PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 22-24, 2016
SGP-TR-209

Geothermal: The Marginalization of Earth's Largest and Greenest Energy Source

Peter Geiser[1], Bruce D. Marsh[2], Markus Hilpert[2]

[1]Global Geophsyical Services, Denver, CO 80202
[2]Johns Hopkins University, Baltimore , MD 21218
Peter.geiser@globalgeophysical.com

Keywords: Enhanced geothermal system, Hot Sedimentary Aquifers, Raton Basin

ABSTRACT

In size, geothermal exceeds all other energy sources including hydrocarbons by tens of thousands of times. It has no carbon footprint and is essentially infinitely renewable. So with such a resource available, why is it hardly even considered as part of the renewable energy solution?

The core of the problem is that approximately 98% of the total geothermal resource is in "Hot Dry Rocks" (HDR) and "Hot Sedimentary Aquifers" (HSA). The remaining 2% of the geothermal resource is represented by hydrothermal and currently the major source of geothermal energy, because nature has created this reservoir, which is not only of high permeability but also easy to exploit from the land surface. In contrast exploiting the HDR/HSA resource requires manufacturing the reservoir to create an "Enhanced Geothermal System" (EGS). A measure of the difficulty of creating a commercial grade EGS is that over approximately the past 40 years more than 1 billion dollars have been spent by various governments and private industry in trying to create commercially successful EGS. If we are candid then we must acknowledge that the results to date amount to failure. The question is why?

Our analysis indicates that the creation of a commercially successful EGS requires solving three problems:

- The low thermal diffusivity of rock.
- Finding or creating sufficient flow paths to allow extraction of commercial quantities of energy.
- The ability to accurately visualize and measure the initial and final states of the system to which the technology is applied. This is the sine qua non of any experimental process.

We have analyzed these problems in the context of current and past attempts to create commercially successful EGS and find that none of them have been either explicitly addressed or solved. Recognition and study of these problems suggests the following solutions.

- Solving the low thermal diffusivity is seen as essentially a physical design problem. We propose to solve it by designing an EGS that emulates a natural hydrothermal system.
- As finding the "Goldilocks" permeability is at best a highly inefficient and improbable solution, the flow paths need to be manufactured. This requires precision fracking only feasible with controllable high strain rate ($10^3 > \dot{\varepsilon} > 10^{-3}$) fracking tools such as rocket propellant.
- The solution to the critical imaging problem is to change the location of the attempts to create EGS from HDR to HSA terrane. HDR terrane is virtually opaque to all currently available imaging technology. HSA terrane allows the use of the highly accurate and precise imaging tools of the Oil and Gas industry.

1. INTRODUCTION

We address here the question as to why even though geothermal energy has no carbon footprint and exceeds all of Earth's energy sources by tens of thousands of times (e.g. Tester et al, 2006), it is barely considered as even a part of the potential solution to humanity's existential problem of climate change and the hydro-carbon trap. Our analysis indicates that the core of this problem is that approximately 98% of the geothermal resource lies in Hot Dry Rock (HDR) and Hot Sedimentary Aquifer (HSA) terrane, each of which has proven problematical for easy energy extraction. In striking contrast to the hydrothermal portion of the geothermal resource, representing about 2% of the total, where nature provides the thermal reservoir, extracting energy from HDR and HSA regions requires the manufacture of the reservoir in the form of Enhanced Geothermal Systems (EGS).

Over the past 40 years more than 1 billion dollars have been spent by various governments and private industry in trying to create commercially successful EGS. Despite this effort of time and money, candidly speaking, the results to date amount to abject failure; albeit much has been learned. Our review of the past efforts to solve the EGS problem indicates that the root cause is failure *to explicitly* address three problems whose solution we believe is fundamental to creating successful EGS.

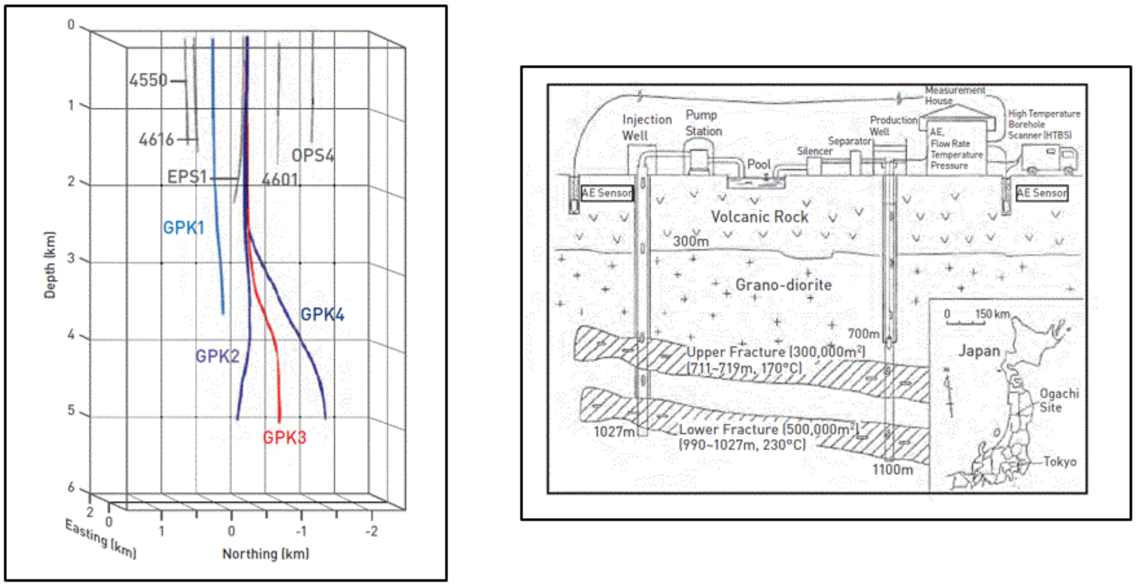
1. The low thermal diffusivity of rock; thus making unreasonably long thermal recharge times.
2. Finding or creating sufficient flow paths to allow extraction of commercial quantities of energy; the "Goldilocks" permeability.
3. The sine qua non of any experimental process; the ability to accurately visualize and measure the initial and final states of the system to which the technology is applied.

Our study of these problems suggests the following solutions.

- Overcoming the low thermal diffusivity is seen as essentially a physical design problem. We solve it by designing an EGS that emulates a natural hydrothermal system.
- Since finding the Goldilocks permeability is at best a highly inefficient and improbable solution, the proper flow paths need to be manufactured. This requires precision fracing only feasible with controllable high strain rate ($10^3 > \dot{\varepsilon} > 10^{-3}$) fracing tools such as rocket propellant.
- The solution to the critical imaging problem is to change the location of EGS development from the current focus on HDR terrane to HSA. Currently, HDR terrane is virtually opaque to all available imaging technology. HSA terrane allows the use of the highly accurate and precise imaging tools of the Oil and Gas industry.

2. THE RAD EGS AND THE THERMAL DIFFUSIVITY PROBLEM

As is well known the very low thermal diffusivity of rock i.e. about 10^{-6} m^2 / sec, is recognized as one of the major hurdles to overcome for successful EGS design (JASON, 2013) . However a literature search of EGS designs reveals that while there is modelling that takes this problem into account, e.g. Bataille et al (2006), with the exception of Leary et al (2014), there is no explicit discussion of the diffusivity problem and how it may affect design geometry. In fact almost all extent EGS well configurations utilize some variation of a single basic design consisting of a production/injection well pair linked by a zone of fractures, either induced or natural. The fracture zone then acts as a heat exchanger. Typically the wells are either vertical or deviated to some degree, e.g. Soultz, Ogachi, Fenton Hill etc. None of the EGS at these sites have been successful at commercial electrical power generation. Figure 1 shows some typical well configurations at these locations.



Soulz , (Tester et al, 2006)

Ogachi, (Kitano et al, 2001)

Figure 1 Typical EGS well configuration of production and injection wells

Recently a number of papers discuss the advantages of "directional" i.e. lateral wells, [e.g. Lowry et al (2014), Kalina et al (2014), Shiozawa and McClure (2014), Leary et al (2014)] which point out the advantages of using laterals for their greater ability to contact the near vertical natural fracture zones and thereby have a greater potential as heat exchangers as well as decreasing the uncertainty of finding potential flow paths. Modeling by Lowry et al (2014), Kalina et al (2014) and Shiozawa and McClure (2014) find that given sufficient permeability, their designs are all capable of producing economic electrical power generation. In contrast the Leary et al (2014) "well centric" design is only capable of extracting direct heat, but not commercial grade electrical power. The two well designs modeled by Shiozawa and McClure (2014) and Lowry et al (2014) suggests they are capable of producing commercial electrical power are shown in Figure 2.

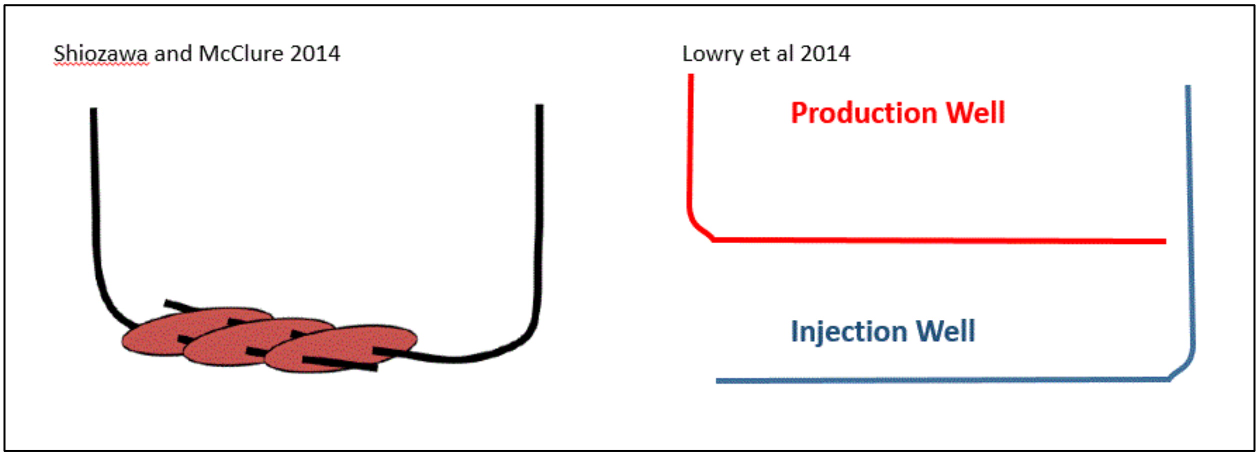


Figure 2: Examples of proposed EGS lateral injection and production wells

These studies are unique and useful as they investigate how the actual geometry of the well configurations as well as the effect of different well spacing's and number of stages affect thermal productivity. What is not discussed is the relationship of the well orientations with respect to the regional stress field. Presumably this is assumed to be normal to Shmax. It is this assumption and it's bearing on the thermal diffusivity problem that the RAD-EGS design geometry (Geiser et al, 2015) addresses.

2.1 A Potential Solution to the low thermal diffusivity problem: The RAD-EGS design.

The RAD-EGS design is, like a number of solutions to physical problems, drawn from the natural world. In this case the recognition that hydrothermal systems are Nature's solution to the low thermal diffusivity problem. Structural analysis of hydrothermal systems shows a common structural attribute, namely, all are fracture zones either located in purely extensional environments e.g. Iceland, the Alvord Valley (Cleary et al, 1981), in trans-tensional ones, or more rarely in active crustal lineaments such as the 38th parallel lineament of the eastern US (Perry et al, 1976).

The basic plumbing of the systems is that of meteoric water circulating to depth where it is heated, then exiting along near-vertical fracture/fault zones as thermal springs or geysers at the surface. The fractured exit zones of are created by either pure extension or trans-tensional shearing. Thus the average orientation of the fracture zones include the S1/S2 plane of the ambient stress field, where S1 and S2 are the greatest and intermediate principal stresses, respectively, which in a normal faulting regime correspond to the vertical stress and the maximum horizontal stress.

Because the water associated with these systems is meteoric and not juvenile it means that the thermal driver of the system can only be by advection of heat from the sub-surface rocks via a dispersed reservoir. Clearly as Nature has "solved" the problem of the low thermal diffusivity of rock, then emulating the design of these systems suggests a path to extracting commercial quantities of thermal energy from both HDR and HSA terranes. This emulation is the basis of the RAD-EGS design (Geiser et al, 2015).

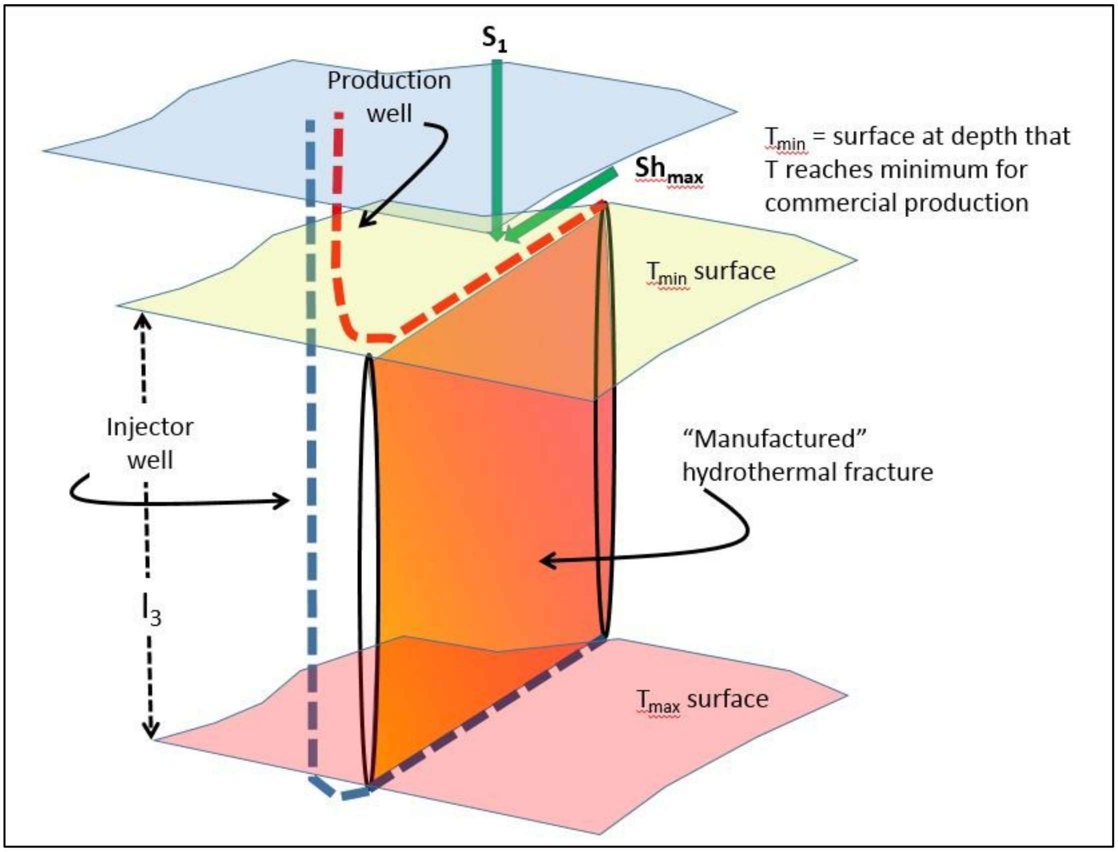


Figure 3: RAD EGS design (from Geiser et al, 2015)

The RAD-EGS design has two principal elements:

1. The location of the production and injection wells. The production well is located at the depth Tmin where Tmin > 150^{o} C, while the injection well is located at the depth of Tmax where Tmax > Tmin.
2. The manufacture of a vertical fracture zone (Vane) whose orientation parallels the orientation of the regional S1/S2 surfaces.

Modelling of the RAD EGS finds that consistent with the work of Lowry et al (2015), the most efficient relative location of the production and injection wells is to have the production above the injection well.

2.2 RAD-EGS Modelling

We have performed numerical simulations of RAD-EGS in a heterogeneous rock domain intended to represent this system installed in a suitable HSA overlain by a confining layer and underlain by relatively impermeable basement rock. These simulations, which are described in more detail in a companion paper (Hilpert et al., 2016), allowed us to understand heat and mass transfer processes that occur during operation of RAD-EGS and to demonstrate that mimicking a hydrothermal system is an attractive EGS strategy.

We attempted to parameterize realistically a RAD-EGS in a relatively permeable HSA. The vane is assumed to be 1 km high and wide, and 60 m thick. The flow rate is 100 L/sec. The geothermal gradient is assumed to be 56^{o}C/km. The top row in Figure 4 shows the temperature field 10 and 40 years after RAD-EGS started operating. Clearly recognizable is a cold front that moves from the bottom to the top of the vane due to the cold water injected at the bottom. The injected water harvests the heat stored in the vane and the surrounding wall rock. Therefore the front moves at a speed smaller than the pore-water velocity. The heat from the surrounding wall rock is transferred into the vane via pore-water advection as becomes evident from the bottom row of Figure 4. This recharge mechanism differs significantly from a conventional EGS in HDR, which primarily relies on heat conduction, a process that seriously suffers from heat diffusion limitations.

While it appears to be natural and not noteworthy to extract the heat through the induced upward flow, not all proposed EGSs do so. For instance, Bataille et al. (2006) in their study of a vertical fractured reservoir, which is broadly similar to the vane we suggest to build, injected and withdrew the fluid on different ends at the top of the vane. They found that depending on the flow rate early breakthrough of the cold injected water occurred, which prematurely ended the lifetime of the reservoir.

In order to highlight the importance of emulating a hydrothermal system in which the fluid rises, we stressed our RAD-EGS by injecting the cold water from the top of the vane to be recovered from the bottom. Similar to the Bataille et al. study, we observed early breakthrough of cold water (see Figure 5) which suggests that injection from the bottom is preferable.

Our findings are also consistent with those by Lowry et al. (2014), who compared two different well configurations. In the horizontal well configuration, a horizontal injector well was placed 800 m underneath a horizontal production well, similar to the RAD-EGS. In the vertical well configuration, both the injector and production wells were vertical and separated also by an 800-m distance (see Figure 3). Lowry et al. found that the vertical wells did not optimally exploit the heat because of density driven-flow that caused early breakthrough of the cold water. The RAD-EGS maintains high temperatures of the produced water for long periods of time (see Figure 6). Because initially water is produced from the top of the vane with a temperature according to the equilibrium geothermal gradient (~55°C/km), the temperature first rises for 5 years. Then the temperature begins to slowly decrease. After 40 years, however, the production temperature is still about 220°C, which would allow for production of electrical energy. Figure 6 also shows that downward flow in the vane preforms much worse than the upward flow in RAD-EGS. The proposed RAD-EGS is able to produce commercial amounts of electrical energy for 40 years and longer.

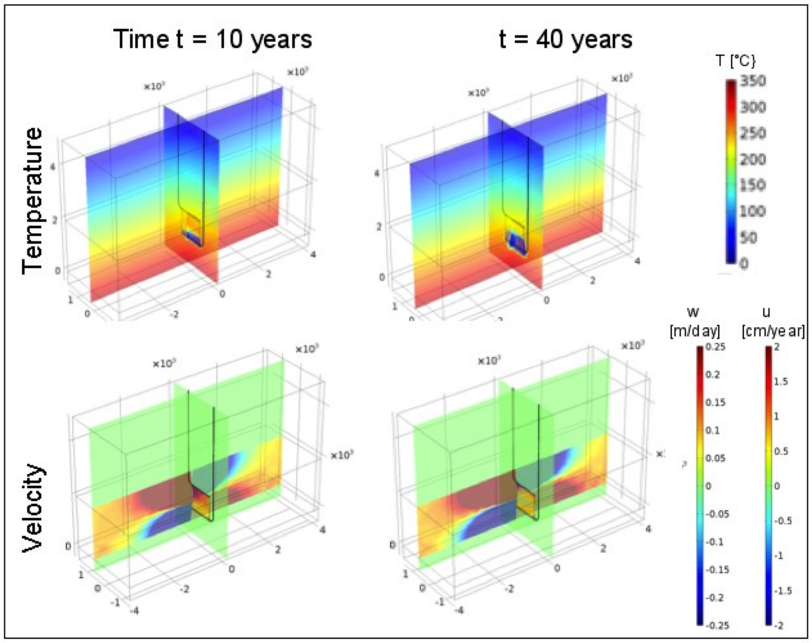


Figure 4 : Top row: evolution of temperature during the operation of RAD-EGS. A cooling front moves from the bottom to the top of the vane while harvesting the geothermal energy from the entire vane and the surrounding wall rock. Bottom row: within the vane, fluid moves upward. In the surrounding wall rock, a circulation develops that supplies hot water to the vane. The slice through the vane shows the vertical velocity w, while the longitudinal slice shows the horizontal velocity u.

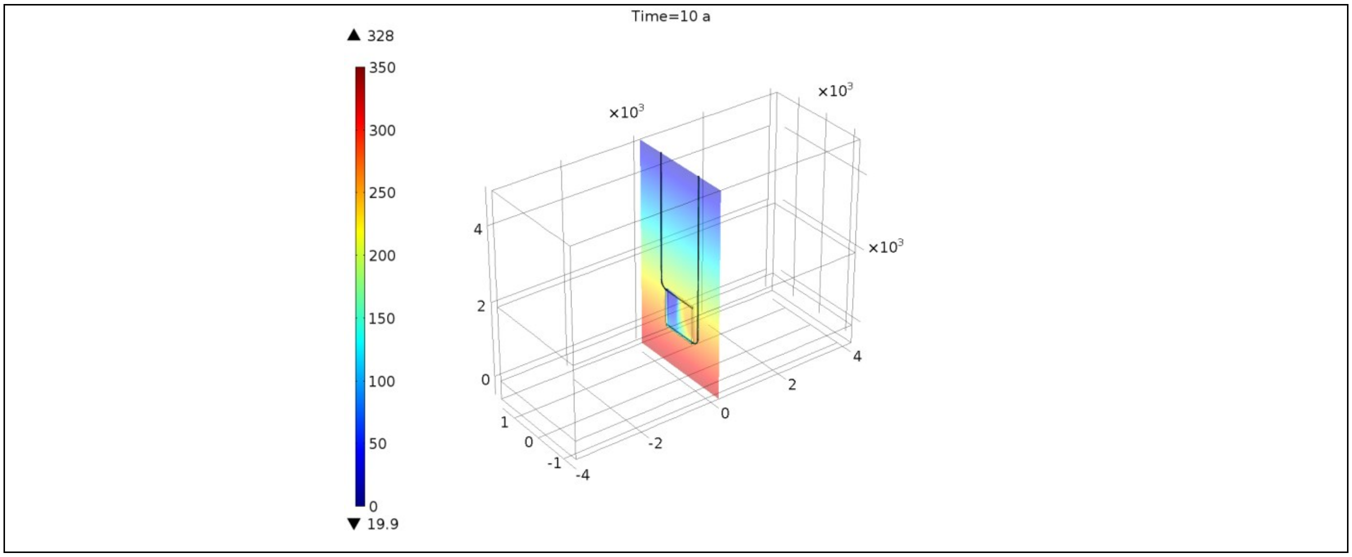


Figure 5 : Induced downward causes early breakthrough of cold water.

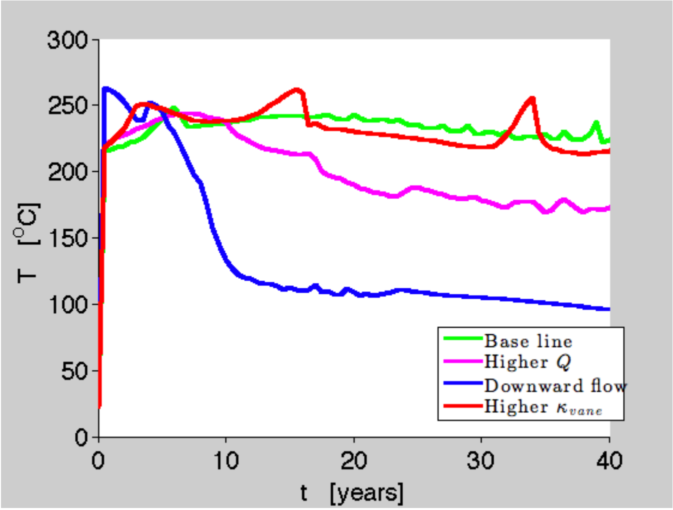


Figure 6: Production temperature versus time.

2.3 MANUFACTURING THE RAD-EGS VANE

As has been long recognized the permeability field of the thermal reservoir is of critical importance for EGS as the permeability must neither be too large (in the sense of "cut offs") or too small. The first case may result in hydraulic short-circuiting and not allowing injected cold water to pick up heat, while the second does not permit sufficiently high flow rates for commercial scale electrical production. In other words, the permeability field must be "just right" or what we call the "Goldilocks" permeability (Geiser et al, 2015). There are two possible ways to encounter such permeability:

1. Exploration for a natural "Goldilocks" permeability.
2. Manufacturing the permeability by either facing or hydro-shearing.

Because there is no way of accurately predicting the location and quality of any natural permeability field, exploring for the "Goldilocks" permeability greatly increases the financial risk of an EGS project. Further, the chance of encountering the "Goldilocks" permeability of sufficient size as to act as a thermal reservoir is very small. Consequently we claim that the least risky path to the necessary permeability is to manufacture it rather than explore for it.

2.4 PRECISION FRACTURING

As discussed in Geiser et al (2015) rock has two different strengths:

1. **Global strength** is defined at the meter or larger scales. Global strength ranges from 10,000 psi – 15,000 psi (~0.7 to 1 kbar) and is controlled by the mechanical heterogeneities manifest as the natural rock fractures.
2. **Fundamental strength** is defined at the centimeter scale. At this length, the strength is controlled at the grain scale. Fundamental strengths range from 20,000 psi – 30,000 psi.

The problem is that as the pressure increases through the global strength, the rock mechanical heterogeneities control the fracturing rather than the operator. This presents a fundamental problem for hydraulic facing whose goal is to control the fracturing by "staying in Zone". This almost never happens. An example of this is shown in Figure 7 which is, a vertical slice showing the natural and induced transmissive fractures imaged with Tomographic Fracture Imaging (TFI™) and the semblance cloud from which the TFI™ are extracted (Geiser et al, 2006 and 2012); see caption for more detail.

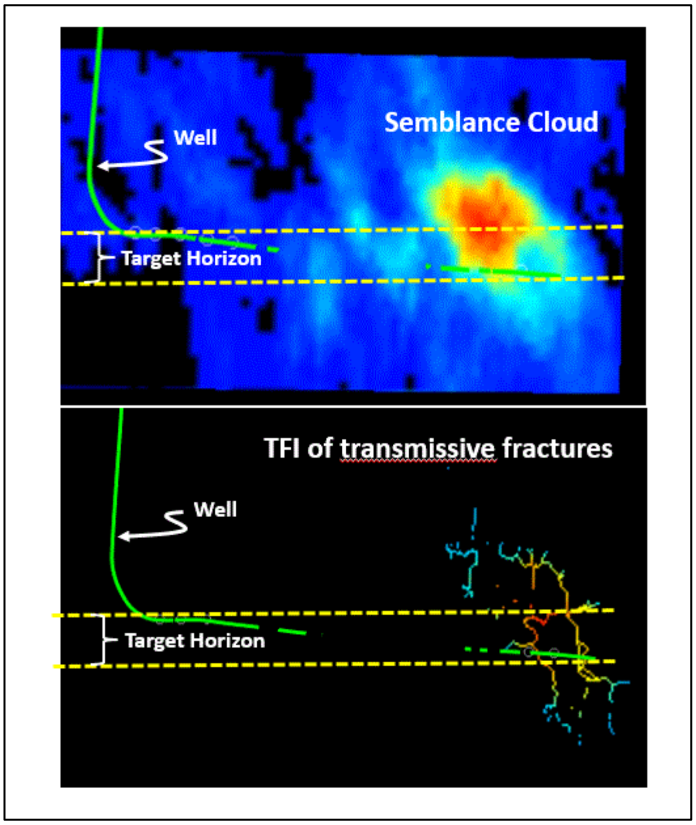


Figure 7: Vertical slice through a lateral showing the results one frac stage. The upper image is the semblance cloud produced by the activation of the damage cloud surrounding the transmissive fractures. The lower image is the TFI extracted from the semblance cloud. The frac, controlled by the natural fracture system, shows the typical out of zone results that occur with hydraulic facing.

Cuderman (1982) suggests that the solution to controlling induced fracturing is to overcome the fundamental rock strength by increasing pressure at a sufficiently high rate such that the rock cannot respond before the fundamental strength is reached. Thus the ability to control induced fracturing is a function of the pressure rise time dp/dt. Based on Cudermans' pioneering studies we find that strain rates ranging from $10^3 > \dot{\varepsilon} > 10^{-3}$ represent a realm in which the fundamental strength of the rock interacting with the propellant induced stress field should allow more controlled "surgical" fracing. Figure 8 shows the field of the propellant regime as a function of bore hole diameter and stress rise time, where it is suggested that operator-controlled fracing is possible in an intermediate field of stress rise times.

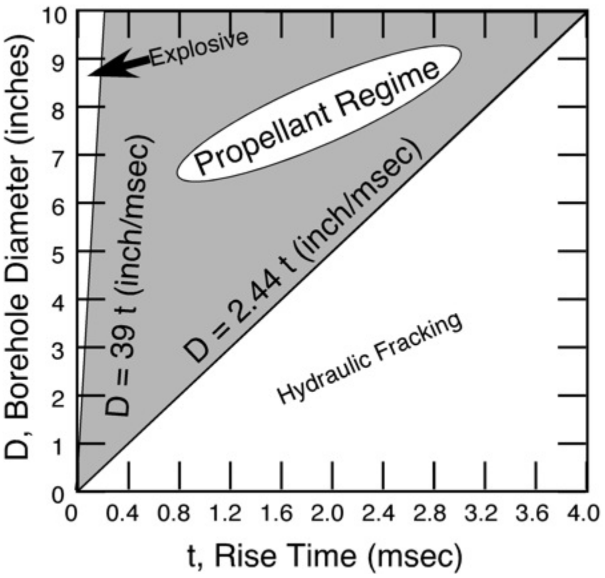


Figure 8: Plot showing the relationship of pressure rise time (dp/dt) and three frac methods. We posit that controlled fracing is only possible in the the Propellant Regime (from Marsh and Hilpert, 2015).

An important attribute of the RAD EGS design is that the vane includes the S1/S2 plane of the ambient stress field. The ambient S1/S2 direction controls both induced and natural fracturing e.g. Zoback (2010). Thus by orienting the vanes to include these stress components, instead of dissipating the frac energy on multiple induced fractures as occurs with laterals oriented normal to Shmax, it should be possible to utilize the additional energy of the ambient stress field to focus on a single surface or zone. Over-coring experiments (e.g. Engelder and Geiser, 1984) show that the fracture directions in relatively weakly deformed terrane such as the New York Plateau are largely controlled by paleo-strains locked into the crystal lattices of the grains and cement. This suggests that depending on the regions tectonic history, additional "locked in" energy may be available.

2.5 The RAD-EGS Design: CONCLUSIONS

Our analysis indicates that

- The most effective EGS design is one that emulates a hydrothermal system, i.e. Nature's solution to the critical problem of the low thermal diffusivity of rock.
- Manufacturing the permeability field is the only feasible path as finding a naturally occurring "Goldilocks" permeability is highly improbable.
- Creating the RAD EGS "Vanes" requires precision fracing. Consideration of the mechanical heterogeneity of rock indicates that precision fracing requires a fracing medium that can achieve strain rates with a range of $10^3 > \dot{\varepsilon} > 10^{-3}$. Solid rocket propellant is the only medium that can both achieve these strain rates and is also highly controllable.

3 SUBSURFACE IMAGING

Here we discuss both the necessity for accurate imaging, the critical phenomena required, and the status of current field of subsurface imaging of the Earths' brittle crust. The basis of our argument is the fundamental scientific tenant that testing any hypothesis requires knowing both the initial and final states of the test. Developing an EGS system requires measuring the response of the Earth's brittle crust to the experimentation required for the system design and manufacture. To do this successfully means meeting two conditions:

1) Detailed knowledge of the geology, geophysics, rock mechanical properties and intensive parameters.
2) The ability to accurately image the subsurface.

While well logs can provide invaluable highly granular and accurate information on crustal properties, it is severely limited statistically by essentially being a static data point source. In striking contrast, the tool kit of seismic imaging methods makes it possible to acquire 5D (X, Y, Z, t, e) data over any given volume at the 5 m to 10 m scale. The most sophisticated and accurate manifestation of seismic methods are those developed and utilized by the Oil and Gas industry.

Application of seismic technology is highly dependent on thorough knowledge of the velocity field of the portion of the crust to be imaged. Velocity fields for HDR terranes are notoriously complex making it difficult to accurately construct velocity models with the precision required for useful imaging. In contrast, the velocity fields of sedimentary basins are relatively straightforward to model and have the benefits of nearly a century of work by the Oil and Gas industry developing imaging technology for it. We therefore conclude that the greatest likelihood for successful EGS development is in HSA and **<u>not</u>** HDR terrane where virtually all efforts to develop EGS have been focused. An indication of this is the long record of failure to create HDR/EGS capable of generating commercial quantities of electrical power. Moreover, in stark contrast is the desire in HDR to make a 'sealed' reservoir whereas the RAD-EGS in HAS is an 'open' reservoir, which is of unlimited thermal potential and is easily recharged.

3.1 Imaging technology capabilities needed for successful EGS development

Ziagos et al (2013) proposed a "Technology Roadmap" for developing EGS. Their roadmap (Figure 9) gives a timeline for developing the set of critical technological capabilities and "flowpaths" judged necessary for successful EGS Development. To be achieved, all of these goals require seismic data

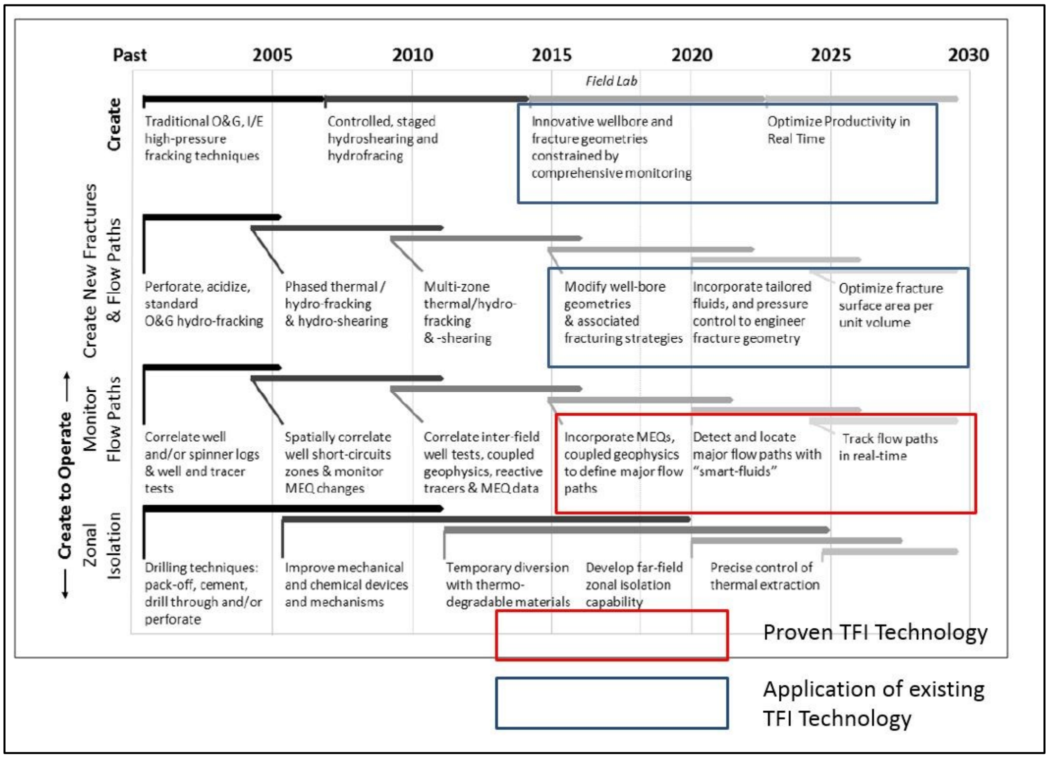


Figure 9: The Status of TFI technology relative to the Ziagos et al (2013) "Roadmap".

to do near real time monitoring of fracture development and fluid flow at the highest resolution possible and in 5D.

Ziagos et al (2013) posited it would take until 2030 to fully achieve all the required capabilities. Recent developments in subsurface imaging technology in the form of Tomographic Fracture Imaging (TFI™) make this time table no longer relevant. TFI, (Geiser et al, 2006; Geiser et al, 2012), is a method that makes use of the critical state of the Earths crust (Geiser and Leary, 2014) for directly imaging transmissive fracture/fault networks both natural and induced. The technology is now in increasingly widespread use in the Oil and Gas industry where it is replacing micro-seismic methods. As shown in the following sections, TFI accomplishes all the following "Roadmap" operations on a regular basis:

- Monitoring Flow Paths;
- Create New Fractures and Flow Paths;
- Monitoring the creation of wellbore and fracture geometries.

3.2 Understanding TFI™ analysis

TFI™ extracts its information from acoustic sources within the Earth's brittle crust using 1 millisecond sampling of the weak but geographically stable acoustic energy emitted by fracturing associated with "damage zones" (e.g. Vermilye and Scholz, 1998; Odling, et al, 2005). Stacking of this weak signal over selected time intervals reveals the damage zones as semblance clouds. Damage zones consist of fracture swarms or "clouds" that surround all mechanically created physical discontinuities of the brittle crust such as faults and fractures. The fracture density increases geometrically as the discontinuity is approached (Vermile and Scholz, 1998; Janssen et al, 2001). The increase in fracture density is reflected by the inwards increase in semblance value of the 3 D semblance "clouds" with the maximum semblance values surrounding the discontinuity.

As Vermilye and Scholz (1998) show, the fracture/fault surfaces approximate the complex medial surfaces of the clouds. This information is used to extract the TFI™ surfaces from the cloud (Geiser et al 2006, 2012). Thus the TFI™ are the images of the actual fracture/fault surfaces that are one voxel in thickness where typically a voxel is a cube with an 8 m dimension. Figure 10 shows a tessalated TFI™. A map slice through a semblance cloud is shown in Figure 11 and a 3D semblance cloud in Figure 12.

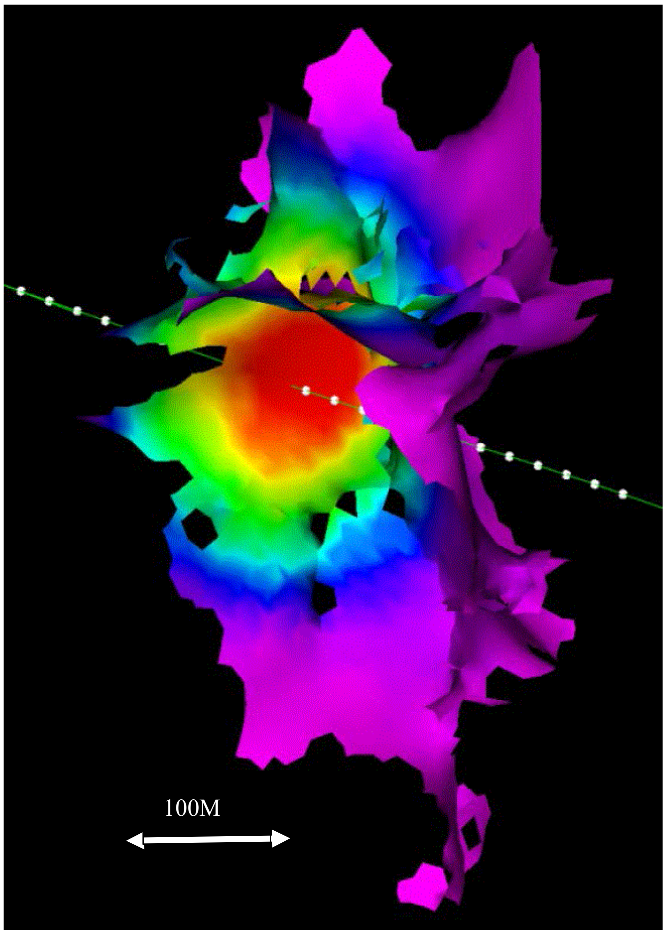


Figure 10: Frac induced TFI™ for a single frac stage contoured for semblance value; red = maximum. The high semblance value is the induced fracture while the low semblance value surfaces are inferred to be part of the natural fracture system activated by the frac that connect to the induced fracture.

Tessellation of the individual fracture surfaces that make up TFI allows them to be used as input to slip tendency analysis (Morris et al, 1996), thereby permitting the TFI fracture data to be inverted for the ambient 3D stress field (Lacazette and Morris, 2015). While Lacazette and Morris (2015) do this at the kilometer scale, domainal analysis (Turner and Weiss, 1963) can potentially extend this to the 100 m scale. Furthermore, by using successive "snap shots" of fracture/fault propagation as input to the slip tendency inversion, TFI has the potential of monitoring progressive changes in the stress field induced during fracing and/or production.

3.3 Examples of TFI achieving "Roadmap" goals illustrated by Oil and Gas industry data

Monitoring Flow Paths: Geiser and Leary (2014) show an example of a frac intersecting a natural transmissive fracture zone that links the treatment well to a nearby monitoring well (star). Figure (11) from that paper shows a map slice through a semblance volume showing the damage zones surrounding the transmissive fractures activated by the increase in fluid pressure of the frac. The figure contains approximately 3 minutes of data from a movie of the entire 155 minute frac.

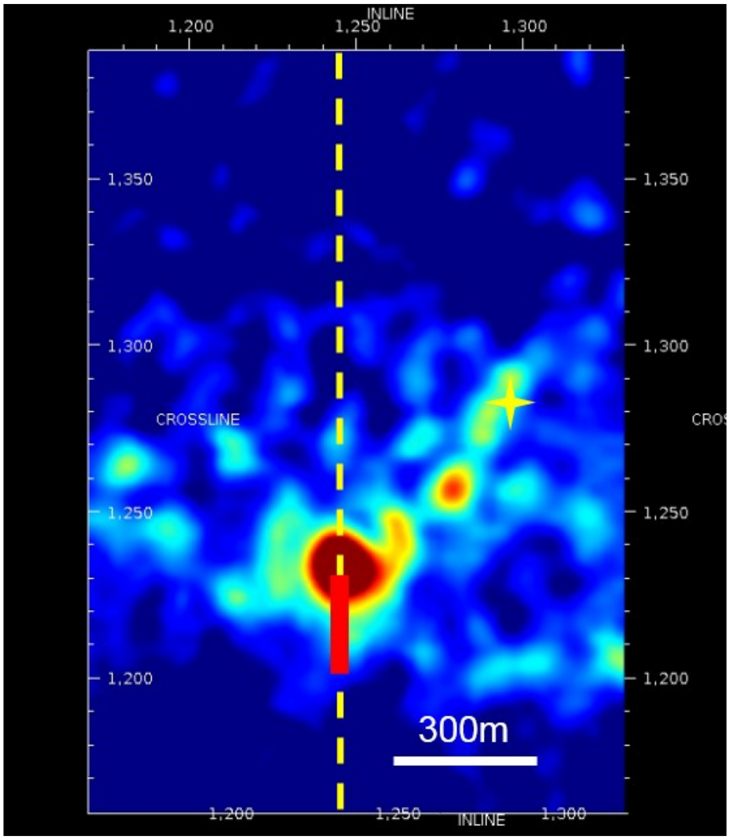


Figure 11: Map slice through semblance volume. Red = high semblance; Blue = low semblance. Yellow dotted line = lateral; Red rectangle = frac stage. Transmissive fracture diagonals to right joining frac stage to observation well (star) illuminated by Pf caused by frac. (from Geiser and Leary, 2014)

Creating New Fractures and Flow Paths: Figure 12 is a sequence of images associated with a single well about 2.5 kms in length, showing the evolution of the transmissive fracture network from it's initial "ambient" pre-frac fracture network (i.e. the natural transmissive fracture network), through the frac manifest as the "Stimulated Rock volume" (SRV) and the final "Active Production Volume" (APV), which is the volume of the reservoir from which the well is actually producing. The pre-frac is the "Before" map slice through the ambient semblance volume. The TFI's of the transmissive fractures extracted from these volumes are shown as the irregular lines in the approximate center of the volumes.

The "During" is a vertical slice through the semblance clouds of the SRV that surround the induced and natural fractures activated by the frac. While the most intense activity, indicated by the highest semblance values (red) is within the target horizon, there is a large amount of "out of zone" fracture activity shown by the blue and purple values. The "After" image is a 3D image of the semblance cloud that forms the APV. Note that the largest volumes are located where the well intersects the natural transmissive fracture networks indicated by the TFI shown in the "Before" map slice.

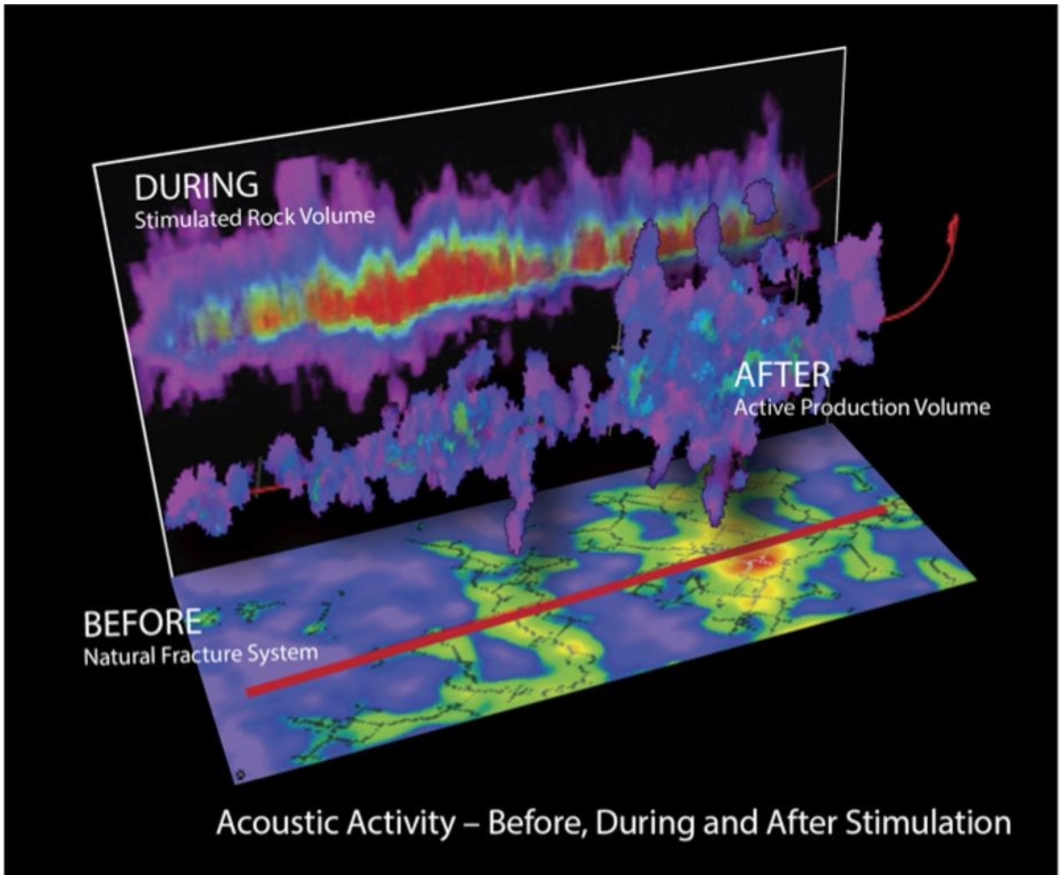


Figure 12: Assemblage of "Before", "During" and "After" activity for a single well. Hot colors indicate high semblance values and purple are low values. The "Before" is a map slice through the ambient, or natural transmissive fracture network. The TFI are the lines within the semblance clouds. "During" is a vertical slice through the well and the semblance clouds of damage produced during the entire frac. This is typically referred to as the Stimulated Rock Volume (SRV). The lateral is in the highest semblance values. "After" shows the "Active Production Volume" (APV). The fracturing that forms the APV is stimulated by the change in fluid pressure due to production. Note that the APV is considerably smaller than the SRV. Lateral length is about 1.4 km.

A further observation is that the largest part of the APV is associated with the natural fracture system and is proportional to the extensiveness of this system shown in the ambient "Before" state.

Monitoring the Creation of Wellbore and Fracture Geometries: Figure 13 shows two types of data that can be extracted from TFI surfaces relevant to the creation of wellbore and fracture geometry. The images are of a set of induced fractures created by a frac stage. The first image shows that the cumulative seismic energy associated with the TFI was concentrated in the immediate vicinity of the well. While this is anticipated, the activation time of the TFI shows that the fracture propagation was asymmetric with respect to the well. Facing right along the well, initial fracture propagation occurred largely on the right side of the well with limited slip on the left side. However, after the first 50 minutes of the frac, fracture propagation ceased on the right side and moved to the left side of the well but was much slower as propagation continued to the left for the next 100 minutes.

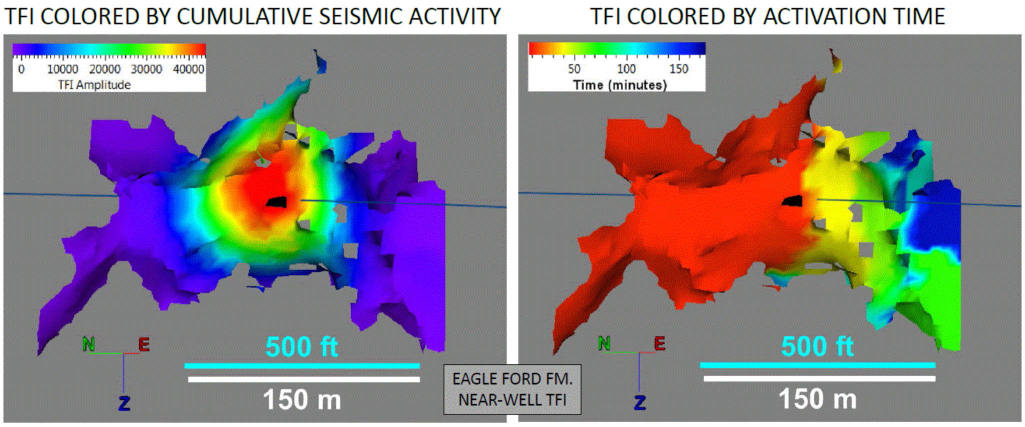


Figure 13: Examples of two types of TFI data relevant the creation of well bore and fracture geometry. Lateral is thin blue horizontal line.

4 A PROPOSED SITE: THE RATON BASIN OF SOUTHERN COLORADO

The foregoing analysis indicates that the criteria necessary to create a successful EGS are;

1. Proper design of the EGS geometry and embedment into the ambient stress field.
2. Manufacturing the "Goldilocks" permeability rather than prospecting for it.
3. As complete knowledge as possible of the structural and geo-mechanical properties of the Earth's crust in the target area.

Essential to all these criteria is that the basic condition for doing scientific research is met, namely the ability to measure the initial and final conditions of any experiment. The better this information is the greater the probability of success. For conducting experiments in the brittle crust this requires imaging and sampling technology that can provide the information necessary to item 3 above. This primarily consists of well and seismic data. The latter being the most important as it is the most complete dimensionally and physically. Because current seismic imaging technology is only capable of adequately providing this information in HSA terrane, it is in this terrane where the research necessary to achieve a successful EGS is best done.

Two other properties that increase the chances for success are;

1) To reduce drilling and imaging costs, the sedimentary basin chosen for EGS development should have a high geothermal gradient.
2) The basin should be in an extensional tectonic environment.

4.1 Raton Basin: Geologic and structural overview

The Raton Basin is a part of the Raton Basin – Sierra Grande Uplift Province. It is somewhat unusual as it is an inverted foreland sedimentary basin that is currently being eroded. The basin is asymmetric being deepest at its axis, which is towards its western margin (Figure 14). The asymmetry may reflect an origin by crustal loading (Molnar and Lyon-Caen, 1988) imposed by eastward vergent Laramide thrusting that formed the Sangre de Cristo Mountains. The sedimentary section includes a complete suite of formations from the Devonian to Recent sitting unconformably on Pre-Cambrian basement. The section varies from 4.9 – 6.1 kms in thickness.

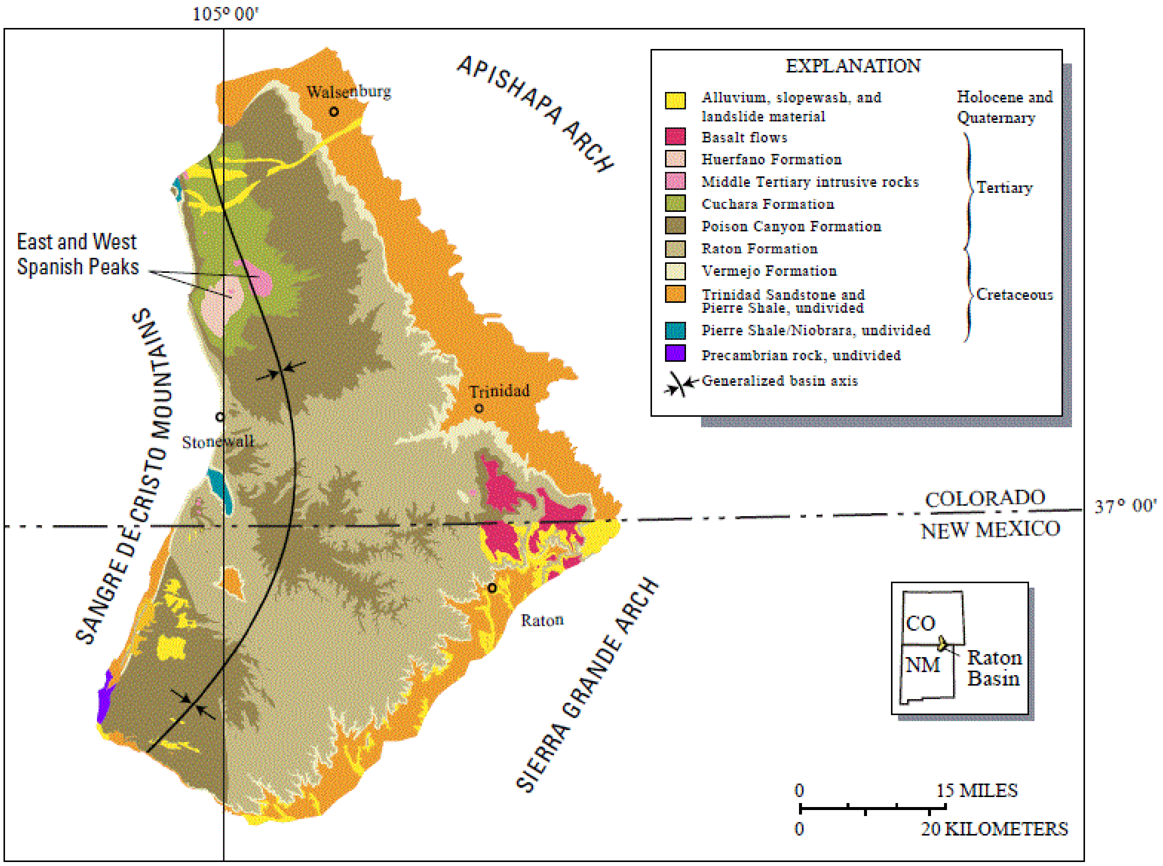


Figure 14: Raton Basin geologic map (from Higley, 2007)

The tectonic history of the Raton (Higley, 2007) indicates that the basin initiated in Early Pennsylvanian time. Its most recent history is one of late Tertiary intrusive activity and uplift in the Oligocene. The intrusive activity produced the Spanish Peaks and Tertiary dike swarms of more northern parts of the Raton. The intrusive activity and uplift is associated with the beginning of rifting in the San Luis Valley portion of the Rio Grande uplift. The basin has been a source of sporadic weak historical earthquake activity (Rubinstein et al, 2008), presumably as part of the ongoing extension associated with the Oligocene initiated Rio Grande Rift (e.g., Hudson, et al, 2008). Rubinstein et al. (2008) have documented a more recent increased seismicity which they correlate with the disposal of produced water in the Dakota formation.

The basin has little internal faulting that breaks the surface but is bounded on the west by a set of thrusts emerging from the Sangre de Cristo mountains that dip steeply to the west. The eastern boundary is a northwest striking normal fault (Rubenstein et al, 2014). The World Stress Map for the Basin and Range, (GFZ, 2008) indicates that Shmax of the current ambient stress field is oriented NE-SW.

4.2 Raton Basin: Geothermal Potential

By several measures the Raton Basin of southern Colorado has exceptional geothermal potential as an HSA. In particular, it has many 100s of Km^2 with geothermal gradients of as much as 90^o C/Km and thicknesses of sedimentary section of > 300 m with temperatures > 150^o C (Paul Morgan, personal communication). Figure 15 is a generalized map of the area of Raton Basin which contains sedimentary section with temperatures ≥ 150^o C.

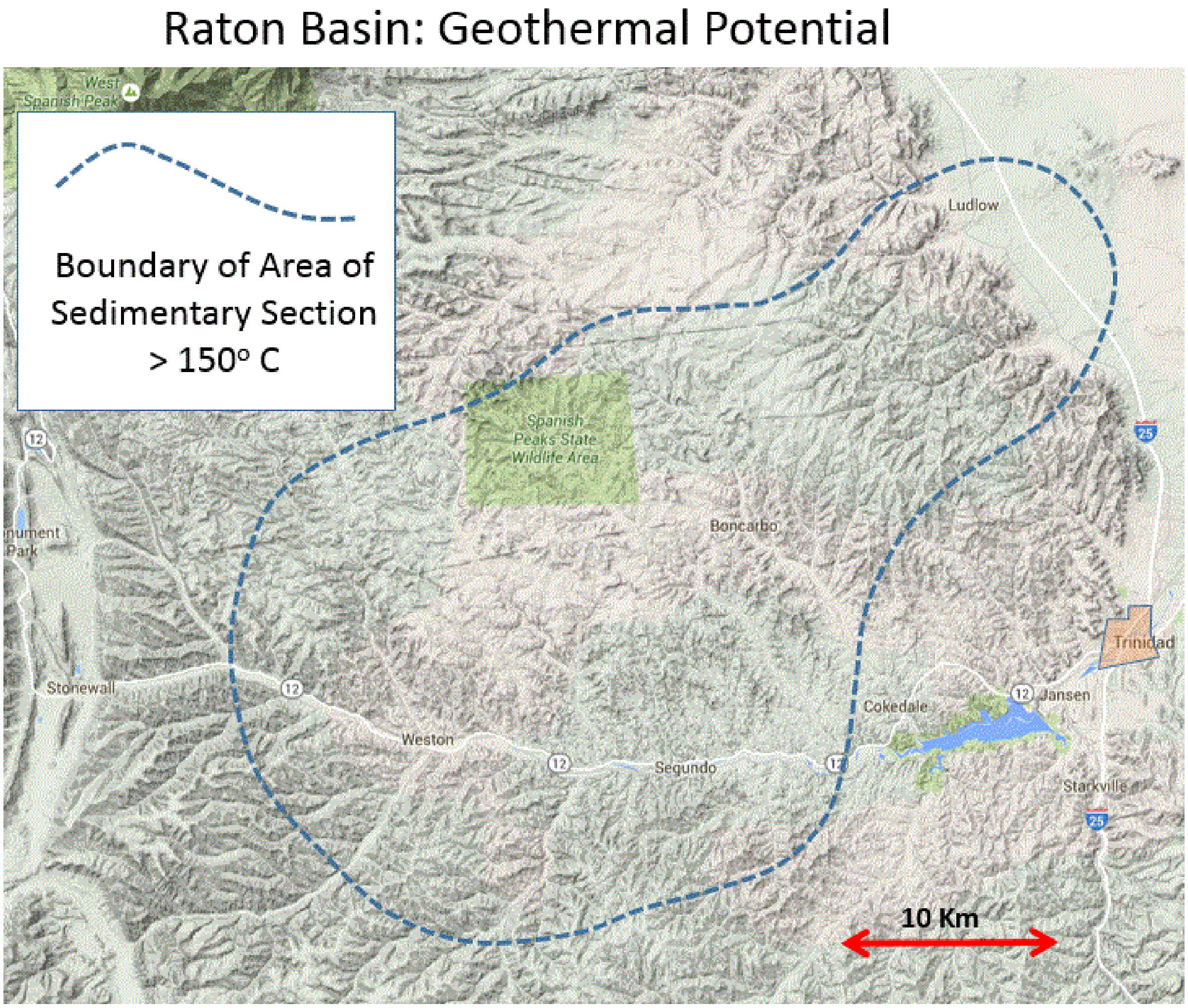


Figure 15 Outline of extent of HSA terrane superposed on topography of the Colorado portion of the Raton Basin. (Paul Morgan, personal communication)

Heat flow within the area outlined above is heterogeneous, however there are on the order of several hundred contiguous square kilometers with geothermal gradients of 80° C/km. Geothermal gradients of this magnitude indicate that in these areas the 150° C isotherm is within 2 km of the surface. Moreover, whereas depth to basement is not everywhere precisely known, it is known to be somewhere between 4 and 6 kms. Assuming a minimum depth to basement in this area of 4 kms and that the gradient is continuous with depth, then at the relatively shallow depth of 4 kms rocks are accessible with a temperature on the order of 320° C. Thus, the thermal characteristics of the Raton Basin makes it highly attractive target for EGS equal to or better than many HDR targets, e.g. Soultz.

5. CONCLUSIONS

We have striven here to understand why after nearly 40 years of attempts and over $1 billion spent, no commercially successful EGS has been achieved. We have identified three major problems preventing success in this endeavor. Namely:

1. Rock's low thermal diffusivity.
2. The need for the "Goldilocks" permeability.
3. The inability to do accurate and precise imaging of the subsurface.

Our study of these problems has led us to suggest the following solutions:

Low Thermal Diffusivity: Recognizing that hydro-thermal systems are Nature's solution to this problem has led us to propose that emulating these systems offers a potential path to a commercially successful EGS. Geological and structural analysis of hydrothermal systems indicates that both the geometric design and its relation to the ambient stress field are critical. We therefore propose the RAD EGS, which consists of a vertical "manufactured" planar fracture zone heat exchanger in the fashion of an internal combustion engine where here the engine is the Earth itself. The fracture zone is oriented to include the S1/S2 directions of the ambient stress field. An additional feature is that because the vertical fracture zone is essentially a heat exchanger similar to a radiator vane, it permits analysis that utilizes the extensive radiator literature.

Modelling of the RAD EGS design indicates that the following parameters are critical:

1. Proper relation to iso-therms,
2. Correct vane permeability
3. Vane size.
4. Relative location of the production and injection wells.

If the appropriate parameter values are met, then modeling indicates that a commercially successful EGS can be created. In terms of the relative location of production and injection wells, our modelling agrees with that of Shiozawa and McClure (2014) who show that the most economically successful configuration is to use lateral production and injection wells with the production well above the injection well.

The "Goldilocks" Permeability: Exploration for the "Goldilocks" permeability, not only significantly adds to the cost of an EGS, it is time-consuming and, above all, notably lacking in success. Consequently, we along with others (e.g. Newbery Volcano and Soultz) recognize that the best solution to this problem is to "manufacture" the required permeability. Two methods have been used to do this, Hydraulic fracing and Hydro-shearing. Frac analysis using TFI™ (see Figures 7 and 12) demonstrates that in addition to requiring large quantities of fluids, the natural mechanical heterogeneity of rock controls the direction and location of the fractures rather than the operator, making these methods too cumbersome and imprecise to allow the kind of precision required to construct a vane.

Analysis of the problem of creating more precise "surgical" fracing methods required for vane creation revealed that the problem is a strain rate issue such that only a fracking method capable of $\dot{\varepsilon} \geq 10^3$ can reach the ultimate rock strength (20,000 – 30,000 psi; ~1.5-2 kb) can potentially accomplish this. Hydraulic fracing ($\dot{\varepsilon} \leq 10^{-3}$) is too slow. However a fracing medium such as rocket propellant which is highly controllable, can achieve the higher strain rates necessary to reach ultimate rock strength. Therefore we consider this as a potential tool for the "surgical" fracing necessary to create the RAD EGS vane.

Imaging and site location: The ability to determine initial and final states of any experiment is a sine qua non for scientific and technical development. Accurate and precise imaging is highly dependent on accurate velocity models. To date, because virtually all attempts at EGS development and the bulk of funding have been or are focused on HDR terrane, e.g. FORGE, where the lithologic and structural complexity greatly inhibit creating accurate velocity models, attempts to create successful EGS have had little success. As HDR terrane precludes application of the highly sophisticated imaging technology developed and used by the Oil and Gas industry, we believe that currently there is little realistic hope of solving the EGS problem in the HDR environment.

We propose that the solution to the imaging problem is to undertake EGS development where it is possible to apply the imaging technology regularly employed by the Oil and Gas industry, namely HSA terrane. To this end we suggest that the southern Colorado portion of the Raton Basin with its 100s of square kilometers with geothermal gradients on the order of 80^o C/km is the ideal site to undertake the development of RAD-EGS. The basin itself, currently undergoing uplift and extension, consists of mid Paleozoic to Recent sediments varying in thickness from 4 to 6 kms that are essentially undeformed.

The high geothermal gradients in the basin create large areas where the critical 150^o C isotherm is within < 2 km of the surface and temperatures of > 300^o C are within 4 kms. Thus, the relatively shallow depths at which temperatures consistent with commercial energy generation occur make the Raton highly comparable with much HDR terrane. Furthermore, these shallow depths also mean that imaging is relatively inexpensive and can achieve high degrees of accuracy and precision. On this basis we conclude that the Raton Basin is a site where the chances of developing a commercially viable EGS far exceeds those currently focused on EGS development in HDR.

REFERENCES

Bataille, A., P. Genthon, et al. :"Modeling the coupling between free and forced convection in a vertical permeable slot: Implications for the heat production of an Enhanced Geothermal System." Geothermics 35(5-6): (2006), 654-682.

Cleary, J., Lange, I. M., Qamar, A. I., and Krouse, H. R.: Gravity, Isotope, and Geochemical Study of the Alvord Valley Geothermal Area, Oregon, Geological Society of America Bulletin, 92, 6 Part II, (June 1981), 934-962, doi:10.1130/GSAB-P2-92-934

Cuderman, J. F,: Multiple fracturing experiments- Propellant and borehole considerations, SPE/DOE 10845, (1982), 534 – 539.

Elena A. Kalinina, Teklu Hadgu, Katherine A. Klise, and Thomas S. Lowry: Thermal Performance of Directional Wells for EGS Heat Extraction, Proceedings, 39th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2014}

Engelder, T. and Geiser, P., Residual stress in the Tully Limestone, Appalachian Plateau, New York. Journal of Geophysical Research, 89, 9365-9370, (1984).

Geiser, P. A., Vermilye, J., Scammell, R. and Roecker, S.: Seismic used to directly map reservoir permeability fields. Oil & Gas Journal, Dec. 11, Dec. 18, (2006).

Geiser, P., Lacazette, A. and Vermilye, J.: Beyond “Dots in a Box”, First Break, 30, 63 – 69, (2012).

Geiser, P. and Leary, P.: Tomographic Fracture Imaging (TFI): Direct 5D Mapping of Transmissive Fracture/fault Zones Using Seismic Emission Tomography (SET), Proceedings, 39th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, CA., (2014)

Geiser, P., Marsh, B. and Hilpert, M., The Radiator-EGS System: A Fresh Solution to Geothermal Heat Extraction, Proceedings, 40th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 26-28, (2015).

GFZ, Helmholz Centre, Potsdam: The World Stress Map Project – Basin and Range region, North America, (2008).

Higley, D.K., compiler: Petroleum Systems and Assessment of Undiscovered Oil and Gas in the Raton Basin–Sierra Grande Uplift Province, Colorado and New Mexico—USGS Province 41: U.S. Geological Survey Digital Data Series DDS–69–N, 141 p., (2007).

Hilpert, M., Marsh, B. and Geiser, P.: The Radiator-Enhanced Geothermal System: Benefits of Emulating a Natural Hydrothermal System, Proceedings, 41st Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, CA., (2016).

Hudson, M. R., Grauch, V. J. S., Minor, S. A.: Rock magnetic characterization of faulted sediments with associated magnetic anomalies in the Albuquerque Basin, Rio Grande rift, New Mexico, Geological Society of America Bulletin, 120, 5-6, 641-658, (2008).

Janssen, C., Wagner, F.C., Zang, A. and Dresen, G.: Fracture Process Zone in Granite: a Microstructural Analysis, International Journal of Earth Sciences (Geol. Rundschau), 90, 46–59, (2001)

JASON: Enhanced Geothermal Systems. Washington, DC, The MITRE Corporation. JSR-13-320. (2013).

Kitano, K., Y. Hori, and H. Kaieda: Outline of the Ogachi HDR Project and Character of the Reservoirs. Proc. World Geothermal Congress 2000, Japan, (2000).

Lacazette, A. and Morris, A.: A New Method of Neostress Determination from Passive Seismic Data, URTeC: 2174187, (2015).

Leary, P. and Malin, P.: Is Theis Flow Modelling Sufficient for EGS/HSA Geothermal Energy Production? GRC Transactions, 35, 444 – 450, (2011).

Lowry, S., Kalimina, E., Hadgu, T., Klise, K. A., Malczynski, L. A.: Economic evaluation of directional wells for EGS heat extraction; Proceedings, 39th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2015)

Marsh, B. and Hilpert, M.: Propellant Fracing: Some fundamentals, Unpublished Ms., Johns Hopkins University, (2015).

Morris, A. P., Ferrill, D. A., Henderson, D. B.: Slip Tendency and Fault reactivation. Geology, 24, 275–278, (1996).

Molnar, P. and Lyon-Caen: Some Physical Aspects of the Support, Structure, and Evolution of Mountain Belts, Clark, S. P. Jr., Burchfiel, B. C. and Suppe, J., (eds.), Processes in Continental Lithospheric Deformation, GSA Special paper 218, 179 – 208, (1988).

Odling, N. E., Harris, S.D., Vaszi, A. Z. and Knipe, R. J.: Properties of Damage Zones in Siliciclastic Rocks; A Modelling Approach, in Shaw, R. P. (ed.), Understanding the Micro to Macro Behavior of Rock Fluid Systems, Geol. Soc. London, Special Publication 249, 43 – 59, (2005).

Rubinstein, J. L, Ellsworth, W. L., McGarr, A., and Benz, H. M.: The 2001 – Present Induced Earthquake Sequence in the Raton Basin of Northern New Mexico and Southern Colorado, Bulletin of the Seismological Society of America, 5. No. 4, 2014

Shiozawa, S and McClure, M.: EGS Designs with Horizontal Wells, Multiple Stages, and Proppant, Proceedings, 39th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, CA., (2014).

Tester, J. F. - Chair, MIT Interdisciplinary Panel: The Future of Geothermal Energy, Massachusetts Institute of Technology, (2006).

Turner, F. J. and Weiss, L. E.: Structural Analysis of Metamorphic Tectonites, McGraw Hill Publishers, 545 p., (1963).

Vermilye, J. M. and Scholz, C. H.: The Process Zone: A Microstructutral View of Fault Growth. Journal of Geophysical Research – Solid Earth 103, 2223-12237, (1998).

Ziagos, J., Phillips, B, R Boyd, L., Jelacic, A., Stillman, G., and Hass, E.: A Technology Roadmap for Strategic Development of Enhanced Geothermal Systems, Proceedings, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA., (2013).

Zoback, M. D: Reservoir Geomechanics, Cambridge University Press, 449 p., (2010)