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Geothermal Power Generated from UK Granites (GWatt)

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ABSTRACT

Deep geothermal systems have the potential to provide sustainable, reliable, carbon-free power for the UK. However, exploitation of the UK deep thermal resource is held back by knowledge gaps about permeability and fluid/heat flow within fractured hot rocks. The GWatt project aims to fill these gaps via novel studies of rock stress, natural fracture networks, heat transport, coupled thermo-hydro-mechanical processes, and injection/production optimisation, in order to maximise reservoir utilisation whilst minimizing risks. In this context, the project aims to achieve a better understanding of processes that will enable the prediction of the economically-utilisable geothermal resource, the optimisation of reservoir development, and the quantification of geological uncertainty and geological risks (such as induced seismicity). Here we provide an introduction to the GWatt project.

1. INTRODUCTION

The UK has a statutory commitment of achieving net zero emissions by 2050 relative to 1990 levels (Priestley, 2019), and is considering a move to carbon neutral status by that date. This will necessitate a massive decarbonization of the energy sector and maximising the use of renewable resources. Engineered Geothermal Systems (EGS) align well with these goals and can provide power from regions devoid of conventional hydrothermal resources (Baria et al, 2016; Olasolo et al. 2016).

Whilst there have been notable EGS successes (e.g. the Landau and Insheim projects), EGS has yet to achieve its full potential. Previously, a key constraint on EGS deployment has been the cost of drilling. Recently however, drilling technology has advanced rapidly, with improved penetration rates. Thus, reaching depths >5 km, where the potential power provided by UK EGS increases dramatically (from 2 GWe at 5 km to 222 GWe at 7 km [Busby and Terrington, 2017]), is now achievable within realistic budget constraints. However, there are significant geological uncertainties associated with characterising geothermal reservoirs, which impact upon the engineering of the reservoir and surface infrastructure, ultimately causing operational risks, missed economic opportunities, and potentially damaging public acceptance (Breede et al., 2013). Given the above, key challenges for successful development of EGS in the UK are; to gain a detailed knowledge of the accessible volume of hot rock, the fluid and heat flow pathways (i.e. 3D fracture network), the stress field, and the heat transfer medium (i.e. water or brine). It is further required to better understand fluid flow and heat transport in deep fracture systems, to apply this understanding to predict the economically-utilisable geothermal resource, to optimise reservoir development, to quantify geological uncertainty, and to better understand geological risks (such as induced seismicity). We aim to tackle these challenges within the GWatt project – a £1.8M project funded via a grant from the UK Natural Environment Research Council (NERC). Our work programme involves combining innovative and detailed scientific understanding from new laboratory testing, field measurements and predictive modelling, with data coming from two new boreholes at the UK's deepest onshore geothermal project at United Downs in Cornwall.

2. EGS RESEARCH AND DEVELOPMENT IN THE UK

Initial research and experimentation into EGS (then called Hot Dry Rock – HDR) was first initiated in 1973 at Fenton Hills, USA (Kelkar et al., 2016) and was followed in 1977 by the 'Hot Dry Rock' project in the Variscan Carnmenellis Granite in Cornwall, led by the Camborne School of Mines (Richards et al., 1991). Granites in SW England have the highest heat flow in the UK (Downing and Grey, 1986) and are predicted to largely exceed 200°C at 5 km depth (Beamish & Busby, 2016). They represent the prime target for high temperature geothermal energy production in the UK. A key aspect of the HDR project was the investigation of the potential of creating a geothermal reservoir in crystalline rock. Advances in knowledge achieved as part of the project included establishing the importance of the stress field, that reservoir enhancement occurred through shearing on natural joints, and that these joints would be held open by their opposing rough surfaces (MIT, 2006). At the conclusion of the UK HDR project in 1992, much of the expertise transferred to the EU EGS research project at Soultz-sous-Forêts in France. This established that the connectivity of natural fractures dominated the enhanced reservoir (Korlbet and Genter, 2017), and that creating an artificial reservoir in the absence of such connected fractures would be unlikely (MIT, 2006). Since the conclusion of the UK HDR project, a number of EGS (and heat only [Baujard et al., 2015]) projects around the world have gone on to establish some of the fundamental concepts and challenges in EGS while, until recently, progress in the UK has stalled.

Two companies have been trying to develop commercial EGS projects in the SW England: Geothermal Engineering Ltd at United Downs near Redruth in the Carnmenellis Granite (https://www.uniteddownsgeothermal.co.uk), and EGS Energy at the Eden Project (near St Austell) in the St Austell Granite (http://www.edenproject.com/eden-story/behind-the-scenes/eden-deep-geothermal-energy-project). Both have struggled to raise private sector investment even though they were awarded kick-start capital grants by the Deep Geothermal Challenge Fund (via DECC) in 2010. The £18M project at United Downs is now progressing due to the award of a substantial European Regional Development Fund (ERDF) grant, a financial contribution from Cornwall Council, and private investment. It is clear from these experiences that private investors are unwilling to support projects until they are demonstrably market-ready (House of Lords, 2017), being discouraged by perceived geological risks (https://www.theguardian.com/world/2009/dec/15/swiss-geothermal-power-earthquakes-basel), and so these need to be quantified from an appraisal of all the data available, and be presented using terms familiar to potential stakeholders.

3. UNDERLYING RATIONALE BEHIND THE GWATT PROJECT

Exploitation of the UK deep thermal resource is held back by knowledge gaps about permeability and fluid/heat flow within fractured hot rocks. The GWatt project aims to fill these gaps via novel studies of rock stress, natural fracture networks, hot rock permeability, heat/fluid transport, and optimisation, in order to maximise reservoir utilisation whilst minimizing risks. These will be achieved via detailed laboratory studies, field based and remote sensing measurements of fractures across SW England, and integration of data coming out of the United Downs Deep Geothermal Power (UDDGP) project (the first commercial project in the UK with the aim of developing an economically viable EGS (Ledingham et al., 2019). The UDDGP project will exploit natural permeability in a regional NW-SE fault (Porthtowan Fault Zone - PFZ) in the Carnmenellis Granite (Fig. 1), and is strongly focussed on drilling and the production of hot fluids for a working power plant. While it provides an unparalleled opportunity to gather unique data in the form of downhole fluids, rock samples, geophysical logs, flow data, and seismic data, it does not have the remit or finance to use these unique datasets to drive forward understanding of EGS potential and utilisation in the UK. GWatt will maximise the scientific potential from these unique data, and carry out innovative additional analyses and interpretation, combining site-specific observations with regional studies of SW England and state-of-the-art uncertainty quantification workflows, to address the challenges associated with regional EGS development.

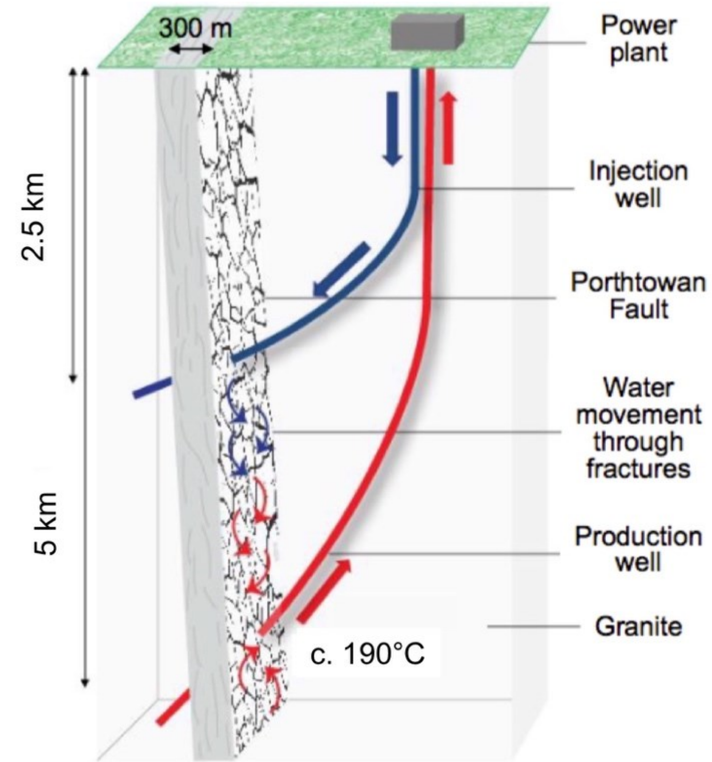

Figure 1: The United Downs two borehole EGS project led by Geothermal Engineering Limited utilises the fracture permeability of the Porthtowan Fault Zone (PFZ).

4. AIMS AND OBJECTIVES OF GWATT

The GWatt project aims to achieve a better understanding of fluid flow and heat transport in deep fracture-dominated systems that will enable the prediction of the economically-utilisable geothermal resource, the optimisation of reservoir development, and the quantification of geological uncertainty and geological risks (such as induced seismicity). Through close collaboration between research and commercial partners it will facilitate collaboration between industry and academia. It will also provide an opportunity for knowledge transfer, providing young scientists with valuable, first-hand experience of an EGS operation.

Objectives of the work undertaken are to:

- Increase knowledge of the geological conditions needed for deep fracture-controlled fluid flow, via an in-depth study of the granites and their adjacent host rocks of SW England.
- Identify indicators of deep fracture flow from shallower measurements.
- Develop new 3D fracture/structural/tectonic models of the SW England granites and their immediately adjacent host rocks that reflect the complete post-Variscan tectonic evolution.
- Develop a quantitative understanding of the heat resource and sustainability of the reservoir.
- Provide an assessment of seismic potential due to fluid flow through the Porthtowan Fault Zone.
- Construct robust geological risk assessments based on well-established oil & gas uncertainty quantification and optimisation methods, with a view to reducing perceived risks.
- Apply the integrated results of site-specific research at United Downs to new geothermal exploration models of the other granites of SW England.
- Identify key findings having application to crystalline basement rocks in other parts of the UK.

Implementation of work within GWatt will be via a number of integrated Work Packages (WPs) which will use information from detailed site-scale monitoring (WP1), high-resolution (micro-scale) lab-based analyses of samples (WP1&2), and lab-scale process-oriented studies (WP1&2) for the production of enhanced reservoir-scale models (WP2). This reservoir-scale understanding will be combined with an enhanced model for regional granite evolution and fracturing (WP3), and will be brought together into risk-based models (WP4) to facilitate informed assessment of the geothermal potential of SW England (WP5). Each Work Package is broken up into a number of tasks, and these are detailed in the following sections.

4.1 Work Package 1: Measuring and quantifying deep fracture-controlled fluid flow

The GWatt team will study fracture properties in detail, as they are the critical controls of water/heat movement within deep crystalline rocks. WP1 will provide evidence for hydraulically-conductive fractures, quantify fracture properties and initial fluid/heat flow (i.e. natural) conditions, and use these data to improve predictions of sustainable magnitudes of fluid/heat flow. Results from WP1 will feed into reservoir models (WP2) and into regional (WP3) models.

Through analysis of fractures and breakouts detected on UDDGP project geophysical borehole logs, we plan to study the local stress field to obtain overall stress magnitudes and directions, and investigate changes in stress with depth. This will provide constraints on fracture abundance and orientations, and provide a firm basis for fracture network modelling. This will be complemented by lab studies to determine fracture permeabilities under changing stress conditions. These tests will use surface-derived samples and synthetic groundwaters as well as, if available, samples collected from the UDDGP project. Data from all these activities will feed into the static and dynamic reservoir modelling in WP2 allowing us to predict flow directions and potential flow rates.

One of the biggest uncertainties for any geothermal project dependent on fracture permeability, is predicting deep fracture flow. We seek to reduce such uncertainties with new studies building on the potential of the UDDGP project: 1) We will conduct novel isotope analyses (K, Pb, U series) and identify geochemical markers within the geothermal fluids that indicate fluid-rock contact times and fluid origins; 2) We will utilise existing equipment to provide additional passive microseismic monitoring during injection testing, providing additional resolution for locating fracture flow within the reservoir (WP2), and hence inform reservoir modelling (WP2) and risk assessment (WP4).

4.2 Work Package 2: Understanding and optimising the development of geothermal resources

We will test the hypothesis that the geothermal reservoir being targeted by the UDDGP project comprises a c. 250-300 m wide damage zone of the PFZ, with sufficient permeability to sustain economic flow rates, surrounded by granite with a lower fracture permeability. The thermal potential of the reservoir and its sustainable exploitation involves the movement of water/heat between the fractured granite and the PFZ, and along the PFZ. We aim to understand and quantify the factors controlling this, which will lead to optimised reservoir development. Towards these ends we aim to determine a high-resolution profile of heat production down to 5 km; enhanced descriptions of fracture fills with new lab data on their frictional properties and reactivity under geothermal conditions; an enhanced dataset of geothermal fluid compositions; a suite of fracture network models and associated simulations of the geothermal reservoir.

Rock chips collected from the UDDGP project boreholes will be analysed via gamma spectroscopy for U, K and Th (main contributors to radioactivity, and hence heat production, in the granite). Available gamma logs will also be analysed for radioelement content so that a heat production profile to a depth of 5 km can be constructed. Equilibrium temperature measurements from the UDDGP project boreholes will be combined with thermal conductivity measurements on rock chips from the boreholes for revised heat flow determinations. We will use these new data to build on current models (Beamish and Busby, 2016), and generate a revised estimate of the thermal resource of the Carnmenellis Granite.

Key aspects of geothermal reservoirs in granites are the nature and extent of fracture fill, its impedance to flow, and its evolution during geothermal exploitation. We will study the composition and structure of fracture fills using representative samples from surface exposures of the PFZ, as well as borehole material, if successfully recovered. Detailed mineralogical, paragenetic and fluid inclusion analysis will inform models of fracture fill and permeability evolution during repeated fault reactivation over geological timescales. These data will be augmented by lab-based fluid-rock reaction experiments under simulated in situ conditions, and associated modelling, to ascertain how fracture-filling phases will change under artificial fluid flow over the decadal timescales of an EGS operation. Results will feed into reservoir modelling and regional modelling.

An important constraint to EGS development is the rate at which water can be re-injected. High injection rates will increase pressure and change in situ stresses, risking reactivation of fractures and possible (micro-)seismic events (Majer et al., 2007). Thus, it is crucial to determine under what stress states, temperature, and composition conditions such reactivation could lead to seismicity, and hence constrain the maximum rates of water re-injection in order to avoid public concern or regulatory infringement. We will derive new shear/stress data through laboratory friction experiments using a tri-axial apparatus under in situ conditions. Slip velocities will be stepped to allow interpretation of the data in terms of the Rate and State Friction framework (Dieterich 1978, 1979; Ruina 1983). We will use samples of analogous natural fracture fill materials, samples from UDDGP project boreholes, if available, and appropriate simulated fracture fill. This will allow determination of the evolution of the frictional properties during the lifetime of the UDDGP project, and also make it possible to infer the risk of induced seismicity due to the operation of EGSs in reservoirs with different compositions. These lab-scale studies will complement field-scale observations through microseismic monitoring (WP1), and the results will directly inform risk assessment (WP4).

A recent development benefitting the economics of EGS is the possibility of extracting useful components within the recirculating brine (e.g. dissolved metals), especially in ore deposit areas (Szanyi et al., 2016). We will analyse the compositions of fluids recovered from the UDDGP project boreholes to quantify the concentrations of dissolved components, and extend chemical datasets from the UDDGP project and the CHPM2030 project (http://www.chpm2030.eu). We will also use laboratory-leaching experiments to quantify the rates at which these can be replaced through mineral dissolution. By combining these data with fluid flow modelling, we will quantify the potential for metal extraction, as well as the risk of mineral scaling, which could occlude reservoir permeability, over the decadal lifetime of an EGS.

Discrete fracture network modelling will be used to create a suite of geological models of the fractured granite system, conditioned to borehole measurements and other static data (e.g. surface mapping) that captures the range of possible geological scenarios fitting the regional geological setting. The ensemble will first require the creation of different conceptual models integrating information from both local- (WP2) and regional-scale studies (WP3), and relevant monitoring data (WP1) to create a robust representation of the geothermal system. Geostatistical models will then be created that capture the nature of the fracture network with its inherent geological uncertainties. Model resolution will be scaled appropriately, using well established upscaling methods (Dershowitz et al., 2000) and relevant software (Fracman and Petrel).

Dynamic simulations of the geothermal reservoir models will be carried out using the Computer Modelling Group suite of reservoir simulation tools (https://www.cmgl.ca/software). In particular, we will use the thermal simulator STARS to model convective and conductive heat-flow. STARS has many advantages over other models, including; containing advanced models for modern production/injection boreholes; offering adaptive gridding to resolve temperature fronts in the reservoir more accurately; and the ability to be readily linked to modern uncertainty quantification and optimisation workflows. The various outputs will provide parameters such as: heat flow rates at boreholes; 4D temperature distributions in the subsurface; and reservoir permeability evolution. These simulation outputs will be combined with information from WP4 to provide a comprehensive geological risk assessment.

4.3 Work Package 3: Regional geological and geothermal model for the SW England granite

Key to the wider development of EGS technology across SW England are the large, regional, NW-SE steeply-inclined fault zones (known locally as ‘cross courses’). These are predicted to be prime deep EGS targets due to their near parallelism with the in situ maximum horizontal stress direction (Batchelor and Pine, 1986) and predicted good reservoir characteristics. However, (i) they show complexities in terms of their distribution, evolution, size, geometry and structural/fluid flow/wall rock alteration histories, and (ii) their connectivity with other, regional, fracture sets are poorly constrained. Such uncertainties present a substantive risk to future EGS development in the region. We will synthesise a range of existing data (onshore mapping, mine records, offshore data), with new data (regional mapping and modelling, data from the UDDGP project), to enhance understanding of the characteristics and structural evolution of the regional fracture system. The emphasis will be on the identification of scenarios/locations for enhanced deep fracture permeability. When combined with heat flow/temperature and other data, these outputs will contribute to risk-based prospectivity mapping for deep EGS reservoirs (WP4) and underpin assessments of the regional geothermal potential (WP5).

Many of the regional ('cross-course') fault systems in SW England developed as transfer faults during Variscan thrust-faulting, and were subsequently reactivated as extensional faults during Triassic rifting (Shail and Alexander, 1997), and as strike-slip faults during Cenozoic intraplate shortening. They have controlled multiple regional fluid flow episodes and locally host Triassic, and later epithermal, mineralisation, as well as displacing earlier granite-related Sn-Cu lode systems. We will synthesise published data from onshore and adjacent offshore areas, pertaining to the characterisation and evolution of post-Variscan fracture systems (Shail and Alexander, 1997) with an emphasis on understanding the nature and timing of the many complex processes that might have had an impact upon fracture permeability.

One of the project aims is to produce new digital (ArcGIS) maps of key faults near to the UDDGPP site and across the SW England granite. This study will incorporate: (i) semi-automated lineament detection methodologies, based on pre-existing high resolution ‘Tellus South West’ LiDAR and airborne radiometric and magnetic data (Beamish et al., 2014; Yeomans et al., 2019); (ii) BGS mapping data; and (iii), historical mine data. This will be combined with historical data to create 3D structural models of key fault zones during post-Variscan tectonic regimes. The modelling will focus upon the potential for different stress fields to develop enhanced zones of fault damage in areas of regional scale fault bend and fault overstep. The results will identify critical locations for higher resolution remote and outcrop mapping using satellite data and UAV mapping. Results will be combined with reservoir simulations (WP2) to inform estimates of thermal resource of SW England granites, and inform risk assessment (WP4).

The Carnmenellis Granite (part of the Cornubian Batholith underlying much of SW England) shows zoned composition in its near-surface expression (Simons et al., 2016), but the characteristics of its deeper (>2.5 km) parts are unknown. Mineralogical and geochemical variations, reflecting the emplacement of different melt batches, are likely to exert a fundamental control on the distribution of the heat producing elements (U, Th, K), thermal / physical properties, and hence heat production and flow. We will use whole rock geochemical and mineral chemical data from UDDGP project samples to build upon recent work (Simons et al., 2016; Simons, 2017), and generate a revised model for the generation and construction of the upper 5 km of the Carnmenellis Granite and its control upon the distribution of heat-producing elements. This will be combined with laser-ablation/mass spectrometric dating techniques of zircon crystals to constrain this construction history. These new data from the deeper Carnmenellis Granite will be used to inform a revised deeper regional Cornubian Batholith model, particularly with respect to heat generation and thermal properties, thus contributing to the quantification of uncertainties in extrapolating geothermal potential from one granite body to another, and hence informing risk assessment (WP4).

4.4 Work Package 4: Uncertainty quantification and risk assessment

Here we aim to: 1) identify and rank potential risks to the operation of the UDDGP project; and 2) quantify reservoir uncertainties in order to assess the magnitude and impact of said potential risks. The novelty within this WP is leveraging data and models provided by WP1-3, with a comprehensive geological and reservoir engineering assessment, to quantify risks related to minimum acceptable heat flow rates or induced seismicity. This will result in the quantification of the effectiveness of prevention and mitigation measures. We will address this area via; a risk assessment workshop to elucidate key factors, create a formalised dataset of bow-tie diagrams and metadata. This will enable us to create a range of uncertainty and risk models that allow extrapolation of site-specific information to the regional scale.

We will apply the 'bow-tie analysis' method (Delvosalle et al., 2005) a recognised risk assessment tool (ISO 17776, 2016) involving building a bow-tie diagram (Fig. 2), to depict the relationships between the causes of unwanted events, their escalation to a range of possible outcomes, the measures preventing the event, and measures in place to mitigate the consequences. This has advantages over other techniques (ISO 31010, 2009), in the illustration of prevention and mitigation controls along with their causes and consequences. The bow-tie approach is widely used in the oil & gas industry to assess and rank risks (Shahriar et al., 2012), though has had only limited use in other subsurface applications (an exception being CCS [Bourne et al., 2014; Dean and Tucker, 2017]). Bow-tie analyses provide a readily-understandable summary of the entirety of a particular situation, and are very useful for identifying where potential system weaknesses arise, and also for communication with non-specialists. One or more workshops will be held to create the initial basis for the bow-ties. As well as site-specific bow-ties, a general bow-tie will be created for application to other potential EGS projects in SW England. We will also integrate data and concepts from WP1-3 to inform a set of statistically-based models to quantify uncertainty in the forecasts of the reservoir models produced in WP3, prioritising models that focus on the key risks.

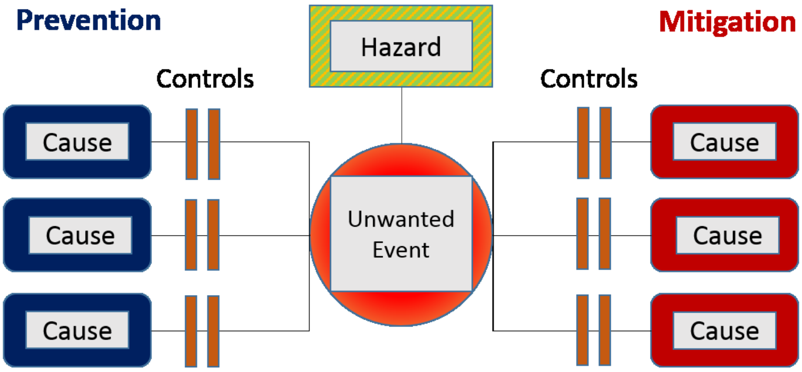

Figure 2: Generalised layout of a Bowtie diagram.

Uncertainty quantification techniques, such as Bayesian approaches (Shahriar et al., 2012), will provide probabilistic ranges of reservoir behaviours based on forecasts from models conditioned to known data (from WP1&2). Model forecasts will estimate uncertainty in reservoir response to production (Christie et al., 2006), and inform the likelihood and magnitude of key risks (e.g. permeability impairment due to fractures closing) to the operation of the UDDGP project. The bow-tie approach will be expanded to include quantitative risk assessment, to determine the relative contribution of prevention and mitigation measures. The best combination of proxy modelling and model clustering from those created in WP2&3 will be used to develop an optimal ensemble for uncertainty quantification. We will also apply 'multi-objective optimisation' methods (Schulze-Riegert et al., 2007) to simulation models. These will estimate the range of behaviours of the reservoir to changes in field operation (e.g. injection temperature, borehole spacing) to help identify the trade-off of competing objectives, such as maximising enthalpy recovery from the reservoir while minimising the risk of mineral scale formation, or minimising drilling cost. 'Quantification of margins and uncertainties' approaches to identify ways to optimise reservoir operation. Application of state-of-the-art uncertainty quantification and optimisation workflows to an actual geothermal reservoir will advance previous work on synthetic representations of a hot aquifer (Schulte et al., 2016). Such workflows are well-established in the oil and gas industry and are flexible enough to support reservoir management decisions while the geological understanding of the reservoir evolves over the lifetime of the field (Arnold et al., 2016). The numerical algorithms that underpin such workflows are available in CMOST-AI and the commercial Raven software (http://useraven.com/).

4.5 Work Package 5: New insights to enhance uptake of geothermal energy from granites

Here we will combine the outputs from the other WPs and deliver both a detailed understanding of the subsurface environment at United Downs, and an enhanced understanding of similar environments across SW England. This will involve integrating the results of detailed site-specific studies (e.g. monitoring, stress analysis, heat resource, fracture properties, chemical resource, local reservoir modelling) with those of regional-scale investigations (e.g. fracture surveying, granite evolution), together with analyses of uncertainties (bow-tie and uncertainty quantification), to provide a well-constrained and quantified understanding of the geothermal potential of SW England, the generic lessons from which we will identify for potential application to other parts of the UK.

Through this work we aim to: 1) Reduce apparent uncertainties associated with geothermal development in SW England, and thus increase investor confidence; 2) Provide stakeholders (e.g. local people, industry, scientists) with an enhanced understanding of the potential for geothermal energy; 3) Develop well-tested methodologies of monitoring, measurement and modelling that have application to fractured basement rocks elsewhere in the UK.

5. CONCLUSIONS

The UK has a statutory commitment of a reduction in greenhouse gas emissions to net zero by 2050 relative to 1990 levels. Engineered Geothermal Systems align well with these goals, can provide power from regions devoid of conventional hydrothermal resources, and have the potential to provide sustainable, reliable, carbon-free power for the UK. However, exploitation of the UK deep thermal resource is held back by knowledge gaps about permeability and fluid/heat flow within fractured hot rocks. Here we provide an introduction to the GWatt project, which aims to fill these knowledge gaps. This will be done via novel studies of rock stress, natural fracture networks, hot rock permeability, heat/fluid transport, and optimisation, in order to maximise reservoir utilisation whilst minimizing risks. We will focus our work on the granites of SW England, and our work programme involves combining innovative and detailed scientific understanding from new laboratory testing, field measurements and predictive modelling, with data obtained from two new boreholes at the UK's deepest geothermal project at United Downs in Cornwall. GWatt will maximise the scientific potential from these unique data, and carry out innovative further analyses and interpretation, outwith the UDDGP project, combining site-specific observations with regional studies of SW England and state-of-the-art uncertainty quantification workflows, to address the challenges associated with regional EGS development. The project will facilitate collaboration between industry and academia, and also provide young researchers with valuable, first-hand experience of an EGS operation.

6. ACKNOWLEDGEMENTS

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REFERENCES

Arnold D., Demyanov V., Christie M., Bakay A., Gopa K. (2016). Optimisation of decision making under uncertainty throughout field lifetime: A fractured reservoir example. Computers and Geosciences, 95, 123-139.

Baria, R., Baumgaertner, J., Teza, D., Bennett, T., Glass, H. and Jupe, A. (2016). Development of geothermal technology to address the climate change issue in the densely populated areas of the world. Proceedings of the European Geothermal Congress 2016, Strasbourg, France, 19-24 sept 2016.

Batchelor, A.S. and Pine, R.J. (1986). The results of in situ stress determinations by seven methods to depths of 2500 m in the Carnmenellis granite. Proceedings of the International Symposium on Rock Stress and Rock Stress Measurements, Stockholm, 1-3 September 1986. International Society for Rock Mechanics and Rock Engineering, 467-478.

Baujard, C., Genter, A., Graff, J-J., Maurer, V. and Dalmais, E. (2015). ECOGI, a New Deep EGS Project in Alsace, Rhine Graben, France. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015, pp. 6.

Beamish, D. and Busby, J. (2016). The Cornubian geothermal province: heat production and flow in SW England: estimates from boreholes and airborne gamma-ray measurements. Geothermal Energy, 4:4, 25pp, DOI 10.1186/s40517-016-0046-8 .

Beamish, D, Howard, A S, Ward, E K, White, J, Young, M E. (2014). Tellus South West airborne geophysical data. Natural Environment Research Council, British Geological Survey. (see: http://www.tellusgb.ac.uk/home.html).

Bourne, S., Crouch, S. and Smith, M. (2014). A risk-based framework for measurement, monitoring and verification of the Quest CCS Project, Alberta, Canada. International Journal of Greenhouse Gas Control 26, 109-126.

Breede, K., Dzebisashvili, K., Liu, X., and Falcone, G. (2013). A systematic review of enhanced (or engineered) geothermal systems: past, present and future. Geothermal Energy, 1:4, pp. 27.

Busby, J. and Terrington, R. (2017). Assessment of the resource base for engineered geothermal systems in Great Britain. Geothermal Energy,5:7, pp. 18. DOI 10.1186/s40517-017-0066-z.

Christie, M., Demyanov, V. and Erbas, D. (2006). Uncertainty quantification for porous media flows. Journal of Computational Physics, 217, 143-158.

Dean, M. and Tucker, O. (2017). A risk-based framework for Measurement, Monitoring and Verification (MMV) of the Goldeneye storage complex for the Peterhead CCS project, UK. International Journal of Greenhouse Gas Control 61, 1-15.

Delvosalle, C., et al. (2005). Identification of reference accident scenarios in SEVESO establishments. Reliability Engineering & System Safety, 90(2), 238-246.

Dershowitz, B., LaPoint, P., Eiben, T. and Wei, L. (2000). Integration of discrete fracture network methods with conventional simulator approaches. SPE Reservoir Evaluation and Engineering, 3(2), 165-170.

Dieterich, J. H. (1978). Time-dependent friction and the mechanics of stick-slip. Pure and Applied Geophysics, 116, 790-806.

Dieterich, J. H. (1979). Modeling of rock friction 1. Experimental results and constitutive equations. Journal of Geophysical Research 84(B5), 2161-2168.

Downing, R.A. and Grey, D.A. (1986). Geothermal Energy: The potential in the United Kingdom. Her Majesty's Stationary Office (HMSO), London, ISBN-10: 9780118843669, ISBN-13: 978-0118843669, 187 pp.

House of Lords Select Committee on Economic Affairs (2017). The Price of Power: reforming the Electricity market. 2nd Report of Session 2016–17, Published by the Authority of the House of Lords, 68pp.

ISO17776 (2016) Petroleum and natural gas industries - Offshore production installations -Guidelines on tools and techniques for hazard identification and risk assessment. https://www.iso.org/standard/ 63062.html

ISO31010 (2009) Risk management - Risk assessment techniques. https://www.iso.org/standard/51073.html

Kelkar, S., WoldeGabriel, G. and Rehfeldt, K. (2016). Lessons learned from the pioneering hot dry rock project at Fenton Hill, USA. Geothermics, 63, 5-14.

Korlbet, T. and Genter, A. (2017). Enhanced geothermal systems: The Soultz-sous-Forets Project. In: 'Towards 100% Renewable Energy. Techniques Costs and Regional case Studies', T.S. Uyar (ed.), 243-248, Springer.

Ledingham, P., Cotton, L. and Law, R. (2019). The United Downs Deep Geothermal Power Project. Proceedings of the 44th Workshop on Geothermal reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019, SGP-TR-2314, 11pp.

Majer, E. L., et al. (2007). Induced seismicity associated with Enhanced Geothermal Systems. Geothermics, 36(3), 185-222.

MIT (Massachusettes Institute of Technology) (2006). The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st Century, US Department of Energy, Washington, D.C. http://mitei.mit.edu/publications/reports-studies/futuregeothermal-energy.

Olasolo, P., Juárez, M.C., Morales, M.P., D'Amico, S. and Liarte I.A. (2016). Enhanced geothermal systems (EGS): A review. Renewable and Sustainable Energy Reviews, 56, 133-144.

Priestley, S. (2019). Legislating for net zero. House of Common Briefing Paper CBP8590, House of Commons Library, 11 pp.

Richards, H.G., Willis-Richards, J. and Pye, J. (1991). A review of geological investigations associated with the UK Hot Dry Rock programme. Proceedings of the Ussher Society, 7, 321-326.

Ruina, A. (1983). Slip instability and state variable friction laws. Journal of Geophysical Research, 88(B12), 10359-10370.

Schulze-Riegert, R.W., Krosche, M., Fahimuddin, A. and Ghedan, S.G. (2007). Multi-objective optimisation with application to model validation and uncertainty quantification. SPE Paper SPE-105313-MS.

Schulte et al., 2016 http://adsabs.harvard.edu/abs/2017EGUGA..1916338S

Shahriar, A., et al. (2012). Risk analysis for oil & gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis. Journal of Loss Prevention in the Process Industries, 25(3), 505-523.

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, 154, 163-168.

Shahriar, A., Sadiq, R. and Tesfamariam, S. (2012). Risk analysis for oil & gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis. Journal of Loss Prevention in the Process Industries, 25(3), 505-52.

Simons, B.J., Shail, R.K. and Andersen, J. (2016). The petrogenesis of the Early Permian Variscan granites of the Cornubian Batholith: Lower plate post-collisional peraluminous magmatism in the Rhenohercynian Zone of SW England, Lithos, 260, 76-94.

Simons, B.J., Andersen, J., Shail, R.K. and Jenner, F.E. (2017). Fractionation of Li, Be, Ga, Nb, Ta, In, Sn, Sb, W and Bi in the peraluminous Early Permian Variscan granites of the Cornubian Batholith: precursor processes to magmatic-hydrothermal mineralisation, Lithos, 278-281,491-512.

Szanyi, J., Medgyes, T., Kóbor, B. and Osvald, M. (2016). Conceptual Framework For Orebody-EGS. CHPM2030 project report D1.4, 38pp. Available at: http://www.chpm2030.eu/wp-content/uploads/2017/02/CHPM2030_D1.4_public.pdf

Yeomans, C.M., Middleton, M., Shail, R.K., Grebby, S. and Lusty, P.A.J. (2019). Integrated Object-Based Image Analysis for semi-automated geological lineament detection in southwest England. Computers & Geosciences, 123: 137–148 [Available Online November 2018].