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Release the Kraken – How Geothermal Feedback Forms Fractures

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ABSTRACT

Geothermal systems are more than just water circulating in fractures that happen to be open and connected near a heat source. Multiple interacting feedback loops convert mechanical, thermal, and chemical energy during water circulation into changes that widen and extend or narrow and seal fractures and fracture networks during natural system evolution and exploitation. Positive fracture feedback can result in large, rapid changes in permeability. Activation thresholds and negative or competing positive feedback processes form important controls on fracture formation, opening, and sealing patterns. Taken together geothermal feedback processes involving rapid dissipation from multiple energy sources modify fracture permeability in self-organized systems. These systems form their own emergent permeability patterns beyond what might occur in areas of water circulation in fractures formed simply from faulting or jointing.

Some of these feedback mechanisms have been interpreted to control important permeability patterns and seals in exploited systems. In several cases feedback mechanisms have been artificially stimulated to result in permeability changes during field operations. Similar feedback processes are also likely to occur outside of self-organized geothermal systems in areas of faulting and water circulation in hot rock and may be important in locally modifying upper crustal permeability even if they do not create fully developed, self-organized hydrothermal permeability patterns or exploitable systems.

Better understanding of these feedback processes might help us create new geothermal systems by stimulating the release and conversion of natural-stored potential energies to fracture formation and modification where we can exceed activation thresholds. This is likely to require an abundant water supply and initially available or attainable vertically-extensive permeability (even if it starts out sub-commercial). Stimulation would then apply water-frack methods that have been successfully tested in near-field EGS experiments to greenfield or distal near-field areas with concentrations of thermal and mechanical energy in active fault irregularities.

1. INTRODUCTION

Norton (1984) developed hydrothermal theory for magmatic hydrothermal systems on the basis of interacting feedback processes driven by chemical, thermal, and mechanical energy in the crust. To approximate some of this feedback, Norton described a mathematical model of feedback using linked differential equations based on conservation of mass and energy. He accompanied the equations for his model with descriptions of the geologic progress of magmatic hydrothermal system formation including a history of fracture permeability development that initially focuses on the magma-wallrock contact but expands into the wallrock and then into the magma as it solidifies and fractures. In contrast other publications interpret simpler fault-valve permeability initiation and re-initiation by fault movement in hydrothermal systems (eg. Cox et al, 2001) with subsequent rapid mineralogical re-sealing, neglecting many other processes that proceed during circulation.

Numerous hydrothermal fracture feedback processes, including those described by Norton, are available during deep circulation (even without magma involvement). This complex set of interacting processes suggests that while a faulting event may trigger initial circulation and control many aspects of fracture network geometry, contributions from various energy sources act to re-distribute patterns of fracture permeability and extent. These processes invert the normal pattern of decreasing permeability with depth and build sustained open fracture patterns that can allow active circulation in hydrothermal systems to persist long after a faulting event. Beyond the expression of these feedbacks in the energy-rich hydrothermal environment, they may also occur anywhere that fracture permeability allows vertically extensive circulation. Consequently what we learn about these processes from geothermal fields where there can be hundreds of wells and rich geoscience data sets might be applied in other fractured systems.

Possible cooling-fracturing feedback was considered during the original work to create an artificial circulation system in the Hot Dry Rock experiments at LANL (Murphy, 1978). Given the continued research efforts on developing useful artificial fracture circulation networks in Engineered Geothermal Systems (EGS), it may be appropriate to learn from a broader set of natural processes to select sites where in situ conditions make artificial fracture permeability stimulation more likely to be successful. In other words, “Make it easy on yourself, because breaking up is so very hard to do” (Bacharach and David, 1962).

2. FEEDBACK PROCESSES

Stress energy can open vertically extensive fractures in rock to allow convective water flow. Thermal energy transfer then cools deep and heats shallow rock. Cooling and heating mechanically open and close fractures (respectively), acting in some processes in combination with stress energy. This provides feedback that improves or degrades circulation. Thermal energy in water helps drive re-mineralization that can also open, maintain, or close fractures in combination with chemical energy and in some cases with stress energy. Various specific processes associated with this summary have been identified. The following examples are loosely categorized into deep and shallow feedback loops that are each described in a simplistic fashion for depth intervals associated with deep reservoir and cap rock, respectively. Each feedback process is designated as positive or negative by bullet list symbols.

2.1 Deep Feedback

+ Deep downflow causes rock cooling that shrinks rock back from open cracks to enhance permeability and circulation.

+ Deep downflow causes cooling that shrinks rock to locally reduce compression, weaken rock, and extend fractures due to stored stress.

+ Deep downflow causes cooling that shifts rock behavior from ductile to brittle such that deformation results in fractures.

+ Circulation of water can dissolve minerals on low stress, high flow rate fracture faces, to create enhanced flow channels and prop fractures with dissolution surface textures. This may be important in extensional stress settings in the main reservoir.

- Circulation of hot water into compressively-stressed rock can dissolve minerals on fracture asperities allowing fractures to close and seal fractures. This may be more important on in locally compressive margins of the system.

+ Circulation of water in hot rock can result in high grade alteration that strengthens and embrittles rock or fractures such that fractures can support continued circulation.

2.1 Shallow Feedback

- Upflow results in boiling that drives deposition of silica and calcite in veins. This can act to seal the fractures and reduce flow. Cooled liquids in upflow also deposit silica.

- Upflow results in boiling that concentrates gases in the steam phase. These gases can penetrate into even low permeability overlying rock and condense with steam into mildly acid liquids. Acid liquid and heat induce argillic alteration that weakens rock and seals fractures.

+ Upflow results in boiling water which pressurizes fractures above the depth of boiling, driving water mass out of the system. The lower water mass results in deeper boiling. This feedback can accelerate to cause an explosive fracturing event, radically increasing permeability and flow.

- Circulation of hot water swells thermally expansive rock into cracks between asperities, resulting in lower permeability and less circulation. Relatively high porosity at shallow depths may limit rock thermal expansivity.

In spite of the complexity evident in this list, the list is not exhaustive and the above processes can be complicated or interact. Also these processes are not strictly limited to one or other of the broad depth categories but rather might occur locally depending details of the flow pattern, rock types, temperatures, and stresses or perhaps not occur at all in some systems. The point of the list is that there are many processes that can reform fracture permeability either working together or in competition during geothermal circulation.

3. EXAMPLES

There are numerous examples of geothermal fracture feedback processes interpreted in developed geothermal fields. Although these examples are only circumstantial support for the multiple powerful linked feedback loops envisioned for natural system development, they at least suggest that some of the phenomena known to occur in lab settings are active and important in exploited geothermal systems. Here are a few examples from known geothermal fields:

3.1 Heat Transfer Fracture Formation

Natural geothermal circulation involves heat transfer that cools deep and heats shallow rocks. Both ends of this process influence fracture behavior and permeability as suggested in Section 2. Fracture formation due to cooling can be evident from induced seismicity.

Seismicity at the Geysers reveals positive feedback between cooling, fracture formation, and permeability during water circulation. Cold water injection correlates with deep seismicity interpreted to be mostly triggered by injection cooling (Smith et al, 2000; Mossop, 2001) as has been interpreted in other fields (e.g. Sewell et al, 2015). Focal mechanisms at the Geysers (Boyle and Zoback, 2014) show that offset is driven by stored tectonic energy. The typical normal fault offset in these events appears to occur in an extensional step-over between the Big and Little Sulphur Creek Faults where energy is provided by San Andreas crustal boundary stresses. Deep induced seismicity at the Geysers now extends down past the natural state impermeable reservoir barrier at about 3 km depth (Garcia et al, 2012 and Beall et al, 2013). Conductive gradients in the High Temperature Zone indicate very limited permeability in a zone underlying the reservoir in the natural state. Cooling-induced seismicity and permeability improvement has apparently extended permeability down to

6 km depth, deep into the High Temperature Zone (Figure 1), representing an increase in the thickness of circulation at the Geysers by a factor of 2.5 (from 2 to 5 km).

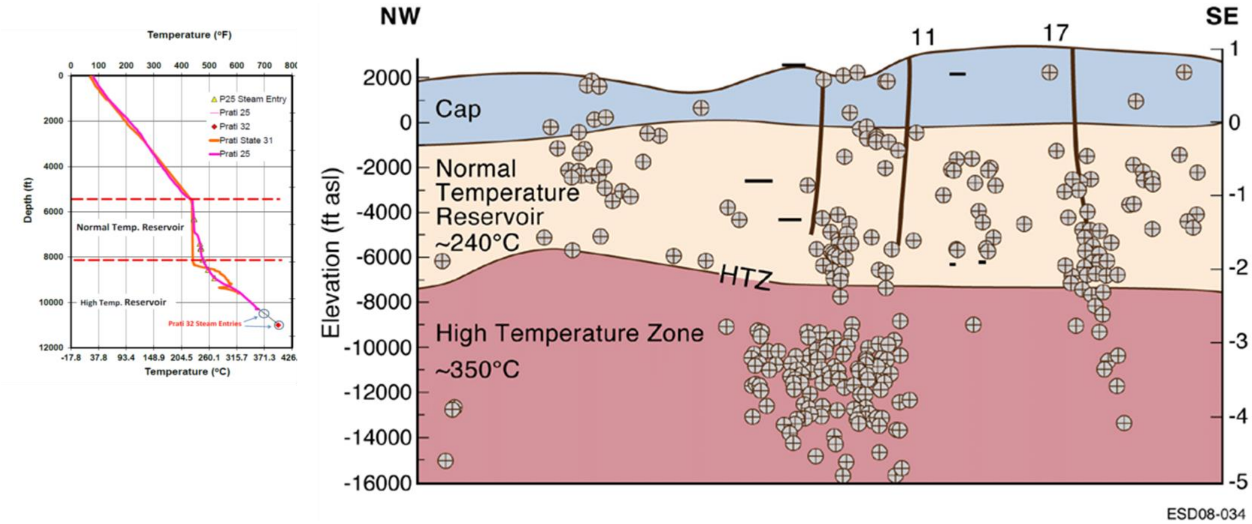

Figure 1 - Static temperatures in Figure 1a (Garcia et al, 2012) show the influence of convection in the normal reservoir and initial state conduction in the high temperature zone below. Figure 1b (Beall et al, 2013) shows that injection cooling-induced seismicity has penetrated into the initially impermeable high temperature zone reflecting fluid circulation down to depths of 6 km. Figures 1 a and b are at the same vertical scale.

Meanwhile Mossop (2001) interpreted shallow seismicity at the Geysers to be related to fluid pressure decline. Shallow fluid pressures are declining due to water mass extraction and boiling-induced cooling in the pores. So in this interpretation, as steam is extracted, production-induced fracturing supports more steam extraction, another fracture formation feedback in an exploited state.

One of the other models for induced seismicity at the Geysers suggests that production operations induce a change from creep to stick-slip behavior on faults in relatively shallow fault zones (Smith et al, 2000). This conversion would shift the fault from ductile to brittle behavior and may be due to cooling or fluid pressure reduction. The ductile-brittle transition can happen at a wide range of temperatures in rock lab tests from only about 100ºC to as high as 700ºC depending on rock type (Violay et al, 2012) such that this feedback process may be pertinent from shallow to deep fractures.

Another example of cooling induced permeability change is evident from cold water geothermal well stimulation. These stimulation efforts are commonly associated with seismicity and increased permeability. A review of hundreds of Unocal injection stimulation tests in Indonesia and the Philippines and published results worldwide revealed that most cold water geothermal well stimulation attempts result in increased permeability. Stimulation tests in this data set were below hydraulic fracture pressures. For example long term, massive, cold water injection resulted in much improved permeability in injection wells at Awibengkok (Yoshioka et al, 2009). Thermal stimulation tests in New Zealand show that this stimulation is typically successful and can improve permeability up to two orders of magnitude (Grant et al, 2013). Grant et al also show that some of this thermal permeability improvement is reversible upon re-heating. The evidence for reversible thermal stimulation shows that both cooling and re-heating can cause permeability feedback.

3.2 Metasomatism

Metasomatism refers to dissolution, transport, and deposition of mineral materials in hydrothermal systems. Dissolution can result in fracture opening or closing while deposition can result in fracture sealing or propping. In these processes water flow and water-rock disequilibrium induces reactions and transports reactants that feedback to open, maintain, or close fractures.

Filled veins are commonly observed in cap rock drill cuttings in many fields revealing material deposition that reduces fracture openings. In the Tiwi Field, Philippines early well flow tests may have mimicked the natural sealing process by forming calcite scale in wellbores immediately above the reservoir top due to boiling. The extensive flat reservoir top in this area may be due to natural reservoir boiling where vein openings above that pressure point are quickly filled. Meanwhile prior to being filled, deposition can increase fracture surface roughness such that incompletely filled cracks are less likely to close from stress or thermal changes. Partially filled open veins are commonly observed in euhedral cuttings and in reservoir core samples at Tiwi (Moore et al, 2000) and in many other fields.

Imperial Valley geothermal systems are commonly associated with gravity anomalies that may be due to massive metasomatic transfer from reservoir depth into shallow cap rocks (Cumming pers. comm., 1994 and Dobson, 2016). An alternative gravity interpretation suggests that the positive anomalies are due to buried magma bodies. However dense silica-mineralized zones in sealed cap rock occur in the Dunes system on the margin of the valley (Bird, 1975) where the positive gravity anomaly reported by Coplen et al (2018) is unlikely to be related to an underlying intrusion.

Documentation of dissolution is more difficult than vein deposition since evidence for dissolution is primarily textural rather than the observation of material that can show up in cuttings. Nevertheless detailed studies and sometimes just visual inspection of core reveal dissolution textures in geothermal reservoirs (e.g. Lynne, 2015). Dissolution can affect fracture permeability by dissolving stressed asperities decreasing permeability (Polack et al, 2003) or by local mass removal of rock on fracture faces under low stress or subject to high rate channelized flow (Deng et al, 2018 or Blaisonneau et al, 2016) increasing permeability. Geothermal reservoirs are commonly associated with zones with low or extensional stress. Meanwhile more highly stressed field margins could show dissolution of asperities that allow cracks to close.

Dissolution of Mesozoic calcite veins by downflow of mildly acid heat pipe condensate was interpreted to explain common horizontal feed zone correlations in wells at the Geysers (Thompson, oral comm., 1982). This feedback of chemical dissolution to permeability was interpreted to be a general process in steam system evolution by Truesdell (1991). Calcite metasomatism in geothermal systems has other feedbacks for permeability and is described more generally by Simmons and Christianson (1994).

3.3 Mineralization Strengthening or Weakening

Although re-mineralization is broadly known to increase strength in processes that range from diagenesis to metamorphosis, evidence for strength changes during hydrothermal circulation in known fields is less well studied.

One example occurs in the Imperial Valley where drilling commonly proceeds from the surface at extremely high penetration rates that decline rapidly near the top of the reservoir, revealing much stronger rock. The dramatic decrease in penetrations rates as the bit approaches reservoir depths has been interpreted to be due to metasomatic mineralization filling the pores and deeper propylitic hydrothermal mineralization of the rock matrix, although it must also be partly due to compaction. Open fractures generally occur below upper parts of this strength transition.

Weakening due to argillic re-mineralization is often interpreted to help form geothermal cap rock and is commonly observed in high rates of penetration in the argillic zone above the reservoir. An interesting example of hydrothermally altered rock that seals fractures comes from Awibengkok where weak weathered/argillically altered tuff in shallow reservoir horizons will often slough into the wellbore (showing mechanical sealing during drilling). These tuffs are commonly associated with nearby fluid entries in lavas (Ganefianto, pers. comm. 1998). The association of weak rock with nearby open fractures may be due to fracture formation associated with rapid strength variation (National Resource Council, 1996). This was a particularly vexing issue since drilling commonly encountered very weak rock followed immediately by total lost circulation, dramatic wellbore pressure drops, sloughing, and stuck pipe.

Davatzes and Hickman (2010) interpreted feedback processes at Coso, California where the type of mineralization affected fracture strength and re-current brittle opening or ductile deformation to help control fracture permeability. Secondary minerals related to the fracture strength feedback in weak and strong fractures included phyllo-silicates and calcite or quartz veins respectively. They suggest that the differences in secondary mineralogy in fractures can account for a three order of magnitude difference in permeability. This results in hydrothermal fracture strength zonation on a reservoir scale but also between the fractures and matrix.

4. HYDROTHERMAL FRACTURE FEEDBACK SYSTEM CHARACTERISTICS

4.1 Energy Sources and Activation

In geothermal settings overlapping concentrations of stored tectonic, thermal, and chemical energy are available to perform work on fracture patterns through multiple feedback processes. In particular foci of energy occur in active fault irregularities (e.g Siler et al, 2018), areas of high heat associated with magma or thin crust, and chemical gradients and activity associated with introduction of magma or rock type changes.

Fracture feedback processes, like other engines of change, can require an activation step that allows feedback to proceed. In other words feedback can be “like a Harley, you gotta kick it to start” (Zappa, 1971). In the case of hydrothermal feedback a key activation step involves achieving threshold percolation (Cox et al, 2001) across a significant, vertical extent that can access temperatures that increase with depth and variations in chemistry, stress, and strength. Once circulation starts, new chemical gradients can be created by flow of a water solvent, cooling at depth and heating shallow proceeds, and new fault movement partly triggered by feedback can redistribute stresses in a weakening and strengthening earth. This threshold permeability might be created by fault movement or magmatism.

Once activated, positive feedback to open fractures in parts of a circulating system can accelerate. This suggestion is based on the general observation that positive feedback accelerates in an exponential fashion until it consumes the energy supply or is counteracted by another feedback process that limits or reverses the process (Martin, 1997). In the hydrothermal case multiple cooperating feedback mechanisms might help drive acceleration. A prime example of rapidly accelerating feedback that reforms fracture patterns in hydrothermal systems is the hydrothermal brecciation-eruption process.

4.2 Feedback Process Limits and Reversal

Negative feedback or competing feedback processes can drive contrary change that limits or reverses a feedback loop, especially as the initial process reaches limits of the locally available energy. This type of competition is characteristic of the complex geothermal fracture feedback formation process. Reversals can in turn be reversed such that competing processes can result in oscillatory behavior, evident in hydrothermal systems in oscillatory vein deposits.

An example of a negative feedback process occurs nears the bottom of a circulating system where down-flowing hydrothermal water deposits silica and seals fractures as water temperature increases above the point where silica solubility begins to decline. So as the water heats due to access to deeper hot rock, silica deposition acts to limit the access.

An example of a process reversal occurs when a hydrothermal eruption is followed by cold influx. When hydrothermal boiling is activated by fault movement, water level drop, or other triggers; boiling expansion drives feedback that can build into a steam explosion, leading to eruption of fractured wallrock further opening the vent (Brown and Lawless, 2001). Rapid mineralization due to boiling in fractures during such an event is initially overwhelmed by fracturing and flow such that new vein material can be brecciated and thrown clear. As boiling proceeds it may be limited by local hot water supply, boiling-related cooling, or mineral sealing such that shallow flowing pressures decline. Reduced steam pressure can then allow cold water influx from shallow aquifers that quenches the steam (further reducing pressure) and invades the broken and partially-resealed hydrothermal system. This overprints the pre-existing and new eruptive permeability pattern with a cold influx permeability pattern with its own opening and sealing characteristics. This kind of reversal leaves evidence in vein paragenesis, fluid inclusions, and surface expression.

An eruption-influx reversal event occurred at Tiwi, Philippines during exploitation when a hydrothermal eruption induced by water level drop due to reservoir production was followed by massive cold water influx through the eruption vent. In this case an attempt was made to reseal the newly opened eruption-influx vent through injection of seawater into the vent. This attempt was based on the hope that the retrograde solubility of anhydrite would result in anhydrite deposition-sealing as the seawater heated in influx fractures (Koenig, pers. comm. 1985). Unfortunately the negative feedback from anhydrite sealing could not apparently compete with the positive feedback effects of cold influx such that the influx permeability did not seal. Another eruption-cold influx reversal was interpreted to have occurred in the natural state at Tiwi (Moore et al, 2000).

Another case was detailed from fluid inclusions and mineralogy of core and local outcrop observations at Tolhuaca, Chile (Melosh et al, 2012). The data reveal a natural history of boiling high temperature reservoir water flow to the surface followed by hydrothermal eruption, cold water and condensate flow reversal, re-sealing, and development of a shallow thin steam zone sealed-off from an overlying bicarbonate warm spring aquifer. The bicarbonate waters may be partly heated by rocks previously heated by chloride reservoir outflow. Just the surface evidence at Tolhuaca, ie secondary bicarbonate warm springs in areas with silica sinter and intense alteration suggest a permeability change. Other geothermal fields like Amatitlan, Guatemala and La Primavera. Mexico show similar surface patterns.

4.3 Schematic Hydrothermal Fracture Permeability Histories

A fault-valve model for fault zones by Cox et al (2001) interprets a schematic history of fault fractures during hydrothermal circulation as shown in Figure 2a. Under the influence of fracture permeability feedback processes, geothermal permeability may show a wider range of behavior that includes post-fault movement permeability increases, decreases, and oscillations that can persist through times longer than the fault movement recurrence interval.

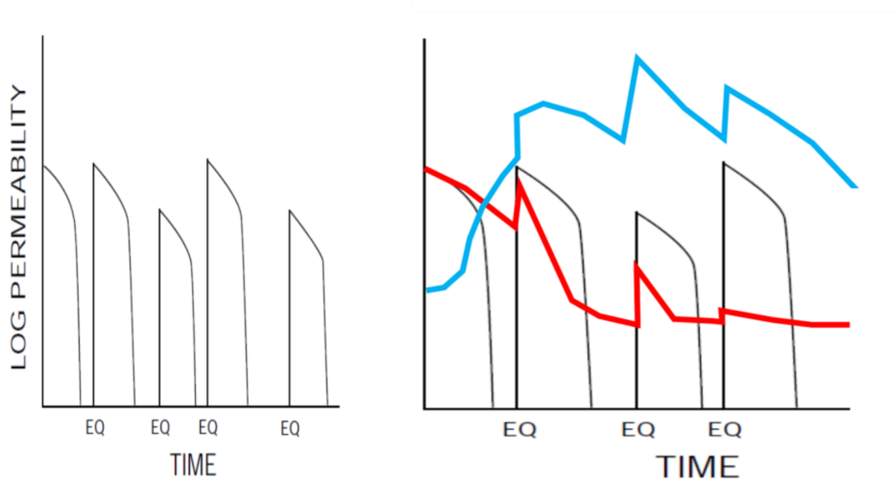

Figure 2: This figure compares schematic histories for hydrothermal fault permeability. EQ identifies fault movement events. Figure 2a shows a fault-valve model for fracture permeability in a hydrothermal system from Cox et al (2001). Figure 2b shows possible fracture feedback permeability histories for two geothermal depth intervals, cap and deep reservoir (red and blue) overlain on the fault-valve model (black). Initially the two feedback permeability histories depend on their relative depths. Permeability inversion, where deep permeability exceeds shallow permeability, develops quickly due to exponential positive and negative feedback while energy supply is abundant. Shallow permeability never recovers to high levels due to the long term impacts of argillic alteration. Deep permeability stays high due to strengthening. Time in 2b was stretched relative to 2a.

Feedback at shallow levels may tend to seal fractures as suggested by the list in Section 2. Meanwhile deep fractures may tend to open from mechanical feedback due to cooling, rock material dissolution, and increased brittle behavior. As a result the normal exponential permeability decrease with depth in the earth (Ingebritsen and Manning, 2010) can be inverted by feedback processes such that permeability increases with depth, as dramatically observed at the top of geothermal reservoirs during drilling. At the bottom of some fields negative feedback associated with silica deposition and increasing overburden stress may restrict other feedback mechanisms such that deep permeability reverts to very low levels.

Expression of a feedback model for permeability reformation through time is shown by schematic histories for two depth levels overlaid on the fault-valve model in Figure 2b. Early feedback effects are rapid and result in permeability inversion. Later permeability changes are subdued or reversed after energy depletion, re-initiated by renewed faulting or intrusion, maintained by re-mineralization, and subject to changes due hydrothermal eruption, cold water intrusion, or otherwise re-routed flow.

Metasomatic and remineralization feedback processes may be relatively slow to develop and result in changes that persist long after feedback fracture patterns emerge. These long term effects can allow re-initiated geothermal activity in already prepared reservoir patterns or simply remain after thermal energy is dissipated if they are not sealed during waning activity. This is especially important for changes to the rock matrix where lower primary permeability and larger total mass can result in slow re-mineralization. An example from Awibengkok is evident from the persistence of argillic alteration in tuffs inside a reservoir zone characterized by propylitic alteration. In this case it appears that altered tuff formations do not rapidly convert to higher grade mineralization probably due to their low permeability. In some cases geothermal reservoir fracture permeability patterns persist even beyond the geothermal field lifetime as evident from geothermal permeability patterns in oil reservoirs in Nevada (Hulen et al, 1997). Long term persistence of permeability patterns from mineralization processes allow a model in which geothermal fields grow over time as fault offsets occur in nearby locations across a broad irregularity while older parts of the system created by earlier fault movements remain permeable.

4.4 Feedback Networks and Self-Organization

The variety of possible feedback loops, the overlap of concentrations of the energy sources in geothermal areas, and the coincidence of these processes inside circulating fractures indicates that these feedback loops probably interact. In some cases dominant processes may carry secondary feedback processes along or there may be multiply-linked feedbacks in an energy dissipation network. Meanwhile different sets of these processes may interact more powerfully in different geothermal settings.

An assembly of linked feedback processes in areas with high available energy and high energy dissipation is consistent with the characteristics of self-organization in a range of systems from simple chemical reaction networks to living organisms (Der and Martius, 2011). Convection (without the fracture feedback) is the most commonly cited example of self-organization. Based on this analogy we should expect geothermal fracture network feedback to develop the emergent characteristics typical of self-organized systems. In the geothermal case these characteristics include cap rocks, deep upflow, outflow, and very high internal permeability as observed in many systems. Other self-organized fracture characteristics such as power law distributions of aperture in typical fault-stress fracture patterns (Gale, 2004) should be expected. Based on the analogy to other self-organized systems we should expect that the emergent patterns of geothermal permeability and flow are metastable and resistant to change over long periods from imposed shocks to the system (e.g. new fault movement or geothermal exploitation) especially where magmatic heat and tectonic stress provide abundant energy supply. When they are induced to change, they may re-stabilize in a dramatically new broad reservoir pattern, such as the impressive reversal from outflow to broad and sustained influx that stopped production from more than one hundred production wells at Tiwi.

Based on the living organism analogy, in the following discussion the geothermal fracture feedback self-organizing process will be referred to as “The Kraken” (a mythical sea monster).

4.5 Habitat

So where does the Kraken thrive? Clearly extensional zones in active fault irregularities, young magmatism, and thin crust all contribute to habitat. The Kraken can grow to monstrous dimensions in extensional step-overs and around the fires of magmatic activity. Meanwhile it appears that the silica and calcite solubility patterns are important contributors to habitat patterns, supporting behavior in which the Kraken curls up in the subsurface in internally highly permeable and marginally sealed fault-fracture networks at drilling depths, with only a few hot exhalations to the surface.

Although geothermal exploration and development thrives in the Kraken’s large vibrant habitats, the Kraken also may be active in higher numbers of smaller, cooler, and more intermittent foci of fault movement and appropriate rock character that may have single flow-through circulation patterns (eg. many hot spring areas in Nevada). With lower energy availability, feedback will be less dominant in developing emergent characteristics but may nevertheless be important for fracture formation.

Some of these areas have small, low or moderate temperature geothermal systems but others may be more appropriately considered fault zones with circulation. So for example episodic bursts of vertical permeability in an active fault may trigger circulation that helps drive brittle deformation behavior down into the brittle-ductile transition by cooling. The resultant increases in deep permeability might be sustained to influence longer term circulation and rock behavior down into the middle crust in these localities, at least to temperatures of retrograde silica solubility (which could allow circulation to more than 10 km depth). Since open brittle fractures appear to be available up to 10 or 15 km depth in some faults, even in zones that show dominantly ductile behavior (e.g. Melosh et al, 2014), fracture feedback with circulation may reach far below the 5 km bottom of common geothermal reservoirs. Norton (1984) interprets magmatic hydrothermal feedback down to the base of the oceanic crust near oceanic spreading zones although that environment may include super-critical conditions not considered here.

Another marginal habitat could occur in areas where conditions are nearly appropriate and energy is concentrated but where relatively low permeability, late stage sealing from previous circulation, or barriers to vertical flow have not recently allowed the threshold percolation that can kick off feedback. In these areas there may be evidence of expired or late stage hydrothermal activity, moderately high heat flow, and less frequent offset recurrence.

5. RELEASE THE KRAKEN

Figure 3: Liam Neeson exhorts the DOE (Warner Bros., 1994).

Many attempts have been made to establish circulation in fracture systems created by human intervention. Targets for this work usually seek high temperature rock away from active faults. The primary tool of choice for fracture formation is high pressure hydraulic fracturing. Recognition of the multiple natural mechanisms that can reform natural geothermal fracture networks suggests an alternative or complementary strategy of targeting areas with concentrations of thermal and mechanical potential energy, with some initial vertical permeability and varying rock strength and rock chemistry. Massive low pressure water-frack thermal stimulation could then attempt to activate abundantly energized natural processes to create fracture networks.

A stretch goal for this type of project might be to reduce the minimum compressive stress below hydrostatic in an extensional sector of a fault irregularity in order to induce fracture mesh formation as described in natural systems by Sibson (1996). To effectively spread the cooling without overly reducing local temperatures multiple wells would be needed to drive multiple flow paths.

This strategy is similar to the near-field EGS approach but is more aggressive in seeking greenfield targets that are nearly a field, but not necessarily near a field, and driving fracture formation with stronger activation, i.e., more wells and systematic injection over longer periods. Demonstrated success enhancing permeability in near-field stimulation experiments in areas like the Geysers, CA and at Raft River, ID or more generally in geothermal injection well fields supports this proposed next step. As an example a possible intermediate target between near-field and green near-field exists in the broad fault irregularity at Tuscarora, NV (Figure 4).

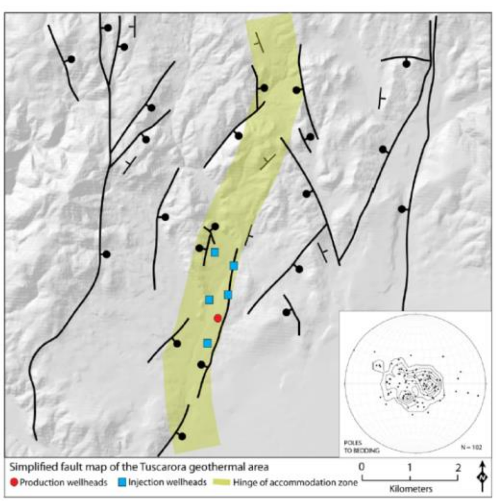

Figure 4: Simplified Structural Map of Tuscarora (from Dering and Faulds, 2012) showing stereograph of poles to bedding, geothermal wells, and hinge zone. The broad irregularity associated with a small geothermal field suggests large possible step-outs for application of not-so-near field resource stimulation.

The historical reticence of EGS practitioners to target active faults may be partly due to social pressure from fear of the seismicity that injection can stimulate. Indeed stimulating seismicity to generate fractures is the goal of this proposal. However experience with large volume rate injection in areas of active faulting and high temperature in operating geothermal fields shows abundant seismicity but relatively low magnitude events and very little infrastructure damage. This suggests that fears of earthquake damage associated with geothermal injection may be overblown (Smith et al, 2000 and Bromley, 2014). Meanwhile stored stress concentrations in active geothermal fields may be higher than in appropriate green near-field targets such that seismicity triggered by injection in green near-field targets may be even more limited. Although the risk of damage is real and may be heightened in an initial condition target, it seems that selection of a site away from vulnerable infrastructure in a fault zone with low expected maximum likely earthquake events could mitigate this risk, while still attempting to access a natural store of mechanical energy. Recent review of EGS seismic risk resulted in a proposed protocol to be able to manage the risk (Majer et al, 2012).

Research should consider the potential risk severity of a green near-field EGS project in more detail. Studies of dam safety could provide guidance. Both dams and injection can induce earthquakes. Studies of dam site safety attempt to constrain the maximum credible earthquake to assess seismic risks for dam project development (e.g. Wieland, 2016). In the case of dam seismicity, damage could potentially unleash catastrophic floods, consequently dam development decisions are linked to higher risk severity than the type of damage we have seen near geothermal field injection.

6. CONCLUSION

A complex, dynamic network of geothermal facture permeability feedback is recognized from examples in drilled reservoirs. Some feedback processes have had strong influence on reservoir permeability patterns during exploitation including a rough doubling of the circulating reservoir thickness at the Geysers and the opening of the Tiwi reservoir to influx that reduced the production field size by about one third. In the natural state it appears that feedback results in dramatic inversion of the normal pattern of permeability vs depth and helps create geothermal reservoir permeability patterns that persist and can be later occupied by oil reservoirs. Overlap of feedback energy sources, the variety of possible fracture permeability feedbacks, and their likely interaction support a holistic view of these complex and powerful processes as a self-organizing system. Focus on the energy sources that drive feedbacks, the activation thresholds, and the work these processes perform together to create emergent patterns simplify our conceptual understanding of feedback in geothermal and other habitats.

The water frack methods shown to be successful in near-field EGS experiments and during thermal well stimulation might be applied to re-organize the behavior of geothermally-inactive, hot, stressed fault irregularities to become actively circulating geothermal resources through broad scale, high volume, long term injection to achieve threshold percolation in multi-well engineered geothermal fields. The first steps in this proposal would be to assess risks, model linked feedback processes, identify possible green-near field targets, and assess project design feasibility.

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