Abandoned coal mines: From environmental liabilities to low-carbon energy assets[1].

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Since the advent of industrial-scale coal mining in the late 16th Century, coal has repeatedly transformed economies at the regional, national and global scales (Freese, 2003). The lasting historical ramifications of the British Empire, for instance,were very largely based on the availability of vast quantities of cheap coal. Most recently, coal fuelled much of the spectacular economic growth in China that has lifted more than 650 million people out of poverty since the turn of the Millennium. It is therefore unsurprising that coal still occupies a central position in the development plans of other highly-populous developing countries, such as India and Indonesia, and still remains a major export commodity of more prosperous countries such as the USA and Australia. Nevertheless, the mining and use of coal has always been accompanied by the twin spectres of environmental degradation and workforce morbidity and fatalities (e.g. Younger, 2004a; Harris et al., 2014). Add to that the present preoccupations with greenhouse gas emissions (e.g. Li et al., 2015) and many contemporary commentators enthusiastically welcome the closure of coal mines. Yet mine closures have been devastating for innumerable local communities and economies (Freese, 2003). Furthermore, mine closure does not lead to a cessation of environmental problems. Since large-scale coalmine closures became increasingly widespread in many regions from the 1960s onwards, legacies of gas emissions (e.g. Robinson, 2000) and polluted water outflows from abandoned mines (e.g. Younger, 2004b; Younger et al., 2002) have been repeatedly documented.

For the last 40 years, much scientific effort has been dedicated to understanding the mechanisms by which such pollution arises (e.g. Singer and Stumm, 1970; Younger, 2004b), and how it varies over time (Younger, 1997), as well as to devising cost-effective, ecologically-compatible approaches for remediating the pollution (Younger et al., 2002; Wolkersdorfer, 2008). While the use of abandoned coal mine methane for energy generation has effectively minimised greenhouse gas emissions from large abandoned mine complexes (Jardine et al., 2009), more recently the possibility of using the water present in flooded, abandoned mines as a low-carbon thermal energy source has been increasingly investigated (e.g. Watzlaf and Ackman, 2006; Preene and Younger, 2014). With the exception of methane capture and use, which is a very mature technology essentially adapted directly from long-established underground mining practice, this Special Issue presents state-of-the-art contributions in all of these areas.

The contaminant hydrogeology of abandoned coal mine sites is addressed in relation to the principle foci of such investigations worldwide (Younger, 2004b), namely:

(i) regionally-interconnected deep coal mines (Younger, 2016 - in this issue);

(ii) backfilled opencast mines (Huisamen and Wolkersdorfer, 2016 - in this issue); and

(iii) colliery waste piles (Shokri et al., 2016-in this issue).

The very scale of regionally-interconnected deep coal mines makes them notoriously difficult to analyse and model on the basis of complete physically-based, distributed mathematical models (Adams and Younger, 2001; Wolkersdorfer, 2008). When the last colliery in an entire coalfield closes, such thorough modelling techniques can rarely be afforded, in terms of time and money. To provide some means of predicting rates of water level rise, future equilibrium water levels and the rates and

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quality of any future outflows of mine water to rivers and/or aquifers, Younger, (2016-in this issue) has developed a simplified, lower-cost modelling method, based on summary coalfield information that is usually available at any colliery, such as coal production records, dewatering pump runtimes and surveyed positions of the principal mine access features.

In contrast, at the much more manageable scale of discrete bodies of opencast backfill, it is eminently possible to use physically-based models of flow and thermodynamically-constrained geochemical models to predict the future evolution of water quality (Huisamen and Wolkersdorfer, 2016-in this issue), including prediction of temporal changes in that can transform ambient groundwater quality from a grossly polluted state to a condition in which they can again be used to serve a range of human needs and ecological purposes.

Coal mine waste piles, comprising masses of shattered rock, predominantly siliciclastic (most commonly mudstones and sandstones) are of comparable scale and are therefore also amenable to process-based modelling of groundwater flow and geochemical reactions. By constraining such models using geo-electrical survey data, Shokri et al. (2016-in this issue) were able to propose effective remediation strategies to minimise long-term pollutant release by minimising the ingress of oxygen to the interior of the waste pile, where it would otherwise perpetuate release of acidity by means of pyrite oxidation.

Over the last decade, the search for low-carbon energy source has led to the identification of flooded mine workings as potential sources of low-grade heat which can be harnessed using heat-pumps (Watzlaf and Ackman, 2006; Preene and Younger, 2014). A new motivation for characterising the hydraulics and geochemistry of abandoned coal mines has therefore emerged, and two examples of the exploration of abandoned mines as heat-sources are included in this Special Issue:

(i) Burnside et al. (2016-in this issue) use major-ion chemistry and isotopes to constrain water provenance in Caphouse Colliery in England, noting the presence of a substantial component of ancient (Late Pleistocene?) waters in the changing blend of iron-rich waters pumped from the shaft and passed to the pilot heat-pump system described by Al-Habaibeh et al. (2016-in this issue).

(ii) Janson et al. (2016-in this issue) use a similar approach to gain insight into the present-day flow rates and chemistry in a coal mine near Bytom in southern Poland that is still actively dewatered, providing a platform for evaluating future evolution of both when mine closures in the region finally prompt the cessation of dewatering. Remarkable stability in temperature is observed in the current pumped system, reflecting a mature groundwater heat source.

Once a given flooded mine system has been identified as a potential heat-source, a variety of evaluations must be implemented to quantify the overall source and assess its sustainability. In this task, mathematical modelling of subsurface heat-exchange processes in flooded mine roadways and other elements of the workings may yield valuable insights. Robust methods for undertaking such mathematical modelling have been reviewed by Loredo et al. (2016-in this issue). Using a combination of such hydraulic, geochemical and mathematical approaches, the scale of the potential mine water heat resource can be evaluated. Bailey et al. (2016-in this issue) have evaluated the potential for heat recovery from existing mine water pumping systems in the UK, which are already operated for purposes of environmental protection. Although the potentially recoverable heat source (47.5 MW) dwarfs the amount of electrical energy (2.3 MW) already used in these pump-and treat operations the carbon emissions reductions are rather modest given the continued predominance of fossil fuels in producing UK grid electricity. A heat resource of similar magnitude was identified by Farr et al. (2016-in this issue) in the South Wales Coalfield (UK) alone: a resource of

42 MW could be harnessed from existing outflows from abandoned collieries alone, with even greater resources being accessible if renewed pumping from deeper workings were implemented.

In many cases, treatment of polluted mine water outflows will continue to be necessary for decades (and probably even centuries) after coal-mine closure (Younger et al., 2002). Since the mid-1990s, geoscientific principles have been widely applied in the design of 'passive' mine water treatment systems, in which natural hydraulic and biogeochemical processes are harnessed to achieve the required improvement in mine water quality without the need for continual inputs of energy and reagents typical of the more conventional 'active' treatment systems (Younger et al., 2002).

In the first decade or so of development of passive treatment technology, systems were designed using evolving empirical criteria. However, as the number of such systems has multiplied, process-based evaluations of system hydraulics and biogeochemical functioning have become possible. For most reactions that serve to improve water quality, the hydraulic retention time of polluted mine water within reactive substrates is one of the key controls on the degree of water quality improvement achieved. Multiple tracers have been used to assess hydraulic retention times in subsurface flow bioreactors in the UK which are based on bacterial reduction of sulfate. For instance, for the Bowden Close treatment system in County Durham (England), Wolkersdorfer et al. (2016-in this issue) used bromide, uranine, lithium and sodium chloride tracers to deduce retention times on the order of 4 to 5 days. Sodium chloride was also used in the Tan-y-Garn treatment system in SouthWales by Banks et al. (2016a - in this issue),with ion exchange resulting in a relative retardation of sodium relative to chloride. In an appealing link to the thermal energy studies elsewhere in the Special Issue, Banks et al. (2016b-in this issue) also evaluated the efficacy of heat as a hydraulic tracer in the Tan-y-Garn system. Introduction of iced water resulted in a thermal signal that was too weak to allow unequivocal identification of retention times. However, the natural diurnal variation in temperatures proved to be more useful, with a clear lag time between nocturnal cooling of input waters and the later release of waters at the outflow from the treatment system. This observation opens the door to the wider use of this essentially free tracer in the future analysis of passive treatment systems at abandoned coal mines.

The concept of 'passive' also arises in relation to a further 'use' for abandoned coalmines: Leslie et al. (2016-in this issue) describe how timely intervention in the public management process can prevent loss of invaluable geological exposure when opencast coal mines are abandoned. The long-term educational value of large, clean exposures of coal-bearing strata cannot be over-estimated, especially in those countries in which mine abandonment has removed the many opportunities for direct observation of such strata which operating mines once afforded.

In conclusion, it is hoped that this collection of papers on abandoned coal mines will prove useful to the wider community of coal geologists as they explore the full dimensions of the geoscientific dividend to be gained from a rigorous approach to that most fascinating, valuable and still-enigmatic of rocks: coal.

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