Recycling, Reuse and Rehabilitation of Mine Wastes

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If we want to ensure a sustainable future for the human race, we must learn to prevent, minimize, reuse and recycle waste. Reuse of mine wastes allows their beneficial application, whereas recycling extracts resource ingredients or converts wastes into valuable products. Yet, today, many of the proposed reuse and recycling concepts for mine wastes are not economic. Consequently, the great majority of mine wastes are still being placed into waste storage facilities. Significant research efforts are required to develop cost-effective reuse and recycling options and to prevent the migration of contaminants from rehabilitated waste repositories in the long term.

Keywords: recycling, reuse, rehabilitation, sustainability, mine waste, zero waste

INTRODUCTION

Humanity faces many environmental challenges in the 21st century. The issues of land degradation, resource depletion and waste recycling are regarded as some of the critical global challenges for present and future generations. At the first United Nations Earth Summit in 1992, environmentally sound management of wastes was identified as one of the major concerns in maintaining the quality of the Earth's environment. At the World Summit on Sustainable Development in 2002, governments reaffirmed the importance of solid-waste management. They called for priority attention to be given to prevention, minimization, reuse and recycling of waste.

A sustainable future for the human race must include the effective reuse and recycling of waste streams. The concept of waste as a resource is not new to the modern world. Since the dawn of civilization, the recycling or reuse of originally discarded materials, including mine wastes, has been practised. For example, during Roman times, iron ore slags were used in construction, road surfacing and as a flux in the production of iron. To this day, the recycling and reuse of mine wastes are largely driven by their practical applications and financial returns. The increasing demand for mineral and energy resources by a growing world population will make the recovery of waste – through reuse, recycling and energy recovery – even more attractive. Also, compared to historic mine sites, the environmental footprint of modern mines is generally reduced and mine wastes are better managed due to (1) environmental professionals working on site, (2) voluntary efforts and innovative actions by mine operators, (3) the use of improved scientific knowledge, (4) a framework of laws and regulations that carries through from the establishment to the closure of mine sites, (5) greater public involvement and community expectations, and (6) agreed standards by the financial industry for managing risks in the financing of mining projects (i.e. The Equator Principles). Each of these factors contributes to more responsible environmental stewardship of mine sites and better waste management.

Modern mining operations produce vast waste streams that compel planning and informed decision-making in matters of waste reduction, resource recovery, waste disposal and environmental protection. The waste hierarchy is a well-established guide for prioritizing waste-management practices, with waste prevention being the preferred option and disposal and treatment being the least desirable (Fig. 1).

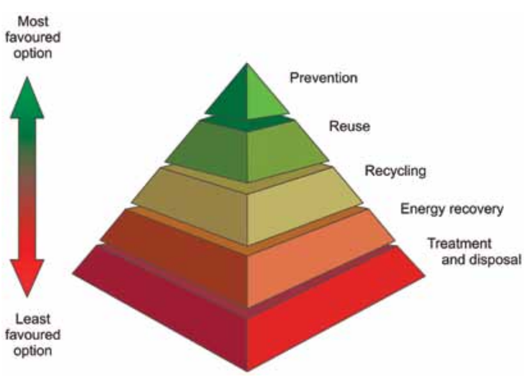

Figure 1 The mine waste hierarchy, from prevention, through reuse, recycling, and energy recovery, to treatment and disposal. The reuse option considers mine waste for alternative uses that are environmentally sound, and the recycling and energy recovery options view mine waste as a resource.

Regardless of our increasing reuse and recycling efforts, the great majority of waste produced at mine sites is still placed into storage facilities. The reclamation of such repositories has become an integral part of modern mine development and mine closure. Consequently, mine sites and their wastes have been the subject of considerable rehabilitation efforts and countless scientific studies. Recent developments in mine waste rehabilitation have led to more sophisticated reclamation approaches and solutions. However, the impacts of poorly rehabilitated or non-rehabilitated wastes are well known, and there is growing concern whether our best practice rehabilitation efforts will be successful and protect the environment in the long term.

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In the following sections, the recycling, reuse and rehabilitation of mine wastes are documented, focussing on mining wastes that accumulate at mine sites. Consideration of mineral processing and metallurgical wastes is limited to those waste types accumulating at or near mine sites. Readers interested in the resource recovery and recycling of mineral processing and metallurgical wastes are advised to consult the relevant literature (e.g. Rao 2006).

DEFINING THE "R WORD"

The "R word" has proliferated in the scientific literature covering aspects of mine waste management, resource recovery and mine closure. Authors freely use the terms *remining*, *reprocessing*, *recycling*, *resource recovery* and *reuse*, as well as *rehabilitation*, *reclamation*, *restoration*, *recuperation*, *reconstruction* and *remediation*. Moreover, these terms are sometimes used inconsistently. In this paper, *remining* refers to the extraction of an energy or mineral resource from previously mined areas. *Reuse* of mine wastes is defined as the process that involves the new use or application of the total mine waste in its original form for an identified purpose directly without any reprocessing. By contrast, *recycling* of mine wastes is the practice that extracts new valuable resource ingredients, or uses the waste as feedstock and converts the entire mine waste into a new valuable product or application with some reprocessing. Recycling activities subject the waste to physical, thermal, biological or chemical methods designed to extract valuable elements, compounds, minerals or energy, rendering the remaining waste material suitable for a new benign use or disposal on the mine site. *Reprocessing* is different from *treatment* because reprocessing is designed to use the waste material as a feedstock for producing a valuable product, such as recovered minerals and metals. By contrast, *treatment* of mine waste is intended to reduce the waste's toxicity or volume. Numerous terms refer to post-mining measures that return waste repositories and mined land to a standard allowing future land use. In this work, the terms *rehabilitation* and *reclamation* of mine wastes are used interchangeably to refer to measures that alleviate environmental impacts during post-mining waste storage.

REUSE AND RECYCLING OF MINE WASTES

Ideally, the reuse and recycling of mine wastes, like all other recycling efforts, create financial assets, slow consumption of natural resources, limit waste production, encourage innovation and local industries, create jobs and teach responsibility for the environment shared by all. In addition, the reuse and recycling of solid mining wastes and mine waters may also decrease the exposure of humans and ecological receptors to contaminated materials. Various reuse and recycling options have been proposed for mine wastes by numerous researchers (Table 1). Today only some of these options, such as reprocessing and using tailings as backfill, are commonly applied at operating mine sites.

Table 1 REUSE AND RECYCLING OPTIONS FOR MINING, PROCESSING AND METALLURGICAL WASTES ACCUMULATING AT MINE SITES

Waste type		Reuse and recycling option
Mining wastes	Waste rocks	• Resource of minerals and metals • Backfill for open voids • Landscaping material • Capping material for waste repositories • Substrate for revegetation at mine sites • Aggregate in embankment, road, pavement, foundation and building construction • Asphalt component • Feedstock for cement and concrete • Sulfidic waste rock as soil additive to neutralize infertile alkaline agricultural soils
	Mine waters	• Dust suppression and mineral processing applications • Recovery of metals from AMD waters • Drinking water • Industrial and agricultural use • Coolant or heating agent • Generation of electricity using fuel cell technology • Engineered solar ponds to capture heat for electricity generation, heating, or desalination and distillation of water
	Mine drainage sludges	• Extraction of hydrous ferric oxides for paint pigments • Extraction of Mn for pottery glaze • Flocculant/adsorbant to remove phosphate from sewage and agricultural effluents
Processing wastes	Tailings	• Reprocessing to extract minerals and metals • Waste reduction through targeted extraction of valuable minerals during processing • Sand-rich tailings mixed with cement used as backfill in underground mines • Clay-rich tailings as an amendment to sandy soils and for the manufacturing of bricks, cement, floor tiles, sanitary ware and porcelains • Mn-rich tailings used in agro-forestry, building and construction materials, coatings, cast resin products, glass, ceramics and glazes • Bauxite tailings as sources of alum • Cu-rich tailings as extenders for paints • Fe-rich tailings mixed with fly ash and sewage sludge as lightweight ceramics • Energy recovery from compost–coal tailings mixtures • Phlogopite-rich tailings for sewage treatment • Phosphate-rich tailings for the extraction of phosphoric acid • Ultramafic tailings for the production of glass and rock wool • Carbon dioxide sequestration in ultramafic tailings and waste rocks
Metallurgical wastes	Bauxite red mud	• Treatment of agricultural and industrial effluents • Raw material for glass, tiles, cements, ceramics, aggregate and bricks • Treatment of AMD waters • Carbon dioxide sequestration
	Historical base metal smelting slags	• Production of concrete and cement • Use as fill, ballast, abrasive and aggregate • Extraction of metals (e.g. Cu, Pb, Zn, Ag, Au)
	Phosphogypsum	• Soil amendment • Building and construction material • Extraction of elements and compounds (e.g. U, Y, REE and calcium sulfate)

Reprocessing

Mine wastes are generally considered worthless at the time of production, yet they can still contain mineral and energy resources that may become valuable. Changing circumstances may turn a particular waste into a valuable commodity, either because the economic extraction of metals, energy and minerals may now be possible using superior technology, or a market has been identified for the previously discarded waste. Most importantly, improved commodity prices fuel the interest in waste reprocessing and the extraction of metals and minerals from a waste stream. What may be waste to some can be a very useful resource to others, either now or in the future.

Reprocessing of mine wastes subsequent to the original mining or site abandonment has been carried out for hundreds or possibly thousands of years. In the 16th century classic *De Re Metallica*, Agricola (1556) described this practice in central Europe:

"There are some people who wash over the dumps from exhausted and abandoned mines, and those dumps which are derived from the drains of tunnels; and others who smelt the old slags; from all of which they make an ample return."

Yesterday's waste can be today's resource (Lottermoser 2010). This approach is widely used in the modern mining and metallurgical industries. Today, reprocessing of mine wastes is gaining importance because of vastly improved mineral processing technologies, which in turn lead to economic benefits and address environmental concerns. In some cases, the mining industry supports major research efforts that will identify novel and economically viable methods and allow increased resource recovery (e.g. Barrick's Unlock the Value program; Barrick 2011).

Reuse and Recycling of Waste Rocks

Rehabilitation of mine sites and waste repositories commonly makes use of benign waste rocks for landscaping as well as capping and revegetation of waste repositories (Table 1). Waste rocks are also exploited as backfill in open voids, reducing waste piles and leaving fewer mine workings. The most promising reuses for coarse-grained mining wastes and especially barren waste rocks from coal and metal mining are as building and construction materials. These wastes are used as fill for subsided land or as aggregates in embankment, dam, road, pavement, foundation and building construction. They also find applications as feedstock for the production of cement and concrete. Whether these alternative uses can be pursued depends on the waste's geotechnical, mineralogical and geochemical characteristics. For example, pyritic waste has been evaluated as a soil amendment to neutralize infertile, alkaline agricultural soils (e.g. Castelo-Branco et al. 1999). Yet, the presence of potentially mobile and bioavailable trace metals and metalloids in pyritic waste limits its possible use as a soil additive. While sulfide oxidation and the development of acid mine drainage (AMD) represent a major environmental menace, the exothermic sulfide oxidation reactions in large oxidizing sulfidic waste rock dumps may provide future opportunities to obtain geothermal energy and thus use these waste heaps as unconventional energy sources (e.g. Raymond et al. 2008).

Recycling Mine Waters and Sludges

Water scarcity, local regulation and environmental impacts are forcing the mining industry to reuse much of the waste water it produces. As a result, the reuse and recycling of process water for dust suppression and mineral processing applications are commonly pursued at operating mines (Table 1). The recovery of metals and salts from mine waters is also achievable. For example, the selective and sequential extraction of metals is possible from AMD waters by employing metal-accumulating algae or establishing sulfate-reducing bacteria in a bioreactor (e.g. Tabak et al. 2003). The hydrogen sulfide produced in the bioreactor is used to precipitate metals as insoluble sulfides. Advanced treatment technologies, such as filtration, reverse osmosis and ion exchange, allow mine waters to be processed into drinking water. Furthermore, benign or treated mine waters may find applications as water for aquaculture enterprises and the irrigation of agricultural crops. Whether such alternative applications are possible is largely controlled by the chemical characteristics of the treated water. Regardless, underground mine water may be exploited for heating or cooling purposes using geothermal heat pump systems (Banks et al. 2004). Acid mine drainage waters may even be treated using fuel cell technologies, generating beneficial products such as electricity and recovered metals (Cheng et al. 2007).

Acid mine drainage is associated with the formation of solid phases and treatment sludges that mainly consist of amorphous and poorly crystalline hydrous ferric oxides. These sludges have high adsorption capacities and therefore may be used as adsorptive material to remove phosphorus from sewage effluent and agricultural wastewaters (Sibrell et al. 2009; Dobbie et al. 2009). Iron-rich mine drainage sediments and sludges can also be a resource for iron minerals and industrial pigments (Zinck 2005).

Reuse and Recycling of Tailings

At mine sites, sandy tailings may be mixed with cement and disposed of in underground workings as backfill to provide ground or wall support (Table 1). Such a practice also reduces the amount of tailings that needs to be stored in waste repositories. Moreover, benign tailings can be placed as a surface cover over metalliferous or acid-generating tailings. This establishes a hydrogeological barrier and protects the underlying wastes from oxygen and water ingress.

The targeted extraction of gangue minerals from previously discarded tailings or a current waste stream may also be pursued. For example, the extraction of lithium-bearing minerals may be possible from micaceous tailings. Also, gangue pyrite may be removed for the production of sulfuric acid, ferric or ferrous sulfate, and pigments – a practice that may also reduce the likelihood of sulfide oxidation and AMD generation. Such careful extraction of targeted minerals from a waste stream or existing tailings pile requires a detailed knowledge of the waste's mineralogical, geochemical and bulk physical properties (Geise et al. 2011). This is to ensure that the extracted minerals are suitable for their intended application and that the remaining material is safely disposed of.

A detailed mineralogical characterization of waste clay present in coal spoils and metalliferous tailings can reveal suitable resources for the building and ceramics industries. Clay-rich tailings can be alternative raw materials for the manufacturing of bricks, cements, floor tiles, sanitary ware and porcelains. Also, the addition of clay-rich mine spoils and tailings to agricultural land can improve the structure of sandy soils.

Tailings of certain mineral commodities may have particular reuse and recycling potentials. For example, manganese-rich tailings may be used in agro-forestry, building and construction materials, coatings, cast resin products, glass, ceramics, and glazes. Bauxite tailings could be sources of alum; copper-rich tailings have been tested as extenders for the development of paints; and iron ore tailings mixed with coal fly ash and sewage sludge can be sintered into lightweight ceramics. Finney et al. (2009) proposed the recovery of energy from coal tailings by combusting them with compost. Phlogopite-rich tailings may have potential applications in the treatment of sewage effluent. Ultramafic tailings can have the appropriate composition for the production of glass and rock wool insulation materials. However, any reuse or recycling of tailings, for example into waste-derived fertilizers, requires a solid evaluation of the potential release of contaminants from these materials (cf. Williams et al. 2006).

Recycling Wastes of Aluminium Ores

Bauxite red mud is a solid alkaline residue produced during the digestion of bauxite with sodium hydroxide at alumina refineries. Red mud has a very high alkalinity and consists of a mixture of amorphous phases and finely crystalline minerals, including gypsum, quartz, hematite, calcite, böhmite, gibbsite, sodalite and whewellite. Neutralizing red mud with seawater lowers the pH value to approximately 8.5, allowing secure disposal and revegetation. Several alternatives to the disposal of bauxite residues have been proposed, such as using the metallurgical waste as a raw material for extracting elements or making glass, tiles, cements, ceramics, aggregate or bricks (Table 1). In addition, red mud can be used to treat dairy wastewaters, to remove dyes from wastewater and to remove metals from solution (Genç-Fuhrman et al. 2004). Seawater-neutralized red mud has been applied successfully to neutralize AMD waters, to strip AMD waters of their dissolved metals and metalloids, and to promote revegetation of sulfidic wastes.

Recycling Slags

Slags are a partially vitreous by-product of smelting ore to separate the desirable metals from unwanted elements. Slags have unique physical and mechanical characteristics that make them suitable in a wide range of applications (e.g. for the production of concrete and cement, and as fill, ballast, abrasive and road aggregate) (Table 1). The reuse of ferrous slag has been a widely accepted practice since Roman times.

Slag piles commonly occur at historical base metal mine sites of the 19th and 20th centuries (Fig. 2). Such slags are known to be mineralogically and chemically diverse and heterogeneous (Parsons et al. 2001). They are commonly characterized by elevated metal and metalloid contents as a result of inefficient metal recovery technologies (weight percent levels of Cu, Pb and Zn; Ettler et al. 2001; Lottermoser 2002). In some cases, the metal contents of historical base metal smelting slags are similar to or even higher than those of geological ore deposits currently mined for metals. Consequently, the extraction of metals from ferrous and non-ferrous slags has been considered. Much of the metals are hosted by glass and microcrystalline silicates and may be extracted using electro- or hydrometallurgical treatment processes.

Reuse and Recycling of Wastes from Phosphate Ores

The necessity to provide adequate food supplies to a growing world population has resulted in the significant growth of phosphate mining and fertilizer consumption over the last 100 years. This growth has also led to the ever-increasing volume of phosphate mine wastes, including waste rocks, tailings and phosphogypsum. Phosphatic waste rocks can be put to good use in landscaping and in the capping and revegetation of waste repositories (Table 1). Similarly, the extraction of phosphoric acid from phosphatic tailings is achievable. However, phosphogypsum is the major waste product of phosphate fertilizer production, with over 1000 million tonnes of phosphogypsum stored in Florida alone. Phosphogypsum consists dominantly of calcium sulfate crystals, but it also contains minor reaction products, unreacted phosphate rock and gangue mineral particles, as well as liquid inclusions and process waters trapped in the interstices of mineral particles (e.g. Silva et al. 2010). The term *phosphogypsum* is, therefore, a collective expression for an acid waste mixture.

The ever-increasing volume of phosphogypsum has stimulated research into extracting resource ingredients from it or finding alternative uses for the material. Recycling of phosphogypsum aims to extract pure elements (e.g. sulfur for sulfuric acid production) or pure calcium sulfate solids (e.g. for building materials such as gypsum plaster boards, tiles, cement, hydraulic binder, mineralizer, artificial marble, fibre boards, glass, glass-ceramics). The reuse of phosphogypsum involves minimal or no reprocessing for large-scale applications in agriculture, mine and landfill reclamation, earthworks and construction (Pérez-López et al. 2010). However, phosphogypsum has to compete with synthetic gypsum produced as a coal combustion by-product and with mined natural gypsum, which has considerably higher purity. The reuse of phosphogypsum is limited due to its residual phosphate, acid, metal, radionuclide, fluorine and water contents, fine particle size and variable composition. To be used for building and agricultural applications, phosphogypsum may need to be puri-

Figure 2 Historic dump of smelting slag facing the Río Tinto, Spain. The ~1 km long slag dump (~10 million tonnes) is the result of smelting of sulfide ore during the 19th and 20th centuries. Weathering releases environmentally significant elements into pore and seepage waters and, consequently, white mineral efflorescences (gypsum, epsomite, hexahydrite, blödite, copiapite, römerite) occur at seepage points at the base of the slag dump and as solid aggregates in protected overhangs. The slags contain weight percent concentrations of zinc, minor copper and lead (>1000 ppm), sub-minor (100–1000 ppm) to traces (<100 ppm) of cobalt, antimony and tin, as well as traces (<100 ppm) of silver, arsenic, bismuth, cadmium, molybdenum, nickel, thallium and tungsten.

fied. Despite significant research efforts, there is no large-scale recycling or reuse of phosphogypsum. Elevated acid, metal and radionuclide levels, inefficient and costly extraction procedures, and competing gypsum products have so far prevented the extensive reuse and recycling of this particular waste.

REHABILITATION OF MINE WASTES

Mine Site Rehabilitation

Rehabilitation of mine wastes returns wastes and their repositories to a state allowing future land use. Similar to the mine waste hierarchy (Fig. 1), the mine site rehabilitation hierarchy is a guide for prioritizing rehabilitation strategies of mined land, including its waste repositories (Fig. 3). The future land use of a waste repository is site specific. In sparsely populated areas, mine waste repositories may be rehabilitated to a standard which requires fencing off or allows only limited grazing, and tailings may be placed under water cover or capped with benign rocks. Yet in densely populated areas, rehabilitated mine waste dumps have become centres of social amenity, such as parklands, football fields, golf courses, open air theatres, and even artificial ski slopes (Pearman 2009).

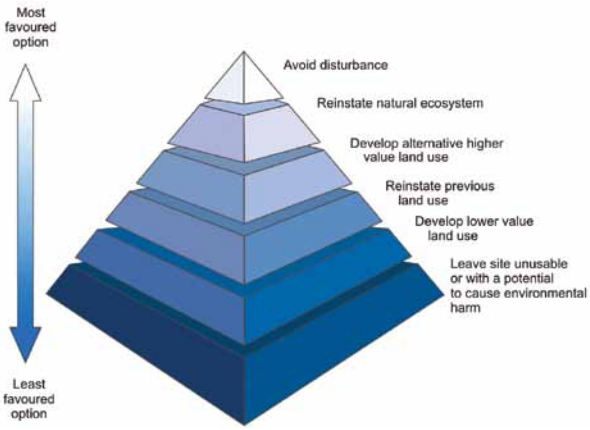

Figure 3 The mine site rehabilitation hierarchy, in descending order of favourability, from avoiding disturbance to leaving the site unusable or environmentally harmful. After EPA (2008)

Revegetation of Waste Repositories

The presence of environmentally significant elements and compounds in some mine wastes invariably requires their isolation in suitably constructed waste repositories. Capping mine wastes with a thick layer of solid, inert material is an effective strategy for isolating tailings and waste rocks. Materials used for dry covers include benign waste rock and tailings, clays, soils, organic wastes and neutralizing materials (e.g. limestone). Such engineered dry covers have been developed to prevent migration of solid and dissolved contaminants from tailings storage facilities and waste rock dumps into the surrounding environment. The long-term performance of dry covers is strongly affected by climate, material selection and availability, cost and construction practices, physical stability, volume change, soil evolution, ecological stability and vegetation growth. Mine operators and government authorities install these technologies with the expectation that such covers will provide a long-term solution to waste isolation and will reduce the likelihood of interaction with the biosphere, acid generation, contaminant drainage and treatment costs. Yet, there is little evidence of the proven long-term performance of engineered dry covers, despite the fact that the design life of cover systems has been predicted to extend up to hundreds of years.

Vegetation is one key to the efficient functioning and sustainability of dry covers, partly because plants protect covers against erosion and transpire infiltrated water. Therefore, a solid understanding of vegetation performance on dry covers is crucial to the successful long-term establishment of vegetation over waste repositories. Nevertheless, the cover design of waste repositories still focusses on the physical and engineering properties of the cover materials, and gives minimal consideration to vegetation growth needs and the effect of vegetation on cover performance in the long term. In particular, the uptake of metals and metalloids into plants colonizing dry covers is still poorly understood. This is despite the knowledge that salt-rich solutes rise in engineered waste covers in response to capillary and evaporative suction forces, potentially threatening the integrity of cover systems. For example, at the Rum Jungle uranium mine in Australia, the soil covers have been acidified and contaminated with copper by the capillary rise of water from pyritic wastes underlying the soil capping (Menzies and Mulligan 2000). At this particular site, plants take up metals from the capped tailings, introducing the contaminants into the surrounding environment and leading to vegetation dieback on the capped waste repository. In general, colonizing plants that have a significant root penetration depth and a tendency to accumulate metals into their above-ground biomass may penetrate dry covers and transfer metals from capped waste repositories into their above-ground tissue, potentially causing harmful effects on animals feeding on them (Lottermoser et al. 2009). As a result, the effectiveness offered by dry barrier–type covers can be compromised, even though the waste remains physically isolated.

Genetically metal-tolerant plants (i.e. metallophytes) are known to occur over metal-rich soils. In particular, metallophytes that accumulate metals in their biomass have received much attention because hyperaccumulating plants can potentially be used to extract metals (i.e. phytomining) from soils and wastes (e.g. Tack and Meers 2010). By contrast, only a few studies have investigated species that colonize metalliferous ground without acquiring significant element concentrations (e.g. Lottermoser et al. 2008). Yet, metal-excluding plants are of significant interest in mine site rehabilitation. Such plant species do not acquire high metal concentrations in their biomass despite elevated metal concentrations in the root substrate (Fig. 4). The exclusion of metals from the above-ground plant biomass reduces the exposure of wildlife and grazing animals to metals and limits the transfer of metals up the food chain.

Figure 4 Natural colonization of metalliferous mine wastes by metal-excluding gorse (*Ulex europaeus*), bramble (*Rubus fruticosus*) and heather (*Calluna vulgaris*) at the historic Botallack tin mines, at Cornwall, UK. Geobotanical and biogeochemical investigations of abandoned historic mine sites can reveal metal-excluding plants that are suitable for the rehabilitation of mine sites and waste repositories.

CONCLUDING REMARKS

Since the first attempts to salvage metals during the Bronze Age and the recycling practice of reusing slags during Roman times, humanity has pursued the recycling and reuse of mine wastes. Yet today, many concepts of reuse and recycling of mine wastes remain ideas that have not been taken up by industry, because poor economics have prevented their application in the real world. More than ever, geochemists and mineralogists have important contributions to make by providing the knowledge necessary for the identification of cost-effective reuse and recycling options that will be adopted by industry and for rational decision-making in critical areas such as waste recycling and reuse.

The most urgent problem facing scientists working on the recycling and reuse of mine wastes is the quantification and distribution of elements in wastes. We must precisely describe the chemistry and mineralogy of wastes and understand their long-term behaviour. Developing predictive tools and reliable, field-tested modelling of long-term waste behaviour are among the greatest challenges. We need to drastically improve our scientific effort to explain the occurrence and distribution of elements and minerals in wastes on all scales, from the nano-scale to the macro-scale as well as in space and time. Such data are needed to establish the recycling and reuse potential of wastes.

While the rehabilitation of many mine sites and waste repositories is pursued by using best practices, we must continue to search for innovative, cost-effective reclamation technologies and sustainable rehabilitation methods. Hydro- and biogeochemical evaluations of recently rehabilitated mine sites and waste repositories would produce data on the successes and failures of modern rehabilitation efforts. Such studies should sharpen our ideas on the development of new rehabilitation technologies. Successful rehabilitation of mine wastes requires a new precision in the total description of wastes and their repositories and an understanding of whether our current rehabilitation practices are sustainable in the long term.

We are increasingly recognizing the need to put all components of mined resources to good use and to protect the environment from waste disposal. If innovative alternatives to current waste-disposal practices are pursued and if all waste is recycled or reused, then waste-disposal problems will be eliminated. Total resource utilization, where all of the material mined is put to good use, is a challenging concept for researchers and miners. Achieving zero waste would be the ultimate solution to waste production, disposal and rehabilitation.

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