

1 **Physicochemical composition of wastes and co-located environmental designations at**  
2 **legacy mine sites in south west England and Wales: Implications for their resource**  
3 **potential**

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11 **Highlights (85 characters max)**

- 12 • Physicochemical composition of key UK metalliferous mine waste is determined
- 13 • Cu, Zn, As, Pb, Ag and Sn recorded in appreciable concentrations
- 14 • Waste has significant economic value but unlikely a sole driver for site rehabilitation
- 15 • Many mine sites are protected for their environmental and cultural resources
- 16 • Remediation strategies must consider cultural, geological and ecological designations

17

18 **Abstract**

19 This work examines the potential for resource recovery from metalliferous mine wastes in  
20 south west England and Wales. It does this through an assessment of the physicochemical  
21 composition of several key metalliferous legacy mine waste piles and an analysis of their co-  
22 location with key cultural, geological and ecological designations. Solid samples were taken  
23 from 14 different sites and analysed for metal content, mineralogy, paste pH, particle size  
24 distribution, total organic carbon and total inorganic carbon. The majority of sites contain  
25 relatively high concentrations (in some cases up to several % by mass) of metals and metalloids,  
26 including Cu, Zn, As, Pb, Ag and Sn, many of which exceed guideline concentrations.  
27 However, the economic value of metals in the waste could be used to offset rehabilitation costs.  
28 Spatial analysis of all metalliferous mine sites in south west England and Wales found that  
29 around 70% are co-located with at least one cultural, geological and ecological designation.  
30 All 14 sites investigated are co-located with designations related to their mining activities,  
31 either due to their historical significance (e.g. mining infrastructure), rare species assemblages  
32 (e.g. lichens and bryophytes) or geological characteristics (e.g. mineralisation). This  
33 demonstrates the need to consider the cultural and environmental impacts of rehabilitation and  
34 resources recovery on such sites. Further work is required to identify non-invasive remediation  
35 and resource recovery methodologies to allow sites to be rehabilitated at minimal cost and  
36 disturbance.

37

## 38 1 Introduction

39 There are few locations world-wide where historic metal mining is more evident than in  
40 mainland Britain. Extensive mining of major ores for metals including copper, lead, tin and  
41 zinc at locations such as the Devon Great Consols in south west Devon and Parys Mountain in  
42 north west Wales fuelled profound societal and industrial change world-wide (particularly  
43 during the Industrial Revolution) but as a consequence created a significant legacy of waste.  
44 Most mine sites in the UK were in peak operation in the 18th and 19th centuries and, as a result,  
45 mine sites were not subject to restoration practices which have been required in more recent  
46 years. In England and Wales alone, it has been estimated that there are over 8,000 disused metal  
47 mines located predominately in 12 ore producing regions (Jarvis, 2007; Palumbo-Roe, 2010).  
48 Rather than simply rehabilitating such sites one option is to also recover any economically  
49 valuable metals that are present. Mine wastes and tailings are an obvious target for metals  
50 recovery as there are often significant quantities of such material in relatively easily accessible  
51 locations (i.e. above ground). To date, however, there is a paucity of studies that have  
52 characterised mine waste sites in terms of their metal content and extractability. This study is  
53 the first effort to present these data for prominent legacy mine sites in England and Wales.

54 Legacy mines also provide environmental or landscape 'resources'. This study examines the  
55 resource potential of these legacy mine wastes in the context of site rehabilitation. Further to  
56 the potential recovery of economically valuable metals, there are often other drivers. For  
57 example, site remediation may: enable the land to be developed; enhance the conservation of  
58 industrial heritage and the related tourism features; and/or decrease the release of pollutants  
59 from the site into the surrounding environment. Similarly, there are also often a range of  
60 existing services that the mine sites provide which must be considered when implementing site  
61 remediation, including: cultural, scientific and educational features (such as historic industrial

62 ruins); and rare fauna and flora. Thus it is important to appreciate the multifaceted value, both  
63 positive and negative, depending on perspective, that these sites currently have and would have  
64 if remediated. Within this a cost benefit approach must be applied to accurately assess to what  
65 extent the economic gain (that can be made through metal extraction) can offset the economic  
66 cost of such an intervention. This study thus considers multifaceted characterisation of value  
67 and resource through various lenses and the authors use the word “resource” in a wide sense  
68 (e.g. Freeman, 2014) to cover both tangible resource of, for example, the metal/ore as well as  
69 functional and intangible resource stemming from the ecological, sociocultural and landscape  
70 value of the mine sites.

71 In this work key geological, ecological and cultural designations (herein grouped under the  
72 umbrella of “environmental designations”) of case study legacy mine sites are presented as a  
73 means of assessing the potential positive and negative consequences of the remediation of these  
74 sites. The specific aims of this paper are therefore to: (i) present data from the physicochemical  
75 characterisation of mine wastes from 9 major sites in the south west of England and 5 major  
76 sites from Wales; (ii) delineate the co-located environmental designations of the case study  
77 sites with respect to environmental and ecological services, human health and environmental  
78 pollution; (iii) appraise broader considerations of value and resource relevant to metal mine  
79 sites; and (iv) consider potential decision making tools to determine appropriate methodologies  
80 for optimising resource value. Very few studies currently exist which have applied this holistic  
81 approach to mine waste characterisation and to our knowledge this is the first time that the co-  
82 location of UK mine waste with geological, ecological and cultural designations has been  
83 examined.

## 84 **2. Key drivers/deterrents for the reclamation of legacy mine waste**

### 85 **2.1. Environmental pollution**

86 A large number of historic metal mine sites world-wide are responsible for the release of metals  
87 and metalloids into surface and groundwater (Hudson-Edwards, 2011; Plumlee, 2011). For  
88 example, a preliminary national assessment in 2009 revealed that as much as 6 of surface water  
89 bodies in England and Wales are currently adversely affected by pollution from historic  
90 metalliferous mines (Mayes et al., 2009). In the UK ore extraction ceased at the majority of  
91 mine sites in the first half of the twentieth century or earlier, and as such ownership and/or  
92 legal liabilities for clean-up are often either unclear or orphaned (Palumbo-Roe, 2010). This is  
93 also the case in many of the ore fields of North America (e.g. the USA and Canada have  
94 approximately 35,000 and 10,000 legacy metal mine sites respectively), Asia (e.g. Japan has  
95 approximately 5,500 legacy metal mines) and Europe (e.g. Sweden has approximately 1,000  
96 legacy metal mines) (Mayes et al., 2009). The financial cost of remediating and rehabilitating  
97 these mine wastes is significant. For example, in 2012 a series of joint reports commissioned  
98 by the Department for Environment, Food and Rural Affairs (DEFRA) and the Welsh  
99 Government in collaboration with the Environment Agency estimated that the total cost to  
100 remediate all of the water related environmental problems associated with abandoned non-coal  
101 mines in the UK would be approximately £370 million, excluding operating costs, and take  
102 upwards of ten years (Jarvis, 2012a; Jarvis, 2012b). Moreover, the pollutant discharge from  
103 such sites often continues for many decades through to centuries, before water quality recovers  
104 to the pre-mining baseline. For example, despite ceasing major operations in the late 18<sup>th</sup>  
105 century Parys Mountain in north Wales remains a major contributor of Cu and Zn to the Irish  
106 Sea, discharging an estimated 24 and 10 tonnes of each element respectively each year  
107 (Mullinger, 2003).

## 108 **2.2 Ecological resource**

109 The unique (and often extreme) physicochemical conditions and lack of disturbance has  
110 resulted in the development of a rich ecological resource on many different metalliferous mine  
111 wastes world-wide (Bradshaw, 2000). For example, legacy mine sites often contain numerous  
112 species of rare metal-tolerant plants and lichens (Rodwell et al., 2007), grasslands, wildflowers,  
113 orchids and important invertebrates, birds and mammals (e.g. the lesser horseshoe bat) (Barnatt  
114 & Penny, 2004). In the UK this has resulted in specific recognition and protection for some  
115 mine waste sites. Examples include: the designation of Sites of Special Scientific Interest  
116 (SSSI) status for rare metal-tolerant plants, and lichens, and two priority habitats: Calaminarian  
117 grasslands (BRIG, 2008) and Open Mosaic Habitats on Previously Developed Land (OMH)  
118 (BRIG, 2010).

### 119 **2.3. Geological and mineralogical resource**

120 The amount of metal produced at major UK mine sites has generally been relatively well  
121 recorded over the peak production years (i.e. during the Industrial Revolution), however,  
122 definitive figures for the quantity and type of waste produced are often lacking, with estimates  
123 typically calculated from predictions on the mineral to waste ratios, which are often highly  
124 variable, even for the same commodity (Palumbo-Roe, 2010). To date a number of studies have  
125 attempted to quantify the mass, distribution and composition of mine waste located at specific  
126 sites across the UK, however, no conclusive inventory is yet to be created due to the large  
127 number of mine waste sites and the inherent complexity of differentiating between the mine  
128 waste and the natural ground surface. As such a first estimate (e.g. to within an order of  
129 magnitude) for the mass and composition of mining waste present at many major legacy metal  
130 mine sites in the UK has not yet been conducted with their associated economic value therefore  
131 unknown.

132 Historic ore beneficiation processes were typically less efficient than today and as such it is  
133 likely that appreciable concentrations of economically valuable metals were discarded as waste  
134 and are currently stored at legacy metal mine sites in the UK and world-wide. Furthermore, the  
135 material has often already undergone size reduction during historic ore beneficiation and is  
136 often stored as unconsolidated material in relatively accessible locations (in piles above  
137 ground). Mine waste (in particular mine tailings waste) is also often of a relatively homogenous  
138 physical and chemical composition compared to other waste streams such as municipal solid  
139 waste. These extraction and processing activities have often resulted in the occurrence of rare  
140 and unusual geological, mineralogical or physiographical features deemed worthy of  
141 protection. Many mine wastes in the UK are therefore designated, for example, as Sites of  
142 Special Scientific Interest (SSSIs) because of these characteristics. Similarly, where relics  
143 demonstrate technological advancement of the mining industry they may also be designated as  
144 Scheduled Monuments.

#### 145 **2.4. Sociocultural resource**

146 The cultural heritage of many mine sites is considerable and the waste piles themselves are an  
147 intrinsically valuable component of this heritage landscape, i.e. in addition to remnant buildings  
148 and processing equipment (Howard et al., 2015). As such many landscape-scale historic mining  
149 districts have been granted official conservation status, for example the Cornwall and West  
150 Devon Mining Landscape World Heritage Sites as well as the numerous individual Scheduled  
151 Monuments and Listed Buildings that are associated with a rich legacy of mining. Physical  
152 features such as hushing scars; prospection pits and mine shafts; roads, tramways and leats  
153 linking the mines and settlements as well as the spoil tips themselves are regarded as valuable  
154 heritage (e.g. Schlee, 2007). The ecological and cultural significance of mine wastes, coupled  
155 with their setting within the mine site and the wider landscape, provide a range of benefits to



156 local people and visitors, with the former mine sites often being important economically with  
157 respect to industrial heritage tourism (e.g. Jones, 2001). These benefits can be framed as  
158 ecosystem or, perhaps more helpfully in this context, landscape services (Swanwick, 2009).  
159 For example, prior to its World Heritage Site status being granted it was estimated that the  
160 mining attractions in Devon and Cornwall benefitted from nearly 1 million visitors each year,  
161 with around 2.5 million visitors to the region citing the mining heritage as an important  
162 consideration in their visit. This generates significant revenue to the local economy at an  
163 estimated £120 million per year (Atlantic Consultants, 2003). Economic growth associated  
164 with mining heritage tourism has also been highlighted as a realistic development option in  
165 many economically marginal areas of Wales and there is active promotion led by the European  
166 Union for the maintenance of mining heritage e.g. the commercial Mining Heritage Network  
167 (Jones, 2001; Edwards, 1996).

168 It is much more difficult to assign a monetary value to many of the other services provided by  
169 such sites which include recreation for local populations, cultural and spiritual enrichment,  
170 education and research (Bloodworth et al., 2009; Barnatt & Penny, 2004; Swanwick, 2009).  
171 For example, local communities also often place an emotional value on mining landscapes  
172 (Ballesteros, 2007). Many legacy mine sites also have educational and academic value and are  
173 often the subject of a diverse range of lower and higher education and research in subjects from  
174 earth sciences, archaeology and engineering to social sciences and economic history. The  
175 cultural value of the sites is reflected by the wide number and type of stakeholders including  
176 archaeological and local history groups. However, the rural location of many mine wastes  
177 means that in addition to ecological and cultural resources arising from past mining activity  
178 there is likely to also be additional designations that may be adversely impacted on by pollution  
179 from the waste. Therefore it is crucial that the multifaceted nature of such sites and the  
180 landscapes in which they are located is understood.

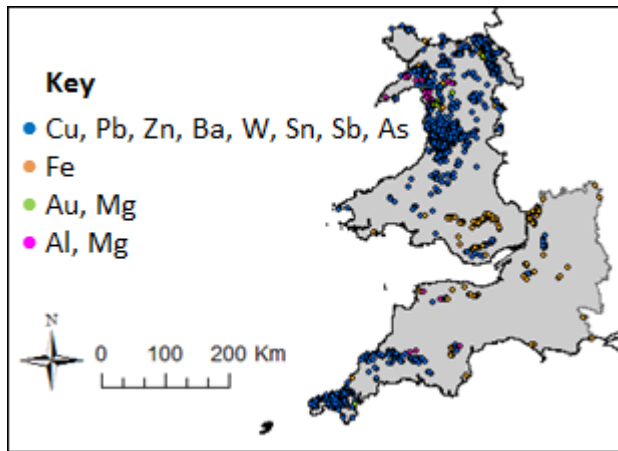
### 181 3. Methodology

#### 182 3.1 Site selection

183 In England and Wales there are estimated to be over 3,000 legacy non-ferrous metal mines  
184 (Jarvis, 2007) concentrated in three main ore producing regions: Cornwall and west Devon;  
185 Northumbria and north Humber; and Wales. The focus of this study is on the districts of  
186 Cornwall and west Devon and Wales because they both contain significant quantities of  
187 metalliferous legacy waste (Figure 1), are representative of Cu/Sn and Pb/Zn mining areas,  
188 have a high density of UK Mine Waste Directive sites (Palumbo-Roe, 2010) and a range of  
189 cultural and environmental designations.

190 Cassiterite ( $\text{SnO}_2$ ), chalcopyrite ( $\text{Cu,FeS}_2$ ) and later arsenopyrite ( $\text{Fe,AsS}$ ) bearing ore were  
191 principally extracted in Cornwall and west Devon and processed for Sn, Cu and As  
192 respectively. Chalcopyrite and galena ( $\text{PbS}$ ) bearing ore was principally extracted in Wales and  
193 processed for Cu and Pb respectively. In many cases galena also contained relatively high Ag  
194 content, especially at Cwm Ystwyth, which was also extracted. Large quantities of sphalerite  
195 ( $\text{Zn,FeS}$ ) was also mined, however, Zn was only occasionally removed and much remains in  
196 mine waste. The sites investigated which are located in south west England were: Alfred  
197 Consols (ALF), Caradon (CAR), Consols (CON), Devon Great Consols (DGC), Levant (LEV),  
198 Nangiles (NAN), Prince of Wales (PWM), Poldice (POL) and Wheal Maid (WHM). The sites  
199 investigated which are located in Wales were: Esgair Mwyn (EGM), Frongoch (FRG),  
200 Grogwynion (GRG), Parys Mountain (PYM) and Wemyss (WEM). Sites were selected which  
201 contain considerable mine waste volumes and are also located across different mining districts  
202 (as determined by different geographical and mineralogical constraints) of the region. Within  
203 south west England this was the Tamar valley and Tavistock (PWM, DGC), Caradon (CAR),  
204 Gwennap Kennal Vale and Perran Foundry (CON, NAN, POL, WHM), Port of Hayle (ALF)

205 and St Just (LEV) mining districts. Within Wales this was the Central Wales (EGM, FRG,  
206 GRG, WEM) and Anglesey (PYM) mining districts.



207

208 **Figure 1. Location of metalliferous mines in south west England and Wales. Produced**  
209 **using BRITPITS database; Licence No. 2014/098BP ED British Geological Survey**  
210 **NERC. Boundary data from UK Data Service. URL: <http://census.edina.ac.uk>.**

### 211 3.2 Sample collection procedure

212 Mine waste samples were collected from each site following the methodology of ASTM  
213 D6009-12 (ASTM, 2012) which provides an appropriate method for the sampling of  
214 unconsolidated, aggregated waste piles. Many sites contained notable waste pile(s) of which  
215 the largest was typically targeted for characterisation (see Supplementary Data for sampling  
216 locations). Samples were collected using a stainless steel trowel at equal distances around the  
217 base of each mine waste pile at a depth of 0.2m. The sample depth of 0.2m was selected because  
218 it was determined as likely to represent a suitable compromise between sampling beneath the  
219 surface weathered zone whilst also exerting minimal aesthetic damage on the waste piles.  
220 Moreover, visual inspections in the field revealed the material, in almost all occasions, to be  
221 relatively homogenous with depth, i.e. no surface weathered zone could be identified.

222 At most sites the mine waste is considered to be mine tailings (based on literature records and  
223 the relatively fine particle size observed). Each sample had a volume of approximately 5 L with  
224 a mass typically between 6 and 8 kg, depending on bulk density. Once collected the samples  
225 were dried at 105°C for 24 hrs. The number of samples taken from each site was dictated by  
226 the pile volume, ranging from 3 samples taken for LEV to 21 samples taken from WHM (see  
227 Supplementary Data).

### 228 **3.3 Sample and site characterisation procedures**

229 Composite samples were created for each site by riffing each sample 6 times and then mixing  
230 (using a mixing pad) each final aliquot together thoroughly. Each composite sample was then  
231 riffled to yield an appropriate mass for each analysis technique. Particle size distribution (PSD)  
232 measurements were performed via dry sieving and sedimentation (BS, 2009) using 400 g from  
233 each composite. Uncompacted aggregate bulk density measurements were performed  
234 following BS 812: 1995 (BS, 1995). A cylinder of 1876 mL in volume was used and a tamping  
235 rod of 16 mm in diameter. Paste pH measurements were performed via ASTM D4972 – 13  
236 (ASTM, 2013), using a 1:1 solid liquid ratio, i.e. 40 g from each composite and 40 mL of Milli-  
237 Q water (resistivity > 18.2 MΩ cm). Samples were prepared for X-ray diffraction (XRD),  
238 inductively coupled plasma optical emission spectroscopy (ICP-OES), total organic carbon  
239 (TOC) analysis and total inorganic carbon (TIC) analysis by crushing (to particle size <75 μm),  
240 using a Labtech Essa LM1-P puck mill crusher at 935 RPM for 120 seconds, a 200 g subsample  
241 of each composite sample. Each crushed sample was then prepared for XRD analysis by  
242 packing approximately 2 g of the material into an aluminium XRD stub. Analysis was  
243 performed using a Phillips Xpert Pro diffractometer with a CuKα radiation source ( $\lambda =$   
244 1.5406Å; generator voltage of 40 keV; tube current of 30 mA). Spectra were acquired between  
245  $2\theta$  angles of 5–90°, with a step size of 0.02° and a 2 s dwell time. Each crushed composite

246 sample was prepared for ICP-OES analysis via a 4 acid digest (EPA, 1996). Firstly, 0.01 g was  
247 placed in a PTFE lined microwave digest cell and 3 mL of analytical grade 45.71% hydrofluoric  
248 acid (HF) was then added and left for 12 hrs. 6 mL of aqua regia solution (1:1 ratio of analytical  
249 grade 32% hydrochloric acid (HCl) and 70% nitric acid (HNO<sub>3</sub>)) was then added and the  
250 container was then placed in a microwave digest oven (Anton Paar Multiwave 3000) and heated  
251 at 200°C (1400 watts) for 30 minutes (after a 10 minute up ramp time period) and then allowed  
252 to cool for 15 minutes. The resultant solution was then neutralised using 18 mL of analytical  
253 grade 4% Boric acid (H<sub>3</sub>BO<sub>3</sub>) at 150°C (900 watts) for 20 minutes (after a 5 minute up ramp  
254 time period) and then allowed to cool for 15 minutes. ICP-OES analysis was performed using  
255 a Perkin Elmer Optima 2100 DV ICP-OES. Total carbon (TC) measurements were performed  
256 using a Leco SC-144DR sulphur/carbon analyser. Samples of 0.35 g mass were loaded into the  
257 instrument and heated at 1350°C in a pure O<sub>2</sub> (>99.9%) atmosphere. The concentration of CO<sub>2</sub>  
258 released by each sample was then measured using an infrared detection cell at a constant flow  
259 rate. Total inorganic carbon (TIC) measurements were performed using a Shimadzu SSM-  
260 5000A using 99.9% O<sub>2</sub> at 500 mL/min and catalytically aided combustion oxidation performed  
261 at 900°C. Total organic carbon (TOC) was calculated by subtracting each TIC measurement  
262 from each samples corresponding TC measurement.

### 263 **3.4 Hydrometallurgical extraction experiments**

264 Hydrometallurgical extraction experiments were conducted using a 1:10 solid-liquid ratio; 40  
265 g of each composite sample and 400 mL of a 1M H<sub>2</sub>SO<sub>4</sub> solution. Samples were sealed in 500  
266 mL glass jars and constantly agitated at 200 RPM using a Stuart SSL1 orbital shaker table.  
267 Liquid samples for ICP-OES analysis were extracted from each batch system after 24 hrs and  
268 filtered using a 0.45 µm PTFE filter.

### 269 **3.5 Spatial analysis of mine locations, ecological and cultural designations**

270 In addition to the analytical characterisation of the waste materials spatial analysis was  
 271 undertaken to: i) understand the scale of past mining activity in the south west of England and  
 272 Wales; and ii) examine the co-location of mine sites with areas protected for their geological,  
 273 ecological or cultural benefits. The British Geological Survey BRITPITS database was used  
 274 along with spatial data for the main geological, ecological and cultural designations (as detailed  
 275 in Table 1) held by Natural England, Historic England and Natural Resources Wales. These  
 276 designations were selected as they meet at least one of the following criteria: they are  
 277 ‘specified’ ecological receptors under Part 2A of the Environmental Protection Act (1990)  
 278 (DEFRA, 2012), they are known or suspected to be co-located with past mining activity and  
 279 there are spatial data available for them.

280 **Table 1 Ecological and cultural designations included in the study**

Designation	Summary and protection
<i>Geological and ecological</i>	
Local Nature Reserve (LNR)	Designated because of their nature conservation and/or geological interest by local authorities under the National Parks and Access to the Countryside Act (1949) and the Natural Environment and Rural Communities Act (2006).
National Nature Reserve (NNR)	Sites of biological and geological interest with a strong research and educational remit, most are publicly accessible. They are designated under the National Parks and Access to the Countryside Act (1949) but also receive protection under the Wildlife and Countryside Act (1981).
Site of Special Scientific Interest (SSSI)	Sites of biological and geological interest in the UK designated under the Wildlife and Countryside Act (1981). They range in size from less than a hectare to over 30,000 ha. SSSIs often overlap with other designations including LNRs, NNRs, SACs and SPAs.
Special Area of Conservation (SAC)	Designated for their internationally significant habitats and species under the 1992 Habitats and Species Directive and the Conservation of Habitats and Species Regulations (2010). Together with SPAs they are also known as Natura 2000 sites, all terrestrial SACs and SPAs are also SSSIs.
Special Protection Area (SPA)	Designated to protect threatened or endangered internationally significant bird species under the 1979 Birds Directive and the Conservation of Habitats and Species Regulations (2010).
Ancient Woodland (AW)	Defined as woodland that has been present since 1600AD. They take hundreds of years to develop and are irreplaceable yet are not protected

	by specific legislation. They are however protected under the planning policy in both England and Wales.
Priority Habitats (PH)	Priority habitats are published through the Natural Environment and Rural Communities Act (2006). They are not specifically protected but local planning policies should provide opportunities for their preservation and enhancement.
Open Mosaic Habitat on Previously Developed Land (OMH)	A relatively new priority habitat in acknowledgement of the ecological significance of many previously developed (brownfield) sites. An inventory of potential OMH sites has recently been published.
<i>Cultural</i>	
Area of Outstanding Natural Beauty (AONB)	Designated solely for their landscape qualities under the National Parks and Access to the Countryside Act (1949).
National Park (NP)	Also designated under the National Parks and Access to the Countryside Act (1949) they have an explicit purpose to promote education and recreation as well as conservation of landscape, wildlife and cultural heritage.
Scheduled Monument (SM)	Designated under the Ancient Monuments and Archaeological Areas Act (1979) for their archaeological character.
World Heritage Site (WHS)	Designated by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) for their natural or cultural features of international significance.
Landscape of Historic Interest (LHI)	A non-statutory recognition of the special or outstanding historic character of landscapes in Wales. There is an expectation that they are considered as part of the planning process (CADW, 2007).

281

282 The BRITPITS database details all known mine locations in Great Britain as point data  
283 categorised by the commodity (e.g. coal, Cu, Pb, gravel), type of mine (e.g. underground, open  
284 pit), status (e.g. active, ceased) geological age (e.g. Carboniferous, Permian), lithostrat (e.g.  
285 Alluvium, West Maria Lode) as well as address and operator information. Co-ordinates are for  
286 the working or entrance to the mine (tolerance of 5 m) (Cameron, 2012), not the location of the  
287 waste, but the assumption was made that all non-active mine sites have waste materials in their  
288 immediate vicinity. There are around 170,000 entries in the complete database, of which 4670

289 are non-active metalliferous mines in England, with 717 in the south west region and 3350 in  
290 Wales which are the focus of this study.

291 The analysis was carried out in ArcMap 10.1. First, the BRITPITS data were limited to those  
292 mine sites with the metalliferous commodities (Sb, As, Cu, Ba, Au, Fe, Pb, Mn, Ag, Sn, Sr and  
293 Zn), those that were mine locations (as opposed to associated infrastructure such as rail depots  
294 and wharfs) and those that were non-active (ceased, inactive, dormant, historic; there were only  
295 two active metalliferous mines in the areas of interest). Where multiple commodities were  
296 mined BRITPITS contains duplicate records, one per commodity, so these records were  
297 merged.

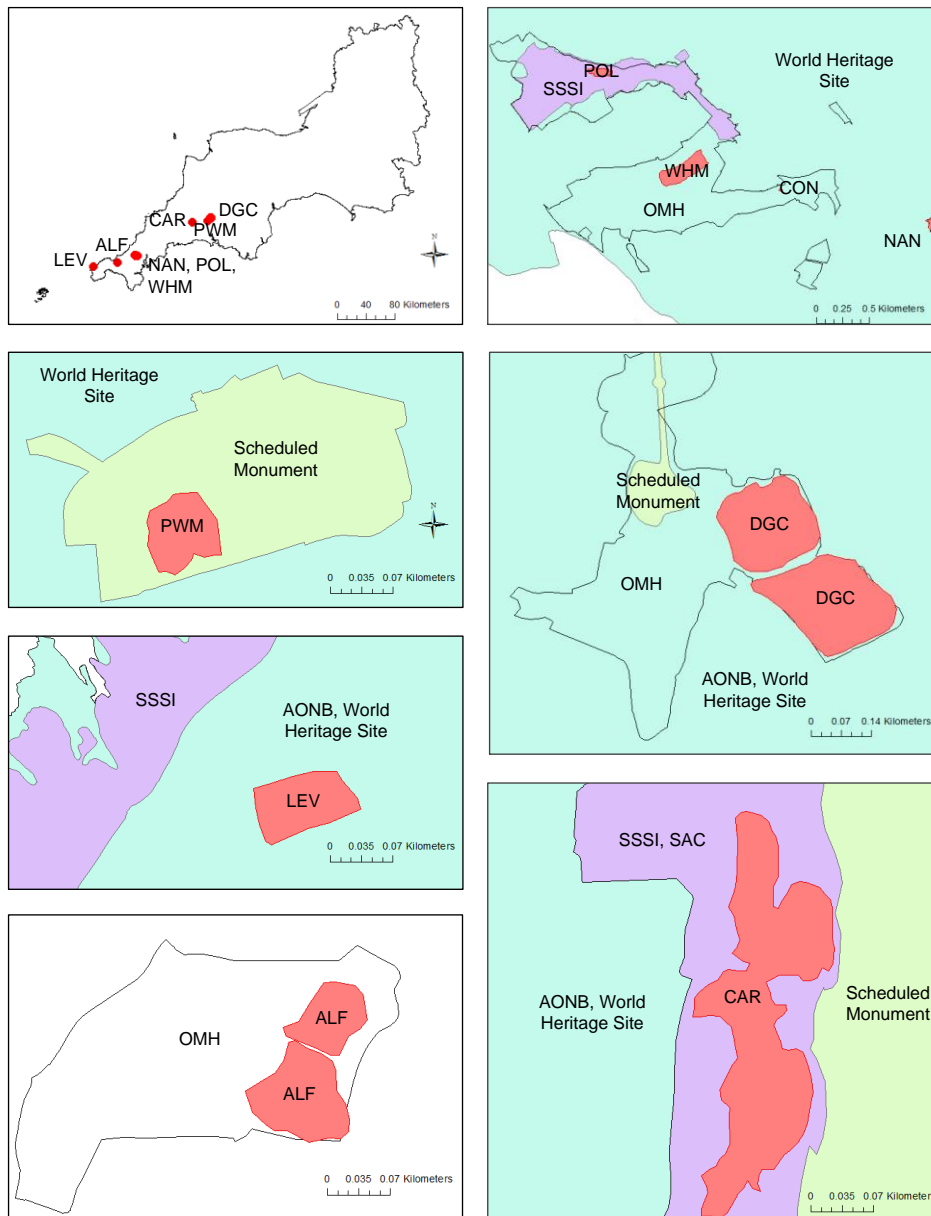
298 Next, the spatial joining function in ArcMap was used to identify which mine sites are co-  
299 located with the geological, ecological and cultural designations (Table 1). Additional  
300 designations were also considered but no mine sites were co-located with these in the SW of  
301 England or Wales; these were Parks and Gardens, Battlefields and Nature Improvement Areas  
302 so these will not be discussed further. The split between geological and ecological, and cultural  
303 designations is arbitrary in some cases. Some designations have a clear basis in nature  
304 conservation (e.g. LNRs, SACs) or heritage (e.g. SMs, WHSs) whereas others are more  
305 nuanced. The decision was taken for cultural designations to include those where landscape  
306 and/or recreation as opposed to wildlife conservation is a primary objective (e.g. AONBs,  
307 National Parks) (Gaston et al., 2006).

308 Finally, this analysis was refined using the case study mine sites. The estimates of the spatial  
309 extent of the sampled spoil tips, drawn from aerial imagery, were used to gain further insight  
310 into the co-location with the designations. Polygons were drawn around an aerial view of the  
311 waste pile which has been sampled (see Supplementary Data for individual sampling locations)  
312 using the contrasting colour between the waste pile and the surrounding vegetation along with



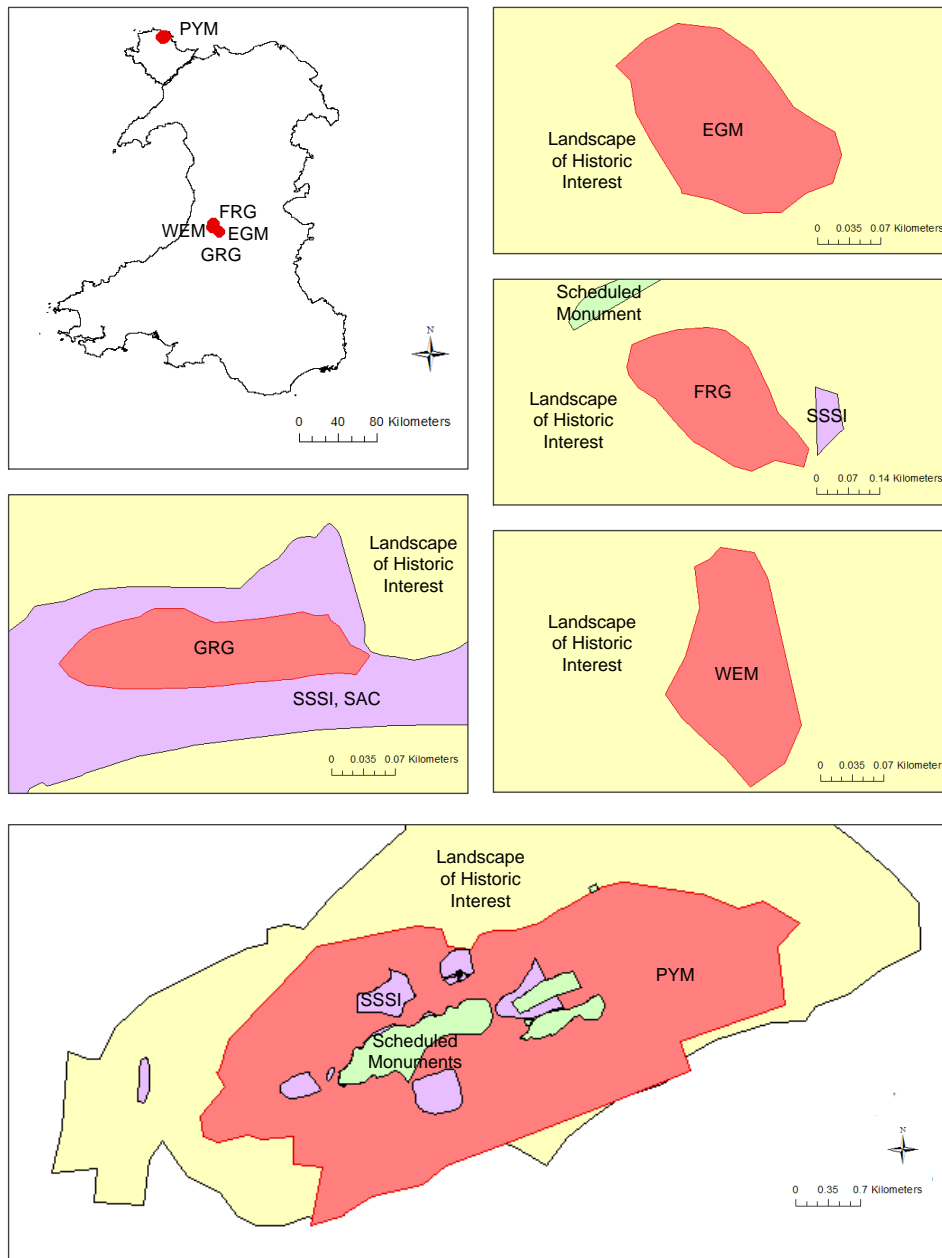
313 field observations as a guide. The specific designations at the site level were then examined  
314 more closely to identify those that are dependent (versus independent) on the mine waste as a  
315 way of exploring the opportunities and constraints for resource recovery. In addition, the case  
316 study sites were compared spatially to those on the inventory of Mine Waste Directive sites  
317 (Environment Agency, 2014). These are known or are suspected to be causing a risk to water  
318 quality and/or human health and therefore likely to require remediation.

319 To estimate the volume of waste in the case study locations polygons were used in conjunction  
320 with digital surface models produced using Light Detection and Radar (LiDAR). The data were  
321 at 1 m resolution with the exception of DGC and NYM where only a 2 m resolution was  
322 available. ArcMap was used to estimate the elevation of the land surface surrounding the waste  
323 material. This was estimated using at least ten points around the boundary of the polygon and  
324 the average elevation calculated. The polygon volume tool was then used to calculate the  
325 volume of waste above this elevation. This is a conservative estimate as the topography of sites  
326 was variable with many of the wastes being located on a slope. In addition, the presence of  
327 vegetation at some waste piles likely led to inaccurate readings due to it both shrouding the  
328 edge of the waste pile and also enabling greater elevations than the land surface to be recorded  
329 in the LiDAR data. Figures 2 and 3 display location of case study mine sites in south west  
330 England and Wales respectively and their co-location with statutory designations.



331

332 **Figure 2. Location of case study mine sites in south west England and their co-location**  
 333 **with statutory designations. Produced using BRITPITS database; Licence No.**  
 334 **2014/098BP ED British Geological Survey NERC. All rights reserved. AONB, SAC, SSSI**  
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339

340 **Figure 3. Location of case study mine sites Wales and their co-location with statutory**  
 341 **designations and Landscapes of Historic Interest. Produced using BRITPITS database;**  
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## 346 4 Results and Discussion

### 347 4.1 Physicochemical characterisation of mine wastes

348 Table 2 displays location, estimated volume, bulk density, total mass, paste pH and TOC data  
349 for mine waste taken from SW England and Wales respectively. The paste pH for all sites is  
350 recorded to be <7 and so cationic metal species are expected to be relatively mobile in the  
351 environment. TIC was recorded as 0.00% for all composite samples (except the EGM site  
352 where it was recorded as 0.04 wt.%) which indicates that the mine waste all have significantly  
353 low carbonate alkalinity. The XRD patterns of the composite samples all indicate quartz ( $\alpha$ -  
354  $\text{SiO}_2$ ) as the major crystalline component present with minor muscovite ( $\text{H}_2\text{KAl}_3(\text{SiO}_4)_3$ ) and  
355 potassium feldspar ( $\text{K}_5\text{Na}_5\text{AlSi}_3\text{O}_8$ ) recorded for some samples (Appendix A). The original ore  
356 minerals arsenopyrite and chalcopyrite were not detected for any of the mine waste samples  
357 from SW England, and no Pb-bearing minerals, e.g. galena ( $\text{PbS}$ ), were detected for the mine  
358 tailing samples from Wales. Particle size as a function of cumulative mass passing for all sites  
359 is shown in Appendix B. It can be noted that the PSD is relatively variable between sites, with  
360 a variation in 0.57-24.81 wt.% recorded for the silt and clay size fractions (particle size range  
361 <0.063 mm), upper and lower values for CAR and FRN respectively; a variation in 19.9-78.8  
362 wt.% recorded for the sand size fractions (particle size range 0.063-2 mm), upper and lower  
363 values for LEV and DGC respectively; and a variation of 3.6-79.1 wt.% recorded for the gravel  
364 size fraction (particle size range 2-64 mm), upper and lower values for PWM and LEV  
365 respectively.

366 As noted above, when estimating the volume of waste in each pile the average elevation from  
367 the area immediately surrounding the waste was used as a baseline, which has resulted in these  
368 estimates being conservative because much of the surrounding material is unlikely to be at the  
369 original elevation and the topography of some sites was extremely variable. For example, the

370 volume of mine waste at DGC and GRG have been determined in other studies to be 274,250  
371 (Mighanetara, 2008) and 50,311 (Excal, 1999) respectively compared to 198,923 and 9510 m<sup>3</sup>  
372 here.

373 **Table 2. Location, volume, bulk density, total mass, paste pH, TOC and TIC data for mine waste. The location data refers to the location**  
 374 **where the first sample was taken from. \* No LiDAR data; † mine waste is located in a valley floor so not possible to estimate volume using**  
 375 **LiDAR.**

Site name	Location (latitude)	Location (longitude)	Estimated volume using LiDAR (m <sup>3</sup> )	Bulk density (g/cm <sup>3</sup> )	Estimated mass (tonne)	Paste pH	TOC (wt.%)	TIC (wt.%)
South west England								
ALF	50°11'01.72"N	05°23'00.62"W	20516	1.44	29543	3.62	0.42	0.00
CAR	50°30'12.88"N	04°26'59.43"W	29286	1.26	36900	4.22	0.22	0.00
CON	50°14'12.46"N	05°09'00.03"W	32	1.04	33	3.73	0.53	0.00
DGC	50°32'16.75"N	04°13'17.32"W	198923	1.30	258600	3.33	0.16	0.00
LEV	50°09'10.80"N	05°40'58.47"W	1408	0.92	1295	3.78	0.68	0.00
NAN	50°14'04.73"N	05°08'13.07"W	15277	1.23	18791	2.68	0.28	0.00
POL	50°14'36.08"N	05°09'58.90"W	8941	1.06	9477	4.92	0.15	0.00
PWM	50°30'45.42"N	04°15'24.76"W	1799	1.39	2501	3.35	0.04	0.00
WHM	50°14'15.32"N	05°09'34.15"W	Unknown†	1.28	n/a	2.39	0.20	0.00
Wales								
EGM	52°18'26.58"N	03°49'39.58"W	Unknown*	1.49	n/a	5.56	0.38	0.04
FRG	52°21'7.05"N	03°52'38.90"W	16802	1.54	25875	3.28	0.16	0.00
GRG	52°19'53.76"N	03°53'18.01"W	9510	1.46	13885	6.36	0.25	0.00
PYM	53°23'14.37"N	04°20'59.73"W	Unknown†	1.03	n/a	2.89	1.35	0.00
WEM	52°20'59.13"N	03°53'12.75"W	34560	1.35	46656	3.89	0.33	0.00

376

377 Table 3 displays metal concentration data for composite samples from each site. An indication  
378 is also provided of where values exceed various guideline concentrations developed to trigger  
379 risk assessments to protect human and ecological health. In general relatively high  
380 concentrations of As, Cu, Pb and Zn were determined for the sites located in SW England. For  
381 example, As concentrations were recorded as being greater than 0.1% for all sites (with the  
382 exception of ALF and NAN) with a maximum of 1.92% recorded for DGC. Relatively high  
383 concentrations of Cu and Sn were also recorded, with a maximum of 1.76 and 0.078% for CON  
384 and PWM respectively. Relatively high concentrations of Cu, Pb and Zn were recorded for  
385 samples taken from sites located in Wales. Particularly high concentrations of Pb were recorded  
386 for all sites, with a maximum of 4.67 wt.% recorded for FRG. Relatively high concentrations  
387 of Zn were also recorded with a maximum of 0.62 wt.% recorded for FRN. Moreover, a number  
388 of these metals and metalloids are determined to be exceeding guideline concentrations (some  
389 substantially) used to trigger risk assessments to protect human and ecological health. As was  
390 recorded to exceed human health guidelines for all sites sampled in SW England and PYM in  
391 Wales, whereas Pb was recorded to exceed both human and ecological health guidelines for all  
392 Welsh mine sites, and also CON, NAN and WHM for ecological risk. Cr, Cu, Zn and Cd were  
393 recorded as exceeding ecological guidelines for almost all sites, and Ni for a number of sites.  
394 As such it can be concluded that all sites comprise significant human health and ecological  
395 risks associated with toxic metal and metalloid concentrations.

396 Although cut-off values are highly specific to the ore and mine setting, a survey of typical cut-  
397 off grades (percentage w/w) for a range of heavy metals indicates that Cu is economic at grades  
398 approximately >0.5%, Zn and Pb at >1% (Environment Agency, 2012) and Ag at >0.02%  
399 (Smith, et al., 1982). A number of sites have yielded metal concentrations above this threshold,  
400 namely: CON (Cu = 1.76%), LEV (Cu = 0.52%), PYM (Cu = 0.92%), EGM (Pb = 2.36%),  
401 FRN (4.67%) and GRG (1.30%). Metal concentrations (wt.%) for individual samples (which

402 were used to create the composites) are displayed in the Supplementary Data. It can be noted  
403 that in general a relatively high variance was recorded between each sample, with a relative  
404 standard deviation (RSD) greater than 100% commonly recorded. This indicates that each mine  
405 waste pile is relatively heterogeneous. It can also be noted that there is a relatively close fit  
406 between the average of these data and the results for the composite sample, with a variance of  
407 <10% typically recorded for each metal. This demonstrates that the composite samples are a  
408 relatively good representation of the individual samples.



409 **Table 3. Notable metal and metalloid concentration data for composite samples from all sites where green cells indicate concentrations above screening**  
 410 **levels for ecological risk<sup>1</sup>; orange indicate those above guideline levels for human health risk<sup>2,3</sup> and red indicate those above both.**

	Li	Na	Mg	Al	K	Ca	Ti	Cr <sup>1,2</sup>	Mn	Fe	Ni <sup>1,3</sup>	Cu <sup>1</sup>	Zn <sup>1</sup>	As <sup>1,2</sup>	Ag	Cd <sup>1,2</sup>	Sn	Pb <sup>1,2</sup>
South west England																		
ALF (wt.%)	0.0233	0.2297	1.4343	5.5579	1.2753	0.1888	0.3367	0.0209	0.2353	10.5592	0.0041	0.1540	0.0426	0.0935	<DL	0.0013	0.0019	0.0120
CAR (wt.%)	0.0132	0.5295	0.3014	6.2791	4.1266	0.8129	0.1141	0.013	0.0474	3.3928	<DL	0.2345	0.0078	0.1219	<DL	0.0002	<DL	0.0023
CON (wt.%)	0.0157	0.3451	0.593	5.1893	0.7046	0.1272	0.2100	0.0108	0.1411	13.6919	0.0016	1.7572	0.0916	0.8293	0.0023	0.0019	0.0238	0.0587
DGC (wt.%)	0.0135	0.4312	0.5295	4.6035	0.8871	1.1426	0.2207	0.0315	0.0610	9.9893	0.0019	0.1833	0.0101	1.9176	<DL	0.0012	0.0290	0.0067
LEV (wt.%)	0.0152	0.3721	1.7030	6.6606	1.9049	0.4451	0.5196	0.0128	0.1433	15.2487	0.0042	0.5168	0.0646	0.2543	<DL	0.0018	0.0216	0.0099
NAN (wt.%)	0.0249	0.3660	0.4250	7.8022	2.2552	0.0806	0.3049	0.0147	0.0354	3.5632	0.0003	0.0126	0.0170	0.0405	<DL	0.0002	0.0039	0.0466
POL (wt.%)	0.0243	0.4456	0.2455	7.2796	3.9765	2.8003	0.1231	0.0105	0.0549	2.7428	0.0004	0.0549	0.0131	0.1059	<DL	0.0001	0.0084	<DL
PWM (wt.%)	0.0119	0.5053	0.5990	6.2204	1.1573	0.0897	0.3126	0.0141	0.0628	6.9515	0.0019	0.0937	0.0254	1.5872	<DL	0.0008	0.0782	0.0120
WHM (wt.%)	0.0098	0.6279	0.6080	5.9665	0.6063	0.0949	0.2704	0.0116	0.0396	11.4857	0.0020	0.0446	0.0680	0.1823	<DL	0.0014	0.0300	0.0386
Wales																		
EGM (wt.%)	0.0138	0.7943	0.9825	7.8934	2.3115	0.4153	0.4998	0.0098	0.0986	4.6388	0.0035	0.2406	0.2103	<DL	<DL	0.0007	<DL	2.3602
FRN (wt.%)	0.0124	0.494	0.3235	2.8913	0.8196	0.1054	0.1758	0.0081	0.017	2.4758	0.0010	0.0337	0.6155	<DL	0.006	0.0016	<DL	4.6662
GRG (wt.%)	0.0145	0.9206	1.0651	8.9666	2.4768	0.5315	0.5331	0.0114	0.1329	4.9254	0.0049	0.0210	0.1948	<DL	<DL	0.0007	<DL	1.3009
PYM (wt.%)	0.0013	0.5467	0.1661	2.7089	1.3942	0.134	0.1600	0.0225	0.0544	27.3302	0.0091	0.9191	0.1494	0.1369	0.0034	0.0052	0.0569	0.9124
WEM (wt.%)	0.0151	0.635	0.5845	6.2005	1.6870	0.0975	0.3769	0.0141	0.0416	3.3651	0.0019	0.0059	0.1797	<DL	<DL	0.0006	<DL	0.6984

411 <sup>1</sup> Proposed Soil Screening Values under the framework for Ecological Risk Assessment (Environment Agency, 2008); <sup>2</sup> Category 4 Screening Values for public open space where there is considered to be a ‘negligible  
 412 tracking back of soil’ (Defra, 2014); <sup>3</sup> Soil Guideline Value for Commercial land use (Environment Agency, 2009a; Environment Agency, 2009b; Environment Agency, 2009c; Environment Agency, 2009d;  
 413 Environment Agency, 2009e). Data on screen levels for ecological risk of As was not available.

## 414 **4.2 Mine waste resource value and hydrometallurgical extraction efficacy**

415 Key elements of economic value at each site (Cu, Zn, Ag, Sn and Pb) are shown in Table 4.  
416 This allows a first estimate of the total economic value for each key element at each site. It  
417 should be acknowledged, however, that this value could not be recovered in practice because  
418 of the limitations of mineral processing and the constraints imposed by the physicochemical  
419 properties of the material. Conversely when estimating the volume of waste in each pile the  
420 average elevation from the area immediately surrounding the waste was used as a baseline,  
421 which has resulted in these estimates being conservative because much of the surrounding  
422 material is unlikely to be at the original elevation and the topography of some sites was  
423 extremely variable. In addition as explained in Section 3.5 the single largest waste pile was  
424 sampled at each site. In many cases additional (but often minor) waste piles were observed at  
425 each site. These piles have not been accounted for both in terms of sample collection (see  
426 Supplementary Data for details) and total waste volume estimation using LiDAR. Moreover,  
427 the accurate sampling of large mine wastes piles is an intrinsically difficult exercise because  
428 the number of samples collected are limited by the resources and time available for any  
429 characterisation programme and the amount collected is never enough to fully characterise the  
430 waste pile (unless the entire waste pile is sampled and characterised). Also due to operational  
431 constraints relatively few samples were taken from each site (see Supplementary Data for  
432 details) and it is therefore almost certain that such samples do not entirely represent the overall  
433 mine waste pile. The results displayed in Table 4 should therefore be considered not as  
434 definitive but rather likely only to be accurate to the nearest order of magnitude.

435 As an indicator of the ease of extraction using conventional hydrometallurgical processes the  
436 recovery of metals in 1 M H<sub>2</sub>SO<sub>4</sub> is also included (Table 5). The greatest Cu value is calculated  
437 for the DGC mine (£1,657,600) where reasonably high value of Sn (£887,000) is also recorded.

438 Relatively high value per tonne of Cu is also calculated for PYM (£32.15/tonne). Zn is not  
439 recorded in appreciable value (>£50,000) for any of the mine sites in the south west of England;  
440 however, relatively high value is estimated for a number of sites in Wales, including FRG  
441 (£1,989,000) and WEM (£104,700). Relatively low Ag value is recorded for all sites in the  
442 south west of England and a number of sites in Wales; however, relatively highly value is  
443 estimated for FRG (£552,400) and PYM (£11.99/tonne). Relatively low Pb value is estimated  
444 for all sites in the south west of England, whereas relatively high value is estimated for all sites  
445 in Wales, with maximum of £1,521,300 calculated for FRG. It can therefore be stated that the  
446 department of value resides with Cu>Sn>Zn>Pb>Ag for the English study sites, whereas it is  
447 Pb>Ag>Zn>Cu>Sn for the Welsh study sites. When comparing these data to ore deposits  
448 (where economically valuable metals are typically present in much greater concentrations and  
449 total mass) it is unlikely that the mine wastes studied would be considered as suitable targets  
450 for resource recovery of the metals alone. However, the study has shown that the metal resource  
451 is present in quantities which are potentially sufficient to offset the costs of site remediation  
452 and rehabilitation. Furthermore the hydrometallurgical extraction data (Table 5) demonstrates  
453 1M H<sub>2</sub>SO<sub>4</sub> as able to solubilise Cu, Zn, As and Pb with reasonably high efficacy (often >20%).  
454 In contrast Ag and Sn were determined as poorly soluble, with <5% dissolution recorded for  
455 all mine wastes. Results therefore demonstrate that strong acids (such as H<sub>2</sub>SO<sub>4</sub>) could be  
456 successfully utilised (even at relatively low concentrations) for the significant removal of acid  
457 soluble metals such as Cu, Zn, As and Pb from UK mine wastes. Following subsequent  
458 recovery (e.g. via electrowinning) the value of such metals could then be utilised to offset a  
459 proportion of the remediation costs.

460 **Table 4. Key elements of economic value at each site displayed in terms of value per tonne**  
461 **and total value per site. Value per tonne was calculated by multiplying current metal**  
462 **price (21/03/2016) of each metal by their concentration in the mine water composite**  
463 **samples. Metals prices used were: Cu = £3498/tonne, Zn = £1249/tonne, Ag =**  
464 **£354,000/tonne, Sn = £11840/tonne and Pb = £1260/tonne. Total value per site was**  
465 **calculated by multiplying value per tonne by estimated total waste mass (from Table 2)**  
466 **and rounded to the nearest £100.**

	Cu	Zn	Ag	Sn	Pb
South west England					
ALF (£/tonne)	5.39	0.53	0.00	0.23	0.15
ALF (£ <sub>tot</sub> )	159,200	15,700	0	6,800	4,500
CAR (£/tonne)	8.20	0.10	0.00	0.00	0.03
CAR (£ <sub>tot</sub> )	28,700	100	n/a	n/a	0
CON (£/tonne)	61.47	1.14	8.29	2.82	0.74
CON (£ <sub>tot</sub> )	2,000	0	300	100	0
DGC (£/tonne)	6.41	0.13	0.00	3.43	0.08
DGC (£ <sub>tot</sub> )	1,657,600	33,600	0	887,000	20,700
LEV (£/tonne)	18.08	0.81	0.00	2.56	0.12
LEV (£ <sub>tot</sub> )	23,400	1,000	0	3,300	200
NAN (£/tonne)	0.44	0.21	0.00	0.46	0.59
NAN (£ <sub>tot</sub> )	8,300	4,000	0	8,600	11,000
POL (£/tonne)	1.92	0.16	0.00	0.00	0.00
POL (£ <sub>tot</sub> )	18,200	1,600	0	0	0
PWM (£/tonne)	3.28	0.32	0.00	9.26	0.15
PWM (£ <sub>tot</sub> )	8,200	800	0	23,200	400
WHM (£/tonne)	1.56	0.85	0.00	3.55	0.49
WHM (£ <sub>tot</sub> )	Unknown	Unknown	Unknown	Unknown	Unknown
Wales					
EGM (£/tonne)	8.42	2.63	0.00	0.00	29.74
EGM (£ <sub>tot</sub> )	Unknown	Unknown	Unknown	Unknown	Unknown
FRG (£/tonne)	1.18	7.69	21.35	0.00	58.79

FRG (£ <sub>tot</sub> )	30,500	198,900	552,400	0	1,521,300
GRG (£/tonne)	0.73	2.43	0.00	0.00	16.39
GRG (£ <sub>tot</sub> )	10,200	33,800	0	0	227,600
PYM (£/tonne)	32.15	1.87	11.99	6.74	11.50
PYM (£ <sub>tot</sub> )	Unknown	Unknown	Unknown	Unknown	Unknown
WEM (£/tonne)	0.21	2.24	0.00	0.00	8.80
WEM (£ <sub>tot</sub> )	9,600	104,700	0	0	410,600

468 **Table 5. Percentage recovery of key elements in 1 M H<sub>2</sub>SO<sub>4</sub> (200 RPM agitation speed,**  
 469 **1:10 solid-liquid ratio and 24 hrs reaction time).**

Site	Cu	Zn	As	Ag	Sn	Pb
<b>South west England</b>						
ALF	21.41	22.30	49.30	n/a	0.00	14.48
CAR	29.79	32.35	71.09	n/a	n/a	42.74
CON	28.33	6.14	60.04	0.31	0.00	3.45
DGC	29.53	18.18	59.70	n/a	0.00	29.85
LEV	77.95	41.81	68.35	n/a	0.00	23.89
NAN	10.83	10.34	49.63	n/a	0.00	5.69
POL	95.27	63.34	106.82	n/a	0.00	n/a
PWM	14.24	7.79	9.05	n/a	3.21	24.41
WHM	21.86	18.70	59.81	n/a	0.00	6.30
<b>Wales</b>						
EGM	11.39	58.19	n/a	n/a	n/a	0.09
FRG	43.37	7.93	n/a	0.06	n/a	0.05
GRG	22.45	34.82	n/a	n/a	n/a	0.19
PYM	65.63	14.10	10.46	0.34	0.00	0.26
WEM	29.76	5.26	0.00	0.00	0.00	0.35

470

471 **4.3 Extent of mine sites in the south west of England and Wales and their association with**  
 472 **geological, ecological and cultural designations**

473 This section focusses on the key considerations which are likely to impact the feasibility of  
 474 mine waste remediation and/or resource recovery processes. This considers the geological,  
 475 ecological or cultural designations that are co-located in areas of mining and how they may act  
 476 as constraints and opportunities for such interventions. This begins with an overview of the  
 477 scale of this co-location in the south west of England and Wales followed by a more in-depth  
 478 examination of the specific reasons for designation in the case study locations.

479 There are 717 non-active metalliferous mines in the south west of England (Appendix C) and  
480 3350 non-active metalliferous mines in Wales (Appendix D. Number of non-active mines by  
481 commodity in each type of geological, ecological and cultural designation in Wales

Commodity	Total number of mines in each designation															
	Total	L N R	N N R	S S SI	S A C	S P A	A W	P H 1	O M H	AO NB	C P	N P	S M	W H S	L H I	More than 1 designa tion (%)
Barytes	3	0	2	2	0	0	0	3	0	0	0	0	0	0	2	2 (67%)
Barytes Lead	4	0	0	0	0	0	0	4	0	0	0	0	0	0	1	1 (25%)
Copper	21 3	2	1 3	5 8	4 1	3	1 6	2 1 2	0	6	4	1 2 0	1 0	0	1 1 7	195 (92%)
Gold	74	0	0	1 7	9	3	7	7 0	0	12	1	6 2	2	0	5 2	74 (100%)
Gold Copper	19	0	0	0	6	0	7	1 8	0	0	0	1 9	0	0	1 8	19 (100%)
Iron Ore	60	0	0	5	3	0	9	5 9	0	1	0	0	1	0	2 0	31 (52%)
Ironstone	17 8	5	0	1 0	8	5	1 0	1 7 7	22	2	4	1 9	0	9	7 5	100 (56%)
Lead	18 47	0	5	4 2 5	2 6 9	2	1 6 0	1 7 9 1	23	375	7	2 6 0	2 7	0	4 7 4	1199 (65%)
Lead Copper	5	0	0	0	0	0	3	5	0	0	0	0	0	0	0	3 (60%)
Lead Copper Zinc	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1 (100%)
Lead Silver	55	0	0	3 1	2 0	0	0	5 4	4	37	0	0	0	0	1	37 (67%)
Lead Silver Copper	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1 (100%)
Lead Zinc	1	0	0	1	0	0	0	1	0	1	0	0	0	0	0	1 (100%)
Manganes e	11 3	0	0	3 1	2 1	1 7	1	1 1 2	0	27	0	7 1	1	0	5 6	112 (99%)
Vein Minerals	77 5	1	1 1	1 0 9	4 8	4 3	1 0 2	7 4 9	3	12	0	7 4	3 5	0	4 4 1	575 (74%)

Zinc	1	0	0	1	0	0	0	1	0	0	0	0	1	0	1	1 (100%)
Grand Total	33 50	8	3 1	6 9 0	4 2 5	1 0 0	3 1 6	3 2 5 8	56	473	1 6	6 2 5	7 7	9	1 2 6 0	2352 (70%)

482 <sup>1</sup>Priority habitat data in Wales is presented as the area within a 1.6 km (1 mile) grid square so the location of the mine cannot be said to be  
483 accurately co-located with the habitats. SSSI=Site of Special Scientific Interest, AW=Ancient Woodland, PH=Priority Habitat PH,  
484 OMH=Open Mosaic Habitat on Previously Developed Land, SAC=Special Area of Conservation (European), SPA=Special Protection Area,  
485 AONB=Area of Outstanding Natural Beauty, NP=National Park, CP=Country Park, SM=Scheduled Monument, WHS=World Heritage Site,  
486 Landscape of Heritage Interest; Sources: mine data from BRITPITS Licence No. 2014/098BP ED British Geological Survey © NERC. All  
487 rights reserved. All other data © Natural Resources Wales copyright. Contains Ordnance Survey data © Crown copyright and database right  
488 2016.D). These are predominantly located in Sn and Cu mining areas of Cornwall (n=456), the  
489 As and Cu areas of Devon (n=49), the Pb and Zn areas of North East and Central Wales  
490 (n=2470), the Cu, Zn, Pb and Fe areas of North West Wales (n=819), and the ironstone regions  
491 of South Wales (n=45) and Gloucestershire (n=102). The majority of mine sites in SW England  
492 (68%) and Wales (72%) are co-located with at least one designation.

493 There are mines located on many of the designated sites in both SW England and Wales.  
494 However, numbers are generally small for ecological or geological designations compared with  
495 the total number of designated sites in the region (Table 6). Despite this, in some cases the  
496 proportion of the area of such designations that are co-located with mines is much greater due  
497 to a few very large sites such as, for example, Exmoor Heath (10,000 ha), Plymouth Sounds  
498 (6,000 ha) and Dorset Heath (5,000 ha) SACs and Dorset Heathlands SPA (8,000 ha).  
499 Similarly, in Wales, despite only 8% of SSSIs being co-located with mines they account for  
500 71% of the area of SSSIs, this is due to four very large sites of over 19,000 ha: Berwyn,  
501 Elenydd, Eryri and Migneint-Arenig-Dduallt (which are also SACs and/or SPAs). In Wales,  
502 there is a disparity between this effect for the SSSIs and European sites where a relatively  
503 modest proportion of area are co-located with mine sites due to the inclusion of far larger areas  
504 of coastal sites (e.g. Liverpool Bay, Cardigan Bay). It is not possible to discern from this  
505 overview whether the SSSI sites are designated for their geology or ecology or whether the



506 LNRs, NNRs, SSSIs, SACs and SPAs are designated due to species and habitats that are  
507 intrinsically linked to the mining activities or whether they are coincidental to it. In the  
508 examples highlighted here the designations are not specifically linked to the presence of mine  
509 wastes. This is important as resource recovery could have a positive or a negative impact  
510 depending on the reasons for designation and this will be discussed in Section 4.4.

511 Regarding priority habitats co-located with the mine waste it is possible in some circumstances  
512 to discern whether these are intrinsically linked to the presence of the mine waste. In SW  
513 England the largest number of mines are co-located with priority habitats other than OMH  
514 which are unlikely to be dependent on the characteristics of the mine waste and may even be  
515 negatively impacted by it. Although these habitats do not receive statutory protection local  
516 authorities are expected to consider their protection and enhancement in local planning policies.  
517 Resource recovery might therefore offer an opportunity for these habitats to be restored or  
518 enhanced if combined with remediation. Overall, 13 priority habitats are co-located with mine  
519 sites in SW England, but in terms of area this only accounts for 0.6% of priority habitats. The  
520 greatest number of mines were located on Deciduous Woodland (n=215), with less than 15 on  
521 the other 12 types. In Wales around 7% of priority habitats are co-located with mines. However,  
522 in Wales, with the exception of OMH, the priority habitat data is not represented as polygons  
523 but as 1.6 km grid squares indicating the presence of the habitat, each grid square then details  
524 the area covered by the habitat within this but the exact boundaries are not available. This  
525 means that mine sites appear to be co-located with several habitats and this has inflated the  
526 proportion of habitats co-located with mines. There were 3741 priority habitats co-located with  
527 almost all of the metalliferous mines in Wales (n=3258). As with SW England, the greatest  
528 number in Wales were on Broadleaved Woodland (n=2517). There were also substantial  
529 numbers co-located with Lowland Dry Acid Grassland (n=1608), Lowland Dry Heathland  
530 (n=1294) and Purple Moorgrass and Rush (n=1127). In both SW England and Wales a greater

531 proportion of mine sites are co-located with OMH at 4% and 7%, respectively. This is not  
532 surprising given that this priority habitat is explicitly focussed on brownfield and previously  
533 developed sites, including mine wastes, and was in part based on an analysis of the BRITPITS  
534 data (Lush, et al., 2013). These sites are much more likely to be adversely affected by any  
535 resource recovery as they have developed over time due to the edaphic conditions on site so an  
536 alteration of these may change the species assemblages present.

537 A far greater number of mines are co-located with areas of cultural significance representing  
538 both the rural landscapes together with the mining history of SW England and Wales. It is often  
539 impossible to disentangle the role of mining in some of the cultural designations. For example  
540 although AONBs and National Parks are not necessarily recognised for their mining activity  
541 *per se*, they are representative of the landscape character and cultural history of an area (e.g.  
542 mining is specifically mentioned in Cornwall and Tamar Valley AONB; Cornwall and Tamar  
543 AONB, 2015). The cultural designations generally operate at the landscape scale hence the  
544 large proportion of area co-located with mines for AONBs, National Parks and the World  
545 Heritage Sites (Table 6) demonstrating the ubiquity of mining in the heritage in these areas.  
546 There are two World Heritage Sites associated specifically with the mining heritage: the  
547 Blaenavon Industrial Landscape, which is recognised for the coal and ironstone mining activity  
548 and associated industries in south Wales; this makes up the vast majority of area of WHS in  
549 Wales (other two are castles and an aqueduct) and the Cornwall and West Devon Mining  
550 Landscape in SW England. Similarly, many of the Welsh mines are in the landscapes of historic  
551 interest designated by Natural Resources Wales.

552 This spatial analysis demonstrates the significance of the mining legacy in SW England and  
553 Wales and its complex interaction with geological, ecological and cultural designations. It also  
554 illustrates that the decision as to whether to recover resources from former mine sites is likely

555 to be dependent on a range of factors outside of the economic viability of such an endeavour  
 556 and that these can only be determined at the site level.

557 **Table 6. Total number and area of designations in the south west of England and Wales,**  
 558 **those co-located with mine sites and the number of metalliferous mine sites in each**  
 559 **designation**

Designation	Total number (area/ha)	Number (area/ha) co-located with mine sites <sup>1</sup>	Percentage of sites (area) co- located with mine sites	Number of mines located within the boundary of the designated area
<i>South west of England</i>				
<i>Geological or ecological</i>				
LNR	185 (4242)	5 (327.5)	3% (8%)	11
NNR	51 (13,980)	1 (61.4)	2% (0.4%)	1
SSSI	975 (201,077)	22 (24,686)	2% (12%)	69
SAC	74 (319,298)	9 (27,409)	12% (9%)	44
SPA	16 (72,344)	1 (8186)	6% (11%)	3
AW	4287 (74,648)	17 (7716)	0.4% (10%)	68
PH <sup>2</sup>	26 (457,173)	14 (2733)	54% (0.6%)	173
OMH	1004 (7481)	39 (321.0)	4% (4%)	52
<i>Cultural</i>				
AONB	15 (9098)	7 (5197)	47% (57%)	203
NP	3 (167,844) <sup>a</sup>	2 (164,822)	67% (98%)	40
SM	7010 (15,060)	12 (206.9)	0.2% (1%)	23
WHS	4 (30,170)	1 (19,719)	25% (65%)	198
<i>Wales</i>				
<i>Geological or ecological</i>				
LNR	93 (6134)	6 (438.1)	6% (7%)	8
NNR	72 (25,504)	5 (2295)	7% (9%)	31
SSSI	1064 (183,435)	80 (129,934)	8% (71%)	690
SAC	99 (683,541)	22 (94,742)	20% (14%)	425
SPA	23 (681,395)	5 (75,467)	22% (11%)	100
AW	48,614 (94,941)	199 (2144)	0.4% (2%)	357
PH <sup>4</sup>	71,237 (480,495)	3741 (32,386)	5% (7%)	3258
OMH	1034 (6,561)	23 (451.5)	2% (7%)	53
<i>Cultural</i>				
AONB	5 (107,268)	3 (76,822)	60% (72%)	473
NP	3 (410,349)	3 (410,349)	100% (100%)	625
CP	37 (4267)	5 (1428)	14% (33%)	16
SM	4180 (6248)	32 (318.0)	1% (5%)	77
WHS	3 (3401)	1 (3290)	33% (97%)	9
LHI	58 (426,005)	30 (265,765)	52% (62%)	1260

560 <sup>1</sup> Caution should be used when using these figures as not all mines are represented in BRITPITS and the point locations are not necessary in  
561 the same location as mine wastes; <sup>2</sup> Refers to broad habitats as opposed to individual sites; <sup>3</sup> Includes a small portion of New Forest; <sup>4</sup> Priority  
562 habitat data in Wales is presented as the area within a 1.6 km (1 mile) grid square so the location of the mine cannot be said to be accurately  
563 co-located with the habitats. Sources: mine data from BRITPITS Licence No. 2014/098BP ED British Geological Survey © NERC. All rights  
564 reserved. Local Nature Reserve (LNR), National Nature Reserve (NNR), Site of Special Scientific Interest (SSSI), Special Area of  
565 Conservation (SAC), Special Protection Area (SPA), Ancient Woodland (AW), Priority Habitat (PH), Open Mosaic Habitat on Previously  
566 Developed Land (OMH), Area of Outstanding Natural Beauty (AONB) and National Park data for England © Natural England copyright.  
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569 contained in this material was obtained on 29<sup>th</sup> June 2015. The most publicly available up to date Historic England GIS Data can be obtained  
570 from HistoricEngland.org.uk. All other data © Natural Resources Wales copyright. Contains Ordnance Survey data © Crown copyright and  
571 database right 2016.

#### 572 **4.4 Geological, ecological and cultural considerations at the case study sites: opportunities** 573 **and constraints to resource recovery and reclamation**

574 All of the case study sites have some form of recognition either for their potential or known  
575 geological, ecological or cultural resources (Table 7). These can provide an opportunity for  
576 resource recovery or a constraint against it. For example, if mine waste is negatively impacting  
577 on ecological or cultural receptors that are not dependent on the characteristics of the mine  
578 waste then this could provide a powerful argument for resource recovery, decontamination  
579 and/or recovery of land value resource. However, some mine wastes have rare geological or  
580 ecological features or are valued for their cultural heritage and these could act as a constraint  
581 to reclamation if the existence of these features were to be adversely affected by such activities.

582 Taking potential constraints first several of the sites are co-located with ecological designations  
583 that are directly related to the presence of mine wastes. In SW England CAR and POL are  
584 protected for their metallophytic bryophytes (liverworts and mosses) (Natural England, 1999a)  
585 as SSSIs. Bryophytes are adapted to Cu-rich substrates and include a number of internationally  
586 and nationally rare species, including one, *Cephaloziella integerrima*, which has only been  
587 recorded at two other sites since 1950 (Natural England, 1999b). CAR is also designated as a

588 SAC for its Calaminarian grasslands of the *Violetalia calaminariae* (JNCC, 2015), recognised  
589 as one of the best in the UK and, globally, is one of only two known sites of the Cornish path-  
590 moss *Ditrichum cornubicum*, which is protected under the Wildlife and Countryside Act (1981)  
591 (Natural England, 1999a).

592 In Wales too, GRG and PYM are co-located with SSSIs, also designated for their bryophyte  
593 communities (Natural Resources Wales, 2004; Carmarthenshire County Council, n.d.a,b;  
594 Countryside Council for Wales, 1995, 1999). In addition, GRG is co-located with a SAC for  
595 its unique assemblage of metallophyte lichens (Calaminarian grasslands of the *Violetalia*  
596 *calaminariae*), one of which, *Epigloea filifera* has not been reported anywhere else in Britain  
597 (Natural Resources Wales, 2004). The SSSI at PYM has over 125 lichen species and includes  
598 a *Lecidea* which is unique in Britain and possibly a new species (Countryside Council for  
599 Wales, 1995).

600 The designation at GRG is also both a SAC and SSSI for its alluvial shingle deposits which are  
601 associated with a mosaic of habitats including heathland communities not usually found in  
602 England or Wales. These support nationally scarce species of beetle and others the latter of which  
603 are protected under the Wildlife and Countryside Act (1981) and European Council Directive  
604 92/43/EEC on the conservation of Natural Habitats and of Wild Fauna and Flora (Countryside  
605 Council for Wales, 1999; Natural Resources Wales, 2004).

606 The SSSIs at GRG and PYM, together with that at FRG are also designated for their geological  
607 characteristics. This includes mineralisations of the waste at FRG and PYM which are unique  
608 to Britain (Countryside Council for Wales, 1995; 1999). At GRG the fluvial geomorphology is  
609 characterised by an actively braiding river system which may be linked to the mining activity  
610 (Countryside Council for Wales, 1999).

611 In addition, six of the case study sites have been identified as potential OMH sites (ALF, CON,  
612 DGC, NAN, POL and WHM) although three of these, CON, POL and WHM, fall on the same  
613 OMH. The inclusion of OMH requires some caution as the initial inventory for these sites has  
614 been predominantly based on an analysis of previous land uses (e.g. BRITPITS and the  
615 National Land Use Database for Previously Developed Land) and aerial imagery. Therefore an  
616 ecological survey would need to be carried out to ascertain the presence of an OMH (Lush et  
617 al., 2013).

618 These designations have the potential to act as a significant constraint to resource recovery,  
619 specifically the management plan for one SSSI highlights that “care must be taken during  
620 preservation or derelict land operations to safeguard the specialised conditions the plants  
621 require” (Natural England, 1999b). This means that any activities that changed either the  
622 physical or chemical characteristics of the waste are likely to be met with opposition. Many of  
623 the species are dependent directly on the elevated metal concentrations in the spoils (Batty,  
624 2005) or tolerant of them. The removal of the metals would reduce the toxicity of the spoils to  
625 other vegetation types which could then colonise the spoils potentially to the detriment of these  
626 rare species.

627 Turning to the historic environment designations, all of the case studies in SW England, except  
628 ALF, fall within the Cornwall and West Devon Mining Landscape World Heritage Site. This  
629 World Heritage Site was designated in 2006 in recognition of the “contribution the area made  
630 to the industrial revolution and formative changes in mining practices around the world”  
631 (UNESCO, 2006, p. 155). The designation also specifically recognises the significant  
632 ecological resources linked to this mining activity in the “distinctive plant communities of waste  
633 and spoil heaps and estuarine areas” (UNESCO, 2006, p. 155). In addition there are numerous  
634 listed buildings (not discussed here) and SMs that are individually protected for their

635 contribution to the mining landscape. Two sites, DGC and PWM are co-located with SMs  
636 whilst CAR is adjacent to one. These are protected for various built features including transport  
637 infrastructure, mine shafts, pumping engine houses and processing infrastructure (Historic  
638 England, 2002a,b; Historic England, 2006). Interestingly the Prince of Wales Mine at  
639 Harrowbarrow Scheduled Monument specifically recognises the importance of the mine wastes  
640 as a record of the technologies in use at the time and as landmarks (Historic England, 2006).

641 None of the case study sites in Wales are in the Blaenavon Industrial Landscape World Heritage  
642 Site. However, all of them fall in one of three landscapes of historic interest (Table 7). All are  
643 recognised for their land management activities including agriculture and forestry but have a  
644 strong association with past mining (Dyfed Archaeology, n.d.a,b; Cadw, Welsh Assembly  
645 Government, Countryside Council for Wales, 2007). Although not receiving of a legal  
646 protection these landscapes are protected under planning policy from development that might  
647 have an adverse impact on their character (Welsh Government, 2016, para.6.5.25). In addition  
648 there are several SMs associated with mining activity on the FRG and PYM sites (RCAHMW,  
649 2000, 2004, 2008) as well as many individual aspects of the mining infrastructure including  
650 the sublimation chambers and kilns at PYM (RCAHMW, 2007).

651 As already mentioned the mining landscapes have the potential to provide substantial economic  
652 benefits. Prior to its WHS designation the Devon and Cornwall mining landscape generated  
653 significant tourism industry and associated revenue to the local economy (Atlantic Consultants,  
654 2003), given that designations can play an important role in tourists choice to visit an area  
655 (Reinus & Fredman, 2007; Selman, 2009) and the increase in heritage tourism in recent decades  
656 (Williams & Shaw, 2009) this is likely to have increased since the designation.

657 In terms of cultural designations not dependent on the mining activity none of the case study  
658 mines fell in the National Parks of SW England and Wales or AONBs in Wales despite the

659 large land areas occupied by these designations. However, in SW England two case study sites  
660 are in AONBs: LEV and DGC. AONBs are designated in recognition of the area's landscape  
661 character, historic and natural environments. So although they are not specifically dependent  
662 on the mining legacy both the Tamar Valley and Cornwall AONBs recognise the significance  
663 of the mining heritage within their wider landscape (Cornwall AONB, 2011; Tamar Valley  
664 AONB, 2014) but would also be protective of contamination impacting on the natural  
665 environment.

666 The value placed on heritage features is not straightforward. Whilst cultural aspects are valued  
667 by the public (Swanwick, 2009; Howley, 2011), landscapes perceived as 'natural' or 'unspoilt'  
668 are often preferred (Swanwick, 2009). The value of heritage features is subject to temporal  
669 changes, with features becoming increasingly important over time (English Heritage, 2008).  
670 Landscape quality is inherently subjective and different groups have different preferences  
671 (Swanwick, 2009). Although designations such as AONBs and National Parks in SW England  
672 and Wales explicitly recognise the contribution of the mining heritage to the overall landscape  
673 the individual features including wastes can also be perceived to have a detrimental impact on  
674 the quality of landscape (English Heritage, 2008). Conversely, inappropriate restoration can  
675 also do more harm than good from both a nature conservation and landscape perspective. The  
676 Cornwall AONB has been estimated to generate bring in 4.5 million visitors to Cornwall  
677 estimated to spend £1.5 billion (Cornwall AONB, 2011). Therefore any activities on mine sites  
678 need to balance the potential negative impacts on these designations. Resource recovery is  
679 likely to be dealt with under mineral planning, permission for which takes into account whether  
680 planned activities will have adverse effects on ecological systems, historic environments and  
681 human health (DCLG, 2012; Welsh Government, 2016). Therefore the co-location of many  
682 waste sites with designated areas that may be detrimentally affected by resource recovery is a  
683 significant constraint.



684 Turning to the potential opportunities for resource recovery to enhance or restore the ecological  
685 or cultural resources none of the case study mines in are co-located with sites protected for  
686 their geological or ecological characteristics not related to their mining legacy. However, DGC  
687 is adjacent to an ancient woodland; Clitters Wood. Several of the sites are co-located with or  
688 adjacent to priority habitats: ALF, WHM and NAN with Lowland Heathland, and WHM and  
689 PWM with Deciduous Woodland. In Wales all sites are co-located with at least three priority  
690 habitats (Table 6), but as already discussed these habitats overlap in the data. Ecological  
691 surveying and risk assessment would be necessary to determine whether priority habitats are  
692 affected by the mine sites. These habitats do not receive statutory protection *per se* but they are  
693 protected under planning policy (DCLG, 2012; Welsh Government, 2016). As Table 3  
694 demonstrates all of the case study sites have wastes with concentrations, particularly Cd, Cu  
695 and Zn, that may pose a risk to specified ecological receptors (e.g. SSSIs, SPAs, SACs,  
696 AONBs, National Parks), and this is likely to be the case across many of the abandoned mine  
697 wastes in the UK. They may also be impacting on aquatic ecology through mine water  
698 discharges (Mayes, et al., 2009) or other designated terrestrial ecological receptors not co-  
699 located with the mine waste through the mobilisation of pollutants in water or food-chain  
700 transfer. The potential risk to ecological receptors is likely to add weight to the case for  
701 remediation and therefore act as an opportunity for resource recovery as a means of remediating  
702 the waste.

703 It is clear from this study that there is substantial variation between mine wastes in terms of  
704 their characteristics and the context in which they are situated. A multitude of different  
705 perspectives will need to be sought when considering their long term management and whether  
706 resource recovery is appropriate. This will need to balance the requirements of a range of  
707 stakeholders and disciplines including environmental scientists, heritage professionals,  
708 ecologists and representatives from the different management bodies and regulators associated

709 with these designations (Selman, 2009). It should also be recognised that land managers,  
710 experts and the general public may have very different preferences in terms of the future of  
711 such sites and these views will also need to be considered (Bloodworth et al., 2009; English  
712 Heritage, 2008; Howard, et al., 2015; Selman, 2009; Swanwick, 2009). Human Ecology  
713 Mapping (HEM) approaches offer promising spatial data gathering and analytical tools that  
714 may enable the views of multiple stakeholders to be considered (McLain, 2013). These  
715 methods, particularly “sense of place” (see Williams, 1998) might be useful in examining the  
716 resources and values of metalliferous mine sites integrating a spatial dimension with the  
717 human-landscape connection. Ultimately, the decision to recover resources from mine wastes  
718 needs to balance the potential negative impacts on geological, ecological and cultural  
719 designations with any positive impacts on those not explicitly dependent on the mining  
720 heritage.

721 There are a number of limitations to the spatial analysis. First, the sampling campaign found  
722 that the mine locations in BRITPITS are not always in the same place as the waste. This means  
723 that there are uncertainties over the co-location of the sites. This is particularly important for  
724 smaller sites such as SSSIs and OMHs. Therefore the large scale analysis presented here is  
725 probably a conservative estimate of the designations linked to mining activity and, as already  
726 highlighted, detailed analysis of the specific sites in question needs to be undertaken. Some  
727 ecological and cultural designations have not been included in this study as no national level  
728 datasets are available. Similarly, the impact of mine wastes on water quality and any  
729 downstream ecological receptors was also not examined here. These, again, illustrate the need  
730 for site analysis and the involvement of a range of stakeholders including those from the local  
731 area (Mayes, et al., 2009; Howard, et al., 2015; Selman, 2009).

**Table 7 Ecological and cultural designations co-located with the case study mine wastes in the south west of England and Wales**

Case study	Potential opportunities				Potential constraints	
	Reduce risks to water quality and/or human health	Resource recovery (£ <sup>a</sup> )	Geological and ecological designations	Cultural designations	Geological and ecological designations	Cultural designations
South west of England						
ALF		186,200	Lowland heathland PH.		OMH.	
CAR	West Caradon MWD site potential water pollution.	28,800			Phoenix United Mine and Crow's Nest SAC; Crow's Nest SSSI; PH due to SSSI but no main habitat type.	Caradon Mining District in the Cornwall and West Devon Mining Landscape (CWDML) WHS; adjacent to South Caradon 19 <sup>th</sup> century copper mine SM.
CON		2,457			OMH.	Gwennap Mining District in the CWDML WHS.
DGC	MWD site potential water pollution.	2,598,900	Adjacent to Clitters Wood AW.	Tamar Valley AONB.	OMH.	Early 20 <sup>th</sup> Century arsenic works at Devon Great Consols Mine SM; Tamar Valley Mining District in the CWDML WHS.
LEV		27,900		Cornwall AONB.		St. Just Mining District in the CWDML WHS.
NAN		31,900	Adjacent to Lowland heathland PH.		OMH.	Caradon Mining District in the CWDML WHS.
POL		19,800			OMH; West Cornwall Bryophytes SSSI.	Gwennap Mining District in the CWDML WHS.
PWM	MWD site potential water pollution.	32,600	Adjacent to Deciduous woodland PH.		OMH.	Prince of Wales Mine at Harrowbarrow SM; Tamar Valley Mining District in the CWDML WHS.

WHM	MWD site potential human and health risk water pollution.	Unknown	Lowland heathland PH.		OMH.	Gwennap Mining District in the CWDML WHS.
Wales						
EGM	MWD site potential water pollution.	Unknown	Blanket Bog (BB); Lowland Dry Acid Grassland (LDAG); Lowland Dry Heathland (LDH); Lowland Wet Heathland (LWH); Purple Moorgrass and Rush Pastures (PMRP)			Upland Ceredigion LHI
FRG	MWD site potential water pollution.	2,303,100	LDAG; LDH; PMRP		Adjacent to Mwyngloddfa Frongoch SSSI	Adjacent to Frongoch Lead Mine SM; Upper Ceredigion LHI
GRG		271,600	Arable Land; BB; Broadleaved Woodland (BW); Coastal and Floodplain Grazing Marsh (CFGM); LDAG; LDH; PMRP		Grogywnion SAC, Gro Ystwyth SSSI	Upper Ceredigion LHI
PYM	MWD site potential water pollution.	Unknown	BW; Fen (basin, valley and floodplain mire); Fen (swamp); LDAG; LDH; LWH; PMRP		Mynydd Parys SSSI	Parys Mountain Windmill Engine House, Precipitation Pits and Great Opencast SM, Mona Mine and Sublimation Chambers, Mynydd Parys SM, Amlwch and Parys Mountain LHI.

WEM	MWD site potential water pollution.	524,900	BB, BW; CFGM; LDAG; LDH; PMRP			Upland Ceredigion LHI.
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733 <sup>a</sup> Estimated total value of Cu, Zn, Ag, Sn and Pb at each site; Sources: mine data from BRITPITS Licence No. 2014/098BP ED British Geological  
734 Survey © NERC. All rights reserved. Mine Waste Directive (MWD) inventory data © Environment Agency copyright. Contains Ordnance Survey  
735 data © Crown copyright and database right 2016; Local Nature Reserve (LNR), National Nature Reserve (NNR), Site of Special Scientific Interest  
736 (SSSI), Special Area of Conservation (SAC), Special Protection Area (SPA), Ancient Woodland (AW), Priority Habitat (PH), Open Mosaic Habitat  
737 on Previously Developed Land (OMH), Area of Outstanding Natural Beauty (AONB) and National Park data for England © Natural England  
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739 England © Historic England 2016. Contains Ordnance Survey data © Crown copyright and database right 2016. The Historic England GIS Data  
740 contained in this material was obtained on 29<sup>th</sup> June 2015. The most publicly available up to date Historic England GIS Data can be obtained from  
741 HistoricEngland.org.uk; All other data © Natural Resources Wales copyright. Contains Ordnance Survey data © Crown copyright and database  
742 right 2016.

## 743 **5. Decision making tools and technology options for intervention**

### 744 **5.1. Decision making tools for optimising resource value**

745 As discussed above legacy metalliferous mining waste sites have multifaceted value and  
746 resource associated with them. This results in the selection of the strategy for optimising  
747 resource value being a non-trivial problem and requires the consideration of a number of  
748 competing criteria to allow identification of appropriate approaches. In similar multi-criteria  
749 problems various decision support frameworks have been developed, many being based on  
750 Multi Criteria Decision Analysis (Wang, 2014), it is proposed that such an approach can be  
751 adopted here.

752 In many environmental problems the criteria considered are classified within a sustainability  
753 assessment framework under three areas or pillars, namely: economic, environmental and  
754 social issues (Pettit et al., 2011). However, for the problem considered here it is necessary to  
755 also consider the technical aspects of resource recovery from wastes. In the proposed approach  
756 three MCDA methods are adopted: simple ranking method, Analytic Hierarchy Process (AHP)  
757 and Compromise Programming, this allows either the individual use of one or the sequential  
758 use of all to allow sensitivity analysis to be undertaken (Pettit et al., 2011). Typical criteria that  
759 can be used are listed in Table 8. The particular criteria considered and their method of  
760 assessment will depend on the nature of the particular site or inventory of sites considered.  
761 However, it can be seen that many of the environmental and social criteria can be directly  
762 related to the various ecological and cultural designations listed in Table 1, for example cultural  
763 receptor criteria can be linked to, for example, AONB, NP and LHI data and ecological receptor  
764 criteria to, for example, SAC, PH and SSSI data.

765 **Table 8. Examples of decision criteria**

<b>Environmental</b>	<b>Economic</b>	<b>Social</b>	<b>Technical</b>
Ecological receptors	Capital Cost	Public acceptance	Feasibility
Human receptors	Operating Costs	Cultural receptors	Infrastructure
Emissions to Water	Value of resource	Amenity use	Safety
Emissions to air	Land values	Health impacts	
Impacts on unique fauna/flora habitats	Reduced financial liability / risk	Nuisance	
Impact on landscape		Employment	

766

767 It is suggested that this methodology will be applied for two main purposes. This first of these  
 768 is site specific and will aid comparison between different options and scenarios. For example,  
 769 the choice between various ex-situ and in-situ remediation technologies can be made and  
 770 compared against a ‘do-nothing’ scenario. The second purpose is to allow inventory appraisal  
 771 where a number of sites at a regional or national inventory scale can be ranked for potential  
 772 resource recovery and also enable classification of an anthropogenic deposit as a reserve or  
 773 resource.

774 **5.2. Technology options for resource recovery from metal mine wastes**

775 It has been demonstrated that many historic UK metal mine sites comprise  
 776 environmental/landscape resources in their existing state. However, in light of stricter future  
 777 legislation associated with the European Union Water Framework Directive it is likely that  
 778 intervention (namely for pollution control) will need to be implemented in the future at many  
 779 sites. Given the multifaceted resource value of metal mine sites, these interventions need to be

780 sensitive to the existing resource (as indicated by the site designations presented) and/or  
781 enhance the resource value of the sites, for example by protecting or enhancing industrial  
782 heritage. Thus the cost-benefit analyses might include the reduced cost of remediation when  
783 including metal resource recovery and the additional benefits might include preservation,  
784 protection and enhancement of industrial heritage with the possible tourist revenue generation  
785 that may arise. The methodology proposed by (Conesa, et al., 2008), which strives to protect  
786 the cultural heritage components of metal mine sites whilst rehabilitating the site from an  
787 environmental perspective, is suggested as a useful approach, and it could be extended to  
788 include metal resource recovery.

789 If the resource comprises the mine site in its current form then remediation for pollution  
790 mitigation would have to be done either through established *in situ* techniques for preventing  
791 or reducing infiltration, reducing leachability and waste stabilisation or containment, *ex situ*  
792 techniques could only be applied where the impact was minimal and the site could be  
793 rehabilitated to a condition satisfying the appropriate stakeholders.

794 Where the metals present are one of the resources to be recovered from the site then an  
795 important processing decision is whether the mine wastes can be excavated. If this is an option  
796 for the site then a wide range of standard processing routes are available for separation,  
797 comminution, concentration and/or recovery metals from excavated materials. For example,  
798 gravity separation methods might in some cases be applied to separate metal-bearing minerals  
799 from gangue minerals which can be returned to site. Metals can then be recovered from the  
800 metal-bearing concentrate using established hydrometallurgical, biohydrometallurgical or  
801 pyrometallurgical approaches.

802 If physical separation is not an option e.g. for cost reasons or because of mineralogy and metal  
803 deportment is not favourable, then the hydrometallurgical and/or biohydrometallurgical



804 techniques of heap (or dump) leaching may be of particular utility for the removal of metals  
805 from mine wastes and tailings. These techniques are routinely used in the mining industry for  
806 recovery of metals (e.g. Cu, Au) from low grade ores. Material is placed on to an impermeable  
807 liner system and a lixiviant is recirculated through the pile, metals are recovered from the metal-  
808 rich “pregnant” liquor. Where material is fine (e.g. tailings) then the material can be  
809 agglomerated prior to heap leaching to improve subsequent recovery. Similar methods such as  
810 soil flushing have been adopted for decontamination of soils and sediments (Leštan, 2008;  
811 Seidel, 1998) - these parallel methods are essentially only different in their aim: metals  
812 recovery or decontamination and thus are applicable within the context discussed here.

813 *In situ* approaches for metal recovery could be attractive given the constraints for mine site  
814 reclamation discussed above, and in this context could under certain conditions be considered  
815 as a more “passive” remediation option (see Cundy, 2013). Phytoremediation (or phytomining  
816 depending on context) is an established *in situ* technology, however the process is very low  
817 intensity and intervention is still required for periodic harvesting, processing of the biomass for  
818 metal recovery also requires significant further processing. *In situ* heap/dump leaching and  
819 metals recovery is a promising option but requires that the material to be flushed overlies an  
820 impermeable stratum or engineered barrier. A pump and treat system can then be applied to  
821 ensure capture of the effluent downstream in collection boreholes/trenches without resulting in  
822 secondary pollution. A compromise may be to capture and recover metals already being  
823 released from sites in mine drainage. Low intensity metal capture are being developed for the  
824 “passive” treatment of metalliferous mine waters. Such systems use a variety of  
825 (bio)geochemical engineering approaches to achieve immobilisation of metals, including:  
826 precipitation, adsorption, microbiological reduction or oxidation and pH manipulation. Thus  
827 these technologies potentially offer low intensity harvesting of metals from legacy mine waste  
828 and would simultaneously achieve: (i) eventual decontamination of the mine waste, (ii)

829 protection of the environment from metal pollution and (iii) recovery of the metals. However,  
830 further research is required to design systems that capture metals in forms that are directly  
831 amenable to recycling.

## 832 **6. Conclusions and implications**

833 There are numerous drivers for the reclamation of legacy mine sites. Many wastes are likely to  
834 be causing significant breaches of water and soil quality guidelines in the UK and the  
835 mobilisation of these pollutant metals may be negatively impacting surrounding ecosystems.  
836 When considering site reclamation strategies a balance needs to be achieved, however, between  
837 protecting human, water and ecological receptors that may be at risk from metal pollution from  
838 mine wastes and designations that are dependent upon it. In addition, the simultaneous recovery  
839 of economically valuable metals from the mine wastes during site remediation may provide a  
840 useful mechanism to offset the cost of such activity.

841 This study has determined the physical and chemical composition of several prominent legacy  
842 metalliferous mine tailing waste piles in SW England and Wales across a range of parameters,  
843 including metal content, mineralogy, paste pH, particle size distribution, total organic carbon  
844 and total inorganic carbon. The co-location of cultural and ecological designations with the  
845 mine wastes have also been determined. The following can be concluded:

- 846 1) Several mine wastes investigated contain a number of different economically valuable  
847 metals (namely Cu, Pb and Sn) at concentrations close to or greater than typical  
848 minimum ore grade;
- 849 2) Several mine wastes investigated contain a number of different pollutant metals  
850 (namely Cr, Ni, Zn, As, Cd, Pb) at concentrations exceeding Soil Guideline Values;  
851 and

852 3) Most of the case study sites receive some form of protection either due to their historical  
853 significance, rare species assemblages or geological characteristics which may limit the  
854 potential for resources recovery and rehabilitation.

855 Results demonstrate that it is unlikely that the potential economic gain of extracting  
856 valuable metals from the mine waste will constitute a sole driver for intervention. Instead  
857 it is suggested that this value could be considered as a useful mechanism to offset site  
858 rehabilitation costs. A substantial number of mine sites in SW England and Wales are co-  
859 located with cultural or ecological designations, many of them due to the mining activities.  
860 These unique geological, ecological and cultural resources will act as a significant  
861 constraint to mine waste remediation and site reclamation if the existence of these features  
862 were to be adversely affected by such activities. This paper has demonstrated that an  
863 integrated assessment methodology for assigning and evaluating resource value is  
864 necessary to allow appropriate evaluation of resource potential. It is clear that further work  
865 is urgently required to apply similar holistic resource value determination approaches at  
866 other legacy mine sites in the UK and world-wide. This will enable the establishment of a  
867 reliable methodology for the quantitative assignment of resource value (economic, cultural,  
868 environmental, etc.) at such sites. In turn this will enable prioritisation of mine sites in most  
869 urgent need of rehabilitation, but also enable such rehabilitation and remediation processes  
870 to be conducted via methodology that is both at appropriate cost and disturbance to existing  
871 environmental and cultural designations.

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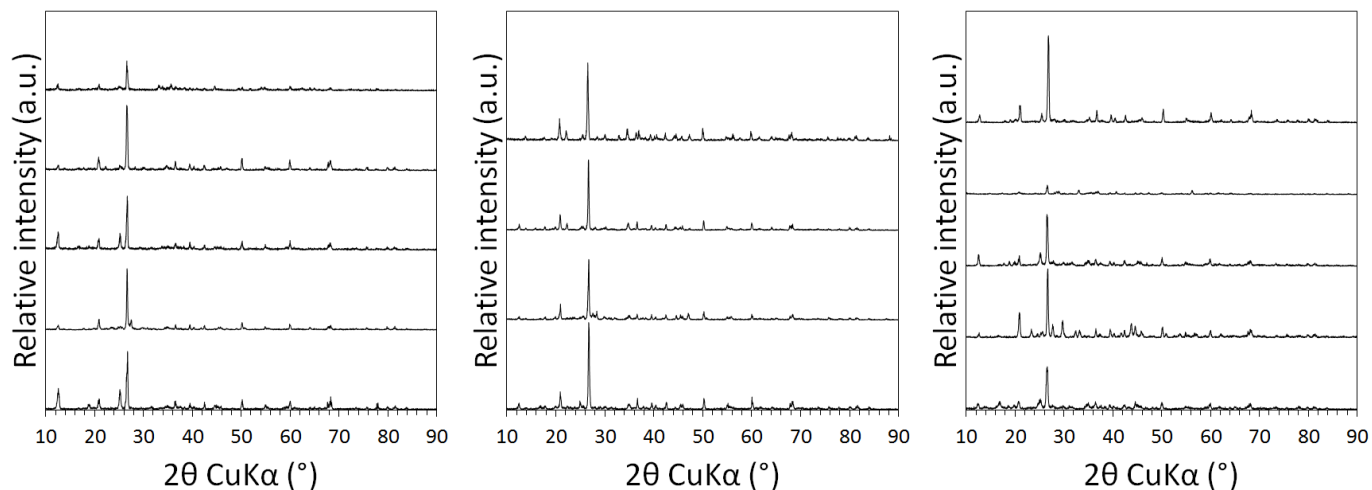
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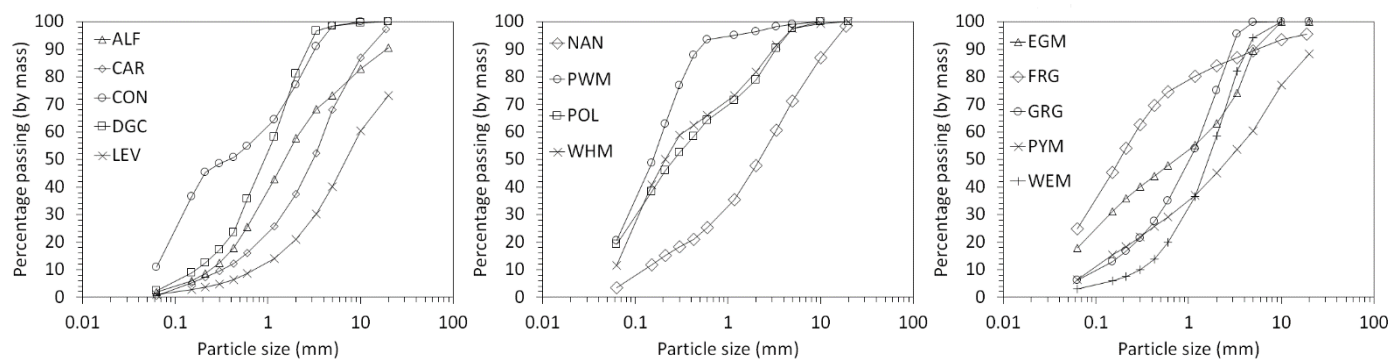
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1133 **Appendix A.** XRD spectra for the mine tailing composite samples. LHS (from bottom): ALF,  
 1134 CAR, CON, DGC, LEV; middle (from bottom): NAN, POL, PWM, WM; RHS (from bottom):  
 1135 EGM, FRN, GROG, PYM, WEM.



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1137 **Appendix B. Particle size as a function of cumulative volume for the composite mine**  
 1138 **tailing samples**



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## Appendix C. Number of non-active mines by commodity in each type of geological, ecological and cultural designation in the South West of England

Commodity	Number of mines in each designation													
	Total	LNR	NNR	SSSI	SAC	SPA	AW	PH	OM H	AONB	NP	SM	WHS	More than 1 designation (%)
Antimony	6	0	0	0	0	0	0	0	0	2	0	0	0	2 (33%)
Arsenic	1	0	0	0	0	0	0	1	0	0	1	0	0	1 (100%)
Arsenic Copper	13	0	0	1	1	0	5	4	1	13	0	2	13	13 (100%)
Barytes	2	0	0	0	0	0	0	1	0	0	2	0	0	2 (100%)
Celestite	20	0	0	0	0	0	0	1	0	0	0	0	0	1 (5%)
Copper	55	0	0	9	8	0	6	16	3	24	1	0	21	38 (69%)
Gold	2	0	0	0	0	0	2	0	0	0	0	0	0	2 (100%)
Iron ore	57	1	1	7	7	0	5	12	2	3	27	2	0	40 (70%)
Ironstone	124	3	0	27	27	3	41	47	1	18	1	3	0	79 (64%)
Lead	15	0	0	2	0	0	0	2	0	11	0	0	0	11 (73%)
Lead Antimony	2	0	0	0	0	0	0	2	0	2	0	0	0	2 (100%)
Lead Copper	1	0	0	0	0	0	0	1	0	0	0	0	0	1 (100%)
Lead Silver	11	0	0	0	0	0	0	0	0	1	1	0	0	2 (18%)
Manganese	11	0	0	0	0	0	3	3	0	1	0	0	0	5 (45%)
Tin	225	3	0	8	1	0	4	46	22	81	5	6	101	173 (77%)
Tin Copper	147	2	0	5	0	0	0	29	21	31	0	10	61	99 (67%)
Tin Tungsten	9	0	0	5	0	0	0	5	0	8	0	0	0	8 (89%)
Tungsten	1	0	0	0	0	0	0	1	0	1	0	0	0	1 (100%)
Vein Minerals (e.g. Pb, Zn, Cu, Sn)	11	0	0	5	0	0	2	2	2	7	2	0	1	9 (82%)
Zinc	3	0	0	0	0	0	0	0	0	0	0	0	0	0 (0%)
Zinc Copper Tin	1	0	0	0	0	0	0	0	0	0	0	0	0	0 (0%)
Grand Total	717	9	1	69	44	3	68	12	52	203	40	23	197	489 (68%)

Sources: mine data from BRITPITS Licence No. 2014/098BP ED British Geological Survey © NERC. All rights reserved. Local Nature Reserve (LNR), National Nature Reserve (NNR), Site of Special Scientific Interest (SSSI), Special Area of Conservation (SAC), Special Protection Area (SPA), Ancient Woodland (AW), Priority Habitat (PH), Open Mosaic Habitat on Previously Developed Land (OMH), Area of Outstanding Natural Beauty (AONB) and National Park data © Natural England copyright. Contains Ordnance Survey data © Crown copyright and database right 2016. Scheduled Monument and World Heritage Site © Historic England 2016. Contains Ordnance Survey data © Crown copyright and database right 2016. The Historic England GIS Data contained in this material was obtained on 29<sup>th</sup> June 2015. The most publicly available up to date Historic England GIS Data can be obtained from [HistoricEngland.org.uk](http://HistoricEngland.org.uk).

## Appendix D. Number of non-active mines by commodity in each type of geological, ecological and cultural designation in Wales

Commodity	Total number of mines in each designation															
	Total	LNR	NNR	SSSI	SAC	SPA	AW	PH <sup>1</sup>	OMH	AONB	CP	NP	SM	WHS	LHI	More than 1 designation (%)
Barytes	3	0	2	2	0	0	0	3	0	0	0	0	0	0	2	2 (67%)
Barytes Lead	4	0	0	0	0	0	0	4	0	0	0	0	0	0	1	1 (25%)
Copper	213	2	13	58	41	3	16	212	0	6	4	120	10	0	117	195 (92%)
Gold	74	0	0	17	9	3	7	70	0	12	1	62	2	0	52	74 (100%)
Gold Copper	19	0	0	0	6	0	7	18	0	0	0	19	0	0	18	19 (100%)
Iron Ore	60	0	0	5	3	0	9	59	0	1	0	0	1	0	20	31 (52%)
Ironstone	178	5	0	10	8	5	10	177	22	2	4	19	0	9	75	100 (56%)
Lead	1847	0	5	425	269	29	160	1791	23	375	7	260	27	0	474	1199 (65%)
Lead Copper	5	0	0	0	0	0	3	5	0	0	0	0	0	0	0	3 (60%)
Lead Copper Zinc	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1 (100%)
Lead Silver	55	0	0	31	20	0	0	54	4	37	0	0	0	0	1	37 (67%)
Lead Silver Copper	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1 (100%)
Lead Zinc	1	0	0	1	0	0	0	1	0	1	0	0	0	0	0	1 (100%)
Manganese	113	0	0	31	21	17	1	112	0	27	0	71	1	0	56	112 (99%)
Vein Minerals	775	1	11	109	48	43	102	749	3	12	0	74	35	0	441	575 (74%)
Zinc	1	0	0	1	0	0	0	1	0	0	0	0	1	0	1	1 (100%)
Grand Total	3350	8	31	690	425	100	316	3258	56	473	16	625	77	9	1260	2352 (70%)

<sup>1</sup>Priority habitat data in Wales is presented as the area within a 1.6 km (1 mile) grid square so the location of the mine cannot be said to be accurately co-located with the habitats. SSSI=Site of Special Scientific Interest, AW=Ancient Woodland, PH=Priority Habitat PH, OMH=Open Mosaic Habitat on Previously Developed Land, SAC=Special Area of Conservation (European), SPA=Special Protection Area, AONB=Area of Outstanding Natural Beauty, NP=National Park, CP=Country Park, SM=Scheduled Monument, WHS=World Heritage Site, Landscape of Heritage Interest; Sources: mine data from BRITPITS Licence No. 2014/098BP ED British Geological Survey © NERC. All rights reserved. All other data © Natural Resources Wales copyright. Contains Ordnance Survey data © Crown copyright and database right 2016.