Title: A deep geothermal exploration well at Eastgate, Weardale, UK: a novel exploration concept for low-enthalpy resources

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Abstract:

The first deep geothermal exploration borehole (995 m) to be drilled in the UK for over 20 years was completed at Eastgate (Weardale, Co. Durham) in December 2004. It penetrated 4m of sandy till (Quaternary), 267.5 m of Lower Carboniferous strata (including the Whin Sill), and 723.5 m of the Weardale Granite (Devonian), with vein mineralization occurring to 913 m. Unlike previous geothermal investigations of UK radiothermal granites that focused on the hot dry rock concept, the Eastgate Borehole was designed to intercept deep fracture-hosted brines associated with the major, geologically ancient, hydrothermal vein systems. Abundant brine (=46 °C) was encountered within natural fracture networks of very high permeability (transmissivity c. 2000 darcy m) within granite. Evidence for the thermal history of the Carboniferous rocks from phytoclast reflectance measurements shows very high values (=3.3%) indicating maximum temperatures of 130 °C prior to intrusion of the Whin Sill. Geochemical analysis of cuttings samples from the Eastgate Borehole suggests radiothermal heat production rates for unaltered Weardale Granite averaging 4.1 µW m^sup -3^, with a mean geothermal gradient of 38 °C km^sup -1^. The Eastgate Borehole has significant exploitation potential for direct heat uses; it demonstrates the potential for seeking hydrothermal vein systems within radiothermal granites as targets for geothermal resources.

Geothermal energy is used globally in applications ranging from electricity generation (using steam to drive turbines) to space heating using ground source heat pumps (GSHP), which extract energy from shallow groundwater and/or soil atmospheres. In Europe, geothermal energy use depends on the balance of availability of differing energy sources. Thus Iceland, with readily available volcanogenic geothermal resources, is one of the world's major users for space heating. The UK has been very slow to develop its more modest geothermal resources, with only one significant scheme (<1.4 MW; a single geothermal well contributing to Southampton's district heating scheme), and a growing number of GSHP applications for individual buildings (mainly new-build domestic premises). The slow uptake in the UK partly reflects the ready availability of indigenous oil and gas over the last three decades. Norway and Sweden show the contrast in geothermal uptake between countries with and without hydrocarbon resources: Norway makes almost no use of geothermal energy, whereas Sweden is one of Europe's greatest users, entirely in the form of GSHP (Sanner et al. 2003).

As energy costs rise, especially for fossil fuels, interest in alternative sources is increasing. Globally, nuclear energy and coal (with varying degrees of 'cleanliness' in burning) will be used increasingly for electricity generation during the 21st century. Interest in renewable sources of energy, such as wind power, is also increasing. But geothermal energy can play a much greater role within a portfolio of energy supply options than is currently considered. There are potentially many locations where geothermal energy is insufficient to generate electricity, but where it can contribute to space heating and other low-grade uses currently met by distributed fossil fuel combustion. Displacement of the domestic gas boiler from tens of millions of homes would contribute more to the UK's greenhouse gas emission reduction obligations than almost any other technological change (cf. Caneta Research 1999).

In Weardale, County Durham, UK, the recent decommissioning of the Lafarge cement works has led to a major redevelopment opportunity at a rural site. The Weardale Task Force anticipates a mixed-use redevelopment, making use of indigenous renewable energy sources, including wind and hydroelectric power generation, and biomass combined heat and power. Geothermal energy is being considered for space heating and for use in a spa tourist attraction.

The concepts underlying the geothermal exploration activity undertaken at the Eastgate site are novel, and represent a significant development from those previously applied to the inferred geothermal resources of the UK. Initiated in 1976 at the time of the Middle East oil crisis, geothermal exploration in the UK focused until its end in 1990 on the potential for generating electricity. The cost-effective generation of electricity from geothermal resources (DiPippo 2005) generally requires that waters yielded by production wells have temperatures considerably in excess of 100 °C, so that on exposure to atmospheric (or near-atmospheric) pressure, they will 'flash', i.e. liberate steam at rates high enough to drive conventional turbines. Additionally, binary cycles (including the Kalina cycle) are used for power generation in which geothermal waters at < 140 °C vaporize other 'working fluids' to produce gas streams sufficient to turn turbines (DiPippo 2005). Outside active volcanic areas, there are few parts of the world in which economically accessible geothermal waters are hot enough for flash or binary cycle electricity generation. However, there are many direct uses that can exploit the thermal energy in sub-100 °C geothermal waters (e.g. space or district heating; greenhouse heating; aquaculture; health spa tourism developments, etc.; Lund et al. 1998; Dickson & Fanelli 2005). These options were not a priority during the 1976-1990 investigations in the UK. Rather, two principal options for deriving supra-100 °C waters from the UK continental crust were examined (Barker et al. 2000).

(1) Hydrothermal aquifers: corresponding principally to Mesozoic basins, in which permeable formations are likely to be present at depths that will ensure that they contain hot water.

(2) hot dry rock (HDR): in which the heat generated by radiothermal granites was to be exploited by drilling deep boreholes, between which fractures would be

developed artificially (e.g. hydraulic fracturing; explosives). Cool water would be pumped down into the fractured granite, left to equilibrate thermally, and then pumped out again at much higher temperatures.

In many ways, both of these exploration concepts were decades ahead of their time. Although the hydrothermal aquifer investigations did not result in the identification of flash or binary grade energy, they did identify resources suitable for direct-use applications, as used to the present day by the Southampton Geothermal Heating Company. Many other similar resources await exploitation. Although the HDR experiments undertaken in the Carnmenellis Granite (Cornwall), using boreholes sunk at Rosemanowes Quarry to depths of 1700-2600 m, did not result in an operational geothermal exploitation scheme (Richards et al. 1994), they did yield a dataset used widely to test numerical simulation codes (Kolditz & Clauser 1998). They provided much of the conceptual basis upon which the European Union pilot project at Soultz-sousForêts (Rhine Graben) has successfully built (e.g. Bachler & Kohl 2005), using artificial fracturing to enhance natural structures in granite to obtain an exploitable resource, which is now generating electricity using a binary power plant.

Given their focus on resources suitable for electricity generation, the 1976-1990 investigations did not fully consider the direct use for space heating of deep groundwater or GHSP resources. They were also too early to investigate the possibilities of man-made hydrothermal aquifers now associated with saturated mine workings at great depth (> 1000m), which have become flooded only since 1990 (see Younger & Adams 1999; Banks et al. 2004).

In this paper, we present a further exploration possibility: the concept that ancient hydrothermal vein structures associated with the radiothermal granites of the UK still function as geothermal plumbing systems, and may be economically viable. In testing this concept, we have sunk the first deep geothermal exploration borehole to be drilled in the UK for 20 years, and only the second borehole ever to penetrate the Weardale Granite, a key component of the classic 'block-and-basin' geology of the Carboniferous of northern England (e.g. Fraser & Gawthorpe 2003).

Geological background

Weardale lies within the UK's first Geopark, designated in recognition of the importance of the North Pennines in shaping views on the origin of Mississippi-Valley Type mineral deposits. The North Pennines Orefield is famous (Dunham 1990) for its zoned fluorite-sphalerite-galena-barite mineralization, which is principally developed in Lower Carboniferous limestones. The zoning of the orefield stimulated geophysical investigations that demonstrated a gravity 'low' coinciding with the fluorite zone of the mineralization (Bott & Masson-Smith 1953, 1957), which was interpreted as being due to the presence of a buried granite. Drilling at Rookhope in 1960 (Dunham et al. 1965) proved the existence of the Weardale Granite, which unexpectedly proved to be Early Devonian in age, hence older than the mineralized host rocks, a finding that required a complete revision of ore deposit models for the North Pennines (Dunham 1990).

Interest in the Weardale Granite as a 'radiothermaP granite is based on its comparatively high concentrations of uranium, thorium and potassium. It is one of a family of similar granites in the UK with high heat production rates (Webb et al. 1985, 1987; Downing & Gray 1986), including the Carnmenellis Granite (the former HDR prospect in Cornwall; Richards et al. 1994).

In the late 1980s, investigations were carried out on a tepid saline water found at depth in Cambokeels Mine at Eastgate (Manning & Strutt 1990), issuing from the eastern forehead of the fluorite-bearing Slitt Vein where it cuts Dinantian limestones and clastic sediments. Manning & Strutt (1990) compared the Cambokeels mine water with saline waters, originating from fractures in the Carnmenellis Granite, reported by Edmunds et al. (1984). They suggested that the Eastgate mine water was derived from deep within the Weardale Granite, and that it had precipitated silica minerals during its ascent through the Slitt Vein fracture system. Use of geochemical thermometers suggested that the water had equilibrated with a granitic host at temperatures up to 150 °C.

There is further evidence of a high geothermal gradient in the Eastgate-Rookhope area. Downing & Gray (1986) reported a temperature gradient of 30 °C km^sup -1^ for the Rookhope Borehole, and Younger (2000) reported a gradient of over 60 °C km^sup -1^ from the Frazer's Grove Mine (Greencleugh Vein, similar in structure and filling to the Slitt Vein), several kilometres west of the Rookhope Borehole and directly above a mineralization spreading centre (Dunham 1990).

On the basis of the geological information summarized above, it was decided that the geothermal exploration well at Eastgate should commence within the Slitt Vein as a suspected pathway for deep water upflow, and attempt to follow the vein and associated splays vertically downwards for up to 1 km (Fig. 1), the total depth being limited by the available budget. A starting position above the sub-crop of the Slitt Vein against the base of the Quaternary deposits was identified by trial-pitting and drilling five inclined boreholes (at 45-60°) to depths of up to 60 m. The final borehole site was precisely surveyed by global positioning system (GPS) with reference to the National Grid, and lies at 393890.932 E 538200.147 N, commencing at a surface elevation of 250.867 m above Ordnance Datum (AOD). In the interests of speed and economy, the deep borehole was drilled Open-hole' (by Foraco, Lunel, France), recovering cuttings at 1 m intervals (within sedimentary rocks and granite) down to 615 m, and then at 5 m intervals (granite). From surface to 93 m the well was cased and grouted to 13 [fraction three-eight] inches, from 93 m to 403 m cased and grouted to 9 [fraction five-eigth] inches (with this casing being continued to surface). From 403 m to full depth at 995 m, the borehole was completed without casing, at a drilled diameter of 8 ½ inches.

Cuttings taken from the well were washed and their lithologies logged on site. A complete suite of cutting samples was deposited with the British Geological Survey. Selected samples of cuttings from the sedimentary sequence were taken for vitrinite reflectance determination, and samples of cuttings from the granite were taken at intervals of c. SO m for analysis using X-ray fluorescence (XRF; fused beads for major elements; powder pellets for trace elements) at the University of Leicester, Department of Geology. Water samples were taken for analysis every 10-20m down to 300m, and then at 50m intervals. Specific electrical conductance ('conductivity') and temperature of the water arising from the borehole were monitored continuously at the cuttings separator at the wellhead.

Summary of findings: geology

The Eastgate Borehole penetrated 271.5 m of recent and Lower Carboniferous cover rocks then nearly 723 m of basement granite. Overall, the sequence closely resembled that penetrated by the Rookhope Borehole (Dunham et al. 1965; Fig. 2). Superficial deposits of Recent and Quaternary age were encountered down to rockhead at about 4 m (all depths in this section are below drilling table, which was at 252.75 m AOD), and consisted mostly of sand, gravel and boulders. The borehole was open-holed to 10 m without casing, so that there was considerable cross-contamination of rock cuttings with caved drift material over that interval.

The Scar Limestone was present from rockhead to about 12 m below drilling table, and was karstified (the shallow inclined boreholes penetrated caves that were entirely filled with damp mud). This was underlain by the 'Alternating Beds', a sequence of thinly bedded limestones, mudstones and sandstones. The Tynebottom Limestone was recognized between 39.5 and 51.5 m. As with the other horizons below the Scar Limestone, this formation was heavily mineralized (by a combination of quartz replacements and veinlets); it was also the source of a significant increase in groundwater influx to the borehole. The Jew Limestone was encountered between 76 and 83 m, again mineralized. Immediately beneath it (83-87 m) was a vein of coarse green fluorite, interpreted as a branch of the Slitt Vein. The Great Whin Sill, extensively carbonated and altered to 'white whin', was intercepted at 92 m, and continued to 158.5 m.

Rocks beneath the Great Whin Sill were heavily silicified and veined by quartz down to about 175.5 m. Beneath this the sequence was essentially devoid of mineralization for almost 50 m, and the Smiddy, Upper and Lower Peghorn, and Birkdale Limestones were easily recognized. The Robinson Limestone (223.5-234.5 m) was fractured and heavily replaced by quartz and calcite. Similar mineralization continued into the Melmerby Scar Limestone (239.5-249.5 m), below which the Orton Group and Basement Beds (sandstones with occasional thin limestones) occurred between 249.5 and 272.5 m, cut by veinlets of mineralization.

The granite surface at 272.5m below table (271.5m below surface) was marked by the occurrence of cuttings of a sticky white clay, presumably kaolinitic, over an interval of 0.5 m. The first few metres of granite were relatively soft, then became harder and more coherent. The granite resembles the cored material from the Rookhope Borehole, and is fairly uniformly coarse grained (2-6 mm), consisting of feldspars, quartz, muscovite and biotite. It has a greenish hue, probably the result of hydrothermal alteration of the feldspars. Mineralization was found throughout the granite, usually as quartz veinlets with sporadic occurrences of pyrite, chalcopyrite or galena.

Cuttings from 415 to 615 m were uniform, with sparse indications of mineralization. Below 615m cuttings were taken at intervals of 5 m. Fluorite mineralization was intersected between 620 and 650m (recognized in waste cuttings, rather than in the samples collected at 5 m intervals). Minor quartz-pyrite veinlets were encountered at 655.5 m, associated with sticky white clay (presumably kaolinite). White quartz veins were encountered at 690 m and 720-721 m. Deeper, three fine-grained quartz veins with pyrite and hematite were encountered (740-742 m, 888.5 m, 912-913.5 m).

Comparing the depths at which different marker horizons have been encountered in other boreholes and at outcrop, it appears that the pre-Carboniferous surface was very flat (8 m or so relief over the 10 km distance between Rookhope and Eastgate). This suggests that future boreholes can be planned with greater confidence using existing deep borehole data.

In summary, typical North Pennine Orefield mineralization was found down to about 720 m, with more complex mineralization beneath that depth. These observations suggest that the borehole followed the Slitt Vein structure down to 720 m. Below this depth the Slitt Vein may have died out, or more probably deviated too far from the borehole azimuth to be recognized.

In addition to the lithological description, phytoclast reflectance (individual macerals were not distinguished because of the high maturity) was determined on cuttings from the sedimentary sequence and compared with those obtained for material from the Rookhope core (Table 1). Reflectance data are similar for both boreholes, and clearly show the contact metamorphic effects of the Great Whin Sill, with a regular profile above the sill (Fig. 3; cf. Creaney 1980), perturbed by the Little Whin Sill in the Rookhope Borehole (the Eastgate Borehole started lower in the succession than this). Below the Great Whin Sill, Figure 3 shows considerable scatter in the profile of reflectance measurements. This may be due to caving from higher in the borehole prior to the installation of casing. Immediately above and below the Whin Sill, reflectance values reach 9% or more, consistent with contact temperatures in excess of 400 °C (Karweil 1955). Furthest below the Great Whin Sill, reflectance values for the lowest two samples are remarkably similar: 3.52% and 3.37% for Eastgate and 3.73% and 3.54% for Rookhope. The similarity between these values and the profiles shown in Figure 3 suggests that the heat flow from the granite to the overlying sediments was very similar for the two locations, which, although separated by 10 km, have identical intervals between the base of the Great Whin Sill and the top of the Weardale Granite (114 m).

Although it is difficult to recast vitrinite reflectance data into palaeotemperarures, it can be assumed that the very high reflectance values reported here (not less than 3.3%) correspond to maximum temperatures of the order of 130 °C close to the contact between the overlying sediments and the granite. These temperatures may have been reached prior to intrusion of the Great Whin Sill (305 Ma; Fitch & Miller 1967; recalculated by Cann & Banks 2001), which, according to the sill emplacement model of Goulty (2005), was into sediments with an approximate depth of 1.4 km (total sediment thickness on top of the granite of 1.5km). This is consistent with the conclusion of Dunham (1987) that the Weardale area had exceptionally high geothermal gradients prior to the emplacement of the Whin Sills.

Geochemistry of the Weardale Granite: implications for heat production

Limited geochemical analyses of selected samples from the granite were made to evaluate its heat production potential, and to provide additional geological information and indicate the degree of uniformity of the rock. Sixteen samples of cuttings were selected at c. 50 m intervals, and analysed for major and trace elements using XRF (Table 2). Originating from a borehole drilled in conditions that were aggressive towards the drilling equipment, the cuttings were contaminated with tungsten, molybdenum and chromium (metals associated with hardened tools), as well as iron. Despite this contamination, compositional data are similar to those reported by Brown et al. (1987) for core samples of the Weardale Granite from the Rookhope Borehole.

Downhole homogeneity is readily assessed from data for Na^sub 2^O, K^sub 2^O and CaO (Fig. 4). For both the Rookhope and Eastgate samples, the top

200 m of the granite show considerable variation. Below this depth, these oxides are relatively constant. Similarly, the trace elements Rb and Sr, and the naturally radioactive elements Th and U show variable behaviour above, and greatest values below, 200 m depth within the granite, in both boreholes (Figs 5 and 6).

Variation within the top 200 m of the granite may partly be due to the presence of fluorite mineralization (consistent with observed F contents; Table 2) as well as weathering prior to the deposition of the overlying sediments. Similarly Dunham et al. (1965) showed considerable enrichment in Al_2O_3 (and K_2O) within the upper 25 m of the granite, consistent with the development of an illitic or micaceous palaeosol.

The heat production capacity of the granite can be calculated from the chemical analysis (Downing & Gray 1986), using the equation (P. C. Webb, pers. comm.)

A = 0.1326?(0.718U + 0.193Th + 0.262K)

where A is heat production in $\mu W\ m^{-3}$, ?!is density in g cm^{-3}, U is uranium content in mg kg^{-1}, Th is thorium content in mg kg^{-1} and K is potassium content in element percent.

For the purpose of calculation, the specific gravity of the granite was assumed to be 2.63 (Dunham et al. 1965); estimation of specific gravity for each sample by measuring the displacement of 100ml of water by 100 g of cuttings to obtain their volume, agitating ultrasonically to remove occluded air, gave a value of 2.58.

Figure 7 shows downhole variations in the calculated heat production capability of the granite at Eastgate, compared with recalculated values for the Rookhope Borehole using geochemical data from Brown et al. (1987). For the Eastgate samples in general, heat production values rise from 3 $\mu W\ m^{-3}$ to an average value of 4.1 $\mu W\ m^{-3}$ below 200 m depth from the granite surface. Observed reductions in heat production values at depths >400 m within the granite may be due to quartz veining, and have been excluded in the calculation of the average heat production value.

Overall, the geochemical data from the granite yield the following results (Table 3).

(1) The heat production value for unaltered granite is estimated to be 4.1 μW m^{-3}, excluding samples at borehole depths of 400 m and shallower, and excluding the 740 and 950 m samples, which contain quartz vein material. This value exceeds that reported by Downing & Gray (1986) for the Weardale Granite (3.7 μW m^{-3}).

(2) Heat production appears to increase with depth, overall, with local perturbations related to the occurrence of veins of quartz and other discontinuities that are unlikely to affect the bulk heat production capacity.

No attempt has been made to measure the thermal conductivity of the granite from the Eastgate Borehole. Heat flow has been estimated on a preliminary basis with the following assumptions. For the entire vertical interval, a mean value for thermal conductivity of 2.99 W m^{-1} K^{-1} has been estimated using values from Downing & Gray (1986) for different rock types (Weardale granite from the Rookhope core and Carboniferous lithologies), weighted according to thickness. Heat production within the granite has been neglected, and a ground surface temperature of 8 °C has been used. With these assumptions, the heat flow at Eastgate is estimated to be 115 mW m^{-2}, well in excess of values reported by Downing and Gray (1986) for Rookhope.

Water strikes and hydrogeological conditions

Significant water strikes were encountered during drilling, with unusually high rates of groundwater ingress from the Carboniferous sequence (requiring a tri-cone roller bit instead of using hammer drilling). At times, the water yield from the

Carboniferous strata of this one borehole exceeded the entire former dewatering rates of a number of local mines. These high water yields reflect the high permeability of fractures associated with the Slitt Vein structure.

Installation of casing isolated shallow-sourced groundwaters from the borehole. The first casing sealed the hole off from water associated with limestones above the Whin Sill, on the assumption that the Sill itself is rarely a prolific aquifer. However, two major water feeders were encountered within the Whin Sill, bringing the borehole water yield back to levels found in the overlying sedimentary strata (c. 60 m^{3} h^{-1}).

Once the borehole had penetrated 13Om into the granite, the installation of the second casing was intended to eliminate all shallow feeders. Given the generally low permeability of granite, subsequent feeders would be expected to be minimal unless there was unusually intense fracturing. As expected, after the second casing had been grouted into the borehole, water yield dropped to zero, and this continued for a further 7 m. However, at around 410m below ground, the drill stem pressure gauge jumped to 23 bar, and the drill bit suddenly dropped by 0.5 m. At this point the pressure gauge went off-scale (>30bar), and water surged into the hole, rapidly rising to within 10 m of the ground surface. It is clear that a major open fissure had been encountered at this point. The electrical conductivity of this water greatly exceeded that of the waters previously encountered in the Carboniferous, and it was also warm to the touch (around 26 °C). Air-lifting at rates of up to 60 m^{3} h^{-1} (maximum capacity of the equipment) failed to lower the water level by more than 1 m, indicating a transmissivity in excess of 2000 darcy m. This is believed to be an unequalled value for granites worldwide (E. Sudicky, pers. comm.), although it clearly reflects the influence of the Slitt Vein, rather than the permeability of more typical extensional joints and faults typical of most plutons. Other fractures were intersected at depths of 436, 464, 492-496, 654, 720-721, 739.5 and 813-814.5 m. These fracture intersections were not accompanied by dramatic events such as occurred at 410 m, and the quantities of water that they introduced to the borehole were difficult to discern given that the 410 m feeder had already exceeded the air-lift capacity of the rig. A gradual increase in the temperature of the water arriving at the well head (>27 °C towards the end of drilling) indicated that a significant amount of warmer deeper water was mixing with the 410 m feeder water.

After the end of drilling geophysical logs for fluid temperature, conductivity and flow rate (by impeller) were run twice: first through the static water column, and then with a 100 mm electric submersible pump stimulating the borehole water column by pumping from just below the water surface at a rate of around 1.4 m^sup 3^ h^sup -1^. Comparison of the two suites of logs indicates significant water feeders associated with fractures at c. 730 and 756 m depth. (Other feeders were also indicated by the geophysical logs at 420, 434, 447, 485, 497, 527, 540, 557, 670 and 686m.) Although none of these were as prolific as the 410 m feeder, they demonstrate the occurrence of permeable fractures at depths approaching those that could be considered for a long-term production borehole.

Groundwater quality

The electrical conductivity and temperature of water from the borehole were measured continuously at the cuttings separator. Water samples were taken initially every 10-20 m, and every 50 m for depths >300 m. Cations were determined using inductively coupled plasma atomic emission spectroscopy, alkalinity by titration, ammonium inductively coupled plasma atomic emission Kjeldahl digestion and anions by ion chromatography. Water samples up to and including 86.5 m were acidified before filtration; this meant that dissolved suspended solids were reported in the chemical analysis, giving misleading results that overestimated dissolved cations (high positive charge balances). From 135 to 995 m samples were filtered prior to acidification, with charge balances predominantly less than ±5%. Analyses are given in full in Table 4.

With depth, conductivity and temperature rise until c. 400 m (Fig. 8), at which point there is a sharp increase in both. This corresponds to the point at which the hole intersected the large open fracture at 41Om. Individual chemical species show contrasting behaviour with depth. The major cations (Na, K, Mg, Ca), lithium, strontium and chloride increase in the same way as conductivity, with a sudden increase once the 41Om feeder had been intercepted (Fig. 9). Observed pH decreases, from 7.6-8.1 to 5.8-6.0, probably reflecting the absence of bicarbonate buffering at depth: alkalinity (expressed as mg l^sup -1^ CaCO^sub 3^) decreases with depth to very low values, as does dissolved sulphate.

The constancy of the chemical composition of the water below 400 m reflects a combination of two possible causes: the water column within the hole is well mixed as a consequence of the drilling operation and/or the contribution of water from the fissure at 410 m is sufficiently strong to dominate water chemistry during drilling. There is no evidence from the water chemistry of any substantial flow of water that is more saline (i.e. deeper sourced) or less saline (i.e. derived from nearer the surface) into the hole at depths greater than 410 m.

The deep brine encountered by the borehole has as dominant solutes 27 700 mg l^sup -1^ chloride, 10 030 mg l^sup -1^ sodium and 5320 mg l^sup -1^ calcium. Comparing its composition with water recovered from Cambokeels mine (Manning & Strutt 1990; Table 5), there is little doubt that the Eastgate Borehole has intersected the same water system (over 15 years after the brine was sampled in the mine) where it is deeper, more saline and wanner.

Importantly, the Eastgate Borehole water is about 25% more saline than seawater, but less than half (36%) the salinity of the water currently produced at the Southampton geothermal plant. It is more than twice the salinity of thermal waters reported from South Crofty Mine (Edmunds et al. 1984). As in South Crofty, molar Cl/Br ratios for the Eastgate water are below that typical of seawater (650), which could be attributed to loss of Cl via precipitation of halite through evaporation; in contrast, the high value for Southampton suggests halite dissolution. Molar Na/Li ratios are very low for the Eastgate and South Crofty waters, indicating substantial interaction with basement rocks, and their molar Na/Br ratios are again consistent with water-rock interaction (whereas the Southampton water's high Na/Li and Na/Br ratios are consistent with halite dissolution). The Eastgate water is close in composition to that identified by Cann & Banks (2001) as being associated with fluorite zone mineralization. Although unlikely to be a mineralizing fluid in its own right (although silica minerals are likely to have precipitated) the Eastgate water seems to have shared a common fluid-rock interaction history with the waters responsible for fluorite mineralization. Psyrillos et al. (2003) discussed the role of water from adjacent basins as part of the kaolinization process in the SW England granites. As the South Crofty and Eastgate waters are so similar in their major solute proportions, it is likely that analogous processes led to their formation, and the Eastgate waters may be derived ultimately from adjacent deep aquifers.

Using the chemical data given in Table 5, temperatures at which the water may have equilibrated can be estimated (Truesdell 1984; Table 6). The quartz geothermometer gives a temperature of 38 °C (less than the observed bottom-hole temperature of 46 °C), whereas the alkali geothermometers give temperatures between 146 and 191 °C, similar to those calculated by Manning & Strutt (1990). It is likely that the water has lost silica by precipitation of quartz close to the surface and possibly in the recent geological past (quartz precipitation is abundant within fractures in the Slitt Vein). The alkali geothermometers suggest that the water achieved equilibrium with respect to Na, K and Ca at depths of 3-4 km (assuming a geothermal gradient of 40 °C km^sup -1^). This suggests that the water in the borehole forms part of a deep circulation system, which appears still to be active given the similarity of the water to that encountered at Cambokeels between 15 and 20 years ago.

Geothermal potential

Geophysical logging of the settled water column in the borehole, 3 days after the end of drilling, indicated the magnitude of the geothermal resource potentially developable in this vicinity. The bottom-hole temperature at 995 m was 46.2 °C, which yields a mean geothermal gradient estimate for this borehole of 38 °C km^sup -1^. This compares very favourably with the UK average (c. 21 °C km^sup -1^; Downing & Gray 1986), from which a bottomhole temperature of only 30-35 °C would be predicted at this depth. As the geothermal gradient is likely to continue on the same linear trend as logged from 411 m to 995 m, the implication of the measured bottom-hole temperature at 995 m is that a borehole sunk to a typical 'production' depth of about 1800 m would be expected to return a bottom-hole temperature in the range 75-80 °C.

Given that the heat production capacity of the Weardale Granite at Eastgate is similar to that previously calculated by Downing & Gray (1986), the key issues relate to the availability of natural groundwater to act as a transmission fluid for heat produced in the granite at various distances from the borehole. The extraordinary transmissivity of the major fracture at around 410 m depth provides unequivocal evidence of the association of highly permeable fractures with the Slitt Vein structure. Although the deeper fractures were not quite so permeable, geophysical logging indicates that they are still significant water-bearing structures. The occurrence of permeable fractures associated with the Slitt Vein at depth means that there is no need to artificially introduce water to the geological environment, in contrast to the usual assumption that similar UK granites are (at best) HDR prospects (Downing & Gray 1986; Barker et al. 2000). Instead of an HDR prospect, therefore, the Eastgate resource may be classified as a 'low-enthalpy hydrogeothermal resource hosted in vein-bearing granites'. This is the first time that this category of geothermal resource has been described (see Downing & Gray 1986; R. A. Downing, pers. comm.). Similar veins occur within the nearby (also radiothermal) granites of the Lake District and Wensleydale. Elsewhere, the Lecht Mine has a similar structure in the radiothermal granite of the Eastern Highlands, and the SW England Batholith hosts many analogous lodes, some known to have transmitted brines similar to that found at Eastgate (Edmunds et al. 1984). It may be that further exploration in geological settings similar to that at Eastgate would lead to the identification of other geothermal resources of significant magnitude.

Table 7 compares aspects of the Eastgate Exploration Borehole with the existing Southampton Borehole. Given that the amount of water that may be produced from Eastgate is very similar to that yielded by the Southampton Borehole, the latter is an appropriate model for possible future development at Eastgate. The Eastgate water has the advantage that it is much less saline than the Southampton water (44 SOO mg l^sup -1^ total dissolved solids (TDS) compared with 124440 mg l^sup -1^ TDS at Southampton).

Given the findings from the Eastgate exploration borehole, it is reasonable to predict that a further borehole sunk to 1800 m could provide a resource similar in magnitude to that at Southampton. However, because the Southampton borehole was drilled to intersect a more or less horizontal aquifer unit, a production borehole at Eastgate would need to intersect fractures associated with the Slitt Vein at the target depth. From the experience of drilling this exploration borehole, it is unlikely that a depth of 1800 m could be reached without intersecting a number of shallower fractures carrying cooler water. Further casing close to the total depth would therefore be needed, so that shallower feeders could be sealed off before drilling on in pursuit of sufficient large fractures at depth to yield a viable low-enthalpy resource. Alternatively, a new production borehole could be deliberately drilled off-centre from the target vein structure, with directional drilling techniques being used to deviate the lower-most parts of the borehole until they contact the permeable fractures along the vein azimuth. Implementation of either of these options would be both the most significant engineering challenge and the most significant risk element in proceeding to full-scale geothermal energy production at Eastgate.

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