Geothermal exploration in the Fell Sandstone Formation (Mississippian) beneath the city centre of Newcastle upon Tyne, UK: the Newcastle Science Central Deep Geothermal Borehole

Paul L. Younger[1,2], David A. C. Manning[1,3], David Millward[4], Jonathan P. Busby[5], Charles R. C. Jones[6] & Jonathan G. Gluyas[7*]

[1] Newcastle Institute for Research on Sustainability (NIReS), Devonshire Building, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[2] Present address: School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK
[3] School of Civil Engineering and Geosciences, Drummond Building, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[4] British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK
[5] British Geological Survey, Environmental Science Centre, Nicker Hill, Keyworth, Nottingham NG12 5GG, UK
[6] Mott MacDonald, 22 Station Road, Cambridge CB1 2JD, UK
[7] Department of Earth Sciences, University of Durham, South Road, Durham DH1 3LE, UK
* Correspondence: j.g.gluyas@durham.ac.uk

Abstract: The postulate that geothermal energy might be recoverable from strata laterally equivalent to the Fell Sandstone Formation (Carboniferous: Mississippian) beneath Newcastle upon Tyne has been examined by the drilling and testing of the 1821 m deep Newcastle Science Central Deep Geothermal Borehole. This proved 376.5 m of Fell Sandstone Formation below 1400 m, much of which resembled braided river deposits found at outcrop, although some lower portions were reddened and yielded grains of aeolian affinity. Downhole logging after attainment of thermal equilibrium proved a temperature of 73°C at 1740 m, and allowed estimation of heat flow at about 88 mW m^{-2}. This relatively high value probably reflects deep convective transfer of heat over a distance of >8 km from the North Pennine Batholith, along the Ninety Fathom Fault. The Fell Sandstone traversed by the borehole proved to be of low hydraulic conductivity ($c.$ 7×10^{-5} m d^{-1}). The water that entered the well was highly saline, with a Na–(Ca)–Cl signature similar to other warm waters encountered in the region. It remains for future directional drilling to establish whether sufficient natural fracture permeability can be encountered, or wells stimulated, to support commercial heat production.

Received 21 June 2016; **revised** 22 September 2016; **accepted** 27 September 2016

Exploration for deep geothermal resources in the UK was concerted from the mid-1970s to the early 1980s (Downing & Gray 1986). There then followed a hiatus of more than two decades, until exploration recommenced with the drilling of the Eastgate Geothermal Exploration Borehole in Weardale, County Durham (Table 1; Manning *et al.* 2007; Younger *et al.* 2012). Besides upgrading previous estimates of the heat production and heat flow rates in the radiothermal North Pennine Batholith (Kimbell *et al.* 2010), the Eastgate Borehole established that the permeable fault intersected within the granite displayed the highest permeability yet reported from a granite anywhere in the world (Younger & Manning 2010). These highly encouraging findings prompted the development of plans to exploit geothermal energy commercially at the Eastgate site. However, following the global economic downturn in 2008, and the abolition of the main sponsor, the regional development agency, in 2010, the wider development of housing and commercial premises planned to accept the geothermal heat was suspended indefinitely. It was clear that a new era of deep geothermal energy use in the UK would not commence at Eastgate after all; other sites would need to be sought where sufficient heat demand could be guaranteed (Younger *et al.* 2012). A redevelopment site in central Newcastle upon Tyne, known as Science Central (Fig. 1), appeared to provide the ideal opportunity, although the geological setting there is rather different from that at Eastgate, as the granite is not present at depth beneath Newcastle.

Science Central overlies the entire thickness of the formerly productive Coal Measures in the Newcastle area, commencing just below ground with old workings in the High Main coal seam. That seam, the highest worked seam in the Great Northern Coalfield, has a consistent thickness of around 2 m in the Newcastle area, and has been extensively mined since the Middle Ages. Flooded coal workings are, of course, a potential geothermal exploration target in their own right (Banks *et al.* 2009; Faull 2011; Preene & Younger 2014; Younger 2014). However, the electricity consumption required to run the heat pumps (needed to upgrade the heat) can detract from the low carbon credentials of the heat supplied. Hence reservoirs with natural temperatures high enough to obviate recourse to heat pumps are more attractive; this is the goal of deep geothermal exploration as currently practised in the UK (Younger *et al.* 2012). The (formerly) economic seams of the Coal Measures extend to a depth of only 220 m beneath Newcastle. At such depths, ground water temperatures would still be far too low to obviate heat-pump use; hence a deeper exploration target was required, albeit this would require drilling a deeper well through the Coal Measures, which can provide challenging ground conditions associated with abandoned mine voids (Younger *et al.* 2002).

Rationale for deep geothermal exploration in Newcastle upon Tyne

Since the earliest days of coal mining in the Newcastle area, there has been an increasing realization that the district has higher geothermal heat flows than many other parts of the UK. Even at relatively shallow depths, generations of miners were accustomed to

Table 1. *Summary details for boreholes mentioned in the text*

Borehole name	BGS registration number	British National Grid Reference		Date drilled	Total depth (m)	Fell Sandstone (m)	
		Easting	Northing			Top	Base
Newcastle Science Central Deep Geothermal	NZ 26 SW 3569	424 010	564 330	2011	1821.0	1418.5	1795.0
Eastgate Geothermal Exploration	NY 93 NW 97	393 870	538 210	2004	995.0	Not present	
Eastgate 2B	NY 93 NW 98	394 526	538 126	2010	420.4	Not present	
Harton Dome 1	NZ 36 NE 80	439 660	565 620	1960	1769.0	1467.3	TD[1]
Longhorsley 1	NZ 19 SW 6	414 442	592 553	1986	1828.0	261.95	1700.78
Rookhope	NY 94 SW 1	393 756	542 789	1960–61	807.7	Not present	
Rowlands Gill	NZ 15 NE 276	416 634	558 141	1986	242.9	Not reached	
Seal Sands 1	NZ 52 SW 308	453 796	523 805	1974–75	4169.7	Not present	
Whitley Bay 1[2]	NZ 37 SW 56	434 900	574 800	1967	2015.0	Not reached	

[1]Base of Fell Sandstone not reached; TD, total depth.
[2]Inclined borehole.

work scantily clad. At a more scientific level, saline waters with geochemical signatures indicative of equilibration at temperatures up to 160°C were found throughout the collieries of the region (Younger *et al.* 2015). Of particular note are the barium-rich Na–Cl brines (Dunn 1877; Clowes 1889; Edmunds 1975), which were found in various collieries that intersected some of the major west–east faults that define the block-and-basin structure of the Carboniferous in northern England (see Turner *et al.* 1995); chief amongst these is the Ninety Fathom Fault (De Paola *et al.* 2005). Particularly prolific inflows of barium-rich Na–Cl brines were associated with the Ninety Fathom Fault and one of its footwall splays (the Rising Sun Fault) in the former North Tyneside collieries of Eccles (UK National Grid Reference [NZ 304 718]) and Rising Sun [NZ 298 683], located 10 and 7.5 km NE of Science Central
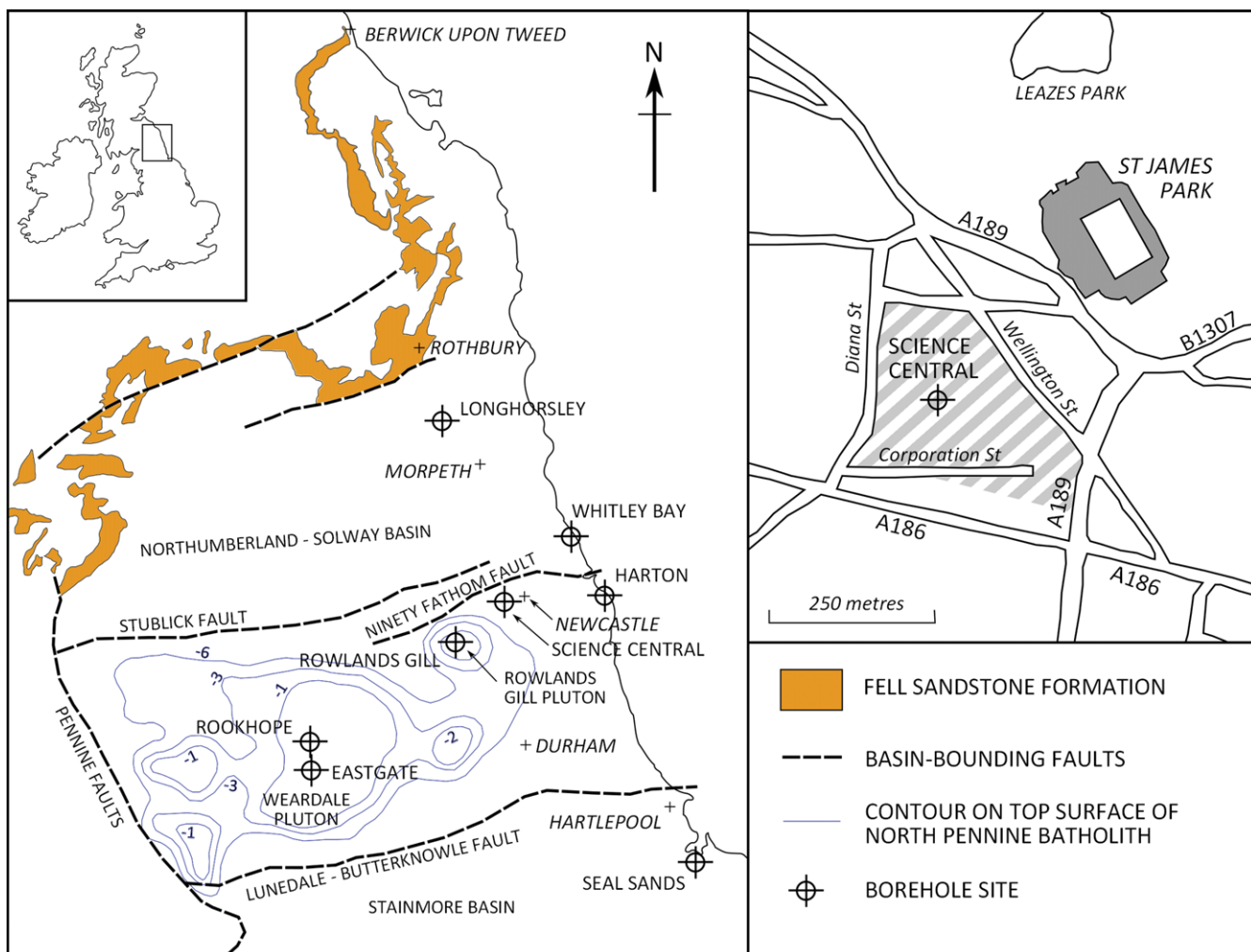

Fig. 1. Map of NE England showing the principal geological features and selected deep boreholes. Contours, in kilometres below Ordnance Datum, indicate the upper surface of the North Pennine Batholith (after Kimbell *et al.* 2010). The larger inset map shows the location of the Science Central Borehole site in central Newcastle upon Tyne in relation to numbered public highways. Contains Ordnance Survey data © Crown copyright and database right 2016. Geological data are from the British Geological Survey DiGMapGB © NERC 2015.

respectively. The recorded flow rates of these brines were significant and remained steady over many years; for example, the Rising Sun pit registered 1.4 million litres per day and Eccles 0.82 million litres per day. These brines were reported as being unusually warm to the touch, and their chemistry indicated equilibration temperatures in the range 150–200°C (Younger *et al.* 2015). At Eccles Colliery, they were so abundant and persistent that they were processed on an industrial scale for their barium content for 43 years until the mine closed in 1978 (Banks *et al.* 1996; Gray & Judd 2003). There are few permanent exposures of the Ninety-Fathom Fault Zone, but at the nearest of these to Newcastle (15 km ENE at Cullercoats Bay [NZ 365 712]) the Permian Yellow Sands, which elsewhere in the region are uncemented, are thoroughly cemented by barite ($BaSO_4$), the same mineral that was precipitated from the brines found in the nearby Rising Sun and Eccles collieries. Clearly, circulation of such brines in the Ninety-Fathom Fault Zone was previously even more widespread. The clear implication is that high-temperature brines might still be circulating within lower reaches of the fault system at greater depths. Where these faults cut competent horizons, fracture permeability might be present.

But is there a suitable thickness of competent rock at suitable depths (1.5–2 km) to ensure commercially viable temperatures (>70°C) beneath Newcastle upon Tyne? At those depths Mississippian strata are the only possibility. Candidate lithologies would be limestone or sandstone. Some of the thicker limestone units in this region, such as the Melmerby Scar Limestone of the North Pennines, could well host permeable fractures, as they do at outcrop; however, they are unlikely to have significant intergranular permeability (Younger 1995). Sandstone might host fracture permeability and also at least some intergranular permeability. The most promising sandstone unit in the regional succession is the Fell Sandstone Formation, which is well exposed in natural crags in mid- to north Northumberland (Fig. 1), where it typically comprises well-sorted, medium- to coarse-grained sandstone, locally coarsening to pebble and granule-grade beds (Robson 1956; Hodgson 1978; Lawrence *et al.* 2011). Between Rothbury and Berwick-upon-Tweed, the Fell Sandstone has long been exploited as a public-supply freshwater aquifer, taking advantage of several large springs and numerous boreholes (Hodgson & Gardiner 1971; Bell 1978; Turner *et al.* 1993; Younger 1995, 1998). All previous boreholes in the Fell Sandstone had been consistent with the facies model erected from outcrop observations (Hodgson 1978; Turner *et al.* 1993): that of a low-sinuosity braided river, with coarsening of the modal grain size in proximity to palaeo fault-scarps (Turner *et al.* 1993). Whether such favourable aquifer properties would persist as far south as Newcastle, given the distances over which facies changes occur in the Mississippian of northernmost England and southern Scotland, or, even if they did, that sufficient porosity would be preserved at burial depths approaching 2 km, were open questions that could not be resolved before drilling.

A more fundamental question concerned whether the Fell Sandstone Formation would be present beneath Newcastle. The possibility that it may not had been mooted previously by Craddock-Hartopp & Holliday (1984), in the context of evaluating potential geothermal prospects. The Harton Dome 1 Borehole (Table 1) penetrated a sandstone unit more than 301 m thick at approximately the right stratigraphic position, although Ridd *et al.* (1970) declined to assign it to the Fell Sandstone 'Group' (later 'demoted' to formation status). However, no sandstone was found in the much deeper (4169 m) Seal Sands 1 Borehole (Table 1; Johnson *et al.* 2011) some 58 km SSE from Newcastle. Therefore, at the start of this project it was not clear that the Fell Sandstone would be found beneath Newcastle upon Tyne.

From the limited deep borehole data available, it was estimated that, if the Fell Sandstone were present beneath Newcastle, it ought to be fully penetrated by a borehole drilled to 2000 m. This was then the maximum drilled depth envisaged for the Newcastle Science

Central Deep Geothermal Borehole (hereafter: Science Central Borehole). However, as the ultimate choice of site was dictated by land availablity and proximity to a putative future heat demand centre (proposed new buildings), it was always clear that the borehole was not ideally located in respect to the Ninety Fathom Fault or any of its known footwall splay faults (see Chadwick *et al.* 1995). It was therefore resolved that, should available funds permit, one or more daughter boreholes would be drilled directionally from the vertical mother hole in the hope of intersecting fault zones within the Fell Sandstone.
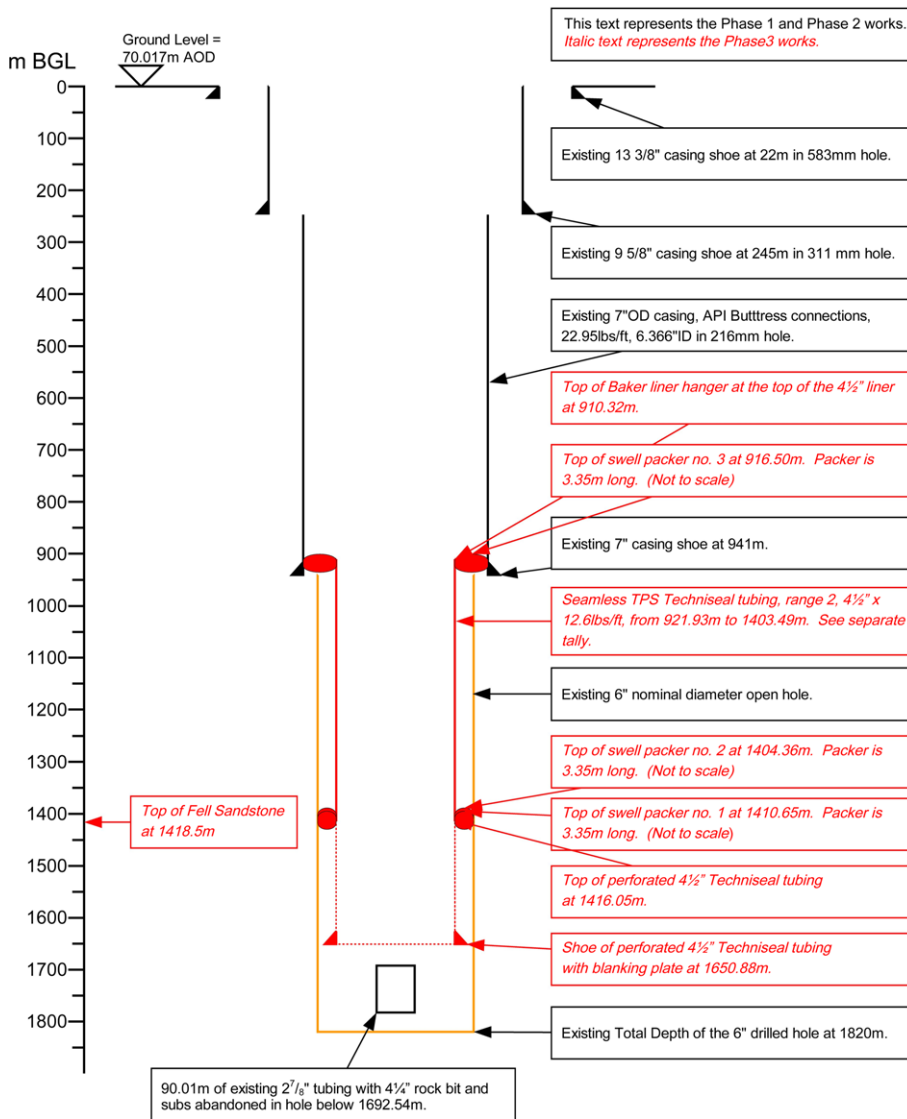
Drilling and well completion

Drilling of the Science Central Borehole (Table 1) started in 2011, with drilling and casing activities taking place in three distinct phases with separate rigs and crews.

In Phase 1 (16 February–15 March 2011) the hole was drilled by Drilcorp Ltd (Drilcorp) using a Beretta T151S rig through the potentially difficult Coal Measures in which old workings were anticipated. A 20 m length of conductor pipe was installed to seal out the shallowest mine workings in the High Main coal seam. Surface casing was then installed to 245.5 m and pressure tested to 10 bar. This depth is some 10.5 m below the floor of the deepest coal seam worked in the Newcastle area (the Brockwell Seam).

During this phase of drilling minor losses of flush occurred, but most coal seams proved to be intact and it appears, fortuitously, that the location chosen for the borehole was on a 'shaft pillar': a radial area of unworked strata surrounding the North Elswick Colliery shaft. However, at a depth of 160 m, a complete loss of flush was experienced through a number of large open fissures cutting a sandstone, which at that point lies about 7 m above the Beaumont (= Harvey) coal seam. Overcoming this loss of flush was not easy and drilling eventually proceeded with lost circulation and no cuttings recovery. It is inferred that the major fissures had propagated from a collapsed mine roadway, probably about 8 m from the borehole.

The shallowest groundwater at about 20 m below ground level (BGL) proved to be perched. Continual saturation was not reached until a depth of about 80 m, which corresponds to the level of the River Tyne about a kilometre away. When the loss of flush occurred at 160 m BGL, the impact on water levels in the borehole was dramatic: where the standing water level in the borehole had been around 6 m BGL, it suddenly dropped to 60.5 m BGL. Cascading water could be clearly heard at the top of the casing. CCTV inspection showed particles being transported downwards into open fractures at around 80 m below sea level; this level appears to reflect the influence of continuing pumping of an old colliery shaft by the Coal Authority at Kibblesworth, some 8 km to the south.

Phase 2 of the drilling (1 June–11 July 2011) was undertaken by Geometric COFOR, working as subcontractor to Drilcorp, using a hydraulic hoist rig (HH102). The drill stack was capped with a blow-out preventer rated to 20.7 MPa (3000 psi), which exceeded by a margin of 4.8 MPa (700 psi) the 'worst-case scenario' in the unlikely event the borehole encountered over-pressured natural gas at 2000 m depth. Casing was installed to 954 m, grouted and pressure-tested to 20.7 MPa (3000 psi). Subsequently, drilling continued using tri-cone rock-rollers in harder strata (such as the dolerite of the Whin Sill intrusion), and polycrystalline diamond compact (PDC) bits with downhole motors in the softer sedimentary strata. Only occasional minor losses of flush were observed and were swiftly rectified by addition of further drilling mud. Drilling was completed on 11 July 2011. Lack of budget prevented drilling of daughter boreholes to intersect faults in the hope of accessing permeability associated with them (see Ellis *et al.* 2014), installation of further casing or screening below 954 m and also delayed geophysical logging until 26 October 2011. Good logs of fluid temperature, conductivity and natural gamma were then

Fig. 2. Science Central well construction diagram.

obtained to a depth of 970 m (i.e. 16 m beyond the toe of the casing). At that depth, the sondes were unable to proceed beyond an obstruction. Subsequently, funds were obtained to deploy a workover rig in July 2012. The borehole was cleaned to 1790 m (which is the base of the Fell Sandstone) using a 122 mm (4¾ inch) drill bit and 72 mm (2⅞ inch) tubing. Although this tubing string became stuck fast at 1782 m, a stabilized bottom-hole temperature of 73.3°C at 1772 m was recorded inside the tubing on 15 August 2012.

A third phase of activity was carried out in 2014 (10 March–2 April), when Newcastle Science City commissioned BDF Ltd, project managed by Mott MacDonald, to reinstate the borehole so that a pump test on the Fell Sandstone could be carried out. BDF mobilized an IDECO 5625 rig and undertook a three-step operation to clear the borehole, install a perforated liner through the Fell Sandstone and carry out a permeability test. The rig was able to rotate the 72 mm tubing but unable to circulate through it or move it

vertically. On 14 March the tubing was cut and 1690 m were retrieved, leaving a 92 m bottom-hole assembly *in situ*. Considerable quantities of backfill were then cleared from the borehole and on 21 March 2014 two geophysical sonde runs (gamma-caliper and gamma short and long resistivity) were made from 1394 m BGL to 1680 m BGL in the open-hole section below a 52 mm drill string. 'Techniseal' tubing was then hung off inside the existing 178 mm (7 inch) casing with a perforated section for the Fell Sandstone interval, from 1418.5 m BGL to the shoe at 1650.88 m BGL. Perforations comprised a series of six drilled holes (12.5 mm diameter) per foot on a spiral pattern of three holes at 120° × 152 mm (6 inch) pitch. Three 'swell' packers were installed on the 115 mm (4½ inch) casing to isolate the casing annulus by sealing against the formation at locations chosen from the gamma-caliper log.

Figure 2 is based on the Phase 3 as-built drawing and includes the casing and drilling details from the earlier phases.

The perforated section was then cleaned and developed by washing with clean water to displace mud, circulation with hypochlorite solution to break down the polymer, airlifting, and repeated forward and reverse circulation with 72 mm (2⅞ inch) eductor at various settings within the slotted section. A short airlift yield test with the eductor at 200 m (the submergence limited by the air compressor) then gave an estimated yield of less than $0.1 \, \text{l} \, \text{s}^{-1}$. Because recovery was very slow, further attempts were made to stimulate flow from the formation by successively lowering the airline by 200 m and airlifting until, ultimately, a pumped water level of 805 m BGL was achieved. From 00:40 on 23 March, final recovery was measured in two stages; first, using the air pressure gauge to calculate submergence; second, using a pressure transducer once water levels had recovered to 200 m BGL.

Once the well had recovered (June 2014), water samples were taken at 500, 1000 and 1500 m using a 2 l motorized water sampler (European Geophysical Services Ltd; EGS). Water samples were analysed using the following techniques: cations by inductively coupled plasma optical emission spectroscopy (ICP-OES) using a Varian Vista MPX axial ICP-OES system with CCD detector according to Standard Methods for the Examination of Water and Waste Water Section 3120B (American Public Health Association; American Water Works Association; Water Pollution Control Federation 1981); anions by ion chromatography, using a Dionex DX 320 ion chromatograph system for Gradient Anion Analysis according to Standard Methods for the Examination of Water and Waste Water Section 4110B; ammoniacal N using a Gerhardt Vapodest distillation unit to conduct the primary distillation step in accordance with Standard Methods for the Examination of Water and Waste Water Section 4500-NH₃ B, followed by titration in accordance with Standard Methods for the Examination of Water and Waste Water Section 4500-NH₃ C; pH and conductivity using a Myron L Company Ultrameter II – pH calibrated with pH 4, 7 and 10 buffers and conductivity with $1413 \, \mu\text{S} \, \text{cm}^{-1}$ standard in accordance with manufacturer's operation manual. Conductivity was also checked using a $12\,880 \, \mu\text{S} \, \text{cm}^{-1}$ standard; alkalinity using a Hach Digital Titrator Model AL-DT kit set up according to manufacturer's operation manual. Two water samples collected during drilling were analysed radiochemically by Tracerco Ltd, Teesside (www.tracerco.com).

Geological and geophysical logging

Interpretation of the geology encountered in the borehole is based on the cuttings log, augmented and corrected for depth using the original natural gamma log. During drilling cuttings samples were taken every 1 m from 4 to 161 m BGL and every 5 m from 251 m to the terminated depth and examined for lithology and reservoir quality; no samples were recovered from the interval 161–251 m as circulation in the borehole was lost. The cuttings are stored in the Materials Collections at the National Geological Repository at the BGS in Keyworth, Nottinghamshire. BGS registration details are given in Table 1.

Wireline geophysical logs were acquired by EGS.

From the customary wireline geophysical log suite available to facilitate geological interpretation, only the natural gamma log was acquired in the first two drilling phases. Problems with side-wall instability meant that, with the exception of the uppermost 239 m through which data were acquired in open hole, the logs had to be acquired through 170 mm diameter steel casing to 943 m and through 60 mm i.d. pipe to the final logging depth of 1782 m. The logs are not corrected for borehole diameter as there was no calliper log. On 3 April 2014 bottom-hole temperature was measured at 68°C (1649 m). Then gamma-caliper and gamma short and long normal resistivity logs were run for the open-hole interval 1394–1680 m BGL. These logs corroborate the interpretation derived

from the earlier geophysical logs. The lack of sonic and/or bulk density and neutron logs makes interpretation of the distinction between sandstone and limestone on the logs difficult. Hence, combining the cuttings and natural gamma logs, the thin limestone and sandstone units recorded within the Yoredale Group may be thicker than they should be. Nevertheless, a consistent lithostratigraphy was determined (Fig. 3). The dip of strata within the succession is unknown but is thought to be shallow in this region, and thicknesses given are apparent. All depths are as measured below ground level.

Stratigraphy

The Science Central Borehole penetrated *c.* 1821 m of Carboniferous rocks, commencing at the ground surface in the Pennine Middle Coal Measures Formation, passing through the Pennine Lower Coal Measures Formation, the Millstone Grit, Yoredale and Border groups, where it terminated in the upper part of the Lyne Formation, as shown in Figure 3. This section provides a summary of the geology and a more detailed account of the sandstone succession in the lower part of the borehole, which was the principal exploration target, and which is here assigned to the Fell Sandstone Formation (Border Group). The lithostratigraphical scheme used is that of Waters *et al.* (2007, 2011) and Dean *et al.* (2011), and summarized by Stone *et al.* (2010).

The succession down to 860 m BGL is comparable with that in the Tyneside area established by Mills & Holliday (1998). Here, the base of the Pennine Middle and Lower Coal Measures formations is dependent upon recognition, respectively, of the Vanderbeckei (Harvey) and Quarterburn (Subcrenatum) marine bands. In the absence of cores these are not identifiable in the Science Central Borehole and the boundaries are established by comparison with boreholes and shaft sections in the Newcastle area reported by Holliday & Pattison (1990). In the Science Central Borehole the base of the Pennine Middle Coal Measures is inferred using the natural gamma log to lie within a mudstone interval at 161.0 m BGL, and the base of the Pennine Lower Coal Measures is inferred to lie within the prominent dark grey siltstone interval at 316.0–320.0 m BGL.

The underlying Millstone Grit Group, 58 m thick, is recognized in the cutting log by the presence, at its base, of a unit of white, coarse- and very coarse-grained sandstone comprising sub-round quartz grains that forms a distinctive low natural gamma response at 360.0–376.0 m BGL. Such a unit is widely present in the Northumberland and Durham region, where it typically overlies the Dipton Foot Shell Beds. This unit was referred to originally as the 'First Grit' within the 'Millstone Grit' of the region (e.g. Dunham 1990), but more recently as part of the 'Stainmore Group' (e.g. Mills & Holliday 1998). Lately, Waters *et al.* (2014) defined and re-established the Millstone Grit Group in NE England.

The Stainmore Formation (Yoredale Group; 293.2 m thick) comprises cyclic successions of thin limestone, mudstone, siltstone, sandstone and coals. Thin limestone beds are identified throughout the formation, the total number conforming to those expected within the formation in this region (Brand 2011). The base of the Stainmore Formation is defined at the base of siliciclastic strata overlying the Great Limestone (Dean *et al.* 2011) and this boundary is established with confidence in the Science Central Borehole through the recognition in cuttings and on the natural gamma logs of marker units consisting of the Little Limestone, Little Limestone Coal(s) and the Great Limestone.

The Great Limestone (15.8 m) is the uppermost unit of the underlying Alston Formation (Yoredale Group). Although lithologically similar to the Stainmore Formation, single limestone units are generally thicker in the Alston Formation. Here, there are also substantial sandstone units; for example, *c.* 12 m in the Four Fathom
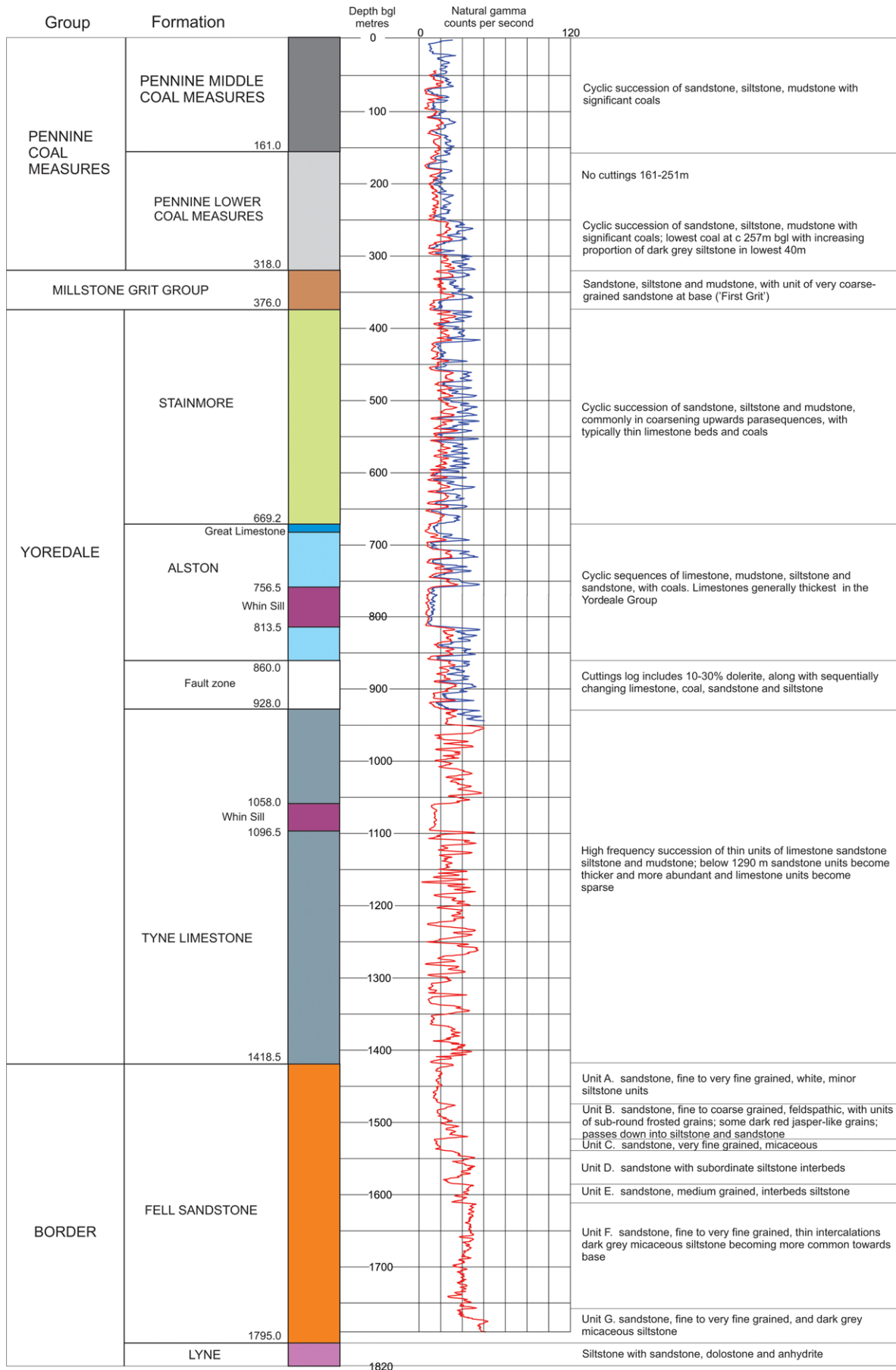
Group	Formation	Depth bgl metres	Natural gamma counts per second	

Fig. 3. Summary interpreted geological log for the Science Central Borehole, with natural gamma-ray logs that were used to assist interpretation of cuttings.

cycle and 6 m in the Three Yard cycle. Between the limestone and sandstone units, intervals of decreasing upward natural gamma log values indicate upwards coarsening from mudstone to sandstone, a characteristic of this formation. Thus, the Alston Formation too has a characteristic natural gamma log profile. However, only a few of the Yoredale cycles are present and at 133.8 m the thickness of the Alston Formation proved in the Science Central Borehole is very much thinner than that seen, for example, in the boreholes (Table 1; Fig. 1) at Rookhope (264.2 m; Johnson & Nudds 1996), Longhorsley 1 (311 m; Lawrence *et al.* 2011) and Harton Dome 1 (467 m; Ridd *et al.* 1970).

The explanation for the unusually thin Alston Formation lies in the interpretation of the cuttings from a 68 m interval from 860.0 to 928.0 m BGL. Throughout this zone quartz-dolerite contributes 10–30% of the cuttings samples. The typically sub-angular shape of the cuttings, and the presence of a gap between the start of this zone and the dolerite seen higher up at 765.5–813.5 m BGL, does not suggest that these are cavings from that unit of dolerite. In addition to the dolerite cuttings, there are changing proportions of limestone, sandstone, mudstone and coal (e.g. at 905 m), suggesting that a stratigraphy is present. This is supported by the character of the natural gamma log, which is similar to that for the Alston Formation above the zone: the constant values for the dolerite would not alter the shape of the curve radically. It is concluded that the zone is a fault, juxtaposing dolerite against Alston Formation. This would explain the very slow drilling rate throughout this section and the worn bit recovered when the drill string was pulled from the bottom of it.

The natural gamma log from the Tyne Limestone Formation entered below the fault zone shows a higher frequency response than that from the Alston Formation and the cuttings contain evidence of many thin limestone and sandstone units alternating with siltstone and mudstone, which is typically micaceous. A few coarsening- and fining-upwards parasequences are noted, although the intervals are generally thinner than in the Alston Formation. Below 1294 m sandstone forms a significant proportion of the formation with units up to 20 m thick. The sandstone is white, fine and very fine grained, and carbonate cemented. The base of the formation at 1418.5 m BGL is marked by the absence of limestone beds and a major change in the character of the natural gamma log. The thickness of the formation is 452 m, less than proved in the Longhorsley 1 Borehole (530 m; Lawrence *et al.* 2011), owing in part to its faulted upper contact.

Of particular interest in the Science Central borehole is the succession of sandstone units, 376.5 m thick, encountered between 1418.5 and 1795 m BGL and interpreted as the Fell Sandstone Formation. This is described in more detail below. The lowest 25 m seen in the borehole consist of red, grey and purple micaceous siltstone with subordinate dolostone, sandstone and evaporite-rock (possibly anhydrite). Although only a few metres were encountered, the lithologies present are similar to the Lyne Formation described from north Cumbria and the Scottish Borders (Day 1970; Ward 1997; Dean *et al.* 2011).

Quartz-dolerite, interpreted as corresponding to the regionally important Great Whin Sill (Randall 1995; Stone *et al.* 2010), occurs at two main intervals in the Science Central Borehole: 765.5–813.5 and 1058.0–1096.5 m BGL, giving a combined thickness of 86.5 m. It is not known whether the further 68 m of quartz-dolerite encountered in the apparent fault zone is a third leaf, a faulted repeat of one of the other leaves, or a dyke. The two main units are perhaps the most readily identified on the natural gamma log and serve as the first-order calibration of the cuttings log. The upper of these two intervals occurs within the Alston Formation between the Four Fathom and Five Yard limestones. The lower interval occurs within the Tyne Limestone Formation. The occurrence here is comparable with that in the Harton Dome 1 Borehole, which proved a combined

thickness of 99.4 m, the thickest known for this unit. However, at Harton all three leaves occur within the Alston Formation.

Fell Sandstone Formation

The Fell Sandstone Formation in the Science Central borehole comprises white, pink and red, very fine- to coarse-grained sandstone with a proportion of dark grey micaceous siltstone that varies from almost none in the lower part to substantial in the upper part. Thin limestone beds are recorded at 1440 and 1750 m BGL. On the basis of the natural gamma log response, the formation is divided into seven units (A–G, Fig. 3). The log response for units D–G displays substantially higher values than for sandstones throughout the rest of the borehole succession, reflecting the argillaceous and commonly highly micaceous nature of the formation. Unit F has the highest gamma values for any sandstone in the borehole succession. The gamma-caliper and gamma short and long normal resistivity logs acquired in 2014 for the open-hole interval 1394–1680 m BGL provide supporting evidence to the subdivisions identified within the Fell Sandstone. EGS reported values of 1.35 and 1.45 ohm m for two samples of the polymer mud in the borehole at the time of logging. The short and long normal resistivity values are around 30 and 35 ohm m respectively over much of the section but where there are depth intervals with higher values (typically in the range 100–150 ohm m; the peak values of 190 and 250 ohm m occur at 1405 m BGL), the long normal value is always the higher.

Most of the sandstone is very fine and fine grained, and weakly calcareous. The exceptions are Unit B, which is coarse grained, and Unit E, which is medium grained. The former is also feldspathic and there are abundant round to sub-round, frosted quartz grains (aeolian) in the upper part of the unit, along with dark red to brown jasper-like grains. The sandstone throughout is quartzitic, although a small proportion of very pale green lithic clasts and dark heavy minerals is evident from visual inspection in all but Unit A, which is also white (all the other sandstones are pale pink to red).

The proportion of interbedded siltstone varies between the units. Unit F appears to contain the least siltstone and Unit B the most. Units D and F comprise two packages dominantly of sandstone separated by siltstone, whereas Unit B coarsens upwards overall from siltstone at the base to sandstone.

With the exception of the occurrence of aeolian grains and the absence of some beds of coal, this sandstone succession resembles the description of the unassigned sandstone formation at the base of the succession in the Harton Dome 1 Borehole (Fig. 1; Table 1). Similarities include the grain size, the argillaceous and micaceous character, and the nature of the cement, with the upper part reported to be calcareous whereas the lower part is siliceous (Ridd *et al.* 1970).

The formation is here equated with the Fell Sandstone Formation, contrary to the conclusion of Ridd *et al.* (1970) for the Harton Dome 1 Borehole. However, there are differences from the Fell Sandstone at outcrop in north Northumberland. There, the Fell Sandstone is typically medium to coarse grained, coarsening locally to pebbly and granule-grade beds (Robson 1956; Lawrence *et al.* 2011); the rocks are generally silica-cemented (Turner *et al.* 1993). Aeolian grains have not, to our knowledge, been reported previously. The grain size of the Science Central Borehole sandstones is more akin to that seen from the Fell Sandstone at outcrop NE of Bewcastle, where the formation is fine to medium grained and more argillaceous, although the rocks there are more lithic rich (Day 1970). The grain-size change is compatible with the more distal location of this new record.

Geothermics

Heat flow is a primary parameter in the assessment of geothermal energy resources and allows more reliable extrapolations of
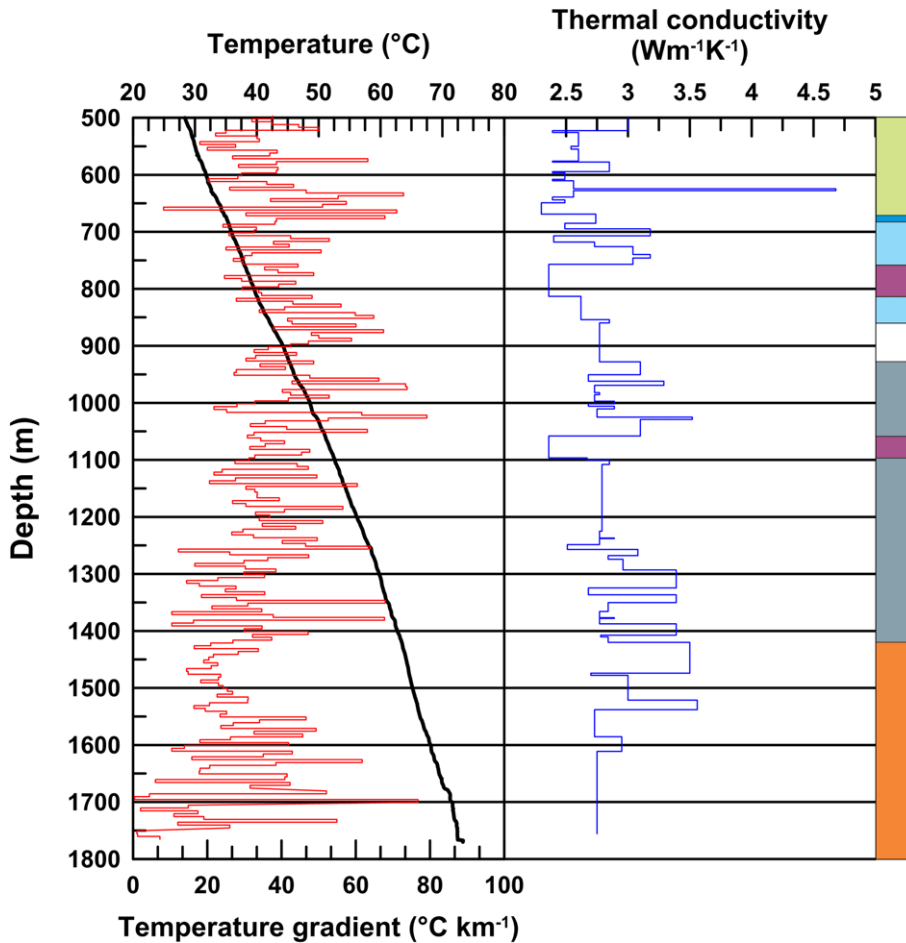
Fig. 4. Plots of temperature (diagonal black line), temperature gradient (grey line in left-hand plot) and estimated thermal conductivity (grey line in right-hand plot) for depths below 500 m in the Science Central borehole. The stratigraphic log, summarized from the full version in Figure 3, is shown on the right.

temperatures to depth than geothermal gradients. Heat flow is considered to be either measured, whereby equilibrium temperatures are combined with measured thermal conductivities from the geological strata over which the equilibrium temperatures were measured (a thermal conductivity log), or estimated, where the thermal conductivities have to be assumed (Rollin 1995). Estimated heat flows are much less reliable than measured, but owing to the lack of onshore boreholes with thermal conductivity logs three-quarters of the UK onshore heat flow dataset is estimated (Busby 2010).

As outlined above, the Science Central borehole was temperature logged on a number of occasions. For geothermic appraisal purposes, the most useful logging event was that carried out on 15 August 2012, more than a year after borehole terminated depth was reached, and a month after the cessation of renewed circulation when the borehole was cleared using the workover rig. An estimate of the residual effect on the temperatures in the borehole owing to flushing has been made with the Horner method (Lachenbruch & Brewer 1959). This shows that at 500 m depth the residual effect is +0.03°C and at 1759 m depth it is −0.03°C. Hence the temperature log recorded in August 2012 can be considered to represent equilibrium temperatures. This is supported by the temperature of 73°C recorded at 1730 m BGL by Schlumberger on 13 March 2014 (20 months after flushing ceased).

The sample returns from the drilling were too fine and too mixed for thermal conductivity measurements. Hence only an estimated heat flow can be determined. However, the Longhorsley 1 Borehole, 30 km to the NNW (Fig. 1; Table 1), drilled in 1986 by Candecca Resources plc has a thermal conductivity log from measurements on chip samples that were corrected for porosities derived from the geophysical logs (Gebski et al. 1987). The sequence penetrated is very similar to that at Science Central except that it commences

below the Millstone Grit (Lawrence et al. 2011). An attempt to transpose this log to Science Central has been made using some key horizons as guides. These are principally the Great Limestone, the Four Fathom Limestone, the Whin Sill (Upper and Lower Leaf), the Five Yard Limestone and the Fell Sandstone. The estimated thermal conductivity log for Science Central is shown in Figure 4 for the depth range 500–1755 m.

Figure 4 also shows the temperature log and, derived from it, the temperature gradient log calculated over 5 m intervals. The temperature gradient log displays significant and rapid variation down the borehole that is consistent with a rapidly varying sequence of siltstone, sandstone and limestone. Below 1400 m the gradient log shows less variation owing to the thick sandstone sequence in the upper section of the Fell Sandstone, and the lower gradients to the bottom of the hole are compatible with a sandstone-dominated sequence.

There are a number of techniques for calculating heat flow. The heat flow Q_d at a depth d is given by

$$Q_d = \lambda_d \left(\frac{\delta T}{\delta z} \right)_d$$

where $(\delta T/\delta z)_d$ is the temperature gradient over the interval of thermal conductivity λ_d. However, a technique that combines all the observations from the borehole is the step-integrated heat flow equation of Bullard (1939). The relationship between the thermal resistance (a measurement of resistance to heat flow in a material) R and the temperature T is linear for conductive, steady-state vertical heat flow with no internal heat production; that is,

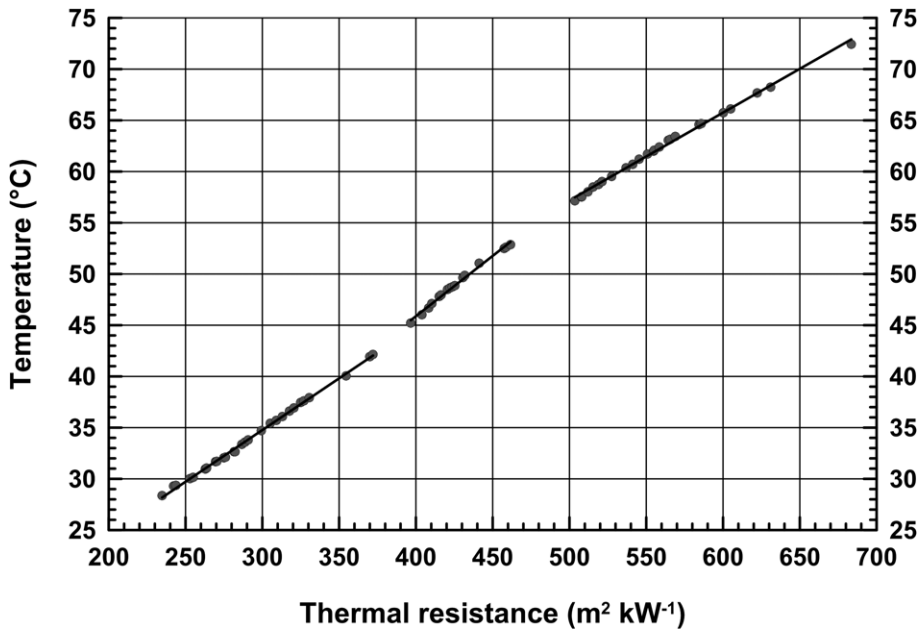$$T_z = T_o + Q \sum_i \left(\frac{\Delta z_i}{\lambda_i} \right)$$

Fig. 5. Bullard thermal resistance plot calculated for depths below 500 m in the Science Central Borehole. Linear regression has been applied to sections of the plot corresponding to the upper, middle and lower sections of the borehole.

where $R = \sum_i (\Delta z_i / \lambda_i)$, λ_i is the thermal conductivity of the ith layer of thickness Δz_i, T_o is the mean ground surface temperature and Q is the heat flow. The Bullard thermal resistance plot is shown in Figure 5. To reduce the influence from palaeoclimate the top 500 m of the borehole has not been used in the analysis. The thermal resistance of this upper section of the borehole has been calculated from the harmonic mean thermal conductivity of the Coal Measures, Millstone Grit and Stainmore Formation (2.13 W m^{-1} K^{-1}). Similarly, the section through the suspected fault zone (860–928 m depth) has been excluded and a general limestone, sandstone and siltstone thermal conductivity has been applied (2.77 W m^{-1} K^{-1}). The best-fit line to all the data has been determined by linear regression, from which the heat flow is 105.0 ± 0.7 mW m^{-2}. On closer inspection of the plot there are three distinct segments corresponding to the upper, middle and lower sections of the borehole. Linear regression of these segments produces heat flows of 101 ± 0.9, 118.0 ± 3.0 and 86.0 ± 1.0 mW m^{-2} respectively.

This range of values is a consequence of the estimated thermal conductivity log. However, within the borehole there are two sections of very homogeneous geology where the measured thermal conductivity from the Longhorsley 1 Borehole can be considered to be a reliable estimate for that at Science Central; these are the two leaves of the Whin Sill. Four measurements of thermal conductivity were made on the Whin Sill dolerite (Gebski *et al.* 1987), the mean of which is 2.36 ± 0.09 W m^{-1} K^{-1}. The Whin Sill was intersected in the Science Central borehole at depths of 765–813 m and 1058–1096 m with corresponding geothermal gradients of 37.25 and 37.63°C km^{-1} respectively. Corresponding heat flows are 88 and 89 mW m^{-2}. It should be noted that the two leaves of the Whin Sill occur in the upper and middle sections of the Bullard resistance plot, indicating the variability of calculated heat flow in these sections. The lower section of the Bullard resistance plot is more geologically homogeneous than the other two sections. In addition, estimates of the mean ground surface temperature from the Bullard resistance plot are 4.5, −1.3 and 14.4°C for the upper, middle and lower sections of the plot. The actual mean ground surface temperature is $c.$ 10°C (Busby *et al.* 2009). Hence, if the associated heat flow determination from the lower section is taken as the best Bullard estimate, then when combined with the values from the Whin Sill the estimated heat flow for the Science Central Borehole is 88.0 ± 1.0 mW m^{-2}.

Within the region four other deep boreholes (Table 1) have yielded heat flow estimates: (1) Harton Dome 1 (15 km east of Science Central), 77 mW m^{-2}; (2) Whitley Bay 1 (15 km NE), 55 mW m^{-2}; (3) Longhorsley 1 (30 km NNW), 92 mW m^{-2}; (4) Rowlands Gill (10 km SW, 99 mW m^{-2}. The elevated value at Longhorsley 1 within the Northumberland trough has been attributed to upward groundwater movement along the Causey Park Fault (Gebski *et al.* 1987). Excluding that localized effect, the general pattern is one of increasing heat flows with proximity to the subcrop of the North Pennine Batholith (Kimbell *et al.* 2010). This
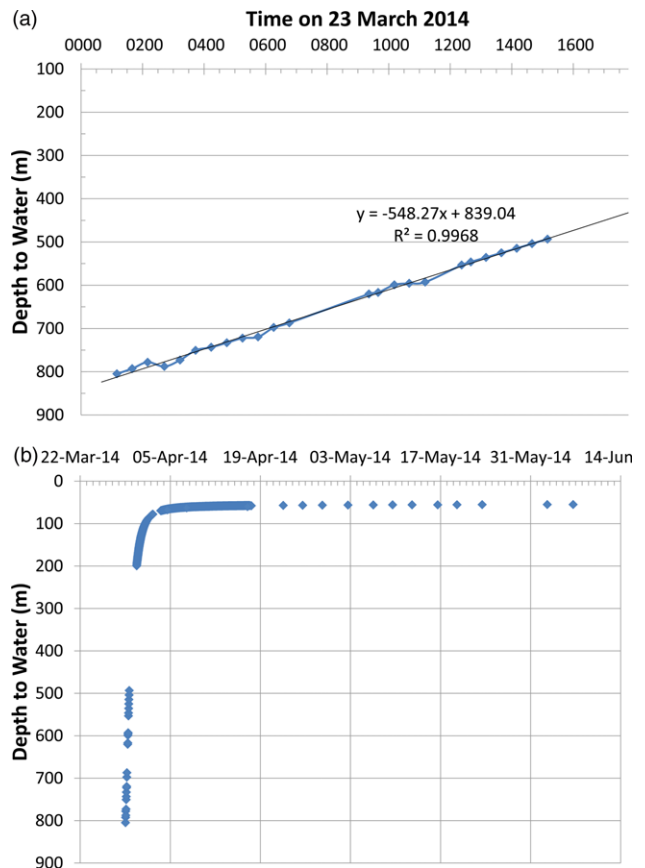

Fig. 6. Water-level recovery data for the post-airlift recovery of water levels in the Science Central Borehole in March 2014 from a maximum drawdown of 805 m. (**a**) Early linear phase of the recovery; (**b**) overall recovery plot.

granite, which has no surface outcrop, has been known to be radiothermal since it was first accessed by the Rookhope Borehole (Table 1) in 1960–61 (Dunham *et al.* 1965), and has recently been a target of geothermal exploration in its own right through the drilling and testing of two boreholes at Eastgate, County Durham (Table 1; Manning *et al.* 2007; Younger & Manning 2010). The northeasterly outpost of the Batholith, the Rowlands Gill Pluton (Kimbell *et al.* 2010), is also its closest subcrop to central Newcastle, lying some 8 km to the WSW of the Science Central Borehole. Given this separation, any influence of that radiothermal granite on heat flow in central Newcastle must be indirect. Inspection of the regional geological framework (Kimbell *et al.* 2010) leads to the suggestion that convection of deep groundwater may be occurring along the major west–east-striking faults of the Stublick–Ninety Fathom Fault system (Fig. 1). These faults appear to intersect the Rowlands Gill Pluton, and the principal fault (the Ninety Fathom Fault) crops out *c.* 2 km north of Science Central. This does not necessarily mean that hot water from the convective zone is entering the Fell Sandstone, but it does at least imply that thermal conduction above zones of hot groundwater flow could explain the observed positive heat anomaly in central Newcastle.

Hydraulic conductivity testing and permeability

The problems encountered in pumping a significant amount of water from the borehole have already been described, and these precluded obtaining a reliable analysis of permeability from time–drawdown data. The best estimate of permeability was thus obtained by analysis of the recovery of water levels from 805 m BGL (Fig. 6), following evacuation of the borehole to that depth by airlifting. The early stage of the recovery is plotted in Figure 6a; this is distinctly linear, and analysis reveals that over the first 300 m of water-level rise, the rate of recovery was around 0.006 m s^{-1}. This rate applied as long as the water level was rising through the 178 mm (7 inch) well casing, which has an internal volume of 19.96 l m^{-1} (and an internal airline in place with a volume of 4.19 l m^{-1}); hence the rate

of recovery equates to a water inflow rate from the Fell Sandstone Formation of about 0.1 l s^{-1}.

The complete set of recovery data for the logger and hand dipped water levels is shown in Figure 6b. As can be seen, the linear recovery continued to around 150 m BGL after which the anticipated curvature of the plot occurs, reflecting progressive decline in effective hydraulic gradient towards the well. The total recovery represents an inflow of 18 125 l.

After considering a number of methods of analysis of the data, that of Cooper *et al.* (1967) was selected (see Kruseman & De Ridder 1990). This method applies to slug tests in fully penetrating wells in confined aquifers and therefore takes into account compressibility of the aquifer (matrix and water) and the borehole well diameters in the inflow section and at the depth at which the water level rise is measured. Although the assumption of an instantaneous slug prior to recovery was not met owing to prior airlifting, the later data, where the ratio of h_t (head change after time t (days)) to h_o (initial head change when $t = 0$) approaches 0.1, occurs at a time where the pumping phase could be considered to be almost instantaneous, owing to its relatively short duration equivalent to only 10% of the subsequent recovery period. (The better-known BSI 5930 1999 method, based on Hvorslev (1951), was not used because of the importance of accounting for compressibility, rather than inflow from some arbitrarily assumed boundary (Chirlin 1989).) No corrections for density have been made as the measured range of levels is so large.

The type curve for $\alpha = 10^{-5} - 10^{-4}$ (Fig. 7) was selected because α is calculated based on the confined storage coefficient (S) multiplied by the factor $(r_{ew}/r_c)^2$, where r_{ew} and r_c are the radii of the effective intake zone and zone of storage change respectively. Kruseman & de Ridder (1990) noted that for $S < 10^{-5}$, an error of two orders of magnitude in S will result in an error of less than 30% in transmissivity. Taking S as being $<10^{-4}$ with β defined as kDt/r_c^2 and reading off the match point for $\beta = 1$ as around 0.4 days, , the resulting value of transmissivity (kD) is 0.016 m^2 d^{-1}.
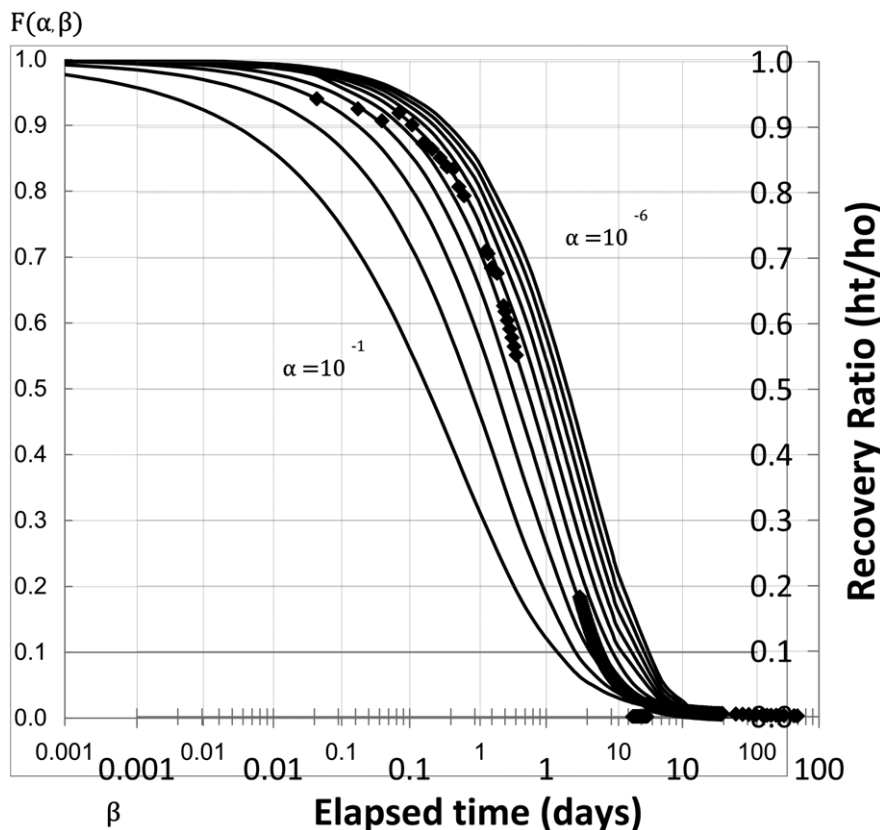

Fig. 7. Analysis of water-level recovery data in the Science Central Borehole (March 2014 test) using the method of Cooper *et al.* (1967).

Table 2. *Analyses of deep water samples taken from the Science Central Borehole (April and June 2014)*

Sample depth (m):	500	1000	1500	1500
Date:	11/06/14	11/06/14	11/06/14	03/04/14
Temperature (°C)	14.4	14.5	14.4	12.9
Conductivity (mS cm^{-1})	84.13	161.7	>200	196.8
pH	4.95	3.75	3.31	3.24
Alkalinity (pH 4.5) (mg CaO$_3$ l)	33	0	0	0
Calcium	5916	13093	19399	18030
Magnesium	573	1248	2047	1623
Sodium	15144	39132	60200	53806
Potassium	312	868	1366	1195
Lithium	28.6	27.0	35.7	16.7
Ammonium	12.2	37.4	57.6	50.4
Strontium	308.0	432	695	720
Barium	46.4	2.6	3.5	2.5
Silicon	0.3	0.6	1.8	1.8
Zinc	1.3	3.2	7.1	3.2
Nickel	<0.1	<0.1	7.4	3.1
Iron	75.1	61.0	44.8	3.1
Manganese	9.6	20.5	33.9	21.8
Copper	0.3	19.0	27.5	37.0
Chromium	<0.1	<0.1	1.1	0.15
Chloride	36940	86100	136100	134800
Sulphate	<100	810	1250	930
Electroneutrality (%)	−0.8	1.2	−0.5	−5.3

Values for elements are in mg l^{-1}. Elements below detection were Pb (<0.5 mg l^{-1}), Cd (<0.1 mg l^{-1}), Al (<0.5 mg l^{-1}) and As (<0.5 mg l^{-1}).

Taking the effective aquifer thickness (D) as 234 m (set equal to the length of slotted casing installed in the well) and using the standard conversion of permeability (k) to hydraulic conductivity (K), the resulting average K is estimated to be 7×10^{-5} m d^{-1} (i.e. 8.1×10^{-10} m s^{-1}). Assuming the slotted casing is partially penetrating over the full 350 m thickness of the Fell Sandstone, K would be 4.7×10^{-5} m d^{-1} (i.e. 5.4×10^{-10} m s^{-1}). This is, however, a lower bound solution and may therefore be an underestimate of the hydraulic conductivity, as the borehole is likely to be plugged somewhere below the slotted casing, thus preventing the inflow from the full thickness of Fell Sandstone. It is more likely that the thickness of the layers contributing flow is <234 m owing to the presence of siltstone beds and mica-rich horizons within the sandstones, which are likely to have significantly lower hydraulic conductivity (permeability) than the better-sorted, quartz-rich sandstone beds.

A K of 7×10^{-5} m d^{-1} is six orders of magnitude lower than reported intergranular permeabilities for the Fell Sandstone Formation aquifer in the Berwick area (see Bell 1978; Turner *et al.* 1993; Younger 1995). Is this very low value representative of the aquifer, or does it reflects a reduction in permeability caused by mud invasion during drilling? The high salinity of the water is a clear signal of communication with the surrounding aquifer. The careful process of development followed in 2014, involving washing the borehole with clean water to displace mud, adding hypochlorite to break down polymer, and then reducing the fluid level to around 800 m below hydrostatic with subsequent recovery to around 60 m, is likely to have substantially cleared the annulus around the 115 mm (4½ inch) perforated tubing. It is also likely that any wall cake left behind from the original drilling would spall off owing to the high differential pressure between the formation and wellbore when head was lowered by 805 m. Hence, it is reasonable to conclude that the test result for average hydraulic conductivity is a reasonable characteristic of the permeability of the Fell Sandstone. Low matrix hydraulic conductivity is also suggested by the short and long resistivity logs where the latter exceed the former, indicating a higher bulk resistivity in the formation than in the

borehole. The electrical conductivity of the water (Table 2) of around 200 mS cm^{-1} shows that the pore fluid is a 20% brine with a resistivity of around 0.05 ohm m. This yields an estimated Formation Factor (F) (i.e. the ratio of observed resistivity (uncorrected for borehole fluid) to interstitial resistivity) of about 700 (for an observed resistivity of 35 ohm). Inserting this value of F into Archie's Law ($F = 0.81 \times \varphi^{-2}$; Archie 1942) yields a porosity (φ) of less than 3.5%, with even lower values where the resistivity is higher. This compares with typical observed values in near-outcrop samples of 15–25% (Bell 1978; Younger 1992).

Water chemistry

As noted above, samples of water were taken on 3 April 2014 as part of a borehole logging exercise. As the sample taken at 1500 m BGL was highly saline, a separate sampling exercise was carried out in June 2014, following recovery of the water level within the well. This sampling exercise involved no other disturbance of the water column. The results of the analyses are given in Table 2. These reveal all of the waters to be Na–(Ca)–Cl brines, with most analytes increasing in concentration with depth. This is consistent with highly saline brine entering the well during recovery and mixing with freshwater that was left in place following drilling.

The Na–(Ca)–Cl hydrochemical facies is consistent with observed compositions of other saline groundwaters in this region (Edmunds 1975; Younger *et al.* 2015). Figure 8 allows comparison with the waters most proximal to Science Central (those reported from deep coal mines in the region; Edmunds 1975), as well as with the water encountered in the Eastgate Geothermal Exploration Borehole (Table 1; Manning *et al.* 2007). A consistent linear trend emerges, suggestive of a regional brine facies at depth, appearing in collieries historically and in the Science Central Borehole at the present time. Importantly, the Science Central water differs from the Eastgate water by being much more saline (which could reflect dilution at Eastgate via the mineralized and mined fracture systems of the North Pennine Orefield), and by lacking a radioactive component related to ^{238}U or ^{228}Th decay (radiological analysis on
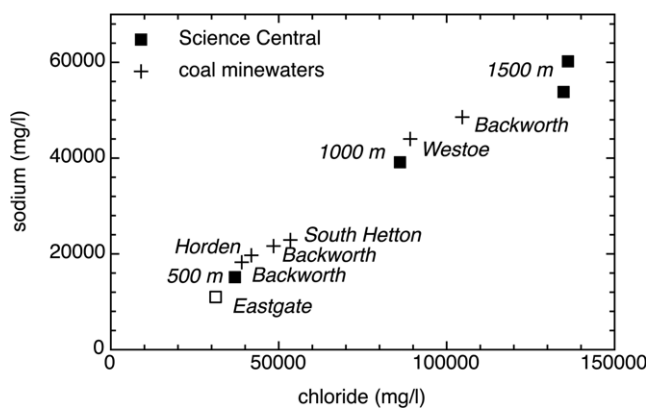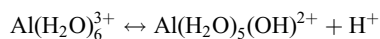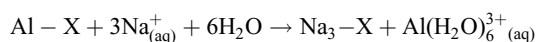
Fig. 8. Water compositions for samples taken from Science Central well, the Eastgate borehole (Manning *et al.* 2007) and Backworth, Westoe, South Hetton and Horden collieries (Edmunds 1975).

samples taken during drilling at Science Central showed no such activity). The water contains significant (but low) concentrations of ammonium, as would be expected (Manning & Hutcheon 2004).

One way in which the Science Central waters differ from those encountered elsewhere in the region is in the very low values of pH they display (Table 2). The values here (3.24–4.95) are clearly distinct from the typical range of 6.1–7.5 reported by Younger *et al.* (2015). The reasons for this are not clear. Low pH is not common in brines, but neither is it unknown. For instance, in Western Australia, Na–Cl brines with low pH are widespread (Lillicrap & George 2010). However, the origins of acidity in those waters are ascribed to near-surface processes that clearly would not be active in the deep sandstones of Tyneside: atmospheric oxidation of iron minerals and/or evaporative concentration leading to precipitation of carbonate minerals in the shallow subsurface, thus denying the buffering capacity of dissolved carbonate to deeper waters (Lillicrap & George 2010). Given that there are a number of possible explanations for the overall salinity of the deep waters in northern England, including evaporite dissolution, equilibration with low-solubility silicate minerals over extremely long time periods and/or sub-permafrost concentration of waters by solute freeze-out (Younger *et al.* 2015), it is conceivable that the low pH observed in the Science Central Borehole reflects subsequent ion exchange reactions between sodium-rich waters and aluminium-rich clay minerals, as previously postulated by Bettenay *et al.* (1964), according to the following reaction scheme:

$$Al - X + 3Na^+_{(aq)} + 6H_2O \rightarrow Na_3 - X + Al(H_2O)_6^{3+}{}_{(aq)}$$

$$Al(H_2O)_6^{3+} \leftrightarrow Al(H_2O)_5(OH)^{2+} + H^+$$

where X represents a binding position on the clay mineral surface. This reaction scheme is not without its problems, however (Lillicrap & George 2010, p. 49). Another possibility might be ferrolysis of the steel casing in the borehole, although why this should occur in the absence of oxygen is difficult to explain. This is clearly a matter for further research.

With this sole exception, however, the hydrochemistry of the Science Central brines fits unexceptionally within the family of Na–(Ca)–Cl brines in northern England, which have been reported to be warm to the touch in some cases, and which have calculated equilibration temperatures in the range 120–190°C (Younger *et al.* 2015), temperatures suggestive of significant geothermal potential where permeability permits, albeit such high salinities would pose engineering challenges for sustained heat-exchange operations.

Discussion and conclusions

The Science Central Borehole has settled the long-standing controversy over the presence of the Fell Sandstone this far south. It has also vindicated the postulated high heat flow on Tyneside, with reliable bottom-hole temperature measurement of 73.3°C at 1772 m. Combination of temperature measurements with thermal conductivity data from a nearby borehole penetrating the same succession has allowed calculation of a heat flow of 88 ± 1 mW m^{-2}. This is significantly above typical background values for the UK (*c.* 50 mW m^{-2}) and is therefore encouraging from the perspective of geothermal exploration. If such heat flows can be harnessed, the potential benefits are significant: Busby (2010) calculated the inferred geothermal (heat) resource for the UK to be around 300×10^{18} Joules for heat that could be abstracted from Permian and younger deeply buried rocks in UK sedimentary basins. This is about 100 times greater than the energy consumed each year to heat domestic and industrial properties in the UK, which represents the single greatest end-use of energy in the UK (Younger *et al.* 2012). If heat in pre-Permian strata (such as the Mississippian rocks reported here) is added to that inventory, then even if only a modest fraction of the resources were to be harnessed, the potential contribution that geothermal energy could make to reducing greenhouse gas emissions and enhancing energy security is truly substantial. To date, very little progress has been made in exploration for geothermal energy in the UK, principally because the availability of cheap natural gas from the UK continental shelf over the last four decades has disincentivized the search for alternatives. Hence, the UK still has only one producing deep geothermal well (in Southampton), although interest in other prospects has been growing, most notably through the drilling at Eastgate and Science Central (Table 1; Younger *et al.* 2012) and more recently in relation to the possibility of repurposing ageing oilfields to deliver warm water for heating purposes (Hirst *et al.* 2015).

The Science Central case illustrates, however, that we still have insufficient knowledge of the transmissivity of potential deep geothermal aquifers to ensure success in early stage drilling. There are only about 2000 deep wells in the onshore UK and most of these are petroleum exploration, appraisal and production wells in the East Midlands, Wessex and Weald basins. Work done prior to drilling highlighted the fact that the Fell Sandstone is a prolific, transmissive aquifer near its outcrop in central and northern Northumberland (Fig. 1; Younger 1995). Therefore there was good reason to expect that, if present beneath Tyneside, the Fell Sandstone might indeed be productive. If our argument is accepted that our hydraulic conductivity estimate is reasonable, then there is clearly a need to expand our understanding of why intergranular permeability is so low at this site, and to investigate whether exploration elsewhere in this deep aquifer might yet prove successful. The low value of porosity inferred using Archie's Law (<3.5%) is significantly lower than the values of 20–30% found near outcrop (Bell 1978; Younger 1992, 1995), but such low permeability values are considerably greater than would be expected if this lower porosity were still as effective (i.e. owing to interconnected pores) as is routinely observed nearer outcrop. The clear implication is that cementation (by carbonate in the upper part of the formation, and by silica in the lower part) has occluded pore necks so that much of the remnant porosity is poorly interconnected. However, where post-cementation fracturing has occurred (e.g. in faults known to have been reactivated strike-slip during the Cenozoic, and/or in faults oriented subparallel to the present axis of maximum compressive crustal stress (see Ellis *et al.* 2014)), then this non-negligible porosity might well have been re-interconnected, offering scope for significant fluid flow and thus geothermal production. The original plan to drill lateral wells to intersect faults and their damage zones thus remains a reasonable avenue of enquiry for future research and exploration.

Acknowledgements and Funding

References

American Public Health Association; American Water Works Association; Water Pollution Control Federation 1981. *Standard methods for the examination of water and wastewater: selected analytical methods approved and cited by the United States Environmental Protection Agency.* American Public Health Association, Washington, D.C.

Archie, G.E. 1942. Electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the American Institute of Mining Engineers*, **146**, 54–62.

Banks, D., Younger, P.L. & Dumpleton, S. 1996. The historical use of mine-drainage and pyrite-oxidation waters in central and eastern England, United Kingdom. *Hydrogeology Journal*, **4**, 55–68.

Banks, D., Fraga Pumar, A. & Watson, I. 2009. The operational performance of Scottish minewater-based ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology*, **42**, 347–357, http://doi.org/10.1144/1470-9236/08-081

Bell, F.G. 1978. Petrographical factors relating to porosity and permeability in the Fell Sandstone. *Quarterly Journal of Engineering Geology*, **11**, 113–126, http://doi.org/10.1144/GSL.QJEG.1978.011.02.01

Bettenay, E., Blackmore, A.V. & Hingston, F.J. 1964. Aspects of the hydrologic cycle and related salinity in the Belka Valley, Western Australia. *Australian Journal of Soil Research*, **2**, 187–210.

Brand, P.J. 2011. The Serpukhovian and Bashkirian (Carboniferous, Namurian and basal Westphalian) faunas of northern England. *Proceedings of the Yorkshire Geological Society*, **58**, 143–165, http://doi.org/10.1144/pygs.58.3.283

Bullard, E.C. 1939. Heat flow in South Africa. *Proceedings of the Royal Society of London, Series A*, **173**, 428–450.

Busby, J.P. 2010. Geothermal prospects in the United Kingdom. *In*: Proceedings, World Geothermal Congress 2010, Bali, Indonesia, 25–29 April 2010. http://nora.nerc.ac.uk/15965/1/GeothermalProspectsUK.pdf

Busby, J.P., Lewis, M., Reeves, H. & Lawley, R. 2009. Initial geological conditions before installing ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology*, **42**, 295–306, http://doi.org/10.1144/1470-9236/08-092

Chadwick, R.A., Holliday, D.W., Holloway, S. & Hulbert, A.G. 1995. *The structure and evolution of the Northumberland–Solway Basin and adjacent areas. British Geological Survey Subsurface Memoir*. HMSO, London.

Chirlin, G.R. 1989. A critique of the Hvorslev method for slug test analysis: the fully penetrating well. *Ground Water Monitoring and Remediation*, **9**, 130–138.

Clowes, F. 1889. Deposits of barium sulfate from mine water. *Proceedings of the Royal Society*, **46**, 368–369.

Cooper, H.H., Bredehoeft, J.D. & Papadopulos, I.S. 1967. Response of a finite diameter well to instantaneous charge of water. *Water Resources Research*, **3**, 263–269.

Craddock-Hartopp, M.A. & Holliday, D.W. 1984. *The Fell Sandstone Group of Northumberland: Investigation of the geothermal potential of the UK*. British Geological Survey, Keyworth.

Day, J.B.W. 1970. *Geology of the country around Bewcastle. Memoir of the Geological Survey of Great Britain, England and Wales. Sheet 12*.

Dean, M.T., Browne, M.A.E., Waters, C.N. & Powell, J.H. 2011. *A stratigraphical framework for the Carboniferous successions of northern Great Britain (onshore)*. British Geological Survey Research Report, **RR/10/07**, Her Majesty's Stationary Office, London.

De Paola, N., Holdsworth, R.E. & McCaffrey, K.J.W. 2005. The influence of lithology and pre-existing structures on reservoir-scale faulting patterns in transtensional rift zone. *Journal of the Geological Society, London*, **161**, 471–480, http://doi.org/10.1144/0016-764904-043

Downing, R.A. & Gray, D.A. 1986. The geothermal resources of the United Kingdom. *Journal of the Geological Society, London*, **143**, 499–507, http://doi.org/10.1144/gsjgs.143.3.0499

Dunham, K.C. 1990. *Geology of the Northern Pennine Orefield; Volume 1 Tyne to Stainmore. Economic Memoir of the British Geological Survey, England and Wales, Sheets 19 and 25, and parts of 13, 24, 26, 31, 32, 2nd edn*. Her Majesty's Stationary Office, London.

Dunham, K.C., Dunham, A.C., Hodge, B.L. & Johnson, G.A.L. 1965. Granite beneath Viséan sediments with mineralization at Rookhope, northern Pennines. *Quarterly Journal of the Geological Society of London*, **121**, 383–417, http://doi.org/10.1144/gsjgs.121.1.0383

Dunn, J.T. 1877. On a water-box deposit. *Chemical News*, **35**, 140.

Edmunds, W.M. 1975. Geochemistry of brines in the coal measures of Northeast England. *Transactions of the Institution of Mining and Metallurgy, London (Section B: Applied Earth Science)*, **84**, B39–B52.

Ellis, J., Mannino, I., Johnston, J., Felix, M.E.J., Younger, P.L. & Vaughan, A.P.M. 2014. Shiremoor Geothermal Heat Project: reducing uncertainty around fault geometry and permeability using Move™ for structural model building and stress analysis. European Geosciences Union General Assembly 2014, Vienna, 27 April–2 May 2014, EGU2014-15069. http://meetingorganizer.copernicus.org/EGU2014/EGU2014-15069.pdf

Faull, M.L. (ed.) 2011. *Heat-pump technology using minewater*. National Coal Mining Museum for England Publications, **13**. National Coal Mining Museum for England, Overton.

Gebski, J.S., Wheildon, J. & Thomas-Betts, A. 1987. *Investigation of the UK heat flow field (1984–1987). Investigation of the geothermal potential of the UK*. British Geological Survey, Keyworth.

Gray, G. & Judd, A.G. 2003. Barium sulphate production from mine waters in South East Northumberland. *British Mining*, **73**, 72–88.

Hirst, C.M., Gluyas, J.G. & Mathias, S.A. 2015. The late field life of the East Midlands Petroleum Province; a new geothermal prospect? *Quarterly Journal of Engineering Geology and Hydrogeology*, **48**, 104–114, http://doi.org/10.1144/qjegh2014-072

Hodgson, A.V. 1978. Braided river bedforms and related sedimentary structures in the Fell Sandstone Group (Lower Carboniferous) of north Northumberland. *Proceedings of the Yorkshire Geological Society*, **41**, 509–532, http://doi.org/10.1144/pygs.41.4.509

Hodgson, A.V. & Gardiner, M.D. 1971. An investigation of the aquifer potential of the Fell Sandstone of Northumberland. *Quarterly Journal of Engineering Geology*, **4**, 91–108, http://doi.org/10.1144/GSL.QJEG.1971.004.02.01

Holliday, D.W. & Pattison, J. 1990. *Carboniferous geology of Corbridge and Prudhoe: geological notes and local details for sheets NZ06 and the eastern parts of NY96NE and SE (Northumberland)*. British Geological Survey Technical Report, **WA/90/013**.

Hvorslev, M.J. 1951. *Time lag and soil permeability in ground-water observations*. US Army Corps of Engineers, Vicksburg, Mississippi, Waterways Experiment Station Bulletin, **36**.

Johnson, G.A.L. & Nudds, J.R. 1996. Carboniferous biostratigraphy of the Rookhope Borehole, Co. Durham. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **86**, 181–226.

Johnson, G.A.L. Somerville, I.D., Tucker, M.E. & Cozar, P. 2011. Carboniferous stratigraphy and context of the Seal Sands No. 1 Borehole, Teesmouth, NE England; the deepest onshore borehole in Great Britain. *Proceedings of the Yorkshire Geological Society*, **58**, 173–196, http://doi.org/10.1144/pygs.58.3.231

Kimbell, G.S., Young, B., Millward, D. & Crowley, Q.G. 2010. The North Pennine batholith (Weardale Granite) of northern England: new data on its age and form. *Proceedings of the Yorkshire Geological Society*, **58**, 107–112, http://doi.org/10.1144/pygs.58.1.273

Kruseman, G.P. & De Ridder, N.A. 1990. *Analysis and Evaluation of Pumping Test Data, 2nd edn*. ILRI Publication, **47**.

Lachenbruch, A.H. & Brewer, M.C. 1959. Dissipation of the temperature effect of drilling a well in Arctic Alaska. *US Geological Survey Bulletin*, **1083-C**, 73–109.

Lawrence, D.J.D., Dean, M.T., Entwisle, D.C., Kimbell, G.S. & Butcher, A. 2011. *Geology of the Rothbury district – a brief explanation of the geological map. Sheet Explanation of the British Geological Survey. 1:50,000 sheet 9 Rothbury (England & Wales)*.

Lillicrap, A. & George, R.J. 2010. *The distribution and origins of acid groundwaters in the South West Agricultural Area*. Department of Agriculture and Food, Western Australia, Report 362. http://researchlibrary.agric.wa.gov.au/cgi/viewcontent.cgi?article=1343&context=rmtr

Manning, D.A.C. & Hutcheon, I.E. 2004. Distribution and mineralogical controls on ammonium in deep groundwaters. *Applied Geochemistry*, **19**, 1495–1503.

Manning, D.A.C., Younger, P.L., Smith, F.W., Jones, J.M., Dufton, D.J. & Diskin, S. 2007. A deep geothermal exploration well at Eastgate, Weardale, UK: a novel exploration concept for low-enthalpy resources. *Journal of the Geological Society, London*, **164**, 371–382, http://doi.org/10.1144/0016-76492006-015

Mills, D.A.C. & Holliday, D.W. 1998. *Geology of the district around Newcastle upon Tyne, Gateshead and Consett. Memoir of the British Geological Survey, Sheet 20 (England and Wales)*, British Geological Survey, Keyworth.

Preene, M. & Younger, P.L. 2014. Can you take the heat? – Geothermal energy in mining. *Mining Technology*, **123**, 107–118, http://doi.org/10.1179/1743286314Y.0000000058.

Randall, B.A.O. 1995. The Great Whin Sill and its associated dyke suite. *In*: Johnson, G.A.L. (ed.) *Robson's Geology of North East England. (The Geology of North East England, Second Edition)*. Transactions of the Natural History Society of Northumbria, **56**, 319–327.

Ridd, M.F., Walker, D.B. & Jones, J.M. 1970. A deep borehole at Harton on the margin of the Northumbrian trough. *Proceedings of the Yorkshire Geological Society*, **38**, 75–103 http://doi.org/10.1144/pygs.38.1.75

Robson, D.A. 1956. A sedimentary study of the Fell Sandstones of the Coquet Valley, Northumberland. *Quarterly Journal of the Geological Society of London*, **112**, 241–262, http://doi.org/10.1144/GSL.JGS.1956.112.01-04.12

Rollin, K.E. 1995. A simple heat-flow quality function and appraisal of heat-flow measurements and heat-flow estimates from the UK Geothermal Catalogue. *Tectonophysics*, **244**, 185–196.

Stone, P., Millward, D., Young, B., Merritt, J.W., Clarke, S.M., McCormac, M. & Lawrence, D.J.D. 2010. *British Regional Geology: Northern England*, 5th edn. British Geological Survey, Keyworth, Nottingham.

Turner, B.R., Younger, P.L. & Fordham, C.E. 1993. Fell Sandstone Group lithostratigraphy southwest of Berwick-upon-Tweed: implications for the regional development of the Fell Sandstone. *Proceedings of the Yorkshire Geological Society*, **49**, 269–281, http://doi.org/10.1144/pygs.49.4.269

Turner, B.R., Robson, D.A., Dearman, W.R., Jones, J.M.M., Magraw, D. & Smith, F.W. 1995. Structure. *In*: Johnson, G.A.L. (ed.) *Robson's Geology of North East England. (The Geology of North East England, Second Edition)*. Transactions of the Natural History Society of Northumbria, **56**, 331–343.

Ward, J. 1997. Early Dinantian evaporites of the Easton-1 well, Solway basin, onshore, Cumbria, England. *In*: Meadows, N.S., Trueblood, S.P., Hardman, M. & Cowan, G. (eds) *Petroleum Geology of the Irish Sea and Adjacent Areas*. Geological Society, London, Special Publications, **124**, 277–296, http://doi.org/10.1144/GSL.SP.1997.124.01.17

Waters, C.N., Browne, M.A.E., Dean, M.T. & Powell, J.H. 2007. *Lithostratigraphical framework for Carboniferous successions of Great Britain (Onshore)*. British Geological Survey Research Report, **RR/07/01**.

Waters, C.N., Dean, M.T., Jones, N.S. & Somerville, I.D. 2011. Northumberland Trough and Solway Basin. *In*: Waters, C.N., Somerville, I.D. *et al.* (eds) *A Revised Correlation of Carboniferous Rocks in the British Isles*. Geological Society, London, Special Reports, **26**, 89–95.

Waters, C.N., Millward, D. & Thomas, C.W. 2014. The Millstone Grit Group (Pennsylvanian) of the Northumberland–Solway Basin and Alston Block of northern England. *Proceedings of the Yorkshire Geological Society*, **60**, 29–51, http://doi.org/10.1144/pygs2014-341

Younger, P.L. 1992. The hydrogeological use of thin sections: inexpensive estimates of groundwater flow and transport parameters. *Quarterly Journal of Engineering Geology*, **25**, 159–164, http://doi.org/10.1144/GSL.QJEG.1992.025.02.09

Younger, P.L. 1995. Hydrogeology. *In*: Johnson, G.A.L. (ed.) *Robson's Geology of North East England. (The Geology of North East England, Second Edition)*. Transactions of the Natural History Society of Northumbria, **56**, 353–359.

Younger, P.L. 1998. Long term sustainability of groundwater abstraction in north Northumberland. *In*: Wheater, H. & Kirby, C. (eds) *Hydrology in a Changing Environment (Proceedings of the International Symposium organised by the British Hydrological Society, 6–10 July 1998, Exeter, UK), Volume II*. Wiley, Chichester, 213–227.

Younger, P.L. 2014. Hydrogeological challenges in a low-carbon economy (The 22nd Ineson Lecture). *Quarterly Journal of Engineering Geology and Hydrogeology*, **47**, 7–27, http://doi.org/10.1144/qjegh2013-063

Younger, P.L. & Manning, D.A.C. 2010. Hyper-permeable granite: lessons from test-pumping in the Eastgate Geothermal Borehole, Weardale, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, **43**, 5–10, http://doi.org/10.1144/1470-9236/08-085

Younger, P.L., Banwart, S.A. & Hedin, R.S. 2002. *Mine Water: Hydrology, Pollution, Remediation*. Kluwer, Dordrecht.

Younger, P.L., Gluyas, J.G. & Stephens, W.E. 2012. Development of deep geothermal resources in the UK. *Proceedings of the Institution of Civil Engineers – Energy*, **165**, 19–32, http://doi.org/10.1680/ener.11.00009

Younger, P.L., Boyce, A.J. & Waring, A.J. 2015. Chloride waters of Great Britain revisited: from subsea formation waters to onshore geothermal fluids. *Proceedings of the Geologists' Association*, **126**, 453–465, http://doi.org/10.1016/j.pgeola.2015.04.001