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Pivot Science Publications

Perspective

A perspective on Paul Younger's work on the Newcastle Science Central Deep Geothermal Borehole and new developments from the NetZero GeoRDIE project

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Abstract

Paul Younger, to whose memory this issue is dedicated, was an early advocate of a geothermal energy renaissance in the north of England. This paper offers background to the experience gained with the Eastgate BH1 and Eastgate BH2B boreholes, focused on exploring the geothermal potential of the Weardale Granite, followed by what has subsequently become known as the Newcastle Science Central Deep Geothermal Borehole (NSCDGB), which found a sequence of (presumed) Fell Sandstones. These efforts represent not only a legacy piece of the energy infrastructure in the UK, but also a legacy of Paul Younger. While the NSCDGB has not been developed using conventional geothermal methods, it has proved invaluable in providing data and a modelling test-bed for the geothermal potential of northern England and it is hoped that in future years it can serve as a testing facility for deep geothermal research. Research carried out as part of the recently concluded NetZero GeoRDIE has confirmed that it could still be converted to a Deep Borehole Heat Exchanger (DBHE), with an indicative total continuous heat yield of >50 kW for a lifetime of 25 years if repurposed to c.920 m depth.

Keywords: geothermal energy; deep borehole heat exchanger; repurposing deep boreholes

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1. Introduction

Paul Younger, to whose memory this issue is dedicated, was an early advocate of a geothermal energy renaissance in the north of England [1,2].

As early as 1961, a group of Devonian granite batholiths, collectively referred to as the Weardale Granite [3], was encountered at 390 m depth below a cover of Mississippian sediments in the 808 m deep Rookhope borehole (British Geological Survey borehole reference NY94SW1, grid reference 393756 542789

[4,5]), located on the horst-like structure of the Alston Block in County Durham, UK. The granite was soon recognised as a radiogenic anomaly [6].

This clearly made an impression on Paul Younger and his colleagues, who, through studies of subsurface temperatures and temperature-related hydrochemical anomalies in mine waters of the area, proposed that the Weardale Granite was a potential geothermal prospect [7,8]. In 2004, the University of Newcastle thus drilled a 995 m exploration borehole (Eastgate BH1, BGS borehole reference NY93NW97, grid reference 393870 538210 [9]) on the south side of Weardale, on the trace of the Slitt Vein, a mineralised structure mined by Cambokeels mine on the north bank of the River Wear [10]. The granite was encountered at 272 m depth, and the bottomhole temperature was around 46 ˚C. The granite contained hypersaline brines, with a major strike of warm water being encountered from a transmissive fracture at 410 m depth. The water pumped from the borehole was only around 27 ˚C, however, suggesting that the yield was dominated by the transmissive fracture at 410 m [11,12]. A second, 420 m deep, borehole was subsequently drilled nearby in 2010 (Eastgate BH2B, BGS borehole reference NY93NW98, grid reference 394526 538126), where the granite was encountered at 286 m. This borehole failed, however, to intercept any significant transmissive features in the granite, preventing it from forming the second half of a geothermal doublet [13,14].

The experience gained with the Eastgate BH1 and Eastgate BH2B boreholes encouraged further efforts towards the exploration of potential geothermal resources in the north of England. The next "north-eastern" prospect to be explored was a potential deep sedimentary reservoir, only some 8 km north-east of the Weardale Granite [13] (**Figure 1**). The site was in the centre of Newcastle, close to the St James' Park football ground, and the target reservoir was the Carboniferous Fell Sandstone Formation, which is known to be a productive aquifer near outcrop further north in Northumberland [15]. It was postulated that the regionally important Stublick-Ninety Fathom fault system might form a hydrogeological connection between the high temperatures of the Weardale Granite and the postulated Fell Sandstones of central Newcastle; indeed coal mines adjacent to the fault structure produced brines which bore a potential geothermal signature ([13,16], see also [17,18]). High geothermal heat fluxes of up to 95 mWm^{-2} [19] have been suggested for the area (**Figure 2**).

In 2011, drilling commenced on what has subsequently become known as the Newcastle Science Central Deep Geothermal Borehole (NSCDGB - BGS borehole reference NZ26SW3569, grid reference 424010 564330 [20]), which eventually reached 1821 m depth. The borehole found a sequence of 383 m of (presumed) Fell Sandstones with the top at 1418.5 m depth, and an equilibrium temperature of 73 ˚C at 1740 m depth, suggesting a heat flow of 88 mW m^{-2}. The formation water was a hypersaline brine containing over 130,000 mg L^{-1} chloride. The Fell Sandstone was described as "white, pink and red, very fine- to coarse-grained sandstone with a proportion of dark grey micaceous siltstone"; the bulk of the formation was, however, fine to very fine-grained, argillaceous and micaceous. The hydraulic properties of the Fell Sandstones were disappointingly poor: a transmissivity of 0.016 m^2 d^{-1} was estimated, implying an average hydraulic conductivity of 7 x 10^{-5} m d^{-1}. Younger *et al*. [20] believed that the low productivity was due to a far lower porosity and permeability in the sandstone in the boreholes than is observed in the Fell Sandstone at outcrop in Northumberland. They speculated that the poor hydraulic properties were due to occlusion of pore necks by carbonate cement in the upper part of the formation and silica in the lower part. The exploration borehole could thus not be taken in use as a conventional fluid-producing geothermal well. Funding was never forthcoming to drill the planned deviated lateral boreholes to encounter putative permeable fracture structures in the formation [13,20]. The borehole has been unused, but "open" and effectively "mothballed" for over 10 years.

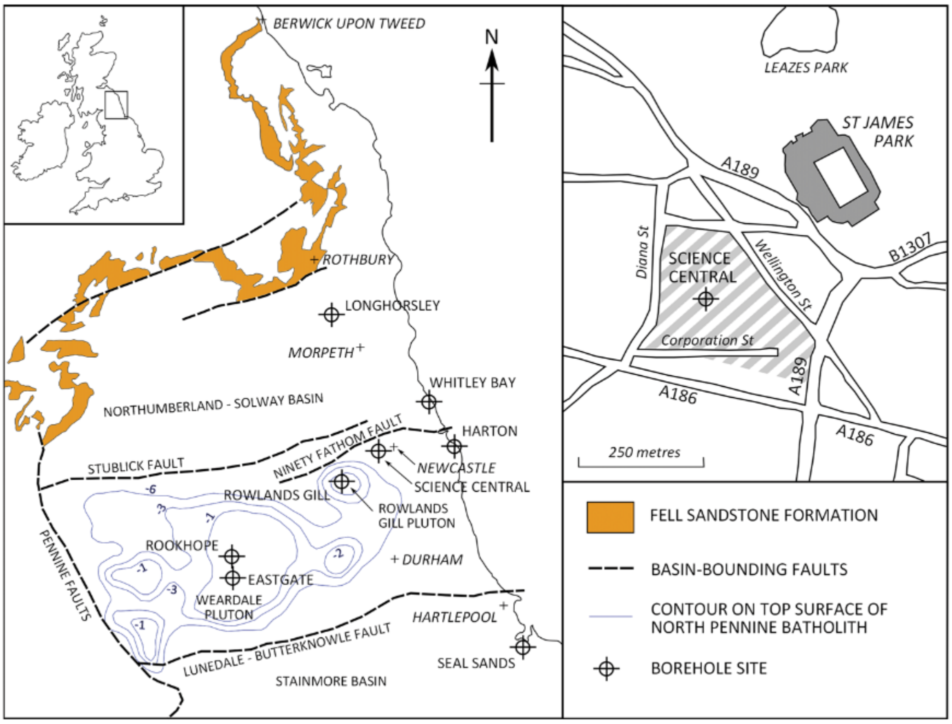

Figure 1 Map of North-east England showing location of boreholes in proximity to the North Pennine Batholith, with contours in km after Kimbell *et al*. [3]. Inset on the right shows the location of the Newcastle Science Central Deep Geothermal Borehole. Figure reproduced after Younger *et al*. [20].

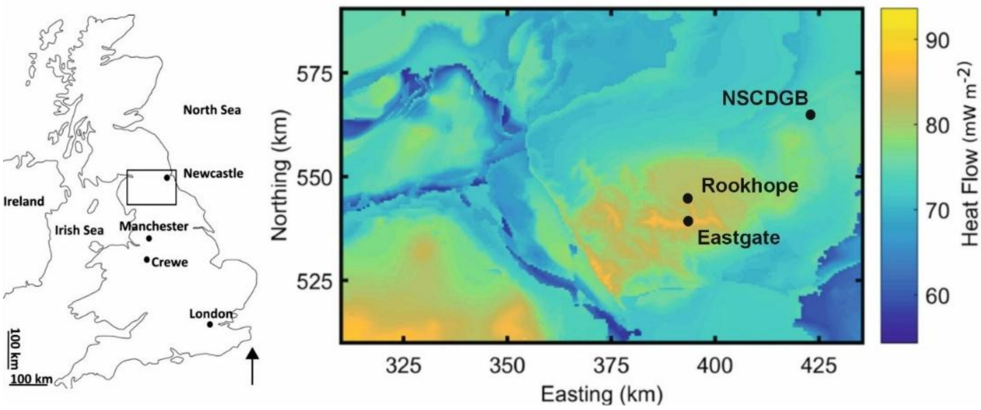

Figure 2 Heat flow in Northern England calculated through the upper 2 km of the crust. Heat flow figure adapted from Brown [21] and UK location from Kolo *et al*. [22] with geological model defined from Howell *et al*. [19].

2. Initial Development of the Newcastle Science Central Deep Geothermal Borehole (NSCDGB)

The drilling of the NSCDGB proved difficult and was a staged task due to constraints in funding. As discussed by Younger *et al*. [20], drilling of the NSCDGB started in 2011 and was completed in 2014, taking place in three phases with separate rigs. The first phase occurred between 16th February and 15th March 2011 and consisted of the hole being drilled to 245 m by Drilcorp Ltd using a Beretta T151S rig. Following this, a c. 20 m conductor pipe was installed to seal out shallow mine workings, followed by 245.5 m surface casing.

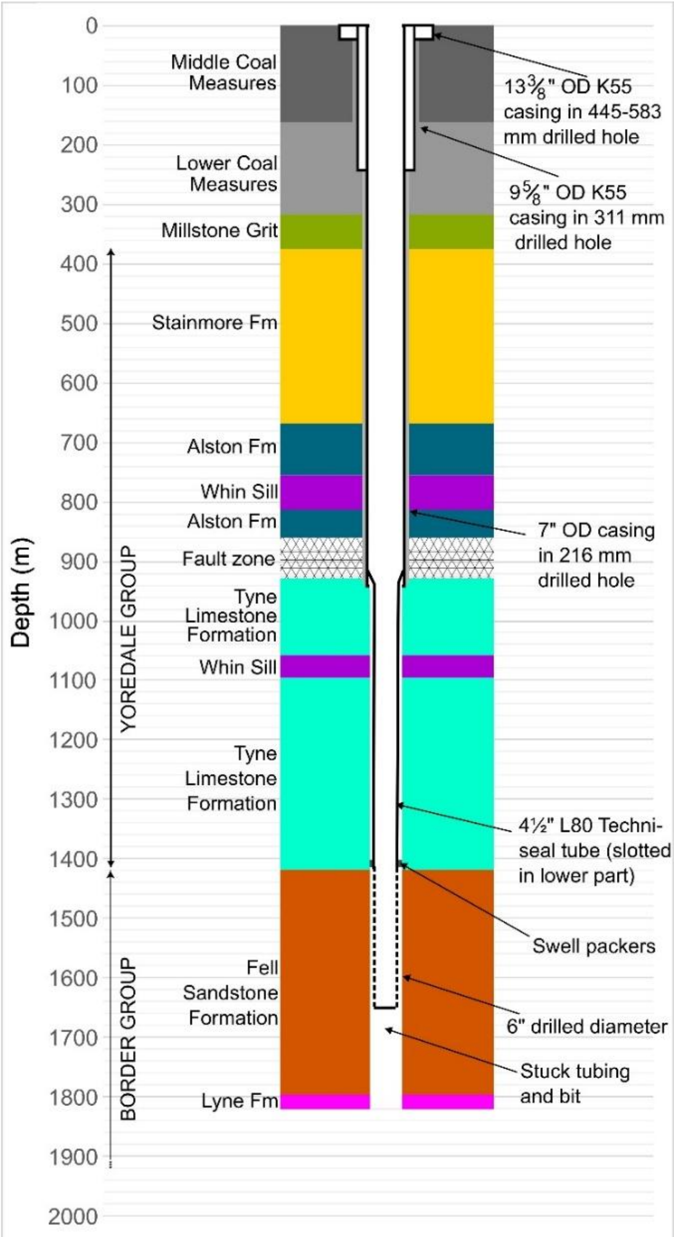

Figure 3 The Newcastle Science Central Deep Geothermal Borehole well completion after phase 3. Stratigraphy taken from Younger *et al*. [20], construction details are based on geophysical logs run for the driller. Note that cited depths vary by several metres between different sources, possibly due to datum discrepancies (rotary table, ground or subsurface chamber level). Fm = Formation.

The second phase was completed between 1st June and 11th July 2011 by Geometric COFOR Ltd who worked as a subcontractor to Drilcorp using a hydraulic hoist rig (HH102). The borehole was drilled at 216 mm (8.5”) to 954 m, with 177.8 mm (7”) steel casing installed to that depth. Drilling continued at 6” to the full depth of c.1820 m. However, the limited budget prevented further development (installation of further casing) and subsequently delayed logging until late October 2011, when fluid temperature, conductivity and gamma logs were obtained to 970 m depth. Beyond this, an obstruction prevented further logging and further funding was sought in July 2012 to clear the borehole to 1790 m.

The third phase of well rehabilitation was conducted between 10th March and 2nd April 2014, to enable a pumping test to determine the permeability and flow rates of the Mississipian Fell Sandstone Formation. Previous cleaning in July 2012 had resulted in a length of tubing becoming stuck at 1782 m (**Figure 3**). As a result, this phase of work comprised (i) clearing the borehole, (ii) installing a perforated liner and (iii) test pumping. Whilst much of the stuck tubing was removed, 92 m of it remained in situ at the base of the hole. 4½” diameter Techniseal tubing was then hung from the near base of the 7” steel casing (922 m depth) to a total depth of 1650.9 m bgl (below ground level), with a perforated section between 1418.5 m and the tubing base. Hydraulic testing proved poor yields (<0.1 L/s) and hydraulic properties.

This subsequently left the borehole unused for several years, prior to conceptualisation of the borehole to be repurposed as a deep borehole heat exchanger (DBHE). The resulting construction of the borehole influenced its suitability for conversion to a DBHE.

3. Repurposing as a Deep Borehole Heat Exchanger (DBHE)

In 2019, a group of academic researchers led by Newcastle University proposed that the borehole could be repurposed as a closed-loop DBHE, and this resulted in the Net Zero Geothermal Research for District Infrastructure Engineering (NetZero GeoRDIE) consortium [23]. Unlike open-loop geothermal systems which hydraulically interact with the reservoir directly, closed-loop geothermal systems do not interact with the reservoir. A DBHE is a closed-loop geothermal system which uses an internally-circulating heat transfer fluid in concentric (coaxial) pipes to extract heat from a geological formation through conduction via the borehole walls. These systems do not rely on subsurface advection of groundwater, nor on permeability, thereby significantly reducing the risk profile of a geothermal system [24]. This concept could theoretically be applied to unsuccessful geothermal exploration wells and abandoned hydrocarbon wells thereby offsetting drilling cost. In a DBHE, as illustrated in **Figure 4**, a heat transfer fluid flows in through the annulus and receives heat from the formation while flowing downwards. The heated fluid returns to the surface through the central pipe and is directed for end-use, usually for space heating applications via a heat pump [22,25].

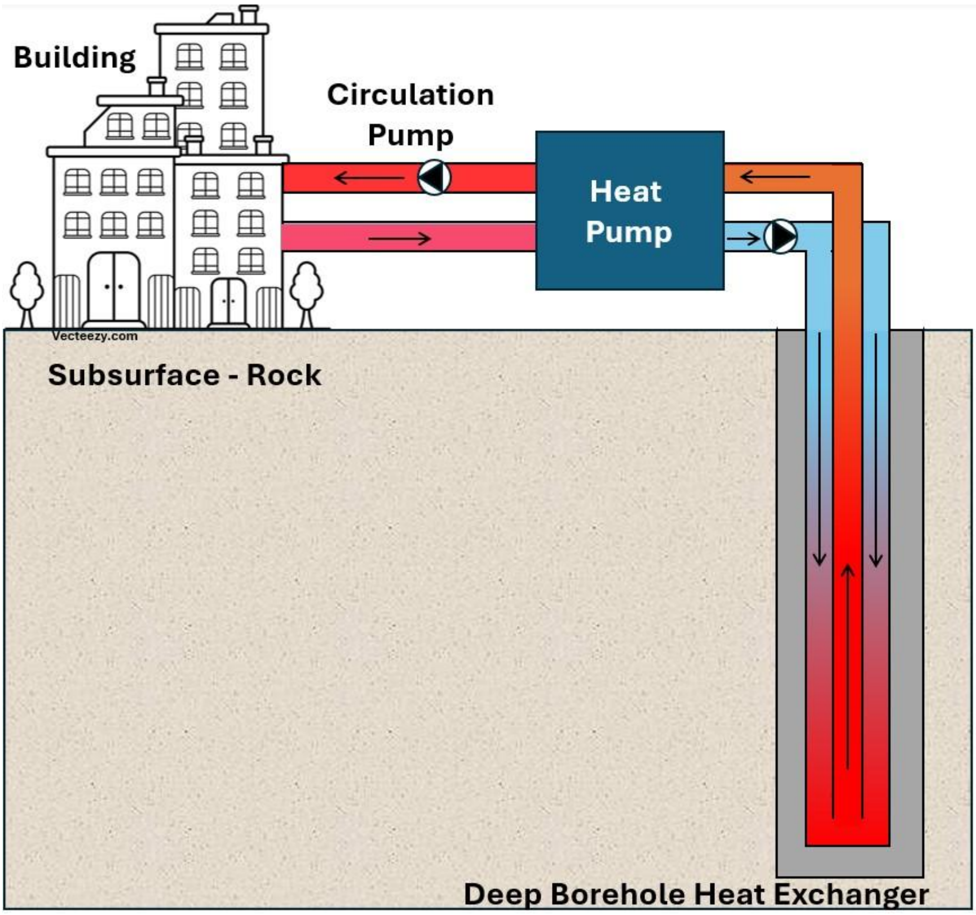

Figure 4 Schematic of a Deep Borehole Heat Exchanger Heating System (after Cai *et al.* [26]).

Between 2020 and 2024, the EPSRC-funded NetZero GeoRDIE Project investigated the potential to repurpose the borehole as a closed-loop DBHE [27]. The project involved a multi-disciplinary team consisting of researchers from Newcastle University, the University of Glasgow and the University of Durham, aiming to (i) quantify the potential to extract heat, (ii) understand potential integration of the DBHE into existing or proposed heating or cooling systems, (iii) provide data from a thermal response test for model validation and ground truthing, and (iv) resolve regulatory and legislative issues.

It was envisioned that the borehole would be re-completed for testing to a depth of ~920 m using a coaxial configuration. This was due to the limitation of the 4 ½ inch Techniseal tubing installed below 922 m depth posing problems with installation of the coaxial pipe and limiting the hydraulic efficiency of the DBHE. The installation would involve fixing a central high-density polyethylene (HDPE) pipe within the existing borehole with an assumption that the borehole would be sealed via a packer at around 922 m depth.

For the modelling exercise, when operating in heat extraction mode, cool fluid (water) would be circulated down the annular space between the pipe and borehole wall, warming with depth via conduction through the borehole wall before being pumped to the surface via the central pipe. A heat pump would likely be used to extract heat from the circulating fluid at the surface before returning it to the borehole annulus.

Numerical modelling studies have been undertaken highlighting that constant heat loads in excess of 50 kW could be sustained for a 25-year system lifetime [22,28]. The NetZero GeoRDIE project investigated the impact of groundwater flow [29], heterogeneity [22], mode of operation, fluid circulation rate [30], thermal energy storage [25], the potential coupling to Newcastle University's Urban Science Building [31] and the impact of different in-hole borehole closed loop configurations (such as single and double U-tube [32]).

Preliminary studies highlighted that the DBHE could yield a heat extraction rate of c.50 kW continuously for 25 years assuming a purely conductive setting [22] [28]. The presence of regional groundwater advection was shown to enhance the thermal productivity of the system: when a regional flow with a Darcy velocity in excess of 1e-6 m/s was applied perpendicular to the DBHE, it improved the thermal yield by around 40%, due to the cold thermal plume being advected away from the vicinity of the DBHE. At lower Darcy velocities, the improvement in thermal yield was minimal. The study did, however, acknowledge that such elevated groundwater velocities would be unlikely to be encountered over the entire length of the DBHE, especially at depth [29].

It was later shown that to minimise the parasitic losses and maximise the thermal yield of the system, the coaxial central pipe is the optimal solution, rather than the U-tube configuration commonly deployed in shallow boreholes [32]. Indeed, U-tubes tend to become hydraulically inefficient at greater DBHE depths than c. 500 m.

Other intricacies of the system were explored, proving the DBHE depth to be a key factor in determining the thermal yield, whilst the circulating flow rate was significant in determining the internal efficiency of the system (*i.e.*, borehole thermal resistance – Banks *et al.*, 2024 [33]). Interestingly, the degree of geological heterogeneity (*i.e.*, lithological layering) only played a minor role when determining the thermal yield of the DBHE [22]. Other factors that could impact the longevity of development would include the mode of operation (e.g., full load equivalent hours per year, or FLEQ). It was shown that around 4 DBHE to 920 m would be required to meet the thermal demand of the adjacent Urban Sciences Building [30].

The efficacy of a DBHE for underground borehole thermal energy storage (BTES) was also evaluated. Sensitivity analysis involving 10 design parameters showed that operational factors – such as the duration of the charge-discharge cycle - would have the biggest impact on the storage efficiency of such systems. The overall ability of DBHEs to store heat is relatively modest and thus, the study concluded that thermal energy storage via DBHEs should only be considered if there is a large source of surplus heat without an alternative value; and, even then, shallower multi-borehole arrays would be more suitable than DBHE [25,34].

A base-load output from the DBHE (*i.e.*, a constant thermal yield) could contribute to the heating of Newcastle University's adjacent Urban Sciences Building, or a nearby heat network as an anchor load. Different ways of operating the system in conjunction with thermal setback strategies were explored. It was shown that a single DBHE could (through a heat pump) be used to replace a preheat gas burner, or through a sufficiently large buffer tank, could meet 50 % of the demand of the building [31].

Unfortunately, over the lifetime of the NetZero GeoRDIE project, it was not possible to repurpose the well for thermal response testing due to financial and procurement-related issues. However, the well remains an asset that may be repurposed in coming years.

4. UK Wide Repurposing

While the NetZero GeoRDIE project did not ultimately test the borehole as a closed-loop DBHE system, it provided insights as to how such systems operate, how they can be integrated into wider energy systems and how they can be impacted by policy. Since the start of the project, two DBHE systems have been installed and tested in the UK with other potential systems being evaluated.

The first such system was developed at the Eden project, proving to be the first coaxial DBHE in a UK context and one of the deepest DBHEs in the world [24,35]. A coaxial DBHE was installed in a 4.5 km directional well, which was connected to the Eden Biomes facilities in June 2023 [36]. The system consists of vacuum-insulated tubing installed to a depth of 3850 m with a plate heat exchanger at the surface level, whilst the bottom of the well has been left open [37].

The second (demonstrator) system installed is at the Kirby Misperton (KM) gas field in Derbyshire. The KM8 borehole was repurposed in 2023, and field tested to depths of 3 km as a DBHE with a HDPE pipe. While limited information on the capacity of the tests has been published, independent studies suggest the likely potential thermal yield to be c. 300kW [38,39].

5. Practical and Environmental Challenges for Repurposing Deep Boreholes as Coaxial DBHE

It can be argued that it is attractive to repurpose “failed” conventional geothermal exploration boreholes (such as the NSCDGB) or failed, abandoned or exhausted hydrocarbon wells as DBHE. This repurposing is fraught with challenges, however:

- The diameter of exploration or hydrocarbon wells may not be sufficient (this issue can be observed in the deepest 4½” Techniseal portion of the NSCDGB). A DBHE requires an adequate diameter to ensure that a coaxial pipe of appropriate dimensions can be inserted to allow an optimal flow rate of circulating fluid in the pipe and annulus, without the hydraulic resistance (and thus circulation pumping costs) becoming excessive. Exploration boreholes may be drilled at narrow diameter to save costs. The same may be true of the lower portions of hydrocarbon wells, where the hydrodynamic considerations for relatively low flows of oil or much larger flows of gas, will be completely different to those for DBHEs.
- Spent or abandoned hydrocarbon wells will often contain plugs, packers *etc.*, that will likely need to be removed prior to repurposing of a DBHE.
- Many hydrocarbon wells will not be vertical but may be highly deviated and even sub-horizontal in parts. This will naturally pose challenges and require additional expenditure for the installation of a deep coaxial pipe.
- Spent or abandoned hydrocarbon wells may contain perforated or open sections that are exposed to the reservoir. These may allow the ingress of

sub-commercial quantities of unwanted oil or gas that may be entrained with the circulating heat transfer fluid (and, if allowed to escape at the surface, may pose a safety, environmental or odour hazard).

- Deep boreholes may penetrate formations containing highly saline fluid (this is the case at NSCDGB). If the borehole is repurposed as a DBHE, circulating fresh heat transfer fluid, it is important to verify that the overall borehole construction – inclusive of any new inserted pipework – can withstand the resulting difference in hydrostatic pressure difference between formation and wellbore. Moreover, the saline water may enter the borehole, if it contains perforated or open sections at depth, mix with the circulating heat transfer fluid, disturb the pressure conditions and salinity (corrosion risk). Any geochemical incompatibilities, pressure or temperature changes may result in mineral precipitation and scale formation.
- In short, it may not be desirable to operate a DBHE in an existing deep well open to brine- or hydrocarbon-bearing formations. Open sections of the bore may need to be plugged off before commissioning.

6. Legal Challenges for Repurposing Deep Boreholes as Coaxial DBHE

Most countries enforce strict safety and environmental regimes around oil and gas wells. A part of these is designed to ensure that "spent" hydrocarbon wells are not simply “abandoned”, but are responsibly sealed and decommissioned [40]. In many countries (such as the UK), such legislation is absent in the case of geothermal boreholes. Thus, the conversion or “re-definition” of a spent hydrocarbon well to a recognised geothermal asset *may* be viewed as a means to avoid the financial and legal liability of decommissioning. Should the conversion of hydrocarbon wells to DBHEs become common practice, legislation will need to be updated to close this potential legal loophole and to ensure that, at the end of its life, the converted hydrocarbon asset is responsibly decommissioned.

In many jurisdictions, a licensing system may be in place that can grant an oil and gas company exclusive rights to explore for and exploit hydrocarbons within a hydrocarbon licence area [41]. It should be noted, however, that such a licence does not (e.g., in the UK) automatically grant similar exclusive rights to exploit geothermal energy [42]. At the time of writing, in England, deep geothermal energy is not subject to any geothermal licencing scheme [43] over and above the environmental permits and licences required from the Environment Agency [44]. This effectively implies that a hydrocarbon company does not necessarily have any automatic, preferential or exclusive rights to exploit geothermal resources within what it may regard as “its” hydrocarbon licence area.

7. Summary

Building on their work on the Weardale Granite, Paul Younger and colleagues facilitated the drilling of Eastgate boreholes (Eastgate BH1 and Eastgate BH2B) for geothermal exploration in Northern England. Their experiences from these boreholes propelled further geothermal exploration in the area resulting in an exploration borehole targeting the aquifer of the Carboniferous Fell Sandstone Formation. The borehole, Newcastle Science Central Deep Geothermal Borehole, was drilled between 2011 and 2014, representing not only a legacy piece of infrastructure but a legacy of Paul Younger. While this borehole has not been developed using conventional geothermal methods, it has proved invaluable in providing data and a modelling test-bed for the geothermal potential of northern England and it is hoped that in future years it can serve as a testing facility for deep geothermal research. Research has confirmed that it could still be converted to a DBHE, with an indicative total continuous heat yield of >50 kW for a lifetime of 25 years if repurposed to c.920 m depth.

Declarations

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Competing Interests

The authors have declared that no competing interests exist.

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