Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

International Cooperation to Address and Mitigate the Climate Change Issue Using Unconventional Geothermal Technology (EGS)

Roy Baria[1], Joerg Baumgaertner[2], Hylke Glass[3], Andrew Jupe[4], Ann Robertson-Tait[5], Graeme Beardsmore[6], Corinna Abesser[7], Dimitra Teza[2], Hiroshi Asanuma[8], Igor Kocis[9].

[1]Mil-Tech UK Ltd, 6A Ladywell, Wrington BS40 5LT, North Somerset, UK., [2]BESTEC GmbH, Bismarckstrase 19, 76870 Kandel, Germany, [3]Camborne School of Mines, University of Exeter, Penryn, Cornwall TR10 9FE, UK., [4]Altcom Ltd, 13 N Parade, Penzance TR18 4SH, UK., [5]GeothermEx, 3260 Blume drive, Suite 220, Richmond, CA 94806, USA., [6]Hot Dry Rocks Pty, room 106, McCoy building, Corner of Elgin and Swanston Street, Carlton, VIC, 3053 Australia., [7]BGS, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire X10 8BB, UK., [8]FREA, AIST, 2-2-9 Machiikedai, Koriyama 963-0298, Japan., [9]GA Drilling, a.s., Priemyselna 5, 917 01 Trnava, Slovakia.

roybaria@onetel.com, baumgaertner@bestec-for-nature.com, h.j.glass@exeter.ac.uk, andy.jupe@altcom.co.uk, Ann1@slb.com, graeme.beardsmore@hotdryrocks.com, cabe@bgs.ac.uk, teza@bestec-for-nature.com, h.asanuma@aist.go.jp, igor@gadrilling.com

Keywords: Engineered Geothermal system (EGS), Unconventional Geothermal Energy, International Cooperation, Climate Change Mitigation, Supply & Demand of Energy, renewable energy, Base load energy.

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. Although geothermal energy should be able to play a major role in addressing this issue, this has not been the case to date due to a disparity in the availability of environment friendly geothermal energy in relation to the high demand for energy from the high density populated areas of the world (China, India, Europe, etc.). At present, the higher demand for energy in these areas is normally met with hydrocarbon resources with associated emission of greenhouse gases and other contaminants into the atmosphere (IEA, 2009), which in turn has led to the climate change effect.

Worldwide conventional geothermal (hydrothermal) development is mainly in areas characterized by volcanism and/or crustal extension and thinning, both of which lead to anomalously high heat flow from the interior of the earth toward the surface. In these locations, the depth required to access high-temperature resources is relatively shallow. Economically, this is a distinct advantage; however, such resources have a limited geographic extent, and often do not coincide with the most densely populated areas. Therefore, geothermal's contribution to the reduction of CO_2 is relatively insignificant on a world-wide scale.

Research is being carried out in many countries and regions to determine if significantly more geothermal energy can be made economically more accessible in the non-volcanic regions of the world. One of these concepts is the Engineered Geothermal System (EGS), whereby deep, naturally permeable faults are hydraulically manipulated at depth to emulate natural conventional hydrothermal systems, allowing injected cold water to be heated at depth and returned to the surface in production wells as high-temperature heat for commercial application; Smith 1975, Baria et al, 1990a and 1990b; Batchelor, 1990; Parker *et al.*, 1989.

Following a public funded, European R&D project at Soultz-sous-Forêts in France (Garnish *et al.*, 1994; Baria *et al.*, 1995; Baumgaertner, 1998; Baria *et al.*, 1999a and 1999b), several small commercial EGS projects are now operational in Germany and France. All are located within the Rhine Graben (Baumgaertner *et al.*, 2013a and 2013bB), which is known to host deep, permeable faults that can be enhanced to enable commercial flow rates of geothermal fluids. These projects have clearly demonstrated that deep faults systems can maintain sufficient *in-situ* fluid productivity for them to be regarded as long term and sustainable local energy resources. Additionally, the value of international collaboration (Soma *et al.*, 2002; Moriya *et al.*, 2003) has shown to be helpful in addressing scientific and engineering problems. Although these projects are relatively small (~5MWe, supplying around 10,000 homes), they have the potential to be scaled-up into much more significant sources of energy (Baria *et al.*, 2012).

This demonstrates that EGS has great potential for geothermal energy production outside volcanic areas. However, for this to become universally applicable, it needs to be demonstrated in various geological environments (not only the Rhine Graben).

Authors of this paper agree that for EGS technology to be effective and help mitigate the climate change issue, a large-scale international collaboration (Baria et al 2016) is essential. It is proposed that a cooperation structure is established under a consortium consisting of bodies such as the International Energy Agency, the World Bank, the United Nations and others; providing the priority and credibility needed. The broad objectives would be to identify and characterise suitable deep fault systems in the vicinity of densely populated areas. This would lead to the establishment of EGS demonstration projects in key areas initially and commercial projects subsequently. Establishing an International EGS Centre of Excellence where scientists and engineers can come together to exchange experiences and drive the technology forward is proposed as a way to facilitate large-scale international cooperation and technology transfer.

Based on experience gained at various sites, a scenario is put forward in this paper which could help the take up of EGS technology worldwide and thus assist the climate mitigation plan.

1. INTRODUCTION

Change in the world climate is well-documented and scientifically supported in many reputable publications. The consequence of this to many countries and communities are apparent by the spurious floods, fires, drought, more frequent and intense natural disasters, the rise in the sea level which may decimate many island-based communities. Unfortunately, it is the poorest and most vulnerable who are being and will be affected the most.

The World Bank has confirmed that the risks of unabated climate change are mounting with each passing year; unless urgent action is taken, the impact of climate change could push an additional 100 million people into poverty by 2030 (https://www.worldbank.org/en/news/feature/2015/11/08/rapid-climate-informed-development-needed-to-keep-climate-change-from-pushing-more-than-100-million-people-into-poverty-by-2030) Future temperature projections indicate that more than 140 million people who live near the equator will experience temperatures in excess of 50°C by 2050. These people will be forced to migrate north or south, leading to the distinct possibility of conflicts between nations and destabilization of these regions.

The effect of climate change is already apparent, has measurable impact on human health, and is expected to grow. Air pollution is expected to be responsible for 7 million premature deaths per year, and the increased cost of health care is estimated to be as much as $4 billion per year. Additionally, the impact of extreme natural disasters is estimated to cost around $520 billion in annual consumption, and is likely to force some 26 million people into poverty each year. The World Bank estimates that the financing required for an orderly transition to a low carbon, energy-resilient global economy must be counted in the trillions of dollars (http://www.worldbank.org/en/topic/climatechange/overview).

Measures must be applied to either slow down the effect of climate change or reverse it, if possible. Therefore, the use of heat and power generation from renewable sources is a constructive way forward.

Geothermal is a vast renewable resource whose exploitation is limited to date. Currently, the predominant method of using the earth's heat is the development of conventional hydrothermal systems using existing drilling and power generation technologies. Hydrothermal resources that have been developed and exploited are generally confined to areas characterized by volcanism and/or crustal extension and thinning; both lead to high heat flow and therefore the ability to access high temperature resources with relatively shallow drilling. Economically, this is a distinct advantage because drilling costs can be relatively low and the resource can be relatively well defined. On the negative side, conventional hydrothermal resources are geographically limited and population density in some of these specific areas is, on average, extremely low. In comparison to the total available geothermal energy resource base of the world, the current level of development from hydrothermal resources does not contribute significantly to mitigating climate change issues.

In a conventional hydrothermal system, meteoric water infiltrates to depth and migrates toward the surface via faults and other permeable pathways. In the process, the water is heated and may contain dissolved minerals, depending on the local geology. One or more permeable zones may then host a hot fluid reservoir, from which some fluid continues to rise toward the surface owing to the buoyancy of hot water. Traditionally, hydrothermal systems are be recognised by their geologic settings, surface expressions (*e.g.*, hot springs, geysers, fumaroles, altered ground), and/or shallow subsurface expressions (*e.g.*, warm waters in shallow wells), and can be further identified and characterized by geophysical and geochemical surveys, typically followed by shallow and deep drilling. Wells are drilled into the permeable zones of the hydrothermal systems to extract the hot fluid. Once the heat has been extracted in the power plant process, the cooled fluid is reinjected into permeable zones at a suitable distance from the production area, in the expectation that this fluid will then be reheated as it returns toward the production area, thereby recharging the hydrothermal system. As discussed above, geologic conditions suitable for the formation of hydrothermal resources have a limited geographic extent (mainly around the Ring of Fire, with some important exceptions).

In contrast, the geographic extent of areas suitable for EGS development is vast. There is a significant proportion of the upper crust that is hot but not sufficiently permeable to enable the development of conventional hydrothermal resources. In many parts of the world, intrusive rock (such as granite) occurs at depths where its temperature is suitable for the production of heat and power, enhanced by its good heat conduction properties and radiogenic composition. The concept of EGS was developed with the understanding that there is a significant proportion of the upper crust which is accessible by drilling and hot, but not sufficiently permeable to create a natural hydrothermal system. The EGS approach allows permeability to be enhanced, ideally exploiting natural fault systems that have some permeability, but not enough to allow geothermal fluids to be produced at commercial rates. Permeability enhancement increases reservoir storage and allows heat to be mined via injection and production.

It is proposed that climate change may be mitigated by international cooperation on the application of EGS technology worldwide (Baria et al 2016) thus reducing the dependence on hydrocarbon and associated pollutants. It is proposed that a cooperation structure is established under a consortium consisting of bodies such as the International Energy Agency, the World Bank, the United Nations and others; providing the priority and credibility needed. Proposed steps are mapping of deep faults, characterising these faults using geophysical techniques to delineating the presence of suitable quantities of fluid at depth, improve drilling technology to assist economics and establish Centre of Excellence to share technology and to train scientists and engineers required to maintain the growth of this process.

2. WORLD ENERGY 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. The global potential for solar power has been estimated by IEA (https://www.iea.org/geco/data/) to be ~570 TWe in 2018

As discussed below, the global geothermal potential is of a similar order of magnitude.

2.1 World Supply of Geothermal Energy

A hydrothermal resource requires heat, fluid, 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, Idaho (USA) 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, and the first large-scale geothermal power plant was installed at

Wairakei (New Zealand) in the late 1950s, followed by the first two units at The Geysers, California (USA) in 1962. Since then, the installed geothermal electricity has increased steadily. 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 and the initiation of favorable power pricing under contracts in the USA and elsewhere.

Almost all the electricity generated by geothermal energy is derived from hydrothermal power plants located predominantly in volcanic domains near the boundaries of tectonic plates (Figure 1) and in areas of crustal thinning; both regions are characterized by high temperatures at economically drillable depths. These systems are often characterized by surface manifestations to provide clues to the underlying resource, but not always.

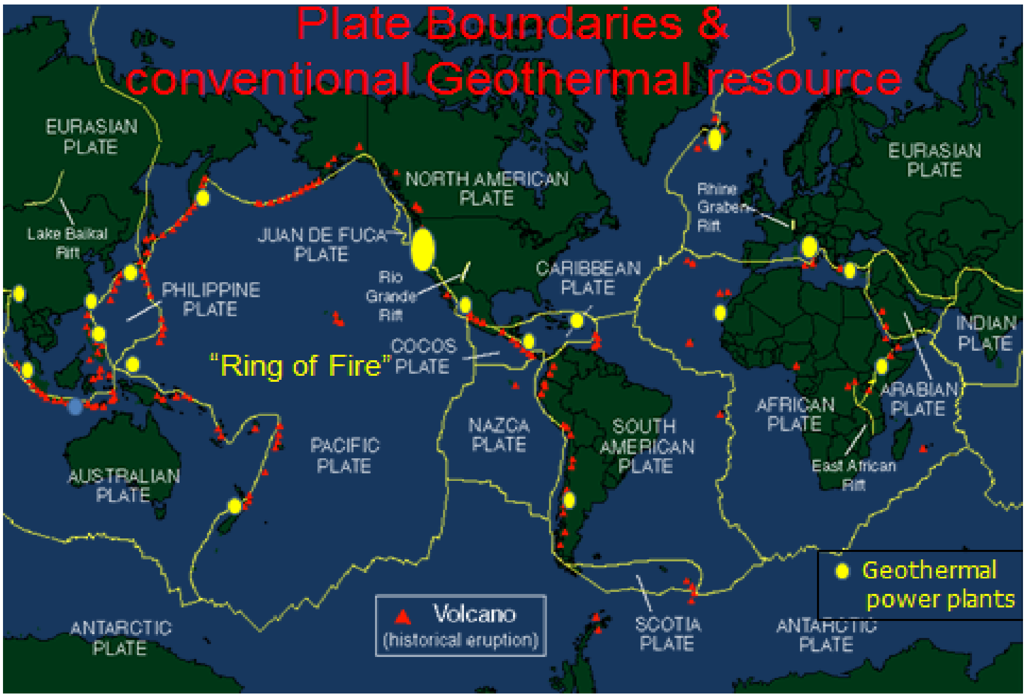

Figure 1: Plate boundaries, volcanoes and hydrothermal resources supplying electric power (modified from US Geothermal Education Office, 2000)

2.2 World Energy Demand

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 of areas of particularly high energy demand. The total world population is estimated to be around ~7.5 billion (UN estimate); a map showing population density is presented in Figure 2. As can be seen, the greatest demand for energy is associated with countries that have a high population density, such as China, Japan, India, Western Europe, USA, Nigeria and Brazil.

2.3 The Role of Geothermal in Energy Supply and Demand

Global potential for geothermal electricity has been estimated by Krewitt et al. (2009) at 45 EJ/yr - 12 500 TWhe, which is almost half of the 2018 global electricity generation based on data from IEA (2018). The Krewitt study also estimates that resources suitable for direct use can potentially supply 1,040 EJ/yr - 289,000 TWht, and notes that worldwide final energy use for heat in 2008 was 159.8 EJ/44,392 TWht. The geothermal estimates presented by Krewitt et al. are conservative in that they exclude 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 power price limitations (geothermal may or may not be the least-cost renewable source) and the limited geographic distribution of geothermal resource relative to centers of high energy demand (International Energy Agency, 2011)

Overlaying the map of current geothermal energy from hydrothermal resources (Figure 1) and the population density map (Figure 2) shows the disparity between areas of potential supply and areas of high demand. For example, New Zealand and Iceland can contribute appreciable amount of hydrothermal energy, but both island nations have low populations (approximately 4.5 million and 350,000, respectively). Unlike commodities such as oil, gas, coal and timber, an important limitation of geothermal energy is that hot water cannot be conveyed over long distances or across continents; therefore, the limited availability of the hydrothermal resource does not lend itself to greater exploitation worldwide.

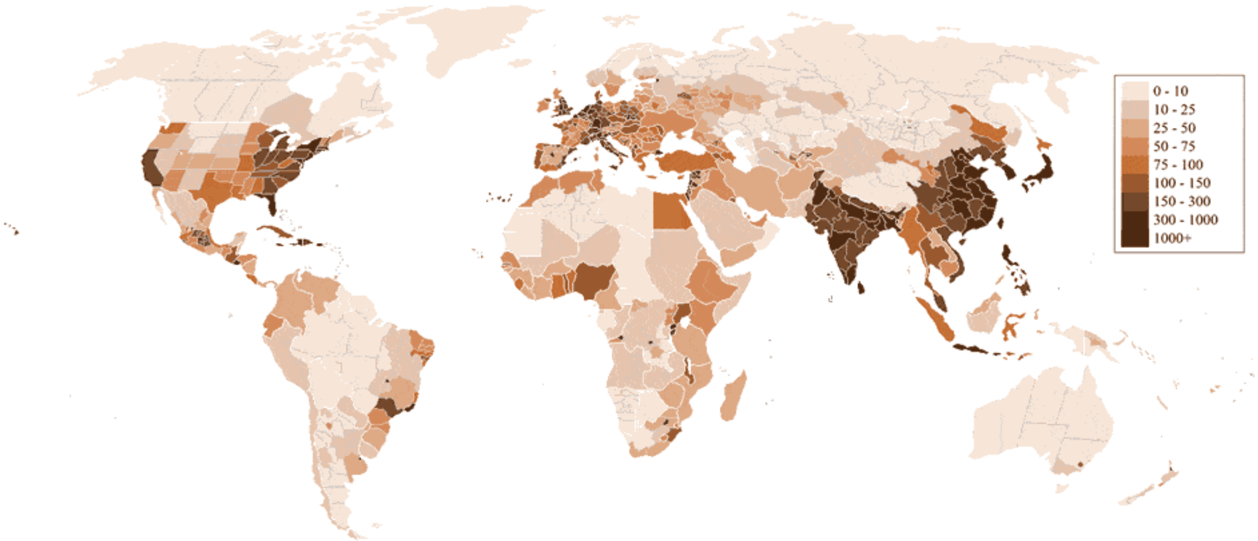

Figure 2: Global population density distribution (UN data base) shows that the demand for power in most areas is or the world not well aligned with areas that host conventional hydrothermal resources

There is an abundant non-hydrothermal (unconventional) geothermal resource in the world; however, current methodologies for extracting this form of energy is limited, and costs are higher than for conventional hydrothermal resources. The idea of creating sub-surface heat exchangers with large effective volume by using hydraulic stimulations remains a valid technique. However, it has not yet been possible to create artificial heat exchangers that are sufficiently large to be sustainable for 30 or 40 years with acceptable flow rates, operating pressures (*i.e.*, suitably low flow resistance) and far-field water losses most EGS (closed system) projects to date (Baria *et al.*, 2012). However, by realizing these parameters more common geologic settings than those hosting conventional hydrothermal resources, EGS can enable geothermal to become a global energy source.

3. THE ENGINEERED GEOTHERMAL SYSTEM (EGS)

3.1 Overview

The original concept of EGS (closed system), 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 meters 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-Richards *et al.*, 1990; Baria & Green, 1989) and at other sites around the world (Abe *et al, 1999)*. The wells at the Rosemanowes site were drilled into granite to a depth of 2,000 - 2,500 m and the project was specifically designed to understand the physics of creating enhanced permeability in igneous rock (Pine *et al.*, 1987; Baria *et al.*, 1989), where shearing of natural fractures was the main mechanism for enhancing permeability.

Knowledge gained from more than 30 years of research in these early EGS projects formed the basis upon which the European project at Soultz was built (Abe *et al.*, 1999; Kappelmeyer and Jung, 1987; Baria *et al.*, 1989, 1990A,1990B, 1999A, 2000; Baumgaertner *et al.*, 1995, 1998; Evans. 2005; Gérard *et al.*, 1997; Valley, 2007). For the first time, wells were drilled successfully to 5,000 m depth in granite basement to access temperatures of 200ºC. Although the Soultz project started as an HDR project (closed system-EGS) with necessity to carry out hydraulic stimulations to enhance permeability (Baria *et al* 1993), the discovery of hydraulically conductive natural faults at greater depth and the relationship of these faults to the *in-situ* stresses opened up a new concept - open system EGS - for extracting energy from depth at higher temperature. It became clear that natural, hydraulically conductive faults were more prevalent than had been originally anticipated. At Soultz and Rosemanowes, it was clear that natural fractures and faults were the dominant flow structures. In this way, they are similar to conventional hydrothermal systems; however, the permeabilities required for high flow rate wells was not present, and therefore there remained a need to engineer the system to enhance permeability.

3.2 EGS Potential in Cornwall

Cornwall has a history deep mining in the UK, yielding a database that gives some indication of the fault systems encountered at depth and their characteristics. 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 (porosity and permeability) characteristics of a granite rock mass are dictated by it cooling history, tectonic history and depth (including times at which it may have been exposed at the ground surface) and this may vary from highly permeable within surface near-surface weathering zones to significantly lower effective primary permeability at depth, 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) oriented approximately NNW-SSE. These fracture zones 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, 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 (Dine, 1956; Garnett, 1961; Shail and Alexander, 1997; Hawkes, 1981). These fractures facilitated the migration and mixing of magmatic, meteoric and basial 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 NNW-SSE for the mineralised faults. 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 (Bromley and Thomas 1988):

a) **Fissure fill crosscourses** – extensional fissures filled with clay and quartz, having a 'vuggy' 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 are generally steeply inclined (70°-80°) and vary from individual veins that are less than 1 m in width with minimal offset of wall rock features to fault zones greater than100 m in width that may can offset tin-copper lodes by more than100 m. Spacing for fault zones, with trace lengths of more than1 km can vary from between 1-10+ km, but between 10 and 500 m for major veins. Crosscourses existed as fault fissures prior to lode mineralisation and were an important component of structural control during mineralisation.

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; Muller *et al*., 1999). 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) tin, lead, copper, zinc and fluorite; (ii) uranium, cobalt, silver and arsenic; and (iii) iron. The gangue (ore host rock) mineralogy typically comprises one or more of quartz, chalcedony, carbonates, fluorite, hematite and clay, often with banding and vuggy 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 crosscourse 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 (hard intrusive rocks found in Cornwall, typically quartz porphyry) 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 are associated with 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 inflows 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).

Observation in deep mines in Cornwall (Figure 3) have shown that these faults at depth can produce significant flow (up to 700 l/s) for infinitum. The presence of these faults are apparent on the satellite images and surface expression (Figure 4). These faults are linked to the geomechanical properties of the rock mass and are aligned around the direction of maximum horizontal stress. A good knowledge of geomechanics and the stress field is therefore crucial to understanding the preferential direction of fluid flow and enhancing the properties of these large conductive faults.

3.3 The Open EGS System

The presence of large conductive faults at depth demonstrate that rather than creating an artificial heat exchanger using hydraulic stimulation of an impermeable jointed rock mass (closed system), it is more advantageous to use existing natural hydraulically conductive faults to mimic a natural hydrothermal system (open system). Where correctly aligned in relation to the direction of maximum horizontal stress, and with some hydraulic stimulation, these deep faults when have the potential to behave like a hydrothermal system by permitting a reasonable sustained flow rate over a long period.

The configuration of injection and production wells is strongly influenced by the natural stress regime. *In-situ* conditions vary between localities, making it difficult to produce a pre-programmed model on which to design deep geothermal reservoirs. Therefore, until more data are available from projects in specific geologic regions, each system needs to be assumed to be site specific and appropriate engineering manipulations are required to bring each system into successful production. As an example of the learning curve effect, the success of this technology at the Soultz project led to the development of first commercial EGS plant within the northern Rhine Graben at Landau (Baumgaertner *et al.*, 2013C) in Germany.

These pioneering R&D projects have led to a number of successful commercial EGS projects being established in Germany (Insheim, Landau) and in France (ECOGI; Rittershoffen), all of which are located in the Rhine Graben. It is apparent now that deep faults in the Rhine Graben, with specific stress orientations, can be hydraulically conductive and therefore be exploited for open EGS systems. Currently designed for small scale local applications, these projects typically produce around 5MWe, sufficient to heat around 10,000 homes. However, open EGS systems could be scaled up to~100 MWe, depending on the temperature and flow rate found at great depth (Baria et al 2012).

Although these small-scale projects have been successful, for the EGS concept to be universally applicable, one needs to test this away from hydrological characteristics of the Rhine Graben.

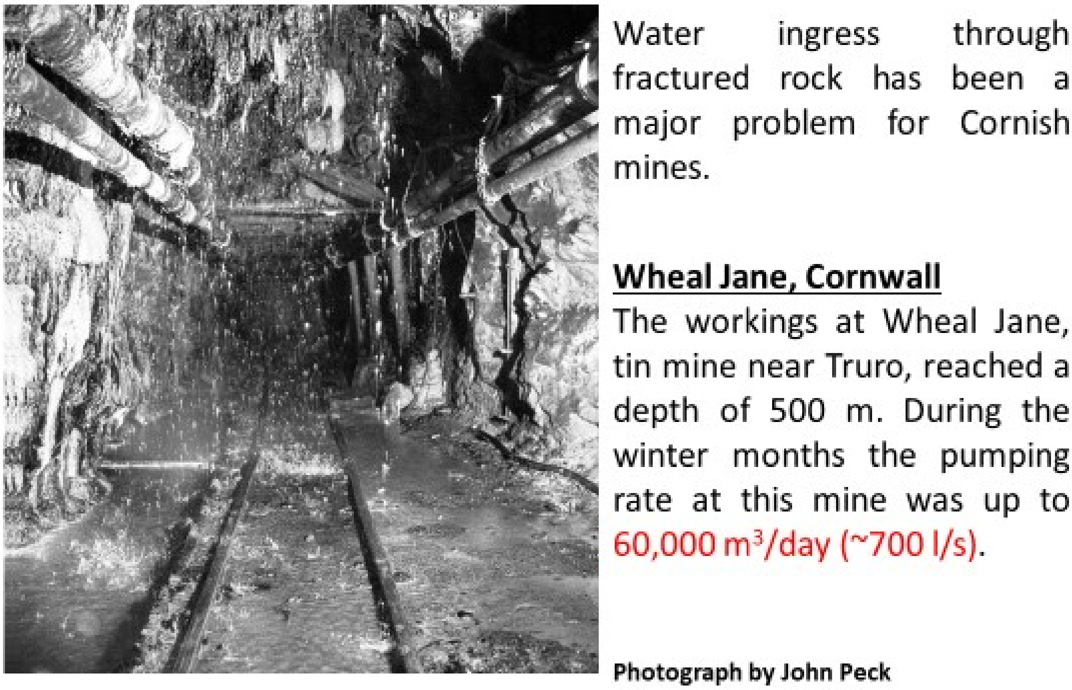

Figure 3: Wheal Jane tin mine near Truro, Cornwall, UK (Courtesy of John Peck)

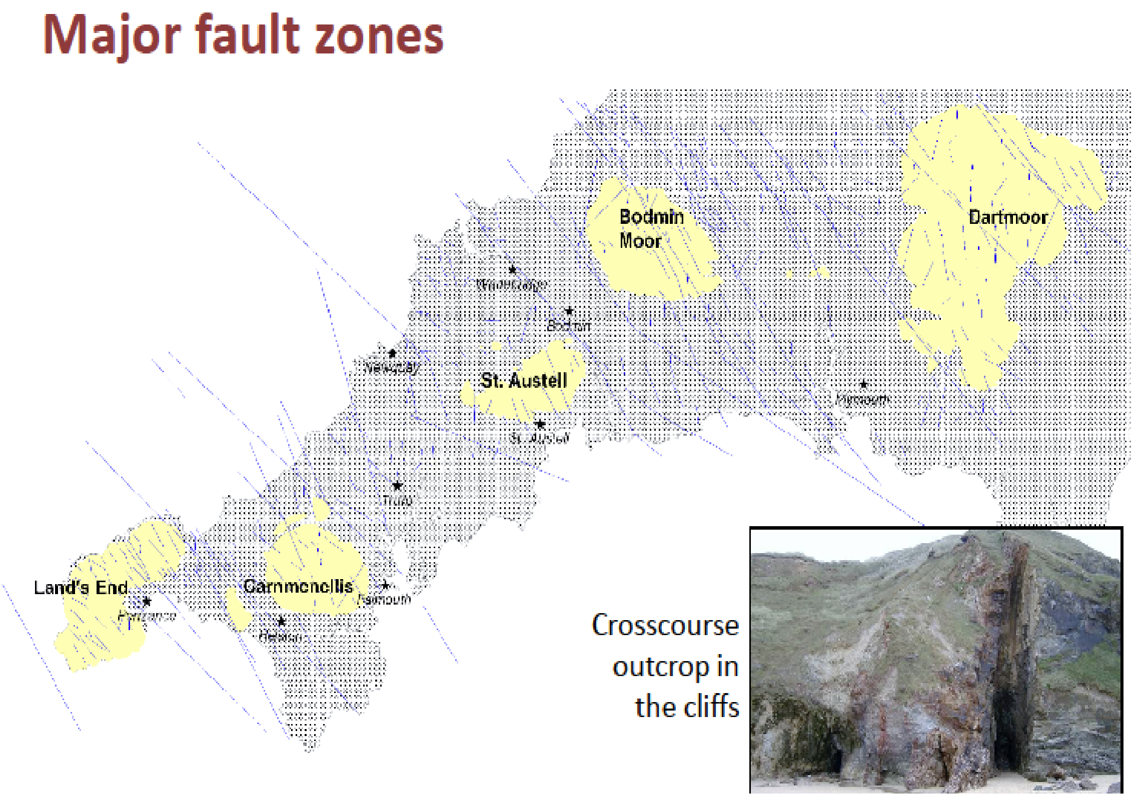

Figure 4: Satellite Image and Surface Expression of Faults (Crosscourses) in SW England

4. INTERNATIONAL COOPERATION ON EGS

Time is of the essence to mitigate the climate change issue. International cooperation and a systematic approach are proposed to make this approach a success. It is therefore proposed that a large-scale international collaborative project addressing EGS is undertaken, following the broad series of steps described below.

4.1 Identify EGS Resources Worldwide

It is proposed that an international cooperation is established under a consortium consisting of International Energy Agency, the World Bank, United Nations, Individual state's geological surveys and others to map/identify specific deep fault systems in all countries using their geologists where possible or seek external help/aid.

EGS resources closer to populated area where the demand is higher should be given priority to demonstrate the value of EGS for mitigating climate change issues. However, several such projects should be undertaken simultaneously to ensure that the program remains viable if there are unforeseen difficulties with any of the sites.

4.2 Reduce the Risk of Low-Permeability Wells

The next step would be to characterise deep faults systems using a combination of stress data (from the World Stress map and other data) and geophysical techniques (including resistivity, gravity and seismic). The purpose would be to identify faults with the greatest inferred permeability. These faults could be characterised by their perceived properties, in order of decreasing risk:

a. Uncertain permeability
b. Moderate permeability
c. High permeability

This characterization of deep faults would guide decisions about pursuing specific sites and the associated risks. In due course, and with significant international cooperation for data and knowledge sharing, experience will demonstrate the characteristics of successful EGS sites, to the benefit of everyone involved.

4.3 Improve Heat Utilisation

To maximise the value of energy produced from open EGS systems, the overall efficiency, performance and cost-effectiveness of above-ground systems need to be optimized: *e.g.*, by

- extending the temperature range of different applications of geothermal energy
- improving binary power plant efficiency; and
- improving the integration of geothermal heating, cooling and electricity supply into local energy systems.

The goal is to maximise the generation at the lowest life-time cost.

The layout of the plant and its usage will need to meet the local requirement and may have to be tailored for a specific need of the local community. It would be an advantage to make information about the optimization process available for international cooperation to build an inventory of best practices and thereby reduce risk, improve the return on the investment, and promote the uptake of this approach worldwide.

4.4 Improve Drilling Economics

Drilling in deep basement is one of the main stumbling blocks to the advancement of open EGS technology worldwide. Recent research and continuing development in percussion drilling suggests that significant improvement can be achieved using this technique when compared to traditional rotary drilling. Tests in Finland (https://www.st1.eu/st1-geothermal-pilot-project-otaniemi-espoo-reaches-stimulation-stage) have demonstrated that percussion drilling can improve the Rates of Penetration (ROP) by several fold to that of convetical rotary drilling, which can improve dramatically the economics of geothermal and make it acceptable worldwide. One of the uncertainties in percussion drilling is the depth to which percussion drilling can work efficiently. The present limitation appears to be a depth of around 4500 m, depending on geology, borehole diameters etc. With continuing research and a greater uptake of percussion drilling by the geothermal industry, EGS technology may grow exponentially.

Development of a worldwide database on percussion drilling and other drilling methods suitable for EGS (together with information on geologic and stress conditions) would provide useful information to EGS developers for selection of the optimal drilling approach and reducing drilling costs as much as possible. Funding for improved deep geothermal drilling techniques (with the goal of increasing efficiency and reducing cost) is being provided in various countries; ideally, there would be coordination between countries to develop ensure that best practices are available to an understood by EGS development community.

One potential means of enhancing the economics for EGS resource development would be to include the co-production of lithium, cobalt and rare metals dissolved in the geothermal fluids, thus providing additional revenue. Although not directly related to drilling improvements, the addition of such a revenue stream could help justify drilling costs, which typically more than half of the costs of developing an EGS project.

4.5 Scaling Up

A two or three well EGS system may produce anything from 5 to 15 MWe, depending on the per-well temperature and flow rate. This is satisfactory for providing small, local energy needs; however, for EGS to become a significant regional resource, scaling up to 100 MWe or more is required (Baria *et al.*, 2012). This is not outside the bounds of current technology and could be attained using multi-well systems. As the understanding of the deep faults grows and the cost of geothermal drilling cost is lowered, scaling up of open EGS system will be the natural result, making geothermal a popular and friendly resource to be exploited worldwide for commercial scale operation by both private- and public-sector developers.

4.6 Establish Legal and Regulatory Framework and Increase Social Acceptance

Introducing and deploying deep geothermal technologies on a large scale has a number of technical and non-technical challenges, notably:

- high investment cost
- the acceptance of the technologies in the developing areas and
- the involvement of consumers in the production chain to enhance the role of energy distribution.

In parallel with the technological research described above, coordinated actions to develop regulatory, financial, political and social solutions would help overcome such barriers and accelerate the deployment of EGS on a global scale, enabling it to become one of the main mitigators of global climate change and meet energy demand targets.

5. DEVELOPMENT OF AN EGS ACTION PLAN

The following sections outline a step-by-step approach for an EGS Action Plan.

5.1 EGS Centre of Excellence

Previous experience at the European EGS project at Soultz, France has shown that interaction and cross-fertilization of ideas between scientists and engineers within the international community helped significantly in the development of the technology. Significant progress in the technology and interpretation of the data were achieved within the European EGS project, which reduced the risk and improved the technology.

As described above, Cornwall is renowned for the richness of its natural mineral resources. The county's history is embedded in mining of valuable economic commodities going back to the Roman times. This tradition would enable a new wave of activity: using EGS technology to recover a vast resource of stored heat in the granite of the Cornubian batholith. Estimates (SKM and REA, 2012) indicate that by accessing hot rocks at 5,000m, up to 20% of the current electricity generating capacity of the UK can be delivered for up to 200.

Using a similar concept as at Soultz, a project can be initiated 1,200 km away at a possible site in the southern part of Cornwall. As described above, geologic and stress conditions are favorable and there is a significant body of knowledge about conductive faults and fractures. Temperature modelling (Willis-Richard *et al.*, 1990) indicates a temperature of around 220°C at 5 km depth. A successful EGS project at this site would demonstrate that these deep fault systems resemble hydrothermal systems, but in deep igneous rock away from Rhine Graben and at other similar locations identified as described in Section 4.1, which will demonstrate the accessibility of open EGS systems in many parts of the world.

It is proposed that an EGS project in Cornwall would become the basis for the initial international Centre of Excellence for EGS technology. The Centre would be operated in conjunction with private- and public-sector organizations, including geothermal developers, mining companies, oil & gas companies, two exceptional local academic institutions (Universities of Exeter and Bristol), and academic institutions from other countries. A high level of participation will be encouraged in this venture to ensure that technology can be transferred globally. It is anticipated that the Centre of Excellence will have a close link with the IEA, World Bank and UNESCO, ensuring the effective application of open EGS systems to address the mitigation of climate change.

Another engineering topic that could be pursued at this center would be the use of geothermal heat for industrial and domestic application. It is well understood that a significant CO_2 reduction can be achieved if one can replace industrial use of heat from hydrocarbon energy with that from geothermal energy, thus moving towards climate mitigation support. It is expected that local academic institutions will develop graduate and post graduate courses in geothermal engineering to facilitate the worldwide deployment of open EGS technology.

Once the concept and structure of the first Centre of Excellence is established, it can be replicated in many parts of the world to facilitate access to regional specificity and address any specific geological conditions and related topics.

5.2 Global Funding and Adoption of EGS

The initial financing of demonstration EGS projects in many countries may be too large a financial commitment in some locations. A possible mechanism to address this issue would be to involve public financial organisations such as the World Bank. The relatively small investment in advancing EGS deployment should be compared with the dire economic predictions if nothing is done to mitigate climate change issue. Once the concept has been demonstrated in a specific country, a mechanism could be put in place for it to be taken up by state or private entities for further development. The authors believe that this is an international issue and continued international cooperation is the only way forward. This may require setting up a specific organization for the advancement of EGS energy, perhaps under established organizations such as the United Nations, the World Bank, or other international institutions, with the goal of worldwide deployment to demonstrate that this technology is for all countries, regardless of their development status.

Each Centre of Excellence would incorporate a long-term funding strategy for R & D to continually improve technology, reduce risk and enhance economics, and a public outreach campaign to enhance public perception of EGS and thus acceptance of it worldwide.

By demonstrating the economics of EGS schemes, there will be a commercial case for investment from companies currently focused on fossil fuels, as their operational strategies already embrace the thinking behind resource optimization. In addition, EGS would provide an added benefit to these stakeholders: unlike a barrel of oil or a ton of coal, they can sell the energy they produce continuously over a long period.

The successful adoption of EGS by an appreciable number of nations would make mitigation effort for climate change more successful and the future for humankind more positive.

5.3 Global Cooperation, Data Collation and Data Sharing

Regular international meetings where various parties are brought together to discuss the current state of specific projects would be highly beneficial for realizing a future with EGS. Such meetings could be held in conductions to existing, well attended geothermal meetings, such as the annual Stanford Geothermal Workshop and other meetings such as the World Geothermal Congress, the Geothermal Resources Council Annual Meeting, and conferences held by the European Geothermal Energy Council (EGEC). A specific website and other information sharing methods would be developed to enable cross-fertilisation between projects, hosting discussion forums and sharing common problems and solutions. Sharing of human resources, knowledge and material should be encouraged.

6. CONCLUSIONS

Open EGS resource represent not only an unprecedented opportunity/mechanism to mitigate climate change issues with renewable energy sources, but would also help developed and developing nations to work together to access an indigenous and ubiquitous energy resource, improving the quality of life, reducing tensions between nations, and sharing the prosperity that EGS can bring.

Overall, the global geothermal potential (hydrothermal + EGS) is huge and renewable. It is an environmentally friendly, strategic global resource well suited to supply baseload power and offset the demand for electricity. By following a path similar to that outlined herein, EGS can become economically attractive and a predominant energy resource for the world in the future.

7. ACKNOWLEDGEMENT

Authors would like to thank international funding agencies and colleagues who have contributed so much of their professional lives and time to provide improved understanding of EGS systems. We are especially grateful to: Ladsi Rybach, Fritz Rummel, Francois Cornet, Don Brown, Subir Sanyal, Roland Horne, Philippe Dumas, Lothar Wissing, John Garnish, Allen Jelacic, Terry Gandy, Hiroki Niitsuma and others who have an exemplary record of their dedication to EGS.

The authors would like to give special acknowledgement to Perry Moore, a genius for drilling in hard rocks, who passed away on 21st March 2003 in Kazakhstan. He had an absolute faith in the EGS concept from his Los Alamos days and supported the program with tremendous drive and enthusiasm.

8. REFERENCES

Abe, H., Niitsuma, H., Baria, R.: Hot dry rock/Hot wet rock academic review: special issue. Geothermics 28(4/5), (1999). Pergamon Press, ISSN 0375-6505.

Baria, R., Baumgärtner, J., and Gérard, A,:*Heat mining in the Rhinegraben*; Socomine Internal project report**,** (1993).

Baria R. and Green A.S.P.: " Microseismic: A Key to Understanding Reservoir Growth", in "Hot Dry Rock Geothermal Energy", Proc. Camborne School of Mines International Hot Dry Rock Conference, Ed. Roy Baria, Camborne School of Mines Redruth, UK, 27-30 June, (1989), Robertson Scientific Publications, London, (1990A), pp. 363-377.

Baria, R., (ed.): Hot Dry Rock Geothermal Energy. Proceedings of Camborne School of Mines. International HDR Conference, June 1989, publ. Robertson Scientific Publications (London), 613 pp, (1990B)

Baria, R., Garnish, J., Baumgaertner, J., Gerard, A., Jung, R., Recent development in the European HDR research programme at Soultz-Sous-Foret (France). Proceeding of the World Geothermal Congress, Florence, Italy, International Geothermal Association, (1995). Vol. 4, 2631-2637, ISBN 0-473-03123-X.

Baria, R., Baumgärtner, J., Rummel, F., Pine, R. J., Sato, Y., HDR/HWR reservoirs: concepts, understanding and creation. Geothermics 28, no. 4/5, pp. 533-552, ISSN 0-375-6505., (1999A).

Baria, R., Baumgaertner J., and Gerard, A., "European Hot Dry Rock Geothermal Programme." Geothermics., (1999B).

Baria, R., Baumgaertner, J., Gerard, A., and Garnish, J., The Euroopean HDR programme: Main targets and results of the deepning of the well GPK2 to 5000 m. World Geothermal Congress 2000, Kyushu - Tohoku, Japan, (2000).

Baria, R., Mortimer. L., Beardsmore, G., 2012. Development of Engineered Geothermal Systems (EGS) and its sustainability. Encyclopedia of Sustainability, Science and Technology (2012), Springer Press, ISBN: 978-0-387-89469-0

Baria, R., Baumgaertner, J., Glass, H.,Bennett, T., Teza, T and Jupe, A (2016). Unconventional geothermal technology to help the climate change issue in the densely populated areas of the world with a demand for higher energy. European Geothermal Congress 2016, Strasbourg, France, 19-24 Sept 2016.

Batchelor, A.S., 1990. Hot Dry Rock and its relationship to existing geothermal systems. In: Baria, Roy (Ed.), Proceedings of the Camborne School of Mines International Hot Dry Rock Conference, Camborne School of Mines, Redruth, UK, 27±30 June. Robertson Scienti®c Publications, London, pp. 13±29

Baumgärtner, J., Moore, P., and Gérard, A., 1995. Drilling of hot and fractured granite at Soultz - Proceeding of the World Geothermal Congress, Florence, Italy, International Geothermal Association, Vol. 4, 2657-26663, ISBN 0-47303123-X.

Baumgärtner, J., Gérard, A., Baria, R., Jung, R., Tran-viet, T., Gandy, T., Aquilina, L., Garnish, J., 1998. Circulating the HDR reservoir at Soultz: maintaining production and injection flow in complete balance. In: *Proceedings of the 23rd Workshop on Geoth. Reservoir Engineering*, Stanford University Stanford, California.

Baumgärtner, J., and Lerch, C. (2013A). Geothermal 2.0: The Insheim Geothermal Power Plant. The second generation of geothermal power plants in the Upper Rhine Graben. Third European Geothermal Review, Geothermal Energy for Power Production, June 24-26, 2013, Mainz, Germany.

Baumgärtner, J., Teza, D. and Wahl, G. (2013B). Gewinnung geothermischer Energie durch Entwicklung und Zirkulation eines Störungssystems im Kristallin und deren mikroseismische Überwachung am Beispiel des Geothermieprojektes Insheim (Extraction of geothermal energy through the development and circulation of controlled systems in the crystalline basement and their microseismic monitoring, using the example of the geothermal project Insheim). Final report to BESTEC GmbH. Accessed online 4 Feb 2016:(http://edok01.tib.uni-hannover.de/edoks/e01fb14/777426781.pdf .)

Baumgärtner, J., Hettkamp, T., Teza, D., Kölbel, T., Mergner, H., Schlagermann, P. and Lerch, C. (2013C): Betriebserfahrungen mit den Geothermiekraftwerken Landau, Insheim und Bruchsal. bbr Fachmagazin für Brunnen- und Leitungsbau.

Bertani, R. (2010). Geothermal Power Generation in the World 2005-2010. Update Report, proceedings at World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010.

Bromley, A. V. and Thomas, L. J. (1988). Structural controls on the circulation of thermal brines at South Crofty Mine, Cornwall. In: Louwrier, K. and Garnish, J.K., (eds).

Chadwick, R. A. and Evans, D. J. (1995). The timing and direction of Permo-Triassic extension in southern Britain. From Boldy, S. A.R. (ed.), 1995, Permian and Triassic rifting in Northwest Europe, Geological Society Special Publication No. 91, pp. 161-192.

Dines, H. G. (1956). The metalliferous mining region of south-west England; Volumes I and II. Institute of Geological Sciences, Memoirs of the Geological Survey of Great Britain.

Evans, K. F., (2005). Permeability creation and damage due to massive fluid injections into granite at 3.5 km at Soultz: part 2 – critical stress and fracture strength. Journal Geophysical Research 110, 14, doi:10.1029/2004JB003169.

Garnett, R. H. T. (1961). Structural control of mineralization in South-West England. Mining Magazine, 105, 329-337.

Garnish, J.D (1976). Geothermal energy: the case for research in the United Kingdom. Energy paper no. 9, London, HMSO, 66 pp.

Garnish, J., Baria, R., Baumgärtner, J., Gérard, A., (1994). The European Hot Dry Rock Programme 1994-1995, *GRC Trans*.

Geothermal Education Office (2000): http://geothermaleducation.org/GEOpresentation/sld006.htm

Gérard, A., Baumgärtner, J., Baria, R. (1997). An attempt towards a conceptual model derived from 1993-1996 hydraulic operations at Soultz. In: *Proceedings of NEDO International Geothermal Symposium*, Sendai, 2, pp. 329-341.

Hawkes, J. R. (1981). A tectonic 'watershed' of fundamental consequence in the post-Westphalian evolution of Cornubia. Proceedings of the Ussher Society, 5, 128-131.

Hosking, K.F.G. (1949). Fissure systems and mineralisation in Cornwall. Trans. R. Geol. Soc. Cornwall, 18, 9-49.

International Energy Agency, 2011. IEA Road Map: Geothermal Heat & Power. Accessed at http://iea-gia.org/wp-content/uploads/2012/08/Geothermal_Roadmap-Final-Pub-Ver-15Jun11.pdf.

International Energy Agency, (2009). IEA World Energy Outlook 2009, Climate Change Excerpt. Paris: International Energy Agency.

Kappelmeyer, O., Jung, R., 1987. HDR Experiments at Falkenberg/Bavaria. In: Garnish, J. (Ed.), Proceedings of the firstEEC/US Workshop on Geothermal Hot Dry Rock Technology, Brussels, pp. 375±392 Geothermics Special Issue, Vol. 16, No 4.

Krewitt, W., Nienhaus, K., Klessmann, C., Capone, C., Stricker, E., Graus, W., Hoogwijk, M., Supersberger, N., von Winterfeld, U. and Samadi, S. (2009). Role and Potential of Renewable Energy and Energy Efficiency for Global Energy Supply, Federal Environment Agency (Umweltbundesamt), Dessau-Rosslau, Germany, available at www.umweltbundesamt.de/uba-infomedien/mysql_medien.php?anfrage=Kennummer& Suchwort=3768.

Mueller, S., Scott, P. W. and Evans, M. J. (1999). Kaolinisation, mineralisation and structures in biotite granite at Bodelva, St Austell, Cornwall. Geoscience in South West England, 9, 310-317.

Parker, R. H. (1989). Hot Dry Rock Geothermal Energy: Phase 2B Final Report of the Camborne School of Mines Project. Pergamon Press, Oxford, U.K, 1391 pp.

Pine, R. J., Baria,R., et al. (1987). "A technical summary of phase 2B of the Camborne School of Mines HDR project." Geothermics **Vol.16**(No. 4): 341 – 353

Scrivener, R. C., Darbshire, D. P. F. and Shepherd, T. J. (1994). Timing and significance of crosscourse mineralization in SW England. Journal of the Geological Society of London, 150, 587-590.

Shail, R. K. and Alexander, A. C. (1997). Late Carboniferous to Triassic reactivation of Variscan basement in the western English Channel: evidence from onshore exposures in south Cornwall. Journal of the Geological Society, London, 154, 163-168.

SKM (Sinclair Knight Merz) and REA (Renewable Energy Association), 2012. Geothermal Energy Potential, Great Britain and Northern Ireland. Accessed on the REA website at: https://www.r-e-a.net/upload/skm_report_on_the_potential_for_geothermal_energy_in_gb__ni_may_2012.pdf

Smedley, P. L., Bromley, A. V., Shepherd, T. J., Edmunds, W. M. and Kay, R .L. F. (1989). Fluid circulation in the Carnmenellis granite: hydrogeological. Hydrochemical and palaeofluid evidence. Geochemistry in relation to Hot Dry Rock development in Cornwall; Volume 4, BGS research report SD/89/2.

Smith, M. C. (1975). The potential for the production of power from geothermal resources - Los Alamos scientific laboratory report, LA-UR-73-926.

Soma, N., Niitsuma, H., and Baria., R., Evaluation of Subsurface Structure at Soultz Hot Dry Rock Site by the AE Reflection Method in Time-frequency Domain [Pure Applied Geophysics, 159, (2002), 543 - 562

Moriya, H., Niitsuma, H., and Baria,R., Multiplet-clustering analysis reveals structural details within the seismic cloud at the Soultz geothermal field, France, Bull. Seismc. Soci. Am., 93, 4, 1606-1620, 2003

Valley, B. (2007). The relation between natural fracturing and stress heterogeneities in deep-seated crystalline rocks at Soultz-sous-Forêts (France). Doctoral Thesis. Swiss Federal Institute of Technology (ETH), Zurich, Switzerland, 241 pp.

Verma, A., and Pruess, K.: Enhancement of Steam Phase Relative Permeability Due to Phase Transformation Effects in Porous Media, *Proceedings,* 11th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (1986).

Wang, C.T., and Horne, R.N.: Boiling Flow in a Horizontal Fracture, *Geothermics*, **29**, (1999), 759-772.

Watkins, D. C. (2003). Determining a representative hydraulic conductivity of the Carnmenellis Granite of Cornwall, based on a range of sources of information. IN: Groundwater in fractured rocks; Published by Taylor & Francis as the IAH Selected papers, Volume 9.

Willis-Richard, J., Thomas-Betts, A., Sams, M. and Wheildon, J. (1990). HDR resource in South West England. in "Hot Dry Rock Geothermal Energy", Proc. Camborne School of Mines International Hot Dry Rock Conference, Ed. Roy Baria, Camborne School of Mines Redruth, UK, 27-30 June, 1989, Robertson Scientific Publications, London, 1990, pp. 215-223.