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Creating Permeable Fracture Networks For EGS: Engineered Systems Versus Nature

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ABSTRACT

The United States Department of Energy has set long-term national goals for the development of geothermal energy that are significantly accelerated compared to historical development of the resource. To achieve these goals, it is crucial to evaluate the performance of previous and existing efforts to create enhanced geothermal systems (EGS). Two recently developed EGS sites are evaluated from the standpoint of geomechanics. These sites have been established in significantly different tectonic regimes: 1. compressional Cooper Basin (Australia), and 2. extensional Soultz-sous-Fôrets (France). Mohr-Coulomb analyses of the stimulation procedures employed at these sites, coupled with borehole observations, indicate that pre-existing fractures play a significant role in the generation of permeability networks. While pre-existing fabric can be exploited to produce successful results for geothermal energy development, such fracture networks may not be omnipresent. For mostly undeformed reservoirs, it may be necessary to create new fractures using processes that merge existing technologies or use concepts borrowed from natural hydrofracture examples (e.g. dyke swarms).

Introduction

The US Department of Energy has established long-term goals for the geothermal energy program - one of which is to expand the economically viable geothermal resource to 40000 MW by the year 2040 (DOE-EERE, 2004). Given that US installed capacity is presently ~2600 MW, our nation must increase geothermal resource at a pace of ~1000 MW per year to reach the projected target. This rate is significantly accelerated compared to historical resource development, which over the past three decades grew at ~60 MW per year (see Figure 1). In comparing historical and projected rates, the prospects of increasing annual geothermal resource by over one order of magnitude seems daunting. It is anticipated that activities linked to enhanced geothermal systems (EGS) will play a major role to help achieve programmatic objectives. Yet, if EGS is to help grow the geothermal industry then the practices that have been employed to date need to be critically evaluated and possibly modified. The long-term success of EGS will depend on several factors, among which are: 1) extensive evaluation of prospective sites; 2) improved efficiency of stimulation procedures; and 3) better understanding of spatio-temporal evolution of geologic processes that modify reservoir properties.

In this paper, I study two recently developed EGS systems: 1. Habanero-1 in the Cooper Basin, Australia; and 2. the Soultz-sous-Fôrets project in France. I analyze these examples in the context of local geology, regional stress state,

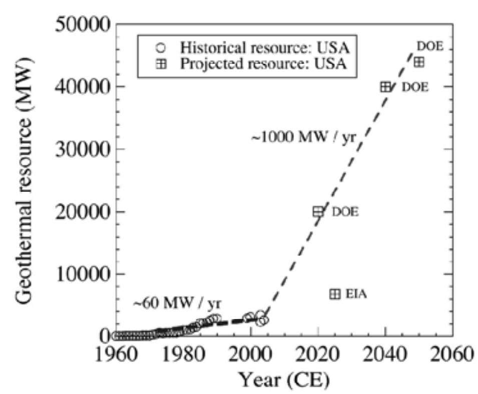

Figure 1. Comparison of historical development and projected increase of economically viable geothermal resource for the USA in the Common Era (CE). Historical data reflect estimates of installed capacity since 1960 (Kruger, 1976; Rannels & McLarty, 1990; Garman, 2004; US-DOE EERE, 2004a, 2004b). Projections from the US Department of Energy (DOE) include the potential benefits provided by EGS activities, whereas the Energy Information Agency (EIA) projection does not account for EGS contributions (US-DOE EERE, 2004a, 2004b).

and geomechanical processes. These engineered systems are then compared in order to identify factors leading to successful EGS development.

Case Study 1: Cooper Basin (Habanero-1 and Habanero-2), South Australia

Background Summary

The Cooper Basin is a non-marine infrabasin situated within the South Australian Heat Flow Anomaly (Thornton, 1979; Cull, 1982; Holgate and Chopra, 2004; Reynolds et al., 2004, 2005). The late-Carboniferous to Triassic Cooper Basin sediments are regionally underlain by the Cambro-Devonian Warburton Basin (SADME, 1986; Chopra and Wyborn, 2000) and locally underlain by intrusive mid-Carboniferous Big Lake Suite granodiorites (Parkin, 1969). Early hydrocarbon exploration of the Cooper Basin identified elevated heat flow linked to these basement granites, which are the target of present geothermal exploration in the region. To date, two geothermal wells (Habanero-1, Habanero-2) have been drilled into the granitic basement. Similar intrusives are currently targeted for geothermal exploration at the south-western edge of the Cooper Basin and elsewhere within South Australia.

Drilling of the Habanero-1 well began on 15 February 2003 and was completed at a depth of 4421 meters on 17 September 2003, during which time the granitic basement was encountered at a depth of 3668 m (Wyborn et al., 2004). While not described in significant detail, image logs obtained prior to completion of the well indicated the presence of several sub-horizontal fractures between 4134.0-4135.8 m with crack spacing of 0.3-0.9 m. While drilling the granites wellhead fluid pressures as large as 34.6 MPa (5020 psi) were recorded, consistent with the drilling mud density of 1.8 g/cc required to balance the overpressure (Wyborn et al., 2004; Geodynamics, 2004). To stimulate the reservoir and extend the fracture network, fresh water was injected into Habanero-1 with wellhead pressures as large as ~64.8 MPa (9400 psi). During stimulation, an extensive sub-horizontal zone of induced microseismicity was recorded with most focal depths between 4000-4700 meters (Asanuma et al., 2004; Wyborn et al., 2004). Drilling of Habanero-2 commenced on 9 July 2004 (~500 meters south-west of Habanero-1) and has recently been completed. Preliminary results from flow testing indicate hydraulic communication between the two Habanero wells (Geodynamics, 2004).

Geomechanical Interpretations: Habanero-1

Observations of sub-horizontal fractures and overpressures within the granite reservoir are consistent with tectonic history models of the Cooper Basin (Parkin, 1969; Thornton, 1979; Gravestock and Jensen-Schmidt, 1998; Reynolds et al., 2004, 2005). The granites underlying the Cooper Basin were emplaced at a time when the region was experiencing northwest-southeast compression coincident with the Alice Springs orogeny. Post-intrusion cooling of the region resulted in thermal subsidence and creation of the central Australian sedimentary depocenters (including the Cooper Basin). Cooper Basin subsidence was interrupted several times during the mid-Permian, late-Triassic and late-Cretaceous by significant episodes of uplift having as much as ~800 m of vertical motion per event (Toupin et al., 1997). When coupled with thermal cooling, the stress variations induced by the vertical motions are likely responsible for the sub-horizontal fracture networks observed in the granitic basement rocks. In deeper sections of the Cooper Basin fluid overpressures developed that subsequently exploited the permeability network of the fractured granite. It is these overpressured fluids that were encountered during drilling of the basement granites in Habanero-1 and Habanero-2, suggesting that the fractures are presently in communication with the overlying basin sediments.

By considering a compilation of well data from Habanero-1 (i.e. stimulation-induced microseismicity, borehole breakouts, drilling induced tensile fractures, mini-frac tests, leak-off tests) the least compressive stress (which is in the vertical direction) and the drilling/stimulation activities at Habanero-1 can be analyzed in terms of Mohr-Coulomb failure analysis (Figure 2). Taking the stimulated depth as ~4250 m and assuming a lithostatic gradient of ~25 MPa/km, then vertical stress (σ_v) at that depth is ~106.2 MPa. Further, coupling an assumed normal fluid pressure gradient of ~10 MPa/km with the recorded fluid overpressures of 34.6 MPa indicates that in-situ fluid pressures (P_p) were ~77.1 MPa and the effective vertical stress (σ_v-P_p) was ~29.1 MPa. By coupling the wellhead stimulation pressure (~64.8 MPa) with a normal hydrostat pressure of ~42.5 MPa, the in-situ stimulation fluid pressure is estimated to be ~107.3 MPa. This is strikingly consistent with estimates of overburden stress (~106.2 MPa) and results in a stimulation effective vertical stress (σ_v-P_{stim}) that is slightly tensile (-1.1 MPa).

These estimates can be considered together with laboratory measurements for fracture strength of Westerly Granite and the frictional strength of cohesionless rock surfaces in contact (Figure 2). The calculated effective vertical pressure for the stimulation is almost perfectly coincident with the frictional failure envelope. This is important, as the above analysis provides no information about the amplitude of the remaining principal stresses. In terms of fracturing intact granite, the other principal stresses must be larger than the vertical stress if the failure conditions are to satisfy Andersonian mechanics and prevailing scientific thought that the Cooper Basin is in horizontal compression (e.g. Mathur, 1987; Reynolds et al., 2004, 2005). Of particular note, at least one of the remaining principal stresses must be significantly large (~200 MPa) if the Mohr-Coulomb failure criterion for intact granite is to be satisfied. Such an interpretation is unlikely as these compressional forces acting at shallow crustal levels should result in regionally widespread and sizable geologic structures – features that today are not observed in this part of Australia. Indeed, estimates of near-surface compressional stresses in central Australia are low (10-40 MPa; see Zhao and Muller, 2004, and references therein).

It is, perhaps, more plausible that the observed sub-horizontal fractures are representative of a previously created fracture network (possibly unloading joints formed during Triassic or Cretaceous vertical motion). This interpretation explains the fluid overpressures encountered during drilling, insofar as basinal fluids could migrate into the granite if the fractures extend to the overlying sedimentary strata. The tensile strength of such pre-existing fabric would be expected to be rather low, having strength properties similar to cohesionless frictional surfaces. Therefore, the reservoir stimulation at Habanero-1 seems to have reactivated pre-existing cracks rather than generate new fractures. This does not preclude generating new fractures linking the pre-existing joints. Such a process is best identified by careful analysis of moment-tensor solutions derived from induced microseismicity, which is beyond the scope of this study.

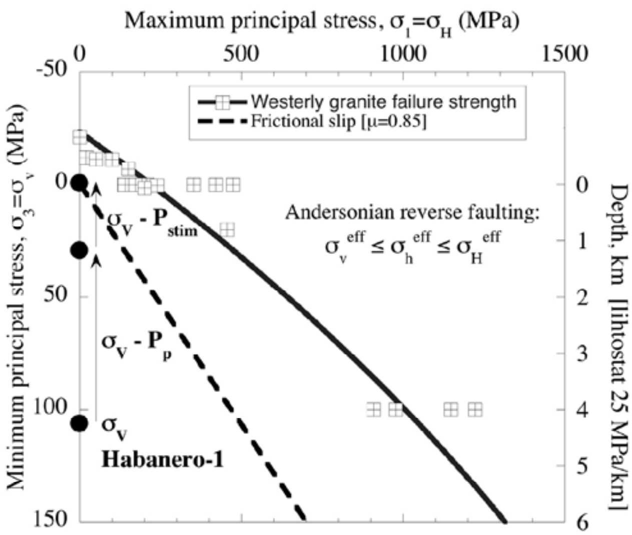

Figure 2. Mohr-Coulomb analysis of stimulation at Habanero-1 (Cooper Basin, Australia). Vertical direction is least compressive stress (σv) acting normal to sub-horizontal plane of stimulation microseismicity. Pore fluid pressures (P_p and P_{stim}) are used to calculate effective pressure at depth (solid circles). Minimum stress is compared to laboratory data (square symbols, with polynomial curve-fit) for room-temperature fracture strength of Westerly Granite (Logan & Handin, 1971; Heard et al., 1974; Johnson et al., 1987). Also shown is frictional strength envelope for a cohesionless surface (μ=0.85). Assuming reverse faulting, failure of intact granite requires a horizontal stress ~200 MPa greater than the value of the vertical stress.

Case Study 2: Soultz-sous-Fôrets, France

Background summary

Soultz-sous-Fôrets is located near the western edge of the Cenozoic Rhine Graben rift system, positioned between Haguenau and Landau in Alsace, France (Bächler, 2003; Baria et al., 2005). Basin formation is thought to coincide with the Alpine orogeny, whereby fault-block subsidence and sedimentary in-fill began in the mid-Eocene (Person and Garven, 1992). The Cenozoic syn-rift sediments are underlain by a Triassic-Jurassic, non-marine to marine transgressive sedimentary sequence which is, in turn, underlain by early-Carboniferous granites (Person and Garven, 1992; Bächler, 2003). The Rhine Graben is a classic rift basin inasmuch as it has high thermal gradients and heat flow, particularly near Landau at the center of the basin (Person and Garven, 1992). It is the basement granites in the central basin that are presently targeted for geothermal resource development (Genter and Traineau, 1992; Baria et al., 2005). Nine boreholes have been drilled at the site, with 5 of these (4550, 4601, 4616, EPS1, OP34) used as subsurface seismic recording stations (Asanuma et al., 2000; Baria et al., 2005). Four wells have been used for hydraulic injection and production tests (GPK1, GPK2, GPK-3, GPK4) with the first geothermal well (GPK1) now converted as a deep seismic monitoring station (Baria et al., 2005). During reservoir development at Soultz, numerous hydraulic injection tests were performed. Using data from these tests, the stress state for the depth range 1458-3506 meters has been described empirically as follows (from Baria et al., 2005; after Klee and Rummel, 1993):

Eq. 1a)
minimum horizontal stress (σ_h) = 15.8 + 0.0149*(z-1458)

Eq. 1b)
maximum horizontal stress (σ_H) = 23.7 + 0.0336*(z-1458)

Eq. 1c)
vertical stress (σ_V) = 33.8 +0.0255*(z-1377)

where stresses are measured in MPa, and depth (z) is in meters. These relations indicate a depth-dependent transition in Andersonian mechanics, from normal faulting above ~3000m to strike-slip faulting below that level. This is completely consistent with recent analyses of moment tensor solutions derived from stimulation-induced microseismicity (Cuenot et al., 2005).

The wells GPK1, GPK2, GPK3, and GPK4 have each been used to stimulate (fracture) the granitic reservoir. The salient details of these stimulation activities are as follows with stress profile and effective pressures from stimulations shown in Figure 3:

1) In 1991, well GPK1 was stimulated between 1420-2002 m;
2) In 1993, well GPK1 was stimulated between 2850-3400 m at flow rates between 0.15-36 l/s with nearly constant wellhead pressures of ~10MPa for the higher flow rates (Jung et al., 1995);
3) In 1995, well GPK2 was first stimulated between 3211-3876 m at a flow rate of ~15 l/s which generated downhole pressures of ~44 MPa, after which flow rates were systematically varied from 6, 13, 19, and 26 l/s to generate pressures (measured at 3200m) of ~32.8, 33.6, 35.2 and 37.5 MPa respectively (Kohl et al., 1996);
4) In 2000, well GPK2 was stimulated at a deeper level (4412-4436 m) with a downhole pressure of ~55.5 MPa for flow rates of 30, 40 and 50 l/s (Weidler et al., 2002);
5) In May 2003, well GPK3 was stimulated at 4244 m with a downhole pressure (at 4244 m) of ~58 MPa and flow rates of ~30 and 40 l/s (Mégel et al., 2005);
6) In 2004, well GPK4 was stimulated at between the depths of ~4700m and ~5050m with a majority of the injectate entering the reservoir at ~5030m and at a downhole pres-

sure of ~60.5 MPa for a predominant rate of ~30 l/s (Baria et al., 2005).

Geomechanical Interpretations: Soultz-sous-Fôrets

Image logs and recovered core from the drilling activities at Soultz clearly indicate the presence of extensive and sealed fracture networks in the granites together with quartz-filled veins (André et al., 2001; Bächler, 2003). These fracture and vein networks are predominantly oriented N-S, consistent with the regional stress field and the trend of the tectonically induced horst-graben features (André et al., 2001). In contrast to the compressional tectonics of the Cooper Basin, the extensional stress field of the Rhine Graben offers a very different relationship between material strength, subsurface depth, and fluid pressures needed for reservoir stimulation.

Using the empirical description of the Soultz stress field with depth (Eq. 1 after Baria et al., 2005) we can consider the Soultz activities in terms of the Mohr-Coulomb analysis used above (Figure 3). The tectonics and wellbore observations at Soultz requires that the maximum compressive stress transitions from being vertical (depths less than ~3 km) to horizontal (depths greater than ~3 km). Further, one of the horizontal directions must be consistently associated with the minimum compressive stress (see Soultz stress profile in Figure 3). Fluid pressures counteract all principal stresses, as denoted by the arrows in Figure 3 that reflect the pressures induced during each stimulation. The effective pressure resulting from each stimulation exceed the frictional strength envelope, but do not exceed the fracture strength of Westerly Granite. The comparison between the strength envelopes and the stimulation effective pressures implies several possibilities exist in terms of mechanical evolution of the permeability network:

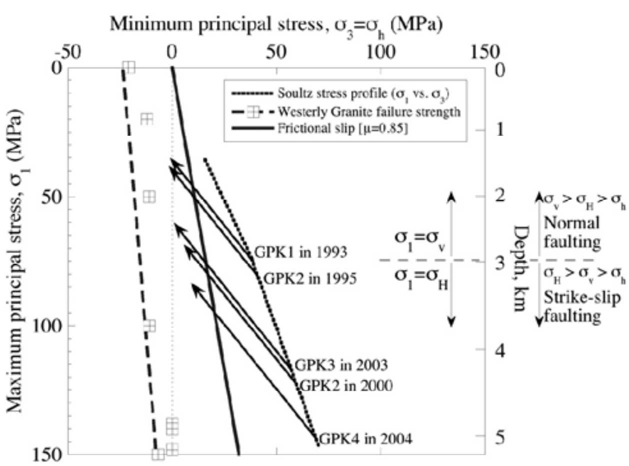

Figure 3. Mohr-Coulomb analysis of stimulation at Soultz-sous-Fôrets (France). Horizontal direction is least compressive stress (σh). Direction of the maximum compressive stress changes with depth, showing normal faulting at shallow levels and strike-slip at deeper levels. Stress-profile for Soultz region (heavy dotted line) is calculated from Eq. 1 in text. Stimulation fluid pressures (see text) are used to calculate effective stresses at failure (diagonal lines). Failure data (square symbols, with solid line curve-fit) and frictional strength envelope (dashed line) are as for Figure 2.

1. the stimulation exploited pre-existing fractures that have some cohesion (perhaps via cementation);
2. the stimulation exploited pre-existing fractures as well as generated new fractures, with resultant effective pressures representing an average of the fracture strength for intact rock and the strength of existing fractures;
3. the stimulation occurred in granites that are weaker than Westerly Granite.

While all these scenarios are plausible, the observations of pervasive natural fracturing suggest that the stimulation likely involved these pre-existing fractures (scenarios 1 and 2 listed above). By combining geomechanical analyses with other research activities (e.g. moment tensor studies from induced microseismicity) it may be possible to determine which of these scenarios is more plausible. This is important, as it is unclear from the published results from the Soultz activities whether or not significant populations of new fractures are generated.

Comparison of Results from Cooper Basin and Soultz-sous-Fôrets

The two sites analyzed here are similar in that the engineered reservoirs have bottomhole temperatures exceeding 200°C, are comprised of granites situated at depths between 4-5 km, and contain a significant number of pre-existing fractures. Yet, the sites are dissimilar inasmuch as they are located in different tectonic regimes that lead to distinctly different stress conditions within the reservoirs. While the presence of the pre-existing fractures facilitates the generation of a network for fluid-flow, the compressional stresses at Habanero-1 (Cooper Basin) resists fluid-induced deformation until the stimulation pressures reach a level that exceeds the vertical overburden stress. Such overburden stresses are typically greater than the stimulation pressures needed in other tectonic environments.

It cannot be denied that the activities at Soultz and Cooper Basin are successfully generating permeability networks that can be exploited for geothermal energy. Yet, it is clear from a geomechanical analysis of these sites that pre-existing fabric plays an important role in the development of the geothermal reservoir. That is, the activities in the Cooper Basin and at Soultz are not so much an EGS exercise in fracturing intact rock, but are rather an EGS exercise in "nudging" pre-existing fabric. For the case of extensional or strike-slip systems, such conditions form the ideal basis for engineering a commercially viable geothermal reservoir. Yet, the stimulation pressures required in these tectonic environments do not preclude those flow networks that might be created in largely unfractured reservoirs. On the other hand, the high stimulation pressures needed to engineer reservoirs located in compressional settings almost requires that the engineered reservoir contain a pre-existing fabric with bulk strength lower than that of the intact reservoir rock. While any prospective locality must be comprehensively evaluated prior to development, those in compressional settings may need more scrutiny that assesses the structural character of the reservoir.

What Has Nature Done That We Might Learn From?

The localities focused on in this paper are prime examples showing how natural fracture systems can be successfully exploited to create geothermal reservoirs. For each site, water-based fluids with relatively low viscosities were used in the stimulations. While the activities at the Cooper Basin and at Soultz successfully re-fractured a crystalline granite body, these cases do not illustrate how fracture networks can be created in intact rocks. To this end we may turn to nature for ideas - such as the spectacular intrusive dyke swarms at Spanish Peaks in Colorado (e.g. Johnson, 1970; Muller and Pollard, 1977) and the extensive fracture networks mapped for volcano-tectonic regions on extra-terrestrial planets (such as Mars, see Cailleau, 2002).

Using Spanish Peaks as an example, the stress field created by the inflating magma chamber likely initiated fracturing (or at least, provided favorable conditions for fracturing) which was subsequently utilized by the pressurized magmas. Acting in concert, these processes generated very large fracture-dyke systems whereby individual dyke lengths exceed 25 km – far exceeding the dimensions achieved via hydraulic stimulation used for EGS. While the stress field generated by the inflating magma chamber is important, it is unclear exactly what role other factors (e.g. fluid viscosity, stressing rate) played in forming the magmatic hydrofracture network. While it may not be possible to recreate all the conditions of these natural systems when working with EGS sites, some of the fundamental processes associated with the natural examples may be of value when designing procedures to engineer geothermal systems. As such, the processes that create these natural examples are worthy of closer scrutiny (perhaps via field-based research, laboratory experiments, or numerical simulations).

Summary

Reservoir stimulation activities at two EGS sites (Cooper Basin, Australia, and Soultz-sous-Fôrets, France) have been reviewed in the context of site characteristics and geomechanics. While these sites are located in dramatically different tectonic regimes, they are similar in terms of the natural thermal characteristics, lithology, and damage state within the reservoir. The stimulation activities at these sites indicates that the presence of pre-existing fracture networks enhances the probability of successful EGS development. However, pre-existing damage features and other fabric may be a necessary precursor for developing geothermal reservoirs at sites located in tectonically compressive regions. In terms of fracturing efficiency, the scale of stimulation activities in geothermal reservoirs is dwarfed by naturally occurring examples of hydraulic fracturing (e.g. Spanish Peaks in Colorado, Alba Patera on Mars). Lessons may be learned from studies of these natural examples and then subsequently deployed at EGS sites.

Acknowledgements

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