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Unconventional Geothermal Technology to Help the Climate Change Issue in the Densely Populated Areas of the World with a Demand for Higher Energy

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ABSTRACT

It is recognised by many international organisations (World Bank, UNESCO etc.) that by 2050, climate change will have a dramatic effect on not just human beings but also on world geopolitics. It is expected that geothermal energy should be able to play a major role in addressing this issue, but this has not been the case to date due to a disparity in the availability of geothermal energy in relation to the increased demand for energy from the high density populated areas of the world (China, India, Europe, etc.). The higher demand for energy in these areas is normally met with a hydrocarbon resource and thus the associated emission of greenhouse gases and other contaminants into the atmosphere which in turn lead to the climate change effect.

Conventional geothermal development worldwide is mainly confined to high enthalpy (volcanic) areas of the world such as Italy, Philippines, Indonesia, New Zealand, Iceland and others where the depth required to access high temperatures is relatively shallow. Economically this is a distinct advantage, but as the density of population in many of these specific areas is extremely low, it makes the contribution of such development relatively insignificant on a world-wide scale. Research is being carried out in various parts of the world to see if the geothermal energy resource can be made more accessible economically in the non-volcanic regions of the world, where the majority of the densely populated regions exists (~ 7 billion). One of these concepts is the Engineered Geothermal System (EGS), whereby deep natural conductive faults are hydraulically manipulated at depth to emulate a natural (conventional) heat exchanger which can then allow cold injected water to be heated up and brought to the surface as high temperature heat for commercial application.

Developments at the Rosemanowes site, in Cornwall UK (1976-1993) and at the European EGS site at Soultz-sous-Forêts in France (1990-2006) have shown that natural hydraulically conductive faults do exist in igneous basement at great depth and these can be hydraulically manipulated for extracting high-temperature fluid. These hydraulically conductive faults are linked with the geo-mechanical properties of the rock mass, where the strike of these faults is oriented in the direction of maximum horizontal stress. Therefore, a good knowledge of in-situ geo-mechanics is crucial to understanding the preferential direction of fluid flow within large conductive faults and the methods that can be used to enhance their performance. Using this concept, a number of commercial projects have been successfully developed in the Rhine graben, however the concept needs to be proven in other parts of the world to demonstrate its application/usage throughout the world and thereby help to mitigate the climate change issue.

A scenario is put forward in this paper, based on experience gained at various sites, which could help to reduce the impact of the climate change phenomenon and to provide a glimpse of hope for future generations. The issue of climate change is becoming critical, therefore it will be the areas of higher population density where the most drastic reductions in fossil fuel usage will need to be implemented in order to slow down the emission of greenhouse gases.

1. INTRODUCTION

Various studies clearly show that the present trend of excessive use of hydrocarbon products will continue to influence climate change and that if this trend is maintained it could result in a devastating impact on many species by 2050. It is envisaged that as a consequence of this some parts of the world (near the equator) will become uninhabitable due to extreme changes in meteorological conditions, such as lack of rainfall or excessive flooding. It is anticipated that this could result in a massive migration of people away from equatorial regions to the northern and southern hemisphere. This mass migration is expected to be in terms of tens of millions of people due to extreme weather conditions, the depletion of food and water supply, and other commodities. The outcome of such mass migration is likely to lead to conflict between nations. It is recognised that reduction in the use of hydrocarbons would slowdown the process of climate change and that renewable energy technologies, such as EGS, have the potential to make a significant contribution to this.

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Current conventional geothermal resources are associated with regions of the earth where temperature is high at shallow depth, but this resource is concentrated in regions of relatively young, active geology where population density is low. Large quantities of heat that are economically extractable tend to be concentrated in places where hot or even molten rock (magma) exists at relatively shallow depths in the Earth's outermost layer (the crust). Such "hot" zones, generally, are near the boundaries of the continental plates that form the Earth's lithosphere, which is composed of the Earth's crust and the uppermost part of the underlying denser, hotter layer (the mantle).

In a hydrothermal system, meteoric water migrates from the surface via faults and other permeable conduits to a specific depth, gaining heat and dissolved minerals dependent on the local geology. This becomes stored as a hot fluid reservoir. Traditionally, these stored hot fluid zones may be recognised by surface expressions (such as geysers) and geological settings, and can be further identified by geophysical surveys, drilling wells or a combination of these methods. Boreholes are drilled into the permeable zones of the hydrothermal systems to extract the hot fluid. Once the heat has been extracted, the cooled fluid is re-injected into known local faults away from the main reservoir, in the expectation that this fluid will then be reheated and will find its way back to the reservoir; thereby recharging the hydrothermal system.

There is a significant proportion of the upper crust that is hot but not sufficiently permeable to be considered hydrothermal. Igneous rock, such as granite, occurs at depth in many parts of the world and in some areas the heat within the granite is enhanced by its radiogenic composition. The concept of EGS was developed with the understanding that there is a significant proportion of the upper crust which is hot but is not sufficiently permeable to permit fluid flow from the surface which can be stored as a hot reservoir of fluid at depth, similar to that of hydrothermal systems. A concept has been developed whereby the permeability can be enhanced or an existing permeable fault system identified which will allow fluid to circulate through this system and will enable the stored geothermal energy to be extracted.

2. WORLD ENRGY DEMAND AND SUPPLY SCENARIO.

The largest source of energy for the Earth is the sun; approximately 220 W are available on each square meter of the surface of our planet when the sun shines. A simple assessment shows that this influx of energy is equivalent to the output of millions of electric power plants.

Global potential for geothermal electricity has been estimated at 45 EJ/yr - 12 500 TWhe, i. e. about 62% of 2008 global electricity generation (Krewitt et al., 2009). The same study estimated resources suitable for direct use at 1,040 EJ/yr - 289,000 TWht; worldwide final energy use for heat in 2008 was 159.8 EJ/44,392 TWht (Ibid.). The estimated technical potential for geothermal electricity and heat excludes advanced geothermal technologies that could exploit hot rock or off-shore hydrothermal, magma and geopressured resources. Although geothermal energy has great technical potential, its exploitation is hampered by costs and ***distances of resource from energy demand centers*** (IEA road map; geothermal heat & power (http://iea-gia.org/wp-content/uploads/2012/08/Geothermal_Roadmap-Final-Pub-Ver-15Jun11.pdf).

2.1 World Supply of geothermal energy.

A hydrothermal resource requires fluid, heat, and permeability. Geothermal hot springs have been exploited for domestic use since ancient times, but geothermal exploitation for industrial use started in the early 19th century where hydrothermal energy was used for extracting boric acid in Larderello (Italy). The first geothermal district heating system began operating in Boise (United States) at the end of the 19th century, followed by Iceland in the 1920s. The first successful attempt to produce electricity from geothermal heat was achieved at the start of the 20th century in Larderello. Installed geothermal electricity has increased steadily from then onwards. The global geothermal power capacity in 2009 was 10.7 GWe and generated approximately 67.2 TWhe/yr of electricity, at an average efficiency rate of 6.3 GWh/MWe (Bertani, 2010). A remarkable growth rate in geothermal energy occurred from 1980 to 1985, which was largely driven by the interest of the hydrocarbon industry – mainly Unocal. In some countries, geothermal electricity provides a significant share of total electricity i. e. Iceland (25%), El Salvador (22%), Kenya and the Philippines.

Almost all the electricity generated by geothermal energy is derived from hydrothermal power plants located predominantly in volcanic geology near the boundary of tectonic plates where the crust is thinner (Figure 1) and higher temperature can be attained at shallower depth. These systems may also occur in diverse geologic settings, sometimes without clear surface manifestations of the underlying resource.

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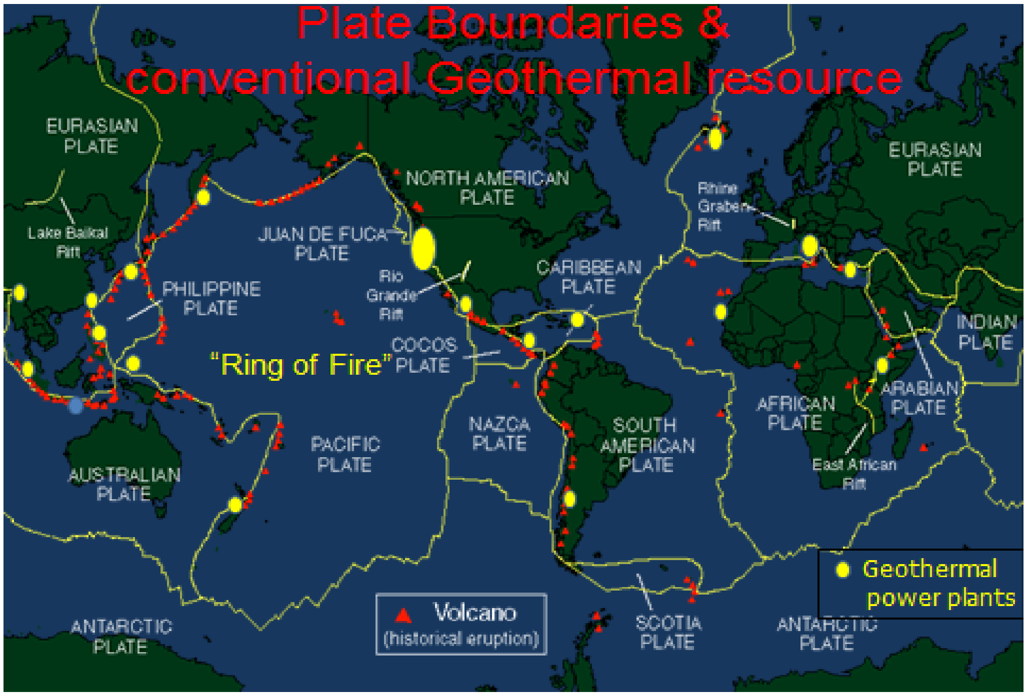

Figure 1: Plate boundaries and hydrothermal energy resource (modified from Geothermal Education Office, 2000)

2.2 World demand for energy.

The intensity of energy demand in the world can be attributed to the population density, the region's stage of industrialization and its growth of birthrate, all of which may fluctuate from decade to decade due to economic cycles and political changes. Although this can be a complex model to represent, a relatively simple indication would be to look at the population density map of the world to give some indication where the major areas for energy demand may lie. The total world population is estimated to be around ~7.5 billion (UN estimate); a density map of the population is shown in see Figure 2.

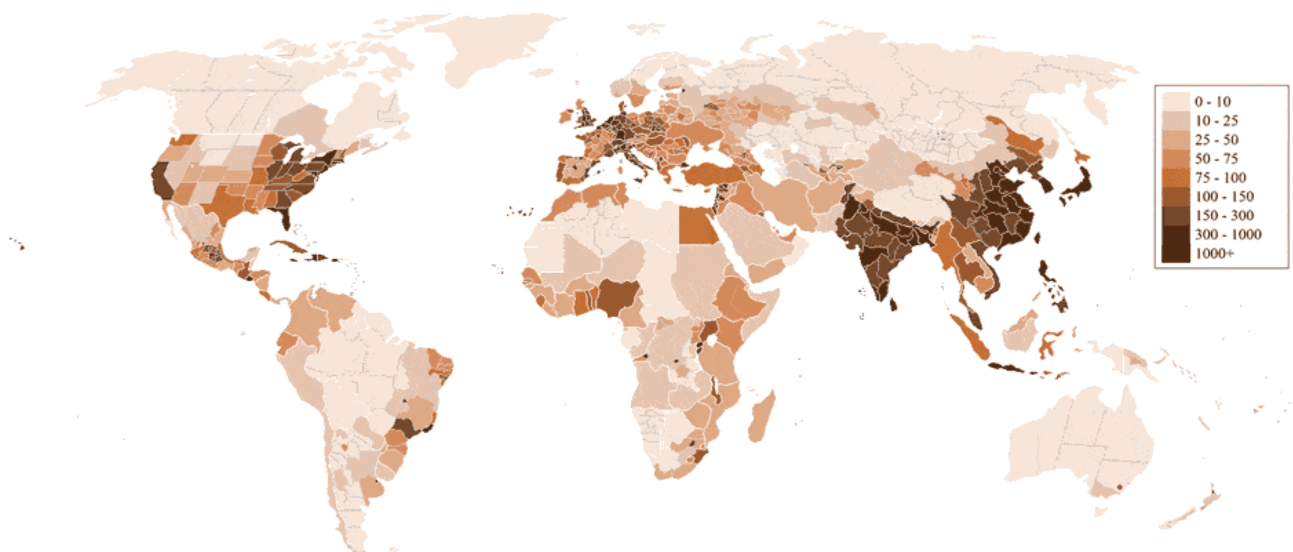

Figure 2: World population density, people/km^2 (Junuxx at en.wikipedia, 2017)

The greatest demand for energy is associated with countries that have a high population density, such as China, Japan, India, Western Europe, eastern and western parts of USA, Nigeria and Brazil.

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2.3 The role of geothermal in supply and demand for energy.

If one overlays the map of the supply of energy from hydrothermal (Figure 1) on to the population density map (Figure 2) which represents demand, then it is apparent that the supply of energy from hydrothermal systems is significantly divorced from the zones of demand. For example, New Zealand and Iceland can contribute appreciable amount of hydrothermal energy, but both countries are islands and their population is around 4.5 million and 350,000 respectively. This example demonstrates the disparity in the supply of hydrothermal energy and high demand areas of the world. One of the main problems with geothermal energy is that hot water cannot be conveyed over long distances or across continents in comparison with commodities such as oil, gas, coal, timber etc., therefore the limited availability of the hydrothermal resource does not lend it to greater exploitation worldwide.

There is an abundant non-hydrothermal resource in the world, but at present the methodology for extracting this form of energy is limited. Although the idea of generating sub-surface reservoirs comprising a heat exchanger with large effective volume by using hydraulic stimulations remains a valid technique, the creation of a sufficiently large artificial heat exchanger that is sustainable for round 25 years with acceptable flow resistance and far field water loss has not been achieved in almost all of the EGS projects to date (Baria et al., 2012). Demonstration that these parameters are achievable within the context of a widely available geology will verify the contribution that EGS can make on a world-wide scale.

3. THE ENGINEERED GEOTHERMAL SYSTEM (EGS)

The original concept of EGS, formerly known as hot dry rock (HDR), was developed in the early 1970s at Los Alamos in the USA (Smith, 1975). It consisted of drilling wells to a depth of 4,500 metres into the flank of a caldera at Fenton Hill, New Mexico, to access high temperature (~300 °C) and then to enhance the permeability of the system by injecting fluid under high pressure into fractures within the rock. This concept was replicated at the geothermal research project at Rosemanowes in the UK (Garnish et al. 1976; Parker, 1989, Willis-Richard et a 1990) and at other sites in the world. The wells at the Rosemanowes site were drilled into granite to a depth of 2,000 - 2,500 metres. The project was specifically designed to understand the physics of creating enhanced permeability in igneous rock (Baria et al., 1986), where shearing of natural fractures was the main mechanism for enhancing permeability.

Knowledge gained from over 30 years of research formed the basis upon which the European project at Soultz was built (Abe et al., 1999; Kappelmeyer & Jung, 1987; Baria et al., 1989, 1995,1995, 2000, 2006; Baumgaertner et al., 1996, 1998; Gérard et al., 1997). For the first time, wells were drilled successfully to 5,000 m depth in granite basement to access temperature around 200 ºC. Although the Soultz project started as an HDR project the discovery of the existence of hydraulically conductive natural faults at greater depth and the relationship of these faults to the in-situ geomechanics opened up a new concept for extracting energy from depth at higher temperature. It became clear that the fracture network at depth varies considerably and that natural hydraulically conductive faults were more prevalent than had been originally anticipated. In both projects, natural faults were observed to be the dominant flow structures. This proved that rather than creating an artificial heat exchanger using hydraulic stimulation of an impermeable jointed rock mass, it was more advantageous to use existing natural hydraulically conductive faults to mimic a natural hydrothermal system. These deep faults when correctly aligned in relation to the direction of maximum horizontal stress have the potential to behave like a hydrothermal system by permitting a reasonable flow rate over a long period.

The study of geology includes many imponderables that have not been understood and have yet to be dealt with in a fully satisfactory manner. Furthermore, it is common that as knowledge of geology improves new problems arise. Determination of the in-situ stress profile with depth is crucial; the major overriding factors include understanding the in-situ stress magnitude and direction. The configuration of the injection and production well is strongly influenced by the natural stress regime. In-situ conditions vary between localities and this makes it difficult to produce a pre-programed model on which to design deep geothermal reservoirs. Therefore, until more data is available, each system needs to be assumed to be site specific and appropriate engineering manipulations are required to bring each system into successful production. The success of this technology used at the Soultz project has led to the development of commercial EGS plants within the northern Rhein Graben at Landau and Insheim in western Germany, with other plants being developed in France.

3.1 Characteristic of deep faults in the Rhine Graben.

The Upper Rhine Plain was formed during the Early Cenozoic era, during the Late Eocene epoch and was associated with the formation of the Alps resulting from the collision of the European and African continents. It is thought that because the collision was irregular, the initial contact between the two continents resulted in the formation of dilational (extensional) structures in the foreland basin to the north of the Alps. The result was substantial crustal thinning, forming a major extensional graben and causing isolated volcanic activity.

To both the east and west of the Rhine Plain, two major hill ranges have formed that run the length of the basin. To the west, in France, these hills are known as the Vosges mountain range and in the east, in Germany, the hills comprise the Black Forest. Both ranges correspond to uplifts of more than 2,500 metres, much of which has since been eroded. This uplift has occurred because of the isostatic response associated with the formation of an extensional basin. As a consequence, the highest mountains exist immediately adjacent to the margin of the basin, and become increasingly low outwards. The boundaries between the hill ranges and the Rhine Graben are defined by major, normal fault zones. The northern section of the Rhine Plain is equally framed by somewhat lower mountain ranges, the Palatinate Forest on the western side and the Odenwald on the eastern side.

At the Soultz site, the granitic basement lies below 1.4 km of sediments. Graben-parallel faults produce a horst-and-graben structure within the basement. Fracture zones within the basement are high-angle and strike approximately normal to the E–W average minimum stress direction. The magnitude of Shmin is about 0.5 SV, which is typical of a graben setting. Thus, the rock mass, and many of the large-scale structures within it, is critically stressed at all reservoir depths (Evans, 2005; Valley, 2007).

During various drilling operations at the Soultz project (1990-2003), granite was sampled and logged extensively to a maximum depth of around 5,000 m depth. The wells (GPK1, EPS1, GPK2, GPK3 & GPK4) crossed many "permeable" fracture zones (faults) within the granite identified from drilling mud losses and/or the thermal signatures after drilling. In general these "permeable" fracture zones/faults are inclined around 70-75° and strike in a nominal north-south direction. On average the spacing of "permeable" fracture zones was found to be approximately 500 m along the vertical profiles. Therefore, considering their steep sub-vertical dip the mean normal distance between two sets of fracture zones can be estimated at 200-250 m.

The information on the joint network has been obtained from the continuous cores in EPS1 and borehole imaging logs in GPK1. The observations suggest that there are two principal joint sets striking N10°E and N170°E and dipping 65°W and 70°E respectively (Genter and Dezayes, 1993). The granite is pervasively fractured with a mean joint spacing of about 3.2 joints/m but with higher variations in joint density.Within the joint network, a number of hydrothermalised zones were also observed. These zones caused drilling fluid losses during the drilling operation indicating a degree of permeability at the wellbore. These were identified at around 2,815 m, 3,386 m and 3,485 m depth in GPK1, and around 2,100 m 3,500 m depth in GPK2.

Similar fracture characteristics were also observed 40 km away at the Landau and Insheim sites (Germany), demonstrating the presence of large conductive faults in the Rhine graben. In Insheim, reprocessing of old 2D-seismic data, acquired by the oil industry, and new 2-D seismic surveys were carried out successfully and allowed to delineate these conductive faults at depth around 3500 m. Subsequently, other successful commercial EGS projects have been developed further south of the Soultz project indicating the presence of deep conductive faults on much larger scale than originally envisaged.

3.2 Commercial EGS project at Insheim, Germany

The Insheim Geothermal Project is located on the western rim of the Upper Rhine Valley in Germany. At the time of reporting, the plant is one of four actually producing geothermal plants in the Upper Rhine Valley, all of which use the binary Organic Rankine Cycle (ORC) for power generation (Figure 3). The Insheim project was commissioned in 2008 and has been generating power continuously since 2012.

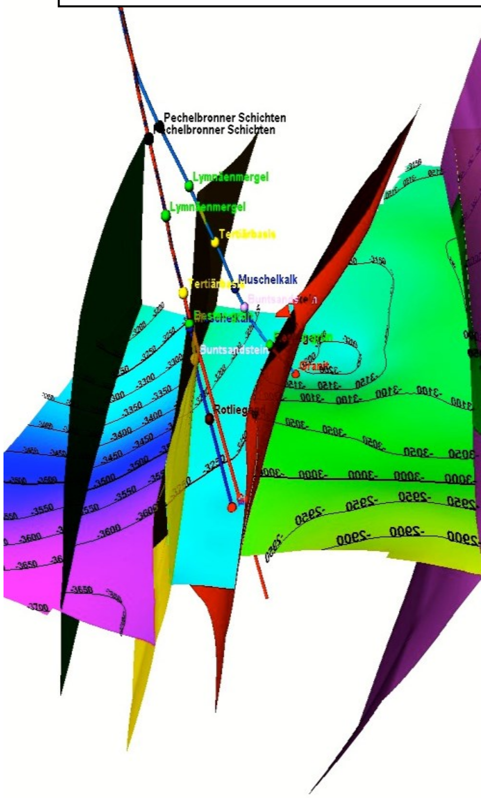
The Insheim project stemmed from an understanding built at the European EGS research project at Soultz, France; of the geomechanical behavior of the regional large deep natural faults (Garnish et al., 1994; Baria et al., 1995). Geologically Insheim is located at the western rim of the Upper Rhine Valley with its typical north-south striking normal faults. Fluid flow takes place through the north-south faults in the Buntsandstein and in the granitic basement rock. This project exploits naturally permeable faults with relatively little requirement for hydraulic stimulation. There is one production well and one injection well to depths of about 3,800 m. It is a closed-loop system that does not require makeup water and does not discharge any harmful products into the atmosphere.

The business plan called for a gradual increase in flow rate from 65 l/s to 85 l/s in gradual steps (Baumgartner et al., 2013). The well head temperature is about 165 °C. During the build-up and testing phase of the development, it became clear that the injection well was not sufficiently permeable. Hydraulic stimulation improved the situation, but not to a sufficient amount. As a consequence a sidetrack starting at 2,500 m depth was successfully drilled off the injection well. This enables the injection flow to divide along both completions, thereby increasing the circulation rates up to 85 l/s, which are now sustainable with acceptable pump loads. The nominal power output of the plant is 4.8 MW (ORMAT systems Ltd.) and works on average about 8,000 h/year. The working fluid is Isopentane. A line-shaft pump installed on the production well is used to assist system performance. A feasibility study for a district heating system to sell heat commercially to 600-800 households from the power plant's rejected warm fluid (an average of 31% (76,500 $MWhr_{th}$) of heat annually rejected by the plant) to service seasonal demand, was found to be financially attractive (Heck et al., 2009).

Basic project parameters are as follows:

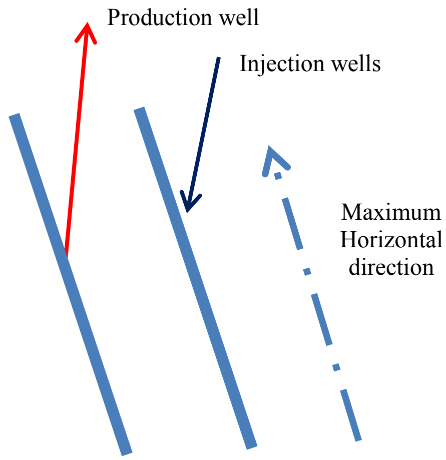
- Wellhead temperature: 165 °C
- Rejection temperature from power plant: 70 °C
- Maximum flow rate: 85 l/s
- Current flow rate: 68 l/s
- Maximum thermal power supplied to the power plant: 34 MW_{th}
- Current regulated thermal power supplied to the power plant: 26 MW_{th}
- Maximum electrical power at reference point: 4.8 MW_e
- Current regulated electrical power at reference point: 3.7 MW_e
- Average yearly production hours for electricity 2012-2015: > 8,000 hr
- Rejection temperature: 45 °C

INSHEIM



<u>Insheim Commercial Power plant</u>

2007-2012, Depth ~3800 m
Temperature 165 °C, Flow 65-85 l/s
Power output 4-5 MWe (~8000 homes)
Thermal output 6-10 MWth (potential)



(Concept of using natural faults)

Figure 3 Commercial EGS power plant at Insheim, Germany

3.3 Existence of such deep faults worldwide

Large natural fault systems are more widely available than the volcanic-based hydrothermal systems and therefore the development of EGS in this wider environment could have a significant impact on addressing the worsening effects of climate change. However, the 'quality' and 'quantity' of such faults in specific regions has yet to be fully ascertained. The identification of deep conductive faults is tricky – where does the direct evidence for their hydrological properties come from? Geologically, exhumed faults show evidence of periodic high permeability. However, it may well be that this period of high permeability is impaired by the deposition of minerals within the fractures that reduce permeability to much lower levels.

Historic information assisted the development and design of sites in Cornwall and at Soultz. In Cornwall, the geology at shallow depth (< 900 m) has been well recorded as a result of extensive metal mining activity and china clay extraction during the 18th and 19th centuries (Dine 1956). This, together with satellite imaging of some of the major faults are exposed at the surface, has provided knowledge on the presence of fault structures both within the granite and the overlying metasediments. The exploitation of for hydrocarbon resources in the Soultz area helped to build up the underground knowledge via the data from numerous oil wells drilled up to 2,000 m depth in the last century, although further exploration was necessary to delineate these faults, using techniques such as 3D seismic surveys. This would suggest that a comprehensive historical and geological survey is required to build up the knowledge of deep faults within any region, but there may be areas of the world where the presence of such faults is apparent. This may provide an opportunity to exploit this resource initially without expensive exploration techniques.

4. TESTING OF EGS CONCEPT AWAY FROM RHINE GRABEN; EDEN PROJECT, CORNWALL UK.

To date, most of the commercial exploitation of EGS has been in the Rhine Graben. For the EGS concept of using deep conductive faults to be more widely accepted in other parts of the world, it needs to be tested at a location which is significantly away from the upper Rhine Graben. One possible place to test this concept would be in the igneous basement in Cornwall, UK, which is approximately 1,200 km from the upper Rhine Graben.

EGS Energy Limited is proposing to develop an EGS geothermal plant at the Eden Project in central Cornwall (Figure 4), utilising technology acquired from the experience that has been gained during the 1980s from the project at Rosemanowes (which lies 35 km from the Eden Project) during the 1980s and subsequently at Soultz (France), and later developed into commercial systems at Landau

(2007) and Insheim (2013), in Germany. The Eden Project, which was opened in 2001, is a modern version of a botanic garden with integrated facilities for holding large pubic venues such as conferences, music events etc. and attracts almost 1 million visitors per year. The Eden Project lies on the southeastern edge of the St Austell granite pluton, comprising megacrystic biotite granite. The site is located in an ideal place in terms of the deep geological faults and also the demand for both electricity and heat for it to function effectively.

Figure 4: The Eden project near St Austell, Cornwall, UK.

The temperature gradient is reasonably well understood (Willis-Richards et al., 1990) and is estimated to be 37-40°C/km. The plant will comprise of a well doublet drilled to a nominal depth of 4,500 m in granite to intersect known deep faults. It is expected to produce water at approximately 180 °C to an ORC plant that would deliver a nominal gross output of 7 MWe, dependent on the hydrogeological characteristics of the target zone. The heat and power produced from the plant will be used primarily to supply the requirements of the Eden Project, with an off-take of surplus power either to the National Grid or to supply the private wire network of the local china clay operator.

4.1 Deep fault systems (cross courses) in Cornwall

The Cornubian Batholith, which underlies much of Cornwall and west Devon, is the largest of the granite batholiths in the UK. It is exposed, from west to east, in six major plutons, namely the Isles of Scilly, Land's End, Tregonning-Godolphin, Carnmenellis, St Austell, Bodmin Moor and Dartmoor granites. All the major plutons have been dated to be Early Permian and were emplaced over a period of approximately 20 Ma, from ~294 Ma (Carnmenellis Granite), ~285 Ma (St Austell Granite) to ~274 Ma (Land's End Granite).

The hydrogeological characteristics of a granite rockmass are dictated by depth and may vary from highly permeable within the near-surface weathered zone to effective lower primary permeability at depth that is confined within discontinuities and fractures. The contemporary stress regime in Cornwall and west Devon is similar to that across much of northwest Europe with the maximum horizontal stress (σH) orientated approximately NNW-SSE. The NW-SE fracture zones (crosscourses) are of particular importance for the development of EGS reservoirs in southwest England as they are near optimally orientated, with respect to the in-situ stress regime. Crosscourses are regional in extent and occur throughout the Devonian-Carboniferous successions and the granites.

Fracture formation and reactivation during granite magmatism and related mineralisation was primarily controlled by the evolving post-Variscan tectonic regime (Garnett, 1961; Hawkes, 1981; Shail and Alexander, 1997). These fractures facilitated the migration and mixing of magmatic, meteoric and basinal fluids that were fundamental to the mineralisation process. The main period of hydrothermal mineralisation was during the late/post-granitic emplacement. The dominant trend for the mineralised lodes is ENE-WSW to E-W and for the mineralised faults is NNW-SSE. The mineralised fracture systems have been interpreted to result from interactions between regional stresses and magmatic fluid pressures, typically resulting in extensional faults (Hosking, 1949).

Crosscoure is the name given to the faults that occur in a general N-S direction. They can be classified into two main types (Henwood, 1843; Bromley and Thomas 1988):

a) **Fissure fill crosscourses** – extensional fissures filled with clay and quartz, having a ‘vughy’ nature (sometimes named ‘cross-veins’),

b) **Shear/wrench crosscourses** – zones of intense micro-shearing in which feldspars and micas have undergone advanced argillic alteration into a clay gouge infill (‘fluccans’).

Crosscourses (Figure 5) are generally steeply inclined (70°-80°) and vary from individual veins <1 m in width with minimal offset of wall rock features to fault zones >100 m in width that may bring about an offset of Sn-Cu lodes of >100 m. Spacing for fault zones, with trace length >1 km, can vary from between 1-10+ km, but between 10 - 500 m for major veins. Crosscourses existed as fault fissures prior to lode mineralisation and were an important component of structural control during mineralisation. If these crosscourses have similar characteristic to that of the productive deep faults in the Rhine Graben then they may be capable of delivering ~70 l/s indefinitely.

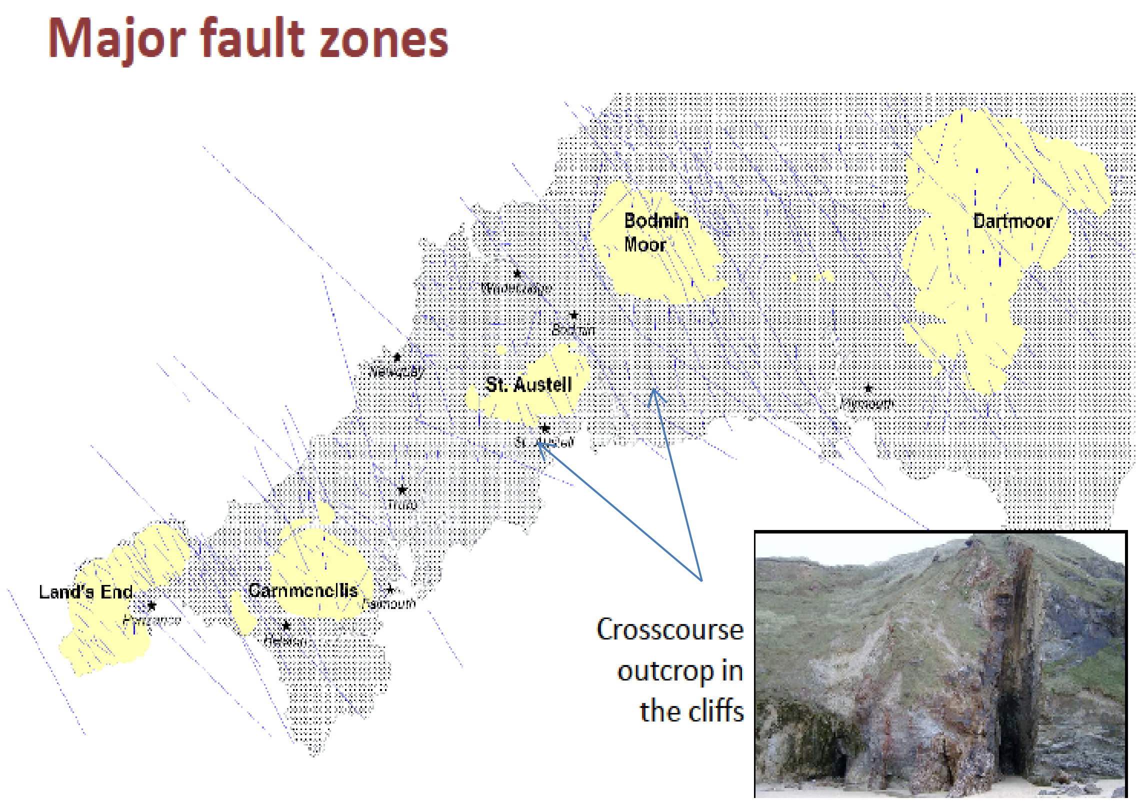


Figure 5: Satellite image of the crosscourses

Crosscourse mineralisation is primarily related to the migration of high salinity basinal fluids from formerly overlying and adjacent Permo-Triassic Basins (Scrivener et al., 1994). Migration of highly saline brines was largely controlled by NW-SE faults and there was only limited mixing with meteoric fluids. Crosscourse mineralisation occurs in several broad paragenetic associations, including (i) lead, zinc and fluorite; (ii) uranium, cobalt, silver and arsenic; and (iii) iron. The gangue mineralogy typically comprises one or more of quartz, chalcedony, carbonates, fluorite, hematite and clay, often with banding and vughy cavities. It is apparent that some of this mineralisation occurred during the Mid - to Late Triassic and is related to regional fluid flow events. The development and reactivation of the cross-course fracture network reflects the onset of a major episode of Triassic rifting that affected much of Western Europe, where the dominant extension direction was ENE-WSW (Chadwick and Evans, 1995), which resulted in the development of NW-SE oriented faults.

Water ingress proved to be a major problem to the Cornish mines, which necessitated expensive pumping as the mines deepened. Evidence from historic underground mining activity shows that the greatest proportion of water that enters shallow mine workings is derived from surface, however, warm saline fluids have been observed in some of the deeper mines. It is the crosscourses, lodes and elvans which are commonly the high permeability structures that enable the preferential flow of meteoric and saline fluids through the rock (Smedley et al., 1989). In addition, rhyolite (elvan) dykes, which are commonly associated with lode structures, often contain microfractures that result in high permeability and groundwater flow in mine workings (Watkins, 2003). Some of the main crosscourses that have been encountered in mines impact on groundwater flow to significant depths. They commonly provide natural pathways for the passage of groundwater and were notorious as sources of inflow into mine workings and for hydraulic connectivity between mine workings. Fluid inflow typically occurred in fractured zones that lie adjacent to, and sub-parallel with, the main crosscourses. Thermal springs in mines were commonly associated with crosscourses, for example, on the 820 m level at South Crofty Mine (Watkins, 2003).

4.2 Proposed EGS system in Cornwall, UK

A major dextral wrench fault, known as The Great Crosscourse or Par Moor Lineament, with a strike direction of N 22° W and a dip of 75° ENE, has been proven through coastal outcrop and in mine workings in the metasedimentary rocks to the south of the site. This crosscourse has been observed to extend inland from the coast and displaces the granite/metasedimentary host rock contact. The NNW – SSE fracture set observed in Bodelva Pit may be associated with The Great Crosscourse (Mueller et al., 1999). The Great Crosscourse consists of several fissures over a width of 45 m, all heaving south. The most easterly fissure has the largest heave of about 90 m south, making the total dislocation 230 m (*Dines, 1956*). The Great Crosscourse has a strike trace length of >10 km, therefore it is reasonable to assume that the structure continues to a depth of over 5,000m. Study indicates that a fault with a plan trace length of ~10 km is likely to persist to a broadly similar depth, unless the trace represents an intersection towards the lower part of the fault (Fossen, 2010).

Phase 1 of the project has been completed and planning permission has been obtained for the proposed geothermal plant at the Eden Project. Phase 2 will comprise the drilling and completion of the first deep well (named EP-1) which will be an exploratory well targeted to intersect the Great Crosscourse at a depth of 4,000-5,000 m. This will provide a thorough appraisal of the hydrogeological conditions at the target depth of the reservoir and will enable academic research into:

- downhole temperature and geothermal gradient;
- stress regime, direction and gradient;
- fracture network characteristics and properties of faults, rock mass mineralogy and geochemistry;
- hydraulic characterisation, near-well impedance and permeability, rock mass porosity.

The performance of the reservoir is paramount to its lifetime viability, for which there are a number of parameters that affect its performance, including:

- Impedance to flow
- Downhole temperature
- Fluid production flow rate
- Water losses
- Short-circuit/thermal drawdown
- In-situ stress regime
- Heat transfer area
- Reservoir rock volume

Once the first well has been drilled and completed to target depth, which is anticipated to take 5 months, a 1-2 month programme of hydraulic testing will be undertaken to assist clarification of the hydrogeological conditions at target depth. A detailed Drilling Programme Report has been produced that includes the plan and design for the first deep well (named EP-1). The well plan is based on the geothermal wells that have been successfully drilled to depths of up to 5,000 m in France and Germany.

The results obtained from the first well and the hydrogeological characterisation of the target zone will be fully assessed to enable a ‘breakpoint’ decision to be taken about whether to continue the project as planned or whether to terminate. The premise will be on continuation unless an appraisal gives strong reason to believe that the forthcoming stages are unlikely to be successful. The first step of Phase 3 will comprise the identification of a precise intersection point for the second well (named EP-2) to intersect an appropriate fault in the optimum location for reservoir performance.

The design and plan for Well EP-2 is likely to be similar to that of EP-1, although the trajectory required to achieve the targeted intersection of the appropriate fault zone may be slightly longer and more complex, and it is anticipated that the drilling programme for the second well will be similar to that of the first well. The second well will be tested and the circulation performance of the system will be assessed over a period of 1-2 months. The results obtained from the circulation will enable the performance of the system to be verified and a ‘breakpoint’ decision to be taken about whether to continue to Phase 4, the construction of the plant as planned, or whether to terminate.

The plant will be a standard binary cycle plant used for geothermal reservoirs with production temperatures of 100-200°C. The efficiency of a moderate temperature geothermal plant typically lies between 22-45%. Several types of binary cycles are available for geothermal power production, including Organic Rankine Cycle (ORC); Kalina Cycle; Vapour Compression Cycle; Variable Phase Cycle. Options will be finalised nearer the time, but the plant is likely to be an ORC system that will utilise heat exchangers and air-cooling of the binary liquid. It is likely to be of similar design to that in use at Landau and Insheim. The construction of the plant and the associated infrastructure will be undertaken by specialist contractors and it is anticipated that this phase will take approximately 10 months to complete.

Once the first EGS system is developed successfully, a number of these systems will be replicated in Cornwall and Devon. Over half the capital cost of development is associated with drilling and completing the deep wells, therefore emphasis will be placed towards the advancement of drilling technology to help improve the economics of EGS.

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5. EXPLOITATION OF EGS THROUGHOUT THE WORLDWIDE

International co-operation is required if EGS is to become a significant contributor to the world's energy demands. For this technology to move faster, international cooperation will be vital to share knowledge that will enable EGS plants to be replicated with a low degree of risk. Additionally, an International Center of Excellence may help to train the scientists, engineers and other specialists needed to take this technology forward. A part of this development could an international data base that assists the technology to advance and not to repeat mistakes, such as have characterized the early stage development of other technologies. Improvement in the drilling technology will not only improve the economics of EGS, but will enable accessibility to even deeper and hotter structures.

The present trend of hydrocarbon usage for energy generation is unsustainable and alternatives renewable energy technologies have to be implemented if future adverse impacts from changes to the world's climate are to be avoided. EGS technology has the potential to make a significant contribution to the world's energy requirements and has the capacity to be major source of renewable energy that will meet the trilemma of greenhouse gas reduction, energy security and energy affordability. However, for EGS to succeed it will require commitment and investment to prove its wider applicability, with the development of schemes such as the one proposed by EGS Energy Limited at the Eden Project in Cornwall. Once the concept of exploitation of deep faults is better understood, the development of EGS could have the potential to provide an appreciable amount of power and heat energy to many parts of the world, particularly in areas of higher population density, where around 40% of the hydrocarbon products in the world are used for space heating and industrial heat use. EGS can be a major player in addressing the issue of climate change and mitigating the potentially devastating knock-on effects that could result from this.

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