the resulting estimates at best relate to stress at a very small scale and are thus impacted by stress heterogeneity.

Very few stress measurement operations can be performed in a commercial EGS hot reservoir setting. The wells are extremely expensive and operators are reluctant to risk damaging or losing the well.

Strategy for site stress characterisation

Assume that an exploration borehole (say to depth < 2.5 km with T < 120°) has been drilled at the site.
Take full advantage of this hole to characterise stress:

Run density ($\gamma-\gamma$) log: S_V

Hydraulic stress tests on natural fractures using packers [HTPF]: *powerful constraints on S_{hmin}, S_{hmin}-orient and S_{Hmax} if enough tests performed.*

Hydrofracture stress tests using packers: S_{min}.

Borehole sonic televiewer log [BHTV]: imaging of breakouts and drilling-induced tension fractures [DITFs]: S_{hmin}-*orient and* S_{Hmax}.

Strategy for site stress characterisation

In the main borehole within the deep hot reservoir, the type of tests that can be conducted are severely limited (not least because of the difficulties with packers at that depth). Performing any operation more complicated that running a wireline log may be ruled out by the project management.

Run density ($\gamma-\gamma$) log: S_V

Borehole sonic televiewer log [BHTV]: imaging of breakouts and drilling-induced tension fractures [DITFs]: S_{hmin}-orient and (S_{Hmax}- S_{hmin})
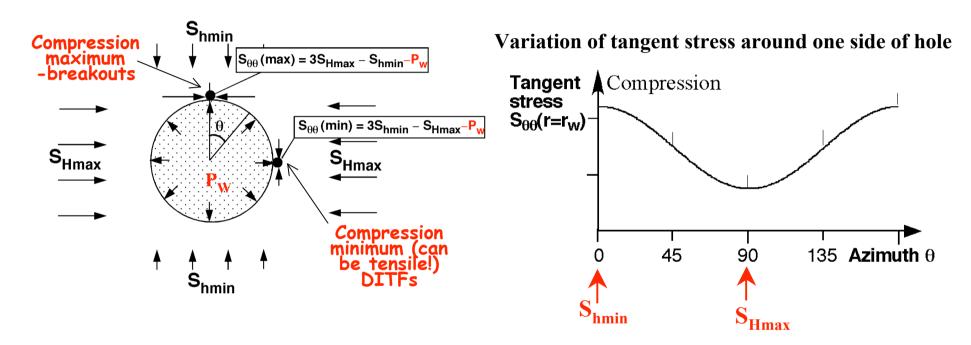
The extraction of stress magnitude information from the breakouts and DITFs is greatly improved if S_{min} can be estimated independently:

- Minifrac tests of top 20 m of open-hole section after sanding back

- Minifrac tests on lower 10-20 m of open hole using alloy packer

- Pressure limiting behaviour during stimulation - requires two stimulation cycles to distinguish jacking from shearing

Wellbore failure - a rich source of information about stress

The wellbore stress concentration around a fluid-filled borehole

Variation of tangent stress around one side of hole

Large differences between S_{Hmax} and S_{hmin} produce large variations in the tangent stress, $S_{\theta\theta}$, at the borehole wall with extreme values that can produce failure.
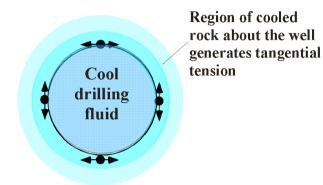
Compressive failure (breakouts) occurs in the direction of S_{hmin} if $S_{\theta\theta}$ > compressive strength of the rock.

Tensile failure (DITFs) occurs in the direction of S_{Hmax} if $S_{\theta\theta}$ < tensile strength.
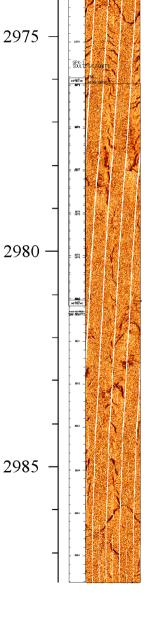
Wellbore failure: Drilling-induced tension fractures

Additional (tensile) component due to cooling of the hole by the drilling fluid

Region of cooled rock about the well generates tangential tension
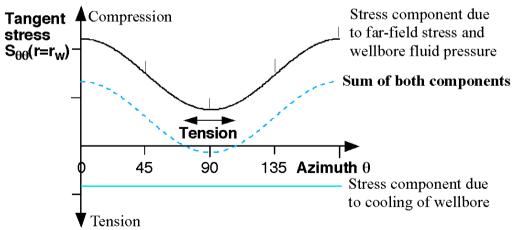
Cool drilling fluid

FMI log of a 15 m section of borehole in granite run just after drilling.

An axial tension fracture can be seen running up the centre and margins of the image indicating the orientation of S_{Hmax} is North-South.
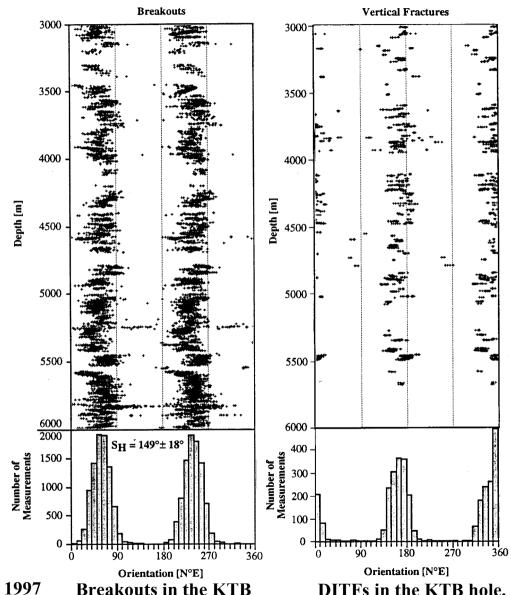
Variation of tangential stress around wellbore wall

Tangent stress $S_{\theta\theta}(r=r_w)$

Compression

Stress component due to far-field stress and wellbore fluid pressure

Sum of both components

Tension

0   45   90   135   **Azimuth** θ

Stress component due to cooling of wellbore

Tension

2975

2980

2985

S_{hmin}-orientation: estimated from breakouts & DITFs

Breakouts and DITFs commonly occur in deep holes.

They constitute the best indicators of S_{Hmax}-orient because they are simply related to stress and can be averaged over long sections of borehole.
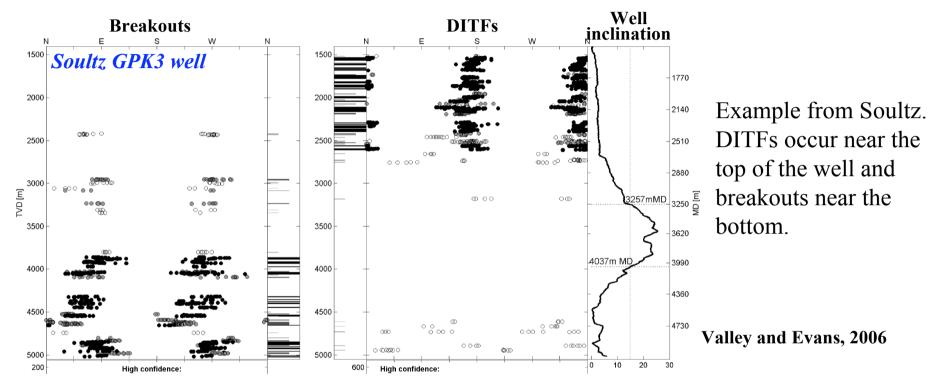
Both can be detected from a sonic televiewer (BHTV) or formation micro-resistivity imager (FMI) logs.

Brudy et al, 1997   **Breakouts in the KTB**   **DITFs in the KTB hole.**

Breakouts and DITFs also constrain S_{Hmax}-magnitude

Breakouts

DITFs

Well inclination

Soultz GPK3 well

Example from Soultz. DITFs occur near the top of the well and breakouts near the bottom.
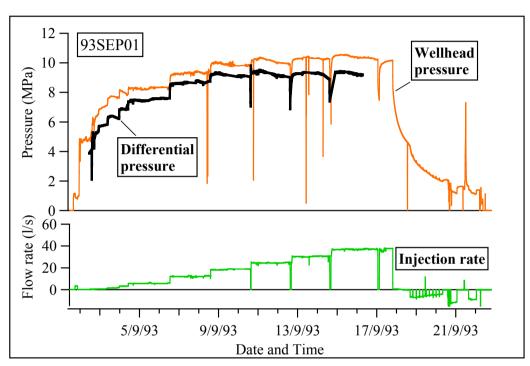
Valley and Evans, 2006

Given knowledge of the S_{hmin}-profile from hydraulic data, we can find the S_{Hmax} profile that reproduces the observed mode and distribution of failure.

-Requires knowledge of compressive and tensile strengths of the rock , and also the maximum cooling of the borehole wall during drilling (Measurement-While-Drilling data is ideal!)

-The constraint is much weaker if the magnitude of S_{hmin} is unknown.

In strongly-inclined holes, the DITFs become en-echelon, and their detailed geometry can be analysed to further constrain the magnitude of S_{Hmax}.

S_{hmin} estimation: Limiting injection pressure

During stimulation, step increases in flow rate often result in progressively smaller pressure increases until a *pressure limit* is reached. This limit can reflect:

1) the jacking pressure, in which case it is S_{min}

2) the shearing pressure in which case it is $< S_{min}$

Since the interpretation is not unique, S_{min} estimates derived from pressure limiting behaviour should be treated with caution.

The two cases can be distinguished if flow rate is cycled up and down since well injectivity increases due to shearing are permanent, whereas those due to jacking are reversible (although jacking is always accompanied by some shearing.)

This may be the only S_{min} estimate available in deep, hot reservoirs.