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The Geothermal Potential of the Fractured Weardale Granite and Associated Aquifers of County Durham and Adjacent Areas Northern England

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ABSTRACT

Though identified in the 1980s, the geothermal energy potential of the United Kingdom has still to be realised. Yet the possibility for supplying geothermal heat from a variety of deep, hot saline aquifers, shallow flooded mines and a suite of radiothermal granites is significant. Our calculations indicate that the resource to production potential based upon entirely supporting the UK heat demand is at least 100 years (Gluyas at al., 2018).

In this paper we explore the potential of one region within the UK that could deliver geothermal heat via a combination of naturally fractured hot granite, deep saline aquifers, shallower karstified limestones and abandoned, flooded coal mines. The Weardale Granite in northern England's County Durham was first tested with a research borehole drilled in 1961 and more recently has been appraised with three further boreholes drilled by a consortium of partners led by Newcastle University and Durham University in 2004, 2010 and 2011. Well Eastgate 1 penetrated naturally fractured granite on the northern boundary of the Weardale Granite with a transmissivity of 4000 darcy m from an interval at 410 m at a temperature of 42°C. Eastgate 2 was drilled 700 m from the first well to test whether fluid flow could be obtained from within the granite. Although the well proved the high geothermal gradient in the area it did not flow water to surface. Science Central was drilled along the same bounding fault as Eastgate 1 and some 60 km further east within the centre of the city of Newcastle. It tested the flanking northern sediment wedge in what is known as the Northumberland Trough. It too recorded a high geothermal gradient but failed to flow, possibly due to loss of permeability along the fault zone targeted.

The geothermal signature from the produced water at Eastgate 1 indicates that the water equilibrated at rock of at least 100°C. Work continues in an effort to understand the architecture of the productive and non-productive reservoir systems in the area.

1. INTRODUCTION

The quest to develop geothermal energy in the UK began in the wake of the 1973 global oil crisis. The threat at that time to national energy security was high. Coal, the concentrated energy source that had been exploited to power first the industrial revolution and then the UK as the world's first superpower was in steep decline from peak production in the first decade of the twentieth century. North Sea gas, although discovered and developed had not then realized its full potential and while the first few discoveries of oil had been made in the North Sea including the giant Forties Field (effectively government owned because of the state's 50% holding in BP), none of the oil was on production. Moreover, few appreciated that oil and gas production would grow to dominate the UK economy by the 1980s. As with so many things in government, the geothermal initiative was slow to develop and by the time the first drilling programme was underway in the 1980s, the UK had essentially become a petro-economy. Only one of the geothermal test bores drilled in the campaign of the 1980s made it through to production and that was due to one visionary person, an accountant, Mike Smith at Southampton City Council. The story of that well and the subsequent development of the Southampton District Energy System has been told elsewhere (Gearty *et al* 2008). We had to wait nearly another 20 years until 2004 before the next geothermal well was drilled in the UK. This time, the well would be drilled in northern England at the village of Eastgate in the English Pennines. It was not a visionary accountant who saw the potential for geothermal energy use in the UK but a geologist. The late Paul Younger, then of Newcastle University won funding from the now defunct Regional Development Agency (RDA) to drill a well into the Weardale Granite a known heat source in NE England. The well was drilled, tested and flowed and geothermal heating was set to become a key energy source for a planned eco-village on site when the financial crisis of 2008 followed shortly thereafter by the dismantling of the RDAs by a new government in the UK brought the project to a premature closure.

A new opportunity arose to supply heat for an expanding Newcastle University and to that end money was sought to drill a deep geothermal well in central Newcastle (Science Central 2011). The well, terminated at 1.8 km did indeed prove high heat flow but not water flow (Younger *et al*, 2016). In recent years another huge, low enthalpy geothermal resource has been recognized in the area, abandoned and flooded coal mines (Adams and Gluyas, 2017). The Durham Coalfield was once one of the most prolific production areas in the UK. All deep mines have now closed and have naturally filled with water. There are several sites in County Durham and adjacent areas where the body responsible for residual mine safety, the Coal Authority, pumps copious quantities warm water out of the mines to maintain safe water levels. Most of the liberated heat goes unused.

The aim of this paper is to report on the geology and geothermal potential of the Weardale Granite and adjacent areas containing both sedimentary aquifers and flooded mines and determine the utility of the heat that could be extracted from the subsurface as well as the potential offset of carbon dioxide emissions by switching to a geothermal heat source.

2. REGIONAL GEOLOGY OF NE ENGLAND

The surface geology of NE England is dominated by eastward dipping Carboniferous strata. A subordinate coastal strip of Permian strata occurs in the east widening from 0 km at South Shields to about 20 km at Hartlepool (Figure 1). Triassic rocks occur at surface in the south east corner of the region. Lower Palaeozoic slates occur in inliers in the far west of the area. From a structural perspective the region can be divided into three elements bounded by two major west to east fault systems. To the north is the Stublick-Ninety Fathom fault array of the Northumberland Trough, within which there are about 4 km of Carboniferous strata. To the south and trending west to east lies the Butterknowle Fault that cuts through around 6 km of Carboniferous strata within the Stainmore Trough. Between the two basins is the Alston Block. Here, the Carboniferous section is less than 500 m thick and beneath the Carboniferous section is a Devonian age (398.3±1.6 Ma; Selby *et al* 2008), eroded, radiothermal granite.

A large quartz-dolerite sill complex, the Whin Sill (299±3 Ma, Goulty, 2005), intrudes the Carboniferous strata but is absent from the Permian strata. Much of the area is heavily mineralized with lead-zinc and associated fluorite, barite and witherite (Dunham, 1990). Mineralisation probably occurred in several phases with the oldest being 284±40 Ma and the youngest around 170 Ma (Dunham *et al* 1968; Halliday *et al* 1990).

The area is cut by a Palaeocene dyke, the porphyritic dolerite, Cleveland Dyke (58.4±1.1, Dunham, 1990).

2.1 Lower Palaeozoic rocks

The oldest rocks in the area are exposed in the west in the Cross Fell Inlier and at Cronkley Spar in upper Teesdale. Both inliers contain Ordovician Skiddaw slates with the addition of many minor intrusions at Cross Fell (Burgess and Wadge, 1974). These same, likely Skiddaw slates are also seen underlying Carboniferous sedimentary rocks in two boreholes at Roddymoor in the east and Allenheads in the west where the slates were encountered at 861.8 m and 467.5 m below surface respectively (Dunham, 1990).

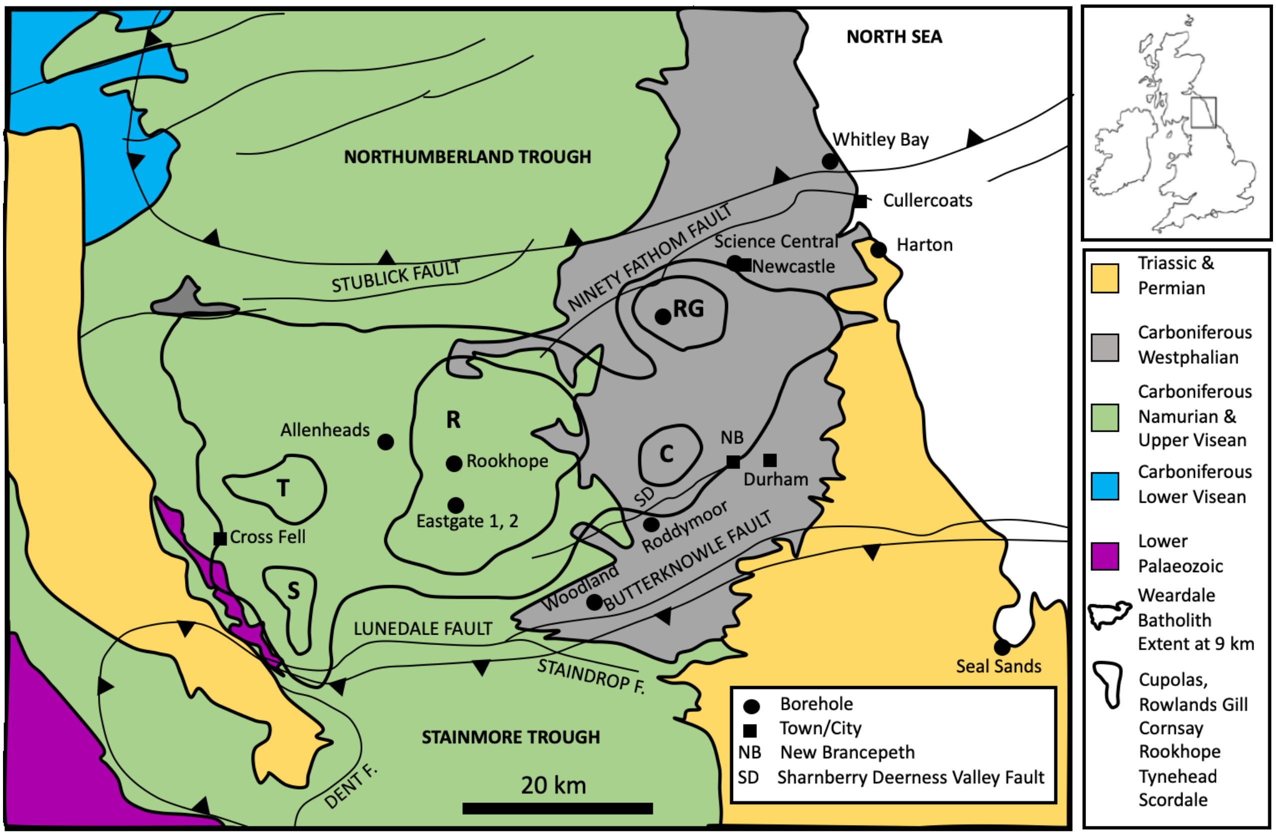

Figure 1: Location map for the Weardale Granite and surrounding area

2.2 Weardale Granite

The Weardale Granite is not exposed at surface but is proven in three boreholes at Rookhope, Eastgate (not numbered but informally referred to as Eastgate 1) and Eastgate 2 drilled in 1961, 2004 and 2010 respectively (Figures 1-3). The granite flat-lying foliation marked by mica and quartz eyes. It contains two micas, albitic feldspar and is non-porphyritic. Minor minerals include monazite, zircon and magnetite ilmenite. Although the granite was emplaced in the Devonian it remains a significant heat source due to the presence of long-lived radioactive isotopes of potassium, uranium and thorium all of which release heat as they decay.

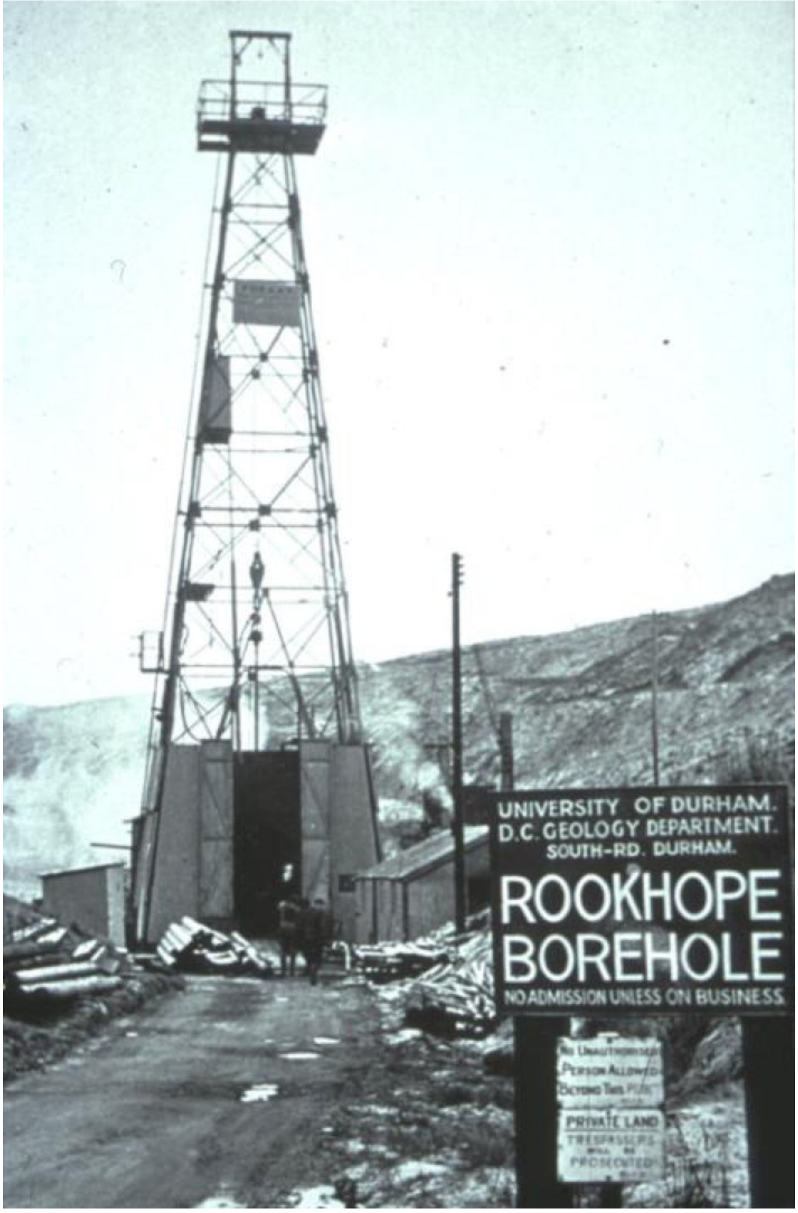

Figure 2: The Rookhope borehole, spudded 15th September 1960, completed 31 July 1961 (photograph courtesy of Department of Earth Sciences, Durham University)

2.3 Carboniferous Rocks

The thickness of Carboniferous strata across the area varies enormously from about 270 m in the Eastgate (1) borehole (Manning *et al*, 2007) to something exceeding 3442 m in the Seal Sands borehole (Johnson *et al*, 2011). This huge difference in thickness occurs in only 60 km between Eastgate and Seal Sands and is a product of both depositional thicknesses and post-Carboniferous erosion. At the core of the Pennine anticline only part of the Lower Carboniferous is present. For example, at Eastgate (1) the Lower Carboniferous section is 202 m thick, excluding 66.5 m of dolerite in the Whin Sill. It comprises limestones with subordinate sandstones and mudstones and is of Asbian age throughout. The basal beds on top of the Weardale Granite comprise thin limestones and mudstones with the boundary marked by a sticky while clay, presumed to be kaolinite (Manning *et al*, 2007). Elsewhere in the area the basal beds of the Carboniferous overlie Lower Carboniferous metasediments and are older, likely of Chadian age and often conglomeritic (Dunham, 1990). The conglomerates are often referred to as polygenetic (Capewell, 1956) reflecting a varied provenance for the clasts. Likely, these coarse clastic sediments infilled irregularities in the pre-carboniferous surface.

The attenuated Carboniferous interval overlying the Weardale Granite is in contrast to the much more complete sections in the Northumberland Trough to the north and Stainmore Trough to the south. The oldest deposits known from the Northumberland Trough are of Chadian age and a complete sequence ranging up to Westphalian D is present and exceeding 3 km (Johnson, 1984). The Stainmore Trough contains an even thicker (3442 m minimum) sequence of Carboniferous sedimentary rocks of which the oldest known are likely Holkerian at the bottom (4169 m sub sea level) of the Seal Sands borehole (Johnson *et al*, 2007). The borehole had been planned to reach what was thought to be a Devonian (Fammenian) sedimentary rock in syn-rift wedge terminated to the north against the Butterknowle fault, inferred from interpretation of seismic data (Fraser and Gawthorpe, 1990).

The Upper Carboniferous is better preserved in the Northumberland Trough when compared with the Stainmore Trough. In broad terms it contains upward shallowing sequences of sandstones and mudstones with abundant coal; the product of delta progradation and retrogradation. Maximum burial is calculated to have occurred at the end of the Carboniferous (Fraser and Gawthorpe, 1990) followed by rapid uplift and erosion by early Permian times.

Figure 3: Eastgate 2 borehole, 1 March 2010 (photograph by J Gluyas)

Pervasive mineralization of the Carboniferous strata occurred at various stages from end Carboniferous to Triassic times. The style of the mineralization and composition of the minerals is typical of Mississippi Valley type deposits and comprises lead and zinc sulphides along with fluorite and barite. Fluorite occupies the core of the mineralized area and barite the outer rim. Barite filled veins extend a considerable distance from the core of the mineralisation. Indeed, barite and witherite were secondary products at New Brancepeth Colliery some 40 km east of the mineralisation center form a vein that was up to 4.9 m wide (Dunham, 1990). The mineralisation was caused by phases of magmatic activity in the late Stephanian and early Permian. First intruded were tholeiitic basalts to form dyke and sills (Whin Sill) followed by alkali basalts. Both magmatic phases resulted in the emplacement of hypabyssal rocks in NE England without any associated preserved lavas. It seems likely that underplating of the Weardale Granite by basaltic magma led to the exploitation of the structural discontinuities associated with the granite (Bott and Smith, 2018).

2.4 Permian Rocks

At the onset of the Permian the area occupied by what is now NE England lay well within the supercontinent of Pangea. The first sediments to accumulate were terrestrial sandstones deposited in a terrestrial basin by a combination of aeolian and ephemeral fluvial processes. The informally named Yellow Sands of County Durham (formally Rotliegend Group sandstones) accumulated as dune sets infilling post-Carboniferous eroded topography (Heward *et al*, 2003). By the mid-Permian a connection had formed to the Tethyan Ocean to the east and the area was flooded by the sea. The connection to Tethys was severed and the marine basin dried out. This occurred at least five times leaving behind cyclic sequences of limestone/dolomite, anhydrite and halides, the Zechstein Group (Tucker, 1991).

3. EXPLORATION, DISCOVERY AND HEAT SOURCE

Dunham (1934) speculated on the presence of a granite beneath the Pennine Ore Field as the cause of mineralization in the area, but it was not until two PhD students Martin Bott and David Masson-Smith conducted gravity surveys in the area that any firm evidence emerged that might support Dunham's (op cit) speculation about a deeply buried granite. Martin Bott's PhD was titled, "*The deep structure of Northumberland and Co Durham – a geophysical study of the granites in relation to crustal structure*" and was completed in 1954. The gravity data were published in 1953 (Bott and Masson-Smith, 1953) and an interpretation of the data some four years later (Bott and Masson-Smith, 1957). This work resulted in the drilling of the Weardale Granite at the Rookhope location in 1961 (Figure 2).

The borehole at Rookhope yielded two surprises, although it would seem that Arthur Holmes, the leading geologist of the day and founding father of the Geology Department at Durham University, was alone in being unsurprised (Bott and Smith, 2018)! The granite was warm, more so than was anticipated given the perceived geothermal gradient in the area. It was also eroded and onlapped by Lower Carboniferous sediments. Emplacement of the granite occurred in the Early Devonian into Ordovician metasediments, it was by Early Carboniferous times exposed to weathering. The principle interest in the Weardale Granite had centered on its twin roles of influencing the structural development of northern England and mineralisation of Lower and Upper Carboniferous sedimentary rocks of the Pennines and Durham Coalfield (Bott and Smith, 2018). The interest in the granite was broadened in the first few years of the twenty-first century when the local Regional Development Agency, One NE (a defunct quango in the UK) sought to redevelop a former cement works site close to the village of Eastgate as an eco-village. The opportunity to add low enthalpy geothermal heating to the planned wind-farm and solar arrays at this off-grid site was too good to miss for Professor Paul Younger, then an academic at Newcastle University. Paul led the work to drill three geothermal research wells in the area between 2004 and 2011.

3.1 Exploration and Discovery

As mentioned above the first well drilled in the area was at Rookhope, completed in 1961. It was designed to test the presence of the granite. This it did and it proved a temperature of 41 ºC at a depth of 806 m beneath ground level. The second significant well drilled in the area was Woodland (1962). This well was drilled about 5 km south east of what is perceived to be the south-eastern edge of the Weardale Batholith at 9 km and some 15 km south east of the much shallower Rookhope cupola (Figure 1). Here the temperature was measured at 30 ºC at a depth of 488 m beneath ground level. The heat flow in Rookhope was calculated to be 2.19 µcal cm^{-2} s^{-1} and that at Woodland 2.29 µcal cm^{-2} s^{-1} (Bott *et al*, 1972). Rookhope was drilled on the crest of what is now called the Rookhope Cupola. It spudded in Lower Carboniferous before passing through an erosion regolith and into the granite proper at 390.5 m beneath ground level. The Woodland borehole was drilled entirely within Carboniferous sedimentary rocks from Lower Coal Measures at ground surface, through the Millstone Grit and into Lower Carboniferous mixed carbonates and clastics. Although not penetrated, the assumption was that Lower Palaeozoic metasediments would be found beneath the Carboniferous at this locality (Bott *et al,* 1972). Bott (*op cit*, 1972) suggested that the higher heatflow at Woodland was due to fluid circulation within the sediment pile, and presumable involving transmission of fluids within the fractures of the Butterknowle Fault system.

Detailed accounts of the first well at Eastgate (1) and Science Central have been published already (Manning *et al*, 2007; Younger *et al*, 2016 respectively). Eastgate 2 (2010) has been little reported in the open literature. Eastgate 2 was drilled 700 m due east of Eastgate (1) and to a depth of 420 m with the aim of creating a well doublet with Eastgate 2 acting as the injection well. The UK's Department of Energy and Climate Change Deep Geothermal Challenge Fund provided the finances with which to drill the well. Severe problems were encountered in the top-hole section of Eastgate 2 due to drilling mud losses into karstified limestone. These were overcome and the granite was penetrated at 286 m below ground level. Relative to ordnance datum the top of the granite in Eastgate 2 was at 33 m about 11 m deeper than in Eastgate (1). Eastgate 2 (Figure 4) proved to be tight with ultra low permeability. This is examined in the section 3.4.

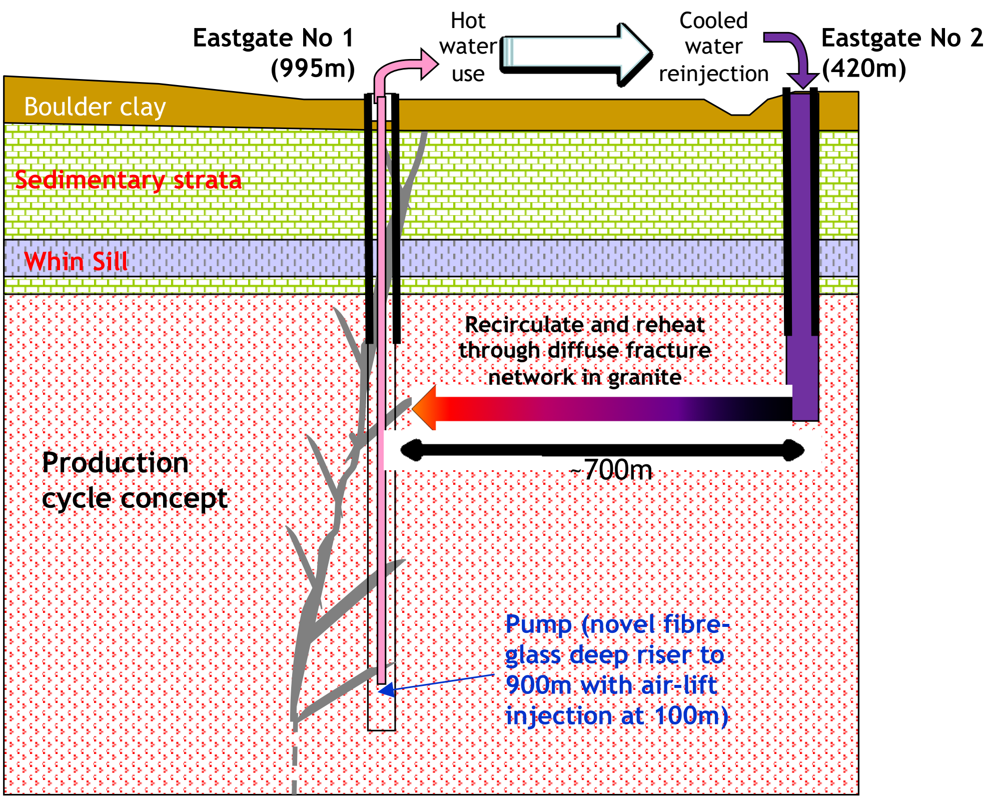

Figure 4: A, Relationship between Eastgate (1) and Eastgate 2 showing both the Slitt Vein and the unrealized development concept.

3.2 Heat source

Analysis of cuttings from the Eastgate (1) well demonstrate that decay of thorium, potassium and uranium isotopes are responsible for the heat generation in the granite but it is the heterogeneous distribution of uranium which causes areal fluctuations in the heat production (Table 1; *Elliot et al*, in prep). Heat flow in the immediate area of the Weardale Granite is around 100 μWm^{-2} but falls to 57.5 μWm^{-2} measured from historical mine-temperature data in the Durham Coalfield (Bott *et al,* 1972). Even so these values are substantially larger than most other places in the UK (Busby, 2010). Only the Cornubian Granites in Cornwall and the Scilly Isles of SW England have comparable and higher heat flows (Busby, *op cit*).

Location	Heat production rate μWm^{3-}	Heat flow μWm^{-2}	Thermal gradient ºC km^{-1}
Rookhope borehole granite	4.5	92 (95.4)	32.45
Woodlands borehole sediment	Not applicable	96 check	47
Eastgate (1) borehole granite	4.1 (4.9 measured on core)	115	38
Eastgate 2 borehole granite	Not determined	Not determined	38

Table 1 Heat production, heat flow and thermal gradients measured from boreholes in the Weardale area

3.3 Pore space and fluid transmissivity

The Weardale Granite and adjacent areas offer an unusual array of natural and anthropogenic pore spaces and transmissivity conduits. These include: conventional intergranular pore spaces in sandstones of Permian and Carboniferous age. Those of the Permian are likely too shallow to be of significant interest from a geothermal perspective and many of the sandstones occurring within the Coal Measures and underlying Millstone Grit are only of modest porosity and low to moderate permeability although they may have some geothermal potential (Hirst *et al,* 2015). Older, Lower Carboniferous sandstones have been identified as possible geothermal targets. The braided, fluvial Fell Sandstone of Arundian to Holkerian age is well developed in Northumberland and is a significant aquifer in Northumberland (Figure 5a, Turner *et al*, 1993). For the Science Central borehole, the Fell Sandstone was considered to be the main geothermal target. It was encountered at the bottom of the borehole and was thick (377 m) but it did not flow on test (Younger *et al,* 2016). There are various possibilities as to why no flow was obtained; the well was damaged during drilling, the reservoir quality of the sandstone may be poorer than in the main play fairway further north in Northumberland or it could be that the local area is cemented by pervasive barite, known to be associated with the Ninety Fathom Fault Figure 5b), adjacent to which Science Central was drilled.

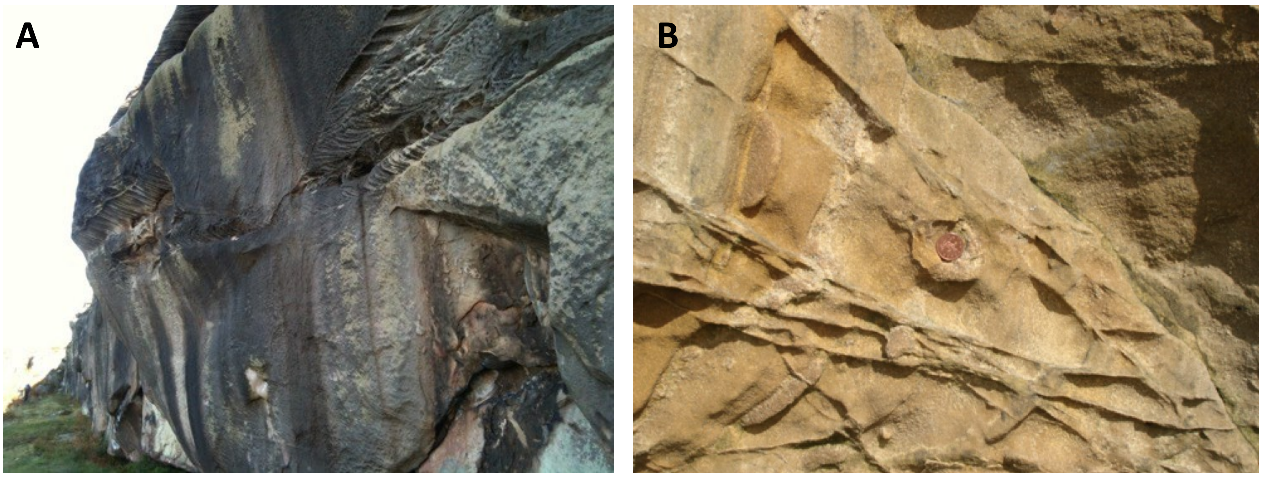

Figure 5: A, Fell Sandstone at outcrop, Bowden Doors, Northumberland, cliff height about 10m, B, fractures and barite cemented Permian sandstones, Cullercoats, Tyne and Wear, exposure is 50m of the Ninety Fathom Fault, diameter of coin 2.5 cm (photographs by J Gluyas).

The Lower Carboniferous limestones in the area are also known to be karstified. Indeed, mud losses into the Lower Carboniferous limestones during the drilling of Eastgate 2 proved to be a major operational issue. That such karstified limestones may occur at depth in the area and act as a highly transmissive geothermal reservoir is also a possibility (Narayan *et al*, 2018).

Eastgate (1) well successfully targeted naturally open fractures associated with the Slitt Vein known in Cambokeels Mine close to the village of Eastgate in County Durham. Dextral movement of the Slit Vein fault during the Tertiary seems not to have been associated with synchronous mineralization and the fracture systems remain open (Hirst, 2012), leastways west of the contemporaneous pinch-out edge of the Permian Zechstein evaporites, derivation of sulphate from which could have caused the barite cementation seen at Cullercoats (Figure 4b) and also in the Amethyst gas field North Sea (Gluyas *et al*, 1997). Although the area of the Ninety Fathom Fault failed to flow at the Science Central well, the same fault system was tested by Eastgate (1) which crossed the Slitt Vein at 410m below ground level. On test, this interval was shown to have a permeability of 4000 darcy m (= 3×10^{-9} m^2), which is one of the highest values ever measured deep within a granite intrusion (Younger and Manning, 2010).

Finally, the most pervasive 'pore' spaces in the whole of the area are anthropogenic, comprising abandoned coal mines, the areas of coal withdrawal and the connecting roadways. The coal mines were located throughout the eastern part of NE England from drift mines in the west to deep mines in the east, beneath the younger Permo-Triassic cover and even deep below the western edge of the adjoining North Sea (Figure 1). For the deep, rather than drift mines, temperatures ranged from about 12 ºC to more than 20 ºC for those on the coast and beneath the North Sea. At several of the former mines, water is pumped to surface at rates in excess of 100 $l\ s^{-1}$ to maintain safe water levels in the mines. Between 1887 and 1956, at least 3.2 billion tonnes of coal was mined in the counties of Durham (76%) and Northumberland (24%). Substantial quantities were mined before this time but records are unreliable. This equates to 2.5 x 10^9 m^3 of initial voidage of which about half will have been lost to collapse and compaction. Assuming that it is possible to extract about 5 ºC from the water than now fills the mining voids then the total technical heat reserve is in the order of 63 x 10^{15} Joules. Part of one mine in Gateshead just south of Newcastle is already exploited for heat. Lanchester Wines use heat from the mines to maintain the temperature within a warehouse (Adams *et al* 2019). This system delivers 3.6 MW_{TH}.

4. POPULATION DISTRIBUTION AND HEAT DEMAND

About 2.6 million people live in NE England, almost all in a 20 km wide coastal strip from the southern extremity of the region to just north of Newcastle 50 km further north. Of these maybe as many as 2 million people live on areas that were once mined for coal. Population density is greatest in the university district of Newcastle at 35,000 people per square kilometer with most the other cities and small towns having maximum population densities of 7,500 km^{-2} (Durham) to 20,000 km^{-2} (Middlesbrough – does not overlie the coalfield). Away from the central districts of Newcastle, Sunderland and Middlesbrough population densities are always below about 10,000 km^{-2} and elsewhere in the region, for example in rural Northumberland the population density may be as low as 2 km^{-2}.

According to UK National Statistics each home in England is occupied by 2.4 people and annually uses 12,400 kWh of gas (almost exclusively for heating) and 4000 kwh of electricity (of which around 1200 kwh is used for heating). For the mined areas of NE England this means that each of the 830,000 homes uses about 13,600 kWh of heat per annum. This equates to an average 1.55 kW 'power' per home for heating. Thus, the system at Lanchester Wines in Gateshead could in theory heat 2323 homes instead of the warehouse. For the 830,000 homes overlying the NE coalfield, 358 systems of similar size to that deployed by Lanchester Wines would be required and with about 266 abandoned mines in Northumberland and Durham it seems likely that there is ample opportunity to meet a large portion of the heating by extracting tepid water from flooded coal mines.

As of yet we have not been able to quantify the heat potential of deep saline aquifers, including karstified limestones and fractured granite in the region and this is the topic of ongoing research. Nonetheless it seems quite plausible to suggest that it should be possible for the Counties of Durham and Northumberland, which contain both urban and rural populations, to completely decarbonise heating and in so doing reduce carbon emissions by about 2.5 million tonnes (UK government figures for CO_2 emissions from domestic gas in NE England in 2014; BEIS, 2019).

4. CONCLUSIONS

There is a substantial opportunity to decarbonise heat using low-enthalpy geothermal fluids. Even in areas normally considered to be cool from a geothermal perspective. Here we have examined the possible sources of water in NE England an area that has seen considerable research activity including the drilling of four geothermal research boreholes since 1961. Although the boreholes have provided data on the thermal gradient and in one instance flowed warm water at a high rate, it is the legacy of mining in the area which has provided the lowest risk opportunity of delivering low-carbon heating. It seems quite plausible that most of the homes in the region could have their heating completely decarbonised by supplying warmth from flooded, abandoned coal mines.

4. DEDICATION

There have been many players in the as yet unfinished story of geothermal energy deployment in NE England but two visionary and determined men stand out as having been the main driving forces behind the discovery of the Weardale Granite and later proof that it would deliver flowing, hot geothermal fluids. Both have recently passed away; Martin Bott (1926 — 2018) and local lad Paul Younger (1962-2018). Geology has lost two giants – we thank you both.

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