Geothermal Energy in the 21st Century: Unconventional EGS Resources

Blundell plant (38 MWe), Roosevelt Hot Springs, UT

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Enhanced geothermal systems are often simply referred to as EGS. They have been the subject of considerable investigation over the last 50 years, and although commercial-scale power generation has yet to be achieved, it has enormous potential.

My name is Stuart Simmons, and I am one of the geoscientists on the Utah FORGE project based at EGI, University of Utah. This presentation deals with unconventional geothermal resources and specifically those called enhanced geothermal systems. It is directed at an audience that has interest in energy resources, geoscience and/or engineering disciplines.

Geothermal energy is attractive because it is available around the clock and all year long, irrespective of weather patterns and sunshine. It is a form of energy that complements the other renewables including wind, solar, and hydro. EGS has a big advantage in that it has the potential of being installed just about anywhere.

The hope is that in the near future plants like the one shown at Roosevelt Hot Springs near the Utah FORGE site, can be used to generate electricity from EGS fields. A fresh new push is now under way to make this happen.

Outline

Background Understanding

EGS Concept

Research & Development Field Test Sites

Energy Extraction & Resource Estimates

Stimulation Methods & Induced Seismicity

Challenges

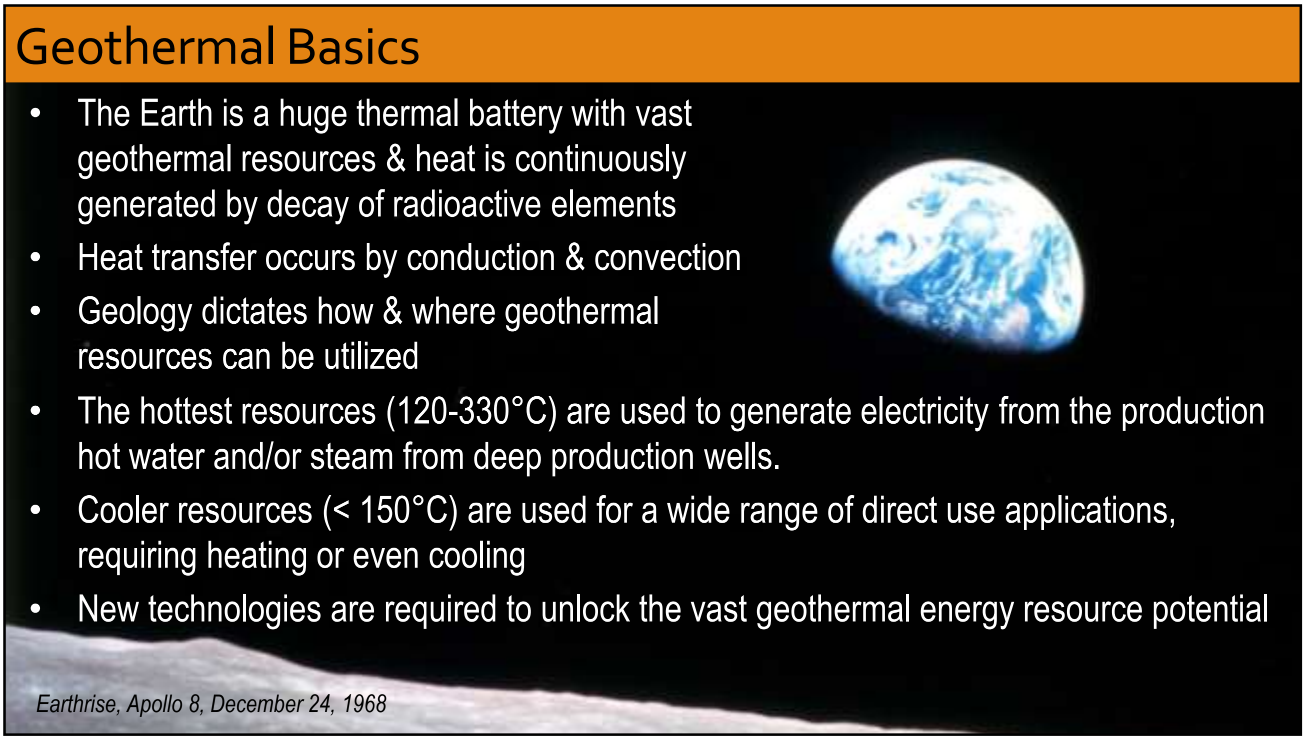
Here are the main topics of this presentation.

To start, I will review a background understanding on geothermal energy and conventional geothermal resources in order to frame the concept of EGS technology.

Next, I want to show you where R & D test sites have been established and to show that they have been set up in a diversity geological settings covering a wide temperature range.

Then we turn to energy extraction and resource estimates followed by stimulation methods and induced seismicity. These facets represent important aspects for EGS success.

Lastly, I will cover some of the challenges that need to be overcome in the near term.



Let's just quickly review some key points about geothermal energy that provide background information relevant to understanding EGS.

The Earth is a huge thermal battery with vast geothermal resources, and heat is being continuously generated by decay of radioactive elements in the Earth's interior.

Heat transfer occurs by conduction & convection.

Geology dictates how & where geothermal resources can be utilized.

The hottest resources (120-330°C) are used to generate electricity from production hot water and/or steam from deep production wells.

Cooler geothermal resources (<150°C) are used for a wide range of direct use applications, requiring heating or even cooling.

Lastly new technologies are required to unlock Earth's vast geothermal energy resource potential, which is the primary aim of EGS.

Definitions

Geothermal System is the set of processes that transfers heat to the surface. The mechanisms of heat transfer involve conduction and convection.

Geothermal Reservoir is the volume of rock from which thermal energy is extracted; it contains fluid in fractures & pores made of hot water & sometimes steam. The thermal energy stored in rock is huge (>10^{17} J/km^3).

EGS (Enhanced Geothermal System) is power production from a volume of hot impermeable rock. It requires stimulation to create fracture controlled fluid flow & convective heat transfer. EGS represents an *enhanced geothermal reservoir.*

Unconventional Geothermal Resources are located in extreme unproven settings/environments, including supercritical & EGS.

Before we get too far along let's review a few definitions

A geothermal system is the set of processes that transfers heat to the surface. The mechanisms of heat transfer involve conduction and convection.

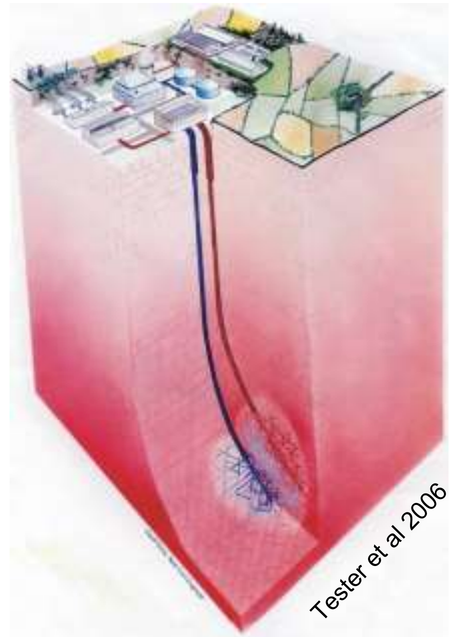
A geothermal reservoir is the volume of rock from which thermal energy is extracted. It contains fluid(s) in fractures & pores made of hot water & sometimes steam. Note, the thermal energy stored in rock is huge.

EGS is the abbreviation for Enhanced Geothermal System and it represents power production from a volume of hot impermeable rock. It requires stimulation to create fracture controlled fluid flow that enables convective heat transfer. EGS really represents an enhanced geothermal reservoir.

Lastly, the term unconventional geothermal resources are ones that are located in extreme or unproven settings and environments. Unconventional can refer to very high temperature-pressure supercritical conditions and it an refer to EGS which is the topic of this presentation.

EGS Concept (evolved since 1970s)

- Produce geothermal energy from hot impermeable rocks; 100-1000GW potential.
- Paired injection-production wells (doublet).
- Enhance permeability & convective heat transfer by stimulating existing fractures.
- Hot Dry Rock (HDR) at 3-10 km depth—widespread.
- Hot Wet Rock (HWR) margins of hydrothermal systems <1-4 km depth—localized.
- Apply drilling & reservoir engineering methods used in unconventional oil & gas production.



EGS is a concept that first emerged in the early 1970s, having been developed by scientists and engineers working at Los Alamos National Lab, and the graphic captures the essential elements.

The idea is to produce power from hot impermeable rocks, and various resource estimates suggest the possibility of producing 100-1000 GWe in the USA alone.

Power production requires the drilling of deep wells, usually as a doublet, where one well is used for injecting cold water and the second well is used for producing hot water.

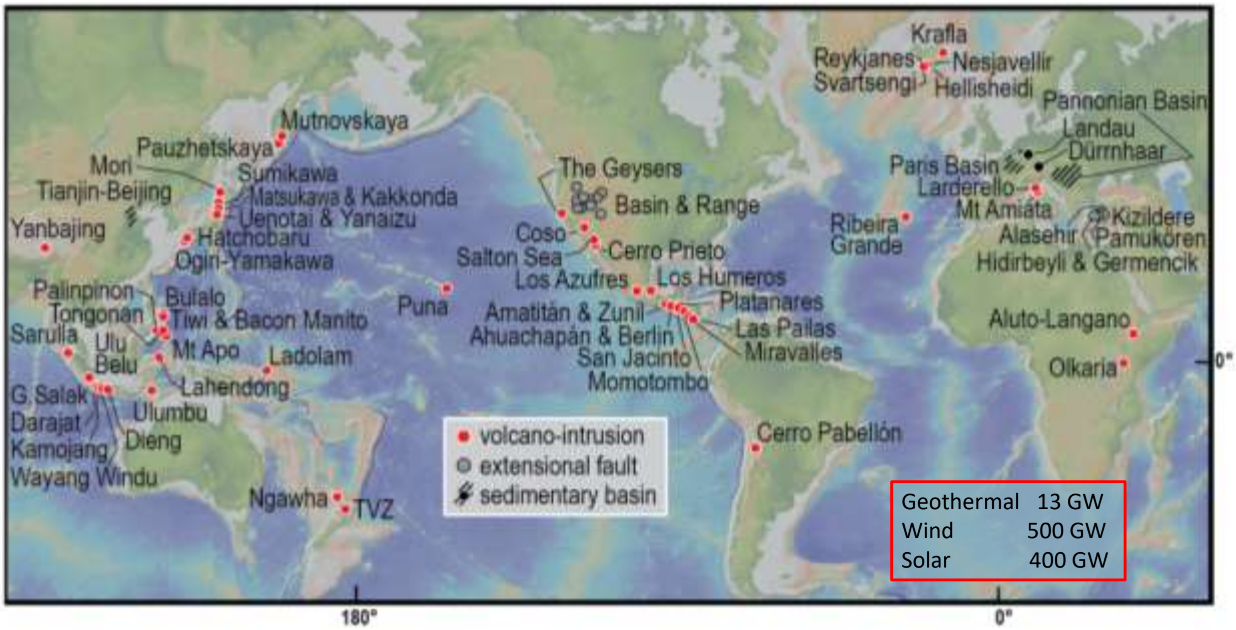
Permeability is enhanced by reservoir stimulation through targeted injection of pressurized cold water. The idea is to pry apart existing fractures in rock just enough to permit fluid flow and convective heat transfer.

Originally, EGS technology was conceived as being developed in hot dry rock, because such hot dry rock is widespread at depths of 3-10 km beneath the surface.

Later on, EGS came to include volumes of impermeable rock sitting within or on the margins of conventional geothermal resources in hydrothermally active areas. This is referred to as Hot Wet Rock.

There is now a concerted effort to trial drilling and reservoir engineering methods used in unconventional oil & gas production in order to advance EGS technology, including the use of highly deviated wells.

Geothermal Power (~13 GW electricity generation)

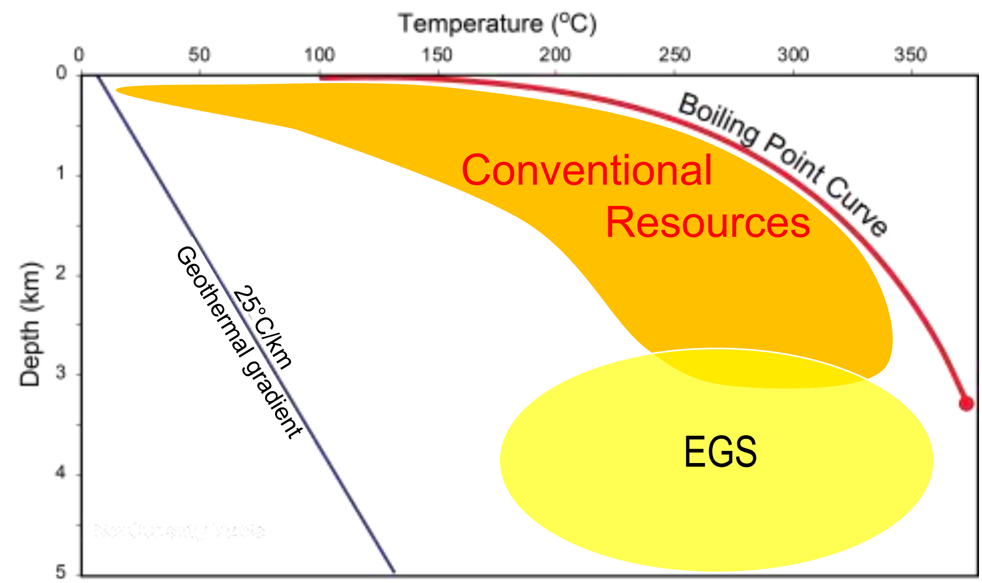


Currently, conventional geothermal power generation occurs all over the world but it only amounts to about 13 GW, which is small compared to wind at 500 GW and solar at 400 GW.

Furthermore, the geothermal resources on the map are all restricted in their location by geological circumstances where subsurface temperature gradients are highly elevated by hydrothermal activity.

One of the goals of EGS is to overcome such restrictions by enlarging the number of places where geothermal energy can be developed.

Geothermal Resources: Temperature vs Depth

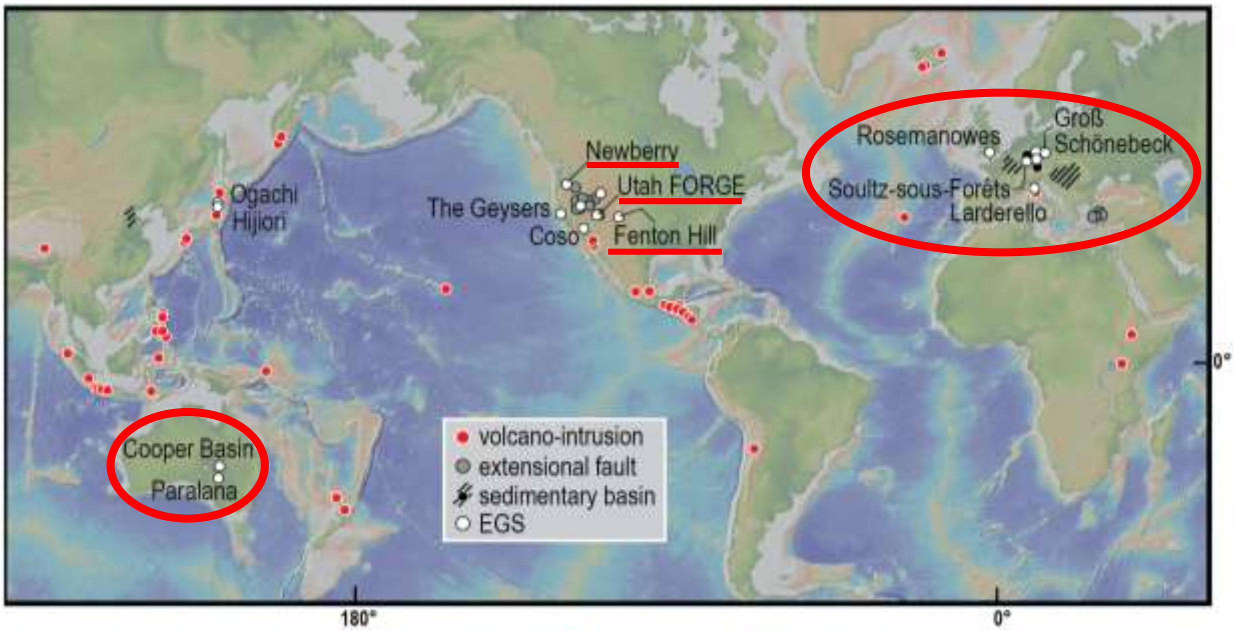


For example, the maximum temperature gradient is shown on the right and labeled Boiling Point Curve. This represents a convective heat transfer regime and the best grade of conventional geothermal resource occurs in hydrothermal environments.

Most of the crust, however, is characterized by a geothermal gradient of 25 deg C/km represented by the straight dark blue line. This means that to find temperatures exceeding 200 deg C under normal crustal conditions, one would have to drill to >8 km depth.

In the western USA, there are large areas having much higher conductive heat flow, and thus the current target for EGS development is the hot dry rock occurring at greater than 3-4 km depth shown by the yellow oval. Once this region is proven to be viable, deeper resources can be tested. We will return to this in a few slides.

EGS Test Sites & Geothermal Production Fields

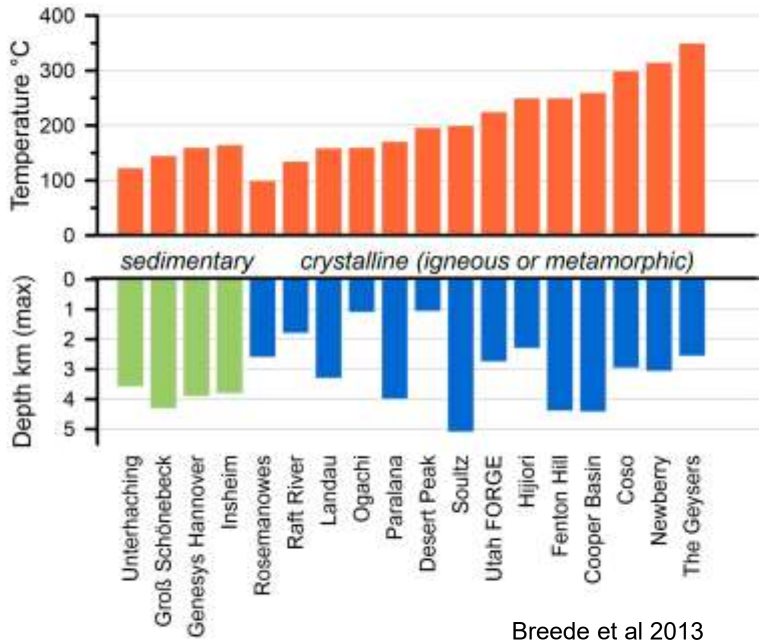


First, I want you to see that EGS has been trialed in a number of countries, and, in some cases, in places that are far removed from belts of conventional geothermal production.

The very first site is Fenton Hill located in northwest New Mexico, just outside the western edge of the Valles caldera in the northern part of the Rio Grande Rift. This pioneering project spanned more than 15 years of drilling and testing and the findings formed the foundation for all subsequent efforts, including developments in Australia and Europe where small scale power plants have been constructed

In the USA, a number of sites have been subject to testing over the last decade and most of these efforts were directed at improving the productivities of hot wet rock reservoirs. Newberry in Oregon is an exception being centered on a hot dry rock resource. More recently, the DOE has set up a new HDR project to advance EGS methods and technologies at Utah FORGE.

EGS Test Sites: Depths, Host Rocks & Temperatures



<u>Hot Dry Rock</u>
Rosemanowes
Utah FORGE
Hijiori
Fenton Hill
Cooper Basin
Newberry

<u>Hot Wet Rock</u>
sedimentary host rocks
Raft River
Ogachi
Desert Peak
Soultz
Coso
The Geysers

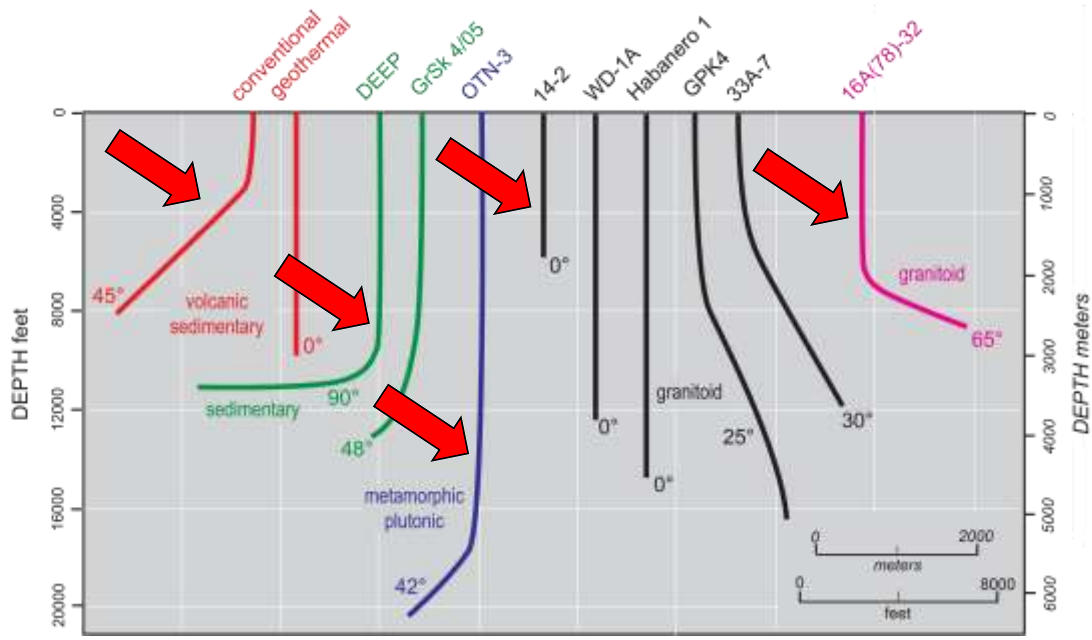
More information about the test sites is shown here.

The reservoirs have been developed in sedimentary, igneous and metamorphic rock types. The ones in sedimentary rocks are all located in Germany and they are represented by green-filled bars on the far left, with drill depths of 3-4 kms and reservoir temperatures between 120 and 165 deg C.

The ones in crystalline rocks, having an igneous or metamorphic origin, are represented by blue filled bars on the right, with drill depths of 1-5 km and reservoir temperatures between 100 and 350 deg C.

It is quite evident that a wide range of circumstances have and continue to be investigated, with about half representing hot dry rock environments and the other half representing hot wet rock environments.

Geothermal Wells: Depth, Reservoir Rock & Trajectory



People often ask why is EGS so difficult to advance, and one of the big issues is the cost of drilling, which is very high. There is also now a desire to drill strongly deviated wells. A lot of progress has been made including just recently, and this has been enabled by advances used to drill unconventional oil and gas reservoirs.

So let's look at the profiles of geothermal wells, the depths, host rocks and trajectories which are summarized here.

On the far left and shown in red, conventional geothermal wells are drilled to a maximum of about 3000 meters, in stratigraphic successions dominated by volcanic and sedimentary rocks. It is common to see both vertical and directionally drilled wells with the latter deviating up to 45 degrees from the vertical.

Next in green, two well profiles drilled in sedimentary basins are shown. The one labeled DEEP is recently completed in southern Saskatchewan in the Williston basin and has a 90 degree deviated leg. The other well is at Gross Schonebeck in Germany and it has a bottom hole temperature of 160 deg C.

The blue well labeled OTN-3 in Finland is the deepest and it was also recently completed (2018). It was drilled through granite and gneiss to over 6 km depth where the temperature is about 120 deg C and the potential of EGS is being evaluated for district heating rather than electricity generation.

The well profiles in black represent wells drilled since the 1980s in granitic rock. I am showing these because this rock type can cause wear and tear on bits and equipment but it is also the type of rock that will be the main host for future HDR-EGS reservoirs. There is a long record of drilling experience in granitic rock, starting with 14-2, which was drilled at Roosevelt Hot Springs, Utah in the late 1970s.

WD-1A, to the right, was drilled at Kakkonda, Japan and is notable for having a bottom hole temperature of ~500 deg C.

Habanero 1 is one of the wells drilled in the Cooper Basin project in Australia, and GPK4 is a deep well drilled at Soultz in eastern France.

The last of the black wells, 33A-7, was drilled at Coso.

This group of wells all emphasize that there is drilling experience in hard crystalline rock, but in all cases, the degree of deviation is modest, no more than 30 degrees from vertical.

It is for this reason that the last well on the far right, labeled 16A (78)-32, is relevant. This is a recently completed well at the Utah FORGE site, and it has a 65 deg deviated leg. It shows that the drilling of subhorizontal well trajectories in granite is within reach, and with practice lower drilling costs should be achievable.

EGS HDR Reservoirs Are Engineered

- Hot crystalline rock with pre-existing fractures.
- Enhance permeability via stimulation.
- Produce thermal energy by coupled conductive & convective heat transfer.
- Circulate chemically benign water & control mineral precipitation/dissolution.
- Continuous distributed fluid flow through fracture network to sustain long term power production.

Let's now summarize the key attributes of EGS engineered reservoirs in hot dry rock.

They require large volumes of hot crystalline rock, such as granite, that have pre-existing fractures but are impermeable.

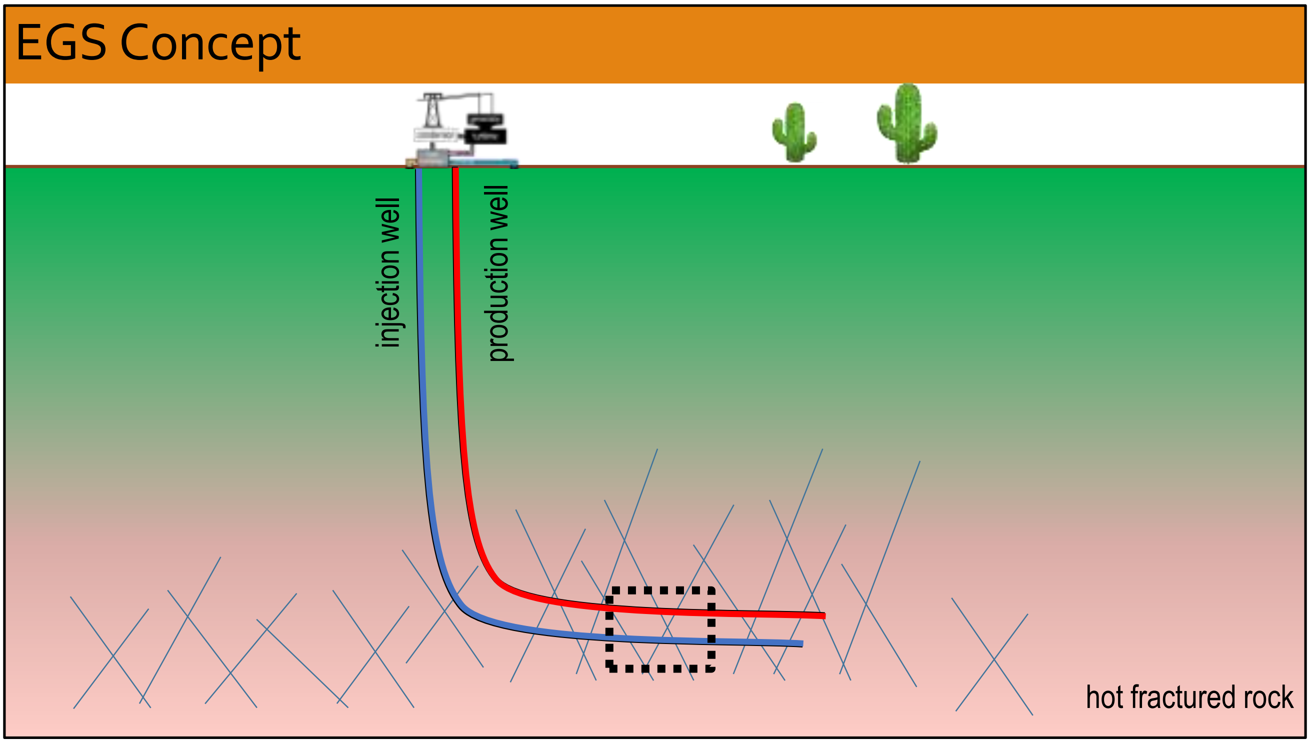
Engineering begins with enhancing permeability of pre-existing fractures by stimulation.

Geothermal energy is produced by the coupling of conductive and convective heat transfer mechanisms in the reservoir. Solid rock conducts heat and injected water carries it to the surface by convection.

Once the system is charged, the water is continuously recycled. Although it is generally chemically benign, even small amounts of mineral precipitation or dissolution may upset engineered fracture controlled flow that has been fine tuned for optimal heat transfer. So this requires careful management.

And this helps to emphasize the overall need for a distributed flow network in order to sustain the continuity of long term power production. Any indications of channelized flow, which is detrimental to subsurface heat exchange, will require corrective action.

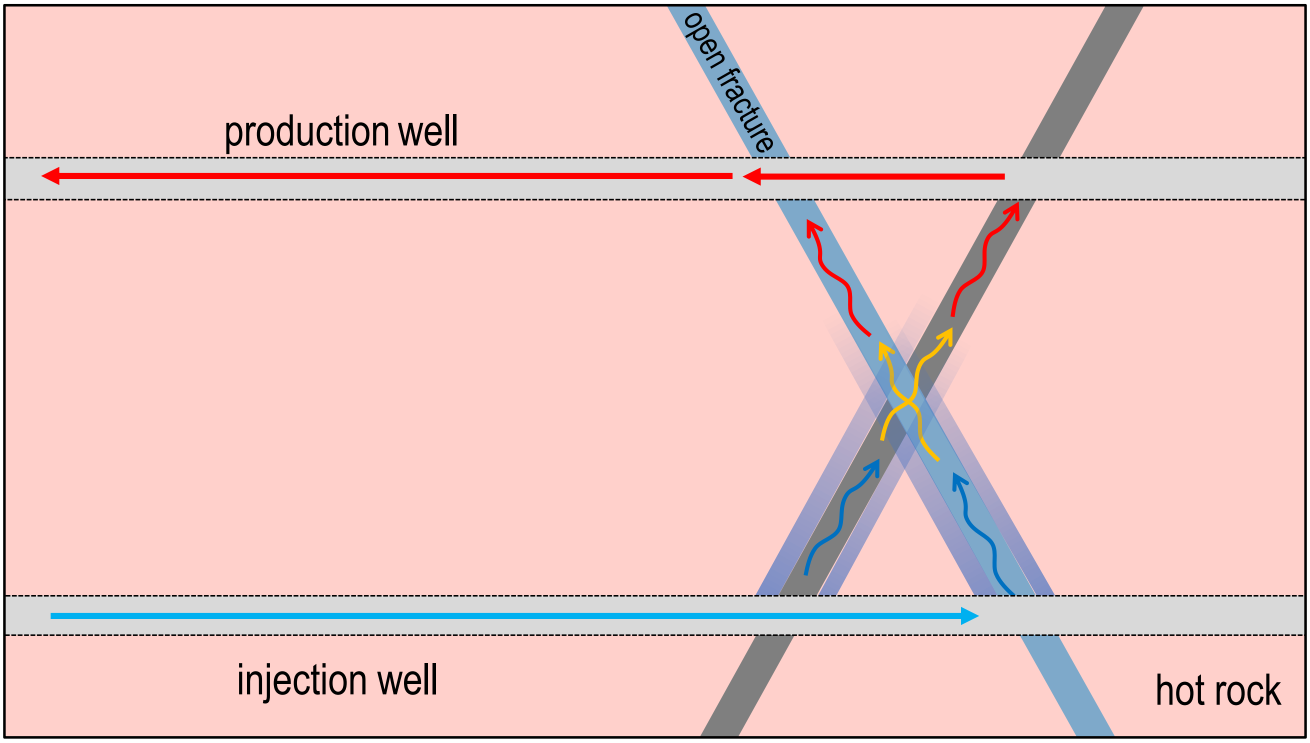
The main points are illustrated in the next two slides.



This is a cross sectional view or vertical slice extending to a few kilometres depth showing the subsurface setting of an EGS Hot Dry Rock reservoir.

We start with the drilling a deep well having a long horizontal leg to intersect subvertical fractures represented by criss crossing blue lines. Once completed, we pump cold water down the well for injection and fracture stimulation. This creates reservoir permeability and cold water heats up as it infiltrates the rock mass. The second well is used for production. It is drilled into the stimulated fracture network, so that heated water can be pumped back to the surface to generate electricity.

Let’s zoom in on the rectangular box to show in finer detail how fluid flow through fractured rock produces hot water.



Shown here is the injection well track on the bottom and the production well track on the top.

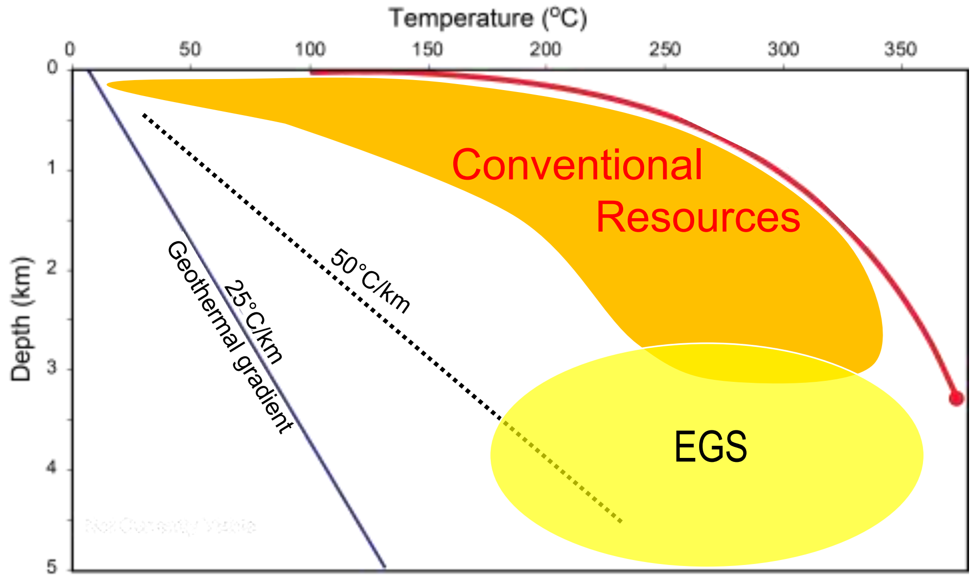
The preexisting fractures are shown in blue and grey colors having subvertical orientations.

The blue one is open, and the injected cold water heats up as it interacts with the rock. Note, the heat is being extracted from the rock just beneath the facture surface. The resulting hot water is then pumped back to the surface via the production well.

In order to facilitate further heat recovery, cold water is injected into a second fracture. Again, hot water is produced by the extraction of heat from the rock along the fracture selvage, and it is then pumped to the surface

A key point is to see how the distribution of fractures and the fracture surface area controls the total amount of water-rock heat exchange required to produce geothermal power.

Geothermal Resource Estimates



Having seen how thermal energy is extracted, we can take this understanding to make a resource estimate. Remember, we are targeting a regime that is generally hotter than 200 deg C and > 3 km depth. To find such resources, we have to locate regions with elevated heat flow of 50 deg C/km or greater.

Stored Heat Hot Rock (ΔT=210-200 °C)

$$Q_R = \rho_R c_R V (\Delta T)$$

ρ_R density = 2550 kg/m^3
c_R specific heat capacity = 1000 J/kg °C
V volume = 10^9 m^3 = 1 km^3
ΔT = 10°C (cooling)

$$Q_R = 2.55 \times 10^{16} \text{ joules/km}^3$$

The resource estimate depends on a fairly simple mathematical relationship that quantifies the producible thermal energy, Qr, that is stored as heat in solid rock. The value of Qr is related to density, specific heat capacity, rock volume and the delta T or amount of cooling in degrees Celsius.

The range of values for rock density are reasonably narrow as is the specific heat capacity of rock. The volume is fixed at a cubic km.

The last variable represents the amount of rock cooling and heat release as a function of change in temperature. So for the purposes of the calculation, a modest value of just 10 deg is used, representing cooling from 210 to 200 deg C.

By multiplying all of the variables, there is about 2.5 x 10^16 joules/km3 of thermal energy release.

Power from Hot Rock (ΔT=210-200 °C)-30 Years

$Q_R = 2.55 \times 10^{16}$ joules/km^3

30 years = 9.46×10^8 seconds

~27 $MW_{thermal}$ over 30 year period

2% recovery factor & 10% conversion efficiency

~0.05 $MW_{electrical}$

Low power density compared to conventional geothermal power generation (5-50 MW*e*/km^2)

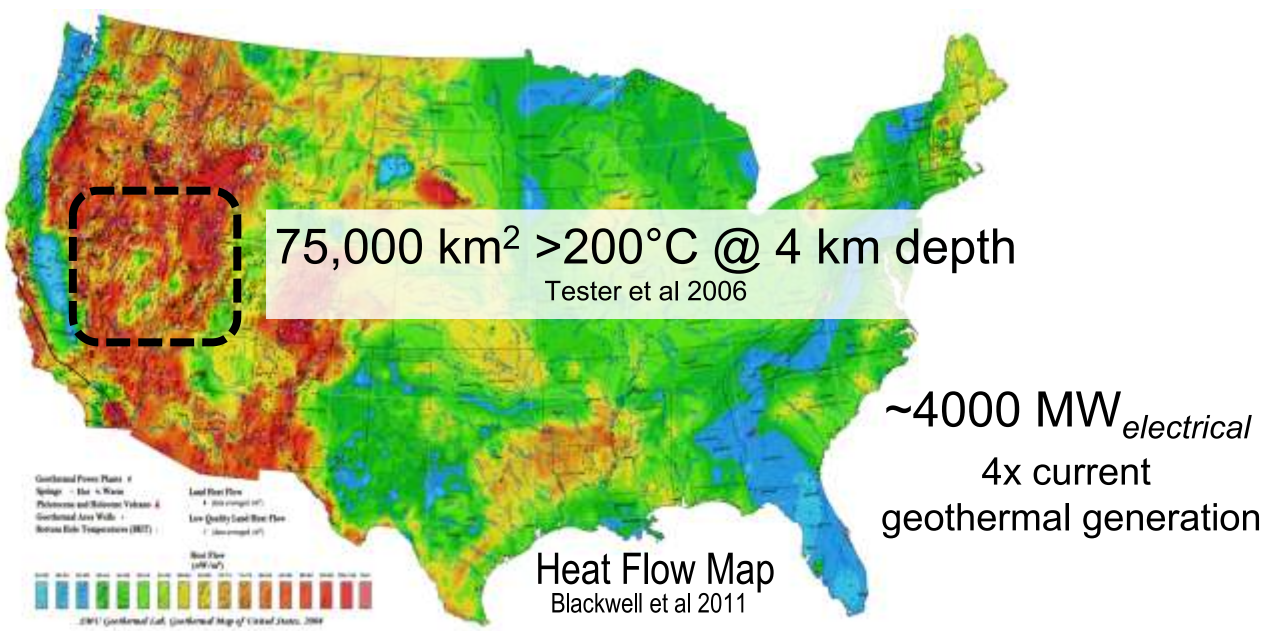
We can now consider how this relates to electricity generation over a 30 year period, which represents the commercial life of a power plant.

So multiplying Qr by 30 years gives a power production of 27 MW thermal.

From experience, we know that only a fraction of this thermal energy will be recoverable. There has been some debate as to how much is practical, and for our purposes, we will be conservative, and designate a recovery factor of just 2%. We also need to convert from thermal to electrical power, which has an efficiency of about 10%.

From this, an electrical output of 0.05 MW is calculated. This rather low value reflects a low power density, especially compared to conventional high grade geothermal resources, which can exceed 5 MW. Nevertheless, the output can multiply several times over simply with improvements in recovery coupled with an increased drop in temperature. Furthermore, the volumes of heat that could be available are huge.

Power from Great Basin (ΔT=210-200 °C)-30 Years



For example, looking at the heat flow map of the USA, the area in red highlights a large region in the west that is endowed with anomalous heat flow.

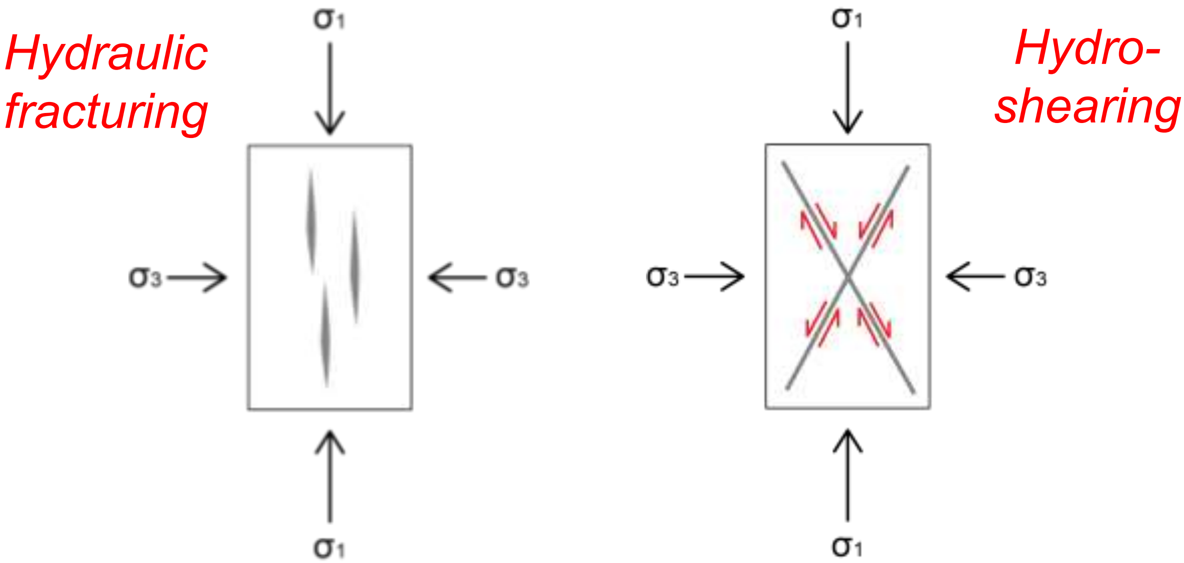
One of the hottest regions is the Great Basin where the temperature exceeds 200 deg C at 4 km depth over an area of 75,000 km^2.

If we take this 75,000 km^2 area to be 1 km thick, and multiplying the volume by 0.05 MW, a geothermal power production potential of about 4000 MW is calculated, which is 4 times the currently installed capacity for geothermal power generation.

Improvements in recovery and deepening of wells, simply multiplies the resource potential.

One of the key take home points is that EGS HDR technology has very broad application, minimizing the geological factors that limit where and how geothermal power is developed.

Stimulation Methods



Stimulation is essential in order to enhance EGS reservoir permeability otherwise it is impossible to extract heat. Stimulation methods have been used for improving oil and gas recoveries in hydrocarbon fields since the mid 1900s and the first applications in EGS studies were trialed at Fenton Hill in the 1970s.

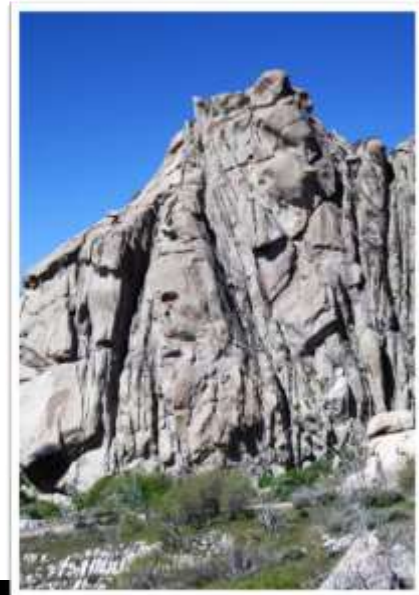
To illustrate effects, I am going to use a 2D representation of stress used in rock mechanics. Sigma 1 is vertical representing the maximum compressional stress, and sigma 3 is horizontal representing the minimum compressional stress or the maximum extensional stress. The volume of solid rock is outlined as a rectangle.

Early on, workers expected that injection of pressurized water would create new tensile fractures oriented perpendicular to the direction of least principal stress (sigma 3) as is characteristic of stimulation effects in hydrocarbon reservoirs. This type of effect is shown on the left, and it is called hydraulic fracturing.

Instead in EGS stimulations, it turned out that pre-existing fractures were opening through shear displacement in the direction of the red arrows illustrated on the right. This process is called hydroshearing. Furthermore, the translation of bumps and dips across the rough fracture surface created openings that enhanced rock permeability. This is known as self propping. Thus reactivated structures were the ones that controlled fluid movement in tight crystalline rock.

Stimulation Methods

- Hydroshear
  - Inject pressurized water to create openings in existing fractures
  - Only structures that are favorably oriented with respect to the existing stress regime become lubricated & subject to slip
  - Creates 3D fracture mesh that controls fluid flow
- Thermal contraction via cold water injection
- Acidization preferentially dissolves soluble minerals

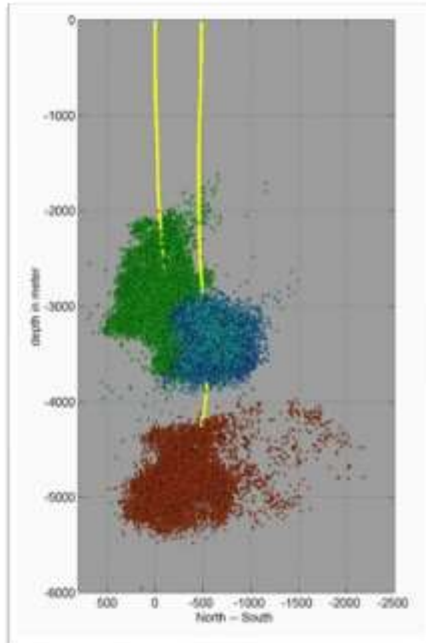


For hydroshear, then, pressurized cold water is injected to create openings in existing fractures. Only structures that are favorably oriented with respect to the existing stress regime become lubricated and subject to slip. The stimulated structures that intersect one another create a 3D fracture mesh which controls the flow and heating of cold water that ultimately provide connected pathways between the wells. This results in each well having a number of exit and entry points.

It is worth pointing out that there are other stimulation methods too, including thermal contraction resulting from cold water injection and acidization, which preferentially dissolves soluble minerals and creates interconnected pores. Both of these, however, have been used mainly in hot wet rock reservoirs.

Seismic Monitoring

- Hydroshear induces microseismicity comprising a clustering of low magnitude events.
- Microseismic cloud(s) trace fluid penetration through the stimulated fracture mesh.
- The detection & location of events (M<0) requires seismic network w/ low noise.
- The occurrence & extent of microseismicity coincides with reservoir development.



Microseismic cloud induced by stimulation of borehole GPK2 at Soultz-sous- Forêts Majer et al 2007

One of the main consequences of hydroshear is induced microseismicity, which is the clustering of many individual earthquake events that are tiny, low magnitude and unfelt at the surface.

The clustering of microseismic events creates clouds that trace fluid penetration through the stimulated fracture mesh.

The detection and location of slip events having magnitudes as low as less than 0 are made possible with a seismic network comprising distributed instruments that have been located in settings with low ambient noise. This often requires borehole deployments, and the sensors may include 3 component geophones, broadband seismographs, and fiber optic cable known as DAS (Distributed Acoustic Sensor).

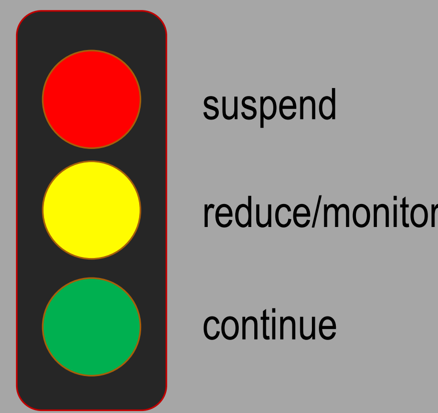
Importantly, the occurrence and extent of microseismicity illuminates how and where the reservoir is being developed and it can be used to interpret the stress field. It is a key tool in advancing EGS technology.

The example on the right from Soultz-sous-Forets shows microseismicity extends outwards from the point of injection up to ~1000 m.

Seismic Monitoring

- Required to mitigate large events
- Caused by change in pore pressure & effective stress along fault-fracture plane
- Can be controlled by:
  - avoiding major fault structures
  - understanding potential mechanisms of slip
  - appropriate monitoring network, includes seismographs & accelerometers
  - advanced planning & response
  - monitoring of EGS site operations

Traffic Light System



That fluid injection induces seismicity in the subsurface has been known and studied >100 yrs. In the last 15 years, there have been well documented large magnitude events that have effectively terminated EGS investigations including one in Basel Switzerland and the other in Pohang, South Korea. One of the lessons learned from these two experiences is the care and detail that is required in characterizing seismic risk before deep drilling operations commence. This means that one needs to know as much as practically possible about the subsurface geology and structure, including the orientations and extents of all faults.

Seismic monitoring must also be installed to detect precursor signals and mitigate large events.

Generally, induced seismicity results from a change in pore pressure and effective stress along a fault fracture plane.

Induced seismicity can be controlled by:

Avoiding major fault structures

understanding potential mechanisms of slip

Having installed an appropriate seismic monitoring network that includes seismographs and accelerometers, the latter used to detect ground shaking.

Advanced planning of action and response.

And lastly, a good communication system and hour by hour monitoring of EGS site operations, particularly during periods of drilling and stimulation.

Traffic light systems are used to communicate a rapid response from seismic monitoring networks. The thresholds that distinguish, green, amber, and red light commands are calibrated according to analyses of seismic risk and threat to infrastructure like buildings and roads.

So for example, drilling and stimulations are given the green light to continue as long as the magnitude of events is below a certain low level, e.g. M<2.

Amber, indicates the need to reduce activities in conjunction with heightened monitoring based on either the detection of a nearby single higher magnitude event or the short term clustering of many small magnitude events within a 24 hr period.

Red is an extension of amber where thresholds are exceeded for example greater than magnitude 3. In this case the EGS site operations are suspended until cause and effect analyses can be thoroughly scrutinized.

Challenges

- Sustain geothermal power production (>20 y) from engineered reservoir; flow >40 l/s.
- Wells have to withstand thermo-mechanical stress cycling & support zonal isolation.
- Long-life tools & electronics that withstand hot operational temperatures need to be available.
- Stimulate & maintain large fracture surface area for effective & protracted heat transfer.
- Physical-chemical influences on permeability managed to sustain even distributed fluid flow.
- Accurate & predictive numerical models.

EGS methods to date have been used successfully to enhance geothermal production in hot wet rock environments, but the real prize of EGS in hot dry rock remains commercially unproven.

There are a number of challenges that need to be overcome, and they center most closely on achieving sustained geothermal power production (>20 y) from an engineered reservoir. And production flows from individual wells will have to exceed 40 l/sec.

Wells will also have to withstand thermo-mechanical stress cycling & support zonal isolation, wherein the injection of fluids can be controlled.

Long-life tools & electronics are required to withstand hot operational temperatures, as illustrated in the photo right where the rubbers around a failed packer degraded due to hot temperatures.

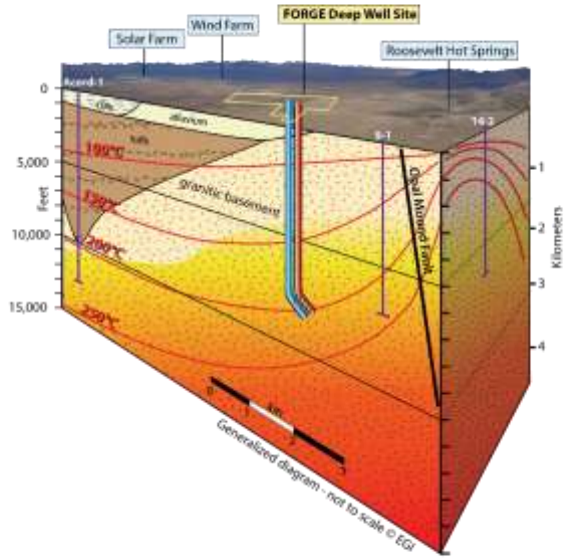
There is also need to be able to stimulate & maintain large fracture surface area for effective & protracted heat transfer.

Physical-chemical influences on permeability need to be managed to sustain even distributed fluid flow through the reservoir.

Lastly, accurate & predictive numerical models need to developed to make reliable forecasts of performance and thermal drawdown.

FORGE: Frontier Observatory for Research in Geothermal Energy

- Improve understanding of how to enhance permeability, create distributed fluid flow networks & promote continuous heat transfer.
- Accelerate development, testing & improvements in EGS technologies that are reproducible & widely applicable.
- Focus on drilling, tools, stimulation, zonal isolation, microseismic detection/monitoring, reservoir analysis & numerical modeling.
- Reduce uncertainty & risk for commercial development.



UTAH FORGE
U.S. Department of Energy

There is now very strong support from the US Department of Energy to advance EGS technologies through the FORGE program.

FORGE stands for Frontier Observatory for Research in Geothermal Energy, and the first test site has been established near the town of Milford in southwestern Utah. This same area was originally identified for HDR energy potential in the 1980s by the Los Alamos National Lab.

The overarching goals of the FORGE program are to build on the previous decades of research findings to

- Improve understanding of how to enhance permeability, create distributed fluid flow networks & promote continuous heat transfer.
- Accelerate development, testing & improvements in EGS technologies that are reproducible & widely applicable.
- Focus on drilling, tools, stimulation, zonal isolation, microseismic detection/monitoring, reservoir analysis & numerical modeling.
- Reduce uncertainty & risk for commercial development.

In closing, EGS provides a means for boosting clean renewable energy production, and with the anticipation of technical breakthroughs, sizeable growth in geothermal development is expected. The thermal energy is there, we just need to extract it, efficiently and cost effectively.

UTAH FORGE
U.S. Department of Energy

www.utahforge.com

Funding provided by
Geothermal Technologies Office
U.S. Department of Energy

This presentation is sponsored by US Department of Energy. For more information about geothermal technologies and Utah FORGE, please visit our website.

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