'*Uisge Mèinne*': mine water hydrogeology in the Celtic lands, from *Kernow* (Cornwall, UK) to *Ceap Breattain* (Cape Breton, Canada)

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Abstract: Mining has historically made a major contribution to the economies of all the contemporary Celtic lands. At the start of the third Millennium, the bulk of mining activity has ceased, and problems associated with hydrogeological changes in abandoned mines are now common to all these lands. In global terms an unusually high proportion of mining in the Celtic lands has been by underground methods, a fact which is reflected in the range of hydrogeological problems encountered in these countries. Recent experiences in these countries offer insights which should be useful elsewhere when currently-active deep mines are eventually abandoned. Particular lessons are drawn from case studies and analyses of previously unpublished data from *Alba* (Scotland), *Ceap Breattain* (Cape Breton, Canada), *Cymru* (Wales) and *Kernow* (Cornwall). These lessons are:

(1) The importance of recognizing the predominance of mined features in the post-closure hydrogeology of abandoned mines.
(2) Dynamic temporal changes in hydrogeological behaviour arise from collapse of mined voids, caused by fluvial erosion by rapidly-flowing mine waters and/or by pneumatic fracturing by mine gases compressed in pockets during mine water rebound; these changes can have significant implications for human safety and environmental protection.
(3) Net-acidic mine waters are generally restricted to situations in which high-sulphur strata are present in (i) recently-flooded deep-mine workings (ii) shallow partially flooded mine workings and (iii) perched groundwater systems in spoil heaps and opencast backfill.
(4) Net-alkaline mine waters are associated with (i) low-sulphur strata in any hydrogeological setting and (ii) high-sulphur strata at depth in long-flooded workings. In practice, this means that the net-alkaline mine waters are far more abundant than the net-acidic.
(5) The presence of limestone in a mined sequence is not on its own a guarantee that mine waters will be net-alkaline; the patterns of groundwater flow (which determine the transport of limestone dissolution products through the mined system) must also be favourable.
(6) Mine water often becomes hydrochemically stratified during rebound. However, when discharge from a mined system commences, this stratification can break down, resulting in discharges considerably poorer in quality than would have been inferred by sampling the uppermost waters alone.

Mining and subsequent metal-working has been a major economic and cultural activity amongst the Celtic peoples from the earliest times (Shepherd 1993). The ancient Celts were remarkably fond of gold and silver jewellery, and indeed the two principal phases of Celtic cultural dispersion (the Hallstatt and La Tène eras) are mainly recognized on the basis of their characteristic artistic metalwork (Ross 1986). In this paper we consider the present-day hydrogeological legacy of the millennia-old mining industry of the Celtic lands, which both fed the Celtic love of precious metals, and supported the economy of the British Empire in its heyday. Although the Celts ranged widely over continental Europe in their early history (see, for

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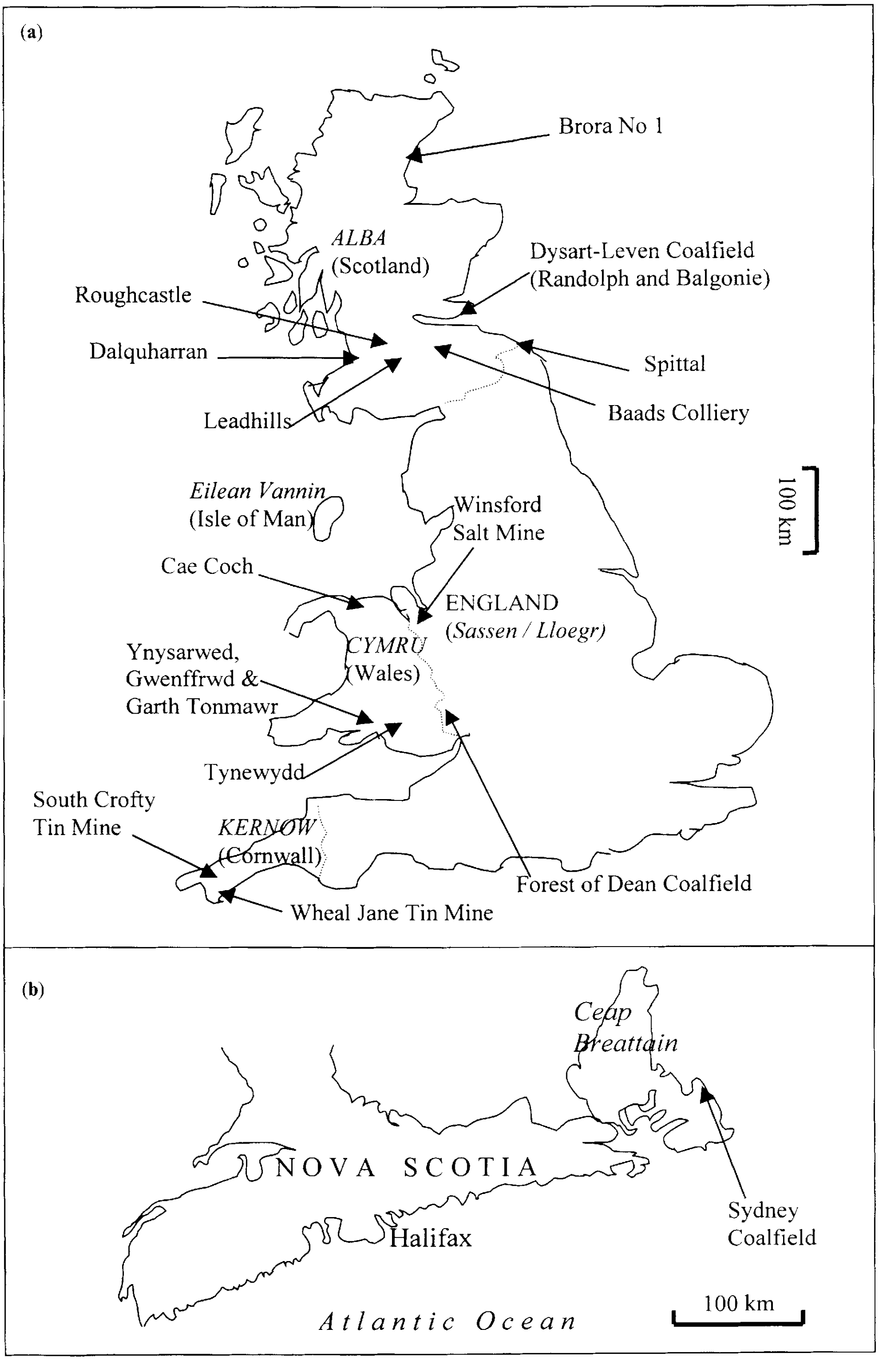

Fig. 1. Location maps for sites mentioned in the text. (**a**) A map showing the Celtic lands of Britain, namely *Alba* (Scotland), *Cymru* (Wales), *Kernow* (Cornwall), and *Eilean Vannin* (Isle of Man). The Celtic language names are also given for England in Scots Gaelic (*Sassen*) and Welsh (*Lloegr*) respectively. The specific sites marked on the map are those discussed in detail in the text. (**b**) Map of Nova Scotia, Canada, showing the location of the *Gaidhealtachd* of *Ceap Breattain* (Cape Breton Island), within which lies the Sydney Coalfield study area.

instance, Herm 1976; Hubert 1993), the focus of this volume is on the remnant nations of Celtic ancestry along the northwestern sea-board of Europe. These nations are sometimes collectively labelled (somewhat ambiguously) the 'Celtic Fringe'. In fact the Celtic languages and their cultural inheritance are not restricted to this 'fringe', for the emigration of entire communities to the New World in the 19th Century resulted in the establishment of enduring Welsh- and Gaelic-speaking communities in Patagonia and Nova Scotia, respectively. For the purposes of the present paper, the focus will be on the mining hydrogeology of the following Celtic lands (Fig. 1):

(a) *Kernow* (Cornwall)
(b) *Cymru* (Wales)
(c) *Alba* (Scotland)
(d) *Ceap Breattain* (Cape Breton Island, the *Gaidhealtachd* of Nova Scotia, Canada; Fig. 1b)

For want of data and space we do not consider Ireland, Brittany, the Isle of Man or Galicia (north-west Spain) in any detail, though all of these have had important mining industries with considerable environmental impacts (e.g. Gray 1996; O'Brien 1996; Dhonau & Wright 1998; Monterroso & Macias 1998). As the third Millennium AD begins, mining has all but ceased in the Celtic lands (with the exception of Ireland, where a renaissance of base-metal sulphide mining is underway; Dodds *et al.* 1994; Dhonau & Wright 1998). It has often been found elsewhere that the hydrogeological changes which accompany mine abandonment have considerable environmental significance (e.g. Younger 1998*a*). Experiences of such problems are now common to all the Celtic territories (e.g. Henton 1974, 1979, 1981; Robins 1990; Cain *et al.* 1994; Hamilton *et al.* 1994; Reddish *et al.* 1994; Gray 1996; Robins & Younger 1996; Bowen *et al.* 1998; Younger 1999*a*). It is the purpose of this paper to draw some general hydrogeological lessons of potentially global relevance from the Celtic experience. As an unusually high proportion of mining in the Celtic lands has been by underground methods (i.e. by 'deep mines', as opposed to 'surface (or opencast) mines'), the experiences distilled below are especially relevant in countries with deep-mining industries.

Data and methods

The data used in this study were obtained from two sources:

(a) the archives of public bodies (the Environment Agency (EA) for sites in Cornwall and Wales, the Scottish Environment Protection Agency for sites in Scotland);
(b) by direct measurement by staff of the Departments of Civil Engineering at the University of Newcastle (UK) and Dalhousie University (Canada).

All analyses were made using the standard methods of the American Public Health Association, following long-established QA/QC procedures, which have been publicly accredited in accordance with the latest norms (most recently, the UKAAS (UK Analytical Accreditation Scheme)). pH, conductivity, Eh and temperature were determined in the field using daily-calibrated electronic meters. The Newcastle team determined alkalinity in the field using a HACH digital titrator. Dissolved metals were determined by atomic absorption spectrophotometry (AAS) and inductively coupled plasma (ICP) with optical and mass spectrometry. Anions were determined by ion chromatography (Dionex 500 machine). The consistency of results between the different laboratories providing data to this study has been established during previous studies (see Younger 1998*a*, 1999*a*; La Pierre 1999).

Selected Celtic experiences with the physical hydrogeology of abandoned deep mines

General observations on the hydrogeology of deep-mined strata

The hydrogeology of abandoned deep mines has recently been reviewed in great detail in a research report prepared for the Environment Agency (England and Wales) by Younger & Adams (1999). Supplementary information on the behaviour of ancient adit systems in Cornwall (as well as northern England) has been presented by Younger (1998*b*). The general comments given here represent a précis and partial update of these earlier sources, with particular emphasis on those aspects of deep mine hydrogeology illustrated by recent experiences in the Celtic lands.

There are three principal factors to consider in relation to the hydrogeological behaviour of abandoned deep mines:

(a) the natural hydrogeology of the country rock within which the mine has been excavated;

(b) the nature and degree of alteration of the hydrogeological behaviour of the country rock by subsidence and fracturing induced by mining;
(c) the hydrogeological behaviour of the mined voids themselves.

With regard to the natural hydrogeology of the country rock, it is worth noting that the majority of productive mines have been developed in strata which are not amongst the most permeable, therefore have not been subjected to the same degree of hydrogeological investigation as the major public supply aquifers. The avoidance of major aquifers by miners is not surprising, for (as Kesserû 1995, has pointed out) miners have just as much interest as water resource managers in minimizing water inflows into active mines (the former for reasons of safety and minimizing the costs of dewatering, the latter for reasons of conservation of water resources). The recently- and currently-worked base metal sulphide mines of Ireland represent something of an exception to this general rule, having been excavated in Carboniferous Limestone which is widely used for private and public water supplies in central and western areas of the country (Dodds *et al.* 1994; Dhonau & Wright 1998). Yet even this exception 'proves the rule' as the operators of Lisheen mine in County Tipperary discovered to their cost in early 1999 when underground work was halted (it is still hoped temporarily) by unexpectedly prolific groundwater inflows which overwhelmed the installed dewatering capacity. Hence, whether the mine is in poorly documented low permeability strata or within a highly permeable aquifer, the lesson remains that the country rock within which mines are developed is rarely sufficiently well-characterized that it is amenable to accurate, deterministic predictions of future behaviour.

The processes by which subsidence and associated fracturing induced by mining alter the hydrogeological behaviour of the surrounding country rock have been the subject of substantial research efforts in the UK, principally in the context of planning and safe working of mines beneath the sea bed. (Although most UK undersea mining was undertaken in north-east England, workings also extended offshore in the Celtic lands, notably in Fife (Scotland; Younger *et al.* 1995), at Point of Ayr Colliery, North Wales (Younger 1996) and in north Cornwall (most notably at Levant Mine; Dines 1956)). Engineers working on behalf of the former UK state mining corporation British Coal developed a certain 'orthodoxy' in relation to the effects of longwall mining on the permeability of the overlying strata (Orchard 1975; Singh & Atkins 1983; Aston & Whittaker 1985). Figure 2 represents a simplified synthesis of the orthodox conceptual model for permeability development above longwall panels (for further discussion see Younger & Adams 1999). It should be noted that this orthodox conceptual model remains somewhat controversial in mining geology circles (Dumpleton, British Geological Survey, pers. comm., 1998; K. Whitworth, International Mining Consultants Ltd, pers. comm. 1–3–1999), although no alternative model has yet been proposed in the open literature. Nevertheless, in the majority of circumstances it can safely be assumed that 'unsupported' mining techniques (i.e. those which allow progressive collapse of the roof in worked out areas, which includes longwall coal workings) result in extensive fracturing of the roof strata (Fig. 2), usually inducing an increase of two to three orders of magnitude in the permeability of the roof strata (Singh & Atkins 1983). Exceptions to this increase in permeability can be expected where:

(a) the roof strata include swelling clays (which expand to fill new pore space upon extension);
(b) the workings are vertical or very steeply inclined (as in many Cornish, Welsh and Scottish metal vein mines);
(c) the country rock is extremely competent (e.g. the Cornish granites) and thus resists collapse indefinitely.

Where underground workings are excavated using a 'supported' method of mining (such as room-and-pillar) there may be little or no fracturing (and hence little or no increase in permeability) in the roof strata. Perhaps the most extreme illustration of this principle comes from north-west England (near the border with Wales) where room-and-pillar workings in Winsford Salt Mine (Fig. 1a) record *zero* groundwater ingress (G. Hall, Salt Union Ltd, pers. comm., 14–10–1998), despite the workings being overlain by saturated Quaternary sands. While the mechanical properties of halite-rich strata will clearly be different from those of coal-bearing strata, the principle that careful, supported methods of mining can greatly reduce the likelihood of water ingress is in principle applicable in a wide range of rock types.

Relatively few direct, formal studies have been made of the hydrogeological behaviour of open, flooded mine voids, and fewer still in the Celtic mining districts (Younger & Adams 1999). One of the earliest well-documented studies was that of Aldous & Smart (1988),

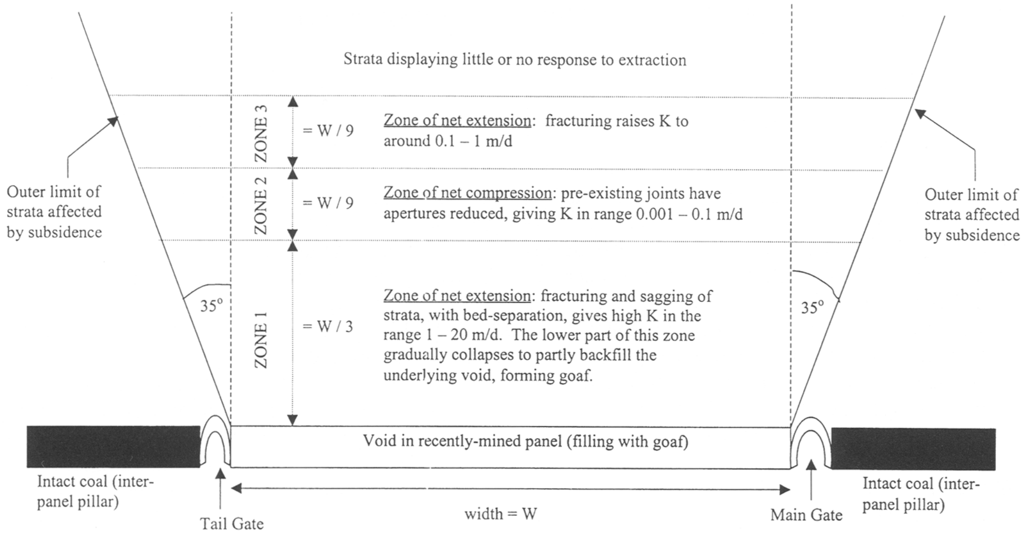

Fig. 2. Schematic diagram showing the 'orthodox' conceptual model for the development of zones of altered permeability above a recently-extracted longwall coal panel (after Singh & Atkins 1983; Younger & Adams 1999).

who applied speleological tracer techniques to abandoned workings in the Forest of Dean Coalfield (Aldous *et al.* 1986), near the Welsh border in south-west England. These studies revealed flow velocities as high as 16 km d^{-1} above the water table (essentially by open channel flow), while roadways below the water table (which are consequently subject to lower hydraulic gradients) display velocities approaching 0.5 km d^{-1}. Given that the roadways in question typically have diameters of several metres, such velocities imply that flow below the water table is still turbulent (cf. Ford & Williams 1989, p. 145). Similar studies of roadways below a very low-gradient water table in the USA revealed velocities of 3–20 m d^{-1} (Aljoe & Hawkins 1994). In the latter case, the velocities imply laminar flow, although imposition of steep gradients (e.g. during a pumping or injection test) could easily induce turbulent conditions. One important corollary of this is that turbulent flow might predominate in roadways and similar features during groundwater rebound, when hydraulic gradients are likely to be steep, with laminar flow becoming more common when rebound is complete and shallow gradients are established.

The importance of mined features in post-closure hydrogeology

Recent experiences in the Celtic mining districts of Britain have illustrated the predominance of mined features in the hydrogeological behaviour of abandoned mines. It is convenient to consider these experiences under two categories:

(1) hydrogeological processes during mine water 'rebound' (i.e. during the flooding of the voids after the cessation of dewatering);
(2) hydrogeological behaviour after rebound is complete.

Hydrogeological experiences during mine water rebound

During mine water rebound, the differences in water level between one set of workings and another may be very large. For instance, in the Dysart-Leven Coalfield of East Fife (Fig. 1a), Younger *et al.* (1995) reported water table elevations differing by as much as 300 m between inland and coastal 'ponds' in the old workings. Where flow paths become established between adjoining ponds (as often occurs when the water table rises to drown some previously dry old roadway), flow in response to such extreme head gradients is inevitably turbulent (Sherwood & Younger 1997), and may be so powerful that it causes rapid erosion of the mined voids. Consider for instance the mine water rebound curve as recorded in the Randolph Shaft of the Dysart-Leven Coalfield (Fig. 3). The short-lived peak on the rebound curve (Fig. 3b) around January 1986 corresponded to a sudden increase of water arriving at the dewatering pumps of the adjoining Frances Colliery

(Fig. 3a) which lies to the south-east of Randolph. At the same time, the suspended solids content of the Frances waters increased markedly. It is considered that this small peak on the rebound curve corresponds to a 'backing-up' of water behind some obstruction between Randolph and Frances Collieries. The drop in head after the peak corresponds to the opening up of this obstruction by erosion, which caused the simultaneous increases in flow and suspended solids at Frances. Similarly the second peak on the rebound curve (towards the end of 1986; Fig. 3b) coincided with a peak in suspended solids encountered in the pumped waters of Michael Colliery (to the north-east of Randolph; Fig. 3a), suggesting further erosion during flow between the collieries.

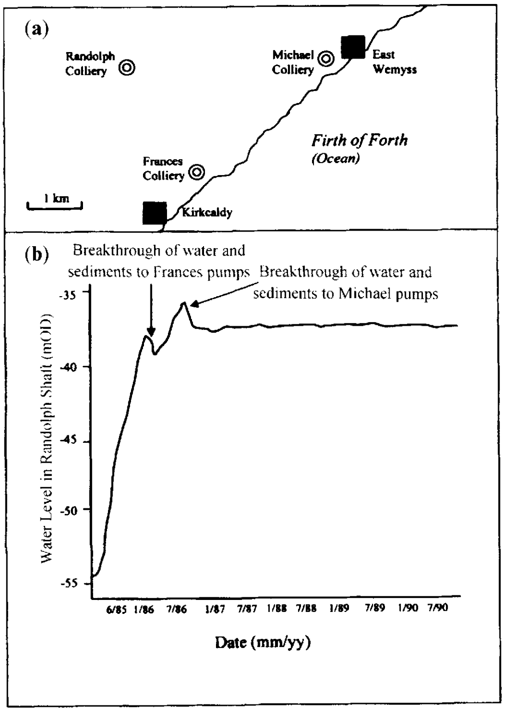

Fig. 3. (**a**) Location map showing the relative positions of the Randolph, Frances and Michael shafts in the Dysart-Leven Coalfield of Fife, (Scotland). (For overall location of Dysart-Leven Coalfield, see Figure 1a). Circular symbols are major mine shafts; black squares are urban settlements. (**b**) Observed rebound (water table recovery) curve for the Randolph Shaft in 1985, following removal of dewatering pumps. The stable level attained eventually corresponds to the level of a roadway connection to Michael Colliery through which the entire recharge to the Randolph workings is transmitted eastwards.

On 13th January 1992, during the final stages of the post-abandonment flooding of the Wheal Jane tin mine in Cornwall (Fig. 1a), physical erosion by rapidly flowing mine water gave rise to a particularly spectacular surface water pollution plume. Although earlier accounts of this event have invoked failure of a man-made plug in the portal of an old mine entrance called the Nangiles Adit (e.g. Hamilton *et al.* 1994; NRA 1994; Banks *et al.* 1997; Bowen *et al.*, 1998), recent underground exploration in this adit revealed no trace of any plug in the portal, but strong evidence that the mine water had been impounded behind a pile of roof-fall debris (Gatley *et al.* 1998*a*). It appears that rapid erosion of flow paths through the debris pile occurred (essentially by piping) once sufficient head of mine water had accumulated behind the pile. The resultant outrush of some 50 Ml of acidic, metalliferous waters in less than 24 hours led to the infamous propagation of a dramatic red plume in the Fal Estuary, drawing media attention to the pollution hazard posed by the mine (Banks *et al.* 1997), and thus providing the basis for sustained public pressure for remedial action, which has already cost the UK government more than £18M over the 7 years to 1999.

At the nearby South Crofty tin mine (also in Cornwall) dewatering ceased in March 1998 (Adams & Younger 1999). Although the ore body at South Crofty contains little pyrite, and hence does not have the same problematic water quality as Wheal Jane, public concern is naturally heightened following the Wheal Jane experience. Extensive underground exploration was therefore undertaken at South Crofty (Gatley *et al.* 1998*b*) to establish the most likely flowpaths of mine water in the shallow subsurface after the completion of flooding. It was found that the deep mine water will migrate via the North Roskear Shaft into the Dolcoath Deep Adit and thence to the Red River. It was also established that this migration will occur via an old roadway which had been partly back-filled with waste rock during adit maintenance operations in the 1950s. To avoid the risk of mine water building up (as it did at Wheal Jane) and bursting out in a spectacular manner, the backfill material was mined out of the roadway before South Crofty was finally abandoned.

Monitoring of the rise of water level in the deep workings of South Crofty has continued in tandem with the development of a physically-based model of the flooding process (Adams & Younger 1999). Although erosion of flow paths can cause temporary peaks and troughs in mine water recovery curves (as seen at Randolph Colliery; Fig. 3b), the more usual expectation is a monotonic rise. This was the recovery pattern expected at South Crofty, where the veins are sub-vertical and have been widely exploited over considerable vertical intervals. However, in early August 1998 an unexpected perturbation in the mine water recovery curve occurred, with measured water levels in the main shaft (which are made manually, at approximately monthly intervals) dropping to about 20 m below the level recorded in June 1998. This drop in water levels followed an unusual subsurface event in late July 1998 (M. Owen, pers. comm., January 1999). The South Crofty office received a number of phone calls from local residents enquiring whether the mine had reopened, for they had heard and felt what they assumed was a large subsurface explosion (indistinguishable from the noise and vibrations associated with large longhole stoping detonations used while the mine was active). The South Crofty mining engineers had also heard and felt the blast, but knew that it could not be a man-made explosion. Comparison of the mine water levels with stope plans suggested the following explanation (Fig. 4). A large open stope at around the 340 fathom level in the mine had been left such that it terminated upwards in a large, closed cupola (Fig. 4a). The rise of the water table was expected to trap gas in this cupola (Fig. 4b). It is hypothesized that the blast sensed on the surface occurred when the gas pressure exceeded the strength of the overlying rock, which was spontaneously pneumatically fractured (Fig. 4c). Once fractured, the cupola allowed mine water to drain into previously isolated workings, accounting for the drop in water level in the shaft. Although it will never be possible to raise this hypothesis beyond this anecdotal level, it remains a credible process explanation to add to those outlined above in relation to Randolph Colliery (Fig. 3).

In this context, it is worth noting also the well-documented occurrence of pockets of compressed air in flooded mines in the Celtic coalfields. The most notable case occurred at Tynewydd Colliery (Fig. 1a) in the Rhondda Valley, South Wales in 1877 (Llewellyn 1992), when a development heading intersected old flooded workings, causing an inrush of water. Although four miners were drowned immediately, ten others survived below the water table for a week, in air pockets which were trapped by the rising water table in isolated up-dip workings. One of the ten trapped miners was sadly killed at the moment of rescue, when the release of compressed air forced him into the hole dug from above by the rescue brigade, fracturing his skull. The remaining nine men survived,

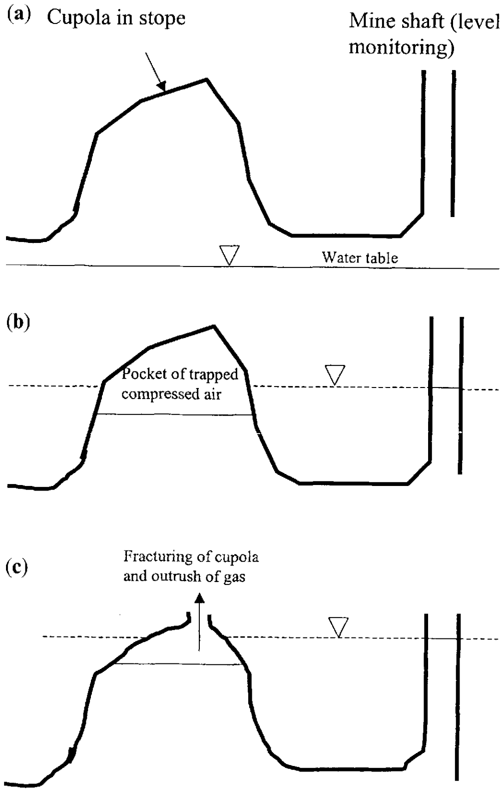

Fig. 4. Possible process of pneumatic fracturing of a cupola in a large open stope, as is postulated to have occurred during mine water rebound in South Crofty Tin Mine, Cornwall, in late July 1998 (translated and modified from Younger, 1999*b*).

although all suffered from the bends following the rapid decompression (Llewellyn 1992).

Similar pockets of compressed methane are a hazard to drillers investigating the hydrogeology of abandoned coalfields (D. Gowans, Drilcorp Ltd, pers. comm., 1998). It is therefore suggested that possible cupolas in flooded workings should be identified by careful inspection of mine plans as part of the risk assessment for drilling contracts in flooded mine-workings in coalfield areas.

Post-rebound hydrogeological experiences

After mine water recovery is complete, flow would normally be expected to be predominantly laminar, reflecting the low hydraulic gradients which typically develop in very permeable ground. Previously unpublished tracer test results from flooded coal mine workings at

Ynysarwed, SouthWales (Fig. 1a) provide corroboration of this expectation. An acidic mine water discharge began to flow from the Ynysarwed Drift (National Grid Reference SN 807017) in March 1993. This drift was used to access a large area of workings in the No 2 Rhondda Seam until 1938. Nearby, at Blaenant–Cefn Coed Colliery (SN 785033), deeper workings accessed by shafts and an inclined drift remained operational until May 1990, when dewatering was finally discontinued. After rebound was complete, the large flow (up to $3.5\,\mathrm{Ml\,d^{-1}}$) of acidic, ferruginous mine water from the Ynysarwed Drift caused severe pollution of 12 km of the Neath Canal (Younger 1994, 1997; Ranson & Edwards 1997). Subsequent investigations of remedial options included evaluation of the possibility of inducing *in situ* sulphate reduction within the mine workings by injecting suitable reactants. To assess the hydraulic feasibility of this proposal, the Environment Agency undertook two tracer tests at the site in July and November 1995 (Edwards 1996), the second of which is presented here. (Very little tracer was recovered in the first test, for unknown reasons). Figure 5 shows the layout of the site and the breakthrough curve obtained. The test was undertaken by slug injection (at 15:15 hrs on 16th November 1995) of 1 kg of rhodamine WT dye into a borehole (SN 805020) accessing flooded workings alongside the Ynysarwed Drift, some 400 m in from the portal (Fig. 5a). Although available mine plans are not clear, these workings are presumed to have been created by room-and-pillar methods, with later secondary extraction of the pillars resulting in wide areas filled with goaf (collapsed roof strata). A Rock and Tyler QMP auto-sampler was installed at the Drift portal to collect a sample every 8 hours. Tracer recovery was not very high (a total of 5% of the tracer mass over the full period of monitoring); nevertheless, the breakthrough curve (Fig. 5b) repays consideration. The relatively short distance from the borehole to the drift portal (400 m) is reflected in the arrival of the leading edge of the tracer slug after only 7 days. However, the commencement of the main rising limb of the breakthrough curve does not become established until day 20, with the peak concentration being attained after 40 days. These first arrival and peak concentrations correspond to linear velocities on the order of 57 and $10\,\mathrm{m\,d^{-1}}$, respectively. These velocities are of the same order of magnitude as those found by Aljoe & Hawkins (1994) in Pennsylvania, and given the dimensions of the roadways at Ynysarwed they imply predominantly laminar flow conditions (cf. Ford & Williams 1989, p. 145). The marked attenuation of the Ynysarwed breakthrough curve (Fig. 5b; with background fluorescence not being attained until March 1996, about 130 days after the tracer injection) can be interpreted in terms of substantial diffusional exchange fluxes between mobile and immobile volumes of water (cf. Younger & Elliot 1995). The operation of such a major dispersive process in these mine workings is consistent with the high dispersivity values (longitudinal dispersivity (i.e. in the direction of advection), $\alpha_L = 60\,\mathrm{m}$; transverse dispersivity (i.e. normal to the direction of advection), $\alpha_T = 20\,\mathrm{m}$) which were invoked in a numerical model for the entire Blaenant–Ynysarwed system, which was used to approximate the flushing of iron (Younger *et al.* 1996; Younger 1997).

Even where a mine has been abandoned for many years, unexpected perturbations in the hydraulics of the flooded mine voids can prompt a renewed phase of turbulent flow, with problems of erosion similar to those which are more often associated with the initial rebound period. For instance, erosion of mine voids by rapidly flowing water has led to urban flooding problems in the small mining village of Spittal (Fig. 1a) on the Anglo-Scottish border. Around midnight on the 24th of June 1998, water suddenly began to surcharge the main storm sewer in Spittal High Street, and quickly flooded 19 homes with ochreous, sediment-laden water, which continued to flow as a torrent for 17 hours. Subsequent investigations (involving hydrochemical analysis, CCTV inspection of the sewer and searching of local archives; Younger 1999*a*) led to the conclusion that a substantial head of mine water had built up behind a roof fall in old coal workings which had been accessed by a now-buried stone-arched adit (NU005514; observed on the CCTV) which was abandoned in 1820. When the head exceeded some critical limit, collapse and/or rapid erosion of the roof fall debris gave rise to the turbulent discharge and the consequent flooding.

At the village of Leadhills (Fig. 1a), in Scotland's Southern Uplands, post-abandonment changes in mine stability led to a serious threat of flooding (Schmolke 1998). Prior to August 1991, an old drainage adit known as the Gripps Level (approximate grid reference NS887141) drained some $23\,\mathrm{Ml\,d^{-1}}$ of water from abandoned lead mines. A roof-fall in the Gripps Level at that time halted the discharge, and led to the impoundment of a vast volume of mine water in the old workings. A head of 25 m built up behind the roof fall, and eventually

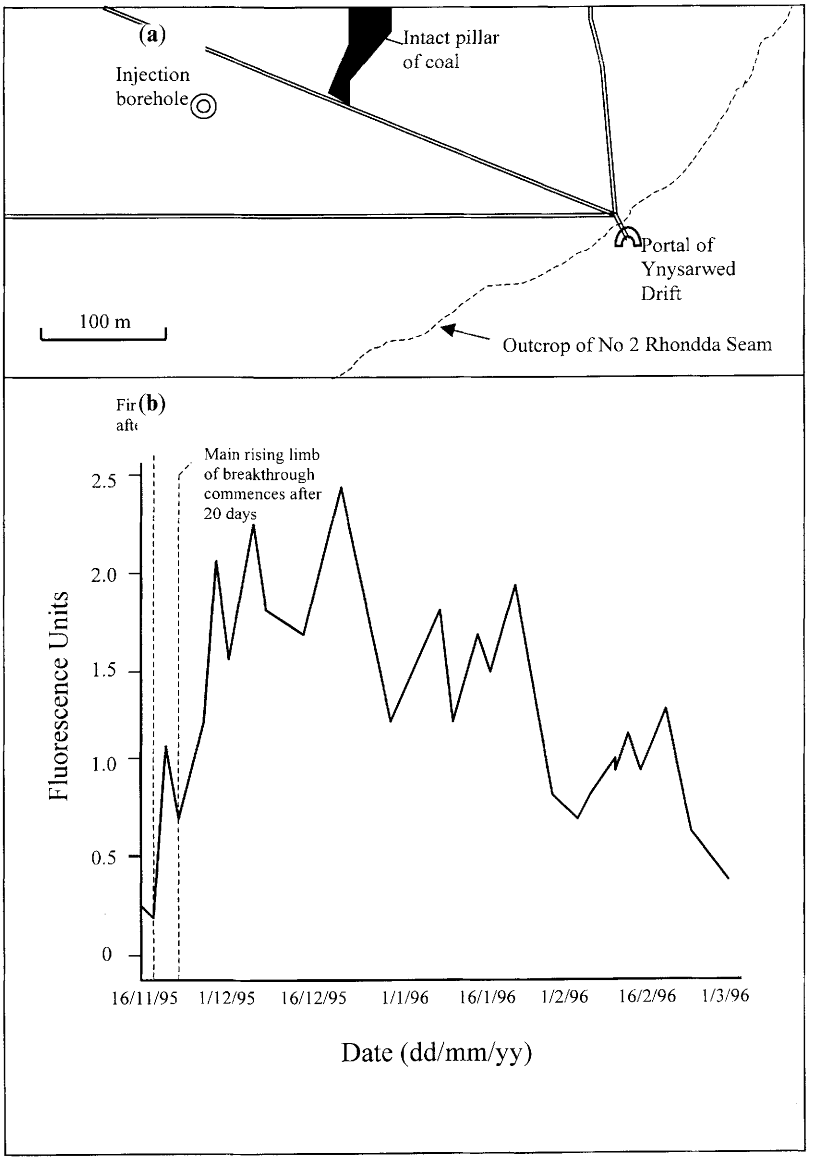

Fig. 5. (**a**) Plan showing the layout of the injection borehole (into which rhodamine WT was introduced), surrounding workings and the major roadways (double lines) of the Ynysarwed Drift mine, radiating away from the portal. Note that all of the subsurface to the left of the No 2 Rhondda Seam outcrop (marked) is recorded as worked, apart from the pillar indicated. (**b**) Breakthrough curve of rhodamine WT dye at the Ynysarwed Drift portal following injection into the borehole on 16th November 1995.

water began to emerge from old air shafts along the Level. More alarmingly, a large tension crack opened up in the hillside, and this also began to yield water. The risk of a catastrophic failure of these newly-flooded workings remains, posing a substantial risk to life and property downstream of the mine site (Schmolke 1998).

An event with echoes of both Spittal and Leadhills (albeit with different consequences) occurred during the winter of 1998/99 in South Wales, at the site of the Gwenffrwd mine water discharge (SS802972; Fig. 1a). The Gwenffrwd discharge had flowed unimpeded for 80 years from an abandoned coal drift mine near the village of Tonmawr, contributing substantially to the pollution of the River Pelenna. In the spring of 1998 the discharge was fitted with a very successful passive treatment system (Ranson *et al.* 1998; Younger 1998*c*). Together with the remediation of two neighbouring discharges, this passive system brought a substantial improvement in the quality of the River Pelenna (Ranson *et al.* 1998). The winter of 1998/99 was the wettest ever recorded in South Wales. After one particularly heavy downpour, residents in Tonmawr village became alarmed when it was noticed that the Gwenffrwd discharge had ceased to flow. A potentially dangerous build-up of mine water in old workings above the village (as at Leadhills) was feared. However, subsequent investigations revealed that the discharge had simply relocated, and was now coming out of a topographically lower mine adit (Whitworth B; SS799974), a few hundred yards further up the valley. Although this meant that the danger of flooding in Tonmawr village could thankfully be discounted, the re-positioning of the discharge meant that the recently-commissioned passive treatment system was almost completely bypassed, so that the pollution of the River Pelenna increased again. At the time of writing, the possible diversion of the mine water back around the hillside to the treatment system is under investigation. In the meantime, studies of mine plans supported by limited excavations around the Gwenffrwd portal have provided a hydrogeological explanation for this occurrence (C. Ranson, Neath Port Talbot County Borough Council, pers. comm., 1999). The bulk of the water which formerly flowed from the Gwenffrwd mine was actually sourced in the lower workings of Whitworth B. Impoundment of the mine water behind roof-fall debris had raised the head in the workings so that the water decanted from the higher man-way drift of Gwenffrwd. The exceptional flows of the wettest winter on record had finally eroded an efficient flow pathway through the roof-fall debris in the Whitworth B workings, allowing the mine water to drain down to the lower portal.

Some Celtic experiences in the hydrogeochemistry of abandoned deep mines

Mine water chemistry

Some of the earliest detailed studies of mine water quality were made in the Celtic countries. For instance Brown (1977) documented tin mine drainage impacts on invertebrate communities in Cornwall. Scullion & Edwards (1980) investigated the effects of coal mine effluents on the fish fauna of the Taff Bargoed river in South Wales. In Scotland, Henton (1979, 1981) documented the pollution of the River Ore following the flooding of the underlying coalfield (a case subsequently updated by Robins 1990, and Younger 1999*a*). Hydrogeochemical studies have become increasingly common in the Celtic coalfields during the last decade in response to widespread mine closures (e.g. Robins 1990; Younger *et al.* 1995; Robins & Younger 1996; Chen *et al.* 1997; Younger 1997, 1999*a*; Sadler & Rees 1998; LaPierre 1999; Wood *et al.* 1999). These studies have significantly advanced the generic conceptual understanding of the hydrogeochemical changes which occur during and after the flooding of deep mine workings. Since comprehensive syntheses of these findings have recently been published (Younger 1998*a*, 1999*a*, 2000; Younger & Adams 1999), there is no need to rehearse them here. Rather, this section aims to highlight some basic geological controls on water quality which should be of generic value in the management of mine waters.

It has frequently been pointed out that the commonly-used term 'acid mine drainage' is often a misnomer, since relatively few polluting discharges from mines have a consistently low pH (e.g. Henton 1981; Robins 1990; Younger 1995). In reality, mine water quality spans a continuum of compositions, most conveniently defined on the basis of the acid-base balance (Hedin *et al.* 1994; Younger 1995). Total acidity in mine waters is a reflection of the availability not just of protons (represented by pH) but also of 'acid' metals (Fe, Mn, Al, Zn etc) which readily form hydroxide minerals at surface temperatures and pressures, and can thus consume alkali during acidity titrations. Total alkalinity in mine waters is primarily a reflection of the bicarbonate concentration. Hence acidity and alkalinity are not mutually exclusive categories in mine waters, and it is therefore convenient to define two principal classes of mine water:

- net-acidic mine waters (acidity > alkalinity)
- net-alkaline mine waters (alkalinity > acidity)

(For further discussion of this concept, the interested reader is referred to Hedin *et al.* 1994; Younger 1995, 1998*a*; Banks *et al.* 1997).

Geological controls on mine water chemistry

Younger (1999*a*) has shown that in Scotland, net-alkaline mine waters are fifty times more abundant (by volume) than net-acidic mine waters.

However, where net-acidic discharges *do* occur, they are usually far more environmentally damaging than net-alkaline discharges (Jarvis & Younger 1997). Hence it is of considerable value to environmental managers to be able to predict which future discharges are likely to be net-acidic and which should be net-alkaline. Similarly, it is of value to know whether a currently net-acidic discharge will always remain so, or whether it will follow the pattern shown by many other such waters and become net-alkaline over time (Younger 1997, 2000).

Existing data from the Celtic mining regions are instructive in this regard. Table 1 lists a number of net-acidic mine waters in the Celtic lands and documents their geological field relations in broad terms. Table 2 repeats the exercise for net-alkaline mine waters.

It is apparent from Table 1 that net-acidic mine waters are generally restricted to situations in which high-sulphur strata (>2.5 weight percent S) are present in:

(i) recently-flooded deep-mine workings;
(ii) shallow, partially flooded mine workings; and
(iii) perched groundwater systems in spoil heaps and opencast backfill.

This is logical, as all of these settings are susceptible to ready ingress of meteoric water and atmospheric oxygen, which are the two

Table 1. *Net-acidic mine waters in UK Celtic lands and their hydrogeological settings*

Site name	Celtic land*	Grid ref	pH	Total Fe (mg/l)	Total acidity (meq/l)	Hydrogeological setting	Source of further info
Brora No 1	S	NC 898042	3.6	8	1.82	Overflowing shaft accessing shallow flooded working in a high sulphur coal seam	Younger (1999*a*)
Baads East	S	NT 005612	2.8	550	48.4	Colliery spoil heap hosting perched water table system	Younger (1999*a*)
Randolph Colliery	S	NT 303957	3.7	43	31.32	Colliery spoil heap hosting perched water table system	Younger (1999*a*)
Balgonie Colliery	S	NT 306990	4.3	62	6.4	Colliery spoil heap hosting perched water table system	Younger (1999*a*)
Dalquharran Mine	S	NS 266017	5.5	150	5.5	Drift accessing extensive shallow and deep workings in a high sulphur coal seam	Robins (1990); Robb (1994); Marsden *et al.* (1997)
Roughcastle	S	NS 847796	5.7	89	3.56	Backfilled coal opencast in communication with extensive underground fireclay workings	Bullen Consultants (1999)
Ynysarwed	W	SN 809018	5.8	200	7.2	Drift accessing extensive shallow and deep workings in a moderate sulphur coal seam	Younger (1994, 1997); Ranson & Edwards (1997)
Garth Tonmawr Drift Mine	W	SS 799973	5.2	35	1.26	Drift accessing extensive shallow workings in a high-S coal seam	Younger (1997)
Cae Coch	W	SH 775653	2.5	1630	62	Adit accessing shallow workings in a pyritic copper ore body	McGinness and Johnson (1993)
Wheal Jane	C	SW 773425	3.7	250	12	Adit accessing shallow workings in a pyritic tin/zinc ore body	NRA (1994) Bowen *et al.* (1998)

* C, Cornwall; S, Scotland; W, Wales.

most important triggers of acid generation by pyrite weathering.

By contrast, Table 2 reveals that net-alkaline mine waters are associated with:

(i) low-sulphur strata (<1.5 weight percent S) in any hydrogeological setting; and
(ii) high-sulphur strata, where these lie far below the water table in workings which have been flooded for a long time (usually a few decades).

The fact that the bulk of the total volume of deep mine workings falls into one of these latter two categories explains why net-alkaline mine waters are volumetrically far more abundant than net-acidic mine waters.

It is also clear that many deep mine waters are initially net-acidic after completion of rebound, reverting to net-alkaline status some time later, following a period of flushing of the flooded mine voids. Younger (2000) has used data from all the UK Celtic lands and England to argue that the transition to net-alkaline status usually takes place within a period of time around four times as long as the time it took for the deep mine workings to flood up to surface level following the cessation of dewatering.

What difference does the availability of limestone make?

Although many of the Scottish mine waters drain strata which belong to a stratigraphic division known as the 'Limestone Coal Group' (Namurian), limestones are very rarely found in

Table 2. *Net-alkaline mine waters in UK Celtic lands and their hydrogeological settings*

Site name	Celtic land*	Grid ref	pH	Total Fe (mg/l)	Alkalinity (meq/l)	Hydrogeological setting	Source of further info
Lathallan Mill	S	NO 465063	6.1	10.8	3.64	Overflowing shaft accessing deep, long-flooded coal workings.	Younger (1999*a*)
Star Road (Markinch)	S	NO 296025	6.5	4.0	3.46	Overflowing shaft accessing deep, long-flooded coal workings.	Younger (1999*a*)
Kames Colliery	S	NS 685262	5.8	14	4.64	Overflowing shaft accessing deep, long-flooded coal workings.	Younger (1999*a*)
Pool Farm	S	NS 987542	6.3	8	1.96	Adit accessing shallow workings in a low-sulphur coal seam	Younger (1999*a*)
Cuthill	S	NS 990628	5.5	37	4.94	Adit accessing shallow workings in a low-sulphur coal seam	Younger (1999*a*)
Gwynfi	W	SS 892973	5.5	8	1.1	Adit accessing shallow workings in a low-sulphur coal seam	EA archives
Morlais	W	SN 572023	6.7	63	4.5	Overflowing shaft accessing deep, long-flooded workings in a moderate-to high-S coal seam	EA archives
Bryn	W	SS 817922	6.9	0.4	0.7	Adit accessing shallow workings in a low-sulphur coal seam	EA archives
Goytre	W	SS 787897	6.8	2.5	1.72	Adit accessing shallow workings in a low-sulphur coal seam	EA archives
Dolcoath Deep Adit	C	SW 648418	7.1	0.5	0.6	Adit accessing deep and shallow workings in a low-sulphur tin/copper ore body	EA archives
Geevor Deep Adit	C	SW 372349	6.4	0.17	0.3	Adit accessing deep recently-flooded workings in a low-sulphur tin ore body	EA archives

*C, Cornwall; S, Scotland; W, Wales.

Table 3. *Net-acidic mine waters in the Sydney Coalfield of Cape Breton Island, Nova Scotia, Canada, and their hydrogeological settings*

Site name	Latitude and longitude	pH	Total Fe (mg/l)	Total acidity (meq/l)	Hydrogeological setting
No 1A Colliery	46°11′52″N 60°03′10″W	5.6	33	0.9	Pipe connecting to adit accessing shallow workings in Phalen Seam (total S = 3.2 wt%)
No 11 Colliery	46°11′03″N 59°57′57″W	3.8	0.6	0.48	Inclined drift portal to shallow workings in the Emery Seam (total S = 2.7 wt%)
No 24a Mine Water	46°10′30″N 59°57′05″W	3.1	7.6	4.74	Spoil heap of waste rock from workings in the Emery Seam
Morrison's Pond	46°19′31″N 60°19′02″W	2.9	49	5.1	Land drain in area of shallow workings in the Hub Seam (total S = 2.3 wt%)
Shaft 1B at 198m depth	46°13′06″N 59°58′44″W	6.4	150	8.5	Deep mine shaft discrete sample at depth. Water in shaft still rising. Accesses deep workings in the Phalen Seam (total S = 3.2 wt%)

close proximity to coal seams in Scotland. (The stratigraphic term arises from the fact that the coal bearing sequence is bounded above and below by prominent limestones, whereas none occur within the sequence itself; Francis 1991.) By contrast in the Sydney Coalfield of Nova Scotia, calcretes and other forms of limestone are relatively common in the seam roof setting. While this might be considered sufficient to guarantee that mine water discharges in Cape Breton will be net-alkaline, a significant number of discharges in Cape Breton are in fact net-acidic (Table 3) (even though these are volumetrically less prolific than the net-alkaline discharges; Table 4). Current data do not make it clear if the net-acidic discharges in Cape Breton are from mines which only began to overflow at the surface recently. Nevertheless, it is clear

Table 4. *Net-alkaline mine waters in the Sydney Coalfield of Cape Breton Island, Nova Scotia, Canada, and their hydrogeological settings*

Site name	Latitude and longitude	pH	Total Fe (mg/l)	Alkalinity (meq/l)	Hydrogeological setting
No. 4	46°10′34″N 59°56′28″W	6.6	5.7	0.56	Low-flow seepage from workings in the Phalen and Emery Seams (3.2 and 2.7 wt% S respectively), abandoned in 1961
No. 8	46°12′54″N 59°59′39″W	7.6	0.1	3.6	Old workings (abandoned 1914) in the Harbour Seam (2.5 wt% S) discharging (probably via an old adit) to a land drain
No. 25	46°11′52″N 60°03′10″W	6.7	21	1.7	Overflowing borehole near old shaft which accesses flooded deep workings (abandoned 1959) in the high sulphur (3.9 wt% S) Gardiner Seam.
Old Harbour Discharge	46°11′39″N 59°57′08″W	7.5	1.5	4.9	Old workings (abandoned 1914) in the Harbour Seam (2.5 wt% S) discharging (probably via an old adit) to a land drain
Shaft 1B at 122 m depth	46°13′06″N 59°58′44″W	7.4	1.5	3.92	Deep mine shaft – discrete sample at depth. Water in shaft still rising. Accesses deep workings in the Phalen Seam (total S = 3.2 wt%)
Shaft 1B at 168 m depth	46°13′06″N 59°58′44″W	6.8	19	1.92	Deep mine shaft – discrete sample at depth. Water in shaft still rising. Accesses deep workings in the Phalen Seam (total S = 3.2 wt%)

that the availability of limestone in the sequence is not on its own a sufficient guarantee of net-alkalinity.

Figure 6 compares the major ion chemistry of uncontrolled discharges from flooded deep coal mines in Scotland with waters from flooded deep coal mines in the Sydney Coalfield, Cape Breton. In broad terms the Scottish and Cape Breton mine waters are similar, in that they are predominantly of Ca–SO_4 facies. However, in the Cape Breton mine waters the sulphate ion generally accounts for less than 80% (as equivalents) of the total anions, whereas in Scotland it usually accounts for between 80 and 100% of the total anions. In terms of absolute concentrations, this difference is also evident, with Scottish mine waters having a mean sulphate concentration of 470 mg/l, whereas the Cape Breton mine waters have a mean sulphate of only 208 mg/l. In neither case is the sulphate sufficiently high that a gypsum solubility control on concentrations might be invoked (a control which would clearly have a logical coupling to the availability of calcite). An alternative explanation for this contrast could be that less pyrite was oxidized per unit volume of water in the Cape Breton mines than in the Scottish mines. This would be consistent with the elevated pH and alkalinity of recharge waters in Cape Breton where these pass through limestone. Interpretation of alkalinity values must be approached with caution, however, as the mean alkalinity of the Scottish mine waters (at 186 mg/l as $CaCO_3$; Younger 1999*a*) is considerably greater than that in the Cape Breton mine waters (50 mg/l as $CaCO_3$; the balance of the anions in the Cape Breton mine waters is chloride, averaging 51.6 mg/l and reflecting the marine influence on mine water quality), despite the fact that the higher sulphate concentrations in the Scottish waters indicate more extensive pyrite oxidation than in Cape Breton. The coincidence of high alkalinities and high sulphates can be explained in the manner expounded by Wood *et al.* (1999), in relation to mine water discharges in Scotland: '... if waters were initially highly acidic, reaction with carbonates ... will result in a correspondingly high level of dissolved HCO_3 after neutralization'. By contrast, weakly acidic mine waters, with correspondingly lower sulphate concentrations (as in Cape Breton), provoke less alkalinity generation in the process of attaining neutral pH.

This brief comparison serves to demonstrate that the presence of limestone in a worked sequence is no guarantee of net-alkaline drainage. It thus follows that hydrogeological factors, such as groundwater flow patterns and the order of encounter of strata and groundwater (cf. Freeze & Cherry 1979), are at least as important.

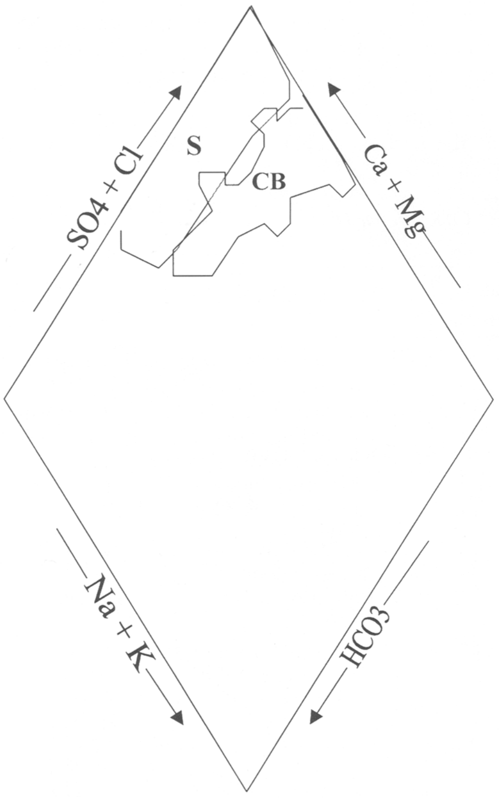

Fig. 6. Upper diamond of a Piper diagram, showing the plotting fields of uncontrolled minewater discharges in Scotland (S) and Cape Breton (CB). The Scottish field is adapted from Younger (1999*a*), the Cape Breton field from LaPierre (1999).

Vertical hydrochemical profiles in shafts during rebound

The obvious way to reduce uncertainty about the risk of pollution after flooding of deep mine workings is to undertake water sampling during rebound using open shafts and boreholes. A rigorous approach to such an exercise would demand that samples be obtained at discrete vertical intervals, to delineate any variations in water quality over depth. Results from two such shaft sampling exercises (one in Cornwall, the other in Cape Breton) are compared on Fig. 7. It is immediately apparent in both cases that the better quality water is found at the top of the water column. This phenomenon has been widely termed 'stratification' in mining circles (see for instance Ladwig *et al.* 1984), even though step changes in the different water quality parameters do not always coincide (Fig. 7).

The stratification of water quality during rebound implies that mechanical mixing of the water column in the mine is minimal. This in turn implies, for instance, that there are few lateral inflows and outflows at depth. As long as flow remains sluggish and laminar, there is little to disturb the stratification. However, when discharge from a mined system commences, turbulent flow in the vicinity of shafts and open roadways can cause substantial mixing of the mine water body, leading to a breakdown in the stratification. Hence the quality of a mine water discharge from a formerly stratified system is more likely to resemble a mixture of all depth intervals rather than the better quality water previously found at the top of the water column. For instance, when the Wheal Jane mine first overflowed, the water was considerably poorer in quality than the uppermost waters marked on Fig. 7a; it in fact resembled the median of the values shown.

This has two practical implications:

(1) Mine water discharges may well be considerably poorer in quality than would have been inferred by sampling the uppermost waters alone. Hence depth-sampling is highly advisable in studies of mine water rebound.

(2) Where stratification is identified, it would be imprudent to assume that future discharges at the surface will resemble the uppermost waters in the rebounding water column. Rather, surface discharges are likely to have a quality approaching that of the mean concentrations found over the full depth of the mine.

Conclusions

Recent experiences in the Celtic lands of Britain (Cornwall, Wales and Scotland) and in Cape Breton (Nova Scotia) yield the following lessons:

(1) The importance of recognizing the predominance of mined features in the post-closure hydrogeology of abandoned mines.

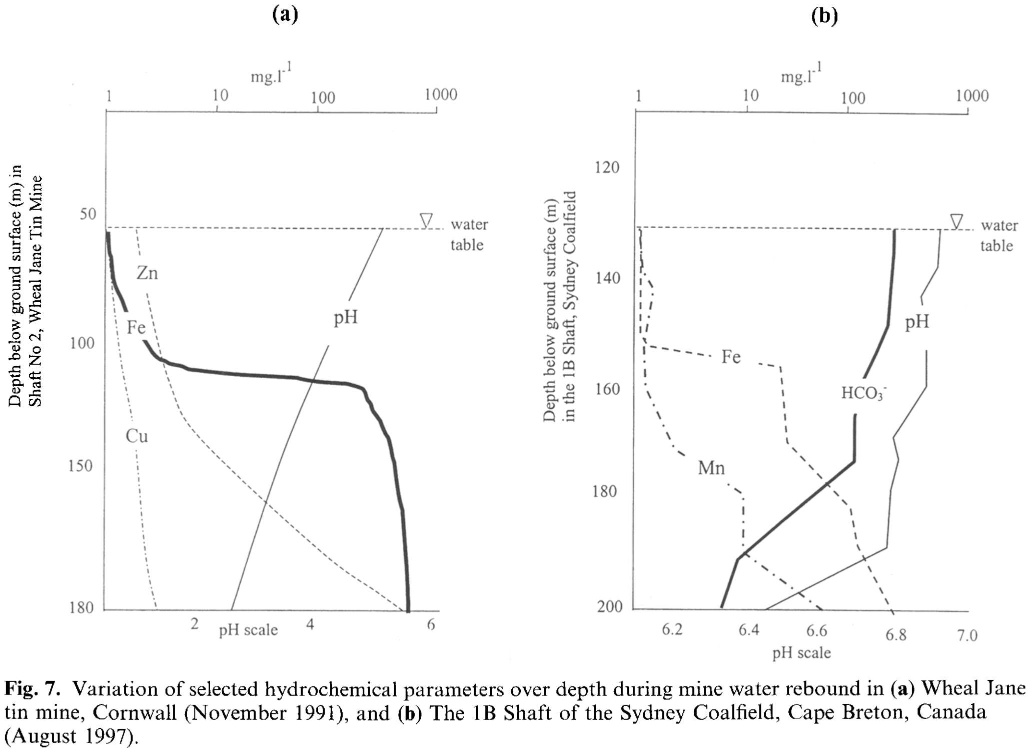

Fig. 7. Variation of selected hydrochemical parameters over depth during mine water rebound in (**a**) Wheal Jane tin mine, Cornwall (November 1991), and (**b**) The 1B Shaft of the Sydney Coalfield, Cape Breton, Canada (August 1997).

(2) Dynamic temporal changes in hydrogeological behaviour arise from collapse of mined voids, due to fluvial erosion by rapidly-flowing mine waters and/or by pneumatic fracturing by mine gases compressed in pockets during mine water rebound (the latter having significant implications for human safety and environmental protection).

(3) Net-acidic mine waters are generally restricted to situations in which high-sulphur strata are present in (i) recently-flooded deep-mine workings, (ii) shallow flooded mine workings and (iii) perched groundwater systems in spoil heaps and opencast backfill.

(4) Net-alkaline mine waters are associated with (i) low-sulphur strata in any hydrogeological setting and (ii) high-sulphur strata at depth in long-flooded workings. In practice, this means that they are far more abundant than net-acidic mine waters.

(5) The presence of limestone in a mined sequence is not on its own a guarantee that mine waters will be net-alkaline; the patterns of groundwater flow (which determine the transport of limestone dissolution products through the mined system) must also be favourable.

(6) Significant vertical variations in mine water quality over depth have been found by means of depth-sampling in abandoned mine shafts. Where water quality is strongly stratified, it is inferred that few mechanical mixing processes are operative. However, when discharge from a mined system commences, turbulent flow in the vicinity of shafts and open roadways can cause substantial mixing, leading to a breakdown in the stratification of the water body, and a mine water discharge quality which is more akin to a mixture of all depth intervals in the formerly stratified water column rather than the 'skimming off' of the (usually better quality) top water.

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