Ineson Lecture

Hydrogeological challenges in a low-carbon economy

Paul L. Younger

School of Engineering, James Watt Building (South), University of Glasgow, Glasgow G12 8QQ, UK
*Corresponding author (e-mail: paul.younger@glasgow.ac.uk)

Abstract: Hydrogeology has traditionally been regarded as the province of the water industry, but it is increasingly finding novel applications in the energy sector. Hydrogeology has a longstanding role in geothermal energy exploration and management. Although aquifer management methods can be directly applied to most high-enthalpy geothermal reservoirs, hydrogeochemical inference techniques differ somewhat owing to peculiarities of high-temperature processes. Hydrogeological involvement in the development of ground-coupled heating and cooling systems using heat pumps has led to the emergence of the sub-discipline now known as thermogeology. The patterns of groundwater flow and heat transport are closely analogous and can thus be analysed using very similar techniques. Without resort to heat pumps, groundwater is increasingly being pumped to provide cooling for large buildings; the renewability of such systems relies on accurate prediction and management of thermal breakthrough from reinjection to production boreholes. Hydrogeological analysis can contribute to quantification of accidental carbon emissions arising from disturbance of groundwater-fed peatland ecosystems during wind farm construction. Beyond renewables, key applications of hydrogeology are to be found in the nuclear sector, and in the sunrise industries of unconventional gas and carbon capture and storage, with high temperatures attained during underground coal gasification requiring geothermal technology transfer.

The water industry was the birthplace of the discipline of hydrogeology, with many of the pioneering aquifer analysis techniques, such as those devised by Jack Ineson (e.g. Ineson 1959; see also Downing & Gray 2004), being developed to quantify the reliable yields of boreholes used for public water supplies. Understandably, therefore, hydrogeology was traditionally regarded as virtually the sole province of the water industry. Nevertheless, in recent decades hydrogeologists have found their skills in high demand in other sectors, notably in waste management (e.g. Stuart & Hitchman 1986; Foley *et al.* 2012), contaminated land remediation (e.g. Rivett *et al.* 2012) and mining (e.g. Younger & Robins 2002). Comparatively little consideration has yet been given to the role of hydrogeology in the energy sector, and especially the contribution it can make to the minimization of greenhouse gas emissions in pursuit of a genuinely low-carbon economy. A flurry of hydrogeological activity in the area of radioactive waste disposal in the late 20th century (e.g. Heathcote & Michie 2004; Birkinshaw *et al.* 2005) has only recently been followed in the UK by a renaissance of similar work. A thematic set of papers in this journal recently considered the role of hydrogeology in heat engineering (Buss 2009), but there has been no synthesis yet of the wider role of hydrogeology in the energy sector. This paper is intended to provide the first such synthesis, and in particular to provide some pointers to the substantial further scope for transfer of hydrogeological skills to address novel challenges in the emerging 'low-carbon economy'. The paper will first briefly consider the ambiguous role of hydrogeology in relation to the minimization of energy use in its traditional heartland, the water sector. It will then consider a well-known energy application of hydrogeology, in the exploration, development and management of mid- to high-enthalpy geothermal resources, and the more recent endeavours in transfer of hydrogeological skills, which has spawned the new sister sub-discipline of thermogeology (Banks 2009, 2012), considering both systems using heat pumps and those that use groundwater directly for cooling without resort to heat pumps. Some niche applications of hydrogeology in renewable energy fields that at first might appear rather remote from groundwater science (such as wind farm developments) are then considered, before proceeding to consider non-renewables, including the well-established role of hydrogeology in the nuclear sector, and its emerging role in the development of unconventional gas and carbon capture and storage (CCS).

Hydrogeology and energy use in the water industry

The water industry is relatively energy intensive, owing to the power needed for pumping, and for various water and wastewater treatment processes. It has been estimated that these activities account for around 3% of total annual energy use in the USA (*c.* 56000 GWh; see Leiby & Burke 2011) and around 5% in the UK (*c.* 9000 GWh in the year 2010–2011; WaterUK 2011). Incentives to reduce the energy consumed per litre of water handled currently arise from two directions: (1) financial savings, as up to 80% of total water company costs are ascribable to energy purchase; (2) environmental responsibility, to reduce greenhouse gas emissions. To minimize net energy consumption and associated greenhouse gas emissions, the water industry is increasingly seeking to improve the efficiency of pumping and of certain treatment processes (especially forced aeration and sludge dewatering) and to generate renewable power within its own operations; for instance, by production of methane from organic sludges by anaerobic digestion and by inclusion of hydroelectric turbines in high-head water mains (Leiby & Burke 2011; WaterUK 2011).

Hydrogeology currently makes a mixed contribution to this initiative. Although some groundwater sources can be exploited without pumping (i.e. springs and overflowing wells; Younger

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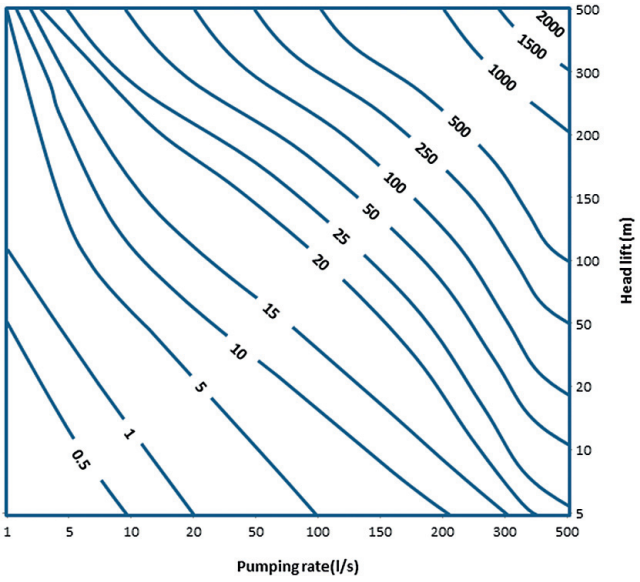

Fig. 1. The best that can ever be achieved in energy efficiency in pumping: the energy requirement in kilowatts for pumping over indicated total head lift at the specified pumping rates, assuming 100% pump efficiency and no head losses in rising mains. To obtain more realistic estimates of energy demand, the kilowatt value for a given head–pumping rate couplet should be divided by a more realistic combined pump–rising main efficiency (e.g. for an efficiency of 60% divide by 0.6).

2007*a*), the vast majority of groundwater sources require sustained pumping. This is in contrast to many surface waters, which can be captured and distributed entirely under gravity. Try as they might, hydrogeologists will struggle to make much contribution to minimization of pumping, though skilful wellfield design to spread drawdowns should allow optimization of pumping head vis-à-vis the total number of wells in large groundwater schemes. Advances in pump technology itself can only ever deliver marginal efficiency gains, as the basic physics of raising a given mass of water to a certain height in a given period of time (see, for instance, Nalluri & Featherstone 2001) leads to an irreducible energy demand expressed by

$$P = \frac{Q\rho g \Delta h}{\eta} \tag{1}$$

where P is the power requirement (Watts), Q is the pumping rate ($m^3 s^{-1}$), ρ is the mass density ($kg m^{-3}$), g is acceleration due to gravity (i.e. $9.81 m s^{-2}$), Δh is the head lift (i.e. how high the water is pumped) (m) and η is the combined mechanical efficiency of the pump and rising main (dimensionless, ≤ 1.0, where 1.0 corresponds to 100% efficient).

For the range of head lifts and pumping rates relevant to borehole abstractions of groundwater, Figure 1 displays the resultant power demand in kW, calculated using equation (1) assuming 100% mechanical efficiency (η) of the pump and rising main. The values shown there represent the best that could ever be achieved by improving equipment efficiency; in reality, efficiencies of 100% will never be achieved and the actual power demands will be higher than those shown, as it is not feasible to eliminate all of the inefficiencies arising from friction losses in pipes and turbulent head losses in pumps and rising mains. It is sobering to contemplate Figure 1 when considering how far the energy use (and thus carbon footprint) of the water industry might be curtailed by 'efficiency gains': anything beyond marginal gains of efficiency will remain beyond reach as long as the need exists for pumping substantial quantities of water over considerable head lifts.

Once pumped to surface and moving in pipe networks, however, there is no reason why more could not be made of the thermal resource that all groundwaters represent: water destined for other uses can, in passing, be processed to extract its thermal energy, using the same methods that hydrogeologists versed in ground-source heat pump technology already apply to groundwater and soils, as outlined below. Extraction of heat from (or dumping it to) water that is destined for other purposes incurs only modest marginal costs and provides a cheap, low-carbon source of thermal energy, useful either for space heating or cooling for site buildings, or else for use in water treatment.

During aquifer storage and recovery operations, there may also be scope for recovery of at least some of the energy originally expended on pumping, using turbines mounted axially on falling mains; this notion has been recently explored quantitatively for the case of flooded former coal mine workings in northern Spain that contain near-potable quality water (Jardón *et al.* 2013), and found to be both practically achievable and economically viable.

In contrast to its generally higher pumping needs, groundwater typically requires far less treatment than surface water: in many cases, this will amount to no more than precautionary contact-tank chlorination near the wellhead, in contrast to the intensive suspended solids removal and disinfection that most surface waters require (Binnie *et al.* 2002). The overall best environmental and economic solution, reconciling the low-treatment advantages of groundwater with the lower pumping needs of many surface waters, will often lie in the judicious conjunctive use of surface waters and groundwaters. This concept had wide currency in the 1970s (e.g. Downing *et al.* 1974) but has been less fashionable in more recent decades. Perhaps the emergence of the contemporary energy-minimization imperative will finally breathe new life into this valuable concept.

The hydrogeology of mid- to high-enthalpy geothermal resources

Hydrogeology has always had an important role in the exploration and development of deep geothermal resources (e.g. Armstead 1978; Downing & Gray 1986). The term 'deep geothermal' has recently come into use (Younger *et al.* 2012) to differentiate high-temperature resources, which can be exploited without resort to heat pumps, from lower temperature resources (such as shallow groundwaters and unsaturated soil), which can only usefully be exploited using heat pumps. Deep geothermal resources are not only valuable for various direct uses, such as space heating: at the high end of the temperature spectrum they can also be used for electricity generation. The term 'deep geothermal' is a little unsatisfactory, as many thermal springs can provide usable heat without resort to heat pumps; however, in most cases, temperatures high enough for such use are associated with deep aquifers accessed via equally deep boreholes.

A more rigorous way of classifying geothermal resources than by depth or temperature is in terms of enthalpy, which in the geothermal context can be understood as the total thermal energy content of a fluid, manifest in both its temperature and pressure. However, the lexicon of geothermal resources does not yet benefit from a universally agreed classification on the basis of enthalpy (Dickson & Fanelli 2005). Traditional literature on geothermal energy tended to distinguish only between 'low-enthalpy' and 'high-enthalpy' systems, with the notional division between the two usually taken to lie somewhere between 150 and 200 °C (usually neglecting to specify pressure, without which a definition of 'enthalpy' is in any case incomplete). As time has gone on, it has become evident that practical considerations favour a more refined

Table 1. *Proposed classification of geothermal resources on the basis of enthalpy (the temperatures quoted are normalized to atmospheric pressure)*

Geothermal resource category	Lower-bound temperature	Upper-bound temperature	Comments
Very low enthalpy	None, even ice can be used	*c.* 50 °C	Only exploitable for direct-use purposes using heat pumps
Low enthalpy	*c.* 50 °C	*c.* 85 °C	Exploitable for direct use purposes, but not suitable for electrical power generation
Mid-enthalpy	85 °C	150 °C	Suitable for electricity generation using binary-cycle plant (e.g. Organic Rankine Cycle)
High-enthalpy	150 °C	*c.* 374 °C	Suitable for power generation using single or double flash steam turbine cycles. NB: upper-bound temperature depends on pressure regime, as it corresponds to the lower-bound temperature for super-critical only where *in situ* pressure equals or exceeds 2.2 MPa
Super-critical	*c.* 374 °C	No theoretical upper bound, but will not exceed local magmatic temperatures	The lower-bound temperature quoted assumes a minimum *in situ* pressure ≥2.2 MPa, and low ionic strength water. For more typical saline waters, a lower bound of about 430 °C is more likely (see Bischoff & Pitzer 1989)

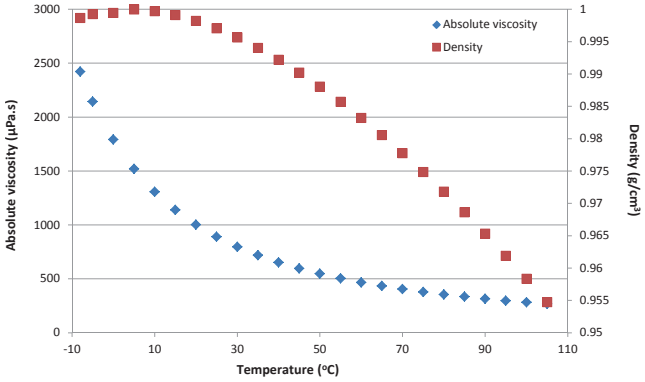

Fig. 2. Variation of absolute viscosity and density of freshwater (at atmospheric pressure) as functions of water temperature. Compiled from NTIS data (www.ntis.gov) and Kestin *et al.* (1978).

classification of geothermal resources, into three, four or (most recently) five categories. Table 1 sets forth a contemporary classification of geothermal resources on the basis of their enthalpy, which most current practitioners would recognize.

The classification proffered in Table 1 has been shaped by practical considerations. For instance, 'very low-enthalpy' resources (i.e. less than *c.* 50 °C at atmospheric pressure) cannot even be used economically for space heating without at least some artificial manipulation of their thermal energy using heat pumps. Low-enthalpy resources (*c.* 85 °C or less) can be used directly for heating, etc., but are still not warm enough (given current levels of technology) to cost-effectively generate significant amounts of electricity. With binary cycle power plants, such as those using the Organic Rankine Cycle (Dickson & Fanelli 2005) or the Kalina Cycle (Kalina *et al.* 1995), it is now possible to economically generate appreciable electricity from water with temperatures >85 °C, albeit the economic viability is enhanced considerably for resources with temperatures of 120 °C or more. Binary power plants are the most efficient solution for resources with temperatures up to as much as 150 °C, though above that threshold, steam flash cycles can usually operate turbines directly with impressive efficiencies (Garnish & Brown 2012; DiPippo 2012), albeit with considerably greater atmospheric emissions than binary plants. At higher temperatures and pressures, geothermal fluids can even be amenable to being flashed twice in succession. Eventually, at the very highest categories of temperature and pressure there are the supercritical resources, which currently remain in the realms of research (e.g. Fridleifsson & Elders 2005). If the considerable hydrogeological and engineering challenges associated with drilling into supercritical reservoirs can be overcome, the rewards are potentially enormous, with projected well yields an order of magnitude greater than those achieved from high-enthalpy reservoirs using flash processes.

Although the temperatures listed against the high-enthalpy and supercritical categories in Table 1 far exceed the familiar 100 °C boiling point of water at atmospheric pressure, the *in situ* pressures are usually sufficient to ensure that groundwater within the reservoirs remains largely in the liquid form. Indeed, even in very high-enthalpy geothermal fields, so-called 'dry steam' resources are rare, with only four such fields currently being exploited commercially around the world (at Larderello in Italy, in The Geysers field of California and two fields in Java: Darajat and Kamojang; DiPippo 2012). Although depressurization in the vicinity of production boreholes can lead to localized occurrence of two-phase flow conditions, for the most part flow within high-enthalpy reservoirs is in the familiar liquid form, and can thus be analysed accordingly using standard hydrogeological modelling techniques, albeit using intrinsic permeabilities rather than hydraulic conductivities, to take account of the temperature dependence of water viscosity and density (Fig. 2).

Having attempted to categorize deep geothermal resources by enthalpy, it is apposite to ask whether the dividing lines are geologically meaningful. In broad terms, the high-enthalpy resources are restricted to volcanic regions, or regions of very active tectonics where heat flows are highly elevated. Mid-enthalpy systems can also be found in such regions, but are probably the only feasible resource in non-volcanic cratonic areas. This is certainly the case in, for instance, Australia, North America east of the Rocky Mountains, and all but the Mediterranean region of Europe. Although mid-enthalpy resources could in principle be found almost anywhere in these regions at great depth (>5 km), the earliest systems are being developed in areas with elevated crustal heat flow, typically above 90 $\mu W\,m^{-2}$. Such values are found in an encouragingly wide range of settings in the UK (Busby *et al.* 2011), for instance, and since the 1970s (Armstead 1978) potential prospects have been identified both in deep sedimentary aquifers and in areas of radiothermal granite (Downing & Gray 1986). The story of attempts to develop these resources in the UK to date has been expounded in detail by Younger *et al.* (2012). Though often dismissed as unsuccessful, the well-known 'hot dry rock' (HDR) experiments in Cornwall in the 1970s and 1980s, which involved development of fracture stimulation techniques to create reservoir zones in granite of originally low permeability, actually led directly to successful applications of the concept in mainland Europe (where the technique is now termed EGS, standing for 'enhanced' or 'engineered' geothermal systems; Garnish & Brown 2012).

Only in the last few years have two companies begun to promote commercial implementation of the concept back in Cornwall.

Although the original HDR/EGS concept took a pessimistic view of natural permeability in granite, developments within the last decade in the buried Weardale Granite of northern England have shown that it is possible to encounter significant natural permeability at depth in granite, thus eliminating (or at least minimizing) any need for artificial stimulation of fractures. (This latter development is ever more welcome in these days of hysterical 'anti-fracking' protests elsewhere in the UK; not that there really is anything much to be feared from fracture stimulation in deep granite (or indeed in shale; Mair *et al.* 2012), but it will certainly be easier to develop projects that do not require police protection for the workforce.) The rationale for exploring for high natural permeability in deep granite was explained by Manning *et al.* (2007), who also described the successful drilling of what is now called the Eastgate No. 1 Borehole. The proving of extremely high permeability in fracture zones intersected by this borehole was described in detail by Younger & Manning (2010). Subsequent work has revealed that the permeability is associated with Tertiary strike-slip reactivation of a pre-Permian fault. As other such faults are known in many parts of the UK, the search is now on for other potential zones of high permeability in areas with elevated heat flow. The second such site to be drilled was in central Newcastle upon Tyne, where 300 m of a deep sedimentary aquifer (the Fell Sandstones) were proved, together with a steep geothermal gradient of 36 °C km^{-1}, and a temperature at the aquifer base (at 1772 m) of 73 °C (Younger 2013). Subsequent work in the same region by Cluff Geothermal Ltd has focused on identifying permeability 'sweet spots' in the Fell Sandstones by means of detailed analysis of reprocessed seismic data that reveal details of fault architecture. The hydrogeological principle in such exploration is to find faults that strike within ±30° of the present-day principal axis of compressive stress in the region (Heidbach *et al.* 2008), as these are most likely to be undergoing natural Coulomb shear failure, and thus to display open apertures capable of yielding significant quantities of groundwater (Olsson & Barton 2001). The same principle emerges in other fields of low-carbon hydrogeology, such as radioactive waste disposal and unconventional gas (see below).

Thermal effects in deep geothermal borehole hydraulics

It is precisely the temperature dependencies that mean that well hydraulics in high-enthalpy settings is rather at odds with the expectations of hydrogeologists brought up on the (often tacit) assumption that the systems they analyse are essentially isothermal. Striking buoyancy imbalances can readily arise during pumping of boreholes that were thermally stratified while at rest before pumping. In high-enthalpy systems, after completion of a borehole it is customary to allow a period of shut-in (total or partial) of the wellhead valves to allow the borehole to 'heat'; that is, the displacement of any water or vapour affected by cooling at surface or near-surface ambient temperatures by far more buoyant mixtures of steam and hot water derived from deep-seated reservoir groundwaters. Once 'heated', the borehole will typically yield wet steam without any need for pumping (Grant & Bixley 2011).

Even in mid- and low-enthalpy systems, non-isothermal conditions can lead to significant buoyancy effects. For instance, during test-pumping of the Eastgate No. 1 geothermal exploration borehole in Weardale in 2006 (Younger & Manning 2010), the immediate response of the borehole to pumping was a 50 cm rise in water levels, which persisted for some 12 h before water levels finally began to decline. This phenomenon, informally termed 'draw-up', can be explained as follows.

(1) The water in the borehole came only from the radiothermal Weardale Granite, which in this borehole is encountered only at depths greater than 273 m, beneath Carboniferous sedimentary cover. The Carboniferous cover and the uppermost 130 m of the granite were cased-off and cemented so that only deeper granite-sourced waters could enter the casing. These proved to have a rest water level about 11 m below ground surface.

(2) The bottom-hole temperature in the borehole (at 995 m) was 46 °C, and during the late stages of borehole completion and development, brine was being produced at surface at temperatures that fluctuated up to this maximum value.

(3) Thus when the borehole was left to rest it originally contained brine with a temperature ranging from 27 to 46 °C.

(4) After a period of rest that amounted to 18 months, the brine in the uppermost parts of the borehole had been chilled by thermal conduction through the casing, so that it had thermally equilibrated with surrounding fresh groundwater in the Carboniferous (which here includes several karstified limestones with vigorous groundwater flow) to a temperature of around 10 °C.

(5) Thus before test pumping commenced, the uppermost reaches of the borehole contained brine that was up to 0.7% more dense, but up to 120% more viscous, than the water in the lowermost reaches (see Fig. 2). This denser, more viscous upper water effectively played the role of an artificial 'slug' in a conventional slug test, forming a 'stopper' above the warmer, less viscous and less dense water below.

(6) When pumping removed the chilled uppermost waters from the borehole, the more buoyant deep waters then surged upwards, causing the observed increase in head of 0.5 m.

Although density and viscosity also vary with salinity (Kwak *et al.* 2005), it should be noted that in this case the salinity was essentially constant over depth, as all of the water in the borehole was ultimately sourced from the granite at depth. Nevertheless, the interaction of thermal, saline and gravitational influences means that the interpretation of groundwater heads in such systems needs to be pursued with particular care (see Post & von Asmuth 2013).

Hydrogeochemistry of high-enthalpy geothermal systems

The use of hydrochemical evidence to reconstruct groundwater flow paths and infer hydrostratigraphy has a long and successful pedigree (e.g. Hem 1985; Lloyd & Heathcote 1985; Appelo & Postma 1993). As in most hydrogeological settings, much can be learned about the provenance and development of geothermal fluids by examining the evolution of relative proportions of the major ions, both the cations (especially Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) and anions (especially Cl^{-} and SO_4^{2-}, and, to a lesser extent in geothermal systems, HCO_3^{-}). Also as in mainstream hydrogeology applications, ternary diagrams expressing the relative proportions of these major solutes are widely used in geothermal studies (e.g. Ármannsson 2010). The ternary anion and cation plots shown in Figure 3 were originated by the late Professor Werner F. Giggenbach, who successfully pioneered the application of quantitative geochemistry to the study of fluids (waters and gases) associated with volcanoes, hot springs and geothermal wells, first in New Zealand (Giggenbach *et al.* 1983; Giggenbach 1986, 1988), and then worldwide (e.g. Giggenbach 1997). At first glance, the plots of Figure 3a and b resemble the lower triangular plots of a standard Piper diagram (Piper 1944), which is very familiar to most hydrogeologists (e.g. Lloyd & Heathcote 1985; Appelo & Postma 1993; Younger 2007*a*). However, the similarities are superficial, and it is important not to be misled by them. For a start, the proportions of the ions represented in Figure 3 are not based on percentages of milliequivalents per litre (which is the convention for Piper diagrams, and for most

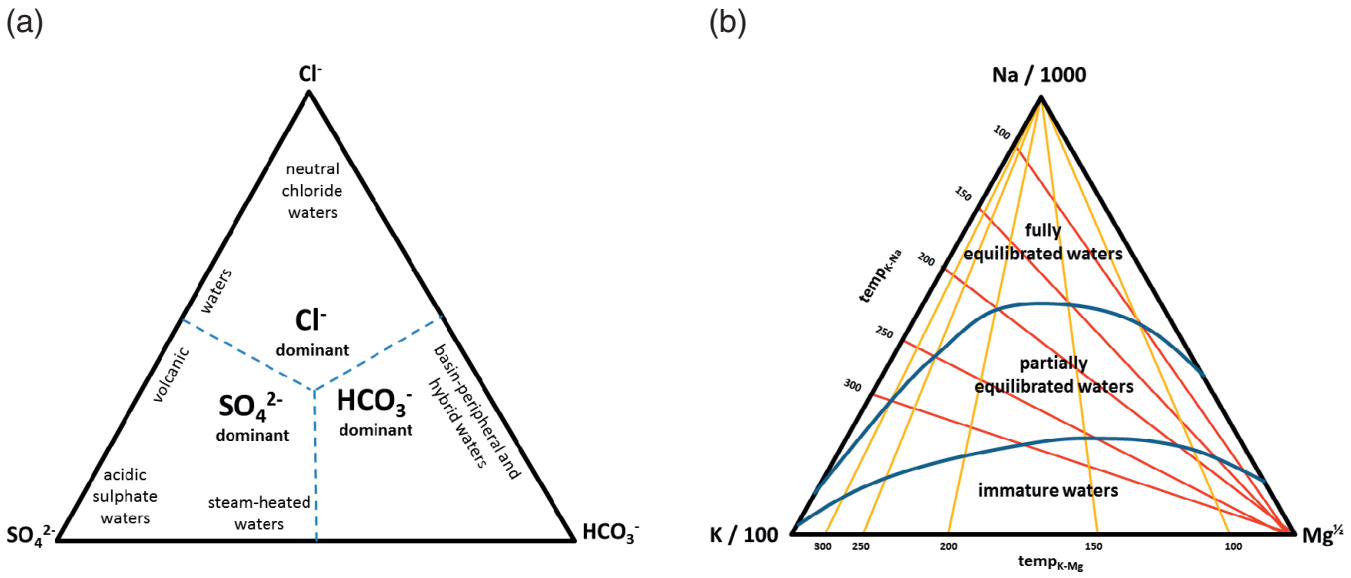

Fig. 3. Trilinear diagrams commonly used in the classification and interpretation of groundwaters encountered in high-enthalpy geothermal systems. (**a**) Anion trilinear classification diagram, based on relative proportions of the sum total of mass concentrations (ppm) of Cl^-, SO_4^{2-} and HCO_3^- (adapted after Giggenbach *et al.* 1983). (**b**) Cation trilinear plot, based on the relative proportions of the three quantities shown, which are derived from the ppm concentrations by division (by 100 for K^+; by 1000 for Na^+) or taking the square-root (for Mg^{2+}). The blue divisional lines approximately delineate various categories of water. The two sets of diagonal lines are isotherms (in units of °C) defined by equilibrium water–mineral interactions for K^+ and Na^+ ($temp_{K-Na}$) in the case of the set of lines commencing at the Mg apex, and by water–mineral interactions for K^+ and Mg^{2+} ($temp_{K-Mg}$) in the case of the set of lines commencing at the Na apex.

other common hydrogeochemical graphing tools; Lloyd & Heathcote 1985); rather, they are calculated directly from the analytical concentrations in $mg\,kg^{-1}$ (= ppm). The anion plot (Fig. 3a; see Giggenbach *et al.* 1983) is based simply on percentages of the total analytical concentrations of the three anions. It is used to make preliminary identifications of possible affinities of waters found in high-enthalpy geothermal settings (see Ellis & Mahon 1977), in particular the following (Fig. 3*a*):

(1) Acidic sulphate waters, typically associated with fumaroles and hot springs high on the flanks of volcanoes, which owe their composition primarily to the dissolution of volcanic gases in young meteoric water infiltrating the eruptive edifice. The high sulphate is due to dissolution of gaseous H_2S, which then oxidizes to SO_4^{2-} (Ellis & Mahon 1977). The lack of chloride reflects its low volatility, which means it remains in solution deep underground when the sulphurous vapours that go to form these acidic sulphate waters evaporate in the first place. The other solutes in acidic sulphate waters tend to reflect dissolution of the more labile components from fresh volcanic rocks in the immediate vicinity of hot springs (Marini 2010), and are thus of limited value in understanding the deeper hydrothermal 'plumbing system'.

(2) Neutral chloride waters, in which the predominant cations are typically Na^+ and K^+, and which are typical of the deeper reaches of hydrothermal circulation systems, where high-temperature rock–water interactions yield the elevated dissolved loads. These waters are typical of hot springs more distal from the active eruptive centres of volcanoes, and typically represent the 'cropping out' of large-scale convective cells. Identification of such waters in springs during regional reconnaissance surveys is often the first step in recognizing the presence of a viable geothermal reservoir at depth (e.g. Ellis & Mahon 1977; Marini 2010; Ármannsson 2010; Younger 2010).

(3) Bicarbonate (HCO_3^-) dominated waters, which tend to be shallow groundwaters that have been heated by steam and other volcanic gases; indeed, the bicarbonate is often inferred to be sourced from dissolution of volcanogenic $CO_{2(g)}$ (and similarly for sulphate derived from gaseous H_2S). In these waters, sodium often remains as the dominant cation, owing to selective removal of Ca^{2+} by precipitation as a carbonate at high temperatures. In settings more distal from the volcanic heat source, bicarbonate waters may simply be conductively heated groundwaters of more mundane origins (e.g. infiltration into sedimentary aquifers), which are regarded as peripheral to the geothermal basin *per se*. Such waters can also mix with the other types to produce mixtures of hybrid composition; this also tends to account for occasional acidic chloride or sulphate waters (Ellis & Mahon 1977).

The cation plot (Fig. 3b; see Giggenbach 1986, 1988) considers only Na^+, K^+ and Mg^{2+}. This is an important difference from the cation triangle of Piper diagrams, in which Ca^{2+} features strongly: although Ca^{2+} is often the predominant cation in many cool, shallow groundwaters, it is less frequently dominant in deep geothermal waters, partly because of the low solubility of $CaCO_3$ in hot waters, which often results in low Ca^{2+} concentrations, and also because rock–water interactions involving Ca^{2+} are highly dependent on dissolved CO_2 concentrations, which means that ratios of Ca^{2+} to other major cations are generally more equivocal about equilibration temperatures than is the case for mutual ratios between Na^+, K^+ and Mg^{2+} (Giggenbach 1988). In devising the cation plot shown in Figure 3b, therefore, Giggenbach (1986, 1988) was particularly seeking a graphical display tool that would directly reveal information about the equilibration temperature of a given well or spring water. This is important, as in many field settings this will provide direct evidence of groundwater temperatures at as-yet undrilled depths; a clear boon when considering possible exploratory drilling. As Giggenbach (1988) himself commented: 'Na, K [and] Mg … contents of thermal waters in full equilibrium with a thermodynamically stable mineral system derived through isochemical recrystallization of an average crustal rock are, at a given temperature and salinity, uniquely fixed. Together with the compositions of waters resulting from isochemical rock dissolution, they provide valuable references for the assessment of the degree of attainment of fluid-rock equilibrium.' It is with this in mind that the two sets of isothermal lines are plotted in Figure 3b: those originating in the $Mg^{½}$ apex of the diagram define equilibration temperatures corresponding to the ratios of K to Na indicated (which are therefore labelled as

'$temp_{K–Na}$' where they intersect the left-hand edge of the triangle). Similarly, the isothermal lines originating in the Na/1000 apex give temperatures of equilibration corresponding to the indicated ratios of K to Mg (and thus labelled as $temp_{K–Mg}$). Fully mature waters are defined by the intersection points of the two sets of isothermal lines: above the line joining those intersections, equilibration with both the K- and Na-bearing feldspars and various important clay and clay-like minerals is assured; below that line, only selective equilibration is indicated, with equilibrium being reached with Mg-bearing minerals such as chlorite and illite, but not with the feldspars. The least evolved waters of all, which have not yet reached equilibrium with many minerals, tend to plot along the base of the triangle (marked as 'immature waters'). The power of Figure 3b is that, as long as the chemistry of a given water has remained aloof from mixing with other waters during its transport to a given well or spring, the temperature of equilibration can be uniquely defined by plotting in terms of its Na^+, K^+ and Mg^{2+} concentrations alone. This is a powerful geothermal exploration tool.

Besides consideration of major anions and cations, the nuances of rock–water interaction at high temperature mean that geothermal investigations often make substantial use of solutes that are only rarely used in other groundwater investigations. Chief amongst these is dissolved silica ($SiO_2°$). In the geochemistry of shallow, cool groundwaters, the silica content tends to reflect incongruent dissolution of aluminosilicate minerals, perhaps tempered by precipitation of modest quantities of cryptocrystalline silica phases, often resulting in dissolved concentrations clustered around about 10 ppm. For this reason, with a few honourable exceptions (e.g. Haines & Lloyd 1985), many hydrogeologists ignore dissolved silica concentrations, and often even neglect to have their samples analysed for them. Things could scarcely be more different when it comes to deep geothermal waters, where it is necessary to quickly unlearn the notion that quartz is essentially insoluble. In fact, the equilibrium solubility of quartz at 150 °C (*c*. 100 ppm) is about 20 times greater than it is at 10 °C (see Fournier & Potter 1982; Marini 2010). Indeed, where water samples can be collected, fixed and analysed sufficiently rapidly, dissolved silica can be a powerful geothermometric indicator (e.g. Fournier & Potter 1982). Quartz is only one of a range of solid SiO_2 phases that can control dissolved silica concentrations by dissolution or precipitation. For instance, at temperatures in excess of about 180 °C, equilibrium with quartz tends to control dissolved concentrations, whereas at lower temperatures, and certainly below about 110 °C, chalcedony equilibrium is often found to be the predominant control (Ellis & Mahon 1977). At lower temperatures still, as water falls below atmospheric boiling point, first cristobalite and finally amorphous silica tend to be the predominant forms of SiO_2 to display equilibrium with the dissolved load. Given the array of solid forms precipitating across a wide temperature range, precipitates of silica are commonly formed from the waters produced by high-enthalpy geothermal wells (Fig. 4), and prevention of clogging of well casings and surface steam–water separation facilities is a frequent maintenance challenge in such settings. The use of chemical scale removal methods (such as injecting sodium hydroxide at high pressure) has met with only limited success, and in severe cases physical removal by means of reaming tends to be required.

High temperatures also mobilize other metals at dissolved concentrations far exceeding those typically found in shallow fresh groundwaters. Thus to the usual major ions analytical suite of the hydrogeologist (i.e. Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, Cl^- and alkalinity) the geothermal investigator routinely adds Li^+, B^{3+} and F^-, as well as the uncharged species NH_3, and, of course, SiO_2 (Marini 2010). Depending on the geological setting and the purposes of the particular investigation, further solutes are also commonly added to the suite, including Al (total, trivalent ion and monomeric), $H_2S_{(aq)}$, Rb^+, Cs^+, Br^-, As^{3+}/As^{5+}, Ba^{2+}, $Hg_{(aq)}$, Au^+, Ag^+, Zn^{2+} and Pb^{2+}. The latter six analytes are familiar to anyone who has worked on the geology of hydrothermal ore deposits, and indeed many geothermal systems are but the distal, upper reaches of hydrothermal convection systems. Thus it is not surprising that some of the more exotic scales precipitating in geothermal wells include sphalerite, galena and even electrum (a natural alloy of gold and silver), which is a notable component of scales forming in surface pipework at the Berlín Geothermal Field in El Salvador (Raymond *et al.* 2005).

As regards the other analytes, the alkali metals Li^+, Rb^+ and Cs^+ resemble the predominant members of the same group, Na^+ and K^+, and in general behave similarly to them (Hem 1985). However, unlike Na^+ and K^+, none of them form particularly low-solubility precipitates at temperatures of relevance to geothermal production, and thus tend to behave rather conservatively once in solution (rather like Cl^-, Br^- and B^{3+}), with their concentrations usually being significantly affected only by dilution or steam formation (Ellis & Mahon 1977; Marini 2010). As such, they can be a useful index of high-temperature origin of a water, and (by comparison with other solutes) sentinels to subsequent steam formation. Boron is even less affected by mineral precipitation reactions than the alkali metals, and where steam formation occurs it tends to be strongly partitioned into the gaseous phase, to an extent that increases with temperature (Tonani 1970). Given that Cl does not partition strongly into steam, elevated B/Cl ratios can be good indications of subsurface formation, migration and condensation of steam (Ármannsson 2010; Younger 2010). For instance, on the Caribbean island of Montserrat, elevated boron concentrations in an alkali chloride spring water were taken to indicate condensation of steam into the rising water (Younger 2010). These findings led to exploratory drilling, which in May 2013 was rewarded with intersection of a high-enthalpy geothermal reservoir (at an estimated temperature of 250 °C) at a depth 2142 m depth (Richter 2013), in the very location originally identified by Younger (2010) on the basis of a surface hydrogeological reconnaissance.

A frequent issue in volcanic regions is whether gases are indeed due to 'flashing' of meteoric groundwater to steam, or else magmatic, or a mixture of the two. Fluoride is widespread in known magmatic gases; indeed, HF is a notable hazard in those gases emanating from magmatic sources. Elevated fluoride in a geothermal water may thus be a crude indicator of a possible magmatic component, helping to short-list those water sources that might be subjected to (more expensive) confirmatory analysis for unequivocal magmatic signatures, such as elevated ^3He contents (e.g. Tedesco *et al.* 1995; Kennedy & van Soest 2012). Application of such techniques frequently leads to hydrogeological surprises. For instance, the Italian National Institute for Geophysics and Volcanology routinely sample gases and waters on and around Mount Etna as part of the volcanic hazard early warning system; it transpires that the samples that consistently show the clearest deep mantle signatures are not those from fumaroles in the actively erupting summit crater area, but rather those from humble monitoring wells some 30 km to the south, in unprepossessing alluvial plains near Paternò (Paonita *et al.* 2012).

From this brief overview, it is hopefully clear that hydrogeologists entering the world of deep geothermal energy need to pay lots of attention to hydrogeochemistry, as an indispensable tool in unravelling processes occurring far below the reach of even our deepest boreholes. In much shallower systems, as we shall now see, the challenges are rather more prosaic.

The hydrogeology of very low-enthalpy systems: thermogeology

Ground-coupled heat-pump systems for heating and cooling

Recent years have witnessed a veritable boom of hydrogeological involvement in the development of ground-coupled heat-pump

(a) (b)

Fig. 4. Typical amorphous silica precipitates (white staining) at active high-enthalpy geothermal wells in the Rift Valley, Kenya, on 23 May 2012. (**a**) Silica scale on wellhead valve work and in the borehole cellar at Menengai No. 1 Production Well (capacity 8 MW_e) of the Geothermal Development Company of Kenya (location: UTM zone 37M; Northings 9976800m; Eastings 171850m). (**b**) Silica scale on four steam–water separators, silencers and water removal pipelines serving the Olkaria No. 11 Production Well (capacity 9.6 MW_e) of KenGen (location: UTM zone 37M; Northings 9900850m; Eastings 200240m).

based systems providing space heating and/or cooling systems, so much so that the term 'thermogeology' has recently been coined to describe this nascent daughter discipline (Banks 2009). The close analogy between groundwater flow and thermal convection means that analytical methods for heat flow are immediately familiar to numerate hydrogeologists (Banks 2012). Descriptions of ground-source heating and cooling systems, and in particular their closed-loop and open-loop variants, are readily available in the literature (e.g. Banks 2009, 2012; Younger 2008, amongst many others) and are therefore not reproduced here. Such systems have a number of generic advantages over many other renewable energy systems. First, once installed they are usually utterly inconspicuous, unlike roof-mounted solar panels and wind turbines. Second, in comparison with the principal competitor technology for low-carbon heat (i.e. biomass combustion) ground-source heating and cooling systems are emissions-free at the point of use. Depending on the source of electricity used to operate the borehole pumps and heat pumps, ground-source heat pump (GSHP) heating and cooling systems might well be emissions free in absolute terms. However, their overall renewability depends on whether the electricity they consume was itself generated renewably: the heat removed from the subsurface typically accounts for more than two-thirds of the thermal energy supplied to a building, so that proportion at least of the rated capacity should always be renewable, provided the subsurface source itself is sustainably managed. However, a third of the energy supplied will typically be ascribable to the electricity consumed by the heat pump, which may or may not be renewable, depending on the electricity supply source used.

Given the high levels of thermal insulation demanded by modern building regulations, and the virtually ubiquitous presence in offices of potent heat sources in the form of the transformers in desktop computers, it is commonplace nowadays for many large commercial buildings to have virtually no formal heating requirement, even in winter, but rather to have year-round cooling needs. Many of the larger GSHP systems currently operative in central London fall into this category (Birks *et al.* 2013). From a hydrogeological point of view, it would be preferable to develop systems that are seasonally balanced; that is, those in which a summer cooling demand is at least approximately balanced by a winter heating demand. In such balanced systems, aquifers essentially become inter-seasonal heat stores: warm water injected during the summer period of building cooling can be exploited for heating during the winter period.

To solely dump heat to aquifers all year round is asking a lot of the groundwater flow systems: they are being expected to assimilate and dissipate heat continually. In reality, the warm water 'bubble' within the saturated zone will typically expand over time until the temperature of groundwater pumped from the aquifer abstraction boreholes begins to rise, eventually reducing its value as a cooling resource. This 'thermal breakthrough' phenomenon is controlled primarily by the hydraulic characteristics of the aquifer in question and the distance (or spacing) between adjacent abstraction and injection boreholes. Well-established groundwater modelling tools, both analytical (e.g. Younger 2008) and numerical (e.g. Gandy *et al.* 2010; Herbert *et al.* 2013), have been successfully used to assess how long it will take before thermal breakthrough occurs between injection and abstraction boreholes in a given aquifer setting. Examination of the range of possibilities for combinations of Chalk aquifer parameters (e.g. porosity *c*. 2%, natural groundwater velocity 1 mm day^{-1} and an active saturated thickness of around 50 m; for further discussion see Younger 2008) and well-spacings commonly encountered in such systems in London leads to the sobering conclusion that many such systems will only operate for a few years before thermal breakthrough begins to undermine their value (Fig. 5). The onset of thermal breakthrough does not correspond to the time horizon for system failure, as it will still take a considerable while for the temperature of pumped water to fully converge on that of the reinjected water. Local variations in transmissivity and ambient piezometric surface gradient may also cause deviations from the idealized conditions that the model of Clyde *et al.* (1983) assumes (i.e. homogeneous transmissivity and an initially flat piezometric surface). The model also neglects conductive loss of heat to overlying or underlying strata, which in practice is likely to prolong the time to thermal breakthrough.

On the other hand, the analytical solution does not take into account the lower viscosity of warmer reinjected water (see Fig. 2) compared with cool native groundwater. For instance, a groundwater that has its temperature raised from 10 °C to 25 °C on passing through a heat pump supporting a building cooling system will

Borehole spacing (m)	kW rating of ground-source heat-pump cooling system				
	40 kW	**80 kW**	**160 kW**	**240 kW**	**320 kW**
100	3.28	1.64	0.82	0.55	0.41
200	13.09	6.56	3.29	2.19	1.64
300	29.38	14.74	7.39	4.93	3.70
400	52.10	26.18	13.12	8.75	6.57
500	81.20	40.85	20.49	13.67	10.26

Fig. 5. Predicted time (in years) to the onset of thermal breakthrough between adjoining abstraction and reinjection boreholes serving a ground-source heat-pump building cooling system, expressed as a function of both installed system capacity (in kW) and borehole spacing (in metres) (after Younger 2007*b*). The simulations were made using an analytical solution presented by Clyde *et al.* (1983), assuming aquifer diffusivities and heat capacities typical of major confined Chalk and Triassic Sandstone aquifers in the UK (as explained by Younger 2008).

experience a decrease in absolute viscosity of around 32% (i.e. from 1307.0 to 890.2 μPa s; see Fig. 2). As hydraulic conductivity is inversely proportional to viscosity, all other things being equal, then a viscosity decrease of this magnitude would lead to thermal breakthrough occurring proportionately sooner than shown in Figure 5.

One important conclusion from an examination of Figure 5 is that the spacings attainable by installing abstraction and injection boreholes at the extremities of a single property in a densely populated urban area are unlikely to be compatible with long-term sustainability. Rather, it would be preferable for neighbouring land-owners to collaborate, with one hosting the abstraction boreholes for several properties and another hosting the reinjection boreholes, so that maximal spacings between the two might be achieved.

Groundwater cooling without heat pumps

The foregoing discussion has considered those groundwater-based heating and cooling systems that incorporate heat pumps. In many circumstances, it will prove possible to achieve space cooling more efficiently, eliminating both the capital cost of a heat pump and the costs of electricity needed to run it, by directly passing cool groundwater through heat-exchangers to provide cooling load. This approach, which is termed 'groundwater cooling', is expanding swiftly in the UK at present, especially in London, where large-scale systems are already in use at large cultural venues, such as the Royal Festival Hall (Clarkson *et al.* 2009) and the Tate Modern art gallery (Birks *et al.* 2013), as well as at Green Park underground station (Payne 2013). Just as in heat-pump based systems, hydrogeological analysis is crucial to assessing just how sustainable such systems are, in relation to thermal breakthrough and allied issues. Where earlier systems in London all relied on using the confined Chalk aquifer, the recent development at the Tate Modern pioneered the use of the Thames Gravels (Quaternary), which are shallow, unconfined and apparently in good hydraulic continuity with the River Thames (Birks *et al.* 2013). All of these attributes favour the efficient dissipation of injected heat, by conductive and convective losses to the overlying unsaturated zone, and by vigorous mixing with surface waters, aided by tidal perturbation of groundwater levels and flow directions twice a day. The Thames Gravels thus have significantly greater potential for cooling-only applications than was appreciated prior to the work of Birks *et al.* (2013).

Hydrogeology and closed-loop systems

The foregoing discussion has focused mainly on open-loop GSHP systems, in which hydrogeology has a clear role, as they involve pumping and reinjection of groundwater. In contrast, closed-loop GSHP systems circulate heat-exchange fluids (essentially anti-freeze) through closed circuits of piping suspended down boreholes (or else buried in coils in the soil), with no groundwater pumping and reinjection, and indeed no direct contact with the groundwater at all. On first inspection, therefore, there would appear to be little need for hydrogeology in closed-loop GSHP design and operation. Indeed, many GSHP installers I have come across fervently recommend closed-loop rather than open-loop installations to developers, specifically because closed-loop can be 'done anywhere', allegedly with no need to worry about the geology at all. There are three problems with geologically blind closed-loop development, as follows.

(1) Cost. Because a closed-loop system typically involves far more drilling than an open-loop system, where a simple choice exists (i.e. there is a suitable aquifer with licensable abstraction capacity beneath the site), then above a system capacity of around 200 kW, the open-loop option will almost always prove far cheaper, given current drilling costs for both options (D. Birks, personal communication).

(2) The likelihood of significantly over- or under-sizing of the heat-exchange ground loops by designing always to a median value of the thermal conductivity of the ground, rather than directly determining how this varies with lithology and on-site stratigraphy (Banks 2012). Whereas thermal conductivity varies over only about one order of magnitude (i.e. from about 0.3 to *c.* 3.5 $W m^{-1} °C^{-1}$), compared with more than 13 orders of magnitude for hydraulic conductivity, the cost of additional boreholes is such that being out by a factor of two (let alone 10) can either impose injurious economic burdens on a project or lead to an under-sized system that cannot operate as desired.

(3) Failure to account adequately for dissipation of thermal energy rejected to the subsurface by advective–dispersive transport in groundwater (Chiasson *et al.* 2000). There are two sides to this failure. On the one hand, it can lead to over-conservative assumptions being made about the capacity of the ground to absorb heat immediately below a property. On the other, it can lead to transfer of heated (or cooled) water beneath neighbouring properties, potentially hindering the scope for those neighbours to also use the subsurface as a heat source or sink.

As some of the consequences of the above problems come home to roost, it is likely that the demand for hydrogeological input to closed-loop GSHP system design will increase substantially.

In general, hydrochemical issues tend not to loom large in GSHP system analysis. This is partly because, where groundwater quality would prove problematic for open-loop GSHP operations, closed-loop installations can neatly side-step the issue. However, there is at least one category of GSHP system where the benefits of using heat pumps are likely to be fully realized only by open-loop installations, and yet water quality is challenging: mine water heat-pump systems.

Mine water heat-pump systems

The UK Coal Authority recently stated that they 'have a number of [pollution prevention pumping] schemes across Britain that collectively pump 3000 l of mine water every second with a typical temperature of 15 °C, which potentially offers approaching

100 MW of heat energy if it can be harnessed through heat pump technology' (Coal Authority 2010). In recognizing this potential, the Coal Authority is echoing growing international experience, which has resulted in several successful systems in operation (Table 2). Flooded underground workings possess a number of favourable attributes that make them attractive as underground thermal energy sources, including the following.

- Permeabilities are high and groundwater storage potential is relatively high, comparable with the best of natural aquifers.
- Temperatures are naturally stable year-round (typically a little above the local annual average air temperature).
- They often host extensive groundwater flow systems, which readily receive recharge from rainfall.
- In some cases, *in situ* oxidation of sulphide minerals can augment the heat available in the mine water.
- Often there is good hydraulic connectivity between relatively shallow mine workings and deeper, warmer workings, so that it is relatively common for pumping to enhance thermal convection, thus transferring warmer water to the shallow subsurface.
- There is no competition for use: unlike many groundwaters in natural aquifers, most mine waters are sufficiently mineralized that they are non-potable and are generally unattractive for most high-value manufacturing purposes.
- Mine workings are near many urban areas (former mining towns), in which there is likely to be a substantial demand for space heating and cooling.

Notwithstanding these advantages, the development of mine water heat-pump systems has not proceeded as briskly as many originally hoped, mainly owing to concerns over clogging of pumps and heat pumps by ochre (ferric hydroxide). In addition, some of the more acidic or saline mine waters would prove corrosive to typical system components. Ochre clogging can be avoided by careful design of borehole and surface pipework to ensure complete isolation of the mine water from the atmosphere during heat-pump operations (Banks *et al.* 2009): in the absence of oxygen, ochre will not form. Where some oxygen ingress has already occurred before the mine water is pumped (which might well occur in mine shafts or adits), maintenance strategies can be devised to manage the ochre accumulation problems, involving de-scaling agents and/or the use of physical tools to dislodge precipitates (e.g. pigging pipes). Oxygen exclusion is also effective in the case of saline waters, although where these are already oxygenated it is possible to overcome the problem by specifying marine-grade heat pumps and pipework in the first place. For example, one of the UK's longest-standing open-loop ground-source heat-pump systems (at the HQ of Groundwork South Tyneside, in Hebburn) uses saline groundwater from Coal Measures sandstones above old mine workings, and has operated successfully with a marine-specification heat pump since 1996 (Banks 2012).

Two less likely (and to date undocumented) potential pitfalls of using flooded mine workings for heat-pump operations are as follows.

(1) The risk of inducing a literal pitfall: formation of a surface crown-hole owing to collapse of old workings as a result of removal of buoyant support from void roofs as water levels drop, and/or erosion by water moving through roadways and fractures at high velocity. The same would of course apply to pollution prevention pumping, yet no examples of such induced crown-holes are reported from the numerous Coal Authority pumping operations in the UK. The risk can thus probably be dismissed for all but the shallowest of mine workings in the most unstable strata

(2) The risk of inducing the release of hazardous mine gases, either by de-gassing from the mine water itself as it is brought to surface and exposed to lower pressures, or by lowering the water table and allowing previously trapped mine gases to move in the newly available headspace. De-gassing from the pumped water can be controlled by the same means as prevention of oxygenation (Banks *et al.* 2009). Generally speaking, most shallow old workings are unlikely to emit explosive gases (methane–air mixtures) but are more likely to release deoxygenated air ('stythe'), control of which is readily achieved by ensuring good ventilation and following standard design practices to avoid the creation of dangerous confined spaces.

Hydrogeological contributions to other renewable energy technologies

Whereas hydrogeology has no obvious role in marine or solar renewables (other than indirectly in the mines that supply materials for them), it has a surprisingly important role in the field of onshore wind developments in high-latitude countries such as the UK. This relates to the potential for installation of upland wind farms to disturb the hydrology of peatland ecosystems (e.g. Waldron *et al.* 2009). These peatlands often overlie low-permeability strata (bedrock and/or drift deposits, notably glacial till) and as such have tended to be neglected by much of the hydrogeological profession. Nevertheless, it has long been realized that peatland hydrogeology is complex, and indeed fascinating, owing to the high degree of compressibility of the organic sediment matrix (Ingram 1983; Stunell & Younger 1995). For instance, Brown & Ingram (1988) demonstrated that significant changes in groundwater storage within peats could be attributed to compaction effects that are not generally found in unconfined aquifers composed of solid minerals. As many peat bodies are rather thin, it is easy for road cuttings or similar trenches (e.g. for cable ducts) to partially or fully penetrate them, potentially leading to sustained dewatering of the deposit by continuing gravity drainage, either feeding open channel flow along roadsides, or moving through coarse-grained pipe-bedding fill material, which then functions like a French drain. This raises the possibility that peats might substantially dry out, oxidize, and begin to release the carbon they contain to the atmosphere as CO_2, at accelerated rates compared with undisturbed conditions. Were this to occur as a result of installing roads and other infrastructure to service wind turbines, it would detract from the carbon emissions reductions that are their principal raison d'être.

Thus there is now a significant driver for hydrogeological investigations of upland peat areas, although most classically trained hydrogeologists would need to play catch-up to contribute to these. Fortunately, specialist teams are already in the forefront of developing and applying new approaches to more accurately characterize the hydraulic conductivity and storativity of peatlands, taking their high compressibility fully into account. For instance, Holden & Burt (2003) found that application of piezometer test analysis methods that fully account for compressibility yield consistently smaller values of hydraulic conductivity than methods that assume a rigid porous medium, which had previously been (mis-) applied to peats. They also found that interstitial hydraulic conductivity of peat bodies varies considerably, although it does not change systematically with depth (as had been previously reported from elsewhere; e.g. Ingram 1983). However, the absolute values of hydraulic conductivity in the peat (*c.* 1×10^{-4} to 1×10^{-2} m day^{-1}) were all very low in comparison with those of major aquifers (in which values in excess of 1 m day^{-1} are common; Younger 2007*a*). The interstitial hydraulic conductivity of peats is only part of the story, however: substantial, natural pseudo-karstic pipe systems have long been reported from upland peat terrains (e.g. Stunell & Younger 1995), and these provide high-permeability drainage pathways through the otherwise low-permeability peat terrain. Recent field investigations (Smart *et al.* 2013) have shown that up to a quarter of the pipe systems in a given catchment flow perennially, representing the largest single component of total catchment

Table 2. *Summary of heat-pump systems exploiting water in flooded mine workings*

Location	Type of mine	Year system installed	Depth of pumped mine workings (m)	Rate of water use ($l s^{-1}$)	ΔT (°C)*	Heat output (kW)	Comments	Reference
Dawdon, County Durham, UK	Coal	2011	280–530 m (pump intake at 100 m)	1.5	4	12	Demonstration system heating buildings of Coal Authority pumping station, using up to 2% of existing pumped flow	Unpublished data from Coal Authority
Ehrenfriedersdorf, Sachsen, Germany (1)	Tin	1994	n.r.	n.r.	n.r.	n.r.	Used to heat a school. Very few details provided in source reference	Wieber & Pohl (2008)
Ehrenfriedersdorf, Sachsen, Germany (2)	Tin	1994	n.r.	n.r.	n.r.	82	Used to heat a museum. Very few details provided in source reference	Wieber & Pohl (2008)
Folldal, Norway	Copper, zinc, sulphur	1998	600	0.7†	n.r.	18	A concert hall in a large underground mine is heated with mine water from deeper in the same old workings	Banks *et al.* (2004)
Heerlen, Netherlands	Coal	2002	690	29	10	700	Purpose-drilled boreholes into deep workings to heat large public buildings and apartments	Roijen (2011)
Heinrich Mine, Essen–Heisingen, Germany	Coal	1984	n.r.	n.r.	n.r.	350	Used to heat a retirement home. Very few details provided in source reference	Wieber & Pohl (2008)
Kongsberg, Norway	Silver	2005	n.a.	n.a.	n.a.	12	Closed-loop system installed in shaft (250 m deep), so mine water not pumped directly	Banks *et al.* (2004)
Lumphinnans, Fife, Scotland	Coal	2001	170	2.5†	11.5	65	System operated successfully for 4 years despite high iron content ($58 mg l^{-1}$) in water, until vandalism of reinjection pipe allowed oxidation of iron to commence	Watzlaf & Ackman (2006); Banks *et al.* (2009)
Mount Wellington Mine, Cornwall	Tin	2008	n.a.	n.a.	n.a.	20	Closed-loop suspended in former mine shaft, heating factory and offices of Kensa Engineering (heat pump manufacturers)	Unpublished data from G. Cashmore of Kensa
Marienberg, Sachsen, Germany	n.r.	2007	n.r.	n.r.	n.r.	n.r.	Used to heat a swimming pool. Very few details provided in source reference	Wieber & Pohl (2008)
Mieres, Spain	Coal	2009	70	11.3	12	117	Research building on new campus uses mine water from the Barredo Shaft; other buildings to be heated using same source	Loredo *et al.* (2011); and other data‡

Table 2. *(Continued)*

Location	Type of mine	Year system installed	Depth of pumped mine workings (m)	Rate of water use ($l s^{-1}$)	ΔT (°C)*	Heat output (kW)	Comments	Reference
Park Hills, Missouri, USA	Lead	1995	122	4.7	n.r.	112.5	Believed to be the first building in the USA to be wholly heated by mine water	Banks *et al.* (2004) and web§
Springhill, Nova Scotia, Canada	Coal	1986	140	4	5	111	The earliest well-documented large-scale GSHP system using mine water anywhere in the world; first planned 1984, and had expanded to full load by 1994	Banks *et al.* (2004); Watzlaf & Ackman (2006); and web¶
Zollverein, Essen–Katernberg, Germany	Coal	2000	n.r.	n.r.	n.r.	n.r.	Used to heat a design college. Very few details provided in source reference	Wieber & Pohl (2008)

n.a., not applicable (see comments); n.r., not reported.
*That is, the difference in temperature between raw mine water and the processed mine water leaving the heat pump.
†Estimated, as measurements either not made or not reported.
†Unpublished report provided by University of Oviedo.
§See www.geoexchange.org/downloads/cs-064.pdf.
¶See www.geothermal-energy.org/pdf/IGAstandard/WGC/1995/1-jessop.pdf.

outflow during periods of low flow ($\leq Q_{90}$). The remaining three-quarters of pipe systems become increasingly active during periods of rainfall (with a typical lag-time of 3 h from onset of rain to increased flow in the pipes), and over an entire year they can account for a significant proportion (13.7% in the catchment studied) of the total annual outflow from the catchment. All pipes tend to take longer to decline to base flow rates than the catchment as a whole, suggesting that they receive substantial contributions from the interstitial pore space in the surrounding peat during dry spells (Smart *et al.* 2013).

These matrix–pipe interactions in natural peat catchments are instructive as regards the concerns over potential dewatering of peat as a result of wind turbine installations. The notion that deeply incised drainage features will lead to desiccation and oxidation of peat ought to apply to natural peatlands with pipes as well as to those disturbed by road construction, etc. Yet the hydrological behaviour of pipe systems during and after storms (Smart *et al.* 2013) shows that drainage from interstitial pore space into deeply incised pipes is perennial in many cases, and it does not lead to desiccation of the surrounding peat (Stunell & Younger 1995). This is almost certainly because of the very low hydraulic conductivity of blanket peat (Holden & Burt 2003), which ensures that the interstitial pore space drains very slowly, even with a free surface boundary condition imposed all along the edge of the peatland by an incised channel. In other words, peatlands are very difficult to dewater. This is consistent with the findings of chemical and isotopic studies of peatland drainage waters (e.g. Waldron *et al.* 2009), which have revealed that, although disturbed peatlands do release more dissolved and suspended organic carbon to downstream catchments than undisturbed ones, the scale of carbon loss is a lot more modest than was originally feared. However, as the site studied by Waldron *et al.* (2009) had only recently been disturbed, that finding may not transfer to sites subject to longer periods of disturbance. Thus further research is needed, on a wider range of sites and over longer time scales, to determine whether such conclusions are indeed generally valid for upland peat ecosystems affected by wind turbine developments. On the basis of the evidence to date, however, the unusual hydrogeology of peat seems to be rendering it rather resistant to wholesale dewatering by gravity drainage.

Hydrogeology and non-renewable low-carbon energy developments

Nuclear industry

Hydrogeology has long been central to various aspects of the nuclear industry, including mining and processing of uranium ores (e.g. Merkel & Hasche-Berger 2008), management of uranium mine wastes (e.g. Abdelouas 2006), site appraisal for nuclear power plant construction (e.g. Mercado 1989*a*,*b*), and geological disposal of radioactive wastes (e.g. Chapman 2009). The hydrogeological community in the UK (and thus the author) have been most active in the last of these areas, and it is to that topic that the following comments are restricted. Since the 1970s, the issue of safe, long-term disposal of radioactive waste has had a chequered history. A recent, thorough review of the key issues surrounding deep geological disposal of radioactive waste has been provided by Chapman (2009). In the public arena, much confusion has attended the topic, with little apparent awareness of the important distinctions between large-volume, low-level radioactive waste (much of which comes from hospital radiography departments, for instance) and the lesser volumes of intermediate- and high-level radioactive wastes. The lack of public understanding is expressed in sustained hostility to the very idea of emplacing radioactive waste underground, which is ironic, as it is far safer to have even a few metres of virtually any rock (let alone hundreds of metres of low-permeability rock) between a human being and a source of ionizing radiation than to have radioactive waste stored at the surface in close proximity to the open air. Yet that will remain the status quo until such time as the technical and political dimensions of

the problem can be brought into convergence. Quite how difficult this will be to achieve is illustrated by the furore and denouement that attended the failed attempt by (the now-defunct) Nirex to get planning permission for an underground 'rock characterization facility' (RCF) in Cumbria. After extensive site investigations, which included 29 deep boreholes and genuinely ground-breaking groundwater modelling studies concerning palaeo-hydrogeology (e.g. Heathcote & Michie 2004), present-day flow systems (e.g. Chaplow 1996; Lunn *et al.* 1997) and predictions for future scenarios (e.g. Haszeldine & McKeown 1995; Thorne *et al.* 2000), the Secretary of State for the Environment finally refused permission for construction of the RCF in March 1997 (Atherton & Poole 2001).

After a subsequent period of soul-searching and public opinion surveys, Nirex realized that lay people were simply not comfortable with the model for deep subsurface disposal of radioactive waste that they had been pursuing hitherto. Under that model, underground galleries excavated to receive the waste would be rapidly stowed with waste, grouted and abandoned. The lack of any provision for monitoring and retrievability repeatedly emerged as sources of public disquiet, prompting a fundamental rethink by Nirex. This led to an intensive period of a priori reasoning and literature review on the possible consequences of deferred repository back-filling, resulting in a report exploring the key challenges (Jackson *et al.* 2002). With respect to hydrogeological aspects, much was learned by analogy to recent experiences in the hydrogeology of mine closure (Younger *et al.* 2002). It was clear that more attention needed to be paid to hydrogeochemical changes arising from disruption of the enclosing rock mass by underground excavation, and in particular to induced changes in near-void permeability, which govern both rates of groundwater inflow and the scope for partial drainage of fractures allowing penetration of oxygen from the ventilated voids back into the rock mass. This not only controls the volume of rock mass potentially subject to undesirable oxidation processes (such as pyrite weathering), but also governs the penetration of evaporation into the surrounding rocks. This is important because evaporative accumulation of halides, and/or (hydroxyl)sulphate salts can both reduce permeability by clogging fractures and further weaken the 'excavation damaged zone' (EDZ) adjoining the void walls. Departure of the pH of the groundwater in the EDZ from a circum-neutral state, to either acidic or alkaline extremes, can reduce rock mass strength by as much as 60% (Younger 2002). In the longer term, eventual abandonment of previously ventilated voids can be expected to lead to an abrupt cessation of evaporite precipitation, with concomitant changes in de-gassing of incoming groundwaters as the ambient atmosphere in the voids equilibrates with the dissolved gas content of the incoming groundwaters. As water levels rise throughout the voids and any surrounding dewatered strata, the salts accumulated in the EDZ and the voids will dissolve, releasing large quantities of solutes to solution. Where the salts are hydroxysulphates, a sharp drop in pH can also be expected (Younger 2002).

Cruachan underground repository analogue study

In the absence of an RCF, these concepts could not be tested in an area where deep geological disposal of radioactive waste was being actively considered; hence an analogue study was undertaken, using as its platform the underground tunnels and chambers of the Cruachan Pumped-Storage Hydroelectric Power Station (CPSHPS) [UK national grid reference NN 077 285] in the Scottish Highlands. The CPSHPS, constructed between 1961 and 1965 and still very much in active use today, was the world's first pumped-storage hydroelectric plant (Young & Falkiner 1966; Knill 1972). The pumped storage concept, which has since been adopted in many countries, is a hydroelectric generation technology that profitably exploits the differential demands for (and therefore costs of) electricity at different times of day. During times of peak demand, water is released from a high-level reservoir and passed through high-speed turbines to a lower reservoir. In the middle of the night, when electricity demands and prices are at a minimum, the turbines are run in reverse, acting as pumps that lift water back to the upper reservoir, where it is stored until the next period of high demand. In the case of CPSHPS, the lower reservoir is Loch Awe (*c.* 40 m Ordnance Datum (OD)) and the upper reservoir is an artificial water body in a cirque known as Coire Cruachan, impounded behind a mass concrete gravity-arch dam (crest elevation *c.* 415 m OD). Apart from these two lakes, virtually all the remaining infrastructure at CPSHPS is located in underground chambers and tunnels excavated in plutonic and metamorphic rocks of generally low permeability (Young & Falkiner 1966; Knill 1972). The penstock and tailrace tunnels are almost always filled with water, and are in any case pressure-grouted and shotcreted throughout to prevent any loss of water to the rock mass. The accessible core of the CPSHPS comprises a turbine hall (90 m long, 38 m high and 26 m wide) accessed via a 1 km long vehicle access tunnel 4 m high and 5 m wide, as well as three separate systems of aqueduct tunnels (totalling 14 km altogether) bringing water to the upper reservoir from distant surface catchments, into which they debouch through portals that lie at about 420 m OD. The turbine hall and tunnel are force-ventilated and maintained dry by means of pumping (albeit averaging only a few litres per second). The turbines act as a heat source, leading to steep gradients in heat and humidity towards the portal. In the vicinity of the underground installations the surface topography ranges from 40 m OD to about 1100 m at the highest summit of the Cruachan Beann (Ben Cruachan) mountain range, so that both the turbine hall–access tunnel complex and the higher aqueduct tunnels have up to 500 m of rock cover. Altogether, with the permission of the owners, around 16 linear kilometres of underground tunnels is potentially accessible for hydrogeological inspection in the CPSHPS, and the vast majority of these features display bare rock, with relatively few concrete-lined sections. The CPSHPS lies in an area of high rainfall (ranging from about 2000 mm per annum in the valley floor to more than 3000 mm on the summit of Cruachan Beann), with a mean annual air temperature of around 9 °C in the valley, declining to just below 0 °C on the summit of Cruachan Beann. The combination of high rainfall, low evapotranspiration (reflecting low air temperatures), and low soil and rock permeabilities ensures that the ground is visibly saturated virtually everywhere.

The geological sequence in the vicinity of the CPSHPS is dominated by two major lithologies: metasediments and granite. The former comprise laminated, interbedded phyllites and quartzites (metamorphosed to greenschist grade), interpreted as having accumulated under alternating tidal flat and low-energy marine shelf conditions. Of Neoproterozoic age (*c.* 600 Ma), these metasediments are assigned to the Craignish (= Ardrishaig) Phyllite Formation (Easdale Subgroup, Argyll Group, Dalradian Supergoup; Stephenson & Gould 1995). At around 400 Ma (early Devonian), the Craignish Phyllite was intruded by a major composite pluton known as the Etive Granite. Most of the 'granite' in which the CPSHPS is developed is actually grey–white monzodiorite, bearing prominent plagioclase phenocrysts in a finer-grained quartz–feldspar–biotite groundmass. Local masses of pink monzogranites and syenogranites, referred to collectively as the Meall Odhar Granite (Stephenson & Gould 1995), also occur in the eastern aqueduct tunnel. A scattering of felsic and mafic dykes is also obvious in the aqueduct tunnels, where they can be seen to cut both the granite and the phyllite.

Detailed hydrogeological investigations were undertaken at CPSHPS over a period of 3 years (Dudgeon 2005), involving the following: lithological and structural mapping of surface outcrops

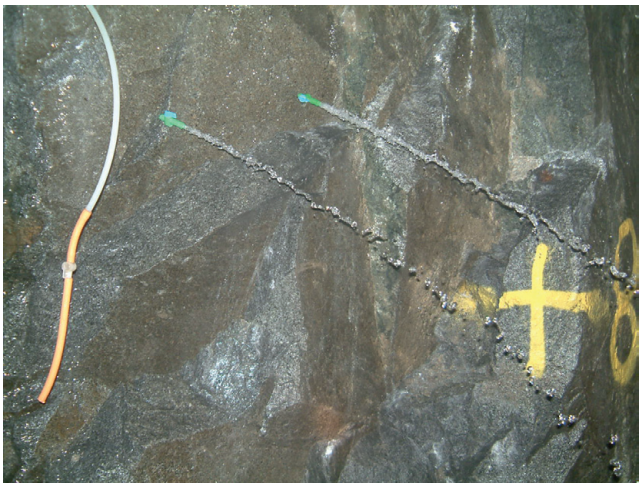

Fig. 6. Cluster of three mini-piezometers at chainage 860 m in the Bhuiridh (eastern) aqueduct tunnel at the Cruachan Pumped Storage Hydropower Station, drilled into granite and fitted with gas-tight taps (two of which were opened when the photograph was taken). The piezometers intersect a fracture some 0.2–0.3 m behind the tunnel wall, which yields groundwater that has not yet encountered the air in the tunnel.

and underground exposures in tunnels and chambers, including orientations of geological contacts and rock mass discontinuities; sampling and analyses of surface water sources and of groundwaters (and some exsolving gases) entering the underground voids; monitoring of atmospheric conditions within the turbine hall and access tunnels; drilling of narrow-bore mini-piezometers into the walls of tunnels to intersect groundwater that had not yet encountered the atmosphere within the voids (Fig. 6); quantifying groundwater inflow rates from specific fractures (using time/volume and thin plate weir methods); X-ray diffraction and chemical analyses of mineral precipitates from void walls and fracture–void intersection planes (for further details see Dudgeon 2005).

It was found that the most prolific water-yielding fractures were those oriented subparallel to the current principal horizontal tectonic stress for this region (i.e. NNE–SSW; Heidbach *et al.* 2008), affirming the current hydrogeomechanical exploration paradigm also being used for geothermal resources (see Olsson & Barton 2001; and see above). Bulk water yields to the tunnels average around $5 \times 10^{-3} l^{-1}$ per linear metre. The groundwaters entering the CPSHPS are all lowly mineralized (conductivities 100–400 $\mu S\,cm^{-1}$), with circumneutral pH and (except for waters immediately adjoining tunnel portals) devoid of dissolved organic carbon. Almost all waters are of Ca–HCO_3 or Ca–Na–HCO_3 facies, although seepage associated with the granite–phyllite contact zone within the main access tunnel is of Ca–Na–SO_4 facies, reflecting localized pyrite oxidation. Near the major heat source in this facility (the main turbine hall) no groundwater enters the voids in liquid form; it all evaporates to dryness as it meets the warm air in the facility, giving rise to accumulations of evaporite salts on the walls (Fig. 7), which are predominantly thenardite (Na_2SO_4) and gypsum ($CaSO_4.2H_2O$), with occasional potassium-rich aphthitalite ($K_3Na(SO_4)_2$). (Although calcite flowstone and stalagmites are found locally, these are invariably associated with leaching of concrete structures.) Avoidance of salt damage to infrastructure during the long-term use of the void requires a continuing inspection and maintenance programme. After eventual abandonment of the void, abrupt dissolution of these salts could make the water highly aggressive towards most common grouts used in subsurface applications; pre-abandonment strategies of 'wash-down' for salt-affected walls therefore warrant consideration, at least for facilities that have been retained open for several decades.

Since the intensive period of hydrogeological research was completed at CPSHPS in 2005, it has been used for further nuclear industry research relating to the corrosion of austenitic steels under realistic repository-like conditions. The facility has immense potential for further investigations, which could well prove valuable as the post-Nirex jurisdiction of radioactive waste management in the UK advances its agenda (e.g. Chapman 2009). Since the demise of Nirex, the autonomous Committee on Radioactive Waste Management (CoRWM) deliberated at length on the key issues, finally aligning itself with the international consensus that safe interim storage leading to deep geological disposal is the preferred long-term solution (CoRWM 2006), albeit with a far higher commitment to transparency and public engagement than had characterized Nirex activities prior to 1997. This includes a commitment to a concept of 'volunteerism' by local communities interested in hosting such a management facility. The Radioactive Waste Management Division (RWMD) of the Nuclear Decommissioning Authority (NDA) has now developed a detailed plan to deliver this strategy (NDA 2010), although at the time of writing it is stalled, after Cumbria County Council rescinded its earlier expression of interest, effectively overruling one of the district councils that were still keen to progress as a volunteer community. Meanwhile, the debate about reversibility and retrievability in radioactive waste management continues to rumble on (OECD 2010), with shallow, retrievable storage remaining the present policy of the Scottish Government (2011), for instance. Research of the sort undertaken at CPSHPS now appears more relevant than ever.

Carbon capture and storage

There is widespread acceptance in professional circles that, in the absence of renewable energy sources that are both available at large-scale and on-demand (rather than just when the weather is appropriate), the shift to a low-carbon economy will inevitably involve continued reliance on fossil fuels for at least a few more decades. Were fossil fuels to be ditched immediately, as many campaigners demand, frequent energy black-outs would be the certain outcome, which no political administration of any colour would survive electorally. A worked example is Germany, which is often hailed as a paragon of low-carbon virtue in Europe, as it has some of the highest per capita installed capacities of wind and solar power. However, in 2011 Germany made two energy policy changes in the face of public protests: it ruled out unconventional gas exploration and (following the Fukushima incident) it announced that remaining nuclear power plants, which provide much of the country's baseload electricity, would be decommissioned faster than had previously been planned. As wind and solar installations prove incapable of meeting baseload and dispatchable electricity demands, and with gas prices being high owing to lack of indigenous supply, the government of Germany has decided that it will avoid power cuts by rapidly commissioning more lignite-burning power plants, the first of which (>2.2 GW) was recently commissioned near Köln (Nicola & Andresen 2012). As lignite has a much lower calorific value than bituminous coal, it is characterized by significantly higher carbon emissions, and thus from a climate change mitigation perspective it is a far less desirable energy source than Westphalian coals, let alone than natural gas (conventional or unconventional) or nuclear energy. In these circumstances, the only hope of Germany protecting its reputation as a responsible 'green' country would be to implement carbon capture and storage (CCS) on its new lignite-fired power stations. Yet the only pilot-scale CCS project yet attempted by the German authorities was cancelled when the government failed to transpose EU CCS law into national legislation on a reasonable time scale, with legislators backing down in the face of vociferous

Fig. 7. Salt accumulations (principally thenardite with subordinate gypsum) on the walls of the Cruachan underground power station, Scotland. (Width of field of view *c.* 1 m). These sulphate salts have formed by evaporation to dryness of groundwater entering the facility, in which the air is heated by operation of hydro-power turbines. (Note the small seepage of groundwater (dark in colour) from a former rock-blot hole, and the badly corroded face plate in the lower right of the field of view; these illustrate the challenge of salt-assisted corrosion in underground voids maintained open for several decades.)

opposition by pressure groups (European CCS Demonstration Project Network 2012). Controversy focused largely around subsurface injection of CO_2: essentially hydrogeological arguments, which were characterized by a total lack of understanding of hydrogeology on the part of the protagonists. There is thus a pressing need for better communication of hydrogeological principles in these urgent public debates. This in turn requires that many more hydrogeologists become *au fait* with the technical issues, and step up to the challenge of public engagement.

The conceptual framework for moving towards deep geological storage of CO_2 has been under development for several years now (e.g. Baines & Worden 2004), and the principal elements are already clear and widely accepted. A thorough summary of the state of the art and current consensus on deep geological storage of CO_2 has been provided by Smith *et al.* (2012). Some critical points of hydrogeological relevance include the following.

(1) The need to inject at depths commensurate with maintenance of the CO_2 in its supercritical form. In that form, the CO_2 has the density of a liquid but the compressibility of a gas, which are necessary properties for storage at scale (Haszeldine 2009). In practical terms, this means searching for target aquifers deeper than about 650 m (or more if the CO_2 is not in pure form).

(2) The need for injected CO_2 to displace pre-existent groundwater in the target horizons, which raises the following issues: hydraulic continuity (i.e. does the displaced groundwater have somewhere to go (a so-called 'open system') or must it be subjected to greatly increased pressures *in situ* (a 'closed system')); CO_2–brine miscibility (e.g. Mathias *et al.* 2011) dissolution–exsolution equilibria (e.g. Gilfillan *et al.* 2009); and mineralization of CO_2 (e.g. Golding *et al.* 2011).

(3) The buoyancy of CO_2: being less dense than water it will preferentially accumulate at the top of a receiving aquifer, 'pooling' below the confining aquitard above (Haszeldine 2009).

(4) The fact that pore entry pressures for CO_2 are significantly lower than those for H_2O, which means that CO_2 might pass more easily into lower permeability strata than water would (e.g. Li *et al.* 2006; Li and Fan 2013).

(5) The susceptibility of stored CO_2 to leakage via faults and similar fractures, even when these were previously regarded as having low-permeability fills (e.g. Shipton *et al.* 2004; Nelson *et al.* 2009).

Although still regarded as a nascent technology for purposes of CO_2 storage, deep subsurface injection of gases (including far more hazardous ones, such as highly explosive hydrogen) has been routine industrial practice for many decades already, even onshore and in densely populated areas, without major problems (e.g. Stone *et al.* 2009). Indeed, injection of CO_2 itself into deep strata has already been practised for many years for purposes of sour gas disposal and/or enhanced hydrocarbon recovery, at several localities both offshore (at Sleipner, in the Norwegian North Sea; Zweigel *et al.* 2004) and onshore (e.g. at In Salah (Algeria), where injection occurred from 2004 to 2011 without leakage to the surface (Mathieson *et al.* 2010), and at Weyburn (Canada), where many advances in CCS monitoring technologies have been made (Riding & Rochelle 2009).

Amongst the currently agreed criteria for acceptability of deep geological storage of CO_2 is that loss of CO_2 from the store should not exceed 1% over the next 10000 years (e.g. Haszeldine 2009). Demonstrating this is a major engineering and geoscientific challenge, although not unique, as we have already seen in the case of radioactive waste disposal (Toth 2011). If any geological stores for CO_2 are to be licensed, predictions of their behaviour over such extended time scales will need to be made to sufficient standards of rigour and quantified uncertainty that regulators (and investors) can be genuinely convinced that they will prove to be effectively leak-proof. Studies of analogues (natural and anthropogenic) for future CO_2 stores have revealed that leakage is most likely to occur either via faults (e.g. Shipton *et al.* 2004) or via poorly designed or poorly completed boreholes (e.g. Miyazaki 2009).

CCS clearly has potential to reduce the emissions from the worst categories of power stations (i.e. those burning coal and oil), and if applied also to natural gas it has the potential to transform newly identified 'unconventional gas' reserves into low-carbon energy sources.

Unconventional gas

Conventional oil and gas exploitation has a long history of interaction with hydrogeology, much of it negative: salinization of aquifers from careless disposal of co-produced waters in the onshore fields of Texas and Oklahoma, for instance (e.g. Richter & Kreitler 1991), or hydrocarbon pollution in urban areas owing to leaking underground (petroleum) storage tanks (LUST) (McLearn *et al.* 1988). More recently, concerns have focused on the widely reported occurrence in groundwater of methyl tertiary butyl ether (MTBE), an anti-knocking agent that replaced lead in petroleum used as vehicle fuel (Chisala *et al.* 2007). Although the hydrocarbon industry has gone a long way towards cleaning up its act in relation to such problems, this unalluring history is partly to blame for the hostility with which the new wave of unconventional oil and gas developments has been greeted in Europe. This is in a sense ironic, as the onshore hydrocarbons industry in Europe has been tiny in comparison with that in North America, with few documented instances of salinization and relatively few of rampant LUST and MTBE pollution. Nevertheless, a sustained diet of televised transatlantic experiences including Hollywood movies (such as the 2000 film *Erin Brokovich*) and the 2010 Deepwater Horizon (Gulf of Mexico) incident has reinforced in Europe the notion that the hydrocarbon industry is essentially synonymous with pollution.

Whereas over-pressured hydrocarbon reservoirs harbour the potential for catastrophic blow-out events, tightly bound gas in low-permeability strata has to be heavily coaxed to come to surface at all, so that the chances of uncontrolled pollution from unconventional gas operations is really rather modest. Yet there is no more controversial issue in modern Britain than the contention that exploitation of recently identified unconventional gas resources

could lead to wholesale pollution of potable water aquifers. Never have the stakes for hydrogeological science, and its public understanding, been higher. Yet neither ever have the stakes been higher for decarbonization of our economy; and natural gas (unconventional or otherwise) is undoubtedly less carbon intensive than coal (which is, as we have seen, precisely what Germany is rushing to burn following its rejection of unconventional gas developments; Nicola & Andresen 2012). Hydrogeology's moment in the spotlight has come. The final few paragraphs of this paper outline the principal hydrogeological issues attending unconventional gas development, considering all major categories. The first category is rarely considered an 'unconventional gas', yet it is one in which hydrogeology has a key role.

Landfill gas

The production of methane within conventional municipal waste landfills has been recognized for more than four decades (e.g. Farquhar & Rovers 1973), although for many years it was viewed primarily as an explosion hazard (e.g. Williams & Aitkenhead 1991) rather than an asset. As scientific investigation of landfill methanogenesis proceeded (e.g. Nastev *et al.* 2001), and as appreciation grew that the potency of methane as a greenhouse gas far exceeds that of CO_2 (Gardner *et al.* 1993), it was realized that landfill gas has significant potential as an energy resource (Jaramillo & Matthews 2005). Control of groundwater (= leachate) levels within landfills plays a critical role in the optimization of methane production for purposes of electricity production, with best performance being achieved where an unsaturated zone of about 4 m thickness is maintained above the water table in the landfill (Rees 1980). Hydrogeological criteria for landfill energy production therefore require careful management of surrounding groundwater to ensure optimal methane yields to on-site turbines.

Shale gas

No unconventional gas source has had more negative publicity in Europe in recent years than shale gas, despite the fact that there are no operating shale gas operations of any scale in the continent yet, and notwithstanding the overwhelmingly positive public attitude to the large-scale shale gas industry in the USA. Most controversy in Europe has focused on hydraulic fracturing, which is perceived by campaigners as a dangerously new technology, despite the fact that it has been in use for 50 years in the UK with an unblemished positive track record, not only in onshore conventional hydrocarbon development at, for instance, Wytch Farm in Dorset (e.g. Cocking *et al.* 1997), but also in geothermal energy development in Cornwall (Downing & Gray 1986) and, most recently, improvement of the permeability of Precambrian strata in the Scottish Highlands to provide clean public groundwater supplies, replacing the highly coloured peaty surface waters previously supplied by Scottish Water (Cobbing & Ó Dochartaigh 2007). Indeed, of more than 2000 onshore oil and gas wells in the UK to date, some 200 are reported by the Department of Energy and Climate Change as having already been 'fracked', with not a single reported incident of pollution, fugitive gas emissions or any other negative impact. In ignorance (culpable or otherwise) of these UK experiences, vociferous campaigners against 'fracking' draw on a sparse catalogue of poorly documented and largely unverified alleged cases of groundwater pollution in shale gas areas of the USA to portray hydraulic fracturing as intrinsically evil. The reality was investigated extensively at the request of the Government Chief Scientist by a joint panel of the Royal Society and Royal Academy of Engineering (on which the author served), which reported in June 2012 (Mair *et al.* 2012). In essence, and in common with other independent studies (e.g. Stuart 2011; Ward 2012), the joint panel concluded that hydraulic fracturing *per se* is extremely unlikely to lead to groundwater pollution (Mair *et al.* 2012). In hydrogeological terms this is because: (1) induced fracture pathways will not extend as far as the base of freshwater aquifers hundreds of metres above (save, perhaps, in close proximity to critically stressed faults) (see Davies *et al.* 2012); (2) even if they did, the hydraulic gradient would direct groundwater flow towards the de-pressurized shale gas production zones, not upwards to the aquifers; (3) after abandonment, there is no reason why the hydraulically fractured zones should develop heads greater than those in the freshwater aquifers; and (4) even if they did, the permeabilities of the aquifers are orders of magnitudes greater than those of the most permeable hydraulically fractured zones in shales, so that only miniscule contributions of water to the major aquifer might result, which would probably prove undetectably small.

The fluids used in hydraulic fracturing are also often cited by campaigners as 'toxic'. It is understandable that conspiracy theories have arisen around this topic, given the self-defeating lobbying by the industry in the USA, which led to the exemption of shale gas operations from generic environmental reporting regulations: this gives the impression that there is something to hide. In reality, there is nothing in contemporary hydraulic fracturing fluids (Mair *et al.* 2012) that has not been used for many decades in the development of potable water abstraction boreholes (e.g. Clark 1988). Of course, any borehole drilling operation (as with any civil engineering operation) has the potential to breach environmental regulations if fuel or other liquids are mishandled on site (Stuart 2011); but this is already well controlled by existing regulations (Mair *et al.* 2012). Similarly, poor casing and grouting can lead to undesirable inter-aquifer flows (Ward 2012), although again this is in no way unique to shale gas developments. The unconventional gas industry has a huge vested interest in borehole integrity in any case, as the safety of their workforce and capture of their product depend on it. Stringent operating procedures are already in place to ensure that grouting takes place to high design pressures, to ensure that blow-out preventers and eventual welltop valves are capable of containing any build-up of gas within the casing.

Induced seismicity is not only an inevitable, but also a desirable companion of hydraulic fracturing operations: if no shear deformation occurs (which cannot happen without producing some seismic signal) then no permeability will be created. Indeed, the industry carefully monitors micro-seismic signals during periods of hydraulic fracturing, as these accurately reveal where dilation of fractures in the shale has occurred. It is precisely these data that allow unequivocal appraisal of how far hydro-fractures have propagated towards overlying aquifers (Fig. 8), allowing categorical assessments to be made of whether or not permeability enhancement has extended into any sensitive areas. As shown in Figure 8, the vast database of hydraulic fracturing of gas shales deep beneath freshwater aquifers displays not a single instance of the induced fractures extending as far as a freshwater body (see Fisher & Warpinski 2012).

It is unfortunate that the first shale gas well in the UK to be hydraulically fractured (at Preese Hall, Lancashire) happened to be close to a previously unknown minor fault that was critically stressed and ready to slip. Indeed, in all the tens of thousands of shale gas fracturing operations in the USA to date, no similar fault reactivation has been reported. One could argue that more pre-development investigation should have been undertaken at Preese Hall. Nevertheless, the resultant tremors were barely perceptible without instrumentation, caused no damage, and were much smaller than those with which inhabitants of coal mining regions have lived for centuries (Mair *et al.* 2012; Davies *et al.* 2013). If any non-damaging vibrations whatsoever are to be deemed publicly unacceptable, the future for UK public bus services, heavy goods vehicle transport and air services must also be bleak.

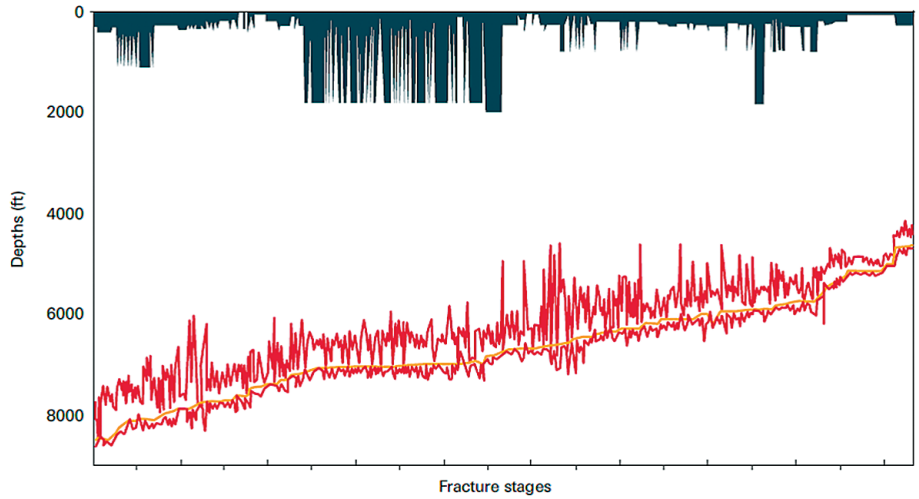

Fig. 8. Depth plot of maximum vertical hydraulic fracture propagation from all known shale gas operations in the Marcellus Shale from 2001 to 2010, with the base of the nearest overlying freshwater aquifer (vertical blue lines at the top of the diagram) plotted for comparison. The depth at which hydraulic fracturing was stimulated (sorted by depth for ease of reference) is given by the yellow line, while the red spikes represent the vertical extent of fracture growth (which is accurately known from micro-seismic monitoring). It is obvious that none of the induced fractures come even close to connecting with the overlying freshwater aquifers. (From Mair *et al.* 2012, with permission of the Royal Society and Royal Academy of Engineering, adapted after Fisher & Warpinski 2012.)

Besides hydraulic fracturing, which generally requires importation of water, shale gas production always requires back-pumping of the injectate, which will typically be admixed with native groundwater from the fractured shale zones. In most cases, the quantities of native groundwater involved are small, as little continuing flow is induced from the unfractured shales beyond the reach of the hydraulic fractures. Some methane may be entrained in back-pumped waters, and this may be de-gassed to the atmosphere if not contained; however, given the kinetics of methane dissolution and exsolution, the quantities are not anticipated to be significant in most circumstances.

The likelihood that the UK has significant shale gas resources has been under discussion for some time (see Selley 2005). The most recent resource estimates (Andrews 2013) suggest that the resources may be sufficient to ease the UK's transition from largely coal-fired baseload and dispatchable generation to lower-carbon natural gas. Given the limited scope for further hydro pumped storage, and the technical and economic limitations of large-scale battery storage systems, then even with maximum penetration of wind, solar, wave and tidal power into the national electricity mix, there will remain a major irreducible requirement for dispatchable sources of generation to 'plug the gaps' when renewable power generation lulls. For the foreseeable future, no such dispatchable sources of sufficient scale are renewable. Of all the options available, specialists at the National Grid contend that the lowest carbon option is natural gas (Lawton 2012). However, unless the hydrogeological realities can be successfully communicated to an increasingly sceptical public, there is a serious risk that the UK will fail to take advantage of the potentially significant bridge to a low-carbon future that unconventional sources of gas offer us.

Abandoned coal mine methane

The rationale for exploiting abandoned coal mine methane corresponds closely to that for landfill gas: it is far better to combust methane to produce energy (even though this releases CO_2) than to allow the methane to escape to the atmosphere, where it is a far more potent greenhouse gas than carbon dioxide. Capturing and using abandoned coal mine methane involves both shaft-cap off-takes at former colliery sites and purpose-drilled boreholes, whence methane is diverted to small gas turbine units to produce electricity, which is then fed into the National Grid (Jardine *et al.* 2009). Hydrogeological considerations arise from the negative correlation between presence of mine water and yield of methane: flooded mine workings cease to yield appreciable methane. Hence abandoned mine methane capture is a strictly supra-water table activity. To date, mine water rebound has been viewed as essentially an independent, inexorable 'show-stopper' for abandoned coal mine methane exploitation systems: the gas may be captured and burned only until the process of water table rise in the deep coal workings (see Younger 1993) drowns out the gas-yielding zones. Thereafter, that gas production point is simply abandoned. A certain amount of consolation may be gained by the observation that rising water tables in old workings tend to increase pressure on gas above, sometimes accelerating gas emissions temporarily, before stifling them altogether upon final submergence.

In certain settings, however, synergies between different motivations for mine water pumping could make it possible to extend the life of abandoned coal mine methane operations beyond those that would apply if rebound is left to take its natural course. As was noted above in relation to mine water heat-pump systems, the UK Coal Authority currently pumps around $3\,m^3\,s^{-1}$ from abandoned coal mines in the UK for environmental protection purposes (Coal Authority 2010). In several circumstances, the precise level of drawdown achieved by such pumping could be chosen to simultaneously satisfy the environmental protection needs, maximize the temperature of the pumped water (deeper waters being warmer), so that it can be utilized more efficiently in a heat-pump system, and prolong the period of abandoned coal mine methane utilization nearby. There are a number of locations in the English Midlands where such a convergence of interests seems distinctly possible.

Coalbed methane

Intact coal seams, including many that simply lie too deep to have ever been exploited by conventional mining, also offer natural gas resources. In this case, the exploitation strategy is thoroughly hydrogeological: boreholes are drilled to the roof of the target coal seam, and all overlying strata are then cased and grouted off. The borehole is then continued through the seam, and extended a short distance below the seam floor to create a drainage sump.

Groundwater from the seam is then pumped until the head level in the coal drops sufficiently to begin inducing unsaturated conditions in the seam, at which point any methane adsorbed on the cleat of the coal will begin to desorb and migrate to the borehole. The presence of a sump means that the entire thickness of coal can be unsaturated around each borehole in this manner. In most modern operations, directional in-seam drilling is used (a similar concept to traditional Ranney Collector Wells in alluvial aquifers) to greatly extend the volume of coal that becomes unsaturated and thus begins to yield up its gas. This method clearly works best where the coal seam is not bounded above and below by aquifers; indeed, ingress of water from over- or under-lying strata can kill a coalbed methane (CBM) production well. As such, productive CBM wells generally yield only modest quantities of water, given the generally low permeability of most coal seams. In some cases, hydraulic fracturing is used to enhance the cleat permeability of the coal seams, although in such cases care has to be taken to avoid inducing fractures in the roof strata that extend as far as the next sandstone in the cyclothem, as ingress of water from such a sandstone could be counter-productive. Unsurprisingly, given these operational imperatives, a study by the US EPA (2004) into alleged cases of aquifer pollution ascribed to hydraulic fracturing in CBM operations concluded that 'although thousands of CBM wells are fractured annually, EPA did not find confirmed evidence that drinking water wells have been contaminated by hydraulic fracturing fluid injection into CBM wells'.

In addition to physical stimulation of permeability, methane yield from CBM wells can also be enhanced by injecting CO_2 into the seam via another well, as CO_2 preferentially sorbs to the coal surface, displacing further methane in the process. This approach is termed 'enhanced coalbed methane'. CBM operations therefore depend on many factors on which hydrogeologists are particularly well placed to advise. Although CBM operations typically produce only modest quantities of water, this is often fairly mineralized, with elevated iron and hardness, rather similar to many deep-strata mine waters (see Younger 1998). These waters will often require some treatment prior to surface disposal or subsurface reinjection (Clarke 1996), although the techniques for doing so are now well established following the last two decades of mine water remediation research (Younger *et al.* 2002).

Underground coal gasification

Whereas CBM recovers the pre-existing methane sorbed on the cleat of coal seams, underground coal gasification (UCG) goes one step further and turns the coal itself into a gas stream, typically comprising a mixture of hydrogen, carbon monoxide, methane and some carbon dioxide. As the last has no calorific value, operating parameters for UCG are generally skewed to favour an optimal blend of the first three gases. The gas produced by UCG typically has as much as 80% of the total calorific value of the original solid coal. The cocktail of useful gases is usually termed 'synthesis gas' (or 'syngas' for short), albeit this is a rather loose application of a term that more strictly refers to a mixture just of hydrogen and carbon monoxide, without any methane. Syngas is not only useful for power production; where available in proximity to existing chemical industry facilities, it is even more valuable as a process feedstock.

In contrast to shale gas and CBM operations, UCG does not involve any pumping of water, although steam is often mixed with oxygen prior to injection to a deep coal seam via an injection borehole. This injectate gas stream reacts briskly with the coal, partially oxidizing it to produce the desired syngas. A number of recent papers have described the UCG process in further detail (e.g. Roddy & Younger 2010; Younger *et al.* 2010, 2011), so it is not explained further here. Despite the lack of groundwater pumping in UCG, it is not devoid of hydrogeological challenges (Younger 2011). In essence, these relate to: (1) the need to ensure borehole integrity, so that surrounding aquifers are not invaded by syngas (which is certainly an objective that well operators and environmental regulators hold in common, as lost syngas is of no value to anyone); (2) the requirement to demonstrate from first principles that the processes of void collapse and fracturing that will inevitably follow the removal of coal by any means will not lead to the development of short-circuiting pathways to shallow freshwater aquifers or surface water bodies.

The starting point for such evaluations to date has been to invoke well construction and completion practices from the geothermal sector, which is accustomed to ensuring well integrity for high-temperature gases (e.g. Finger & Blankenship 2010), and applying the decades of geomechanical learning from total extraction mining beneath aquifers and the sea-bed to ensure that fractures induced by void collapse do not connect hydraulically to freshwater bodies near the surface (see Orchard 1975; Garritty 1982). On this basis, Younger (2011) developed guidance on environmental (largely hydrogeological) risk assessment for UCG projects, and for projects in which the porosity produced by UCG is subsequently utilized as a long-term storage zone for CO_2. The findings of these preliminary investigations are highly encouraging for the development of UCG with CCS as a low-carbon source of syngas for industrial feedstock and power generation. If the current furore over other forms of unconventional gas is anything to go by, however, a substantial public engagement effort will be needed to gain and maintain the social licence to operate.

Conclusion

The nascent low-carbon economy is already proving to be fertile territory for the transfer of hydrogeological skills to address novel challenges. As the examples highlighted in this paper show, the full range of hydrogeological skills is going to be needed, from fundamental hydrostratigraphy and aquifer parameter determinations, through hydrogeochemistry, to modelling and interpretation. In the early stages, at least, of the extension of hydrogeology into the low-carbon industries, practitioners are going to have to be adept also at explaining groundwater science to the public. Recent polemics around shale gas 'fracking' reveal the depths of ignorance about groundwater and subsurface engineering, even amongst otherwise well-educated people. This is not, perhaps, especially surprising, given that hydrogeology has been overwhelmingly taught only as a postgraduate specialism until now, and almost exclusively to students from geoscience and civil engineering backgrounds. The time has clearly come for hydrogeologists to redouble our efforts at promoting public understanding of our science; if we fail to do so, there is every possibility that major contributions to the attainment of a sustainable low-carbon economy will fall by the wayside for no good reason.

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References

Abdelouas, A. 2006. Uranium mill tailings; geochemistry, mineralogy, and environmental impact. *Elements*, **2**, 335–341.

Andrews, I.J. 2013. *The Carboniferous Bowland Shale gas study: Geology and resource estimation*. British Geological Survey for Department of Energy and Climate Change, London.

Appelo, C.A.J. & Postma, D. 1993. *Geochemistry, Groundwater and Pollution*. Balkema, Rotterdam.

Ármannsson, H. 2010. Application of geochemical methods in geothermal exploration. Notes for Short Course V (Exploration for Geothermal Resources), organised by the United Nations University Geothermal Training Programme, the Geothermal Development Company (Kenya) and KenGen. Lake Bogoria and Lake Naivasha, Kenya, Oct. 29–Nov. 19, 2010. www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-11-27.pdf.

Armstead, H.C.H. 1978. *Geothermal Energy: Its Past, Present and Future Contributions to the Energy Needs of Man*. Spon, London.

Atherton, E. & Poole, M. 2001. The problem of the UK's radioactive waste: What have we learnt? *Interdisciplinary Science Reviews*, **4**, 296–302.

Baines, S.J. & Worden, R.H. 2004. Geological storage of carbon dioxide. *In*: Baines, S.J. & Worden, R.H. (eds) *Geological Storage of Carbon Dioxide*. Geological Society, London, Special Publications, **233**, 1–6, http://dx.doi.org/10.1144/GSL.SP.2004.233.01.01.

Banks, D. 2009. An introduction to 'thermogeology' and the exploitation of ground source heat. *Quarterly Journal of Engineering Geology and Hydrogeology*, **42**, 283–293, http://dx.doi.org/10.1144/1470-9236/08-077.

Banks, B. 2012. *An Introduction to Thermogeology: Ground Source Heating and Cooling*, 2nd edn. Wiley, Chichester.

Banks, D., Skarphagen, H., Wiltshire, R. & Jessop, C. 2004. Heat pumps as a tool for energy recovery from mining wastes. *In*: Gieré, R. & Stille, P. (eds) *Energy, Waste and the Environment: A |Geochemical Perspective*. Geological Society, London, Special Publications, **236**, 499–513, http://dx.doi.org/10.1144/GSL.SP.2004.236.01.27.

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://dx.doi.org/10.1144/1470-9236/08-081

Binnie, C., Kimber, M. & Smethurst, G. 2002. *Basic Water Treatment*. Royal Society of Chemistry, London.

Birkinshaw, S.J., Thorne, M.C. & Younger, P.L. 2005. Reference biospheres for post-closure performance assessment: Inter-comparison of SHETRAN simulations and BIOMASS results. *Journal of Radiological Protection*, **25**, 33–49.

Birks, D., Whittall, S., Savill, I., Younger, P.L. & Parkin, G. 2013. Groundwater cooling of a large building using a shallow alluvial aquifer in Central London. *Quarterly Journal of Engineering Geology and Hydrogeology*, **46**, 189–202, http://dx.doi.org/10.1144/qjegh2012-059.

Bischoff, J.L. & Pitzer, K.S. 1989. Liquid-vapor relations for the system NaCl-H_2O: summary of the P-T- x surface from 300° to 500°C. *American Journal of Science*, **289**, 217–248. http://dx.doi.org/10.2475/ajs.289.3.217

Brown, J.M.B. & Ingram, H.A.P. 1988. Changing storage beneath a stationary watertable—an anomaly of certain humified peats. *Quarterly Journal of Engineering Geology*, **21**, 177–182.

Busby, J., Kingdon, A. & Williams, J. 2011. The measured shallow temperature field in Britain. *Quarterly Journal of Engineering Geology and Hydrogeology*, **44**, 373–387.

Buss, S.R. 2009. Introduction to the 'Hydrogeology in Heat Engineering' papers. *Quarterly Journal of Engineering Geology and Hydrogeology*, **42**, 281–282.

Chaplow, R. 1996. The geology and hydrogeology of Sellafield: An overview. *Quarterly Journal of Engineering Geology*, **29**, S1–S12, http://dx.doi.org/10.1144/GSL.QJEGH.1996.029.S1.01.

Chapman, N. 2009. A geological disposal facility for the UK's radioactive wastes. *Proceedings of the Institution of Civil Engineers, Energy*, **162**, 183–192. http://dx.doi.org/10.1680/ener.2009.162.4.183

Chiasson, A.C., Rees, S.J. & Spitler, J.D. 2000. A preliminary assessment of the effects of ground-water flow on closed-loop ground-source heat pump systems. *American Society of Heating, Refrigerating and Air-Conditioning Engineers Transactions*, **106**, 380–393.

Chisala, B.N., Tait, N.G. & Lerner, D.N. 2007. Evaluating the risks of methyl tertiary butyl ether (MTBE) pollution of urban groundwater. *Journal of Contaminant Hydrology*, **91**, 128–145.

Clark, L. 1988. *The Field Guide to Water Wells and Boreholes*. Professional Handbook Series, Geological Society, London.

Clarke, L.B. 1996. Environmental aspects of coalbed methane production, with emphasis on water treatment and disposal. *Transactions of the Institution of Mining and Metallurgy, (Section A)*, **105**, A105–A113.

Clarkson, M.H., Birks, D., Younger, P.L., Carter, A. & Cone, S. 2009. Groundwater cooling at the Royal Festival Hall, London. *Quarterly Journal of Engineering Geology and Hydrogeology*, **42**, 335–346, http://dx.doi.org/10.1144/1470-9236/08-080.

Clyde, C.G., Govindachari, V. & Madabhushi, M. 1983. Spacing of wells for heat pumps. *Journal of Water Resources Planning and Management (ASCE)*, **109**, 203–212.

Coal Authority 2010. *Annual Report and Accounts 2009–10*. The Stationery Office Ltd, London. http://www.official-documents.gov.uk/document/hc1011/hc02/0281/0281.pdf

Cobbing, J. & Ó Dochartaigh, B.É. 2007. Hydrofracturing water boreholes in hard rock aquifers in Scotland. *Quarterly Journal of Engineering Geology and Hydrogeology*, **40**, 181–186, http://dx.doi.org/10.1144/1470-9236/06-018.

Cocking, D.A., Bezant, P.N. & Tooms, P.J. 1997. Pushing the ERD envelope at Wytch Farm. *In*: *Proceedings of the Society of Petroleum Engineers/International Association of Drilling Contractors Drilling Conference*, 4–6 March 1997, *Amsterdam*, Paper SPE/IADC 37186.

CoRWM, 2006. Managing our radioactive waste safely. CoRWM's recommendations to government. Committee on Radioactive Waste Management (CoRWM), London, http://tinyurl.com/3en7fev.

Davies, R.J., Mathias, S.A., Moss, J., Hustoft, S. & Newport, L. 2012. Hydraulic fractures: How far can they go? *Marine and Petroleum Geology*, **37**, 1–6.

Davies, R., Foulger, G., Bindley, A. & Styles, P. 2013. Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. *Marine and Petroleum Geology*, **45**, 171–185, http://dx.doi.org/10.1016/j.marpetgeo.2013.03.016.

Dickson, M.H. & Fanelli, M. 2005. *Geothermal Energy: Utilization and Technology*. Earthscan, London.

Dipippo, R. 2012. Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact, 3rd edn. Butterworth–Heinemann, Oxford.

Downing, R.A. & Gray, D.A. (eds) 1986. *Geothermal Energy—The Potential in the United Kingdom*. British Geological Survey, Nottingham; HMSO, London.

Downing, R.A. & Gray, D.A. 2004. Jack Ineson (1917–1970) The instigator of quantitative hydrogeology in Britain. *In*: Mather, J.D. (ed.) *200 Years of British Hydrogeology*. Geological Society, London, Special Publications, **225**, 283–286, http://dx.doi.org/10.1144/GSL.SP.2004.225.01.20.

Downing, R.A., Oakes, D.B., Wilkinson, W.B. & Wright, C.E. 1974. Regional development of groundwater resources in combination with surface water. *Journal of Hydrology*, **22**, 155–177.

Dudgeon, B.A. 2005. *Hydrogeochemistry of seepage entering deep tunnels in crystalline rock: Cruachan Power Station, Scotland*. PhD thesis, University of Newcastle upon Tyne.

Ellis, A.J. & Mahon, W.A.J. 1977. *Chemistry and Geothermal Systems*. Academic Press, New York.

European CCS Demonstration Project Network, 2012. *Lessons learned from the Jänschwalde project: Summary report*. Cottbuss, http://tinyurl.com/mlypq63.

Farquhar, G.J. & Rovers, F.A. 1973. Gas production during refuse decomposition. *Water, Air, and Soil Pollution*, **2**, 483–495.

Finger, J. & Blankenship, D. 2010. *Handbook of Best Practices for Geothermal Drilling*. Sandia Report, **SAND2010-6048**. http://www1.eere.energy.gov/geothermal/pdfs/drillinghandbook.pdf.

Fisher, K. & Warpinski, N. 2012. Hydraulic-fracture-height growth: Real data. *Society of Petroleum Engineers, Productions and Operations Journal*, **27**, 8–19, http://dx.doi.org/10.2118/145949-PA.

Foley, A.E., Atkinson, T.C. & Zhao, Y. 2012. Chlorofluorocarbons as tracers of landfill leachate in surface and groundwater. *Quarterly Journal of Engineering Geology and Hydrogeology*, **45**, 61–70, http://dx.doi.org/10.1144/1470-9236/10-044.

Fournier, R.O. & Potter, R.W. 1982. A revised and expanded silica (quartz) geothermometer. *Geothermal Resources Council Bulletin*, **11**, 3–12.

Fridleifsson, G.O. & Elders, W.A. 2005. The Iceland Deep Drilling Project: A search for deep unconventional geothermal resources. *Geothermics*, **34**, 269–285.

Gandy, C.J., Clarke, L., Banks, D. & Younger, P.L. 2010. Predictive modelling of groundwater abstraction and artificial recharge of cooling water. *Quarterly Journal of Engineering Geology and Hydrogeology*, **43**, 279–288. http://dx.doi.org/10.1144/1470-9236/08-093

Gardner, N., Manley, B.J.W. & Pearson, J.M. 1993. Gas emissions from landfills and their contributions to global warming. *Applied Energy*, **44**, 165–174.

Garnish, J. & Brown, G. 2012. Geothermal energy. *In*: Boyle, G. (ed.) *Renewable Energy. Power for a Sustainable Future*, 3rd edn. Open University–Oxford University Press, Oxford, 409–459.

Garritty, P. 1982. Water percolation into fully caved longwall faces. *In*: Farmer, I.W. (ed.) *Strata Mechanics. (Proceedings of the Symposium on Strata Mechanics held in Newcastle upon Tyne, 5–7 April 1982)*. Developments in Geotechnical Engineering, **32**, 25–29.

Giggenbach, W.F. 1986. Graphical techniques for the evaluation of water–rock equilibration conditions by use of Na, K, Mg and Ca contents of discharge waters. *In*: *Proceedings of the 8th New Zealand Geothermal Workshop, held 5–7 November 1986* University of Auckland, Auckland, 37–44.

Giggenbach, W.F. 1988. Geothermal solute equilibria. Derivation of Na–K–Mg–Ca–geoindicators. *Geochimica et Cosmochimica Acta*, **52**, 2749–2765.

Giggenbach, W.F. 1997. Relative importance of thermodynamic and kinetic processes in governing the chemical and isotopic composition of carbon gases in high heatflow sedimentary basins. *Geochimica et Cosmochimica Acta*, **61**, 3762–3785.

Giggenbach, W.F., Gonfiantini, R., Jangi, B.L. & Truesdell, A.H. 1983. Isotopic and chemical composition of Parbati Valley geothermal discharges, NW Himalaya, India. *Geothermics*, **12**, 199–222.

Gilfillan, S.M.V., Sherwood Lollar, B., *et al.* 2009. Solubility trapping in formation water as dominant CO_2 sink in natural gas fields. *Nature*, **458**, 614–618, http://dx.doi.org/10.1038/nature07852.

Golding, S.D., Uysal, I.T., Boreham, C.J., Kirste, D., Baublys, K.A. & Esterle, J.S. 2011. Adsorption and mineral trapping dominate CO_2 storage in coal systems. *Energy Procedia*, **4**, 3131–3138.

Grant, M.A. & Bixley, P.F. 2011. *Geothermal Reservoir Engineering*, 2nd edn. Academic Press, Waltham, MA.

Haines, T.S. & Lloyd, J.W. 1985. Controls on silica in groundwater environments in the United Kingdom. *Journal of Hydrology*, **81**, 277–295.

Haszeldine, R.S. 2009. Carbon capture and storage: How green can black be? *Science*, **325**, 1647–1652, http://dx.doi.org/10.1126/science.1172246.

Haszeldine, R.S. & McKeown, C. 1995. A model approach to radioactive waste disposal at Sellafield. *Terra Nova*, **7**, 87–95, http://dx.doi.org/10.1111/j.1365-3121.1995.tb00671.x.

Heathcote, J.A. & Michie, U.M. 2004. Estimating hydrogeological conditions over the last 120 ka: An example from the Sellafield area, UK. *Journal of the Geological Society, London*, **161**, 995–1008, http://dx.doi.org/10.1144/0016-764902-132.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfess, D. & Müller, B. & The World Stress Map based on the database release 2008. equatorial scale 1:46,000,000. Commission for the Geological Map of the World, Paris, http://dc-app3-14.gfz-potsdam.de/pub/introduction/introduction_frame.html.

Hem, J.D. 1985. *Study and interpretation of the chemical characteristics of natural water*. US Geological Survey Water-Supply Paper, **2254**, 3rd edn.

Herbert, A., Arthur, S. & Chillingworth, G. 2013. Thermal modelling of large scale exploitation of ground source energy in urban aquifers as a resource management tool. *Applied Energy*, **109**, 94–103.

Holden, J. & Burt, T.P. 2003. Hydraulic conductivity in upland blanket peat: Measurement and variability. *Hydrological Processes*, **17**, 1227–1237, http://dx.doi.org/10.1002/hyp.1182.

Ineson, J. 1959. Yield-depression curves of discharging wells with particular reference to Chalk wells and their relationship to variations in transmissibility. *Journal of the Institution of Water Engineers*, **13**, 119–163.

Ingram, H.A.P. 1983. Hydrology. *In*: Gore, A.J.P. (ed.) *Ecosystems of the World 4A, Mires: Swamp, Bog, Fen and Moor*. Elsevier, Oxford, 67–158.

Jackson, C.P., Knight, J.L., Lappin-Scott, H., Linklater, C.M., Rodwell, W.R. & Younger, P.L. 2002. *Implications of deferred backfilling on repository geosphere performance*. Nirex Report, **N/056**.

Jaramillo, P. & Matthews, H.S. 2005. Landfill-gas-to-energy projects: Analysis of net private and social benefits. *Environmental Science and Technology*, **39**, 7365–7373.

Jardine, C.N., Boardman, B., Osman, A., Vowles, J. & Palmer, J. 2009. Coal mine methane. *In*: Jardine, C.N., Boardman, B., Osman, A., Vowles, J. & Palmer, J. (eds) *Methane UK*. Environmental Change Institute, University of Oxford, 64–71, http://tinyurl.com/lcryduw.

Jardón, S., Ordóñez, A., Álvarez, R., Cienfuegos, P. & Loredo, J. 2013. Mine water for energy and water supply in the Central Coal Basin of Asturias (Spain). *Mine Water and the Environment*, **32**, 139–151, http://dx.doi.org/10.1007/s10230-013-0224-x.

Kalina, A., Leibowitz, H., Lazzeri, L. & Diotti, F. 1995. Recent development in the application of Kalina cycle for geothermal plants. *In*: *Proceedings of the World Geothermal Congress*, *Florence, Italy*, International Geothermal Association, Florence, 2093–2096.

Kennedy, B.M. & Van Soest, M.C. 2012. Flow of mantle fluids through the ductile lower crust: Helium isotope trends. *Science*, **318**, 1433–1436.

Kestin, J., Sokolov, M. & Wakeham, W.A. 1978. Viscosity of liquid water in the range –8 °C to 150 °C. *Journal of Physical and Chemical Reference Data*, **7**, 941–948.

Knill, J.L. 1972. The engineering geology of the Cruachan underground power station. *Engineering Geology*, **6**, 289–312.

Kwak, H.T., Zhang, G. & Chen, S. 2005. The effects of salt type and salinity on formation water viscosity and NMR responses. *In*: *Proceedings of the International Symposium of the Society of Core Analysts, Toronto, Canada, 21–25 August 2005*, Paper SCA2005-51, Society of Core Analysts, Fredericton. http://www.scaweb.org/assets/papers/2005_papers/1-SCA2005-51.pdf.

Lawton, P. 2012. Balancing the energy network. *Ingenia*, **53**, 20–26.

Leiby, V.M. & Burke, M.E. 2011. Energy efficiency best practices for North American drinking water utilities. Water Research Foundation, Denver, CO, http://www.waterrf.org/PublicReportLibrary/4223.pdf.

Li, X. & Fan, X. 2013. Experimental studies on multiphase flow in porous media and pore wettability. *World Academy of Science, Engineering and Technology*, **74**, 739–743.

Li, Z., Dong, M., Li, S. & Huang, S. 2006. CO_2 sequestration in depleted oil and gas reservoirs—caprock characterization and storage capacity. *Energy Conversion and Management*, **47**, 1372–1382.

Lloyd, J.W. & Heathcote, J.A. 1985. *Natural Inorganic Hydrochemistry in Relation to Groundwater. An Introduction*. Clarendon Press, Oxford.

Loredo, J., Ordóñez, A., Jardón, S. & Álvarez, R. 2011. Mine water as geothermal resource in Asturian coal mining basins (NW Spain). *In*: Rüde, T.R., Freund, A. & Wolkersdorfer, C.H. (eds) *Proceedings of the 11th International Mine Water Association Congress—Mine Water: Managing the Challenges, Aachen, Germany, 4–11 September 2011*, Mine Water Association, Aachen. 177–182.

Lunn, R.J., Lunn, A.D. & Mackay, R. 1997. Development of a hydrogeological model of the Borrowdale Volcanics at Sellafield. *Journal of Hydrology and Earth System Sciences*, **1**, 35–46.

Mair, R., Bickle, M., *et al.* 2012. *Shale Gas Extraction in the UK: A Review of Hydraulic Fracturing*. Royal Society and Royal Academy of Engineering, London.

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*, **164**, 371–382. http://dx.doi.org/10.1144/0016-76492006-015

Marini, L. 2010. *Geochemical techniques for the exploration and exploitation of geothermal energy*. http://www.appliedgeochemistry.it/doc/Geochemistry_Marini.pdf

Mathias, S.A., Gluyas, J.G., Gonzalez, G. & Hosseini, S. 2011. Role of partial miscibility on pressure buildup due to constant rate injection of CO_2 into closed and open brine aquifers. *Water Resources Research*, **47**, W12525, http://dx.doi.org/10.1029/2011WR011051.

Mathieson, A., Midgley, J., Dodds, K., Wright, I., Ringrose, P. & Saoul, N. 2010. CO_2 sequestration monitoring and verification technologies applied at Krechba, Algeria. *Leading Edge*, **29**, 216–222, http://dx.doi.org/10.1190/1.3304827.

McLearn, M.E., Miller, M.J., Kostecki, P.T., Calabrese, E.J., Preslo, L.M., Suyama, W. & Kucharski, W.A. 1988. Remedial options for leaking underground storage tanks. *Journal of the Air Pollution Control Association*, **38**, 428–435, http://dx.doi.org/10.1080/08940630.1988.10466395.

Mercado, A. 1989*a*. Assessment of groundwater contamination resulting from a major accident in land nuclear power plants (LNPP), I: Concepts and methodology. *Journal of Contaminant Hydrology*, **5**, 33–41.

Mercado, A. 1989*b*. Assessment of groundwater contamination resulting from a major accident in land nuclear power plants (LNPP), II: Evaluation of a melt-through event. *Journal of Contaminant Hydrology*, **5**, 43–66.

Merkel, B.J. & Hasche-Berger, A. (eds) 2008. *Uranium, Mining and Hydrogeology*. Springer, Heidelberg.

Miyazaki, B. 2009. Well integrity: An overlooked source of risk and liability for underground natural gas storage. Lessons learned from incidents in the USA. *In*: Evans, D.J. & Chadwick, R.A. (eds) *Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe*. Geological Society, London, Special Publications, **313**, 163–172, http://dx.doi.org/10.1144/SP313.11.

Nalluri, C. & Featherstone, R.E. 2001. *Civil Engineering Hydraulics*, 4th edn. Wiley–Blackwell. Chichester.

Nastev, M., Therrien, R., Lefebvre, R. & Gelinas, P. 2001. Gas production and migration in landfills and geological materials. *Journal of Contaminant Hydrology*, **52**, 187–211.

NDA, 2010. *Geological disposal: Steps towards implementation*. Radioactive Waste Management Division, Nuclear Decommissioning Authority Report, **NDA/RWMD/013**, http://tinyurl.com/lcryduw.

Nelson, S.T., Mayo, A.L., Dutson, S.J., Gilfillan, S.M.V., Shipton, Z., Harris, R.A. & Tingey, D.G. 2009. Enhanced fracture permeability and accompanying fluid flow in the footwall of a normal fault: The Hurricane Fault at Pah Tempe Hot Springs, Washington County, Utah. *Geological Society of America Bulletin*, **121**, 236–246, http://dx.doi.org/10.1130/B26285.1.

Nicola, S. & Andresen, T. 2012. Merkel's green shift forces Germany to burn more coal. *Bloomberg News*, http://tinyurl.com/8cdt8nc.

OECD, 2010. *Selected international bibliography on reversibility and retrievability to Support the current NEA project*. Organisation for Economic Co-operation and Development, Nuclear Energy Agency Document, **NEA/RWM(2010)11**, www.oecd-nea.org/rwm/rr/documents/RR_Bibliography.pdf.

Olsson, R. & Barton, R. 2001. An improved model for hydromechanical coupling during shearing of rock joints. *International Journal of Rock Mechanics and Mining Sciences*, **38**, 317–329.

Orchard, R.J. 1975. Working under bodies of water. *Mining Engineer*, **170**, 261–270.

Paonita, A., Caracausi, A., Iacono-Marziano, G., Martelli, M. & Rizzoa, A. 2012. Geochemical evidence for mixing between fluids exsolved at different depths in the magmatic system of Mt Etna (Italy). *Geochimica et Cosmochimica Acta*, **84**, 380–394.

Payne, K. 2013. Keeping track of energy. *Ingenia*, **54**, 21–26, www.ingenia.org.uk/ingenia/issues/issue54/Payne.pdf.

Piper, A.M. 1944. A graphic procedure in the geochemical interpretation of water-analyses. *Transactions of the American Geophysical Union*, **25**, 914–928. http://dx.doi.org/10.1029/TR025i006p00914

Post, V.E.A. & von Asmuth, J.R. 2013. Review: Hydraulic head measurements—New technologies, classic pitfalls. *Hydrogeology Journal*, **21**, 737–750.

Raymond, J., Williams-Jones, A.E. & Clark, J.R. 2005. Mineralization associated with scale and altered rock and pipe fragments from the Berlín Geothermal field, El Salvador; implications for metal transport in natural systems. *Journal of Volcanology and Geothermal Research*, **145**, 81–96, http://dx.doi.org/10.1016/j.jvolgeores.2005.01.003.

Rees, J.F. 1980. Optimisation of methane production and refuse decomposition in landfills by temperature control. *Journal of Chemical Technology and Biotechnology*, **30**, 458–465.

Richter, A. 2013. High temperature and permeability reported for first well in Montserrat. 'ThinkGeoEnergy' on-line news service, http://thinkgeoenergy.com/archives/15567.

Richter, B.C. & Kreitler, C.W. 1991. *Identification of sources of groundwater salinization using geochemical techniques*. US Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory, Report, **EPA/600/2-91/064**.

Riding, J.B. & Rochelle, C.A. 2009. Subsurface characterization and geological monitoring of the CO_2 injection operation at Weyburn. Saskatchewan. Canada. *In*: Evans, D.J. & Chadwick, R.A. (eds) *Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe*. Geological Society, London, Special Publications, **313**, 227–256, http://dx.doi.org/10.1144/SP313.14.

Rivett, M.O., Turner, R.J., Glibbery, P. & Cuthbert, M.O. 2012. The legacy of chlorinated solvents in the Birmingham aquifer, UK: Observations spanning three decades and the challenge of future urban groundwater development. *Journal of Contaminant Hydrology*, **140**, 107–123, http://dx.doi.org/10.1016/j.jconhyd.2012.08.006.

Roddy, D.J. & Younger, P.L. 2010. Underground coal gasification with CCS: A pathway to decarbonising industry. *Energy and Environmental Science*, **3**, 400–407, http://dx.doi.org/10.1039/b92119g.

Roijen, E. 2011. The use of an open-loop heat-pump systems to heat social housing and an office building throughout the town of Heerlen, the Netherlands. *In*: Faull, M.L. (ed.) *Heat-Pump Technology using Minewater*. National Coal Mining Museum for England Publications, **13**, 15–25.

Scottish Government, 2011. *Retrievability and Reversibility. Scotland's Higher Activity Radioactive Waste Policy*. Scottish Government, Edinburgh, www.scotland.gov.uk/Resource/Doc/211199/0118101.pdf.

Selley, R.C. 2005. UK shale-gas resources. *In*: Doré, A.G. & Vining, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London. Petroleum Geology Conference Series, **6**, 707–714, http://dx.doi.org/10.1144/0060707.

Shipton, Z.K., Evans, J.P., Kirschner, D., Kolesar, P.T., Williams, A.P. & Heath, J. 2004. Analysis of CO_2 leakage through 'low permeability' faults from natural reservoirs in the Colorado Plateau, east–central Utah. *In*: Baines, S.J. & Worden, R.H. (eds) *Geological Storage of Carbon Dioxide*. Geological Society, London, Special Publications, **233**, 43–58, http://dx.doi.org/10.1144/GSL.SP.2004.233.01.05.

Smart, R.P., Holden, J., Dinsmore, K.J., Baird, A.J., Billett, M.F., Chapman, P.J. & Grayson, R. 2013. The dynamics of natural pipe hydrological behaviour in blanket peat. *Hydrological Processes*, **27**, 1523–1534.

Smith, M., Campbell, D., Mackay, E. & Polson, D. (eds) 2012. *CO_2 aquifer storage site evaluation and monitoring: Understanding the challenges of CO_2 storage: Results of the CASSEM Project*. Scottish Carbon Capture and Storage, Edinburgh, http://nora.nerc.ac.uk/17527/.

Stephenson, D. & Gould, D. 1995. *British Regional Geology: The Grampian Highlands*, 4th edn. HMSO, London.

Stone, H.B.J., Veldhuis, I. & Richardson, R.N. 2009. Underground hydrogen storage in the UK. *In*: Evans, D.J. & Chadwick, R.A. (eds) *Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe*. Geological Society, London, Special Publications, **313**, 217–226, http://dx.doi.org/10.1144/SP313.13.

Stuart, A. & Hitchman, S.P. 1986. Borehole sampling techniques and field analysis of groundwater in landfill pollution studies. *In*: Cripps, J.C., Bell, F.G. & Culshaw, M.G. (eds) *Groundwater in Engineering Geology: Proceedings of the 21st Annual Conference of the Engineering Group of the Geological Society held at the University of Sheffield, 15–19 September 1985*. Geological Society, London, Engineering Geology Special Publications, **3**, 225–246, http://dx.doi.org/10.1144/GSL.ENG.1986.003.01.26.

Stuart, M.E. 2011. *Potential groundwater impact from exploitation of shale gas in the UK*. British Geological Survey Open Report, **OR/12/001**, http://nora.nerc.ac.uk/16467/1/OR12001.pdf.

Stunell, J.M. & Younger, P.L. 1995. Hydrogeology of upland peat: Hydrological and chemical processes in Redesdale, N England. *In*: Black, A.R. & Johnson, R.C. (eds) *Proceedings of the Fifth Biennial National Hydrology Symposium. British Hydrological Society. Edinburgh, 4–7 September 1995*, British Hydrological Society, Edinburgh, 5.9–5.16.

Tedesco, D., Miele, G., Sanob, Y. & Toutain, J.P. 1995. Helium isotopic ratio in Vulcano island fumaroles: Temporal variations in shallow level mixing and deep magmatic supply. *Journal of Volcanology and Geothermal Research*, **64**, 117–128.

Thorne, M.C., Degnan, P., Ewen, J. & Parkin, G. 2000. Validation of a physically based catchment model for application in post-closure radiological safety assessments of deep geological repositories for solid radioactive waste. *Journal of Radiological Protection*, **20**, 403–421.

Tonani, F. 1970. Geochemical methods of exploration for geothermal energy. *Geothermics*, **2**, 492–515. http://dx.doi.org/10.1016/0375-6505(70)90049-0

Toth, F. 2011. *Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment*. Springer, Berlin.

US EPA, 2004. *Evaluation of impacts to underground sources of drinking water by hydraulic fracturing of coalbed methane reservoirs*. US Environmental Protection Agency, Report, **816-R-04-003**.

Waldron, S., Flowers, H., Arlaud, C., Bryant, C. & McFarlane, S. 2009. The significance of organic carbon and nutrient export from peatland-dominated landscapes subject to disturbance. *Biogeosciences*, **6**, 363–374.

Ward, R.S. 2012. Can shale gas be extracted safely? *Groundwater, well integrity, use of water*. Presentation to the Geological Society of London, 29 June 2012. British Geological Survey, Keyworth, http://tinyurl.com/ms6kghr.

WaterUK, 2011. Sustainability indicators 2010/11. WaterUK, London, http://tinyurl.com/pb3rfsj.

Watzlaf, G.R. & Ackman, T.E. 2006. Underground mine water for heating and cooling using geothermal heat pump systems. *Mine Water and the Environment*, **25**, 1–14.

Wieber, G. & Pohl, S. 2008. Mine water: A source of geothermal energy—examples from the Rhenish Massif. *In*: Rapantova, N. & Hrkal, Z. (eds) *Proceedings of the 10th International Mine Water Association Congress—Mine Water and the Environment, Karlsbad, Czech Republic, 2–5 June 2008*, Mine Water Association, Karlsbad 113–116.

Williams, G.M. & Aitkenhead, N. 1991. Lessons from Loscoe: The uncontrolled migration of landfill gas. *Quarterly Journal of Engineering Geology*, **24**, 191–207.

Young, W. & Falkiner, R.H. 1966. Some design and construction features of the Cruachan Pumped Storage Project. *Proceedings of the Institution of Civil Engineers*, **35**, 407–450.

Younger, P.L. 1993. Possible environmental impact of the closure of two collieries in County Durham. *Journal of the Institution of Water and Environmental Management*, **7**, 521–531.

Younger, P.L. 1998. Coalfield abandonment: geochemical processes and hydrochemical products. *In*: Nicholson, K. (ed.) *Energy and the Environment. Geochemistry of Fossil, Nuclear and Renewable Resources. Society for Environmental Geochemistry and Health*. MacGregor Science, Insch, 1–29.

Younger, P.L. 2002. Modification of groundwater and mineral chemistry adjacent to underground voids. *In*: Jackson, C.P., Knight, J.L., Lappin-Scott, H., Linklater, C.M., Rodwell, W.R. & Younger, P.L. (eds) *Implications of deferred backfilling on repository geosphere performance*. Nirex Report, **N/056**, 78–97.

Younger, P.L. 2007*a*. *Groundwater in the Environment: An Introduction*. Blackwell, Oxford.

Younger, P.L. 2007*b*. Well spaced out? Adequate distances between boreholes are crucial to the sustainability of ground-source heating/cooling systems. GeoDrilling International (Sept 2007 issue), Special Publication on Ground-Source Energy, 8–9.

Younger, P.L. 2008. Ground-coupled heating–cooling systems in urban areas: How sustainable are they? *Bulletin of Science, Technology and Society*, **28**, 174–182.

Younger, P.L. 2010. Reconnaissance assessment of the prospects for development of high-enthalpy geothermal energy resources, Montserrat. *Quarterly Journal of Engineering Geology and Hydrogeology*, **43**, 11–22. http://dx.doi.org/10.1144/1470-9236/08-083

Younger, P.L. 2011. Hydrogeological and geomechanical aspects of underground coal gasification and its direct coupling to carbon capture and storage. *Mine Water and the Environment*, **30**, 127–140, http://dx.doi.org/10.1007/s10230-011-0145-5.

Younger, P.L. 2013. Deep geothermal: The Newcastle Science Central Borehole. *Geothermal Association of Ireland Newsletter*, **21**, 9–13.

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://dx.doi.org/10.1144/1470-9236/08-085

Younger, P.L. & Robins, N.S. (eds) 2002. *Mine Water Hydrogeology and Geochemistry*. Geological Society, London, Special Publications, 198.

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

Younger, P.L., Gluyas, J., Cox, M. & Roddy, D.J. 2010. Underground coal gasification. *Ingenia*, **43**, 42–46.

Younger, P.L., Roddy, D.J. & González, G. 2011. King Coal: restoring the monarchy by underground gasification coupled to CCS. *In*: Vining, B.A. & Pickering, S.C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers—Proceedings of the 7th Petroleum Geology Conference. Geological Society, London*. Petroleum Geology Conference Series, **7**, 1155– 1163, http://dx.doi.org/10.11044/0071155.

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

Zweigel, P., Arts, R., Lothe, A.E. & Lindeberg, E.B.G. 2004. Reservoir geology of the Utsira Formation at the first industrial scale underground CO_2 storage site (Sleipner area, North Sea). *In*: Baines, S.J. & Worden, R.H. (eds) *Geological Storage of Carbon Dioxide*. Geological Society, London, Special Publications, **233**, 165– 180, http://dx.doi.org/10.1144/GSL.SP.2004.233.01.11.

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