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Habanero Field - Structure and State of Stress

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ABSTRACT

Habanero is an enhanced geothermal system (EGS) in the Cooper Basin, northeast South Australia, operated by Geodynamics Limited. The geothermal reservoir is water-saturated, naturally fractured basement granite. The reservoir is interpreted to be a fault zone and its permeability has been effectively enhanced by stimulation. There is approximately 3650 m of sedimentary cover above the granite which provides effective thermal insulation on top of the heat producing granite. A series of flow tests and stimulations were conducted from October to December 2013. A total volume of 36.5 ML of fresh water was injected into the Habanero reservoir during the stimulations. The seismicity commenced around Habanero 4 well and grew elliptically but was constrained by an apparent boundary along its eastern edge. The state of stress at reservoir depth has been numerically modeled using wellbore breakouts indicating that the least horizontal stress, S_{hmin} is intermediate between S_{Hmax} and S_v. Fracture geometry was analyzed using image logs and was used to predict slip likelihood depending on the orientation of the structures in the recent stress field at reservoir depth using the Coulomb Failure Criterion. Pressure response on failure proven by seismic events is well documented over the stimulation interval. Permeability thickness was increased fivefold up to 10Dm after stimulation and injectivity was up to 4 times higher than achieved in the wells drilled before Habanero 4. The reservoir is confined to a critically stressed low angle fault zone which is prone to slip triggered by injection. A fracture network within the granite succession is proven by image logs but it does not contribute to production.

This paper aims to provide an overview about the reservoir structure and geometry as well as the present-day state of stress which has a major impact on stimulation operations and productivity.

1. INTRODUCTION

Geodynamics Limited (GDY) has been developing an Enhanced Geothermal System (EGS) in hot granites beneath the Cooper Basin, Australia, since 2002 (fig. 1). Four wells have been drilled at the Habanero site to depths exceeding 4,200 m and all four wells have penetrated a major fault which forms the reservoir. The temperature in the reservoir has been measured at 244°C at ~4,220 m below the surface.

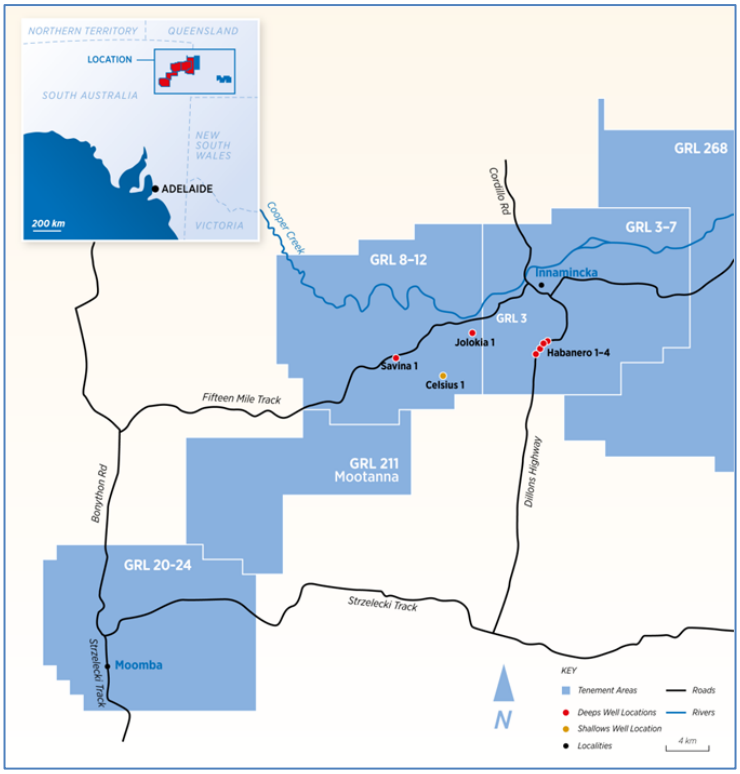


Figure 1: Location of the Habanero EGS field, near the town of Innamincka approximately 900 km NNE of Adelaide, SA.

The Habanero EGS reservoir is contained within high-heat producing granites of the Big Lake Suite which is of Mid to Late Carboniferous age (Gatehouse et al, 1995). The granites are mapped using a prominent gravity low underlying the Nappamerri Trough, a fault bounded structural feature initiated by deformation during the Carboniferous Alice Springs orogeny.

The most recent stress regime in the granite is triggered by the crustal collision of the Indo-Australian Plate with the Pacific Plate (e.g. Hillis et al, 2008). These conditions are associated with the collision of Australia with the New Guinea and New Zealand segments of the Pacific Plate (Sandiford, 2003). The maximum horizontal stresses in the centre of Australia are roughly east-west oriented and are responsible for the critically stressed state of some observed structures at the Habanero geothermal field at reservoir depth. The Habanero Fault is most likely to have been created within the last 5-10 million years. However, is also possible that it might be an older structure which has been reactivated within the recent stress field (Quigley et al., 2010).

Overpressures occur within the Nappamerri Trough below a regional extensive pressure seal composed of upper Early Permian shale dominated formations (van Ruth et al., 2003). Brines in the granite are significantly overpressured with pressure of 72.7 MPa at 4,100 mSS estimated from pressure build-up tests and static pressure gradient surveys. This represents an overpressure of ~34 MPa.

2. STRUCTURAL SETTING

Fractures within the Innamincka granite have been identified using drilling parameters, image log analysis and flow indication from PTS logging. Despite the presence of multiple fractures in various sections of the granite at Habanero, the vast majority of fluid flow, either into or out of the granite, occurs over a short section of intense fracturing often referred to as the "Main Fracture". This structure has been penetrated by all four Habanero wells and is now considered to be a fault (Habanero Fault) rather than a fracture zone (fig. 2).

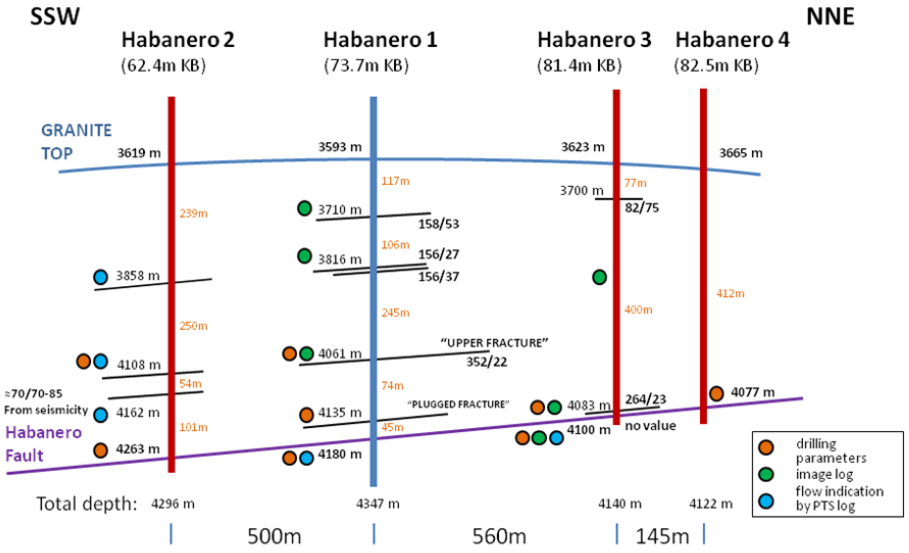


Figure 2: Schematic fracture distribution at Habanero, showing the Habanero Fault intersected by all wells. Depth in mSS. Coloured symbols indicate origin of fracture indication.

This fault has caused severe drilling problems in Habanero 1 and 2, resulting in kicks and mud losses whenever the bottom hole mud pressure was significantly different from the reservoir (over) pressure within the fault. The hydraulic response of the wells during drilling of the fault was the first evidence of the existence of a geothermal reservoir before stimulation. Mud weights were more closely matched with reservoir pressure in Habanero 3 and 4 and, as a result, mud losses were minimal.

The only existing image of the Habanero Fault zone was logged in Habanero 3 with a CBIL acoustic imaging tool (fig. 3). The fault is most likely visible because the well had brine influx from the reservoir, thinning the mud to a level where acoustic imaging was possible. The image above and below the reservoir decreased rapidly in quality because the barite mud system used to balance the reservoir pressure does not allow proper acoustic imaging.

The acoustic image in figure 3 shows a 5-6 m thick fault zone which can be identified by the lack of breakout between the red arrows. Breakout is clearly developed above and below the fault zone but is absent within the fault zone due to stress release caused by slip. The major active fault plane is characterized by a 1 m thick cavern of broken out granite (4,099-4,100 mSS / 4,180-4,181 mRT). Fractures above and below the active fault plane indicate the damaged zone associated with the active shear zone.

Reprocessed 2D seismic data could not be successfully used to delineate indications of faults within the Habanero granite. The internal structural inventory of the granite itself is not well understood and faults on top of the granite are usually identified by mapping small scale offsets of the overlying sediments using seismic data. Mapping of the induced seismicity associated with the stimulations of Habanero 1 and Habanero 4 is the primary tool used to determine the extent of the Habanero reservoir. The cloud of seismic events covers over 4 km^2 after the most recent stimulation in late 2012 (McMahon and Baisch, 2013). The apparent thickness of the cloud is approximately 100 m, with an average formal location uncertainty of up to 68 m in the vertical direction (Baisch and Stang, 2013). The vertical distribution of the seismic events is believed to be driven mostly by the vertical error margin of the hypocenter location.

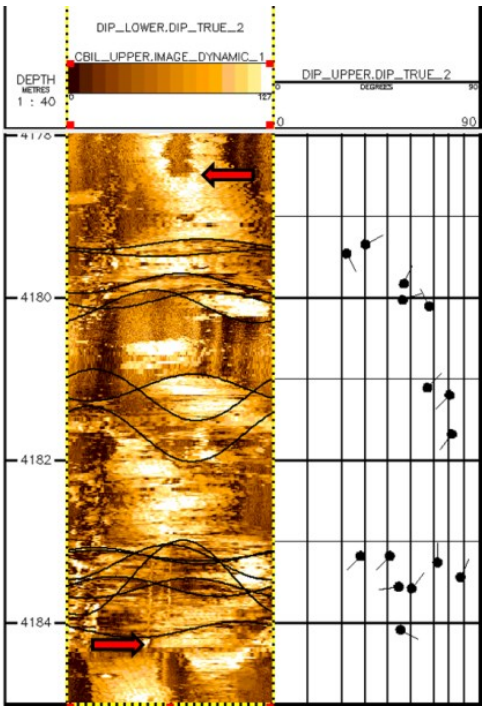


Figure 3: CBIL image of the Habanero Fault in Habanero 3. Red arrows are marking the top and bottom of the Habanero Fault zone. Dip and dip directions of associated fractures of the damage zone are shown in the tadpole diagram in the right track. Depth in mRT.

The Habanero Fault has been modelled as a planar structure, dipping at 10° to the west south west (fig. 4). There is some slight indication of convex downwards curvature in the seismic cloud, but this may be an artifact of the velocity model based on error margins. Because the seismicity shows an almost linear edge along the eastern boundary of the seismic cloud, the Habanero Fault is interpreted to truncate against a vertical fault along that eastern boundary (fig. 5).

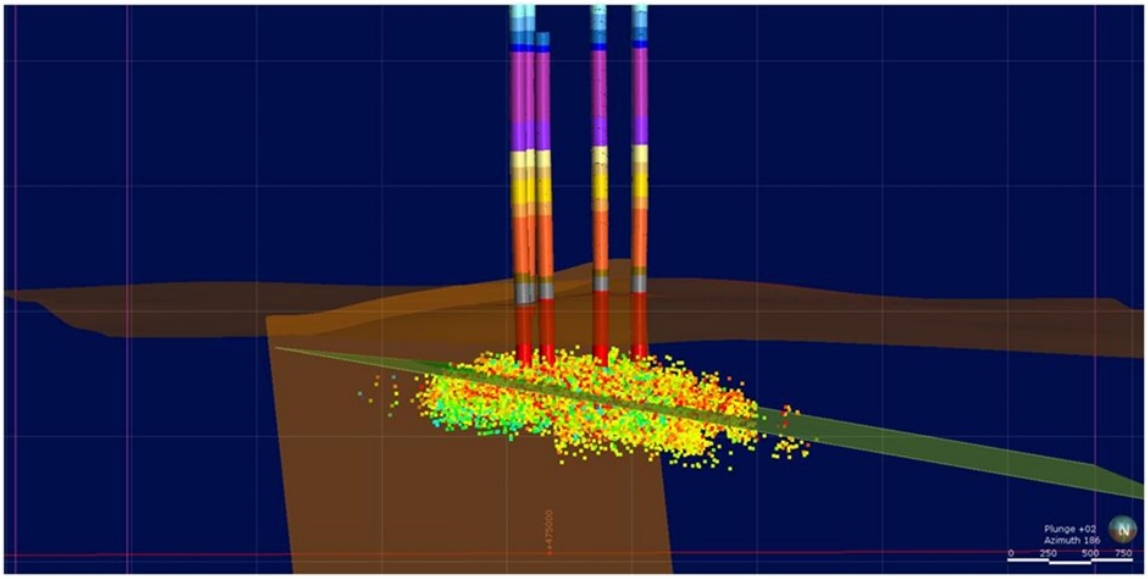


Figure 4: Structural model of the Habanero Fault. View from the North looking southwards: seismic cloud (coloured dots), wells (from left to right: H04, McLeod 1 in the background, H03, H01 and H02) and the Habanero Fault (green colour). The fault dips to the west at 10° and truncates to the East against a steeply dipping fault. Top of the granite is shown as brown horizon defined by well intersections (granite: red colours) and seismic interpretation.

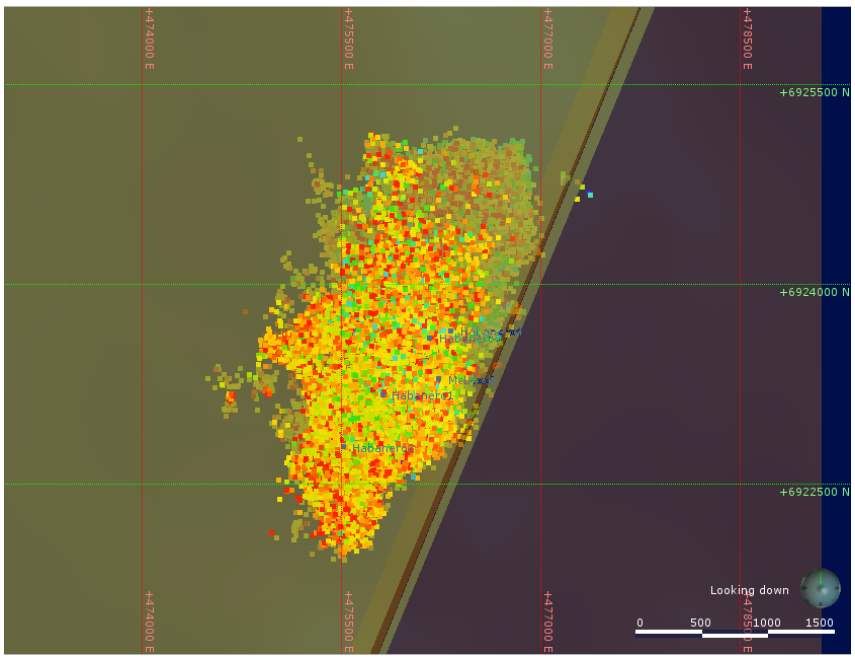


Figure 5: Structural model of the Habanero Fault. View from the Top downwards, North towards the top of image. The eastern boundary strikes NNE-SSW. The extent of the seismic events in the southern part of the cloud is stepping back from the boundary but still shows a linear trend towards the SSW which could be caused by an offset on a secondary fault (releasing bend/step over structure).

3. STRESS FIELD

The state of stress in the Habanero Granite has been determined from data observed from geophysical logging and drilling data analysis (Barton et al, 2013). This stress magnitude analysis clearly indicates a reverse faulting or over-thrust regime at reservoir depth. The azimuth of the maximum horizontal stress, S_{Hmax}, which is also the maximum principal stress, is 82 ± 5° derived from image log analysis of the Habanero wells. Stress modeling results show high differential stresses within the Habanero Field. The maximum horizontal stress, S_{Hmax}, is likely to be as high as 150 MPa at reservoir depth (Fernandez-Ibanez et al, 2009). Numerical modeling results of wellbore breakouts indicate that the minimum horizontal stress, S_{hmin}, is intermediate between S_{Hmax} and S_v (Barton et al, 2013). The overburden stress, S_v, has been estimated by integrating density log data as a function of depth and is significantly lower than S_{Hmax}. Results of the 3D stress modeling are shown for Habanero 4 and the Habanero Field in figure 6 (Barton et al, 2013). The horizontal stresses are calculated within the 3D structural grid based on local pore pressure and overburden values in combination with effective stress ratios. As discussed earlier, the reservoir pressure is significantly overpressured below ~2600 m as is shown in the pressure profile in the left-hand track of figure 6.

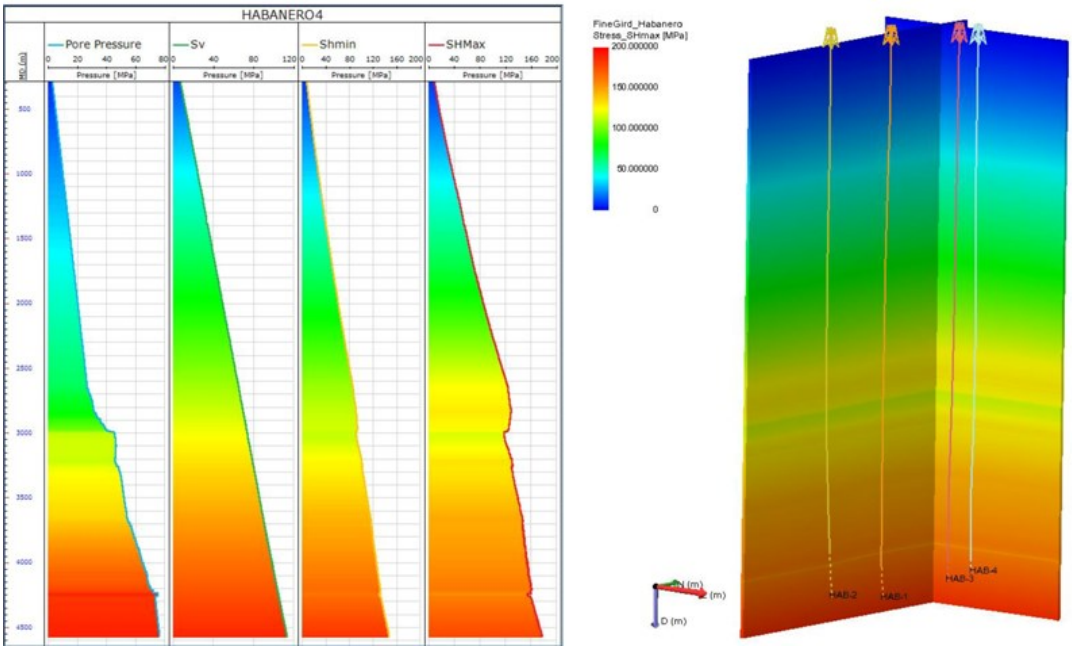


Figure 6: Results of the 3D stress modeling for the Habanero Field (Barton et al, 2013). Left: Pseudo logs of pore pressure and stresses for Habanero 4 generated from the 3D stress model. Right: 3D view including all Habanero wells showing static model of S_{Hmax}.

Figure 7 presents the boundaries of the horizontal stress magnitudes modeled by GMI. The blue lines in the graph are contours of tensile strength based on observation of tensile failure at Habanero 1. The red lines are contours of rock strength and are derived from breakout observations at the same depth as the tensile drilling-induced fractures. The green and blue shaded areas indicate combinations of horizontal stress magnitudes necessary for forming drilling-induced tensile wall fractures. The green and red shaded areas indicate combinations of S_{Hmax} and S_{hmin} magnitudes necessary for forming breakouts for the range of rock strength values of 130-150 MPa. The ratio of horizontal stresses to vertical stress ($S_{Hmax}/S_{hmin}/S_v$) is estimated to be approximately 1.35-1.45/1.10-1.25/1.0 at reservoir depth.

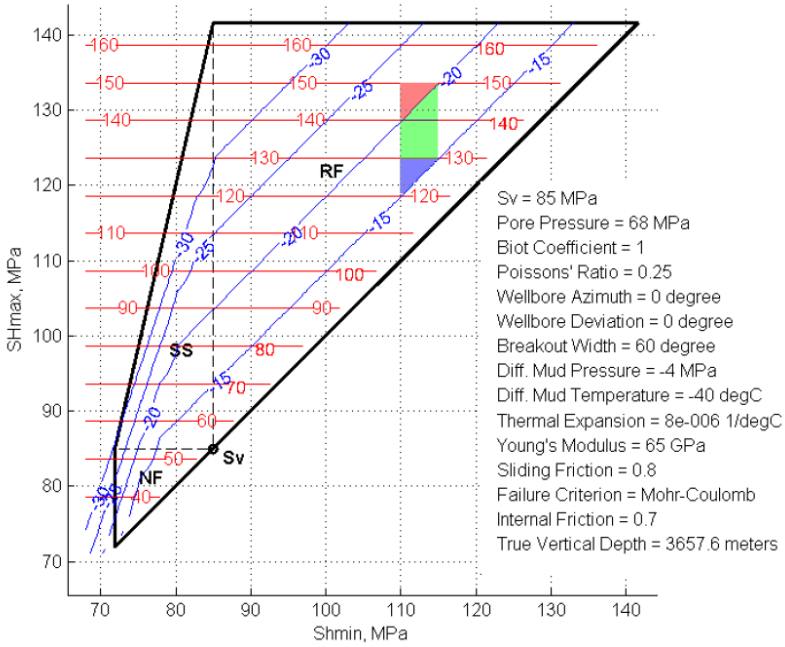


Figure 7: Stress modeling results of wellbore breakouts and tensile fracture at the depth of 3657.6m shows valid ranges of S_{Hmax} versus S_{hmin} magnitudes at Habanero. Three different regions within the polygon are: NF – normal fault, SS – strike-slip fault and RF – Reverse Fault stress regime. Coloured shaded areas and lines within the stress polygon are discussed in the text.

4. STRESS SENSITIVITY OF IDENTIFIED STRUCTURES

As mentioned earlier, fractures in the Innamincka Granite have been identified using acoustic borehole images recorded in Habanero 1, Habanero 3 and Jolokia 1. Fractures with similar orientations have also been identified from an electrical borehole image in Moomba 73, which penetrated the Moomba Granite, 56 km south-west of Innamincka.

The fractures identified on acoustic borehole images can be classified into clusters based upon their orientation (fig. 8/left). Two clusters of sub-horizontal fractures represent conjugate shearing related to the high horizontal stresses in the granite. These sub-horizontal fractures are critically stressed in the overpressured, over-thrust stress regime and are likely to be amenable to stimulation (fig. 8/right). The slip likelihood modeled is based on the Coulomb Failure Function and basically shows the proximity to frictional failure: values > 0 are plotting above the failure envelope in a Mohr diagram whereas values < 0 are stable.

The clusters of sub-vertical fractures present can be interpreted in various ways. They could be a classic orthogonal set of primary joints developed during the cooling phase of the granite. Typically these features form parallel and perpendicular to the maximum principal stress which was active during cooling of the granite. Alternatively, the E-W striking steeply dipping fractures might be interpreted as deformation inventory directly triggered by reactivation of thrust faults after the granite had cooled. In either case, these sub-vertical fractures are not critically stressed in the recent over-thrust stress regime. They are not likely to be amenable to stimulation as long as conductive structures which are more favorable oriented within the recent stress field are accessible for the stimulation fluids.

In the over-thrust stress regime at Habanero reservoir depth, pre-existing N-S striking shallow dipping structures stimulate first. Importantly, because these shallow dipping structures are critically stressed, stimulation will occur at pressures significantly less than the overburden stress (minimum principal stress, S_v). Hydraulic stimulation causes shear failure along pre-existing weaknesses (stress sensitive fault zones) which are optimally oriented to the recent stress field rather than creating new hydraulic tensile fractures. As evidence of this, over 80% of the events analyzed for fault plane solutions from the most recent stimulation in 2012 were consistent with low angle thrust fault mechanisms (McMahon and Baisch, 2015). It is believed that this major proportion of analyzed fault plane solutions is the main fault mechanism which is responsible for the enhancement of the Habanero reservoir. The remaining 20% of events are either secondary structures related to the deformation within the damage zone of the Habanero Fault or events whose fault plane solutions could not be determined.

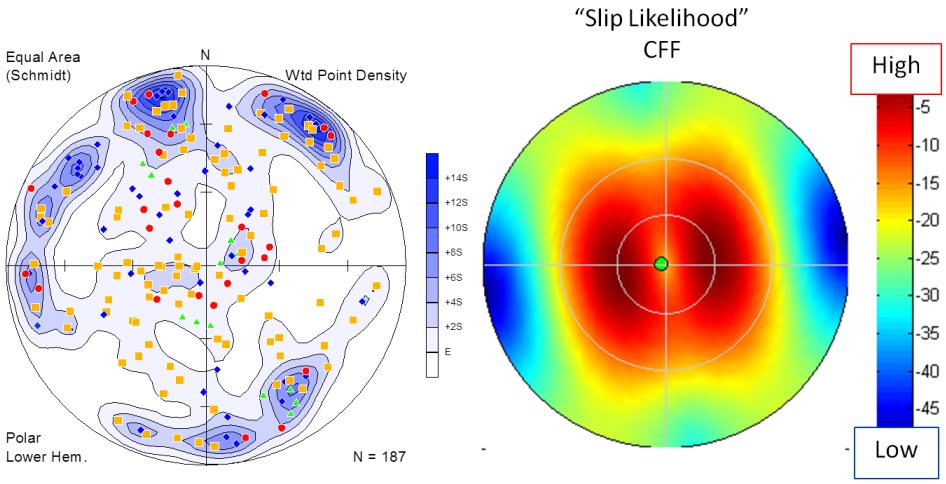


Figure 8: Left: Lower hemisphere Schmidt plot of fractures observed in the granite sections in Habanero 1 and 3 wells. Red symbols: high quality picks, blue: medium, orange: low. Green triangles: aplite dykes. Weighted density Terzaghi corrected for sampling bias. Right: Slip likelihood using the Coloumb Failure Function (CFF). Blue colours indicate relatively stable fracture orientations (more negative values) and red colours indicate less stable fracture orientations (more positive values).

5. STIMULATION OF A CRITICALLY STRESSED SHEAR ZONE

The stimulation of the Habanero reservoir is not comparable with the classic concept of hydraulic fracturing in which a tensile fracture is propagated deep into the target formation. At Habanero, the induced seismicity begins at pressures significantly less than the overburden stress (Figure 9), demonstrating that shear failure happens along pre-existing weaknesses rather than through tensile opening of fractures (Couzens-Schultz and Chan, 2010; McClure and Horne, 2014).

Active shearing of the Habanero Fault zone during stimulation creates both porosity and structural permeability. This permeability is anisotropic as is shown by the elliptical extension of the seismic cloud in the direction perpendicular to the sense of shear derived from the Fault Plane solution analysis. The areal extent of the seismic cloud was used by Llanos et al. (2015) to define the area of stimulated porosity and permeability and the permeability anisotropy ratio of 2:1 as input in the TOUGH2 simulation model.

Figure 9 shows the estimated bottom hole pressure at which seismicity commenced (or sudden pressure drops occurred) for all stimulations in all GDY's deep wells. Several estimates for the vertical overburden pressure (S_v) are plotted. The range of the first shearing pressure results for the Habanero 1, 3 and 4 wells is most likely driven by different skin effects (e.g. reservoir damage at Habanero 1) and different conductivity properties of the heterogeneous Habanero Fault zone at the point of intersection with the wellbore.

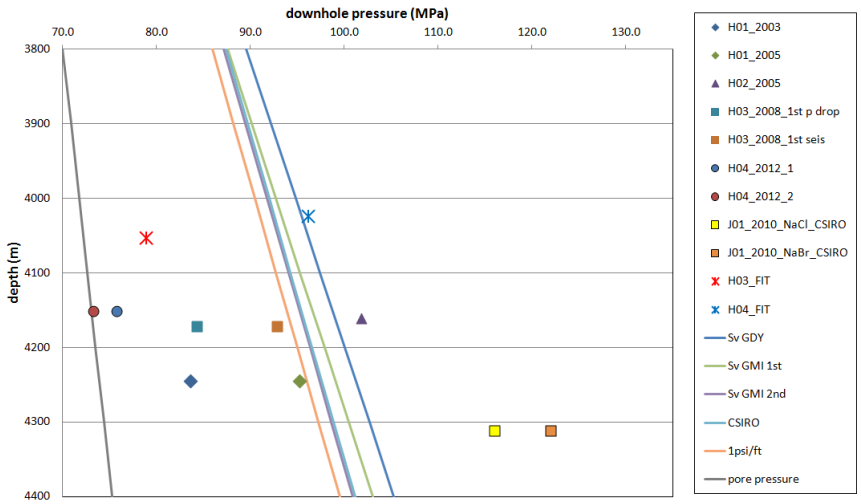


Figure 9: Calculated downhole pressures for all Habanero wells and Jolokia 1 during stimulations at the time of the first seismic event/pressure drop detected. Asterisk symbols show pressure values of FIT's at Habanero 3 and 4. Grey line shows the reservoir pressure and coloured lines are showing the minimum principal stress S_v using different overburden stress models. Depth in mRT.

Habanero 4 was drilled on balance using Managed Pressure Drilling to avoid extensive mud losses into the reservoir. This well has the highest injectivity/productivity so far recorded and is the most successful well drilled in the Habanero Field so far. First seismicity occurred at a pressure differential of only 2.6 MPa (380 psi) above reservoir pressure whilst still ~20 MPa below the stress induced by the overburden.

In contrast, the Jolokia 1 stimulation (conducted in 2010, ca. 10 km WNW of Habanero) is considered to be the only successfully performed classical stimulation operation within the granites of the Big Lake Suite. The stimulation appears to have induced tensile fractures in the borehole wall which connected to steeply dipping, presumably pre-existing faults close to the well. The orientation of one of these faults was mapped by using microseismic events which also provided information about the fault mechanism. The fault plane solutions of this structure exhibits mostly strike slip faulting mechanisms with an oblique thrust faulting component. The fault is striking approximately East-West which is close to the direction of S_{Hmax} and is dipping with 70° to the North. The pressure applied using a heavy weighted brine system (NaBr) was approximately 20 MPa higher than the minimum principal stress. The stimulation did not result in any long-term increase in injectivity. It is believed that the connection of the wellbore to the stimulated structure is a tensile fracture closing immediately after shutting down the pumps.

Habanero 2 also required higher pressures for stimulation, but fault plane solutions from the induced seismicity and event mapping again indicate that this well was stimulating a steeply dipping fault ~100 m above the Habanero Fault (compare fig. 4, 4162 mSS). Again, in the recent stress field, this structure is not optimally oriented for slip.

6. PRESSURE EFFECTS OF SHEARING

Pressure responses upon shear failure are evident during the stimulation process. An example of the pressure response from injection is shown in figure 10. Typically a pressure decline in the range of 0.5-1.5 MPa is seen after higher magnitude events (fig. 10). This pressure decline at stable injection rates suggests the sudden creation of newly formed pore space in the reservoir triggered by self propping effects of the irregular surface of the fault. The opposite case (pressure increase) was also detected, though less frequently. Sudden increase in pressure after seismic events is interpreted as destruction or erosion of asperities which rapidly reduces pore space.

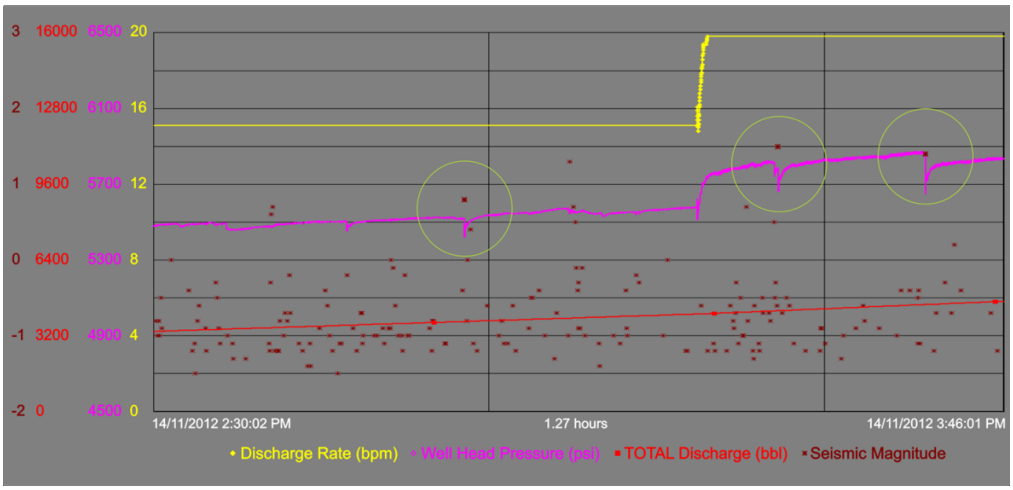


Figure 10: Flow rates, well head pressures and seismic events recorded during the local stimulation of Habanero 4 (November 2012). Green circles pointing on pressure drops related to an increase of detected seismicity. Pressure declines of up to 200 psi are related to increased amount and magnitude of seismicity.

7. CONCLUSIONS

Production and injection tests at Habanero have shown that fluid flow through the granite is controlled by the presence of a pre-existing fault zone. Fractures identified by drilling parameters and image logs outside the Habanero fault zone do not contribute to production as shown by PTS log analysis. Stimulation increases the injectivity and productivity of the fault, which existed already prior to drilling and was to some extent conductive before stimulation as shown by massive drilling fluid losses during drilling of the Habanero 1 well.

Major lessons learned from the stimulation operations at Habanero are:

- Areas with pre-existing critically stressed structures in the recent stress regime are favourable for EGS developments
- Only structures with significant pre-existing conductivity are useful
- Shearing improves fluid flow and pathways
- Induced seismicity is related to long-term hydraulic enhancement and is unavoidable in a successful stimulation

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