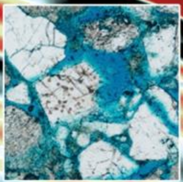
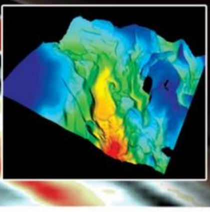
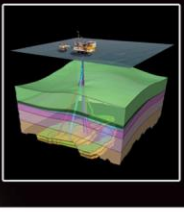




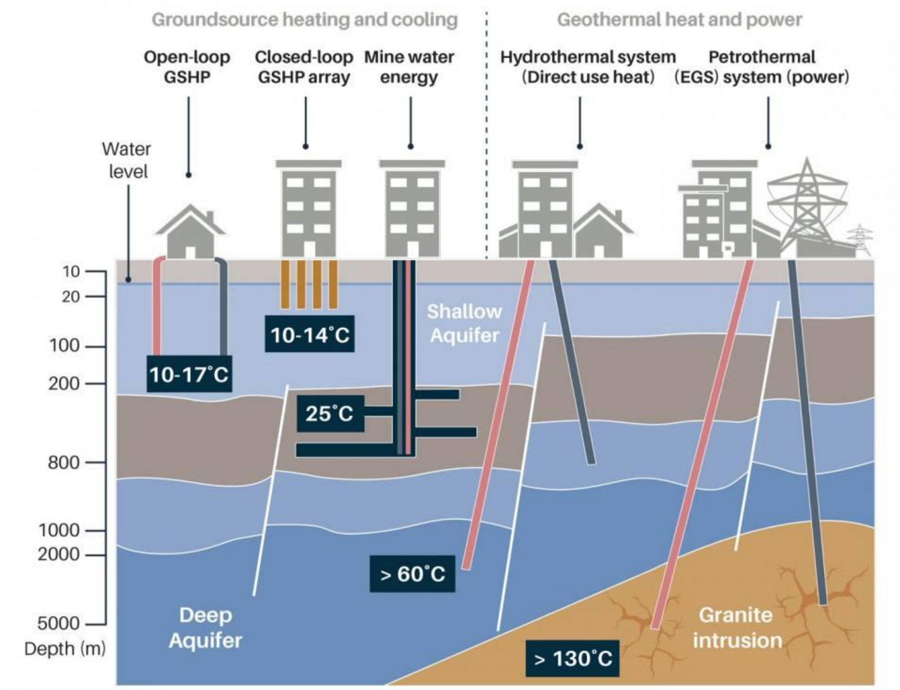


The Geological Society

ABSTRACT BOOK

10th UK Geothermal Symposium

20th - 22nd November 2023
The Geological Society, Burlington House, Piccadilly London



- **The development of geothermal energy to provide sustainable baseload heat and power at different scales is moving at an unprecedented pace.**
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10th UK Geothermal Energy Symposium

20th-22nd November 2023

The Geological Society, Burlington House, Piccadilly, London and Online

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Quantifying the Impacts of Faults and Dykes on Fluid Flow in Northern Ireland Permo-Triassic Reservoirs and Aquifers Mark Cooper, BGS
tanuki™/PyFDEM: a Toolkit for the Permeability Enhancement Optimisation of Geothermal Wells Ado Farsi, *Imperial College London*
Understanding Lithosphere-Asthenosphere Dynamics for Global Geothermal Prospectivity Mapping Megan Holdt, University of Cambridge
Lithium extraction from geothermal waters in Southwest England William Irani, *Cornish Lithium*
Unlocking Geothermal Energy: Recent Developments in Puga Valley and the Global Call for Advocacy Sanskriti Jha
The Geology of Fractures in the Subsurface - applications to Geothermal and CCS Melissa Johansson, *Geode*
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Scope of Subsurface Geological Studies for Geothermal Investigation in Shyok-Nubra Valley, Ladakh Himalaya Parashar Mishra, *Geological Survey of India*
Scalability and geomechanical influence on structurally-controlled fluid flow in Leeds, West Yorkshire Kathryn Page, *University of Leeds*
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Coal Authority Mine Water Heat data Fiona Todd, *The Coal Authority*
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ORAL ABSTRACTS
(In Programme Order)

Session One: Keynote Session

Unearthing the heat beneath our feet in Northern Ireland: The GeoEnergy NI project

M. MacKenzie1 (michael.mackenzie@economy-ni.gov.uk), S. Clements1, M. T. Cowan2 & C. Lydon3
1 Department for the Economy, Adelaide House, Belfast, 2 GSNI, Dundonald House, Belfast, 3 Tetra Tech Europe, 1 Locksley Business Park, Montgomery Road, Belfast.

A new geothermal demonstrator project representing a £3 million investment, GeoEnergy NI is being delivered by the Department for the Economy (DfE), with scientific support from the Geological Survey of Northern Ireland (GSNI) and a specialist contractor team led by Tetra Tech Europe. The project, designed to 'unearth the heat beneath our feet', aims to support how we decarbonise the energy sector in pursuit of net zero carbon targets by 2050.

Whilst shallow geothermal has the potential to be installed in most places across Northern Ireland, there are also significant prospective areas for deep geothermal. This has been recognised since the late 1970s, when a borehole, drilled at Ballymacilroy, Co. Antrim found hot water in Permian and Triassic sandstones, and then a geothermal exploration borehole at Larne in 1982 (part of the UK Department for Energy's Geothermal Programme). Ultimately, of the exploration wells drilled across the UK, only the one at Southampton went on to be used for geothermal.

Despite this, the project provided much needed data that advanced our understanding of the deep geology across the UK. The end of the energy crisis at the time, meant that deep geothermal exploration was not pursued.

Today, the energy landscape is different. We have seen increased volatility in the supply of imported fuels, large price rises and their effects on levels of fuel poverty (22% in 2019, with some studies suggesting it may be higher). Society is more aware of the effect that emissions from fossil fuel combustion is having on the climate and there are legally binding targets to achieve net zero emissions by 2050 in the Climate Change Act (NI) 2022.

The Northern Ireland Executive's Energy Strategy for Northern Ireland, published in December 2021, sets out a pathway for energy to 2030 that will mobilise the skills, technologies and behaviours needed to take us towards our vision of net zero carbon and affordable energy by 2050.

It is accompanied by a series of measures to achieve this. One of which is to develop opportunities for heat networks and assess potential solutions to decarbonise existing heat networks including geothermal and waste heat. This was clarified further in the DfE Energy Strategy Action Plan, with an action to "Develop and commence delivery of a geothermal demonstrator project".

Whilst Northern Ireland has made great progress in the decarbonization of its electricity supply, using renewables, such as wind and solar, our heat (which accounts for 56% of energy related emissions) is harder to decarbonise and will require a number of solutions. Countries across Europe, with similar geological basins have pursued geothermal and now have a growing sector, but the geothermal energy sector in NI remains nascent (Palmer et al. 2022).

DfE is investing in the GeoEnergy NI project to address this. GeoEnergy NI, will examine both shallow and deep geothermal at the Stormont Estate, Belfast and the College of Agriculture, Food and Rural Enterprise (CAFRE), Greenmount Campus, Antrim, respectively. The feasibility study for the shallow geothermal project aims to identify the most suitable geothermal solution to provide future heating and cooling for several pre-identified buildings on the Estate, to understand the carbon savings that could be generated and to optimise the capital expenditure and operational expenditure costs of any future geothermal heating system. Activities at the CAFRE Greenmount Campus, Antrim will involve the completion of several geophysical surveys that will build a fuller picture of the underlying rocks in the area. This study will also include the identification of a potential future drill site and optimum target depths for deep geothermal solutions as well as a suitable heat recovery system for the area. The GeoEnergy NI project will add benefit by including a public and stakeholder outreach campaign. A new website, Virtual Reality educational programme, and a mobile visitor centre, the GeoEnergy Discovery Centre, have all been launched as part of this campaign. The aim of these is to further enhance the public's awareness and understanding of geothermal and the economic potential Northern Ireland's geothermal sector holds.

A large part of the project includes the development of a comprehensive and fully integrated communications programme designed to inform and educate the public and key stakeholders about geothermal energy and deliver positive engagement and awareness of the GeoEnergy NI demonstrator projects. Market research before, during and after the project will benchmark and test changes in awareness and understanding levels of geothermal energy here in Northern Ireland.

In July 2023, the GeoEnergy NI project completed the exploratory geophysical surveys around the CAFRE Greenmount Campus, including high density 2D seismic reflection, magnetotellurics and gravity surveying. The team shall then move on to conduct exploratory drilling on the project's second study site at the Stormont Estate in Belfast. As the project progresses, information will be available on the GeoEnergy NI Webpage at www.GeoEnergyNI.org

Figure 1. – Survey design around the CAFRE site (outlined in red). Antrim town lies just to the north of the survey area.

Palmer et al. 2022

Session Two: Geothermal Finance and Hot Sedimentary Aquifers

Procuring Renewable Energy Directly: The Customer Opportunity

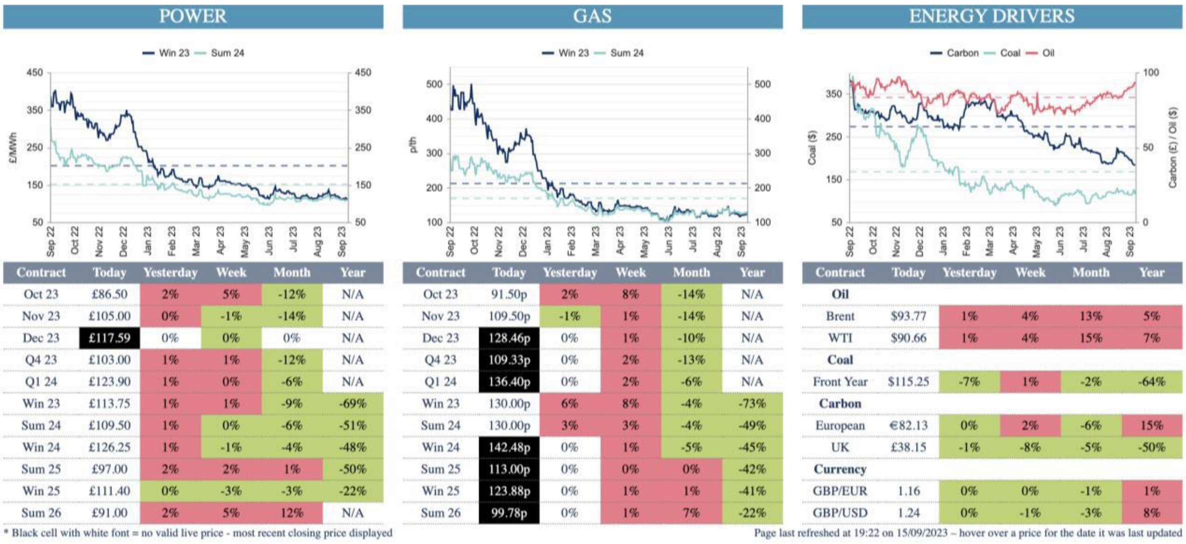
Michael Abbott
Chief Executive Officer – Sustainable Energy First Ltd and Business Power and Gas Ltd.
Email: michael.abbott@sefirst.com Mobile: +44(0) 7971 852 635

Procuring renewable energy directly from source has historically been the preserve of utilities, very large corporates, and pseudo public bodies such as universities and hospitals; scale and financial strength have always been critical. As a result of record power and gas commodity prices during and following the 'energy crisis' and the drive to NetZero, procuring directly over the long term is now attractive to organisations of all sizes, creating a huge new market for renewable energy producers.

The purpose of my presentation is to provide context to the current and future market conditions and explain the drivers for end-consumers. I will also address the commercial frameworks from a practical perceptive and how to overcome the key barriers for end-customers and producers. Established renewable technologies such as wind and solar are intermittent whilst customer usage is not; addressing this mismatch both physically and commercially is key. The traditional large utilities are not sufficiently agile to be able to capitalise on this market opportunity for their customers, a challenge which must be overcome.

In conclusion, I will show how geothermal energy, both in terms of electricity generation and zero carbon heat, has a massive role to play. The baseload nature of electricity from geothermal sources is hugely attractive to the maket and easier to match to customer demand profiles. The scarcity of heat from renewable sources presents an even bigger opportunity for geothermal to address a further customer need.

Figure 1 – Live Power and Gas Commodity Prices as at 15th September 2023



POWER

Contract	Today	Yesterday	Week	Month	Year
Oct 23	£86.50	2%	5%	-12%	N/A
Nov 23	£105.00	0%	-1%	-14%	N/A
Dec 23	£117.59	0%	0%	0%	N/A
Q4 23	£103.00	1%	1%	-12%	N/A
Q1 24	£123.90	1%	0%	-6%	N/A
Win 23	£113.75	1%	1%	-9%	-69%
Sum 24	£109.50	1%	0%	-6%	-51%
Win 24	£126.25	1%	-1%	-4%	-48%
Sum 25	£97.00	2%	2%	1%	-50%
Win 25	£111.40	0%	-3%	-3%	-22%
Sum 26	£91.00	2%	5%	12%	N/A

* Black cell with white font = no valid live price - most recent closing price displayed

GAS

Contract	Today	Yesterday	Week	Month	Year
Oct 23	91.50p	2%	8%	-14%	N/A
Nov 23	109.50p	-1%	1%	-14%	N/A
Dec 23	128.46p	0%	1%	-10%	N/A
Q4 23	109.33p	0%	2%	-13%	N/A
Q1 24	136.40p	0%	2%	-6%	N/A
Win 23	130.00p	6%	8%	-4%	-73%
Sum 24	130.00p	3%	3%	-4%	-49%
Win 24	142.48p	0%	1%	-5%	-45%
Sum 25	113.00p	0%	0%	0%	-42%
Win 25	123.88p	0%	1%	1%	-41%
Sum 26	99.78p	0%	1%	7%	-22%

ENERGY DRIVERS

Contract	Today	Yesterday	Week	Month	Year
Oil					
Brent	$93.77	1%	4%	13%	5%
WTI	$90.66	1%	4%	15%	7%
Coal					
Front Year	$115.25	-7%	1%	-2%	-64%
Carbon					
European	€82.13	0%	2%	-6%	15%
UK	£38.15	-1%	-8%	-5%	-50%
Currency					
GBP/EUR	1.16	0%	0%	-1%	1%
GBP/USD	1.24	0%	-1%	-3%	8%

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UK Planning and Community Engagement for Deep Geothermal development

Dr Ryan Law1, Hazel Farndale1, Jane Charman1 & Amy Peach-Gibson1
1contact@geothermalengineering.co.uk, Geothermal Engineering Ltd, Cornwall, UK,

In the UK, recent planning legislation stipulates that major developments need to increase the biodiversity net gain of the project area by a minimum of 10% within 30 years. This change in legislation has highlighted another potential point of conflict with the community. There is often an assumption that there is a far greater abundance of species on existing land than is actually the case. The public can therefore be protective of this perceived biodiversity, rather than the actual biodiversity. This results in an opinion that many residents would prefer no development than a development that will increase biodiversity. To work with this, geothermal community engagement officers need to acquire new knowledge about biodiversity, and the best methods to explain the concept of biodiversity net gain. In short, developing a renewable energy project is no longer enough, organisations must now also demonstrate their commitment to nature.

To many, the drilling of geothermal wells and the construction of a geothermal powerplant brings to mind images of heavy and dirty industry, likely to cause environmental destruction, not only on the planned site, but to the surrounding area. Opening discussions with the community allows them to voice these concerns and the developer to address such concerns. Community engagement and education staff must discuss current levels of biodiversity (in an understandable way) and how it will be increased. New visual and written resources along with real-world examples, such as bird boxes, bug hotels, and hibernacula act as a conversation starter and allow factual information to be shared and passed on to others in a pyramid effect.

Not all biodiversity is equal, and care must be taken to ensure any rewilding is complementary to the local ecology. Not all species encourage the same diversity, for example, fruit and nut bearing trees bring more benefit than leafy trees. As part of a planning application numerous ecological surveys are carried out over the four seasons, giving the geothermal developer a broad understanding of the ecology and the level of biodiversity at a potential site. Involving a combination of local experts and relevant local businesses, for example, local tree nurseries, can ensure native flora and fauna thrive, build trust with the community, and encourage ‘local ownership’ of the geothermal project.

GEL joined the Cornwall and Isles of Scilly Nature Partnership, making seven pledges for nature at the Nature Partnership Conference 2023. The seven pledges aim to dispel the myth that nature cannot thrive around a drill site. The feedback from this event was that the message needs to be shared more widely, to make more people aware that geothermal power projects can help to improve the natural environment and not destroy it.

The case for deep geothermal energy — unlocking investment at scale in the UK

Corinna Abesser[1], Andres Gonzalez Quiros[2] and Jason Boddy[3]

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[2] British Geological Survey, The Lyell Centre, Currie, Edinburgh, UK.
[3] Arup, Central Square, Forth Street, Newcastle, UK.

The UK has significant onshore deep geothermal potential. While exploitation of this resource is starting in the South West of England, the overall role that geothermal energy could play in the UK's transition to Net Zero is not well defined and there is currently only limited support for this technology, compared to other renewables.

The British Geological Survey and Arup, with funding from the Department for Energy Security and Net Zero and the North East & Yorkshire Net Zero Hub, have developed a White Paper entitled 'The case for deep geothermal energy — unlocking investment at scale in the UK'.

The paper and accompanying report provide an updated assessment of the UK's deep geothermal resource potential and highlight where development opportunities exist. It reviews the environmental, economic and technical advantages that deep geothermal energy delivers in countries with similar geology to the UK, such as the Netherlands, Belgium and Germany, and identifies potential benefits of developing the sector in the UK, including greenhouse gas emission reductions, job generation as well as large-scale district heating (and cooling).

Based on evidence from public consultations and research, as well through extensive stakeholder engagement, the paper identifies key barriers for deep geothermal projects in the UK and proposes a set of actions for building the sector in the UK.

Key recommendations are:

- undertake a review of financial support for geothermal energy
- clearly outline the role of geothermal energy in the UK's net zero efforts
- improve data availability and accessibility
- review the legal status, regulation and licencing of geothermal energy
- develop an understanding of the public perception of geothermal energy
- support communication between stakeholder groups.

Meeting heating demand from deep geothermal aquifers in the UK's sedimentary basins

Mark T. Ireland[1, 6], Tom Charlton[2], Jon Gluyas[3, 6], Hector Barnett[1], Mohamed Rouainia[2], Calum Watson[4, 6] and Kieran Mullan MP[5]

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[2]*School of Engineering, Newcastle University, Drummond Building, Newcastle upon Tyne, NE1 7RU*

[3]*Durham Energy Institute, Durham University, Durham, DH1 3LE, UK*

[4]*Net Zero Technology Centre, Aberdeen, AB15 4ZT*

[5]*House of Commons, London, SW1A 0AA*

[6]*UK National Geothermal Centre*

The International Energy Agency identifies that almost half of building energy demand was for space and water heating (IEA, 2023). In the UK, heating accounts for 37% of carbon emissions, with 17% for spacing heating and 14% for industrial processes and 6% for hot water and cooking and has set a target of 18% of the national heat demand to be met by heat networks by 2050 as part of a least cost pathway to meet it's net-zero commitment (*Heat and Buildings Strategy*, 2023). The shift to expand heat networks could be enabled by the availability of deep geothermal energy. Deep geothermal most commonly refers to resources at a depth greater than 500m and could offer a baseload for heating (and cooling).

To date assessments of the deep geothermal potential of the UK have most commonly been based on heat in place methods. While heat in place methods provide a straightforward approach assessing geothermal potential, in general the method is a poor approximation for geothermal resources as it does not provide an estimate of rate or lifetime, and significantly does not spatially link the resource to a specific production location.

This work considers the geothermal potential of the deep sedimentary aquifers associated with the Palaeozoic sedimentary basins of Great Britain, and specially the areas within England and Wales. These basins which have been described previously as having geothermal potential of ~300 EJTH (Gluyas et al., 2018). In this work we use the heating demand of the built-up urban areas of England and Wales to identify notional development locations. At each of the locations we use existing geological interpretations to investigate the potential heat production from a single conventional doublet system consisting of a producer-injector pair. Our models assume that each development produces from a single aquifer. We implement the semi-analytical solution originally implemented by TNO (Mijnlieff et al., 2014), that is intended to provide an indicative geothermal power for a doublet scheme by specifying the key reservoir properties and details of a simplified well design. Using governing equations for mass, momentum and energy, the flow through the geothermal system can be obtained.

Our preliminary results identify >800 built up urban areas where there are viable deep geothermal exploration concepts where the reservoir depth is likely >1km. Of these ~50% are likely to have reservoir temperatures of >60degC where the produced fluid temperature could be ideally suited for 5th generation district heat networks with the annual production across these sites potentially being ~27 TWh. We identify that at least 50% of local authority areas in England and Wales have one or more viable development concepts, with some development locations have the potential to produce >100GWh annually.

In this study we have not included a detailed examination of a) the impact of operational strategies on short- or long-term production scenarios or b) the specific suitability of a geographic area for heat network development. The method we developed for estimating capacity could be modified in the future to take into account alternative locations incorporating details of heat network plans or revised geological interpretations (e.g. updated reservoir depth maps). Our approach to estimating the potential geothermal resource at a basin scale provides a tool for a wide range of stakeholders with interest in decarbonising heat to begin evaluating the suitability of deep geothermal at the pre-feasibility stage.

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Session Three: Hot Sedimentary Aquifers

De-risking Geothermal Heat in the UK: Lessons Learned from The Netherlands

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There is huge potential for the development of geothermal resources in the UK. ARUP's report of Deep Geothermal Energy (2021) and the UK Parliament POSTbrief 46 (2022) aimed to highlight this heat potential and its potential uses. Multiple forms of geothermal resource exploitation are possible ranging from hot sedimentary aquifers to relatively shallow volcanic regions paired with areas of concentrated heat demand. Combining this with the extensive subsurface knowledge and a highly skilled workforce due to a rich oil and gas heritage, the supply chain is primed to support this transition. If there is heat demand, the potential for commercially viable heat supply and a readily equipped workforce, what is missing to act as a catalyst to grow the UK geothermal sector.

Direct-use heat projects are the low-hanging fruit if the UK are going to meet their net zero ambitions. Many current geothermal developments, either operating or prospective, face stern commercial challenges. Therefore, early-stage de-risking of geothermal developments can alleviate some of these financial hurdles and help to grow investor confidence. De-risking innovative geothermal concepts, such as EGS or AGS, is challenging as the technologies remain commercially uncertain with doubts as to their scalability. However, for direct-use heat projects from hot sedimentary basins, the UK can benefit from the lessons learned across continental Europe to de-risk and kick-start their geothermal heat projects. Geothermal for direct-use heating is a proven technology that has been utilized successfully for decades in countries such as Germany, France, Poland, and The Netherlands. Over the past 15 years, The Netherlands has witnessed multiple innovations, technical improvements, and operational efficiencies to facilitate a commercially viable and sustainable geothermal heat market. This in turn has created jobs and, allowed the Dutch horticultural sector to offer emission free produce to both national and international markets. Sproule have played an active role in the development of the Dutch geothermal sector over the past decade and have identified three key, transferrable learnings that can be utilized to help exploit the UK's geothermal potential.

Firstly, technology developments and optimisations have been able to de-risk new projects such as well design standardization, geochemical treatments and material selection paired with the efficient rollout of heat networks and end-user interfaces. Consequently, the scalability from 5 MWth to >40 MWth output per system is becoming the norm with far improved LCOH and increased reliability. This has allowed for a healthier investment climate where business case risks are less focused on short term challenges such as the drilling phase, and more focused on the commercial longevity of the entire system.

Secondly, project rollout. Early projects in Germany, France, and the Netherlands relied upon a simple concept using known exploration techniques in areas where the subsurface properties were familiar, and the heat demand was easy to link to a simple doublet system. Only once a solid foundation of commercial projects has been realized, should complex concepts involving fractured reservoirs or deep volcanic targets be explored with the required innovation funding.

Finally, stakeholders and government engagement. One of the major opportunities for the UK is that geothermal can benefit the local economy and nearby communities. Given the comparatively small surface footprint of geothermal as a renewable energy source, the aim is to encourage communities to embrace geothermal sites within their local area – the opposite of the NIMBY argument. It can stimulate local businesses and/or local heat networks leading directly to benefits within the community. In greenhouse corporations in the Netherlands, there are many cases where the local communities are the informal ambassadors of the projects. This sentiment is the opposite when compared to the oil and gas industry. This is also an opportunity for local politicians to engage with their electorate and with that, a push for adequate incentives and legal framework from the national government might start.

Temporal and spatial variation in depositional environment and the effect on reservoir quality in the Sherwood Sandstone Group, Northern Ireland

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The Sherwood Sandstone Group (SSG) was deposited widely across Northern Ireland during the latest Permian to Early Triassic. At shallow depth, the SSG is historically an important aquifer in the region for its groundwater resources. Thicknesses of up to 867 m of this sandstone unit have been encountered in boreholes in onshore basins in Northern Ireland (NI) and the sandstone was a target for oil and gas exploration dating back to the 1960s as equivalent sandstones in offshore basins around UK and Ireland (Figure 1) have proven to be highly productive reservoirs. With the globe transitioning towards a low-carbon economy, these sandstones have the potential to become a key resource for geoenergy applications such as geothermal and Carbon Capture and Storage (CCS). Spatial and temporal variation in palaeogeography and depositional environment is the primary control on the sedimentary facies that make up the SSG in NI and therefore also the resulting reservoir quality. Depositional setting and facies architecture of these sandstones in NI are poorly understood due to limited study compared to equivalent strata, where the fluvial and aeolian systems have been mapped across Britain, and the Irish Sea basins. Discourse remains around the provenance of the SSG sediment in these NI basins, and whether they were mostly fed from a western source (Tyrrell et al., 2012; Franklin et al., 2020). Basin structure and the timing of subsidence are likely to have profoundly affected the preserved succession of the SSG across NI, and it was suggested by Jackson et al. (1995) that the upper parts of the SSG recognised in the East Irish Sea basins and onshore Britain, are absent in NI.

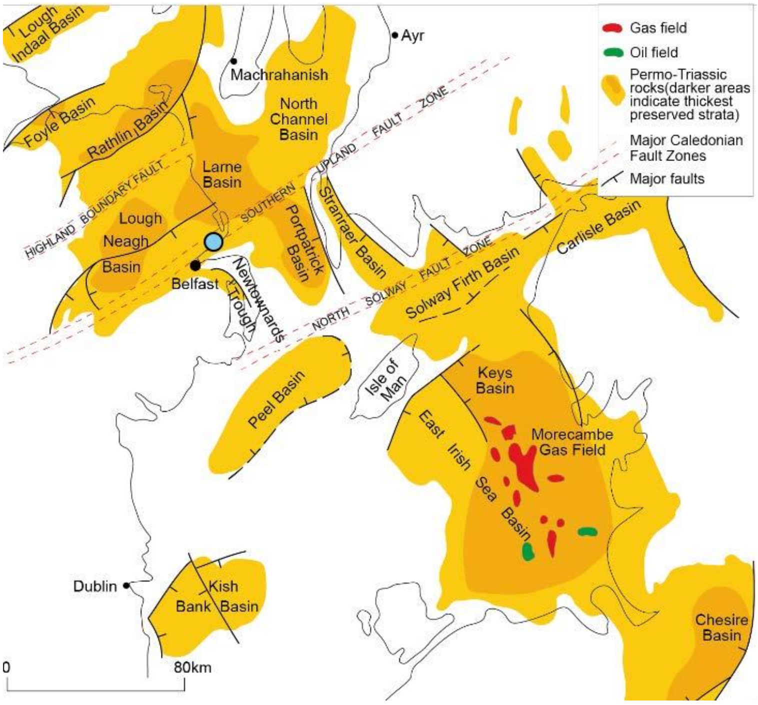

Figure 1: Permo-Triassic basins of Irish Sea and surrounding areas. The location of the Kilroot GT-01 Borehole is represented by a blue dot (modified after Mitchell, 2004).

Limited outcrop and few cores that span the whole succession, along with minimal studies of these means that the internal divisions and facies of the SSG in NI are not well defined. Despite this, most authors have identified a two-fold division, with a marked difference in reservoir quality between the lower and upper division of the SSG. Several authors have put forward diagenetic cementation as a controlling factor for the poor quality in the lower part (Downing et al., 1982), with a facies control also highlighted (Downing et al., 1982; Naylor, 2003). Studies on the Larne-2 borehole (Downing et al., 1982) identified an increased amount of dolomite in the lower part and postulated that this cemented interval was equivalent to the 'silicified zone' recognised in the East Irish Sea Basin (Colter and Barr, 1975).

Naylor et al. (2003), attributed the lower, poorer reservoir quality sections in the Kish Bank Basin to quartz cementation caused by increased temperature related to burial depth. Further work is ongoing to document the diagenetic history of the sandstones and this study aims to identify the main controlling factors.

In the NI sections, the high reservoir quality in the upper part has not satisfactorily been explained other than attributing it to the absence of siltstones and cementation. Examination of available reservoir quality and thin section data suggest that other depositional controls may be a factor. In the East Irish Sea Basin and onshore basins across NW Britain, aeolian sediments are present in the upper part of the SSG and commonly associated with good reservoir quality (commonly being more texturally mature than fluvial sandstones) (Jones and Ambrose, 1994).

As part of the present study, description of the only core through the entire SSG, from the Kilroot GT- 01 borehole, has enabled additional resolution on the interplay between facies and reservoir quality. Current work has also logged available sections in the Newtownards Trough and the Larne Basin and it is found that aeolian facies are uncommon in the Triassic basins of Northern Ireland, with facies dominated almost exclusively by fluvial deposits. The only recorded deposits of aeolian sediments to date are in the Newtownards Trough at Scrabo Hill, where pin stripe laminations, grain flow and curled mud flakes occur (Buckman et al., 1997; Franklin et al., 2019). Attempts in this study to correlate this succession with that in the Kilroot GT-01 borehole in the Larne Basin have not proved successful and it is possible that the Newtownards Trough preserves a part of the succession that was not deposited, or was eroded, from the Larne Basin before deposition of the Mercia Mudstone Group. However, our results from the logging of the Kilroot GT-01 borehole do show that toward the top of the SSG, the sandstones are better sorted and appear to be composed of possible fluvial reworked, aeolian-derived material. This supports the view put forward by Jackson et al. (1995) that the uppermost stratigraphy recognised in the East Irish Sea Basin is not present in NI. It is postulated here that the observed excellent reservoir quality in the upper SSG in NI is either a result of alternating fluvial and aeolian facies (as at Scrabo Quarry), or input of aeolian sand due to evidence from Kilroot GT-01 core and thin sections, distinguishing it from purely fluvial sandstones in the lower part of the group.

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Geothermal heat production from Mississippian limestone (UK) - what is the role of hypogenic voids?

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Mississippian carbonates crop out or are present beneath younger rocks in many parts of England and Wales, including the Derbyshire Platform (Northern England) where the present study was undertaken. These areas have the potential to provide low enthalpy geothermal energy to some major conurbations. An important requirement for the development and exploitation of such geothermal systems is the presence of flow at depth.

As the matrix porosity of Mississippian carbonates in the study area is low, such flow is likely to occur via fractures and/or void systems generated by carbonate dissolution (i.e., karst). The distribution and character of epigene void systems – formed by downward flowing meteoric water – has been well described in the research area, but there has been relatively little study and characterisation of hypogene void systems. Hypogenic void-conduit systems comprise both non-stratabound and stratabound components that display morphological features characteristic of formation by rising flow. They are formed by upward-flowing fluids, with dissolution attributable to fluid cooling, fluid mixing, changes in redox and/or pH due to injection of CO_2 or H_2S-rich water and pressure.

The Derbyshire Platform represents the distal termination of the East Midlands Platform. During the Mississippian, limestones were deposited on the footwall of normal faults before being buried, and then uplifted during the Variscan Orogeny by inversion of pre-existing faults. At this time, overpressure was released, and seismic pumping forced fluids from the nearby basins to the Derbyshire Platform, providing fluids for MVT (Mississippi-Valley-Type) ore deposits (Pb-Zn-F-Ba mineralisation). The subsequent burial history of the platform is not well constrained, but it was probably not deeply buried again. Hypogene void systems, with sizes ranging from decimetres to up to 10s of metres, have been recognised on the Derbyshire Platform, particularly on the northern and southern margins. The presence of these large and connected void systems influences modern groundwater flow and local heat flux. They provide near-surface analogues for studying the processes that may influence the formation of geothermal systems at depth.

In the field, three classes of hypogene void systems have been identified. 1) Partially to completely mineralised cavities with MVT mineralisation. MVT mineralisation is thought to have occurred during the Variscan Orogeny (Carboniferous-Permian), so these void systems are the oldest in the area. 2) Sediment and mineral (including calcite) filled voids; some entirely filled by well-formed very coarsely calcite crystals, commonly >5 cm diameter, that probably represent the last cementation event on the platform. 3) Open, vertical, and sub-vertical cavities. These are very hard to date since there is no fill. However, the lack of any fill and the characteristics of dissolution features (e.g., dissolution surfaces lacking any other alteration) suggest that they are relatively young (Neogene or Quaternary) void systems.

Ongoing research is assessing the relationships between hypogene cavity occurrence, fill, morphology, size, location, and geological context. We are also evaluating the timing of hypogene development, by association with faults, stratal architecture, and diagenetic phases.

By combining further geological and geochemical analysis, evidence of the genesis of the hypogene void systems will be unravelled, allowing assessment of the potential of hypogene voids to facilitate or hinder production of low enthalpy geothermal circulation systems. This analysis helps understand the mechanisms of their formation, so that it would be possible to hypothesise whatever they can occur at depth. This enables us to build conceptual model/s for geothermal modelling and understanding the potential implications for geothermal development.

Petrographical analysis of coarse calcite crystals reveals largely homogenous crystals with dull luminescence and rare zonation under cathodoluminescence. Backscattered electrons (BSE) images and energy dispersive X-ray spectroscopy (EDS) maps using scanning electron microscopy (SEM) also show absence of zonation or variation within the crystals, suggesting constant fluid composition and redox during crystal growth. Preliminary isotopic analysis of coarsely crystalline calcite samples shows low $\delta^{18}O$, probably reflecting precipitation at high temperature or from isotopically depleted groundwater. Although the majority of $\delta^{13}C$ is positive, there are some negative values that might suggest different groundwater chemistry and/or magmatic CO_2. Together, this provides some evidence of the fluid source and temperature following formation of the hypogene void systems.

In terms of geothermal exploitation, the majority of hypogene void systems mineralised by MVT have little to no remnant permeability, making them potentially non-viable targets. The same applies to hypogene void systems that are filled with sediment and calcite crystals. However, within these two groups, there are void systems that are only partially filled and that can potentially sustain flow. Unfortunately, their distribution on the Derbyshire Platform and their connectivity are still uncertain but several large (from decimetres to up to 10s of metres) and open void systems (potentially Neogene or Quaternary) might represent viable targets. These open void systems have very high permeability and so can sustain flow, but it is still unclear if they are only present at shallow depth or if there is connectivity at depth. Some modern epigenic waters flow through hypogenic void systems potentially suggesting some degrees of connectivity at depth. Most springs in the area discharge water close to the average annual temperature but some are slightly elevated, up to 15 ºC suggesting mixing with warmer water and there are several thermal springs with temperatures of over 18 ºC. At the warmest spring the water temperature is 27 ºC and it has been estimated that the water has circulated to a depth of 1-1.5 km.

Reservoir Connectivity Concerns in the Dogger Aquifer? An Assessment through a Geothermal Doublet.

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Previous studies identify carbonate diagenesis as the origin of high permeable geobodies in ooid-dominated and peloid-dominated lithofacies in the Middle Jurassic (Dogger) Limestones. These geobodies, corresponding to low cemented grainstone facies, are significant controls on geothermal movement between doublets This study evaluates the extent and distribution of these geobodies to ascertain their impact on reservoir connectivity and, thus, geothermal production in the limestone reservoir. The study involves (1) geobody geometry delineation from inversed 2D seismic and statistical analysis of petrophysical logs. (2) thermal simulation over thirty years in the Eclipse and PumaFlow simulators. Notable results from seventy simulations are as follows: (i) The initial 0.5 °C drop in scenarios with permeable geobody length lower than 800 m in the XY direction is realized two years after production and about five years with permeable geobody greater than 1200 m in XY direction. High geobody connectivity generates wide hydraulic transmissivity paths for injected water, thus, a higher energy production rate of ~ 9.72 x 108 KJ/d compared to low connectivity scenarios that record ~ 8.70 x 108 KJ/d. (ii) Temperature in the production well decreases with decreasing N/G. For example, with identical simulation conditions, a scenario with N/G of 44.12% records a temperature of 69.78 °C, while an N/G of 10.8% records 63.45 °C after 30 years. Considering the correlation between geobody geometry, connectivity, and hydraulic transmissivity, comparing results to historical production records from the aquifer indicates a well-connected reservoir with a permeable geobody length greater than 1000 m in the XY direction.

Introduction

After forty years of geothermal production, we investigate concerns of reservoir connectivity or otherwise in the Middle Jurassic “Dogger” limestone aquifer to enhance understanding of thermal exchange between geothermal doublets. Studies by Brigaud et al. (2014) and flowmetry data from 78 wells identify high permeable low cemented peloid grainstone and low cemented ooid grainstone (lognormal mean of +1000 mD) as critical controls on geothermal production in the reservoir. The work evaluates the extent and distribution of these high permeable units (i.e. geobodies) and their implications on thermal migration to improve subsurface petrophysics description and simulation. The work relies on existing 2D seismic inversions (Allo et al. 2021) to delineate the geometry of permeable geobodies. The geothermal simulation is for thirty years in the Eclipse and PumaFlow simulators.

Material and methods

Well-logs around the geothermal doublet of Alfortville (i.e. GAL1/GAL2) are extracted from an existing 3D facies model by Thomas et al. (2023) to build three petrophysical and aquifer models covering (1) 9 km2, (2) 25 km2, and (3) 100 km2 around the Alfortville. These model domains are to ascertain the effects of boundary conditions on thermal migration. Through sensitivity testing, the 100 km2 model domain minimizes such boundary effects on particle retention, hence the choice in this study. A depth conversion of an inversed 2D seismic by Allo et al. (2021) was done in Petrel. With a porosity and permeability cut-off of (0.15 – 0.2) and (1000 mD – 10000 mD), the most-occurring range of geobody lengths leads to the generation of multiple reservoir models for the geothermal simulation, like the theoretical studies by Sauty et al. (1982). Water at 49 °C is injected and produced at 4200 sm3/day from an initial reservoir condition of 75 °C and 170 bars at -1606 m. The fluid model (PVT), rock physics, and rock thermal conductivity parameters are from the BRGM report by Gringarten and Sauty, (1977).

Results

Low cemented peloid grainstone (LCPG) with thickness between 1 - 5 m constitute high permeable units in peloid-dominated facies (up to 8110 mD). Similarly, Low cemented ooid grainstone (LCOG) of thickness 2 – 4 m is associated with high permeability in ooid-dominated facies (up to 17870 mD). The results are in five parts (1) Lithofacies geometry effect on thermal transport. Scenarios where the permeable geobody length is < 800 m realize a thermal breakthrough of 0.5 °C drop in the production well after two years, which is about half the average duration of the same event in scenarios where permeable geobody >1200 m. Permeable geobody length > 1200 m produced high connectivity and transmissivity paths leading to an energy production rate of ~ 9.72 x 108 KJ/d compared to permeable geobodies < 800 m scenarios with ~ 8.70 x 108 KJ/d (2) Constant porosity and permeability of 0.17 and 5000 mD in LCPG, with no flow in high cemented grainstone facies (HCGF). Initial 0.5 °C drop after production averages between 3 to 5 years with a production temperature of 59 °C to 65 °C at the end of the simulation. (3) Constant porosity and permeability of 0.20 and 700 mD in LCOG and LCPG, with average porosity and permeability of 0.1 and 25 mD in the HCGF. Noticeably, there is a rise to 76 °C before the temperature decreases during production. Likewise, the initial 0.5 °C decrease from reservoir condition averages 3 to 4 years with a production temperature of 60 °C to 65 °C after 30 years of simulation. (4) Variable porosity and permeability from upscaled wells. Again, there is an initial temperature rise to 76 °C, attributable to the porosity and permeability of bounding lithofacies. The inceptive 0.5 °C drop after production averages 1 to 2 years, with a temperature of 56 °C to 68 °C after 30 years. (5) Net-to-Gross effect on thermal transport in the aquifer. The temperature in the production well decreases with decreasing NG under constant water injection and production rate. For example, scenarios with N/G of 44.12% attain an average of 69.78 °C, and N/G of 32.9% realizes 67.5 °C, while N/G of <=11.0 record 63.45 °C after 30 years of geothermal production.

Conclusion

High permeability geobodies consisting of low cemented ooid peloid facies and their control on geothermal production are the focus of our assessment of this long-producing geothermal reservoir. Comparing results to historical production records from the GAL1/GAL2 doublet supports simulation scenarios with geobody length > 1000 m, therefore, suggesting high connectivity in the “Dogger” limestone aquifer.

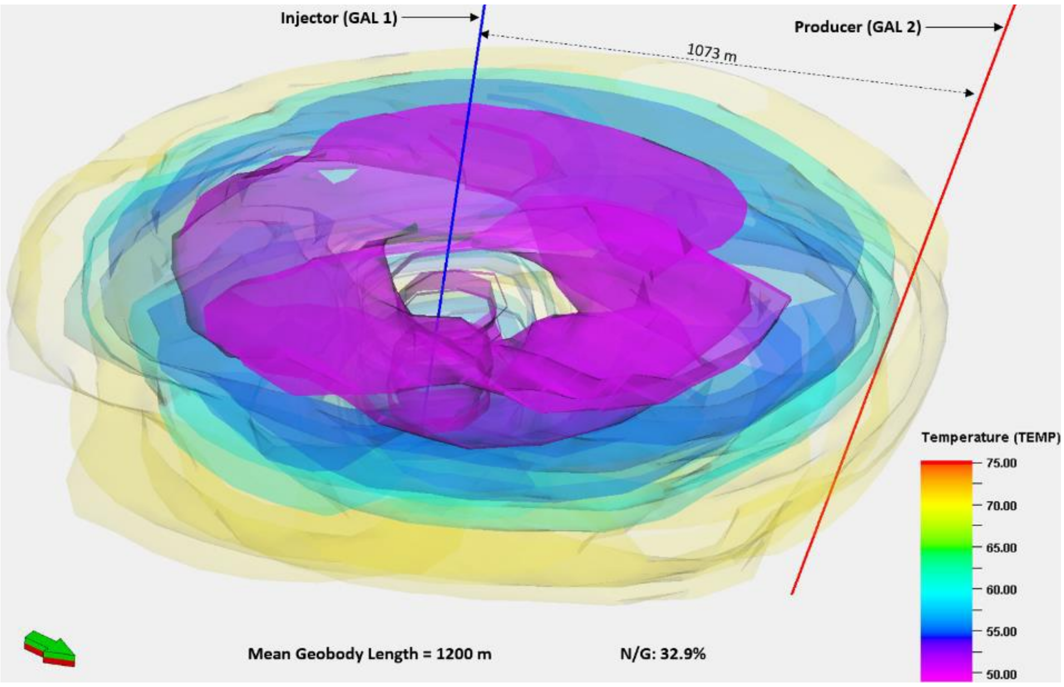

Figure 1. Temperature profile for a model with N/G of 32.9% after 30 years of geothermal production.

Ranking Methodology to Prioritise and Communicate Deep Geothermal Opportunities

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In 2023, Arup developed a robust and dynamic ranking methodology for assessing deep geothermal opportunities across multiple potential sites for our client. This work was undertaken for multiple sites across the Wessex Basin and facilitated the client with an adaptable tool to prioritise investment. BGS provided seismic interpretations and hydrogeological information to underpin the various site models.

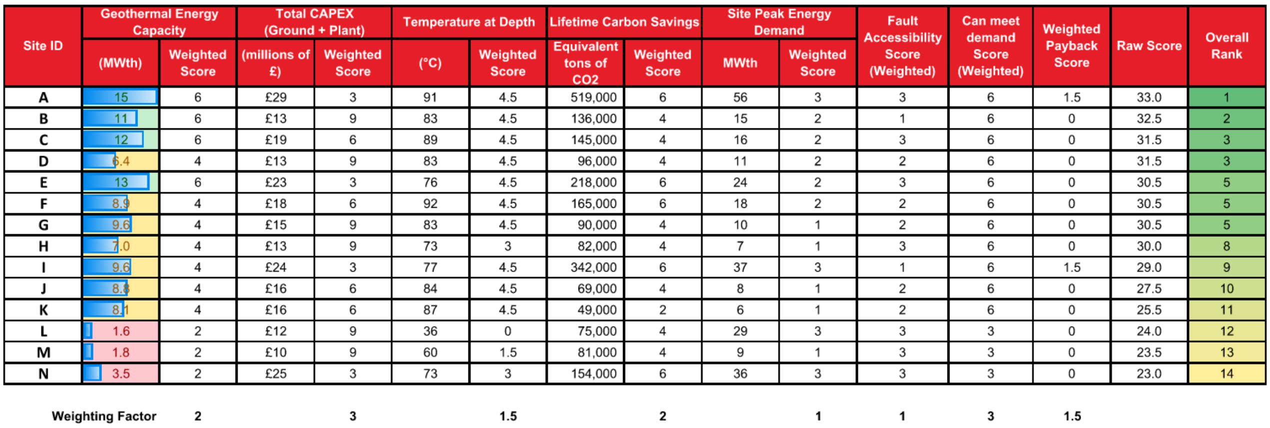
As part of this work, a feasibility study was undertaken to assess the geological and hydrogeological context, and geothermal gradients. This assessment also captured data uncertainty such as data density and spatial distribution. Assessment of ground conditions was paired with an assessment of above ground infrastructure to identify site heating and cooling demands, and the carbon intensity of existing heating/cooling infrastructure.

A ranking methodology was required by the client to consider a range of metrics including technical, financial, and environmental factors. Weightings were applied to each of the identified scoring criteria which reflected the client’s priorities.

The outcome of this work was a practical ranking methodology which can be dynamically adapted by the client should their priorities change in the future. This tool will be used to help inform critical client investment decisions in the future.

This type of ranking methodology is becoming increasingly important as the geothermal market in the UK continues to expand. There are more and more clients and investors looking at geothermal as a solution for power and heating. Having this kind of ranking tool facilitates communication of not only technical feasibility at any given site, but also financial and environmental criteria and uncertainty. In addition, this tool helps to expedite the decision-making process and further progress the geothermal market.

This talk will outline the project scope, Arup’s methodology for collating and distilling available data into an efficient database, and finally the ranking criteria, weighting, and tool as a whole.



Site ID	Geothermal Energy Capacity		Total CAPEX (Ground + Plant)		Temperature at Depth		Lifetime Carbon Savings		Site Peak Energy Demand		Fault Accessibility Score (Weighted)	Can meet demand Score (Weighted)	Weighted Payback Score	Raw Score	Overall Rank
	(MWth)	Weighted Score	(millions of £)	Weighted Score	(°C)	Weighted Score	Equivalent tons of CO2	Weighted Score	MWth	Weighted Score					
A	15	6	£29	3	91	4.5	519,000	6	56	3	3	6	1.5	33.0	1
B	11	6	£13	9	83	4.5	136,000	4	15	2	1	6	0	32.5	2
C	12	6	£19	6	89	4.5	145,000	4	16	2	3	6	0	31.5	3
D	6.4	4	£13	9	83	4.5	96,000	4	11	2	2	6	0	31.5	3
E	13	6	£23	3	76	4.5	218,000	6	24	2	3	6	0	30.5	5
F	8.9	4	£18	6	92	4.5	165,000	6	18	2	2	6	0	30.5	5
G	9.6	4	£15	9	83	4.5	90,000	4	10	1	2	6	0	30.5	5
H	7.0	4	£13	9	73	3	82,000	4	7	1	3	6	0	30.0	8
I	9.6	4	£24	3	77	4.5	342,000	6	37	3	1	6	1.5	29.0	9
J	8.8	4	£16	6	84	4.5	69,000	4	8	1	2	6	0	27.5	10
K	8.1	4	£16	6	87	4.5	49,000	2	6	1	2	6	0	25.5	11
L	1.6	2	£12	9	36	0	75,000	4	29	3	3	3	0	24.0	12
M	1.8	2	£10	9	60	1.5	81,000	4	9	1	3	3	0	23.5	13
N	3.5	2	£25	3	73	3	154,000	6	36	3	3	3	0	23.0	14
Weighting Factor		**2**		**3**		**1.5**		**2**		**1**	**1**	**3**	**1.5**		

Session Four: Geothermal from Granites

Effects of natural geochemical alteration on frictional properties around faults in a deep, granitic, geothermal system in Cornwall: Direct shear experiments and microstructural observations

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Geochemical alteration of host rocks might affect the productivity and the potential for induced seismicity of geothermal systems. Following production and heat extraction, re-injected fluids may no longer be in chemical equilibrium with the surrounding rock, which can impact mineral solubility and dissolution / precipitation processes, and lead to host rock alteration. Furthermore, some projects target fault zones in crystalline rock that provide pathways for fluid flow and show pre-existing alteration. In this study, we investigate the effect of such geochemical alterations on the frictional behaviour of granites, and their seismogenic potential, by investigating the specific example of the United Downs Deep Geothermal Power (UDDGP) Project. It targets the Porthtowan fault zone in the Carnmenellis Granite in Cornwall, SW England, as reservoir for fluid production and reinjection.

We have conducted a number of direct shear experiments under near in-situ UDDGP conditions on a series of Carnmenellis granite samples that represent the formation used for heat extraction and show different states of natural geochemical alteration. We crushed, milled and sieved the rock samples to powders to a < 125 µm grain size. We then used the pulverised matrix material in direct shear experiments at up to 80 MPa effective normal stress and up to 180 °C, representing conditions that are of interest in terms of reservoir depth for UDDGP. In each test, load point velocity was stepped, and shear resistance of the sample was measured to determine the stability of sliding and thus the likelihood of induced seismicity as a function of alteration stage. Following the experiments, the microstructure of the sheared gouges was analysed using scanning electron microscopy to relate the measured frictional data to observed shear mechanisms (see Fig. 1).

The experiments show that the altered samples have lower friction coefficients, indicating a mechanically weaker behaviour and a higher likelihood to slip. This is because the altered material consists of smaller grains and as a result of higher clay contents. However, smaller grain sizes and higher clay contents also increase frictional stability, which again reduce the likelihood of stick-slip behaviour. Therefore, as granites undergo alterations observed in our case study, they become more likely to accommodate aseismic slip, which can contribute to destressing geothermal systems. Our high temperature experiments support the general observation that sliding stability decreases with increasing temperature in granites. This effect is independent of the degree of alteration for the granite samples tested.

Keywords: Cornwall, fault systems, granite, rate-and-state friction, microstructure

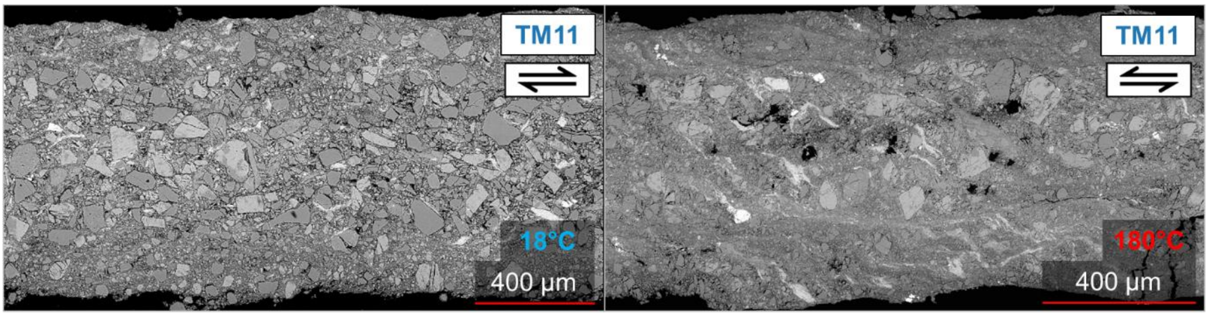

Figure 1: SEM images of thin sections of Carnmenellis granite powders sheared at 18°C (left) and 180°C (right). Sample material (TM11) originates from a near pristine granite but exhibits very different behaviour at low and high temperatures also indicated by very different microstructures following the same displacement. While at low temperature the granular structure of the gouge is maintained, the grains at high temperature are ground to a finer matrix. This indicates a weakening of the gouge at high temperature.

CURRENT STATUS OF THE EDEN GEOTHERMAL PROJECT (November 2023)

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(4) CSM/Exeter University, (5) altcom Ltd, **(6)** British Geological Survey.

The project is being delivered by Eden Geothermal Limited (‘EGL’), a five way-way partnership between Gravis Capital Management Ltd (a clean energy investment company), EGS Energy Limited, Eden Project Limited, University of Exeter and BESTEC (UK) Limited (affiliated with BESTEC GmbH, the specialist geothermal developer and drilling advisor).

On 14 October 2019, EGS Energy Limited and the Eden Project Ltd announced that funding had finally been secured to drill the first well for their pioneering geothermal heat and power project. The project is based on an “open geothermal system concept for an industrial research project”, whereby boreholes are drilled into water bearing features at great depth to access the hot fluid, similar to successfully developed geothermal projects in the Rhine graben (Landau, Insheim, etc.).

The £16.8 million sum was secured from a mixture of public and private sources. These included the European Regional Development Fund (ERDF) as to £9.9m, Cornwall Council as to £1.4m and Gravis Capital Management as to £5.5m.

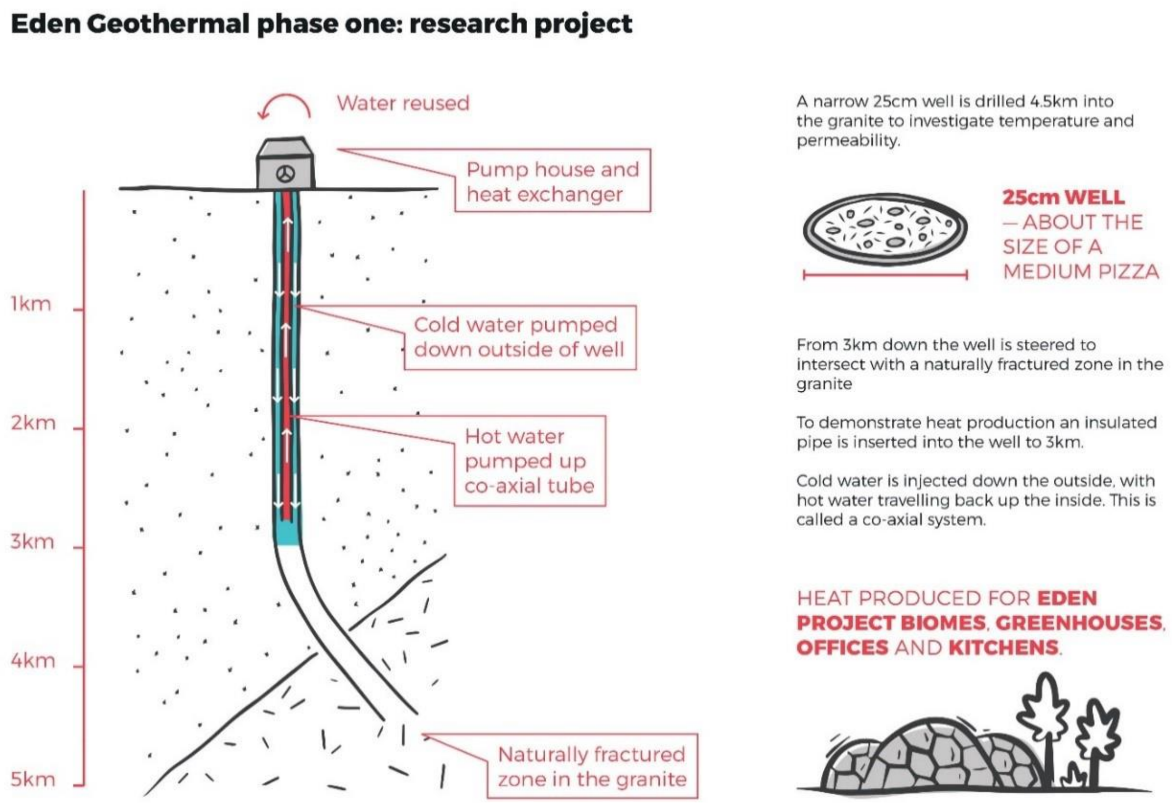
This investment has paid for the first phase of the project, that is the drilling of the first deep well which includes ‘procuring staff’, equipment and services, site preparation, a research programme and a heat main. This has enabled the assessment of the extent of the energy resource 4.5km down in the granite that lies beneath the Eden site. The first well will initially supply a district heating system for the Eden Project’s biomes, offices and greenhouses. It paves the way for the second phase – another 4.5km deep well and the installation of an electricity plant.

EGS Energy’s team has significant experience and expertise, having been part of the Hot Dry Rocks geothermal programme in Cornwall in the 1980s, the follow-on EU programme in Soultz-sous-Forêts, France and the subsequent commercial power generating projects in Landau and Insheim, Germany, among others worldwide. The University of Exeter will be providing academic and research services to the project.

Drilling the first deep well into the granite at the Eden Project began in mid-May 2021. The Eden Geothermal project reached a landmark moment on Friday 5 November 2021 with the successful completion of its first well to nearly 5km into the Earth’s crust. This would provide heat to of the world-renowned Biomes in Cornwall.

The well, known as EG-1, has a vertical depth of 4,871 metres. Its measured depth - the actual length of the well - is 5,277 m (over 190ºC at the bottom), making it the longest successful geothermal well in the UK. The well has found its geological fault structure with early signs of high temperatures and good permeability at depth but without intersecting the anticipated hot fluid reservoir.

The next step at Eden Geothermal was a programme of testing the well, which commenced in early 2022. In mid-2023 the well was configured in to a single well heat exchanger (~3,000 m deep) and connected to a heat main linked to the Biomes at Eden Project to demonstrate the supply of renewable heat.



A narrow 25cm well is drilled 4.5km into the granite to investigate temperature and permeability.

From 3km down the well is steered to intersect with a naturally fractured zone in the granite

To demonstrate heat production an insulated pipe is inserted into the well to 3km.

Cold water is injected down the outside, with hot water travelling back up the inside. This is called a co-axial system.

Fig 1. Schematic presentation of the Eden Geothermal as a single well heat exchanger

The presence of hot fluid was not encountered at great depth by the well EG-1 as anticipated. However, a recent preliminary MT survey near the Eden Project site by the British Geological Survey indicated the presence of hot fluid at depth. The next phase will be to delineate the hot water bearing structure using a dedicated MT survey and then drill a second well in this feature at a similar depth to the first well. Hydraulic tests will be carried out to assess the sustainability of the hot fluid. In principle, one should observe continuous fluid flow from such a well. The first well can then be deviated into the same water bearing structure around 800 m from the bottom of the second well. Once complete, the two-well Eden Geothermal system will have the potential to supply renewable heat to the Eden Project and neighbouring industries equivalent to the heat used by more than 35,000 homes, or renewable electricity to that consumed by around 14,000 homes.

Once this concept is successful, this model can be replicated for the recovery of energy in many parts of the South-West and other parts of the UK.

During the development of this project, extensive research has taken place on site selection, geology, well planning and drilling engineering choices, testing of the initial reservoir, improvement in drilling technology and maximising of the heat/power potential.

Some of the highlights observed have been:

- **Giant leap for renewable energy as the EU and Cornwall Council fund ground-breaking geothermal projects**
- **First well to be sunk 4.5km deep into granite crust beneath a former clay quarry**
- **Drilling for clean energy starts at the home of the world-famous Eden Project – the culmination of more than ten years of planning and preparation**

Eden Geothermal’s heat demonstration at the Eden Project, Cornwall, UK. A novel 3850m coaxial completion in granite. First results: learning to drive the system.

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In the UK, heat use accounts for the greatest proportion of greenhouse gas emissions by sector at 37%. Most (82%) is used for space heating, cooking and hot water, so it is not very ‘hot heat’ at <100 deg. C. So far, decarbonisation of the heat sector has lagged behind that of transport and electricity, and there are few technologies that can provide baseload heat at scale. Geothermal heat technologies come in several flavours: Ground Source Heat Pumps, Mine-water Projects, Direct Geothermal Open Loop and Deep Borehole Heat Exchangers. All can play a part in decarbonising the heat sector. This paper describes the application of the latter: a coaxial system in a deep well in crystalline rock in Cornwall, UK.

The novel system has a vacuum insulated coaxial tube of 3860m deployed to supply heat via heat exchangers and a 3.8km km heat main to the Eden Project Biomes, offices and a new greenhouse array. The system will be brought into full operation in the heating season of Q4 2023, a first for a deep geothermal project in the UK for 37 years. The presentation will describe early results, how the system may be optimised and a discussion of the part that these systems might play in the future of geothermal.

The project is an industrial research project part-funded by the European Regional Development Fund, GCP Investments Ltd. and Cornwall Council. Eden Geothermal was set up as a partnership between Eden Project, EGS Energy Ltd and Bestec (UK) Ltd. University of Exeter is research partner.

Imaging deep geothermal reservoirs with magnetotellurics – A pilot study around the Eden Geothermal drill site, Cornwall

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Successful exploitation of geothermal heat requires a good knowledge of geologic formations at depth. Geophysical exploration methods are a very cost-effective way of studying the subsurface and provide a means to de-risk geothermal drilling. In the UK, the recent revision of heat flow maps based on airborne geophysics has identified the Cornish granitic intrusions as zones of increased heat flow and potential sites for geothermal exploitation. The revised estimates for temperatures at depth encouraged new geothermal projects to go ahead. At United Downs in Redruth, drilling and geothermal heat production is, at present, the most advanced in the UK. A second site for geothermal deep drilling was chosen close to the Eden Project in St Austell. At the Eden Geothermal site, a first drilling phase started in 2020 to intersect the Great Crosscourse fault – a zone of suspected increased fracturing and permeability - at depths below 4 km. Well testing followed in 2022.

Magnetotelluric (MT) measurements have been widely used to image the subsurface for geothermal exploration and heat flow modelling in high enthalpy regions like Iceland and the East African Rift but rarely in lower enthalpy countries like the UK. MT is a passive geophysical deep-sounding technique using the natural variations of the electromagnetic field of the earth to probe the electrical conductivity of the subsurface which is very sensitive to the presence of fluids. In this project we collected and analysed MT data around St Austell, Cornwall, UK, to investigate if it is possible to make measurements with sufficiently high data quality to characterise geothermal reservoirs at depth in a semi-urban area.

During a 10-day field campaign in March 2023 a team from BGS collected broadband MT data at 30 sites in the St Austell area and one remote site in Bodmin Moor to help improve data quality through remote referencing time-series processing techniques. The data collected very close to the drill site and at some locations close to town centres have low quality, but overall data quality was sufficient to allow modelling of the electrical properties at depth. The derived MT impedance tensors were used to construct a 3D model of the area which has low spatial resolution but clearly shows that MT data can image the local geology at depth. The St Austell granite is characterized by high resistivities, whereas the onshore sediments and metasediments surrounding the intrusion have lower resistivities. Some vertical structures of lower resistivity within the granite were identified and are carefully investigated.

Overall, the use of the MT method for the characterisation of geothermal reservoirs in granitic bodies is confirmed in this study. Further data collection and modelling is recommended to improve the spatial resolution at depth.

National Geothermal Centre

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The energy trilemma facing the UK struggles to find the balance to energy security, affordability and net zero goals. The UK is targeting net zero and a 100% reduction of greenhouse gas emissions by 2050, when compared with 1990 levels. Scotland targets net zero by 2045 with an interim target of 75% reduction by 2030[1]. Monitoring reports in Scotland show emissions are down by 58.7% in 2022[2] when compared with the levels of 1990 however total UK reporting shows that the current trends will not meet the 2050 net zero ambitions. Net Zero is a requirement to address the climate change crisis.

While Net Zero remains the long terms strategy globally energy security adds another level of complexity to achieving our net zero ambitions. Within the UK we have seen rising energy prices with the average annual household energy bills having more than doubled since 2021 and causing further problems with an increase to over 6.6 million households driven into fuel poverty in 2023[3]. These scenes are not uncommon across Europe and is a global energy crisis.

A Net Zero future will be an energy mix that involves a transition away from traditional fossil fuels, as these currently account for around 80% of global energy consumption. While in the UK this is around 40% with a growing renewable energy mix predominantly made of wind and topped up with bioenergy, solar and hydroelectric sources. There is and will be a requirement for fossil fuels in the short and medium term with the use of not just energy, but pharmaceuticals, plastics and synthetic rubbers amongst others. While the emissions from these should not be ignored but they offer opportunity to reduce their greenhouse gas emissions. This and the transition to net zero provide an opportunity for innovation. Innovation for process, technology and efficiency improvements as well all of which have been seen to reduce emissions.

The energy trilemma and the need for innovation provides a great opportunity for the UK and there is a missing piece to the current energy mix in geothermal. An opportunity that globally provides 16GW[4] of energy, a sustainable baseload and dispatchable energy source available year-round unaffected by weather conditions. It is extremely versatile that can be used for direct use, for heating and cooling, as well as electricity generation. The UK has significant geothermal resources, which can be harnessed to provide a reliable source of clean energy however unlike our European counterparts like France, Italy and Germany, the UK is not utilising this resource and opportunity that could address both energy security and net zero ambitions.

There are various contributing factors to this including legislation, technical and financial challenges, as well as a lack of coordinated support. Geothermal currently is not considered a resource and therefore not included within any government strategies, which directly impacts the availability of investment in the sector due to the associated risk. This coupled with a lack of coordinated support for the industry development, there are pockets of work being done in the sector but this is disjointed. The most recent deep geothermal development within the UK at the Eden Project, is the first of its kind in over 40 years could be a signal of change.

To truly unlock the potential for geothermal in the UK a single industry entity is required to make significant progress for the good of the industry, our net zero targets and energy security. The National Geothermal Centre, is the answer to this problem, with a clear aim, as a physical centre of expertise, is to accelerate geothermal development and adoption within the UK.

The National Geothermal Centre initiative to establish a centre for geothermal energy innovation in the UK. The Centre would provide a focal point for geothermal within the UK, bringing together leading researchers, industry experts, and policymakers to develop new technologies, improve existing ones, and accelerate the deployment of geothermal projects.

The establishment of the Centre is a critical step towards positioning the UK at the forefront of geothermal energy innovation, creating new opportunities for economic growth, job creation, and sustainable development. The Centre will focus on several key areas, including:

- Accelerate and delivery demonstrator projects across the UK.
- Provide science-based evidence for the development of bespoke geothermal related legislation, policy and regulation; enable the delivery of the Energy Security Plan and low carbon electricity/heat strategies in the Powering Up Britain programme.
- Developing new and transitioning technologies to improve the efficiency, reduce the cost and unlock greater magnitudes of geothermal projects.
- Developing an integrated net zero energy infrastructure to maximise and utilise the potential of geothermal in combination with other renewable energy sources.
- Develop a national geothermal database for the benefit of the industry, government and public. Coordinate and create impact from research being undertaken across the UK.
- Coordinate and create impact from research across the UK.

Geothermal is prevalent across the world with the USA, Indonesia and Philippines leading the way with a growing capacity. So, the opportunity for learnings is there, with 61 countries producing geothermal globally having bespoke legislation and regulation to support this. The Centre can be the impartial coordinator to provide these learnings to enable an industry to flourish. It is estimated that 227 of the constituency regions in the UK have potential for the geothermal developments, this could enable the growth of heating networks in local communities and address the rising energy prices and strain on the national grid.

The geothermal industry within the UK has almost a ready-made supply chain in waiting available from the oil and gas industry that can pivot to provide the skills, technology, expertise and more importantly people. The Eden Project noted that of the 25 contractors working on the development 23 were from oil and gas. Providing a renewable energy alternative for this skilled workforce, will reduce the impact of the transition away from fossil fuels for net zero target. This could secure around 250,000 indirect supply chain jobs that would have significant export potential in future.

Supporting technology and innovation will remain a key piece of the Centre strategy to utilise the potential and work holistically with other renewable energies to maximise the return of the UK's energy availability. To further enable this the Centre would act as a hub for knowledge exchange, networking, and collaboration, bringing together stakeholders from across the geothermal energy value chain. With the development of a geothermal database to assess and provide access to the vast amount of data currently available and being acquired to reduce the risk of demonstrator pilot projects.

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[2] Scottish Emission Targets: 2022 Report, Climate Change Committee, 2022

[3] Energy Crisis, NEA, 2023

[4] IRENA, Global Geothermal: Market & Technology Assessment report, 2023

Session Five: Shallow Geothermal

Geothermal Energy: Status Quo or "Deeper and Down"?

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This talk is intended to complement an article (Banks, 2023b) of the same name to be published in the Autumn 2023 edition of the Geological Society's "GeoScientist" magazine.

The UK has a large and enthusiastic geothermal energy community, with big ambitions. It has a proud history of geothermal innovation:

- Jacob Perkins patented and, with John Hague, built the first prototype heat pump in London in around 1834 (Banks, 2012).
- Lord Kelvin proposed the concept of the heat pump for building space heating at Queens College, Belfast in 1852 (Thomson, 1852; Banks, 2015a).
- Charles Parsons suggested a mine shaft lined with refrigerant pipes as an early deep geothermal collector in 1904, and invented a fantasy "Hellfire Exploration Company" to develop the concept (Banks, 2015b).
- Graeme Haldane installed an early groundwater-sourced heat pump at Auchterarder, Perthshire, Scotland in 1927-28 (Banks, 2015b).
- Miriam V. Griffith and her colleague John Sumner carried out fundamental trials of buried heat exchange pipes in the 1940s and 1950s (Griffith, 1948; Sumner, 1976).

Nevertheless, the numbers of commissioned deep geothermal projects in the UK can be counted on the fingers of one of Marge Simpson's hands – and these have largely been promoted by dynamic geologists and engineers who have eschewed academia and got things done in the commercial sector. We are constantly told that Britain needs a geothermal component to our energy mix – yet we forget that we already have upwards of 30,000 shallow geothermal systems operating in the UK (a rough estimate based on Abesser & Jans-Singh's (2022) cumulative tally of 43,700 GSHP units sold).

Geothermal symposia often degenerate into an argument between those who believe shallow ground source heat pump (GSHP) systems aren't "real" geothermal energy, and those who support GSHP. It's a bit like arguing whether a deep confined artesian aquifer is more "real" as a water supply, than a shallow aquifer whose water table is 20 m below ground level. Both contain water – in the latter case you simply use a pump to exploit it. Similarly, deep boreholes and shallow GSHP both access heat from the ground – in one case, we simply need to use a pump – a "heat pump". If we waste time arguing about it, we are neglecting our customers, who simply want low-carbon, affordable heat in their buildings.

I will argue that there are three factors (there may well be more) that should control our decision as to whether to prefer the *"status quo"* of shallow GSHP at a given site, or to drill *"deeper and down"* to access deep geothermal heat. These are:

1. Price of electricity, relative to the value placed on space heating (Banks, 2023a). The value of hot water increases with temperature (this is related to the concept of exergy). If we require heat at 55°C for a building, we can extract shallow ground source heat at 12°C – but we need to use electricity in a heat pump to boost the temperature to 55°C. Or we can drill to, say, 1600 m in the hope of accessing a fluid around 55°C, thus avoiding the use of a heat

pump (or any depth in between – the warmer the ground, the cheaper the heat pump becomes to run). In short, the lower the current/future price of green electricity, the more attractive it is to opt for shallow GSHP. As electricity becomes more costly, deeper drilling becomes more attractive.

2. Cost of drilling. This increases disproportionately with depth and will clearly depend on the lithology that is being considered. The author uses widely-cited industry algorithms for drilling cost with depth (polynomials or power laws). It is found that, in some scenarios, the increased cost of deep drilling may be outweighed by the increased value of heat that can be accessed. In other scenarios, where the price of electricity is relatively low and drilling is expensive (i.e. the UK until the start of the recent Ukraine war), the increased value of deep heat may not justify the expense of drilling.

3. Geological trends of permeability and porosity with depth. Standard geotechnical models for porous sedimentary rocks often assume an exponential decline in porosity with depth (increased pressure and compaction) and a log-linear relationship of permeability with porosity. These models are applied to Sherwood Sandstone reservoirs, using documented UK data. All other things being equal, rock permeability typically decreases non-linearly with depth.

While depth trends relating to the costs of drilling and the value of heat appear similar and partially overlapping, the hydrogeological trends are potentially the strongest. We conclude that, while cheap deep drilling and high electricity prices favour exploration for deep geothermal heat, it is essential to have an "*attractive reservoir target at depth that "bucks" the general permeability-depth trend, identified through good hydrogeological characterisation or play-fairway analysis. Such a reservoir may be attractive by virtue of its great thickness and/or anomalously high permeability … or its anomalously elevated temperature or pressure"* (Banks, 2023b)

Other factors that will influence decision-making regarding deep drilling include (i) co-production of other valuable substances, such as lithium, from deep boreholes, (ii) co-production of coolth (i.e. potential for heat disposal) in shallow GSHC systems.

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Reflections on a decade of shallow geothermal research in Cardiff, UK.

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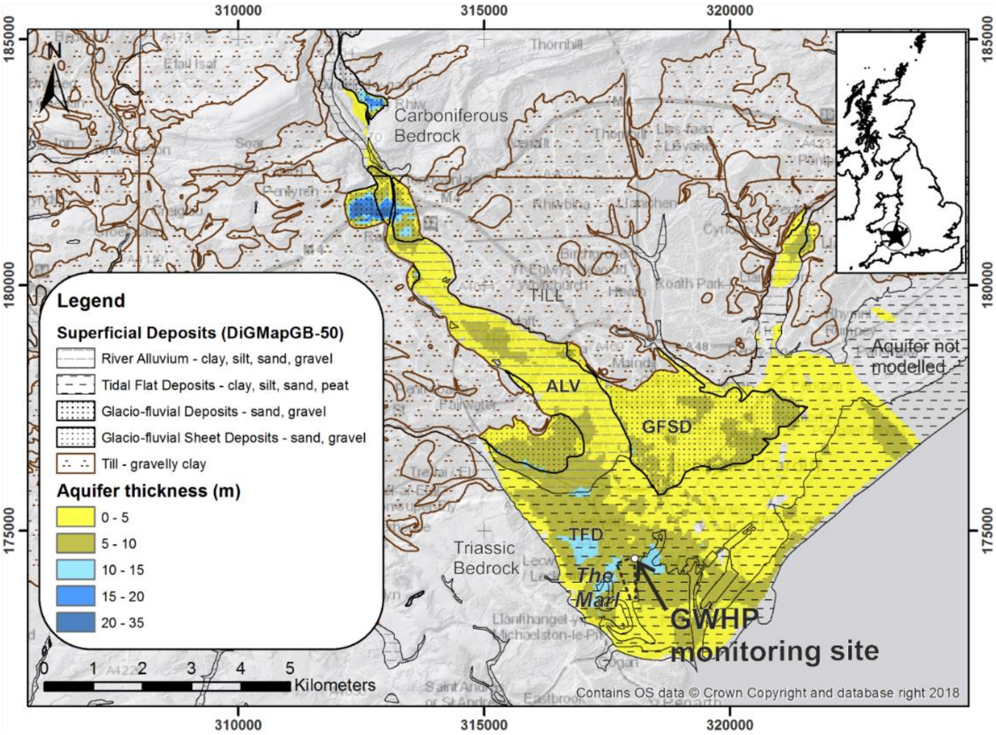
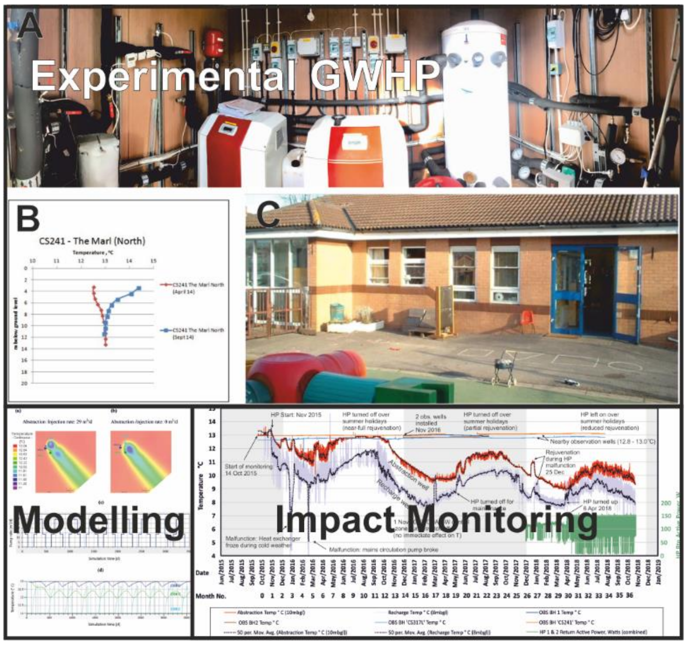
Urban communities and businesses are under increased pressure to decarbonise their heating and cooling systems to hit our legally binding Net Zero targets by 2050. Cardiff council have a target to be carbon zero by 2030. Fuel poverty is also a major challenge across the UK and air source and ground source heat pumps have been identified as a readily deployable technology for addressing these complex challenges to decarbonise the energy system.

Since 2014 the BGS have been working in collaboration with Cardiff Council and Cardiff Harbour Authority to characterise and monitor the shallow glacial gravel aquifer that underlies much of the city. Deployment of continuous temperature monitoring sensors in a network of around 50 boreholes has generated a high quality decadal environmental record of groundwater temperatures. Along with data collected since the 1990's by Cardiff Harbour Authority and Met Office data, this record forms a long-term baseline for assessment of climate driven impacts on the subsurface environment, and yielded insights into variations in the subsurface urban heat island effect and magnitude of impacts of future shallow geothermal/ GSHP, geo-exchange structures and SuDS schemes. Much of the data collected by the BGS is available for download from the UKGEOS website www.ukgeos.ac.uk/affiliated-sites/cardiff and NORA and has already been used by academic researchers (BGS and Cambridge University) for urban heat flow modelling studies, European geothermal management and policy studies (https://geoera.eu/projects/muse3/), and by the Welsh Government for screening of low carbon heating options for public sector buildings.

In a parallel project, the BGS and partners also monitored the in-service performance and impact of a groundwater source heat pump system installed at a school. Long-term monitoring for 5 years through several heating seasons proved that these shallow geothermal systems, when designed, installed and maintained well, can operate with high seasonal performance factors of at least SPF H4=4.5 (W13/W50). Injection capacity of the c.20m deep injector well has remained good but recirculation (rapid thermal breakthrough) due to a close (22m) well spacing slightly reduced whole system efficiency. The low groundwater ΔT of 2K across the primary heat exchanger meant that the environmental impact on the aquifer was minimal but oxygenation did affect the microbiology. Finite element modelling of the thermal plume suggests a >30m well spacing would have been more optimal for this 18kW heating only system that abstracts c.2.2 L/s when operating at full load.

Maps showing the undisturbed ground temperature and highlighting the thickest parts of the gravel aquifer - representing the best small-medium scale open loop GSHP opportunities - have been drawn based on a 3D superficial geology model of the city which is now available on the BGS GeoIndex (www.bgs.ac.uk/map-viewers/geoindex-onshore/) and are intended for use in desk studies, ground models, SuDS, energy and infrastructure planning, heat network zoning, and geoscience education. A groundwater water balance model has also been developed, thermal conductivity analysis of Triassic bedrock cores performed, and a register of GSHP schemes initiated as a precursor to a national database.





Aquifer Thermal Energy Storage in the UK: Current Status and Future Prospects

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Aquifer Thermal Energy Storage (ATES) is a shallow geothermal technology with the potential to provide large scale, seasonal, low carbon heating and cooling to the built environment. Heating and cooling currently produces 23% of the UK's greenhouse gas emissions. ATES can be a key technology for the UK to meet its net zero targets, particularly as cooling demand is set to increase in a warming climate. ATES offers a higher overall coefficient of performance compared to conventional, open-loop shallow geothermal systems: waste heat and cool is captured and stored underground as warm and cool water, so less electrical energy is required by a heat pump to provide heating, and cooling can be delivered directly without the need for a heat pump.

The potential for ATES developments in the UK is significant: it has a seasonal climate, and many major cities are underlain by suitable storage aquifers such as the Chalk beneath London, and the Permo-Triassic sandstones beneath Manchester and Liverpool. Despite this large potential, the uptake of ATES in the UK has been limited, with only 11 installations over the past 16 years. 10 of these installations target the Chalk aquifer and 9 are located in London. In this study, we review the current status of ATES installations in the UK. A case study of an operational ATES system in the fractured Chalk aquifer in London is presented. Monitoring data over a 7 year period are used to quantify the performance of the system, with key metrics such as energy balance and thermal recovery being reported. The case study demonstrates that ATES systems can be operated successfully in heterogeneous aquifers.

We also report some observed challenges to widespread uptake of ATES in the UK. Poor performance due to a lack of understanding of the technology is observed. Inadequate monitoring of installed systems as well as large imbalances between heating and cooling loads are identified as key issues. ATES system designs that neglect the impact of aquifer heterogeneity on subsurface flow and energy storage can return suboptimal performance. A lack of awareness of ATES technology is recognised as a key barrier to uptake; it is not considered as an option to provide heating and cooling to buildings by key stakeholders such as local and national planners and policy makers. We report ongoing research to overcome these challenges.

Celsius Energy: a digital-native geoenergy solution to decarbonize heating and cooling

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Proposed for oral presentation

Celsius Energy is a technology company with the mission to decarbonize the building HVAC industry by designing and developing shallow geothermal energy installations. A Celsius Energy system consists of three elements: a borehole heat exchanger (BHE), a heat pump for both heating and cooling, and a digital geoenergy management system.

A pilot system has been designed, constructed and operated in Clamart, France (Thierry et al., GRC 2021). Dozens of other installations have been designed and built for different types of uses and operating requirements, from single buildings to district heating networks. Celsius Energy has already drilled more than 150 wells in several countries, including seven completed borehole exchangers.

One of the innovative features of Celsius Energy systems is the geometry of the BHE, including both vertical and inclined wellbores. Inclined wells, and in particular a star-shaped layout, allow reducing drastically the surface footprint of an installation, making it possible to implement a geothermal exchanger in contexts such as urban areas or existing buildings where vertical wells alone would not be feasible (Figure 1, left).

Celsius Energy leverages the industrial expertise of its parent company SLB to improve the reliability of its solution, while reducing its implementation cost and time. For instance, the use of adequate drilling and surveying techniques and equipment, derived from the oilfield industry experience, ensures that inclined well trajectories do not deviate from the well plan, and proprietary well placement algorithms guarantee that the most efficient BHE geometry is designed and can be updated in real time during the operations (Figure 1, right).

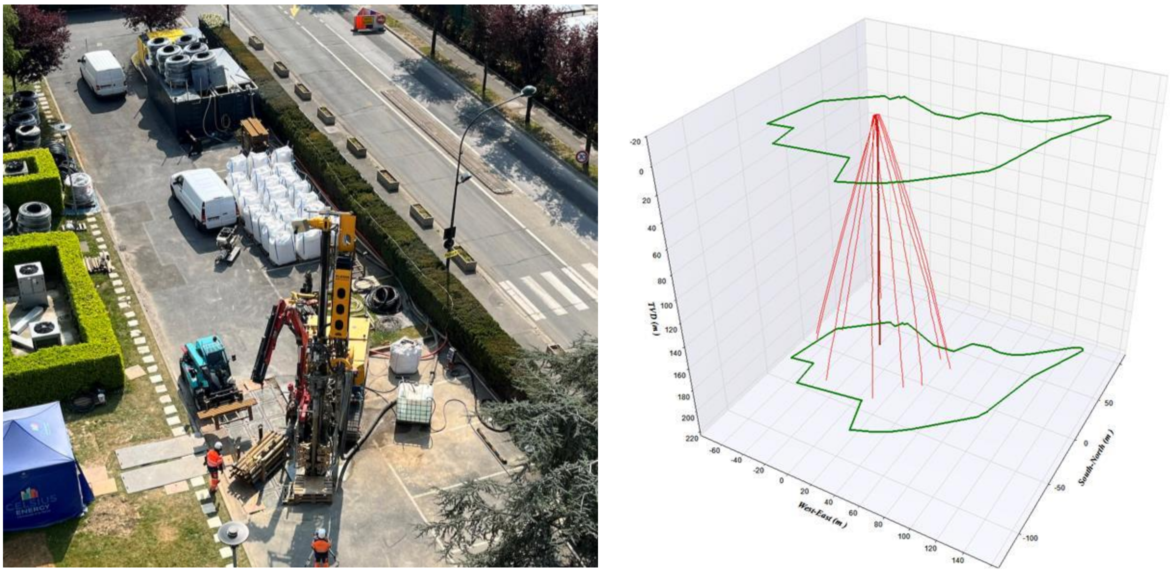

Figure 1: Example of the drilling site layout, showing the reduced footprint of operations (left), and inclination survey results (right) for inclined BHEs at Celsius Energy commercial installations in France

On the other hand, bespoke digital solutions have been developed to build, model and manage the system. The geoenergy management solution (Figure 2, left) uses sensor input, external information and past records to optimize performance. Operations are supported by rig instrumentation and data tracking applications. Integrated modelling tools have been developed in-house to dimension the different components of the system and compare their behaviour to the observed data (Figure 2, right; Parry et al., EGC 2022).

Figure 2: layout of a Geoenergy Management System dashboard (left) and temperature distribution modelling using a bespoke finite-volume simulator (right)

The application of industrial experience to the development and operation of GSHP systems and the development of fully digital energy management and modelling tools allow Celsius Energy to build robust, reliable and efficient systems in contexts where traditional installations would not be feasible. Celsius Energy has already carried out studies for the deployment of these systems at several sites across the United Kingdom, ranging from housing estates to campuses, from health institutions to large commercial buildings. A demonstrator installation (Figure 3) is currently under construction in Southwestern England; the progress will be presented at the UK Geothermal Symposium.

Figure 3: Visual valorisation of a Celsius Energy demonstrator for community outreach

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Session Six: Shallow Geothermal

Impact of Chalk Aquifer Heterogeneity on Low Temperature Aquifer Thermal Energy Storage (LT-ATES) System Performance: A Case Study in London, UK

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We examine an ATES installation in the Chalk aquifer in London, which has been operational since 2013. The system employs 4 cold wells and 4 warm wells and is sized to deliver peak heating of 1.8 MW and peak cooling of 2.75 MW. Analysis of flowrate and temperature data shows that the system has a well-balanced energy ratio of 0.009 but exhibits a low but increasing thermal recovery which is currently ca. 40% for warm storage and 25% for cold storage.

The dual porosity Chalk aquifer is well known to be highly heterogeneous, characterized by intervals of high permeability formed by fracturing and/or karstification. Despite this, models used to predict ATES system operation in the Chalk have typically assumed a homogeneous aquifer, so that simulated warm and cold plumes have a simple 'cylindrical' geometry around the wells (Figure 1a). Here we investigate the impact of aquifer heterogeneity on system operation. We use a Surface-Based Modelling (SBM) approach to represent geological heterogeneity that allows us to accurately capture geometrically complex subsurface features. We develop a range of realistic 3D models of different geological scenarios. Flow and heat transport during system operation is simulated using the Imperial College Finite Element Reservoir Simulator (IC-FERST). The models are calibrated to pressure transient data and well flow logs obtained from the boreholes prior to commissioning, as well as the temperature and flowrate data obtained during operation.

Our results suggest that aquifer heterogeneity has a significant impact on the formation of the warm and cold plumes. A laterally continuous, high permeability interval at the top of the Chalk plays a key role, causing the development of 'pancake' (Figure 1b) rather than 'cylindrical' plumes. Low thermal recovery results from increased conductive heat losses from the thin but laterally extensive plumes. Recovery is predicted to increase as the temperature in the over- and underlying rock gradually changes through time. Thermal interference has been limited to date as the system has operated well below capacity but could also impact thermal recovery if flow rates are increased in future. Our results have broad implications for the design of ATES systems in heterogenous aquifers.

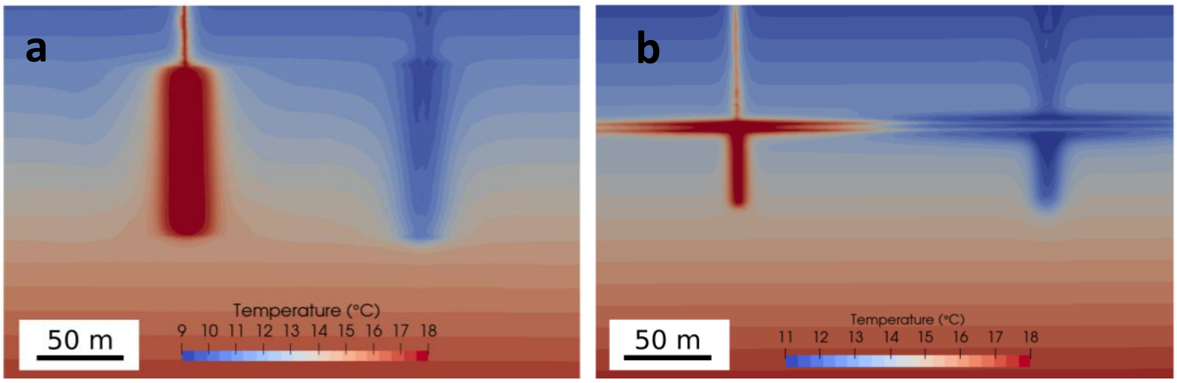

Figure 1: a) Cylindrical geometry of warm and cold plumes simulated in a homogeneous aquifer. b) Pancake-like geometry of warm and cold plumes simulated in an aquifer with a 3m-thick high permeability interval.

New national infrastructure for the in- situ evaluation of aquifer thermal transport and storage: Introducing the UK Geoenergy Observatory in Cheshire, UK

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Transition of domestic and commercial heating and cooling from fossil fuels to renewable energy is integral to the decarbonisation of UK energy use as together they account for over 25% of UK CO_2 emissions. Heat pumps powered by renewable electricity are a green, energy efficient, heating and cooling solution and in 2020 the government announced the goal of increasing the number of heat pump installations from ca. 50 to 600k/ year by 2028. Ground source heat pumps are expected to account for a significant number of these installations, especially for off-grid buildings, 5th generation community heat networks and commercial installations. Given the number of additional installations needed, it is important to optimise the design and performance of these shallow geothermal systems to maximise their thermal yield and minimise the risk of impact to the subsurface environment and potential future users of the subsurface.

The UK Geoenergy Observatory in Cheshire (https://ukgeos.ac.uk/cheshire-observatory) is an at-scale facility open to academic, commercial and regulatory users for research and innovation in aquifer geothermal and in-situ monitoring of subsurface processes. The Observatory, which is located at the University of Chester's Thornton Science Park campus in Cheshire, is due to enter into operation in January 2024. The research infrastructure comprises 20 instrumented boreholes drilled to 100m bgl in the Chester Formation of the Sherwood Sandstone Group aquifer with associated surface control, monitoring and data management systems. Excellent ground truth is provided by high spatial resolution wireline logging, scanning of recovered and preserved drill core and profiling of aquifer properties, porewater chemistry and microbiology. Boreholes are equipped with a dense array of electrical resistance tomography electrodes, hybrid fibre- optic distributed temperature and acoustic sensing (DTS & DAS) cables and multilevel groundwater monitoring systems to allow subsurface change to be observed in real time. Thermal perturbation is achieved using 4 closed loop heat exchanger boreholes for repeat TRT testing and groundwater flow velocity can be controlled using an abstraction/ reinjection system. The Observatory enables testing, monitoring and quantification of subsurface heat transfer processes, ground behaviour, thermogeology and hydrogeology, providing insights into sustainable operational management and maintenance requirements.

This presentation will address the design, ongoing development and capabilities of the Cheshire Observatory, and key findings from the construction phase.

Further information on the Glasgow and Cheshire Observatories and the Core Scanning facility in Keyworth, together with open access data from the construction phase, is available online at: www.ukgeos.ac.uk. To discuss access or ideas for field experiments please contact BGS at: ukgeosenquiries@bgs.ac.uk

Estimating the capacity of shallow aquifer thermal storage in the UK- a National screening approach

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The UK has a vast, largely untapped, low-enthalpy geothermal potential in shallow aquifers. To date, there are over 3000 shallow schemes exploiting heat and cool stored in aquifer systems across the world, with the majority of these schemes installed and successfully operating in alluvial gravels in the Netherlands. A much smaller number of schemes are located in north-west Europe, Turkey, USA, Canada, China and Japan. There are only 11 Aquifer Thermal Energy schemes in the UK, although suitable geology to host schemes is not considered a barrier to wider adoption. The geology that is considered particularly suitable for ATES schemes includes both permeable Superficial Deposits (glacial and post-glacial), and importantly Bedrock Aquifers which typically have high groundwater storativity, transmissivity and production rates at levels required to support medium to large output ATES doublet systems.

Here, we describe the first national-scale assessment of the potential thermal energy storage represented by bedrock aquifers in the UK (including England, Northern Ireland, Scotland and Wales), assuming a nominal 0.5 MW doublet scheme with a maximum change in groundwater temperature of 10 degrees C resulting in a minimum required flowrate per well of at least 10 l/s. These conditions restricted the assessment to 6 Principal Aquifers including the Triassic and Permian sandstones, Permian Dolomites, the Inferior and Great Oolite groups, the Lower Greensand and the Chalk Group. Using a combination of surface and subsurface mapping, we provide an interactive GIS layer showing general information including the spatial distribution of suitable aquifers, and the number of aquifers that may be encountered to a depth of 400 m on a 1 km grid. We additionally map on published heat and cool densities for each unit area to illustrate the potential requirements across the UK. This assessment does not consider some parameters that are best considered at a local-scale such as variability in aquifer properties including groundwater chemistry, groundwater gradients, extraction and injection flow rates and thus storage capacities.

The tool indicates that the UK has extensive spatial coverage of geology that is suitable for the development and utilisation of medium to large scale ATES systems. There is a strong juxtaposition between ATES suitable geological bedrock units and mapped heating and cooling density particularly across south-east, midlands, and north-west England, and parts of Northern Ireland; there are limited opportunities in Scotland. Overall, there is significant potential for the development of ATES within the UK to meet desired carbon reduction targets. This assessment only considers single medium to large ATES doublets and as such the required flow rates are achievable from the aquifer are the principal constraining factor. Engineering alternative systems with multiple doublets of lower output and requiring lower yield rates would allow a significantly greater proportion of the bedrock geology/areas of the country to support the deployment of ATES systems.

There are many opportunities for open-loop ATES systems in locations close to areas of anticipated high demand, such as urban and industrial areas. Aquifer Thermal Energy Storage therefore represents an important thermal management opportunity for the UK that can be integrated into a portfolio of low-carbon energy technologies that will be required to support the stated net-zero ambitions at National, regional and local scales

Deep Geothermal Heat Pumps: cost competitive retrofit of fossil fuel heat in the built environment.

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The use of shallow geothermal less than 200 m (or “ground source”) to decarbonise lower temperature space and water heating in buildings is well understood. The application is particularly efficient in greenfield settings when the building’s energy efficiency can be maximised and the temperature of heat demand minimized. Retrofit scenarios where the existing hydronic heating system requires flow temperatures of 80 ºC or more are more challenging for conventional heat pumps. This is because the Coefficient of Performance is largely dependent on the temperature lift from source to sink (or flow). Hence for example low temperature (10 to 12 ºC) shallow geothermal heat requires to a ~70 ºC lift penalizing the COP. In brownfield settings, where the client is unwilling to re-engineer the existing hydronic system, we can turn to deep geothermal (>400 m) for the thermal energy source. Applications of such “Deep Geothermal Heat Pumps” or “enhanced direct use” are currently few and far between globally. This appears to be a technology diffusion issue as the projected economics of some of the modeled scenarios are very encouraging. There are nevertheless technology development opportunities including the Causeway Energies patent-pending method and system which includes a high lift heat pump and a new borehole heat exchanger design to maximise overall system efficiency.

Session Seven: Environmental of Shallow Geothermal and Mine Water Geothermal

How sensitive is the environment to temperature changes from ground source heating and cooling systems?

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The Environment Agency's role is to protect and improve the environment. In the context of Net Zero, this means making decisions that support climate change targets at the same time as protecting the wider environment. Heating is responsible for over a third of UK carbon emissions, but a heat pump (which can be air, ground, or water source) can reduce carbon emissions by up to 70% compared with a gas boiler. However, their possible impacts on plants, animals, habitats, ecosystems and human infrastructure – "receptors" – are not well understood. We undertook work to identify the receptors and parts of the environment that could be most sensitive to temperature changes resulting from Ground Source Heating and Cooling (GSHC) systems.

We used the systems mapping software (KUMU) to map all possible receptors, environments and pathways that could be affected by temperature changes from GSHC. The map shows direct impacts (e.g., impacts on groundwater fauna) and indirect impacts (e.g., impacts on groundwater-fed wetland fauna) and identifies influences on both biotic (e.g., spawning fish, groundwater fauna) and abiotic (e.g., aquifer chemistry, infrastructure) factors. Receptors are identified as nodes. Links between the nodes are positive (direct relationship), negative (inverse relationship) or complex. Information regarding the temperature sensitivity of the receptors is attached to nodes and linkages and can be viewed by querying the map. Temperature information includes evidence for temperature tolerance thresholds, seasonality, rate of change as well as uncertainties. Workshops were held with 34 experts from within the Environment Agency and external bodies (e.g. British Geological Survey, UK Centre for Ecology and Hydrology, Ground Source Heat Pump Association, and water companies), with expertise covering the whole system of interest, to refine and verify the map.

Receptors are grouped into 8 sub-systems: aquifers; groundwater fauna, groundwater dependent terrestrial ecosystems, wetlands and springs; aquatic biota; water quality, resources and infrastructure; repurposed mine systems; soils and geomorphology; buildings and other surface infrastructure; and other ground heat exchange infrastructure. Existing evidence suggests that receptors across all subsystems can be sensitive to temperature changes directly, heat-induced changes in geochemical processes and contaminant mobilisation, and temperature-induced changes in biotic community composition.

The systems map can be used to identify the sensitivity of receptors, habitats and environments, and inform part of a tiered risk assessment and permitting process that progresses from generic to site specific. This will help protect vulnerable settings at the same time as allowing for development of the industry. Possible further work as part of the Net Zero Environment Agency Research programme could identify the likelihood of temperature changes in different settings and with different sized GSHC systems. This would improve our understanding of risk and consider cumulative impacts from an expanding industry.

Towards a Regional and Local Hydrogeological Understanding of the Midlothian Coalfield: Update on learnings from the Galleries to Calories GeoBattery Pilot Study

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The Galleries to Calories research project led by TownRock Energy and University of Edinburgh seeks to establish a field test site to assess the viability of heat storage in flooded coal mine workings as part of a regional scale heat geo-battery. We plan to target the former Roslin, Burghlee and Ramsay collieries to the SE of Edinburgh. These collieries exploited shallow deposits of the so-called ‘edge coals’ of the Midlothian coalfield. The coalfield underlies the catchment of the River Esk, its North and South branches, and their associated tributaries.

The interaction of water courses with mine water poses a potential risk to ground and surface water quality, and flow behaviours that need to be understood. Prior to commencement of drilling and hydraulic field trials, a conceptual hydrological model of the local and regional hydrogeology was developed in order to provide a baseline understanding of the system, from which any future changes in water quality and flow behaviour could be compared.

We provide an update on our understanding of baseline conditions in the Esk catchment in terms of hydrochemistry, streamflow behaviour, and flow from known mine water discharges. To date this has comprised of stream flow hydrograph modelling to assess the interaction between regional surface water and groundwater, and evaluation of legacy hydro-chemical datasets. Detailed hydro-chemical fieldwork in the North Esk and its tributaries has been ongoing since May 2023 to better constrain local baseline conditions in the immediate vicinity of the geo-battery test site, and current state of progress and preliminary results are presented. We also outline our wider baseline monitoring plan and outline of future expansion to include telemetered data covering soil moisture and stream flow on currently ungauged tributaries.

Testing, monitoring and quantifying mine water geothermal using the UK Geoenergy Observatory in Glasgow, UK

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Over the last 5-10 years, there has been significant growth and interest in mine water geothermal for heating, cooling and thermal storage. But what happens in the subsurface when many people start using the resource? How long will it last? Can cost and risk be reduced for drilling and testing new schemes, as well as for efficient operational transfer of heat via geo-engineering infrastructure?

The UK Geoenergy Observatory in Glasgow is an at-scale facility open to academic, commercial and regulatory users for research and innovation in mine water geothermal and urban environmental change. In spring 2023 it became fully operational including geothermal infrastructure comprising flexible, sealed open loop doublets to two levels of flooded mine workings, coupled to a heat pump/chiller and heat exchangers for simulating thermal energy extraction (=heat abstraction) or cooling/thermal storage (=heat addition). Combined with extensive temperature, geophysical and environmental monitoring (including groundwater, surface water, InSAR, seismic, fibre-optic downhole, electrical resistivity tomography, ground gas/near surface gas), the facility enables testing, monitoring and quantification of subsurface behaviour, geothermal operational management and environmental change.

This presentation will outline ‘baseline’ subsurface and hydrogeological characterisation of the urban coalfield setting and emerging results from heat extraction and thermal storage commissioning tests.

For example, downhole temperature sensing enables tracking, imaging and quantification of ‘warm’ and ‘cool’ pulses of mine water during pumping and recovery phases. The improved understanding of the thermal behaviour (e.g. heat depletion or recharging), reservoir connectivity and rates of breakthrough is critical for answering the types of questions posed above, for security of supply to customers, and for informing regulation.

Towards a fuller understanding of pumping test data from mine water aquifers: Learnings from UKGEOS Glasgow

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Pumping tests provides a routine means of characterising “conventional” aquifers in porous media. They allow a demonstration of achievable yields a borehole can sustain, as well as determination of physical aquifer properties in terms of transmissivity and storage that are required as input to groundwater and heat transport models to evaluate future production scenarios.

Drawdown curves are typically interpreted by assuming the observed can be modelled by the Theis equation. Yet the reliability of the derived hydraulic parameters, and the consequences for modelling, relies on the degree to which the pumped workings match the conceptual model of an ideal confined aquifer required by Theis. Mine water aquifers comprising of large open voids may lead to turbulent flow in open galleries, particularly near pumped wells. Failure of the roof, pillars, or heave of the mudstone floor may enhance leakage from neighbouring sandstone bodies. Therefore, the degree to which pumping tests in mined ground can be interpreted in terms of Theisian analysis may be questioned. Alternative numerical models for the description of aquifer pump tests are available, but have yet to be considered in characterisation of mine water systems.

This presentation will show results of a comprehensive reanalysis of pumping tests conducted in the Glasgow Upper and Glasgow Main coal seams at the UKGEOS Glasgow site. This will allows us to understand the degree to which mine water aquifers can realistically described by traditional flow models, and if this varies as a function of mine architecture. In this work we make use of more advanced groundwater flow equations that account for non-linear flow behaviour due to turbulent flow due to high flow rates in open roadways and coarse back fill material, namely the Forchheimer and Izbash equations, the latter has been used in pipe flow models of mine water systems. Additionally, the Hantush equation is considered to account for leakage effects.

We propose that deviations from classical Theisian behaviour may actually provide further insights into the hydraulic behaviour of the flooded voids. In a practical sense, this can provide circular feedback to allow iterative improvements of our conceptual understanding of the mine water hydrology of a given site. Particularly given the challenges in intercepting mine workings given the vintage of some abandonment plan that may limit the scope for additional observation wells to be drilled.

We will provide some thoughts as to how to recognise when alternative flow models may be required, and considerations that should be made in designing pumping tests in mined ground.

Session Eight: Mine Water Geothermal

Geothermal from Metal Mines in Cornwall – a case study looking at the potential for mine water heating from historic mines Geevor, Levant and Botallack

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The geothermal resources in Cornwall are well known. The county has been at the cutting edge of exploration for deep geothermal energy for many decades, starting with the Rosemanowes Hot Rocks project in the 1970s through to the recent developments of the United Downs Deep Geothermal Power project and Eden Geothermal. But there is one resource that is yet to be explored in Cornwall… mine water geothermal.

The Tin Coast Mine Water Geothermal Feasibility Project was commissioned by Cornwall Council, the National Trust, LiveWest Housing and Pendeen Community Heritage with additional funding from DESNZ (Department of Energy Security & Net Zero) and HNDU (the Heat Network Delivery Unit).

It is the first study at this scale to look at the potential of geothermal from metal mines in the UK and investigates the resources within the famous Geevor, Levant and Boscaswell Mines. Combining historical archive material and sub-surface data collection with surface infrastructure and engineering options, this feasibility study aimed to establish whether the resource can be integrated with heat networks, to supply heat to the heritage site of Geevor Tin Mine Museum, Boscawell Social Housing Estate and to provide a source of pre-heat, to power the oldest working Cornish steam winding engine at Levant Mine. Sub-surface data collection included running temperature, electrical conductivity and CCTV surveys and collecting representative water samples for subsequent analysis. Sample points within the shafts were selected based on changes in water properties noted during the wireline logging operations and samples from adit discharge points were also collected to inform environmental considerations and permitting.

This presentation will offer an overview of the aims and ambitions of the project, highlight the challenges and successes of sub-surface data collection, and present the results. It will provide a comprehensive account of the reality of considering the abandoned flooded metal mines of Cornwall as a potential heat resource, as well as showcasing its potential to drive positive change for the local area, socially and environmentally.

Although the work has been spearheaded by GeoScience Limited, it would not have been possible without the involvement of all consortium partners: members of the Southwest Geothermal Alliance (Tony Bennett, Carrak Consulting and Camborne School of Mines), TownRock Energy and Tomson Consulting. The geothermal industry relies on successful collaborations between sector specialists to engage in innovative solutions. This project has been a testament to the saying “teamwork makes the dream work”.

Developing the Gateshead Mine Heat Scheme

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The Great North Coalfield fuelled much of the North East's industrial revolution and the innovation, advancement and economic prosperity it delivered. Numerous cities, towns and villages in the region owe their very existence to their underlying coal reserves. In 2015, Britain's deep coal mining industry ended with the closure of Kellingley Colliery leaving a legacy of around 23,000 disused collieries comprising shafts and galleries that have and are slowly refilling with water heated by naturally occurring geothermal process. Reflecting Britain's transition away from coal, the UK celebrated a 67 day period where no coal was burned for electricity production in June 2020. The coal industry has been much maligned as a dirty industry, yet the infrastructure the miners created presents a valuable asset for future low carbon heat supply.

In 2019, Gateshead Energy Company (GEC), commissioned the Coal Authority to undertake feasibility work to determine whether mine workings beneath Gateshead town could provide heat for a planned heat network expansion. The town had an existing heat network and gas fired combined heat and power plant (CHP) supplying up to 4MW of heat. The intention was to double the size of the heat network without doubling the carbon emissions. GEC highlighted 5 key development areas that could potentially host the boreholes and the mine abandonment plans beneath these areas were inspected. The seams were predominantly worked by room and pillar methods in this area. Seven collieries worked the seams beneath these sites, coal was worked in the area from at least the 1700s up until the 1920s. Although some of the mine workings overlap in different seams, all of the seams might not be interconnected (e.g. by mining connections).

It is assumed however, that all workings within each colliery are connected. It is important to understand the potential connections between seams and collieries for several reasons. Firstly it is important to ensure that the abstraction and reinjection points are hydraulically connected so that there is potential for a flow cell to develop i.e. pressure differentials are not built up between points of abstraction and reinjection. Secondly, the flow paths need to be sufficiently long enough to avoid short circuiting and cooling the abstraction. The length of these flow paths will vary according to flow rates and heat demands and the question of the sustainability of these resources is the subject of current research.

The age of the depth of the worked seams is also a key consideration. Accessing shallower workings can reduce borehole drilling costs however shallower workings are generally associated with older/earlier dates of working which can impact upon plan availability, quality and accuracy. For the Gateshead project this created challenges with geo-referencing plans and hitting drilling targets. Following an inspection of the plans beneath the sites, the High Main Seam (ca. 50m below surface) and Hutton Seams (ca. 150m below surface) were selected as possible targets for reinjection and abstraction respectively due to their prevalence beneath the areas of interest and more widely beneath the town.

Water levels in the area are around 20m below surface and have been static for over a decade. Hydrogeologically, workings in the area are considered part of the Walker mining block. Both the Hutton and High Main Seams are hydraulically distinct. Water in the High Main unit is believed to drain directly to the Tyne River Tyne through the overlying High Main Post sandstone formation. The Hutton unit is separated from the High Main by ~ 110m of competent rock and is connected to the deeper mine workings present across the region. Both units display a diurnal tidal fluctuations (two maxima per day). The effect is more pronounced in the Hutton which is likely an elastic response to tidal loading as opposed to a direct diffusive hydraulic response as is likely the case in the High Main Seam.

The High Main Seam "aquifer" comprises locally pervasive workings and the fractured sandstone of the overlying High Main Post. Water levels indicate that it is marginally confined beneath the overlying glacial boulder clay. The unit is highly transmissive and during scheme operation displacement is less than +3m even at the highest injection rates. Water temperature in the High Main Seam (11 to 12 °C) is cooler than the deeper Hutton Seam (15 °C to 16 °C) which is why the former was chosen as the reinjection target.

The Hutton Seam "aquifer" is confined against the overlying Carboniferous sequences. Initial testing of the Hutton boreholes demonstrated a near uniform response to pumping across monitored areas of the unit which was observed alongside higher than expected drawdown. Despite transmissivity being inferred to be quite high, the unit did not effectively release water from storage. The aquifer's performance was improved (abstraction Specific Capacity improved by ~ 4x) following drilling of a multi-seam borehole that created a proximal connection between the Hutton and High Main seam workings effectively depressurising the lower unit.

The completed mine water heat network comprises two abstraction boreholes into the Hutton Seam (to provide resilience and flexibility when peak heat demand is not required) and one re-injection borehole into the High Main Seam through which water will be returned underground following heat recovery at the heat exchanger. Plus the multi-seam borehole that improves hydraulic efficiency. The mine water source temperature in the Hutton Seam is around 15°C, this will be dropped by around 7.5°C at the heat exchanger. Heat pumps will increase temperatures to 65°C-80°C with a heat output of 6MW at maximum flow rates of around 140L/s with a constant coefficient of performance of around 3.

The subsurface challenge was the age and quality of mine plans limiting the accuracy with which they could be georeferenced, also the condition of the workings was unknown. More boreholes had to be drilled than planned during the exploratory phase to find acceptable open connections with the target seams.

The scheme received funding from the Heat Network Investment Project, has taken around 3 years to complete and will provide up to 6MW of heat from the mines for the growing heat network. This renewable heat will support GEC's target of achieving net zero emissions by 2030, and help to reduce reliance on gas CHP. This project demonstrates an immediate opportunity to repurpose a former fossil fuel industry that has been viewed as a liability for a future low carbon heat supply that potentially offers energy security, improved air quality, competitive pricing, and wider economic opportunities.

The Mine Water Geothermal Resource Atlas for Scotland (MiRAS)

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Mine water geothermal (MWG) energy describes the low-carbon practice of using water held in abandoned flooded mines to heat or cool surface thermal demands. The low temperatures (as low as 10°C) require heat pump technology to upgrade thermal energy to usable temperatures for heating homes or industrial applications. The intention of the Mine Water Geothermal Resource Atlas for Scotland (MiRAS) is to highlight the most promising areas to exploit MWG energy in Scotland. If the scale of the nation's mine water thermal resource, estimated at 12 GW, becomes better communicated we envisage that the atlas will prove influential for increasing the rate and success of MWG deployment. Ideally, the provision of feasible MWG sites will influence stakeholder decisions i.e., where to invest and develop land to make the best use of the low-carbon resource, resulting in MWG potential included as part of a standard appraisal for a residential or industrial development plan. Whilst it is acknowledged that focused expert input would be required to integrate surface heat demand and subsurface resources in detail, the SMGM provides non-experts and decision makers with a first-pass high-level summary of the potential MWG resource located within their area of interest. The four criteria for site selection are summarised below:

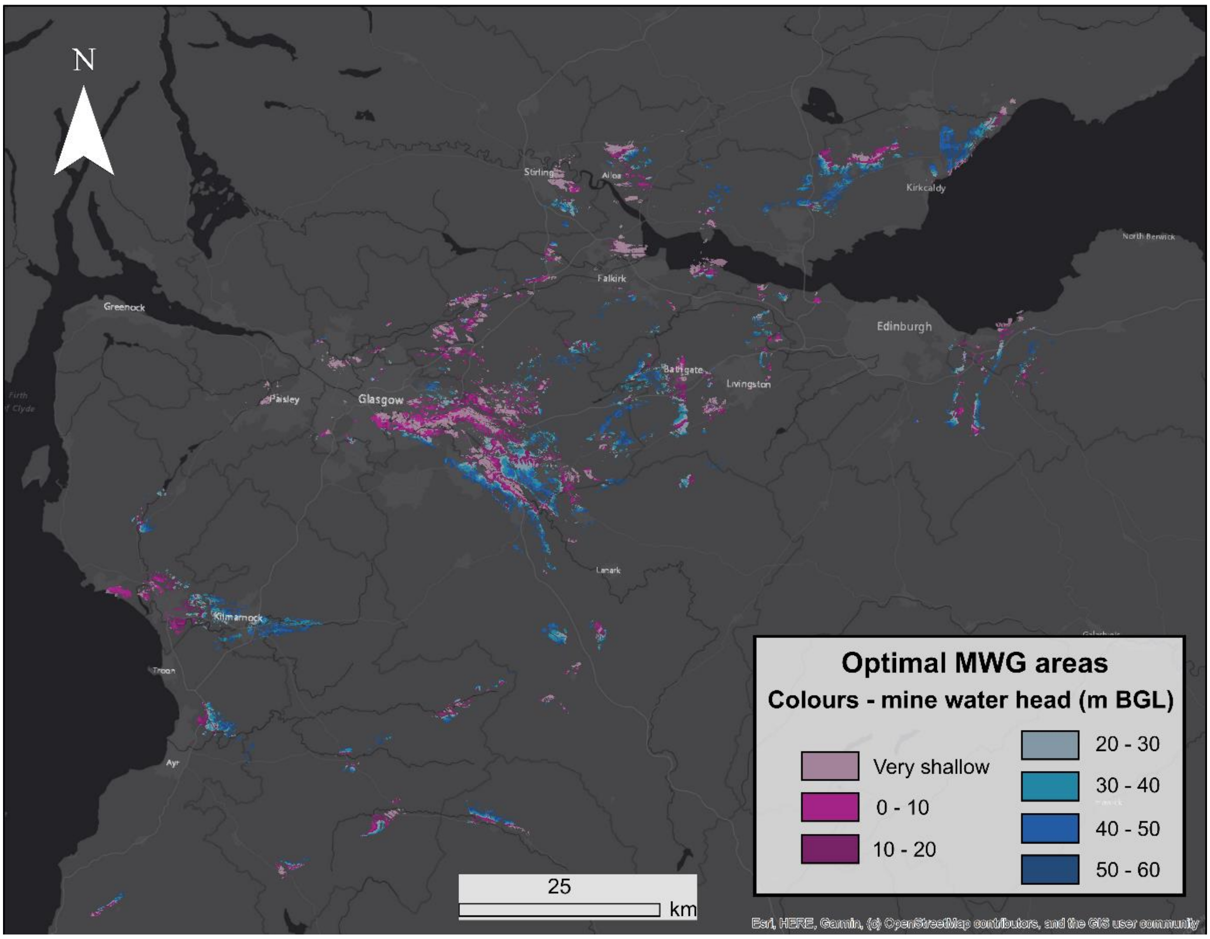
1. There are more than one (overlapping) worked coal seams.
2. The coal seams are deeper than 30 m to minimise subsidence risk.
3. The mine water head (i.e., mine "water table") is not excessively deep (< 60 m below ground level) to avoid excessive pumping costs.
4. The mines are shallower than 250 m below ground level to minimise drilling costs.

As a result, this atlas has identified a total of 370.3 km^2 across 19 local authority areas which are most suitable for MWG development (Figure 1).

The MiRAS can be downloaded as a WMTS for GIS application:

https://www.spatialdata.gov.scot/geonetwork/srv/eng/catalog.search#/metadata/63ccefed-0165-461d-a5a5-025b0b2463c5

Or viewed on the Improvement Services Spatial Hub Online viewer by selecting the correct layer.



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 2. Mine Water Geothermal Resource Atlas for Scotland with optimal areas coloured corresponding to the depth to mine water (m BGL). Reproduced with the permission of © The Coal Authority. All rights reserved. Crown copyright and database rights 2022 Ordnance Survey.

Net Zero thanks to Coal? Exploring the Potential of Mine Water Geothermal from a Coal Mine in Kent.

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Achieving net zero by 2050 is a challenging target, but innovative geothermal solutions can contribute to make this ambitious goal a reality. In the United Kingdom, where space heating accounts for more than 70% of domestic energy consumption, geothermal energy emerges as a game-changer, offering the potential to diversify the energy mix and create an impact.

Mine water geothermal technology, has substantial upscaling potential considering that 25% of the UK's homes and businesses are situated above abandoned mine workings. The implementation of geothermal mine water schemes has the potential to deliver a sustainable heating solution to often overlooked mining communities.

In March, Gateshead Council successfully pioneered a geothermal mine water scheme, funded by a £10 million investment from HNIP aimed at diversifying their energy portfolio. This success story stands in stark contrast to the early days of mine water geothermal in Shettleston, Glasgow (1999-2019), where challenges such as clogging and inefficiency led to the project's abandonment.

This project studied Snowdown mine, located in the southeast of Kent, nestled between Dover and Canterbury. One of four collieries in Kent active for the better part of the 20th century, Snowdown's history is marked by both trials and triumphs. The mine's first shaft struck water at a depth of 80 meters, resulting in the tragic loss of twenty-two lives. Nevertheless, the pursuit of coal continued, and in 1926 they struck gold by reaching the Kent 6 (Milliard) coal seam, where they mined an area of 10 square Km at a depth of approximately 800 meters.

However, this victory came at a cost. Due to its extreme depth, Snowdown was regarded as the hottest and most humid pit in Kent, with frequent cases of heatstroke among miners. Miners had to consume a staggering 14 litres of water per shift merely to survive. Locally, it was aptly named "Dante's Inferno" for its searing conditions.

In recognition of the challenging realities faced by Snowdown's miners, a low enthalpy mine water geothermal project holds immense promise. Two overlapping seams with temperatures of 19°C and 30°C at depths of 350 meters and 800 meters, respectively, present the potential for a temperature differential (ΔT) of 15 °C with a cascade of use. With an abstraction rate of 24 litres per second, this could yield a 2 MW mine water geothermal plant capable of having a cascade of use heating local homes, businesses and agricultural greenhouses. Moreover, it could be integrated into brownfield development, serving as a compelling proof of concept for deep mine water geothermal. The deeper (350 m - 800 m) workings at Snowdown provide a unique testing ground, challenging the higher relative costs of deep drilling against the benefits of accessing hotter water.

The proposed Snowdown mine water geothermal project involves abstracting 30°C + water from a depth of 800 meters, using heat pumps to deliver the desired heat supply, and subsequently re-injecting cooler waters at the shallower seam. Key challenges include uncertainties regarding aquifer communication, external recharge from outside the coal seam, the distinctive depth range (deeper than conventional mine geothermal but shallower than 1-2Km deep geothermal), potential interference from the chalk and greensands aquifers, increased OPEX for deeper pumps, and the project's sensitivity to heat extraction and drilling costs.

To address coal seam communication uncertainties, we employed a model developed by academics at Durham University to determine fluid flow rates and assess the risk of thermal drawdown. For profitability assessment, we created an economic model incorporating discounting, various payback metrics, and estimated costs. This model was tested using Monte Carlo analysis, revealing an 11% risk of no simple payback, a 36% risk of no discounted payback, and a 38% chance of never reaching positive NVP(5). While most scenarios showed profitability, they also highlighted the significant associated risks. Further research into drilling costs and technologies, coupled with the refinement of our fluid flow model, could mitigate uncertainties and bolster the project's viability.

In conclusion, the Snowdown mine water geothermal study can contribute to a sustainable energy future, leveraging the unique geological and thermal conditions of the site. While challenges persist, careful research, innovative technologies, and a commitment to addressing environmental and economic concerns position this project as a step towards a net-zero future by 2050.

Session Nine: Faults, Fractures and Fluids

Keynote: Geothermal development in Chile: a long history of some lights and many shadows

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The Chilean Andes evidences the perfect alignment of continuous heat sources (related with volcanism and surficial magmatic bodies) with the intersection of main fault systems creating secondary permeability as the ultimate controls of both medium- as high-enthalpy convective geothermal systems along the country (Figure 1). This perfect confluence of favourable factors has been present in the geothermal development of Chile from the beginning of last century up today, a long history with probably more shadows than lights. In fact, the first formal geothermal exploration campaign in South America (one of the firsts in the world), was launched at the early beginning of the XXth century in Northern Chile. Since that romantic time, different national initiatives to promote geothermal energy have been applied, but all of them failed in the aim to develop a generation power plant. At the end of the 60s and early 70s, several production wells were drilled by the National Geothermal Company (Empresa Nacional de Geotermia -ENG-, closing operations by 2010) in El Tatio-La Torta geothermal field (Figure 1). These initiatives were shut down in the mid-70s, initiating a time gap in Chilean geothermal exploration. However, from the 80s to early XXI century, Chile (and the rest of Andean countries) was presented to the international geothermal community as one of the largest undeveloped and unexploited geothermal provinces in the world (see Morata *et al*., 2020 and references therein). Chile's geological conditions, placed on one of the most active subduction zones, with the highest concentration of active volcanoes under the continental crust, allow to effectively remark the huge geothermal potential existing in the Andes. Nevertheless, it wasn't until late 2017 that Chile crossed from the expectation phase and finally entered the geothermal club. Cerro Pabellón, the first geothermal power plant in Chile (and South America) began its operation through Geotérmica del Norte (GDN), a joint venture between Enel Green Power and Empresa Nacional del Petróleo (ENAP) in the altitude (4500 m a.s.l.) of the High Andean Cordillera. Two high-enthalpy ORC twin units (24 MWe each) injected 48 MWe to the national electricity grid (Capetti et al., 2020). By end of 2022, additional 33 MWe were installed, conforming a total installed capacity of 81 MWe.

This new scenario for geothermal energy in Chile was the consequence of several economic and political efforts. In 2000, the Chilean government passed the "Chilean Geothermal Law (law 19.657)" allowing private developers to explore and exploit geothermal energy. During the first decade of the XXI century, up to 14 private companies were exploring for geothermal resources in the Chilean Andean Cordillera (see Lahsen et al., 2015). However, a dramatic decrease in the electricity prices in Chile combined with unsuccessful geothermal exploration programs and the strong entry of solar energy in the electricity Chilean market, resulted in a progressive reduction of companies exploring for electricity generation using geothermal energy. New shadows in the turbulent history of the Chilean geothermal development. In fact, between 2015 and 2017 geothermal exploration in Chile was reduced to the minimum expression, meanwhile solar energy strongly increased moving Chile to a renewable scenario with a lower dependence on fossil fuels. Today, only three geothermal companies are really active in the country and the question about where (and when) the second geothermal field could be exploited is completely open.

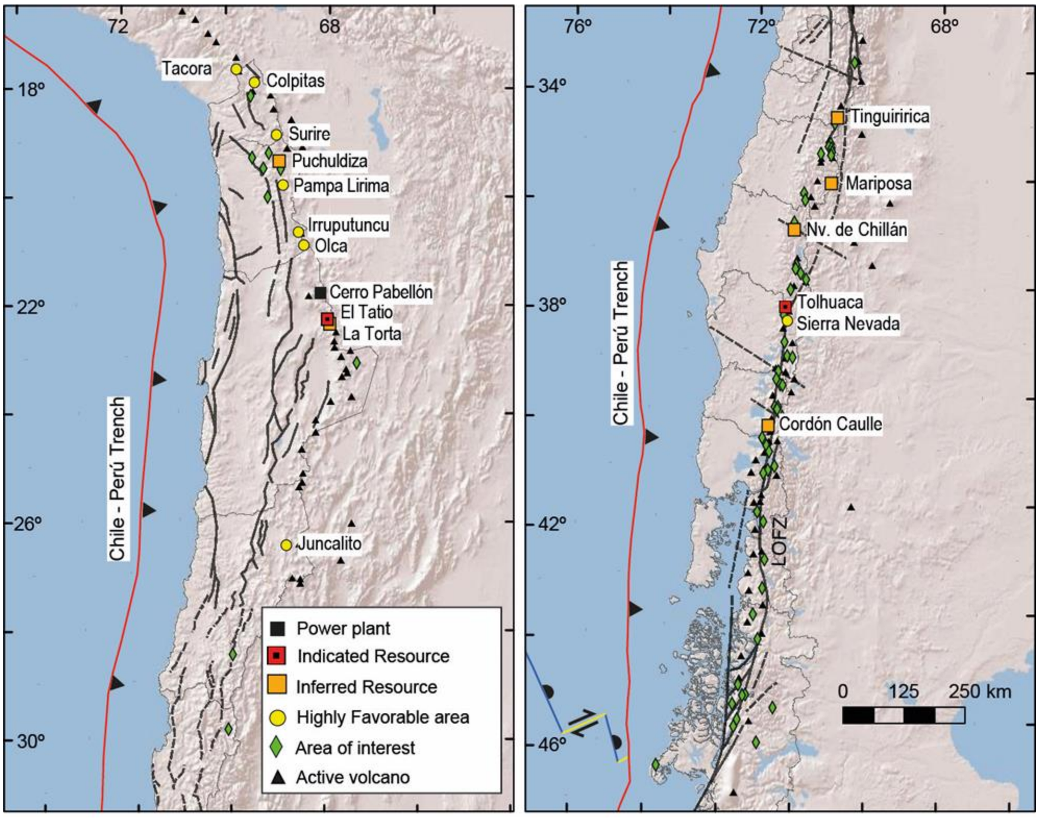

Figure 1: Active volcanism and location of the more developed geothermal fields (after Aravena et al., 2016).

However, new changes in the Chilean energy policy promoted a new optimistic window for geothermal development. The new Chilean energy policy aims to have a 100% renewable matrix by 2050, moving progressively towards a coal-free country. This new scenario could imply an opportunity for the increase of geothermal energy in Chile. By June 2023, the total installed electricity capacity in the country was 34.548 MWe, being 37.0% generated by fossil fuels (12.779 MWe, including 3.952 MWe based on coal) and the rest by renewable energies (including hydropower), strongly dominated by solar (PV and CSP, ~9.000 MWe) and wind (~4.600 MWe). There is, in consequence, an open space for geothermal energy in the Chilean grid, not only for electricity production but also for the incipient direct use. We hope that during the next years, the geothermal development in Chile could offer new lights (and lower shadows) in the energy transition to a fossil fuels-free grid.

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Transport properties of fault related geothermal systems in Cornwall: An experimental approach

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Granite based geothermal systems are currently being explored in Cornwall for their potential to decarbonise energy production. Fault structures, known locally as cross-courses, are currently targeted due to their potential to both host fluids at depth and create zones of enhanced permeability through fault related fractures. These structures have been transmissive in the past, evidenced by mineral veins, and surrounding host rock alteration. Hydrothermal alteration has the potential to affect the petrophysical properties of a rock, however these effects on potential geothermal systems has received little attention to date.

We have measured the tensile strength, porosity and permeability of samples of Carnmenellis Granite which have been hydrothermally altered to different amounts. We have found that hydrothermal (argillic) alteration leads to a weaker, more porous and permeable rock, which has implications both in terms of reservoir volumes and fluid production rates. The alteration of feldspars into clay minerals results in microporous regions that are connected throughout the material, and consequently an increase in total porosity by an order of magnitude and matrix permeability by up to 4 orders of magnitude. However, fractures hosted in the altered material are more likely to close under higher effective stress than those hosted in comparatively unaltered material, which leads to a lower fracture permeability. Finally, we demonstrate that hydrothermally altered zones have the potential to host significantly greater amounts of accessible fluid than the fractures alone, and that they should be considered when assessing reservoir volumes in these types of geothermal systems.

A quantitative assessment of the risks of induced seismicity and potential for fluid flow in the fractured Carboniferous Limestone of northwest England with implications for geothermal energy

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Faults slip in response to changes in stress or fluid pressure, and these changes can be natural or anthropogenic. Estimating the likelihood of fault slip for a given change in loading is critical for safe geological storage and energy extraction in faulted rocks, as well as effective communication of risks to policy makers and the public. The energy transition and decarbonization are urgent and essential tasks: we will only be successful if we manage to balance public perceptions of risk with the technical challenges inherent to the exploitation of faulted rock. To accomplish both, we need to do a better job of quantifying the uncertainties in our mechanical and geometrical data.

Measures of fault stability include slip (T_s) and dilation (T_d) tendency, and fracture susceptibility (S_f, the change in fluid pressure to push effective stress to failure). The input values for any of these measures are always uncertain, and they are uncertain to varying degrees. For example, while the vertical stress can be well constrained from wireline density log data, the maximum horizontal stress is generally much harder to quantify from any source. Probabilistic models of fault stability and flow potential for the Carboniferous Limestone underlying much of northern England are presented. Fault maps are derived from published geological maps and recently reprocessed seismic reflection data. Stress and pressure constraints are derived from legacy onshore hydrocarbon wells and wireline logs. Coefficients of friction and cohesive strength remain poorly constrained, not only in terms of their magnitude, but critically in the shapes of their statistical distributions. In addition, the applicability of simplified indices of fault stability (T_s, T_d, S_f) to complex natural fault zones is questionable, and our predictions could be improved through weighting by information derived from long-term seismological records and laboratory experiments.

This contribution focuses on a key issue: a currently popular model for fault-related fluid flow states that such conductive faults are critically stressed. This implies that exploiting these faults as conduits for hot water for geothermal energy could change their stability and induce seismicity. We reconsider the evidence for critically stressed faults in the light of new laboratory experiments, and present new maps of the Carboniferous Limestone with fractures colour-coded by a new geomechanical index to highlight zones of high flow potential and low seismic risk.

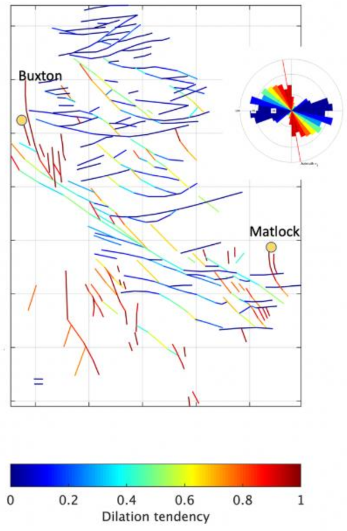

Figure 1. Map of faults and fractures in the Carboniferous Limestone of the Peak District, UK. Colour-coding is for dilation tendency (dimensionless; 0 is low, 1 is high) for a strike-slip stress regime at 2 km depth with the maximum horizontal stress (and maximum principal stress) oriented 170 degrees. Inset shows a rose plot of the same fractures colour-coded for the same index.

Fluid flow in fractured geothermal systems: an example from the Nevados de Chillan Volcanic Complex (Southern Volcanic Zone, Chile)

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Understanding the controls on crustal fluid flow is of significant and urgent relevance for society as this process directly impacts the occurrence of natural geological resources and hazards. However, there are still many unresolved problems relating to the directionality of crustal fluid flow due to the coupled complexity of anisotropic fracture networks formed in heterogeneous rock segments that experience anisotropic regional/local stress and strain conditions. In this work, we present the Nevados de Chillan Volcanic Complex (NChVC, ~37°S), a well-recognized but poorly characterized, fracture-controlled volcano-geothermal system, as an exceptional case study because it is a prime example of evidence for both long-term and short-term evolution of fracture-related (both past and present) fluid flow. The flow of crustal fluids is evidenced by both intruded and erupted magma in the form of NW-trending aligned craters, preferentially NE-trending oriented dikes, and recent eruptions, as well as past hydrothermal fluids (today expressed by filled veins) and present-day geothermal activity with preferentially oriented hot springs and fumaroles, defining the called Nevados de Chillan Geothermal System (NChGS).

Host rocks of the NChGS are Miocene volcanoclastic rocks intruded by Miocene granodiorites and Pliocene diorites. At the southwestern flanks of the NChVC, thermal springs, boiling pools, mud pools, and fumaroles (the latter having temperatures up to 95°C) evidence the active geothermal system. At the beginning of this century, one exploration well (Nieblas-1) was drilled by the Empresa Nacional de Geotermia (ENG), providing a continuous record of hydrothermal alteration up to a depth of ~1000 m. This full-core exploratory well, together with geological, geochemical, and geophysical data acquired by ENG, confirmed the high gradient and the presence of an active geothermal system hosted in the crystalline rocks, with measured temperatures of 216°C at 985 m depth. However, the exploratory well did not reach the fractured granitoid (assumed as reservoir host rocks), and the company abandoned the project.

The detailed structural analysis developed from a regional (lineament analysis from satellite images) to the mesoscale in selected outcrops allows us to identify the main deformation pattern controlling past (and present) hydrothermal fluid flow. We performed fault characterization and collection of fracture attributes (orientation, spacing, opening or infill, spacing, intensity, and density) at each site with 1D linear and 2D circular scanline methods. A sampling of surficial geothermal manifestations and identification of the alteration mineralogy using XRD and SEM methodologies, coupled with structural geology modeling based on +1000 fracture/fault measurements, allow us to perform a conceptual model for this geothermal system.

Preliminary results show that sub-vertical fractures and transcurrent faults have preferential orientation in E-W, N40-60E, N40-60W, and NS directions. Also, low-angle reverse faults (N20W/30E), with attitudes subparallel to the stratification of volcaniclastic rocks, control surficial thermal manifestations, including intense argillic alteration. We also remark on the first-order lithological control on fracture density because it is much higher in crystalline rocks and lower in volcanoclastic units. On the contrary, present-day volcanic lavas have no registered fractures or faults.

Our data suggest that the intersection of main transcurrent fault systems controls the vertical permeability of past and present fluid flow in the deeper system (dominated by crystalline fractured rocks). On the other hand, low-angle reverse faults control the location and distribution of surface thermal manifestations in the Miocene volcanoclastic rocks outcropping over the fractured granitoid.

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Session Ten: Faults, Fractures and Fluids, Lithium, and Drilling

Using Electron Backscatter Diffraction to discover geothermal reservoir scaling controls

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Geothermal reservoir permeability requires the maintenance of open fluid flow pathways to remain viable fluid flow conduits into production wells. Geothermal fluid flow pathways in many geothermal reservoirs are dominated by structural permeability, networks of open fractures and faults that facilitate geothermal fluid circulation. As geothermal resources become an increasingly promising solution to realizing net zero targets with respect to energy production, the ability to maintain open, fluid flowing structural networks in a geothermal reservoir is crucial. Therefore, is becomes important to understand geological processes that serve to reduce a structural networks ability to circulate geothermal fluids. One such fluid flow inhibiting process is mineral scaling within a geothermal reservoir, by which mineral precipitate nucleates and growths within these structural networks, eventually sealing them off from fluid circulation. The controls on mineral nucleation and growth within fractured geothermal reservoirs need to be characterized if we are to determine appropriate mitigation strategies to inhibit this process and secure sustainable geothermal reservoir well production.

Research at the University of Liverpool focuses on determining the nucleation and growth mechanisms of quartz, calcite, and other geothermal minerals, utilizing natural examples of geothermal scaling. Here we present new findings on the influence of adularia on both calcite and quartz formation in geothermal reservoirs as determined from the Kibiro geothermal region of Uganda and the hydrothermal regions of the Coromandel Peninsula in New Zealand, as well as new insights into quartz precipitation in granite hosted fractures from Cornwall hydrothermal systems in the UK. Samples of hydrothermally scaled fractures from these sites have been analyzed using SEM techniques such as electron backscatter diffraction (EBSD), energy dispersive X-ray Spectroscopy (EDS), and cathodoluminescence (CL). Sealed fractures from these resources shows mineral scaling can be either single or multiphase implying that dynamic geothermal reservoir conditions can influence the methods by which reservoir scaling can occur. We find that geothermal systems that develop fine-grained adularia, a hydrothermal K-feldspar, which exhibits well-defined crystal faces, are often followed by periods of either quartz and/or calcite precipitation. EBSD analysis of such multiphase scaled geothermal fractures shows consistent angular relationships between the <100> crystallographic directions of both quartz-adularia and calcite-adularia neighbor crystals. Such a crystallographic relationship between these hydrothermal mineral pairs a previously unknown scaling nucleation control in geothermal systems, whereby adularia encourages the nucleation and oriented growth of subsequent calcite and quartz scaling phases. Once nucleation is achieved via these relationships, differences in grain size between adularia and subsequent scaling phases, suggests rapid quartz/calcite growth and fracture sealing. These results suggest that initial nucleation of quartz or calcite on adularia may requires significant energy but once reached rapid fracture scaling is able to proceed. This observed adularia – calcite/quartz relationship appears in both geothermal sites studied, suggesting the process is a common component of fracture sealing in such geothermal environments.

Initial SEM analyses of quartz mineralization in Cornish granites, an important focus for UK geothermal development, show that the growth of reservoir quartz scale has complex crystallographic textures that evolve two major ways; 1) scaling begins via the development of bands of alternating finer and coarser crystalline quartz, which is later texturally overprinted by large, elongate, euhedral quartz crystals, and 2) large quartz crystals which show a ‘feathered’ crystal margin microstructure containing dense dauphine twinning, surrounding a dominantly structureless quartz crystal center. The first observed quartz scale texture suggests hydrothermal conditions in the granites changed with time triggering changes in the style of quartz growth. Such a finding shows that variable reservoir quartz scaling mechanisms operate under different hydrothermal conditions, which with further research may provide insights into devising reservoir operational controls on the scaling process. The second quartz scaling texture documented suggests that quartz growth processes change with time, likely reflecting changing fluid chemistry or changing geothermal reservoir conditions. Further analysis of these datasets is required to discover how changing growth processes in the geological record may inform on current scaling rates and what geothermal conditions facilitate various mineral nucleation and growth mechanisms.

Cornish Lithium: Exploration for lithium-enriched geothermal waters in Southwest England

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The UK's commitment to reducing carbon emissions by 68% by 2030 is unlikely to be met without decarbonising travel and heating that account for 24% and 33% of emissions respectively (BEIS, 2016). Lithium is a critical metal for the transition towards a low-carbon economy due to its use in Lithium-ion batteries. Global demand for Li is predicted to increase to 785,000 t Lithium Carbonate Equivalent (LCE) by 2025 (Roskill), from 217,000 t LCE in 2017 (Reuters) driven predominantly by the move towards electric vehicles.

Warm geothermal fluids (<50°C) containing elevated lithium values (50-220 mg/L) have been known within Cornish mines since circa 1864 at which time great expense was dedicated to dewatering mine workings (Miller, 1864). Now, 250 years on it is clear there is huge potential to utilise both the lithium and heat contained within these fluids for fuelling the transition towards a low carbon economy. Through exploration drilling, subsurface modelling and GIS based mapping, we demonstrate there is substantial untapped potential for geothermal heat production as a by-product of lithium extraction in southwest England.

Cornish Lithium has access to a wealth of historic data from the extensive tin and copper (+/- W, Zn, Pb, Ag) mining from the 17th century to present. Mining records show that lithium-enriched geothermal fluids are hosted at depth within a geographically widespread network of permeable fractures comprised of ENE-WSW trending Sn-Cu lode structures as well as NW-SE oriented faults termed cross-courses. Historical records are observations of the subsurface geology in the form of plans and section. These structures have been implicitly modelled in 3D modelling software Leapfrog Geothermal and integrated with accounts of geothermal springs, remote sensing, and geological mapping data. Since 2019 Cornish Lithium has drilled four exploration boreholes <2 km depth to intersect fault structures based on the modelling in-part from historical records. Sampling of these holes reveals lithium concentrations ~100 mg/L and geothermal gradient of <45 C/km with fluids encountered throughout the permeable fracture network. Data collected from these drilling campaign, including data from a borehole televiewer, has provided a greater understanding of the fracture network and the scale of the thermal and lithium resource.

Here we demonstrate that lithium is present with hot geothermal fluids. We show that historical records supplemented with modern geological and remote sensing techniques can be used to target lithium bearing fracture networks with high accuracy and we explore the potential for direct heat use as a by-product of lithium water extraction in Cornwall.
The lithium will be extracted using Direct Lithium Extraction techniques that either make use of sorbent or membrane technologies to selectively remove dissolved lithium from the geothermal waters. In March 2022, Cornish Lithium commissioned a pilot plant at the United Downs Geothermal Research Facility. At the time of writing further testing is underway to optimise lithium extraction and the integration of heat exchangers into the processing flow sheet.

Exploring the deep fractured reservoirs for extracting heat and lithium from geothermal brine: a case study of Les Sources (Northern Alsace, France)

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Lithium de France is the first independent French operator who aims to extract heat and geothermal lithium. Their project consists in producing hot and Li-rich fluid naturally circulating inside a fracture network in the Upper Rhine Graben (URG). From August 2022 and July 2023 an exploration campaign was conducted to improve the knowledge of the area and build a 3D model integrating geological, geophysical, and geochemical data. Aware of the unaddressed issues in subsurface exploration and populations' concerns, this 3D model is used to mitigate the risks, prepare future drilling operations, and plan reservoir development.

Context of the study

The area benefits from an extensive geothermal experience with several industrial projects on stream since the beginning of the XXIst century. Several deep wells have demonstrated that hot brine circulates inside a complex network of natural fractures. The latter is particularly developed in the Triassic sandstones and in the altered granitic basement. More recently, scientific studies have revealed that geothermal lithium could be extracted from this brine at industrial level. The opportunity for environmentally friendly lithium extraction with a low CO2 emission gave resource exploration in the URG a second wind.

Exploration campaign

In June 2022, Lithium de France was awarded the first exploration license named Les Sources in Northern Alsace (Figure 1). An exploration campaign started few weeks after to improve knowledge of the subsurface in the area through several geophysical operations:

1) 3D seismic campaign over 60 km^2 in order to provide a 3D image of the reservoir;
2) Controlled Source Electro-Magnetic (CSEM) acquisition to identify fluid circulations;
3) Vintage 2D lines reprocessing to help with 3D seismic processing and interpretation.

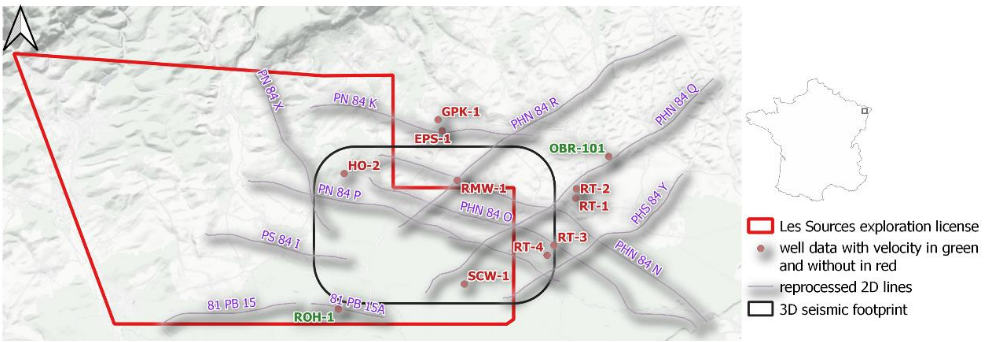

Figure 1 Exploration license Les Sources with 3D seismic footprint, vintage 2D lines acquired and reprocessed by Lithium de France and historical well database

The 3D seismic campaign has been an effective tool for imaging large-scale faults that intersects the sedimentary cover and the granitic basement located at 2km depth approximately in the area. In addition, reprocessed vintage 2D seismic lines were used to characterize structures beyond the seismic cube giving more confidence in structural and horizons interpretation.

CSEM acquisition crossed the 3D seismic footprint, and large drops of resistivity correlated with major normal faults observed in seismic data. These anomalies could be related to the increased porosity within the fault zone and/or the presence of hotter and/or more saline hydrothermal fluid. As they also match thermal anomalies known from hydrocarbon wells, such resistivity measurements emerge as promising exploration tools for permeable structures that cannot be spotted based on seismic data only.

Construction of the 3D model

Based on these data, a 3D geological model was created with the Leapfrog software (Seequent) to obtain a 3D spatial representation of the reservoir (Figure 2a). In parallel, a comprehensive conceptual model was developed incorporating a large database legacy from hydrocarbon and geothermal experience. A large amount of well data was collected, analyzed and incorporated, such as:

- Geological data including lithology, temperature, petrophysical properties, alteration mineralogy and information on zones of circulation losses;
- Hydrogeological data including production/injection tests, tracer tests, location of up-flow/ recharge zones;
- Structural data including survey of fracture and fault zone and stress field;

As predicting the thermo-hydro-mechanical behavior of the future exploitation is essential, a numerical modelings were conducted with 3DStress software (South West Research Institute), representing the slip tendency of the faults (Figure 2b), and the DISROC software (Fracsima), simulating the geomechanical behaviour of the reservoir. Particularly, the pressure conditions of the reservoir were carefully studied. The risk mitigation of induced seismicity is a key point for developing a project in a populated area such as Alsace and seismological data were cautiously taken into consideration in well-planning.

These models aim to evolve with future drilling operations, well-data acquisition, and hydraulic tests. As new data are obtained, a continuous model update is critical for the successful development of the field.

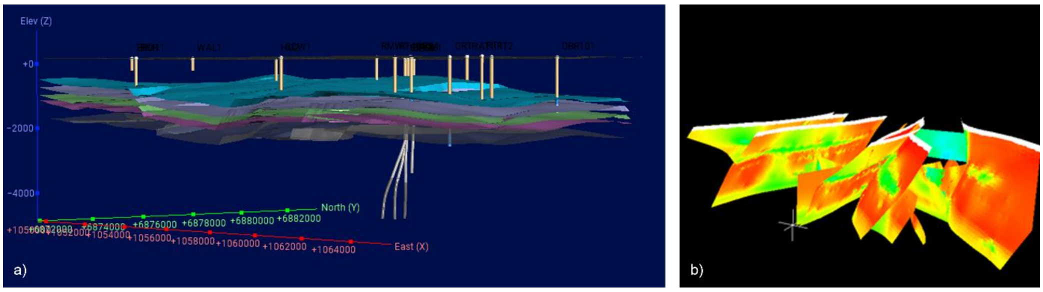

Figure 2 a) 3D geological model constructed with the Leapfrog software b) slip tendency modelled on main faults with the 3DStress software

Perspectives and concluding remarks

A viable combined extraction of heat and geothermal lithium requires the best possible knowledge of the fluid flow and fluid-rock interactions inside the reservoir. Thus, the geochemical approach will be also integrated to the model. This project development involves a series of steps in resource reconnaissance, risk mitigation and stakeholder communication that are essential for an economically, socially and environmentally respectful project.

OptiDrill – Back to the future.

Co-Authored: Kevin J Mallin (Geolorn Limited – kevinmallin@geolorn.co.uk); Andrew Kingdon, Matthew Arran (British Geological Survey); Shahin Jamali (IEG-Fraunhofer) Henning Knauer (IEGFraunhofer)

Geothermal energy is an underutilised, yet highly sustainable, low-carbon resource that where successfully implemented can aid the drive toward a clean energy transition by 2050. Its impact, however, has thus far been limited by the cost of accessing the resource through the uncertainties associated with identifying, evaluating and drilling into suitable subsurface conditions, coupled with the complexities and time taken to complete a project. The result has been that in many territories both investment and state support have been directed towards other renewable energy (low carbon) technologies, particularly wind and solar, both of which require additional storage to avoid curtailment of excess energy production and to allow for base-load flexibility.

A number of research and white papers quote the cost of drilling at around 55% of the total project spend, so reducing this must be exponentially beneficial to increasing the number of geothermal energy projects undertaken.

The OptiDrill project, which is funded by the European Union Horizon 2020 programme. sought solutions to a number of issues associated with accessing the sub-surface using drilling technologies through optimising drilling performance.

The objective is to develop data-driven machine learning methods based on multiple sensoric solutions for prediction of drilling performance, drill tools wear rate and drilled lithology, and ultimately unite the latter methods under one system to enable drilling process optimization and intelligent decision making.

The OptiDrill specific scientific and technical targets are:

- Develop enhanced drill monitoring systems based on MWD systems and acoustic- and
- vibration-based sensors.
- Develop automated machine learning-based analysis methods to predict drilling
- parameters using sensoric data-driven models.
- Develop coupled drilling optimization models to reduce geothermal drilling costs.
- Develop a real-time drilling monitoring and optimization tool as a unified system to
- combine the existing data and the newly developed methods.

The project has analysed data from significant numbers of wells, including drilling reports, wireline data, geophysical and ‘lessons learned’. These will be integrated to produce a thorough understanding of drilling issues related to all parameters and through the application of Machine Learning (ML) and Artificial Intelligence (AI), the OptiDrill team have developed a highly analytical system to predict likelihood of potential drilling problems before they happen.

The OptiDrill project builds upon work carried out within the EU 2020 funded Geo-Drill project (ID: 815319), where bespoke sensors/tool-joints were developed in conjunction with a novel fluid hammer and advanced coating technologies, along with 3D-Printing of components.

Data produced as drilling progresses will be analysed in real-time and compared to the training data to assist the drill team to make more informed decisions, reducing costly Non-Productive Time (NPT). Additionally, lithology prediction will be a major part of the development to better optimise the in-hole tools, their ability to efficiently drill formations and overcome the difficulties of the associated with a 'best-fit' approach being adopted.

Selecting the correct methodology for any given lithological sequence will increase overall Rates of Progress and lower the number of operational days over each well.

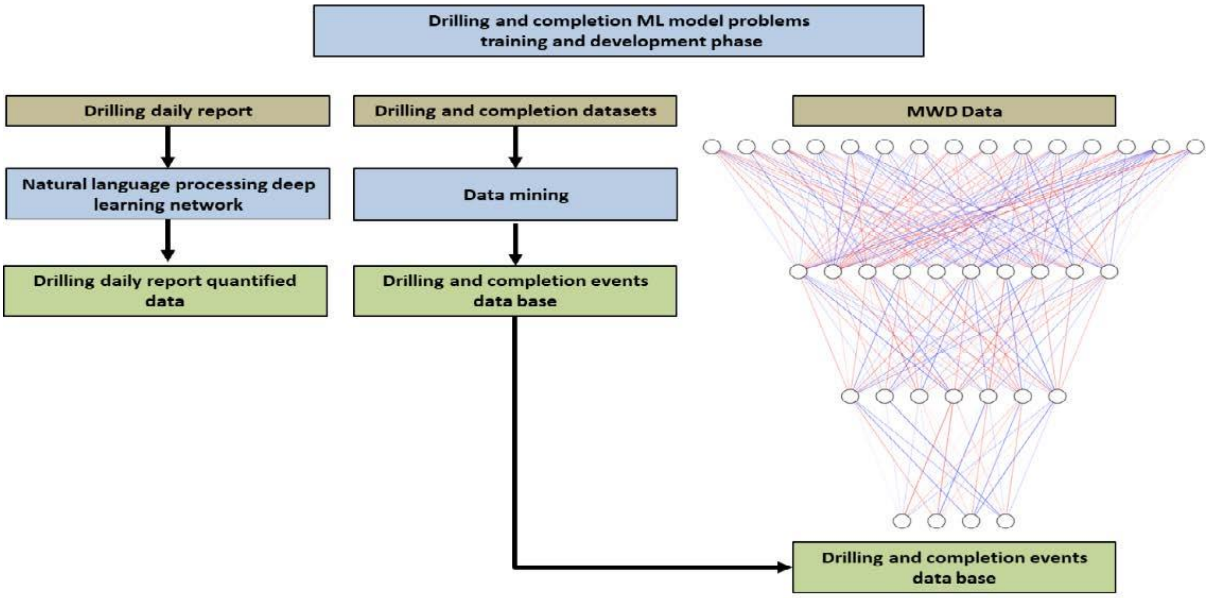

Fig 1: The OptiDrill 'system'

OptiDrill will benefit all drilling operations, as it is agnostic to methodology of drilling and will continuously advise the operational team to achieve optimal parameters for a successful outcome.

Improved data quality fidelity and analytics at surface and downhole to deliver improved wellbore understanding in geothermal applications and technology development.

Stephen Pink, eVolve & WDP

Over the last 10 + years the Oil and Gas industry has gone through a transformative period in relation to use of data for improved wellbore understanding. Key to this has been the realisation that high fidelity datasets open up new insight. It is just about the norm today for data faster than 1hz to be acquired at surface and at much higher rates downhole with industry leading technologies acquiring and storing data at 1500Hz. Recently these technologies have been brought to bare on several geothermal applications including the optimization and tuning of new innovative particle drilling bit designs, deployment at the forge facility in Utah and today high frequency surface data is being acquired in Germany to allow improved well optimization.

It is not always possible to acquire downhole data in all applications but with the introduction of low thermal coefficient coatings, insulation and improved cooling the envelope is expanding. We can however develop analytics and understandings leveraging relationships between surface data and downhole and look for synergies. This then allows us to make educated conclusions on the downhole environment using surface data when we can no longer run downhole data acquisition.

The presentation will look at a number of recent applications where downhole measurements have been deployed for improved understanding of the system dynamics in both a technology design application and in a well delivery case. We will then also look at the feasibility of intelligent correlation with surface data and how modern analytics can effectively predict certain downhole conditions using pattern recognition and various data methodologies. The aim is to illustrate a cost-effective industry leading solution that aids the geothermal industry gain performance and shorten the learning curve by leveraging knowledge and technology from O&G

LOW-GRADE HEAT – THE UK's GEOTHERMAL SWEET SPOT

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The presentation will demonstrate that combining petroleum industry drilling technology, methodologies and experience with geothermal research can unlock affordable, decarbonised heat such that geothermal energy use becomes a societal norm across the UK.

Drilling costs are cited as a barrier to the advancement of geothermal energy potential, yet this need not be the case. The authors will demonstrate where application of innovative technology reduced well costs to make previously uneconomic projects viable. They will then indicate how this can be applied to development of deep geothermal energy to provide affordable, secure heating for all.

The drilling experience gained by the petroleum industry shows that wells up to 1500 m (5000 ft) can consistently be drilled within seven days. The depth of 1500 m arises as this is the crossover between accessing usable UK temperatures, depth capabilities of lower-cost drilling rigs, site access and depth-related drilling challenges. Analysis of current geothermal drilling operations confirms the potential for a step change reduction in risk, time, and cost.

Use of energy for heating makes up 50% of the UK's total energy consumption and has been particularly challenging to decarbonise. Geothermal for heat solves this issue and unlocks a significant opportunity to achieve demanding net-zero targets.

The authors have a combined experience exceeding 100 years of delivering some of the oil and gas industry's most demanding wells in complex projects worldwide. They perceive an opportunity to leverage this experience across the geothermal industry to unlock its potential and accelerate the UK to the forefront of geothermal drilling for heat.

This advancement is game-changing. Pilot projects will be better served with larger rigs which will result in higher costs and larger environmental and social footprints. However, this requirement for larger rigs will not persist and as operations move towards scale. Wells are expected to be reliably delivered within the targeted seven days from rig arrival to heat being available at the surface. Using the proposed methodology the expected well cost is under £250,000, with an average wellsite site size equal to 10 car parking spaces.

The authors will share proven approaches to deliver success in complex drilling projects and demonstrate how to evolve from pilot projects to country-wide adoption, such that the appetite for ever more demanding geothermal projects grows.

The presentation is based on field experience, supported with credible analogues, and is biased towards commercialism supporting geothermal viability.

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Understanding the Impact of Paleoclimate Corrections on the Cheshire Basin with Application to Deep Borehole Heat Exchangers

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The UK government has committed to achieving net zero carbon emissions by 2050; this can only be achieved if the supply of heat is decarbonised. Geothermal energy could play an important role in decarbonisation, due to the significant estimated geothermal potential in the UK. Furthermore, there are opportunities to repurpose existing infrastructure for geothermal development; there are c.2000 onshore ex-hydrocarbon wells in the UK (e.g., Watson *et al*., 2020), with many of these having the potential to be repurposed as closed-loop, deep borehole heat exchangers (DBHEs) with low geological risk, as there are no hydraulic interactions with a reservoir at depth (Nibbs *et al*., 2023).

In this study, the Cheshire Basin was investigated as it has a significant geothermal potential holding over 23 % of the energy from the UK's Mesozoic Basins (Downing and Gray, 1986; Rollin *et al*., 1995; Brown, 2023), and additionally, many wells have been drilled which could be re-entered and converted to DBHEs at relatively low-cost. Although there are significant resources associated to the basin, the heat flow is relatively poor and below the UK average. It is likely that estimates of heat flow have been underestimated as a consequence of not factoring in corrections of past paleoclimatic conditions. As a result, the Knutsford-1 borehole, within the Cheshire Basin, was selected as a case study to understand: i) the impact of Paleoclimate corrections on both heat flow in the Cheshire Basin, and on transient DBHE modelling simulations, ii) how engineering parameters can be optimised to maximise performance when repurposing an ex-exploration hydrocarbon well as a DBHE, and iii) to understand the impact of groundwater flow of varying deep geothermal reservoirs of thickness up to 2 km within the basin.

The uncorrected heat flow of the Knutsford-1 borehole was calculated through detailed analysis of the borehole's lithological and temperature logs. The effect of palaeoclimate on heat flow was then accounted for, following the methodology outlined in Westaway and Younger (2013). Corrected values indicate that past heat flow measurements within the basin have been underestimated and in shallow boreholes the impact could be even more pronounced. This not only impacts the prior basin-wide geothermal potential /basin basal temperature calculations, but also static and transient wellbore modelling.

Following the corrections of heat flow data, a series of numerical models were developed on OpenGeoSys to understand the static and transient thermal response of the subsurface for un-corrected and corrected heat flows. Optimum engineering conditions, such as flow rate and wellbore properties, were then established based on DBHE performance (i.e., from both hydraulic and thermal changes). Lastly, the impact of the mechanism of heat transfer in the subsurface around the DBHE was evaluated; the two scenarios considered were conductive and advective heat transfer around the DBHE (i.e., with or without groundwater flow).

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Uncertainty quantification of conceptual open and closed loop geothermal developments in Newcastle and Gateshead

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The potential for geothermal energy across the Northeast of England has been investigated since the 1970s. Over the past two decades work led by Newcastle University and Durham University furthered earlier exploration work, through the drilling of the Eastgate Geothermal Exploration Borehole in 2004 and the Newcastle Science Central Deep Geothermal Borehole in 2010. The work presented here updates our understanding of geothermal potential in the region by using publicly available geological data to model two conceptual deep geothermal developments with a focus on quantifying the effect of geological uncertainty on the recoverable heat.

In this study, we estimate the potential geothermal production at two notional sites, one in Newcastle city centre and one in Gateshead. The modelling considers two alternative development concepts at each site with a minimum 30 year design life: a conventional open loop doublet system, targeting the Fell Sandstone at ~1km depth, and a closed loop coaxial deep borehole heat exchanger (DBHE), of 2km and 5km depths. Recent semi-analytical solutions (Mijnlieff et al, 2014; Beier, 2020) are implemented and used to estimate an indicative geothermal power available from each development concept. The model parameters are obtained from nearby offset geological data from across the region. These data sources are not site-specific, and a high degree of uncertainty surrounds several key geological parameters. In view of this, we investigate the impact of geological uncertainties on the recoverable geothermal heat by using a probabilistic approach in which the uncertain parameters are represented as random variables and then propagated through the models. We use a smoothed triangular distribution to quantify the sources of uncertainty and Monte Carlo simulation with Latin Hypercube sampling to characterise the distribution of the model response. We also conduct a global sensitivity analysis by computing the Sobol' indices from the coefficients of a polynomial chaos surrogate model.

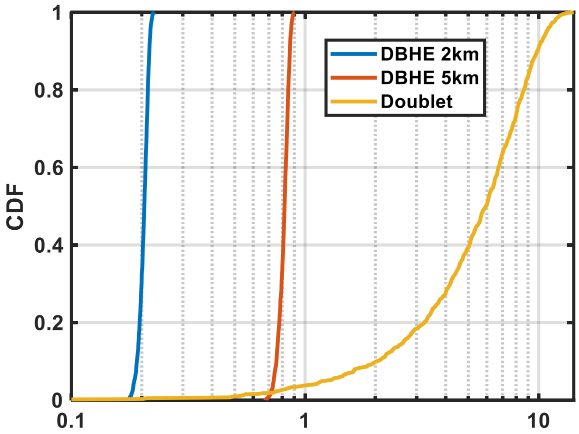

Figure 3. CDFs of geothermal power at Newcastle site.

The cumulative distribution function (CDF) of the geothermal power is shown in Figure 1 for the Newcastle site. A doublet system could potentially produce between 2.03 (10th percentile) and 9.89 MW (90th percentile). In contrast, for a DBHE production is between 0.191 and 0.216 MW for a 2km deep borehole and between 0.754 and 0.861 MW for a 5km deep borehole. Similar findings were observed for the Gateshead site. The doublet system has the potential to provide more power but is also subject to significant uncertainty. The sensitivity analysis shows that permeability is the most influential factor on the extractable power, explaining ~80% of the variance, but currently only limited data on the permeability of the Fell Sandstone is available. The DBHE power is controlled by the geothermal gradient and, to a lesser extent, the rock thermal conductivity. It should be noted that we have limited our investigation to the geological parameters and an expanded study should also consider well design and construction.

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Session Twelve: Modelling of Geothermal Systems, and Overviews of UK Geothermal

The optimisation and sensitivity of coaxial heat exchangers (Oral Presentation)

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With the goal of net-zero carbon emissions a global target more work is been put into geothermal as a way to facilitate the decarbonisation of power and heat. The drilling of the deep geothermal wells needed to provide sufficient temperatures to generate power are often associated with high cost and risk. One way to reduce this risk is to prepare for the possibility that the well is dry and other alternatives may need to be used to extract usable heat from the sub surface. A coaxial borehole heat exchanger is one such way to do this. These systems can be easily retrofitted into existing failed or decommissioned wells allowing for what once may have been considered a liability into a useful asset with the ability to deliver low carbon heat for many years to come.

This study investigates the effects of well construction and completion material choice on the performance of a theoretical 4000 m deep coaxial heat exchanger hosted within granite with a geothermal gradient of 38.7 °C/km.

Simulation of various casing materials and cement thermal conductivities has shown that while the casing has no real impact on system performance the type of cement used can vary outlet temperatures by over 9 °C (Figure 1) and well power by 400 kW. This influence can be leveraged to tailor the system based on the expected injection temperature. At low injection temperatures best performance is achieved by utilising a cement with a high thermal conductivity for the entire wellbore. However, for a high temperature injection, gains in well power of over 100 % and 3 °C at the outlet are possible by insulating the upper sections of the wellbore.

Dependant on the thermal conductivity of the riser a low flow rate may not give the highest outlet temperatures. In this theoretical study a high-density polyethylene (HDPE) riser delivered its maximum outlet temperature of 43 °C at 5 L/s while a riser constructed from vacuum insulated tubing (VIT) was able to deliver its peak outlet temperature of 90 °C at 1 L/s suggesting that the VIT riser is far superior to the HDPE equivalent. However, at high flow rates both examples operate within 2 °C at the outlet making them far more comparable in this scenario (Figure 2).

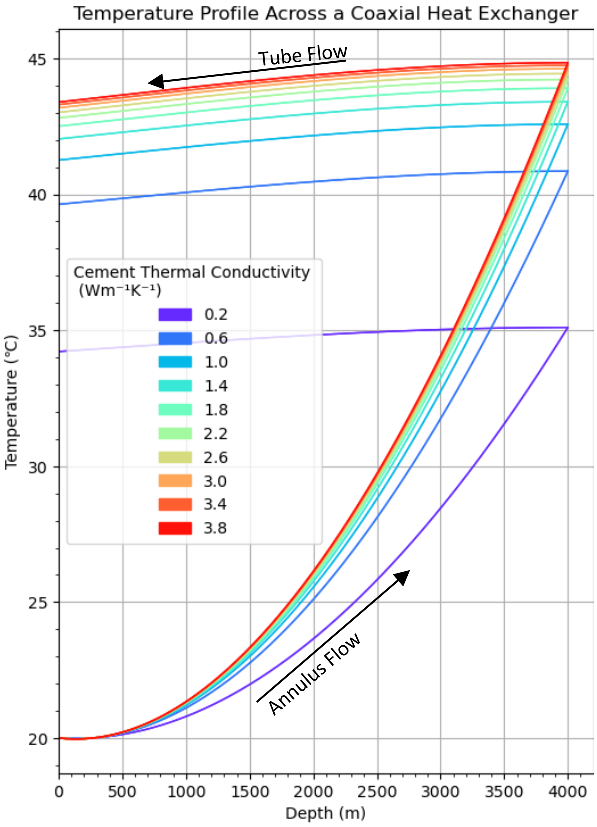

Figure 4: *The affects of varying cement thermal conductivity on temperature distribution within the wellbore after one year's run time.*

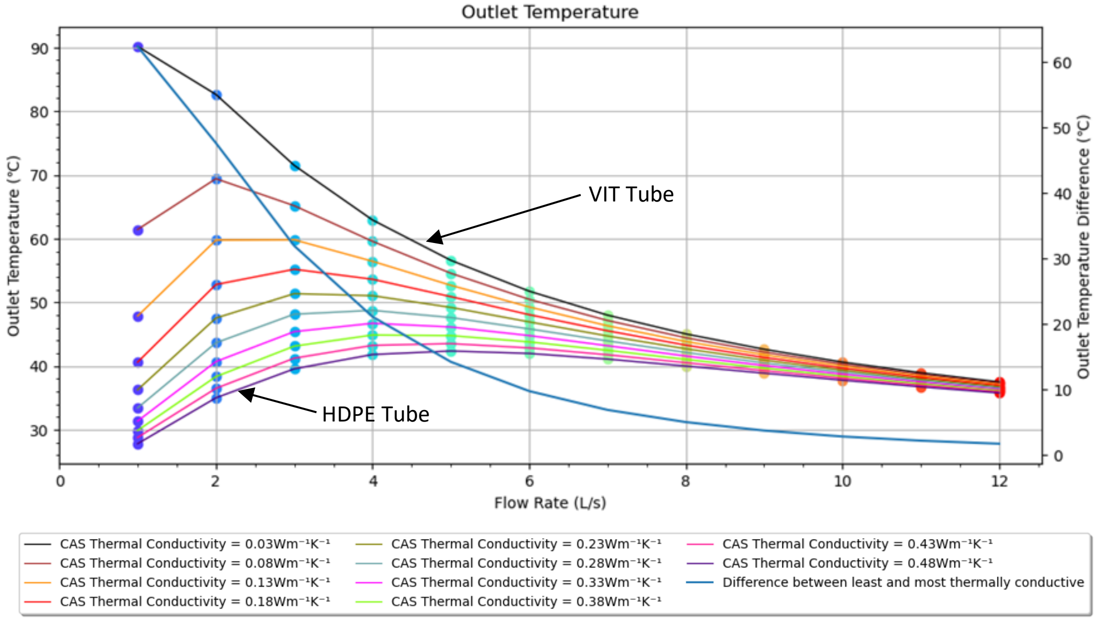

Figure 5: The affects of flow rate and tube (CAS) thermal conductivity on the outlet temperature for a 20 °C injection

While this study may be purely theoretical it comes at a time where deep coaxial systems in the United Kingdom are becoming more common with the recent commissioning of EG-1 coaxial heat exchanger at the Eden Project and the installation and testing of a coaxial heat exchanger by CeriPhi Energy into Third Energy's decommissioned KM8 gas fracking well in Ryedale, North Yorkshire. With systems of these depths greater than 2500 m, it is crucial to fully understand the systems end use case before completing its specification. A system designed to operate its whole life at high flow rates around 10 L/s is far less sensitive to material changes than one deigned to operate at flow rates down to 1 L/s depending on demand.

Repurposing a Geothermal Exploration Well as a Deep Borehole Heat Exchanger: Updates from the NetZero GeoRDIE Project

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The Newcastle Science Central Deep Geothermal Borehole (NSCDGB) was drilled to 1821 m between 2011 and 2014, targeting the Mississippian Fell Sandstone Formation as a conventional geothermal resource. Unfortunately, the formation was tight and the wellbore encountered low hydraulic conductivity values of 8.1×10^{-10} m/s, preventing development and exploitation (Younger et al., 2016). The NetZero GeoRDIE project investigates the potential to repurpose the NSCDGB as a closed-loop system with the intent of extracting heat from an otherwise unused asset. The project analyses i) the impact of uncertainty in the subsurface through detailed numerical modelling of a coaxial deep borehole heat exchanger (DBHE) on heat abstraction, ii) the capability of the wellbore to provide heating through thermal response testing and monitoring, and iii) the integration of the DBHE to either a heat network or adjacent buildings.

Transient analysis of the subsurface has been undertaken using both numerical and analytical solutions to quantify: how much heat can be extracted, the potential to use the DBHE for underground thermal energy storage, performance under varying methods of operation (i.e., constant heat load, variable heat load) and uncertainty in the subsurface. Results indicate that the borehole repurposed to a depth of ~920 m, with a ground thermal conductivity of 2.55 W/(m.K), can be operated sustainably with thermal extraction rates of 50 kW (flow rate of 5 L/s) for 25 years, supplying a building load of 65 kW after passing through a heat pump (Kolo et al., 2023). Under varying methods of operation, the rate of heat extraction can be improved with short periods of heat reinjection, or if intermittent operation is applied (Brown et al., 2023a,b). Geological variations in the subsurface also impact performance, particularly the natural geothermal gradient, or rock thermal conductivity; however, groundwater flow has a minor impact on heat extraction unless Darcy velocities exceed c. 1×10^{-6} m/s (Brown et al., 2023c). Further uncertainty analysis has also been considered to quantify the effect of spatial variability in the subsurface by using surrogate models and stochastic simulations.

At present, the repurposing of the wellbore to recomplete as a coaxial DBHE and undertake a thermal response test is in planning and will hopefully be complete by 2024. This will allow us to measure the in-situ properties of rocks at depth (i.e., thermal conductivity) and the effective borehole thermal resistance. These will allow better estimates on the amount of heat that can be recovered, and allow the calibration of models against empirical data.

Subsurface data can then be integrated to building energy simulation models of the Urban Science Building, which is derived from monitored data of over 4000 sensors. Building energy simulation models are used in predicting heat load under varying global warming scenarios, whilst also allowing thermal comfort and temperature setback strategies to reduce heat demand and CO_2 emissions. Initial uncalibrated numerical models have been used to match demand with geothermal energy supply, highlighting that a DBHE is better suited to meeting a constant base load of energy, rather than a variable heat load. This is because conduction is the dominant method of heat transfer and thus heat cannot be extracted quickly enough to meet the surges in demand in winter for the variable load (Ben et al., 2023).

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POSTER ABSTRACTS

UK geothermal data, maps, products and tools: plans and your views

Alison Monaghan, *BGS*

Pending

Improvement of Thermal Efficiency of Energy Piles by a Novel Approach Using Integrated Numerical, Experimental and Digital Tools

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One of the major challenges of our generation is the rapid increase in energy demand and rising energy costs on a global scale. Unfortunately, to meet these demands, there is still a significant reliable on energy generation using fossil fuels resulting in increased carbon emissions and adverse impact on the plant. Furthermore, to achieve 2050 net zero vision on a global scale, a strategy is needed to ensure a sustainable transition to renewable energy sources to allow natural recovery of renewable sources and safeguarding the future. Recent studies have shown potential or current adverse impacts of climate change on the leading renewable energy sources (hydropower, wind, solar)[1]. New research suggests that changes to regional climates caused by climate change could adversely impact zones currently considered idea for solar power production less viable in the future[2]. Similarly, climate change can impact wind circulation patterns on a global scale resulting in reduction of energy generation by wind power[3]. Furthermore, significant effects are expected on production of energy by hydropower due to change in precipitation, temperature and enlarged erosion[4]. Although geothermal resources are practically independent of climate factors, these factors may potentially impact the use of Earthw's natural heat sources[5], to date, no studies has proven similar scale of adverse impacts of climate change compared to solar, wind and hydropower.

Geothermal sources of energy production are available in all geographical locations usually at shallow depths. This source of energy is available 24/7 and 365 days. However, compared to solar, wind and hydropower, less contributions are provided to development of geothermal energy production compared to global market. Geothermal energy is a sustainable energy source that allows using shallow depths of Earth's crust to transfer heat for cooling and heating of infrastructure. Ground Heat Systems are categorised into two main categories based on the system design: open-loop systems and closed loop systems. Energy piles are dual purposetype of geothermal energy capable of structural load bearing and energy generation for heating and cooling. These particular type of geothermal energies are particularly popular due to reduced costs of drilling and land usage compared to other ground heat exchangers.

Studies conducted to understand the short-term and long-term studies of behaviour of energy piles is divided into 2 categories: Thermo-hydro-mechanical behaviour and Thermal Performance. This study focuses on improvement of thermal efficiency of energy piles by proposing an integrated novel approach using numerical, experimental, and a digital twin.

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Quantifying the Impacts of Faults and Dykes on Fluid Flow in Northern Ireland Permo-Triassic Reservoirs and Aquifers

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Building on a national-scale understanding of the distribution of faults and dykes 1,2,3, this work aims to assess their impact on Northern Ireland Permo-Triassic and other key reservoirs and aquifers. Structural and architectural data is being gathered to gauge how faults and dykes influence fluid flow. An immediate application of this work is that conceptual models can now include measured fault and dyke attributes, eg key orientations, average spacings, segments lengths, dyke thicknesses and gaps. Such information is helping to define compartment dimensions and connectivity which aids the development of realistic 3D and 4D flow models required for future geothermal, energy storage and groundwater applications.

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tanuki™/PyFDEM: a Toolkit for the Permeability Enhancement Optimisation of Geothermal Wells

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Permeability enhancement optimization holds pivotal significance for geothermal wells as it directly influences the efficiency, sustainability, and economic viability of geothermal energy extraction. By fine-tuning the permeability of reservoir formations through techniques such as hydraulic fracturing, chemical stimulation, or thermal treatments, geothermal wells can significantly augment fluid flow rates, heat transfer capabilities, and overall reservoir productivity. This optimization ensures optimal utilization of the Earth's geothermal resources, leading to heightened energy generation, extended well lifespans, and reduced operational costs, and ultimately accelerating the transition towards a greener and more resource-efficient energy landscape.

There is currently no computational software offering high-fidelity simulation of discrete fracture for geothermal wells: it is crucial for the cost effectiveness of geothermal energy that companies in the sector are able to perform permeability enhancement optimization and predict fracture behaviour at different stages of the lifetime of a geothermal well. Tanuki Technologies is at the forefront of the development of advanced computational tools to allow UK companies in the geothermal energy extractor sector to significantly reduce costs and emissions.

Tanuki Technologies is developing an advanced computational mechanics toolset for engineering and research. tanuki (http://tanuki.ai/discover) is a toolset for engineering and research powered by state-of-the-art technology in computational mechanics, meant to be employed by companies and researchers in the energy sector to allow sustainable energy production and green infrastructure. tanuki will bring to the market state-of-the-art computational technology, in particular the finite-discrete element method [1]–[5] for multi-body and fully coupled multi-scale simulations.

This presentation will focus mainly on the computational aspects of the software currently being developed at Tanuki (tanuki™/PyFDEM), and in particular on the challenges of modelling fracture propagation in rocks for different in situ conditions and fluid flow in porous media. We will also discuss case studies of application to geothermal wells.

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Understanding Lithosphere-Asthenosphere Dynamics to Improve Geothermal Prospectivity Mapping.

Megan Holdt and Nicky White

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Most geothermal energy is produced in specific geological settings (e.g., subduction zones, mid-oceanic ridges and ocean hotspots). These regions are prospective for geothermal as they are all associated with elevated heat flow. To increase the proportion of geothermal energy produced globally, it is essential to improve our understanding of geothermal prospectivity in regions that are not traditionally explored. An important component of de-risking geothermal is developing an accurate prediction of subsurface heat flow. In this study, we investigate the relationship between heat flow, asthenospheric mantle anomalies, dynamic topography and lithospheric thickness. This study demonstrates that high heat flow is associated with elevated mantle temperatures, positive dynamic topography, youthful volcanism, and thin lithosphere. Our results suggest that the long-wavelength component of heat flow is significantly influenced by mantle-convective processes. We explore the potential for observational measurements of dynamic topography, seismic tomographic models, the distribution of volcanism, and calculations of lithospheric thickness to predict heat flow in the absence of direct measurements. Finally, we show how these datasets will be used in Project InnerSpace's global geothermal resource mapping initiative to improve our understanding of geothermal prospectivity on a global scale.

Presentation: Lithium extraction from geothermal waters in Southwest England

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Lithium is the lightest solid metal and is abundantly available in the earth's crust. Lithium is the ideal element to use as a cathode as it has a very low electrochemical potential. It can donate an electron very easily and therefore transfer charge.

Lithium is predominantly produced from two main sources: Hard-rock deposits and lithium rich brine deposits. Approximately 65% of lithium is sourced from hard rock, predominantly from Australia and China. This is followed with` approximately 30% sourced from continental brines from Chile and Argentina.

Brines in south America are produced from Salars. These are vast facilities where brine is pumped from shallow aquifers into large ponds on surface where evaporation takes place. Once the water evaporates, a lithium rich mineral salt is left behind which can be further refined into battery grade products. Salar lithium production does however have significant drawbacks which include, large land area usage, significant water usage, minimum 18-month cycle times and are highly dependent on climatic conditions.

To overcome the issues Salars face, a technique called Direct Lithium Extraction (DLE) has been developed by various companies. These various technologies aim to extract lithium dissolved in the water to produce an enriched and purer solution. Meanwhile vastly improving on efficiency, waste, speed, and land use compared to Salars. DLE technologies consist primarily of Adsorption, Ion Exchange and Membrane technologies to selectively extract Lithium Ions. Innovative technologies such as DLE will be solution for viable mineral extraction from Geothermal waters such as those being explored by Cornish Lithium.

In the highly competitive and emerging market of DLE, there is no 'one size fits all' solution. Cornish Lithium are testing various company's DLE technology to determine which performs the best with Cornish Geothermal waters. In 2022 Cornish Lithium set out to build the UK's first DLE pilot plant to test the technology. This allowed us to upscale from off-site, small-scale lab tests to a larger real-world system located on our sites.

To achieve this, the pilot plant was built in shipping containers to separate the supporting, ancillary equipment from the DLE skid allowing it to be easily modified or replaced.

The pilot plant was successfully commissioned in March 2022 with Cornish Lithium's first DLE partner, Geolith, to test their Lithium selective ion exchange system: Li-Capt®. The technology, developed in France, was tested for several months before modifying the plant for an adsorption-based process supplied by SENFI, a subsidiary of Thai chemical company, SCG. Cornish Lithium are now in the process of trialling Koch Industries' two step Lithium Sorption and Ion Exchange system to assess its performance and suitability with Cornish waters.

Besides DLE, many other processes are required to transform raw brine into a saleable lithium product. Cornish Lithium are testing other pre-treatment and post treatment processes at pilot scale alongside DLE. This will allow us to build unified flowsheet for future plants. These other processes include techniques such as filtration, chemical dosing & precipitation, reverse osmosis (RO), and membrane distillation (MD). Concentration technologies such as RO and MD are essential for commercialising a DLE plant for pre and post concentration of the Lithium bearing solutions.

Looking ahead, Cornish Lithium will build a demonstration scale DLE plant to incorporate all pre-treatment, DLE and post treatment processes in one plant. This plant will be located be in the vicinity of a geothermal well allowing immediate processing of Geothermal water. A second well would be located on site for responsible disposal of the Lithium depleted water. Cornish Lithium aim to produce a saleable lithium concentrate solution from a demonstration plant by 2026.

Unlocking Geothermal Energy: Recent Developments in Puga Valley and the Global Call for Advocacy

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Geothermal energy, a promising and sustainable power source, is gaining prominence in India, with the potential to make a significant global impact. This poster explores the recent geological developments in geothermal energy prospects in Puga Valley, situated in the Ladakh region of India, and underscores the urgent need for global advocacy.

While India's geothermal power generation is still in its nascent stages, the Geological Survey of India (GSI) has identified around 340 geothermal hot springs across the country. Many of these springs offer suitable conditions for direct heat applications, aligning with India's push for eco-friendly and cost-effective energy solutions. These geothermal resources are categorized into seven geothermal provinces, including the promising Puga Valley in Jammu and Kashmir.

Puga Valley, nestled in the Himalayan geothermal belt, displays compelling evidence of geothermal activity, boasting hot springs, mud pools, and deposits of sulfur and borax. However, tapping into this potential requires concerted efforts and collaboration. The exploration costs for geothermal energy remain a challenge, necessitating innovative approaches to make it economically viable.

In this context, global alliances and research collaborations play a pivotal role. The ONGC (Oil and Natural Gas Corporation) and its partnership with Iceland Geothermal (ISOR) exemplify the potential for game-changing collaborations in this field. Such initiatives bridge the gap between exploration and implementation, paving the way for sustainable geothermal projects.

The poster also highlights the broader significance of geothermal energy in the context of global energy policies, with a particular emphasis on the G20 nations. India's commitment to harnessing geothermal power aligns with the G20's clean energy initiatives, reinforcing the country's role in the global transition to cleaner and more sustainable energy sources.

In conclusion, the poster underscores the immense geothermal potential within Puga Valley, Ladakh, as a critical step towards achieving India's renewable energy goals. A detailed literature review has been done to bring out the synergy of recent developments, global advocacy, and collaborative efforts Geothermal energy being a viable and impactful contributor to India’s energy landscape and the global fight against climate change, Puga Valley holds a geopolitical stance requiring scientific collaborations for improvised geothermal policy frameworks.

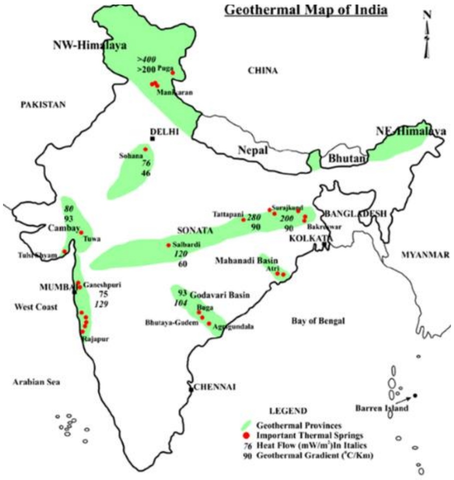
Keywords: Geothermal Energy, Puga Valley, Global Advocacy, Geological Survey of India, Sustainable Energy, ONGC, Iceland Geothermal (ISOR), G20 Clean Energy Initiatives

Approximate expanse of the main valley hot springs

lying south of Indus Suture Zone with visible borax deposits. Created with Google Earth Pro

Geothermal spring, fountain. Image courtesy: Google Earth

Braided streams can be observed within Puga Valley, which eventually join river Indus beyond Sumdo, Image courtesy: Google Earth



Geothermal Map of India details important geothermal springs, Puga being the oldest, undergoing research and prospected for the first few thousand meters.

Map by Singh et al. (2016). Potential Geothermal Energy Resources of India: A Review. Current Sustainable/Renewable Energy Reports. 3. 10.1007/s40518-016-0054-0.

Geology of Subsurface – Application to geothermal and CCS Exploration

Johansson, M. Farag, S. Phillips, J. van Doorn , J & Roberts. I

Fractures are present in most rocks and are a result of brittle failure under stress. Fractures are characterised as more or less planar features, whether diffuse and strata bound, clustered in fracture swarms or associated with a fault or fold system. The key descriptive characteristics of a subsurface fracture are the depth, density, strike orientation and aperture. Those fractures with an aperture ranging from micron to centimetre in width are currently beyond the resolution of most subsurface borehole logging tools, however a large data contrast or a tight cluster of fractures can influence the tool readings. These measurements derived from a variety of sources and tool types are acquired through the process of geological, geophysical, drilling, petrophysical and production data acquisition and it is often anomalous data readings that are symptomatic of fractures. In order to identify the geology of fractures in the subsurface, an ensemble of supporting evidence is accrued through the life cycle of a borehole. Advanced measurements and methodologies for fracture characterisation developed for Oil and Gas exploration exist and similar methodology can be applied to the currently developing geothermal and the CCS industry.

The United Downs project: geothermal electricity, heat and critical raw materials

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The United Downs deep geothermal project, developed by Geothermal Engineering Ltd (GEL), is the UK's first geothermal electricity project. The geothermal doublet was drilled and tested throughout 2018-2021, including a production well (UD-1) to 5,275 m MD, the deepest onshore well in the UK, and an injection well (UD-2) to 2,393 m MD. The bottomhole temperature was more than 180°C and the production fluid has high concentrations of lithium (more than 270ppm). The power plant for the project is currently being assembled and will switch on in Q4 2024.

Further to proving that geothermal electricity is possible in the UK, the project will also deliver 100% of its available heat to the UK's first net zero housing development, Langarth Garden Village. This will be over 3,500 homes. The heat network has been backed by the Department for Energy Security and Net Zero with funding of £22m. Over the past two years GEL has also been working with European partners via the Horizon scheme to investigate the potential for producing critical raw materials from the geothermal fluid. This has resulted in the company being backed by the Automotive Transformation Fund (£1.8m grant) to install a pilot lithium extraction plant at United Downs to produce circa 100 tonnes per annum of lithium carbonate equivalent. This will also switch on in Q4 2024 and will be demonstrate the potential to produce zero carbon lithium in the UK.

The United Downs project is a demonstration of how the UK could harness geothermal energy to provide multiple green, sustainable resources. GEL is now backed by Thrive Renewables plc and recently (March '23) Kerogen Capital and will expand to other projects based on the United Downs model.

Repurposing Disused Coal Mines for Geothermal Heat Networks: Towards an Environmental and Social Sustainable Solution

Jingyi Li, *University of Manchester*

Pending

Regulating the environmental impacts of geothermal energy

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Geothermal energy is underutilised in the UK and a significant reason for this is the lack of a clear regulatory framework for addressing the environmental impacts. This presentation will identify the key environmental risks relating to the extraction and use of deep geothermal energy. It will then examine if, how and to what extent there is regulation in place to address those risks. It will then make a number of recommendations for strengthening the regulation of deep geothermal energy and discuss the regulatory reforms needed to implement those recommendations.

The drilling and construction of deep geothermal operations can result in a number of adverse impacts in relation to noise, alterations to the soil, contamination of groundwater, habitat disturbance, and visual impact. Once operational, there are continuing risks relating to noise and air pollution, adverse impacts on groundwater, and visual impact. Open-loop deep geothermal operations carry a number of additional risks relating to the overabstraction of groundwater, subsidence, and the release of potentially harmful matter found in deep geothermal water into the ground.

There is no bespoke regime for the regulation of deep geothermal energy and it is instead regulated through a number of regulatory regimes, including those relating to the extraction and discharge of water, town and country planning, and health and safety. Open-loop geothermal operations will need a licence from the Environment Agency to abstract water from the ground and an environmental permit from the Environment Agency to discharge geothermal water back into the ground. The Environment Agency can therefore regulate the amount of water abstracted from the ground and prevent overabstraction. It can also, through the use of licence and permit conditions, require measures to be taken to address the wider environmental risks of the operation. Closed-loop geothermal operations do not involve the abstraction of water and therefore do not require an abstraction licence. Neither do they currently require an environmental permit. Closed-loop geothermal energy operations are therefore not currently within the regulatory remit of the Environment Agency, although changes to the environmental permitting regime due to take effect in October 2023 will bring those operations where there is a risk of heat pollution to the ground within the regime, potentially significantly increasing the Environment Agency’s regulatory powers in relation to closed-loop geothermal operations.

Planning permission is required for deep geothermal operations and any associated buildings and infrastructure. Local planning authorities therefore have the opportunity to take account of the potential environmental impacts of a proposed operation before deciding whether it should be given permission to go ahead, as well as the ability to make planning permission conditional upon meeting such requirements as they consider necessary to address the environmental risks. The requirement for an environmental risk assessment in relation to those operations that pose a higher risk to the environment helps ensure that local planning authorities have all the relevant information before them when making their decision in relation to higher risk deep geothermal operations. However, local planning authorities also have to take account of a range of other, including social and economic interests, and are not required to prioritise environmental protection over other interests. Furthermore, different local authorities can take different approaches, leading to inconsistency in decision-making and the amount of environmental protection provided.

Geothermal operations will also need to comply with the applicable health and safety legislation. This legislation can help to minimise the environmental risks of goethermal operations, for example by ensuring the integrity of equipment used, but its purpose is to protect workers and the public rather than the environment. Furthermore, the detailed health and safety regulations relating to boreholes, wells, drilling, and pipelines were introduced to address the risks associated with petroleum operations and have very limited application to geothermal operations.

It can therefore be concluded that the regulation of deep geothermal energy is piecemeal and it is questionable whether it adequately addresses the environmental risks of operations for its extraction and use, particularly in relation to closed-loop geothermal operations. Whilst there is an argument for large scale regulatory reform and the introduction of a new, independent geothermal regulator responsible for licensing all geothermal operations, the anticipated uptake of geothermal energy may not justify this, and it may be that the approaching extension of the environmental permitting regime to cover closed-loop as well as open-loop deep geothermal operations will be sufficient to address the environmental risks, at least until the industry is more established.

Scope of Subsurface Geological Studies for Geothermal Investigation in Shyok-Nubra Valley, Ladakh Himalaya

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Geothermal energy is a renewable and environmentally friendly form of energy that has the potential to contribute an imperative role in fulfilling the world's expanding requirement for energy. The Ladakh Himalayan region of the Shyok-Nubra Valley is distinguished by its distinctive geological setting and is thought to be a desirable location for geothermal study. This abstract aims to assess the feasibility of conducting subsurface geological studies for geothermal investigation in the Shyok-Nubra Valley.

The Shyok-Nubra Valley, situated in the Northern Region of India, falls under the Trans-Himalayan belt, known for its diverse geological formations represents a dynamic environment where continuous tectonics has influenced the landscape, geologic and geomorphic processes. This region has significant geothermal potential due to its tectonic setting, which is influenced by the collision of the plates. The presence of active faults, hot springs, and elevated heat flow values suggests the existence of geothermal reservoirs beneath the surface. However, detailed subsurface geological studies are required to fully comprehend the geothermal resources of the area and assess their viability.

The Ladakh Himalaya is known for its complex geological terrain, including sedimentary, metamorphic, and igneous rocks. The Shyok-Nubra area is situated between the Indus Suture and the Shyok Suture, relics of the collision between the Indian and Eurasian plates. The valley is divided into two parts: the NW-SE-trending Shyok Valley and the NS Nubra Valley. Both valleys exhibit distinct structural control, associated with the Karakoram Fault and the Shyok Suture Zone. The Shyok-Nubra Valley and surrounding Karakoram landscapes are tectonically active, with sedimentary, metamorphic, and magmatic rocks remnants of an accretionary complex. Quaternary deposits, including alluvium, glacial and fluvioglacial sediments, lacustrine sediments, and debris accumulations, cover the basement rocks. The existence of fault systems may allow geothermal fluids to move to the surface.

In this area several geothermal indicators are present which signifying the potential existence of geothermal reservoirs. These indicators include the presence of hot springs, high heat flow values, and geological evidence of hydrothermal alteration in rocks, hydrothermal deposits etc. Hot springs, such as the Pulthang, Tirisha, Panamik and Chumathang are known for their high-temperature discharges, and chemical analysis of their waters provides valuable information about the geothermal system. Currently, these reported prospective geothermal regions are just being investigated using surface geothermal indicators and surface geology only.

Therefore, there is ample opportunity to test the viability of a subsurface geological exploration for geothermal purposes in the study area. It aims to determine the presence, size, temperature, and permeability of geothermal reservoirs that can be tapped to generate renewable energy. These Subsurface Geological Investigation may include **(I)** *Geophysical* *surveys*, which play a crucial role in assessing the subsurface geology and identifying potential geothermal reservoirs. Techniques like Magnetotelluric (MT), electrical resistivity imaging (ERI), Gravity, and Seismic surveys are commonly employed in geothermal exploration. MT surveys are particularly useful in mapping the electrical resistivity structure of the subsurface, which can delineate potential geothermal reservoirs. Gravity surveys can help identify subsurface density variations related to geothermal features, while seismic surveys can provide information about subsurface structural settings. These geophysical methods aid in delineating the subsurface structure and identifying potential reservoir zones with enhanced fluid saturation. **(II)** *Drilling, Logging and Well Testing*: Exploratory drilling is a crucial step in geothermal exploration to confirm the presence of geothermal reservoirs and assess their productivity. Once potential geothermal reservoirs are identified through geological and geophysical methods, exploration wells are drilled to investigate subsurface conditions and collect rock and fluid samples. Logging tools can be lowered into the boreholes to measure physical properties, such as temperature, pressure, porosity, and permeability. These data are crucial for understanding the geothermal system's characteristics and its potential for power generation.

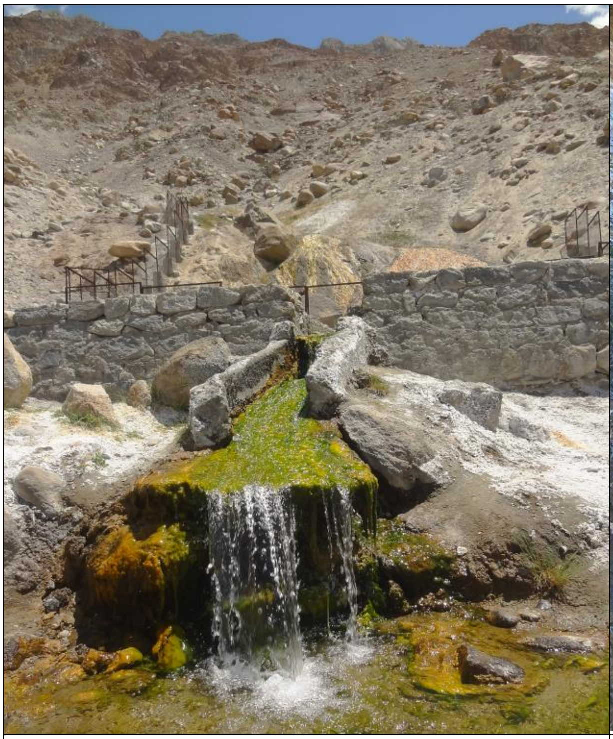

Photo: 1 Hot Springs emerging from Karakoram Granitoids at Panamik, Nubra Valley, Ladakh, India.

Photo: 2 Geothermal manifestations at Changlung, Nubra Valley, Ladakh, India.

(III) *Geochemical Analysis of subsurface fluids*: Geochemical analysis of fluid samples obtained from the wells helps in understanding the reservoir's chemical composition and thermal maturity. Geochemical data can reveal the source of the geothermal fluids, the reservoir temperature, and the presence of potential indicators of a geothermal resource. **(IV)** *Reservoir Modeling*: Subsurface data collected from wells and geophysical surveys are used to construct a three-dimensional model of the geothermal reservoir. Reservoir modeling involves integrating geological, geophysical, and geochemical data to estimate the size, temperature distribution, and productivity of the reservoir. **(V)** *Geothermal Resource Assessment*: Based on the information gathered from the subsurface study and reservoir modeling, a geothermal resource assessment is performed. This assessment estimates the

potential energy capacity and economic viability of the geothermal resource and finally, **(VI)** *Monitoring and Evaluation*: After the exploration phase, ongoing monitoring of the geothermal reservoir is essential to track changes in its behaviour and productivity over time. This monitoring helps in optimizing the geothermal power plant's performance and ensuring sustainable production.

Subsurface geological studies for geothermal investigation should consider global relevance, case studies, and environmental impacts. These proposed studies can provide insights into the feasibility and viability of geothermal resources in a promising geological setting. A systematic approach, considering environmental considerations, is essential for sustainable geothermal development in the region.

Key words: Subsurface Geological Studies, Geothermal Exploration, Shyok-Nubra Valley, Geophysical survey.

Scalability and geomechanical influence on structurally-controlled fluid flow in Leeds, West Yorkshire.

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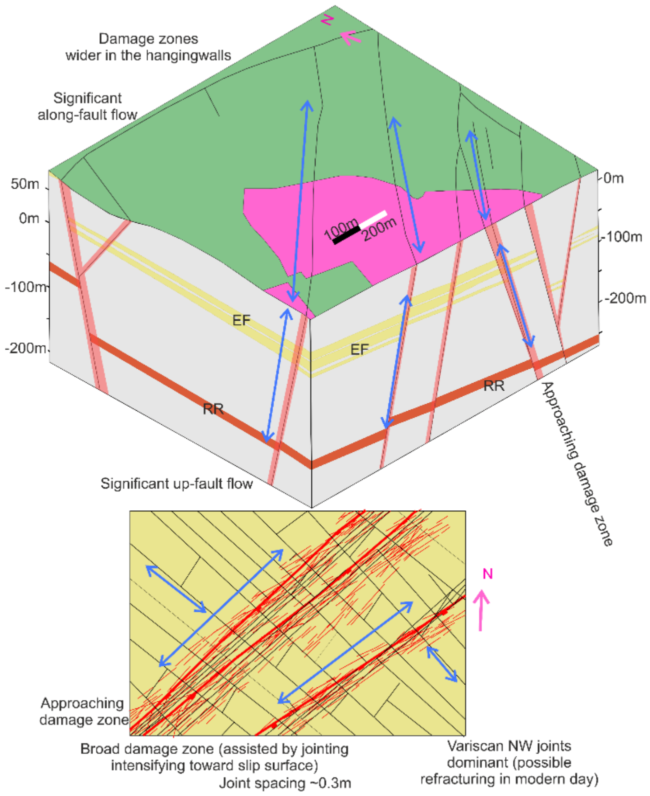
This study is a place-based investigation of structurally controlled fluid flow within the Elland flags using seismic survey and field site observations to ascertain scalability of flow and fracture networks and their geomechanical response. It represents part of the feasibility phase for a potential low enthalpy geothermal heat network for the University of Leeds.

At outcrop scale, local flow is dictated by joints, with intensity increasing towards faults even with low displacement. As they are stratabound, this would increase horizontal flow along fault within the unit, especially as shales have lower fracture density than the main sandstones. At seismic scale, power-law distributions in length frequency are apparent, within a context of segments above inherited structures, allowing greater potential for high strain zones at areas of interaction. Vertical along-fault flow will likely be limited to brecciated fault cores, while horizontal along-fault flow may be locally enhanced in the sandstone-hosted damage zones compared to shales.

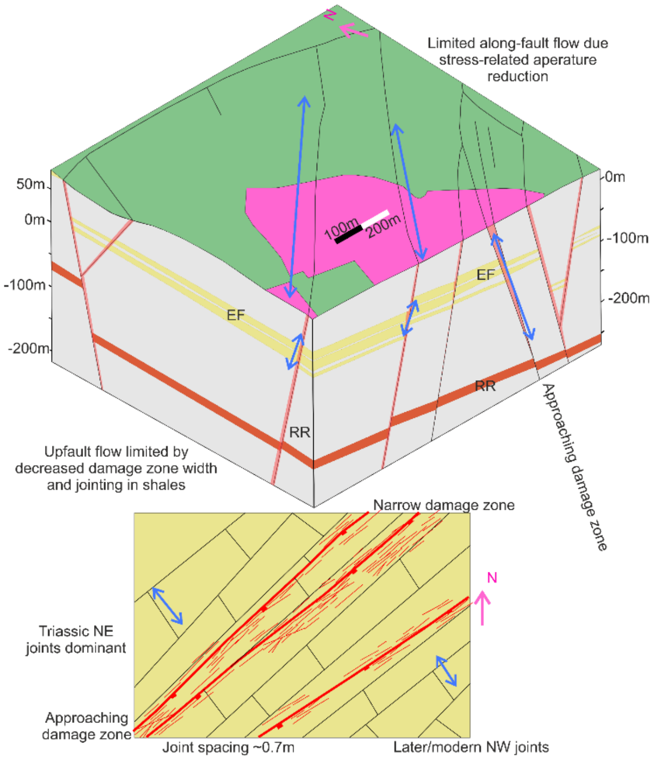
The common NE-trending faults along campus will either be neutral or conduits to flow depending on the effect of near surface stress perturbation. In both cases joint-associated flow will be the more sensitive to pressure changes than faults.

There are major uncertainties remaining, and further investigation is required into the interrelation of joint and faults, and quantifying the hydrology below University of Leeds campus to confirm the projections of this study.

High flow case



Low flow case



Geothermal Campus Leeds – shallow geothermal direct heat use in an urban environment

Authors: **Arka Dyuti Sarkar**[1],**[*]**, Joseph Kelly[1], Emma Bramham[1], Nicholas Shaw[1], David Barns[1], Fleur Loveridge[1], Chrysothemis Paraskevopolou[1], Simon Rees[1], James Van Alstine[1]
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Space heating generates 23% of UK carbon emissions and this must be addressed for the UK to meet its legally binding climate change commitments. The University of Leeds (UoL) is primarily heated through natural gas combustion via a traditional high-temperature heat network but has committed to fully decarbonise the campus by 2030. The University envisions the creation of a series of smaller low temperature heat networks, each with their own 'Energy Centre' supplied by heat pumps with the heat source a combination of air and geothermal, utilising the potential for warm aquifer fluid in the subsurface where available, and exploring the potential for heat storage and cooling as part of the solution.

There is potential for higher efficiency with geothermal compared to air sourced heat when used in the UK. Ground and groundwater geothermal offer a higher temperature than air sources in winter, resulting in a larger source to delivery temperature differential, hence driving lower electricity usage at the heat pump. Effective planning of multi-faceted energy source use within heat networks is therefore essential not only at a local level in terms of running costs, but also nationally in terms of reducing demand for valuable green electricity and ensuring the best and most efficient choices are made for supplying heat networks.

Understanding how the UK subsurface responds to extraction and storage of heat is pivotal to sustainable use of the subsurface for heat provision, storage and cooling. Yorkshire's geology offers a multitude of opportunities for multi-level geothermal energy and the subsurface of the UoL campus provides an ideal test environment. The impact of widespread faulting in the area presents a key pre-drill uncertainty for such projects. Leveraging the subsurface expertise within the Geosolutions group at the UoL, a phased development plan has been adopted with an initial six potential Energy Centre sites. Prior to drilling we have performed static subsurface modelling of the campus subsurface with reservoir properties estimated from field-based proxies, in order to investigate the viability of such a pre-drill model without using legacy data. Exposures of the target Carboniferous Elland Flags sandstone from quarries in the local area provided the analogues for fracture and fault modelling.

On-site infrastructure is planned around a 'living lab' with a matrix of monitoring and testing equipment to provide real time data output in the long term, thus enabling a fuller understanding of subsurface energy use on campus. Planned phase one infrastructure includes a pair of reversible injection and abstraction water wells targeting the Elland Flags aquifer (between 50 – 100 m depth); two deeper geophysical test wells and five thermal response boreholes, all permanently fitted with fibre optic monitoring equipment. The initial suite of geophysical test data, core samples, and experimental fibre optic monitoring equipment for thermal and elastic properties, will be contrasted against the pre-drill results of the initial field-data based static model to investigate the viability of a pre-drilling reservoir model for energy estimations.

This project approach provides a template for similar geothermal based heat networks, and as such the University of Leeds is collaborating with Leeds City Council to explore district heat networks adopting this methodology.

Coal Authority Mine Water Heat data

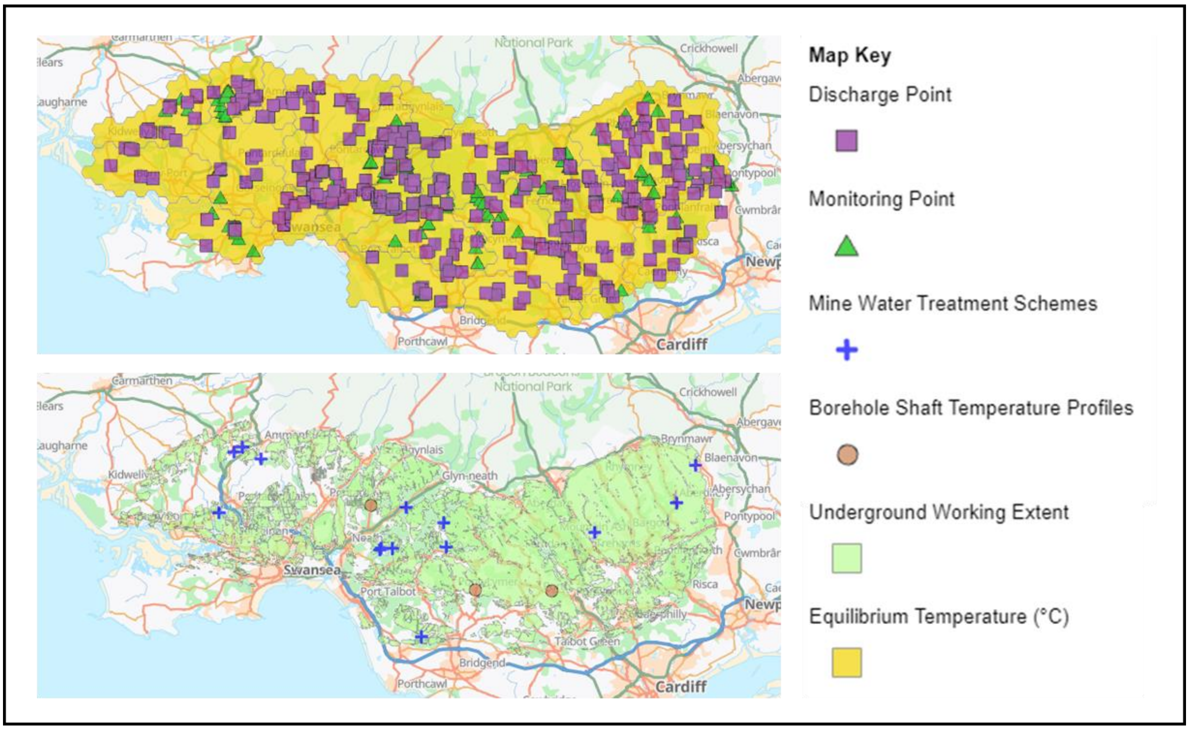
Fiona Todd
The Coal Authority, fionatodd@coal.gov.uk

The Coal Authority is the public body tasked with managing the legacy from Great Britain's coal mining past, making a better future for people and the environment in mining areas. We are seeking alternative ways to maximise low carbon opportunities from closed and disused mines and offset the costs of their ongoing management. Mine water heat and energy storage projects can provide low carbon, social and economic benefits to communities whose identity was built from coal.

The Coal Authority holds unique knowledge, assets and data but recognise that we don't have all the skills or direct influence to maximise the value this can generate. Our ambitious business plan for the next five years aims to make available our historical data assets so they can be used to support innovation and education and to develop a longer term plan to allow our data to be used by others to enable wider outcomes for businesses and communities.

To enable this, a new mine heat theme has been added to our online interactive viewer (https://mapapps2.bgs.ac.uk/coalauthority/home.html). This resource provides a number of different layers which are useful for assessing the initial feasibility of mine heating and cooling projects, including temperature data sets, locations of shaft profiles, monitoring points and discharges. The underlying data is currently available free of charge for academic purposes and under licence commercially.

This interactive poster will provide an overview of how to access the online viewer, which data sets are available and how to obtain the underlying data.



Integrated reservoir assessment of Middle Buntsandstein sandstones in West European Basins: Insights into diagenetic processes.

Husnain Yousaf [a], Gert Jan Weltje [a], Hannes Claes [a], Rudy Swennen [a]

[a] *Department of Earth and Environmental Science, Katholieke Universiteit Leuven, Belgium.*

Buntsandstein sandstones are important hydrocarbon, geothermal and gas storage reservoirs in Western Europe. Therefore, understanding the reservoir quality is of great importance also due to their complex local geological history. The purpose of this comparative study is to conduct a thorough examination of sedimentological, petrographical, and petrophysical data from four West European Basins: Gres Vosgien Basin (France), Trier Basin (Germany), Campine Basin (Belgium), and West Netherlands Basin (the Netherlands) to determine the geological factors influencing reservoir quality. Petrographical examination reveals a variety of mineral dissolution and/or precipitation phases. Grain size, clay content, cements, burial depth, and diagenetic fluid composition all affect the reservoir quality, which varies spatially within and across the basins. This study explores that diagenesis is an essential factor that is closely tied to depositional environment. Different bleaching processes corroborate the complex fluid-rock interactions and influence the reservoir quality accordingly. Medium to coarse grained fluvio-aeolian sandstones with low amount of diagenetic cements exhibit good reservoir quality. This research has important implications for characterization of geothermal and aquifer storage reservoirs as well as understanding the geological controls of sandstone reservoirs, deposited in similar geological settings.

Keywords: diagenesis, sandstone reservoirs, bleaching, fluid-rock interaction, geothermal and gas storage reservoirs

Empirical and simulated earth-friendly subsurface geothermal surveillance technology

G. Stove1, K. van den Doel1, R. Baria2, H. Glass3
1 Adrok, 2 EGS Energy, 3 University of Exter

The deep geothermal development at the Eden Geothermal site has shown that, without an appropriate geophysical survey to delineate the resource target (a fluid bearing fault), it is very risky and may dissuade further investment and thus deep geothermal development in Cornwall. It is therefore worth investigating techniques which can reduce such a risk.

There are a number of such techniques available which uses change in the electrical properties of the rock mass to delimited storage of fluid and fault associated with it such as MT, AMT, Adrok and others. The Electromagnetic (EM) technology that Adrok has been developing aims to locate sources of geothermal heat prior to drilling. Through empirical fieldwork, the EM technology can non-invasively provide a proxy temperature measurement of the subsurface without physical drilling. Key aspects of the technology have been field tested, including depth and capacity to identify water. Furthermore, simulated models have been developed for different European geothermal settings.

This EM technology is based on the principle that different materials will reflect and absorb electromagnetic radiation (radio waves) at specific frequencies and energy levels. The system transmits a pulse of electromagnetic energy containing a multispectral wave packet that resonates and reacts with the sub-surface materials. The reflections from the subsurface are recorded as a time domain trace and provide information about the location and composition of the materials encountered. Given that radiowaves are good at identifying conductive water layers, the hypothesis is that radiowaves (high frequency electromagnetics) should be able to pick out the conductivity associated with hot rock layers in the ground associated with deep aquifers.

The EM techniques merit further investigation to enable efficient and optimal exploration of the natural resources useful for geothermal energy generation.

Introduction

Prior to such investment in deep geothermal, it is a traditional practice on the European continent to carry out an appropriate geophysical survey to delineate the local geothermal resource/deep fault, taking into consideration the geology involved, the depth of investigation and the resolution required.

Historically, in Rhine Graben 3D normal incident seismic reflection survey has proved to be very successful in delimiting the characteristics of the resource/fault because the interface is granite and sandstone giving sufficient impedance contrast to delineate it.

In Cornwall, this interface may consist of granite and killas (the metamorphic rock) where the mechanical impedance contrast between the two-rock type is not large enough to give clear reflectors and thus make the delineation of the fault more difficult. An example of such an investigation was carried in late 1980’s where a 72 km normal incident seismic reflection survey was carried out in Cornwall to delineate faults suggested faults at around 6000 m depth. The survey was not successful as it did not reveal the presence of any such faults because of the lack of contrast between the suggested fault and surrounding rock. On the other hand, during the Hot Dry Rock Project development at the Rosemanowes site in 1980’s, seismic monitoring indicated that the hydraulic stimulation fluid left the bottom of the injection and migrated downwards contrary to predicted direction horizontally to the production well. An AMT/MT survey was carried out by the British Geological Survey which showed that this was the case and that the fluid did migrate downwards and was stored up to a km below the injection well. This phenomenon was caused by the deviation of stress with depth. This demonstrated that a method which uses contrast in conductivity is perhaps a more appropriate technique for location of fluid in the rock mass in Cornwall.

There are a number of such techniques available which uses variations in the electrical properties of the rock mass to delimited storage of fluid and fault associated with it such as MT, AMT, Adrok and others. Most electrical based technique require laying of extensive cables across fields and it can be anything up to a km long. The advantage with Adrok method is that it does not require long cables as it uses electromagnetic pulse to investigate the conductivity of the rock mass.

Method

The Atomic Dielectric Resonance (ADR) technology is based on the principle that different materials will reflect and absorb electromagnetic radiation (radio waves) at specific frequencies and energy levels. The ADR geophysical system transmits a pulse of electromagnetic energy containing a multispectral, patented (Stove G.C. et al, 2023) wave packet that resonates and reacts with the sub-surface materials. The reflections from the subsurface are recorded as a time domain trace and provide information about the location and composition of the materials encountered.

The ADR signal generator produces a pulse of electromagnetic energy (frequencies typically range between 1MHz to 70MHz) that is fed to the antenna and is transmitted into the ground. Once the signal has been sent to the transmitting antenna a signal is sent to the receiving control unit to synchronise collection of the subsurface reflected data, which is collected through the receiving antenna and then digitized. The transmitted pulse is depicted in Figures 1 and 2, where we also show the power spectrum (Stove & Doel, 2015). It is not the usual localized pulse with a single centre frequency but a more complicated waveform. The higher frequency components allow accurate localization at shallow depths, but attenuate rapidly in the ground, while the lowest frequency component around 3Mhz can penetrate much deeper. We thus combine the advantage of high spatial resolution at high frequencies with the advantage of greater depth penetration at low frequencies at the expense of requiring more sophisticated analysis (Doel et al., 2014).

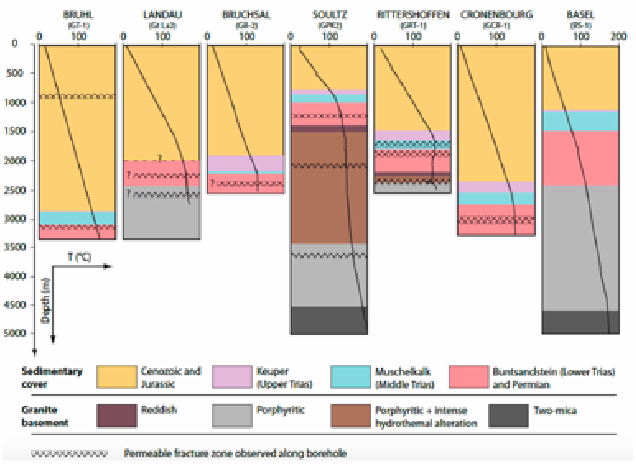
ADR is a time domain electromagnetic (TDEM) method but differs significantly from methods such as inductive polarization (IP) and resistivity methods. Those methods employ much lower frequencies and do not involve propagating waves but rely on measuring currents and polarizations induced by (relatively) slowly varying electric or magnetic fields. ADR on the other hand uses propagating wave packets and derives subsurface properties from the changes in spectral content and energy measured in the reflections. As such the data analysis resembles seismic methods more than the usual TDEM inversion techniques. However, ADR waves are electromagnetic which are governed by different physics than seismic pressure waves.

Adrok has developed ray tracing and finite-difference time-domain (FDTD) simulation software for numerical simulation of the ADR wave propagation through various subsurface materials (Doel & Stove, 2016). Simulated scans are used for preliminary feasibility studies and for experimental design of specific field scans using ground models based on known geology and/or borehole data if available. For example, in the case of simulated the Upper Rhine Graben effects on the EM waves, Figure 1 was used as input data to the model.

The ground is modelled as a stratified layer model with dielectric values according to the model in Figure 1, for example. The coupling to Maxwell's equations is modelled with the Debye model (Debye, 1929), which considers the materials as a mix of mobile charges, described by the static conductivity, and inertialess dipoles that lose energy due to friction. Parameters were taken from the measurements described in Doel et al., 2014 and Stove G. et al., 2023. In figure 2, the ADR wave packet (top) travels from surface (left z=0) into the ground. At each change in dielectric (lower plot), corresponding to material interfaces, part of the wave packet is reflected back up to the surface where it is detected by the surface receiver (Rx). Homogeneous regions generate continuous backscatter (small wiggles traveling up (left)) caused by granularity of the material. This backscatter contains spectral information regarding material composition, whereas the timings of the interface reflections can be used to compute velocity and thereby dielectric.

To account for observed backscatter in homogeneous regions, small random fluctuations are added to the dielectric values at random horizons. In the context of the simulations described here their only effect is a slight increase in energy loss due to the backscatter in addition to conductivity losses. This process is described in Doel & Stove, 2016 and Doel et al., 2020.

The depth of penetration of the transmitted ADR wave packets can be tuned to different transmission frequencies and energies (and two-way travel times) to suit different distance scales of propagation through solid objects. Adrok are keen to explore deep penetration applications for subsurface natural resource mapping at the geological scale as well as shallower penetration applications for close-range geotechnical imaging (for further explanations, refer to Doel & Stove, 2018; Doel et al., 2014). Depth is measured from time and velocity by ray tracing and Normal Move Out (NMO) computations, similar to the methods used in the seismic industry (Doel et al., 2014; Stove, G. D. C., Stove, G.C., and Robinson, M., 2018; Doel 2023).



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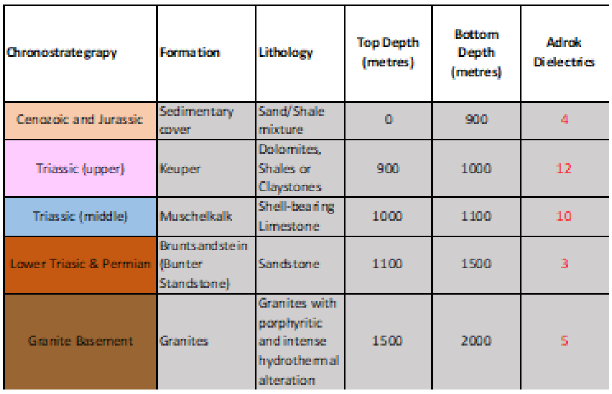

Chronostrategrapy	Formation	Lithology	Top Depth (metres)	Bottom Depth (metres)	Adrok Dielectrics
Cenozoic and Jurassic	Sedimentary cover	Sand/Shale mixture	0	900	4
Triassic (upper)	Keuper	Dolomites, Shales or Claystones	900	1000	12
Triassic (middle)	Muschelkalk	Shell-bearing Limestone	1000	1100	10
Lower Triasic & Permian	Bruntsandstein (Bunter Standstone)	Sandstone	1100	1500	3
Granite Basement	Granites	Granites with porphyritic and intense hydrothermal alteration	1500	2000	5

Figure 1 Example of simulated model input data based on Upper Rhine Graben geological data for drillhole Soultz 1 (Ledsert & Herbert, 2020) and theoretical dielectric values, based on Adrok’s experience of similar rock types.

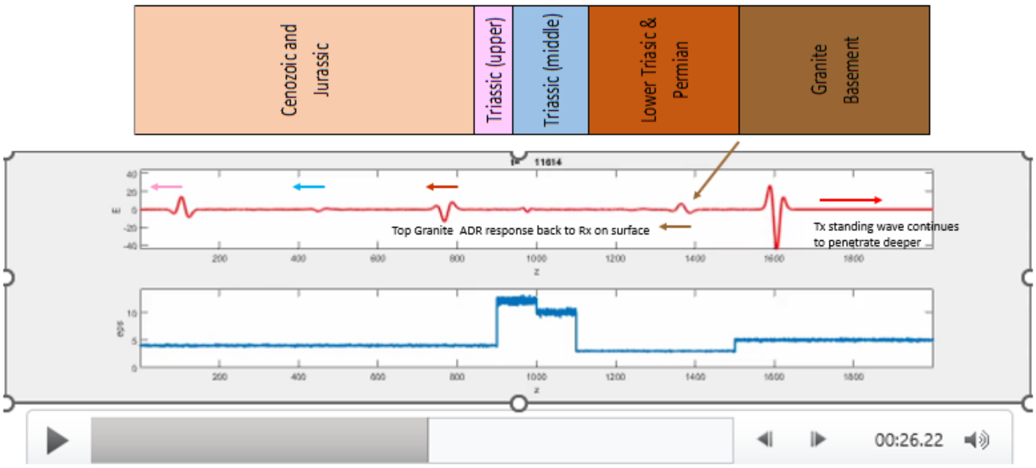

Figure 2 Simulated electromagnetic pulse and reflections (red line) modelled against dielectric values in the ground (blue line). Depth below ground level shown in the x-axis. The electromagnetic pulse emitted by Tx enters the ground and subsurface reflections are recorded at the receiver Rx. Noise level is defined as the ratio of the background noise at the receiver and the peak signal when entering the ground.

Results

Simulated models will be presented for the following three geothermal settings in the:

i. Upper Rhine Graben, France;
ii. North German Basin, Denmark (Fuchs, S., et al., 2020);
iii. Rhône Valley (Swiss Alps) near Lavey-les-Bains, Switzerland (Link, K., et al, 2020).

All these simulations show that the pulsed EM waves can propagate deeply into the earth.

Field measurements will be presented for the United Downs and Eden Project geothermal projects in Cornwall, United Kingdom.

Overall, the EM methods have demonstrated:

Measuring subsurface Temperature effects: The principal application for Adrok would be in the pre-drilling terrain to prospect-scale thermal characterization of the Earth's crust. Thermal maps could be easily generated which point towards the best target areas. Adrok requires some calibration work before providing absolute values.

Measuring water: Water has a high dielectric (>80). Due to this natural feature, the pulsed EM can measure peaks in relative dielectric values with depth. The identification of water-rich/aquifer layers at depth could be targeted in a similar way to the lithium brines in fracture hosted fluid pathways in Cornwall (UK) or thinner water-filled fractures in Switzerland.

Monitoring Temperature effects: Adrok can be used at key location around a geothermal borehole for example to monitor the change in temperature over time. If survey stations are established, ADR measurements could be made from the same station 12 months apart to provide a guide as to the annual change in temperature. This can, in turn, be used to better forecast the longevity of a geothermal field.

No special permits needed to deploy ADR: The ADR tool uses lower energy and transmits low power. The non-destructive, non-invasive nature of the technology means that surveys can be carried out almost anywhere including built up areas, in farmland, or in forests. Adrok leaves nothing but footprints. The ability to carry out geophysics in built up areas is an advantage as many potential geothermal drill sites are located near towns and communities, therefore the technology offers a viable option to test numerous drill locations/targets prior to committing to highly disruptive and expensive drilling. The portability and ease of manipulation of the equipment means it is very user friendly, cheap, and non-invasive.

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Geological Society
Fire Safety Information

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation.

Do not stop to collect your personal belongings.

Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshall on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:
Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.

Lecture Theatre
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.

Main Piccadilly Entrance
Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid

All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities

The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of The Geological Society