

River sediment geochemistry and provenance following the Mount Polley mine tailings spill, Canada: the role of hydraulic sorting and sediment dilution processes in contaminant dispersal and remediation

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1 River sediment geochemistry and provenance following the Mount Polley mine tailings spill, Canada:
2 the role of hydraulic sorting and sediment dilution processes in contaminant dispersal and
3 remediation.

4

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ABSTRACT

The failure of the Mount Polley tailings storage facility (TSF) in August 2014 was one of the largest magnitude failures on record, and released approximately 25 Mm³ of material, including c. 7.3 Mm³ of tailings into Hazeltine Creek, part of the Quesnel River watershed. This study evaluates the impact of the spill on the geochemistry of river channel and floodplain sediments and utilizes Pb isotope ratios and a multi-variate mixing model to establish sediment provenance. In comparison to sediment quality guidelines and background concentrations, Cu and V were found to be most elevated. Copper in river channel sediments ranged from 88-800 mg kg⁻¹, with concentrations in sand-rich and clay/silt-rich sediments being statistically significantly different. Concentrations in river channel were believed to be influenced by hydraulic sorting during the rising and falling limbs of the flood wave caused by the tailings spill. Results highlight the importance of erosive processes, instigated by the failure, in incorporating soils and sediments into the sediment load transported and deposited within Hazeltine Creek. In this instance, these processes diluted tailings with relatively clean material that reduced metal concentrations away from the TSF failure. This does however, highlight environmental risks in similar catchments downstream of TSFs that contain metal-rich sediment within river channels and floodplain that have been contaminated by historical mining.

KEY WORDS: tailings, spill, metals, lead isotopes, fingerprint

HIGHLIGHTS

- Copper concentrations exceed sediment quality guideline level following the spill.
- Hydraulic sorting influenced spatial trends in metal concentrations.
- Lead isotopes used to fingerprint sediments after the tailings spill.
- Mixing model data indicate the importance of spill-induced erosive processes

INTRODUCTION

56

57 Mine tailings are the milled solid waste left over from the recovery of the valuable commodities
58 from mined material (Kossoff et al., 2014). Although the chemical properties of mine tailings can
59 vary substantially, the material represents the most voluminous metalliferous waste produced by
60 metal mines (Lottermoser, 2010). However, the volume of tailings compared to unmilled waste
61 rock, produced during mining, may be lower and will vary between surface and underground mines.
62 Despite the growth of other storage approaches, currently the majority of mine tailings are
63 transported and stored as a slurry, with tailings storage facilities (TSFs) representing substantial
64 pieces of mine site infrastructure. Worldwide, there are estimated to be over 12,000 TSFs (Macklin
65 et al., submitted), of varying construction type and in numerous mining operations the land area
66 covered by TSFs now exceeds that being used for mining activities (Hudson-Edwards et al., 2011).

67 Since 1960 there have been a reported 158 mine tailings dam failures worldwide (Project), 2020). It
68 is therefore apparent that these structures represent a substantial global risk to the environment
69 and local populations. The environmental impacts of the failure of tailings dams, associated with
70 the release of large volumes of metal-rich tailings and water into recipient environments, have been
71 noted by many studies over the last two decades (Hudson-Edwards, 2016; Hudson-Edwards et al.,
72 2003; Macklin et al., 2003). Of concern is the potential that the frequency of such events may
73 increase over the coming years, due to a) the growing number of active and inactive tailings ponds,
74 driven by higher waste to ore ratios, as high-grade ores are exhausted (Mason et al., 2011), and b)
75 an increase in extreme hydro-meteorological events, a common contributor to many failures (Rico et
76 al., 2008).

77 The tailings:water ratio commonly varies among failure events (Rico et al., 2008), and the volume of
78 tailings released can have an important influence on 1) approaches to post-event remediation, 2) the
79 geomorphological disturbance within the recipient river systems, and 3) the longer-term fate of
80 metals released into recipient environments. Furthermore, the chemical nature of spilled material
81 varies considerably (Kossoff et al., 2014), reflecting the mineralogy of the ore-body from which the
82 tailings derive, the efficiency of the extraction process and any substances used in ore processing
83 (for example CN^- in the case of Au extraction). However, what is common is that mine tailings dam
84 failures represent a major environmental risk with the potential to impact river systems in terms of
85 geomorphology, geochemistry and ecosystem health (Kossoff et al., 2014; Macklin et al., 2006).

86 The partial embankment breach at the Mount Polley TSF on 4th August 2014, is the second largest
87 mine waste spill by volume on record (Project), 2020). The causes of the spill have been reported in

88 detail elsewhere (Byrne et al., 2018; Hudson-Edwards et al., 2019). The spill resulted in
89 approximately 25 Mm³ of material being released into the Quesnel River watershed (Petticrew et al.,
90 2015). This comprised approximately 7.3 Mm³ of tailings, 17.1 Mm³ of supernatant and interstitial
91 water and 0.6 Mm³ of TSF materials (Petticrew et al., 2015). The release of water and sediment
92 from the TSF created a flood wave that eroded the existing river valley and resulted in the deposition
93 of material along the valley floor of Hazeltine Creek. Deposits were up to 3.5 m thick and extended
94 up to 100 m from the river channel.

95

96 The impacts of the Mount Polley spill have been studied with respect to the influence on water
97 quality in Hazeltine Creek (Byrne et al., 2018) and Quesnel Lake (Petticrew et al., 2015) and the
98 release of Cu and V, specifically, into the environment (Hudson-Edwards et al., 2019). In addition,
99 data have been published on the geochemistry of the mine tailings (Kennedy et al., 2016). To date,
100 however, there has been no published study into the fate of particulate material released by the
101 spill, and in particular the mixing and subsequent deposition of released tailings and eroded valley
102 floor sediments. These factors are crucial to understanding the storage of tailings and longer-term
103 environmental impacts of the spill. To this end, this study aims to utilize geochemical fingerprinting
104 to understand the contribution of different source materials within the Hazeltine Creek catchment
105 and to quantify their influence on post-spill river sediment dynamics. Our primary objective was to
106 quantify the contributions of different types of tailings material released by the spill and to establish
107 which contributed most significantly to river sediment contamination. Our expectation was that a
108 better understanding of the fate of material released by the spill and by erosive processes generated
109 by the post-spill flood, will help to provide a better understanding of the potential legacy of tailings
110 dam failures.

111

STUDY AREA

112 The Mount Polley deposit is an alkalic porphyry Cu-Au deposit (Panteleyev, 1995), formed
113 approximately 180 Ma ago within Late Triassic (235 – 201 Ma) and Mesozoic (252 – 66 Ma) bedrock
114 geology (Kennedy and Day, 2015). Sulfide mineralization consists principally of chalcopyrite (CuFeS₂)
115 and pyrite (FeS₂) but, at least 50% of the Cu mineralization is not sulfidic, and includes primarily
116 malachite (Cu₂CO₃(OH)₂) and chrysocolla ((Cu,Al)₂H₂Si₂O₅(OH)₄.nH₂O) (Henry, 2009). Overall, the
117 tailings produced at Mount Polley have a low sulfide content (0.1-0.3 wt. %) and are not acid-
118 generating (Kennedy and Day, 2015), making the Mount Polley event unusual compared to many
119 other tailings spills (WISE, 2020).

120 The deposit is located approximately 55 km north-east of Williams Lake, British Columbia, within the
121 112 km² Hazeltine Creek catchment (Figure 1). Hazeltine Creek is a tributary catchment within the
122 larger Quesnel River Catchment, and flows for 10.3 km from the southern end of Polley Lake at 920
123 m asl, into Quesnel Lake at 730 m asl (Burge and Cuervo, 2015).

124 Mining began at Mount Polley Mine in 1997 and 95 M tonnes of ore were processed between the
125 commencement of mining and 2014, producing 94.2 M tonnes of tailings in the same period
126 (Kennedy and Day, 2015). Concentrations of most metals within the tailings are relatively low, but
127 the material is relatively enriched in Cu and V (86-296 and 8-55 mg kg⁻¹, respectively) (Kennedy and
128 Day, 2015).

129



130

131 Figure 1. Map showing the study area including the location the Mount Polley TSF and sample sites
132 used for the collection of river channel sediment and floodplain sediment and the location of longer-
133 term sampling in Hazeltine Creek.

134

135

MATERIALS AND METHODS

136 Extensive geochemical datasets were provided by the Mount Polley Mining Corporation based upon
137 the analysis of samples of tailings and stream sediments collected following the tailings spill
138 (Minnow Environmental Inc, 2015; SRK Consulting, 2015). These data were utilized in addition to
139 data produced by this study from the analysis of samples: 1) collected by this study and 2) samples

140 collected for, and provided to the authors by the Mount Polley Mining Corporation (Mount Polley
141 Mining Corporation, 2015).

142

143 In July and August 2015 determinations of metal concentrations in river channel and floodplain
144 sediment from Hazeltine Creek and mine tailings deposited in the Hazeltine Creek river corridor
145 were made in the field at 86 sites, using a portable x-ray fluorescence (pXRF) (Niton XLp 300) with an
146 analysis time of 60 seconds. At 46 of these sites, samples of river channel and floodplain sediment
147 from Hazeltine Creek, and deposited tailings, were collected for subsequent laboratory analysis of
148 metal concentrations and Pb isotopes (Figure 1). Sampling of floodplain material was carried out at
149 varying depths from exposed river bank profiles at sites MP14, MP25, MP26 and MP75 (Figure 1). In
150 all instances, samples were collected as composite samples using a stainless steel trowel. Composite
151 samples comprised 5-10 sub-samples collected over a c. 1 m² area (river channel sediments) or from
152 the same floodplain depth, bulked together to form a single sample of c. 500 g.

153

154 In the laboratory, all samples were air-dried at 30 °C, disaggregated using a pestle and mortar and
155 sieved to isolate the < 2mm fraction. Samples were digested in concentrated aqua regia (HCl and
156 HNO₃ in a 3:1 v/v ratio) prior to multi-elemental analysis by Inductively Coupled Plasma – Mass
157 Spectrometry (ICP-MS). The accuracy and precision of multi-element analyses was monitored
158 through the analysis of a certified reference material (GSD-6, a stream sediment near an area of
159 porphyry Cu mineralization), and the resultant data are presented in Supplementary Material 1. The
160 aqua regia digestion matches the method was used in this study to provide consistency with
161 methods used to generate the datasets provided by the Mount Polley Mining Corporation. To
162 monitor the comparability of datasets provided by the Mount Polley Mining Corporation and those
163 generated by this study, 20 randomly selected samples previously analysed by the Mount Polley
164 Mining Corporation, were reanalysed by this study using the methods outlined above. The mean
165 differences in concentrations between the duplicate analyses ranged from 9.3-27.7%
166 (Supplementary Material 1) with greater variability generally found in samples with low element
167 concentrations.

168

169 Lead isotopes ²⁰⁴Pb, ²⁰⁶Pb, ²⁰⁷Pb and ²⁰⁸Pb in a selection of sediment samples were determined by
170 Magnetic Sector ICP-MS (Thermo-Finnegan Element2) at Aberystwyth University. Solutions for
171 analysis were prepared at 50 ng ml⁻¹ and analysed in batches along with blank samples (2 per batch)
172 and NIST 981 reference material (2 per batch). Analytical precision was found to be 0.12 %
173 (²⁰⁶Pb/²⁰⁷Pb), 0.18 % (²⁰⁸Pb/²⁰⁶Pb), 0.25 (²⁰⁸Pb/²⁰⁴Pb), 0.15 (²⁰⁷Pb/²⁰⁴Pb) and 0.16 (²⁰⁶Pb/²⁰⁴Pb).

174 Analytical accuracy versus the NIST 981 reference material was found to be 0.19 % ($^{206}\text{Pb}/^{207}\text{Pb}$), 0.09
175 % ($^{208}\text{Pb}/^{206}\text{Pb}$), 0.27 ($^{208}\text{Pb}/^{204}\text{Pb}$), 0.17 ($^{207}\text{Pb}/^{204}\text{Pb}$) and 0.26 ($^{206}\text{Pb}/^{204}\text{Pb}$).

176

177 A mixing model was used in order to quantify the contributions of mining and non-mining sources to
178 the river channel and floodplain sediments present in Hazeltine Creek after the spill. The principles of
179 the mixing model approach have been described in detail by Yu and Oldfield (1989) and Collins et al.
180 (1997), and the range of model approaches that have been developed, and the geochemical properties
181 of sediments used within the models, have been reviewed by Haddadchi et al. (2013). Given the small
182 spatial scale of the study catchment and limited number of potential sources within it, this study
183 utilized a model based upon Pb isotope signatures as fingerprint properties (Miller et al., 2007). In
184 short, the approach utilises the following equation:

$$185 \quad b_j = \sum_i^m \frac{m}{i} = 1X_i a_{ij} \quad (\text{Equation 1})$$

186

187 where b_j ($j=1,2,3,4$) are Pb isotope ratios ($^{206}\text{Pb}/^{207}\text{Pb}$, $^{208}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{204}\text{Pb}$)
188 of a stream sediment sample composed of m distinct source materials (Table 1), a_{ij} ($i=1,2,3,\dots,m$) are
189 the corresponding Pb isotope ratios of the i th source materials and X_i being the proportion if the i th
190 source in the sediment. Given values of b_j and a_{ij} , a series of n linear equations were optimized using
191 the Solver function in Microsoft Excel to quantify the contributions of the five sources identified. Two
192 important constraints are that all source proportions must be non-negative (Equation 2) and source
193 proportions must sum to unity (Equation 3).

194

$$195 \quad X_i = \geq 0 \quad (\text{Equation 2})$$

196

$$197 \quad \sum_i^m = 1X_i = 1 \quad (\text{Equation 3})$$

198

199 The validity of the mixing model results was assessed by comparing the measured parameter values
200 in the sediment with the values predicted in the optimization of the linear equations (Equation 4). This
201 assessment quantifies relative errors and indicates whether the mixing model generates an acceptable
202 prediction of the fingerprinting properties (Miller et al., 2007). Errors for five iterations of the mixing
203 model (one per source group) ranged from 0.27-0.54%.

204

$$205 \quad \% \text{ error} = \sqrt{\frac{(\sum_{i=1}^m (b_i - \sum_{j=1}^n a_{ij} x_j))^2}{\sum_{i=1}^m (b_i)^2}} \times 100 \quad (\text{Equation 4})$$

206 Potential sources of uncertainty within mixing model approach have been summarized and
 207 discussed by Collins et al. (2010; 2012). These include the potential for statistically similar solutions
 208 during the optimization process, especially close to 0 and 100% sediment contribution, and the
 209 possible variability in fingerprint properties that is not captured by the analysis of samples of the
 210 source materials. The relative errors produced by the mixing model are small, although mindful of
 211 these potential uncertainties, the mixing model should be seen as providing a general insight to
 212 sediment contributions and therefore interpreted in terms of broader trends.

213 Table 1. Source materials (source group) used to establish river sediment provenance.

Source material / source group	Description
Background sediments (as termed by Mount Polley Mining Corporation). Analysis of 12 samples.	Sediments from the Hazeltine Creek valley floor beyond the extent of material deposited by the spill. Samples provided by Mount Polley Mining Corporation and analysed by this study.
Native channel sediments (as termed by Mount Polley Mining Corporation). Analysis of 3 samples.	Material from the Hazeltine Creek channel banks that was not covered by, or disturbed by the spill. Reflects material present in Hazeltine Creek prior to the spill event. Samples provided by Mount Polley Mining Corporation and analysed by this study.
Sand-rich tailings. Analysis of 3 samples.	Sand-rich tailings released by the spill. Samples provided by Mount Polley Mining Corporation and analysed by this study. Average sediment composition of analysed samples ^a : <0.1% gravel; 70% sand; 25.5% silt; 4.8% clay
Silt and clay-rich tailings. Analysis of 4 samples.	Fine grained, silt and clay-rich tailings released by the spill. Samples provided by Mount Polley Mining Corporation and analysed by this study. Average sediment composition of analysed samples ^a : <0.1% gravel; 16.1% sand; 67% silt; 17% clay
Mixed tailings. Analysis of 2 samples.	A mixture of sand-rich and silt and clay-rich tailings released by the spill. Samples provided by Mount Polley Mining Corporation and analysed by this study. Average sediment composition of analysed samples ^a :

<0.1% gravel; 52.1% sand; 36.8% silt; 11% clay
--

214 ^aSedimentological data from previous analysis of the same sample material by Minnow
215 Environmental Inc (2015) and SRK Consulting (2015).

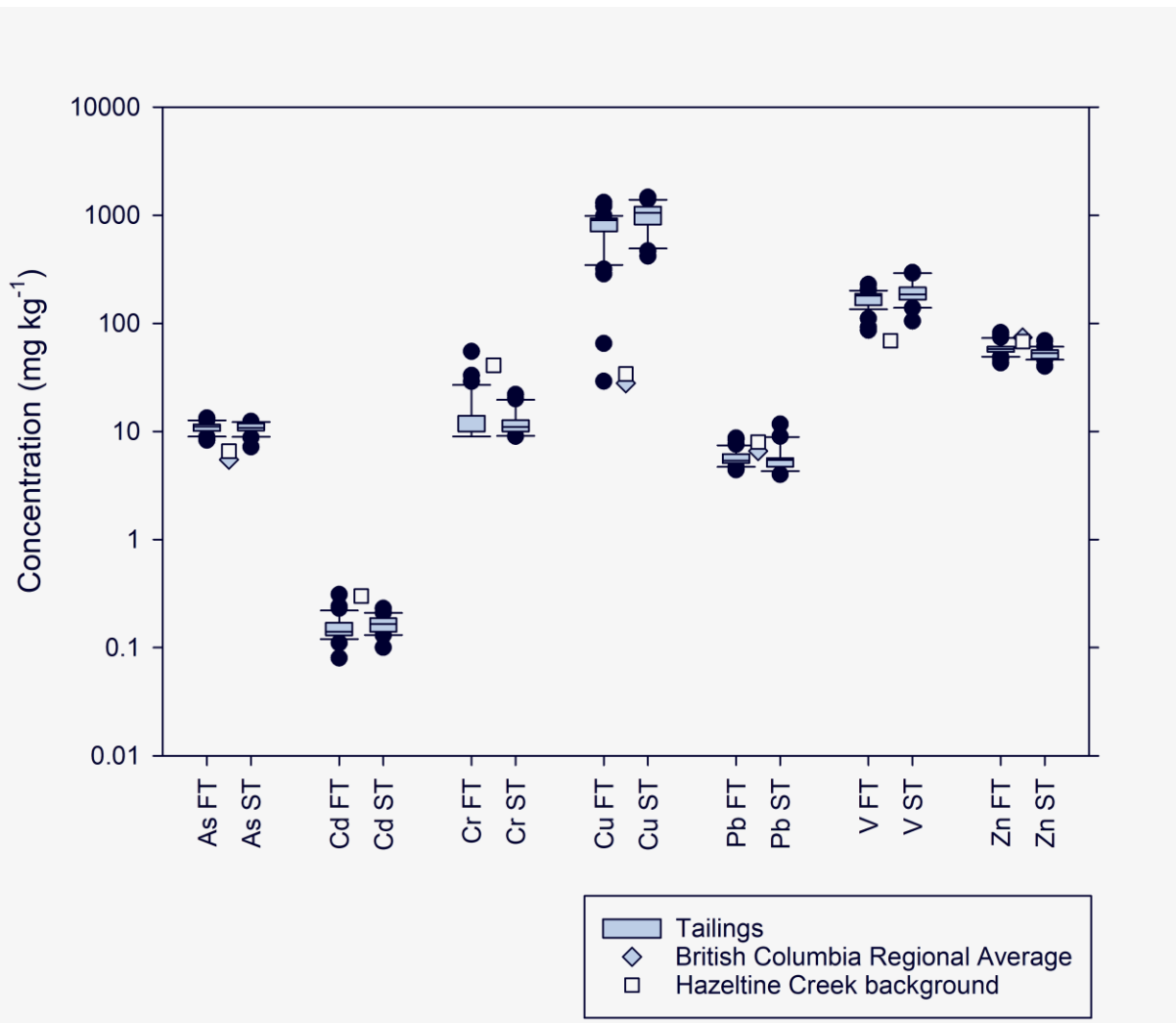
216
217 Finally, selection of river channel sediment (n = 8) and floodplain sediment samples (n = 6),
218 specifically, those used for the mixing model, were also analysed for their sedimentological
219 composition. The % proposition of sand (2 mm – 63 µm), silt (63 – 3.9 µm) and clay (< 3.9 µm) was
220 determined, firstly by sieving to separate the sand and combined silt/clay fraction, and secondly
221 using a Mastersizer 2000 to determine the relative proportions of silt and clay following Malvern
222 Instrument’s standard protocol (Malvern Instruments Ltd, 2007). Gravel-sized material (> 2mm) was
223 not present in any samples analysed.

225 RESULTS AND DISCUSSION

226 Metals in mine tailings

227 Tailings released by the spill comprised two types of material: first a sand-rich material (‘sandy
228 tailings’, ST), comprising an average 73% sand, 26% silt and clay and 1% gravel (Minnow
229 Environmental Inc, 2015; SRK Consulting, 2015); and second finer-grained material (‘fine-grained’
230 tailings, FT), comprising an average 38% sand, 61% silt and clay and 1% gravel (Minnow
231 Environmental Inc, 2015; SRK Consulting, 2015). The two material types represent different products
232 of ore processing.

233
234 Copper and V were generally the most enriched trace metals within both types of tailings (Figure 2),
235 reflecting the nature of mineralization at Mount Polley, which is also reflected in the regional and
236 local background geochemistry (Table 2). Average Cu and V concentrations were higher in the sandy
237 tailings (1000 mg kg⁻¹ and 195 mg kg⁻¹, respectively) compared to the finer-grained tailings (808 mg
238 kg⁻¹ and 170 mg kg⁻¹, respectively). In comparison to Cu, V concentrations exhibited less variability in
239 both tailings materials. Average concentrations in the tailings of other potentially harmful elements,
240 such as As, Cd, Pb and Zn (Figure 2) were also above average background concentrations determined
241 for the British Columbia region and for the Hazeltine Creek catchment.



242

243 Figure 2. Summary of metal and As concentrations in clay and silt-rich tailings ('fine-grained' tailings
 244 [FT]) and sand-rich tailings ('sandy' tails [ST]). Number of samples: n = 41 (fine-grained tailings) and
 245 n = 20 (sandy tailings). Data adapted from SRK Consulting (Canada) Inc. (2015). Data also plotted for
 246 British Columbia regional average (As, Cu, Pb Zn only) (Geological Survey of Canada, 1981) and
 247 background concentrations (Minnow Environmental Inc., 2015).

248

249

250 Table 2. Minimum, mean, median and maximum background concentrations (mg kg⁻¹) determined
 251 for the Hazeltine Creek catchment and the British Columbia region (As, Cd, Cu, Pb and Zn only).

	Arsenic	Cadmium	Copper	Lead	Vanadium	Zinc
Hazeltine Creek background ^a						
Minimum	3	<0.1	6	4	40	32
Mean	7	0.3	34	8	69	68
Median	6	0.2	22	6	61	53
Maximum	14	2	135	22	133	149
British Columbia regional background ^b						
Minimum	1	ND	0	1	ND	4
Mean	6	ND	29	7	ND	75
Median	3	ND	24	4	ND	54
Maximum	96	ND	701	96	ND	3701

	Hazeltine Creek native channel sediment ^c					
Minimum	0.4	<0.1	6.3	4.1	2	2.3
Mean	7	0.2	36	7.3	60	54
Median	7	0.2	32	6.4	61	51
Maximum	14.7	0.4	87	14	100	94

252 ^aData for 26 soil samples from Hazeltine Creek catchment; adapted from Minnow Environmental Inc.
 253 (2015). Concentrations determined following aqua regia digest.

254 ^bData for 1290 stream sediment samples adapted from the Geological Survey of Canada (1981).
 255 Concentrations determined following aqua regia digest.

256 ^cData for 17 native channel sediment samples within Hazeltine Creek adapted from SNC-Lavalin
 257 (2015). Sampled from channel banks and was not covered by, or undisturbed by the spill, reflecting
 258 material present in Hazeltine Creek prior to the spill event. Concentrations determined following
 259 aqua regia digest.

260 ND = no data

261

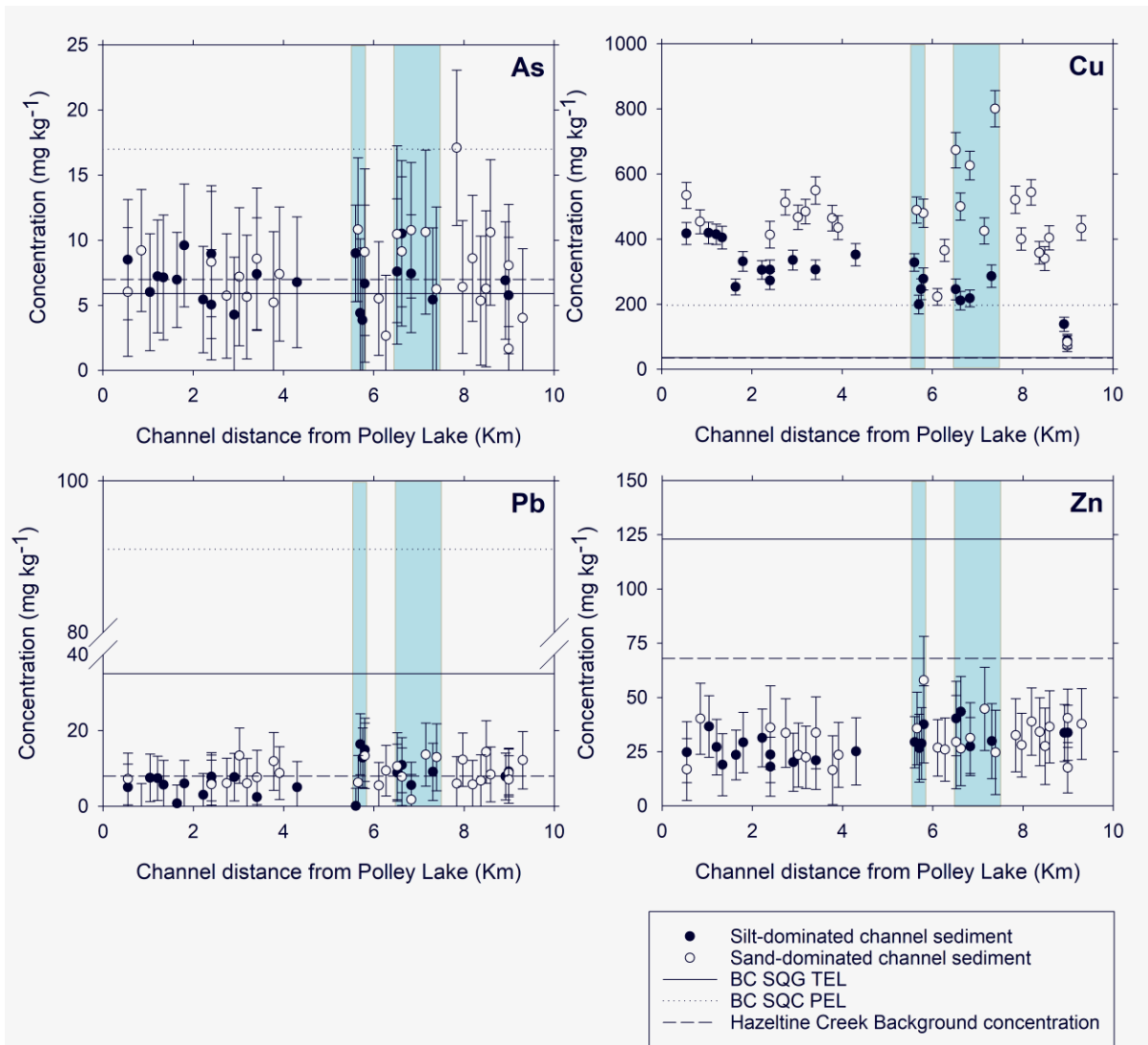
262 **Metals in river channel sediments**

263 Concentrations of As, Cu, Pb and Zn in Hazeltine Creek river channel sediments are plotted for silt-
 264 rich and sand-rich sediments in Figure 3; all Cd concentration were non-detectable and are not
 265 plotted. Non-parametric significant difference analysis (Mann-Whitney U test) indicates that,
 266 although there is no significant difference between As ($p=0.288$), Pb ($p=0.276$) and Zn ($p=0.283$)
 267 concentrations in sand- and silt-rich samples, Cu concentration are significantly different ($p<0.000$).
 268 The sedimentological analysis of a selection of river channel sediments indicated that silt-rich
 269 sediments ($n = 4$) were found to contain: 35-43 % sand, 56-63 % silt and 1-5 % clay. Sand-rich
 270 sediments ($n = 4$) were found to contain: 75-95 % sand, 4-11 % silt and 0.3-0.5 % clay (Figure 4a).
 271 Data indicate that channel sediments present within Hazeltine Creek are present in accumulations
 272 that have notably higher sand (sand-rich) or silt (silt-rich) contents (Figure 4a). The spatial trends
 273 suggest that sand- or silt-rich sediments have accumulated throughout the study reach, likely
 274 reflecting spatial variation in processes influencing sediment transport and deposition.

275

276 Concentrations are compared to British Columbia (BC) Sediment Quality Guidelines (SQG) (Table 3),
 277 which comprise a lower Threshold Effect Level (TEL) concentration and an upper Probable Effect
 278 Level (PEL) concentration and are based on those produced by the Canadian Council of Ministers of
 279 the Environment (CCME) (2017). In addition, background concentrations determined for Hazeltine
 280 Creek (Table 2) are also plotted for comparison. All As concentrations fall below the BC SQG PEL,
 281 whereas all Pb and Zn concentrations are below the lower BC SQG TEL. In contrast, Cu
 282 concentrations in 92% of samples were above the upper BC SQG PEL. It is important to note that
 283 SQGs do not consider the potential bioavailability of sediment-associated metals, for example, as
 284 influenced by their physico-chemical speciation. Therefore, concentrations above a guidelines value

285 may pose a lesser or greater significant environmental risk depending on the degree of bioavailability
 286 (Guan et al., 2018).



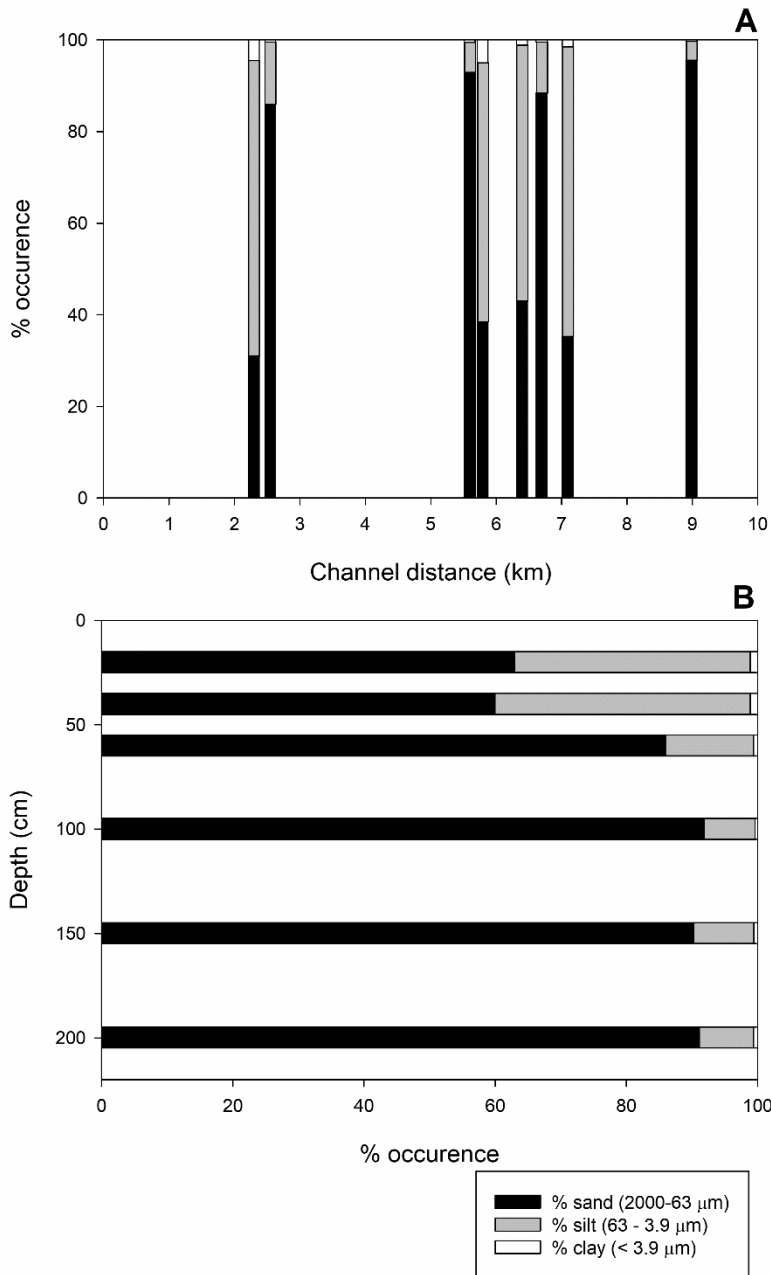
287
 288 Figure 3. Metal concentrations in stream channel sediments in Hazeltine Creek. Data plotted for silt-
 289 rich and sand-rich sediments measured in the field by pXRF. Shaded areas represent the location of
 290 two bedrock gorges through which Hazeltine Creek flows. British Columbia (BC) Sediment Quality
 291 Guidelines (SQG) and background concentrations are also plotted. Note: the BC SQC PEL for Zn (315
 292 mg kg⁻¹) is not plotted. Note: for Cu, the BC SQC TEL (36 mg kg⁻¹) and background concentration (35
 293 mg kg⁻¹) are very similar and overlap.

294

295 Table 3. British Columbia Sediment Quality Guideline concentrations (mg kg⁻¹) for selected metals
 296 and the metalloid As (BC Ministry of Environment, 2017).

	Threshold Effect Level (TEL)	Probable Effect Level (PEL)
As	5.9	17
Cd	0.6	3.5
Cu	35.7	197
Pb	35	91
Zn	123	315

297



299

300 Figure 4. Percentage occurrence of sand (2 mm – 63 μm), silt (63 – 3.9 μm) and clay (< 3.9 μm) in a
 301 selection of river channel sediments (A) and floodplain sediment at site MP26 (B)

302

303

304 Figure 3 also indicates that for Cu, which is present in concentrations above the BC PEL, there is a
 305 general downstream trend of reducing concentrations in the silt-rich channel sediments ($r^2 = 0.68$).

306 This is likely to reflect hydraulic sorting and/or dilution of Cu in these silt-rich sediments (c.f. Lewin
 307 and Macklin, 1987). The same downstream pattern does not exist for Cu concentrations in sand-rich

308 sediments ($r^2 = 0.08$). It is apparent that the weaker downstream relationship for Cu in sand-rich
309 sediment is influenced by the presence of higher Cu concentrations present in material sampled within
310 two bedrock gorges in the lower half of Hazeltine Creek (Figure 3).

311

312 The spatial trends observed in Cu concentrations in silt-rich and sand-rich channel sediments may
313 reflect the influence of hydraulic sorting driven by discharge and associated stream power variation
314 during the spill event. Finer-grained, silt-rich materials will have been preferentially transported in
315 the earlier and later stages of the spill-associated event, during the rising and falling limbs of the
316 flood. Transport of sand-rich material would have been highest during peak flow, which would also
317 have reworked finer-grained material released earlier in the event. The preferential transport of
318 fine-grained, silt-rich material during the falling limb of the flood event explains the 'top-dressing' of
319 sediments with a higher proportion of silt over coarser material on the floodplain. For example, at
320 site MP26, floodplain sediment at 0-40 cm depth contains on average 38% silt, compared to an
321 average of 10% silt in sample below (Figure 4b).

322

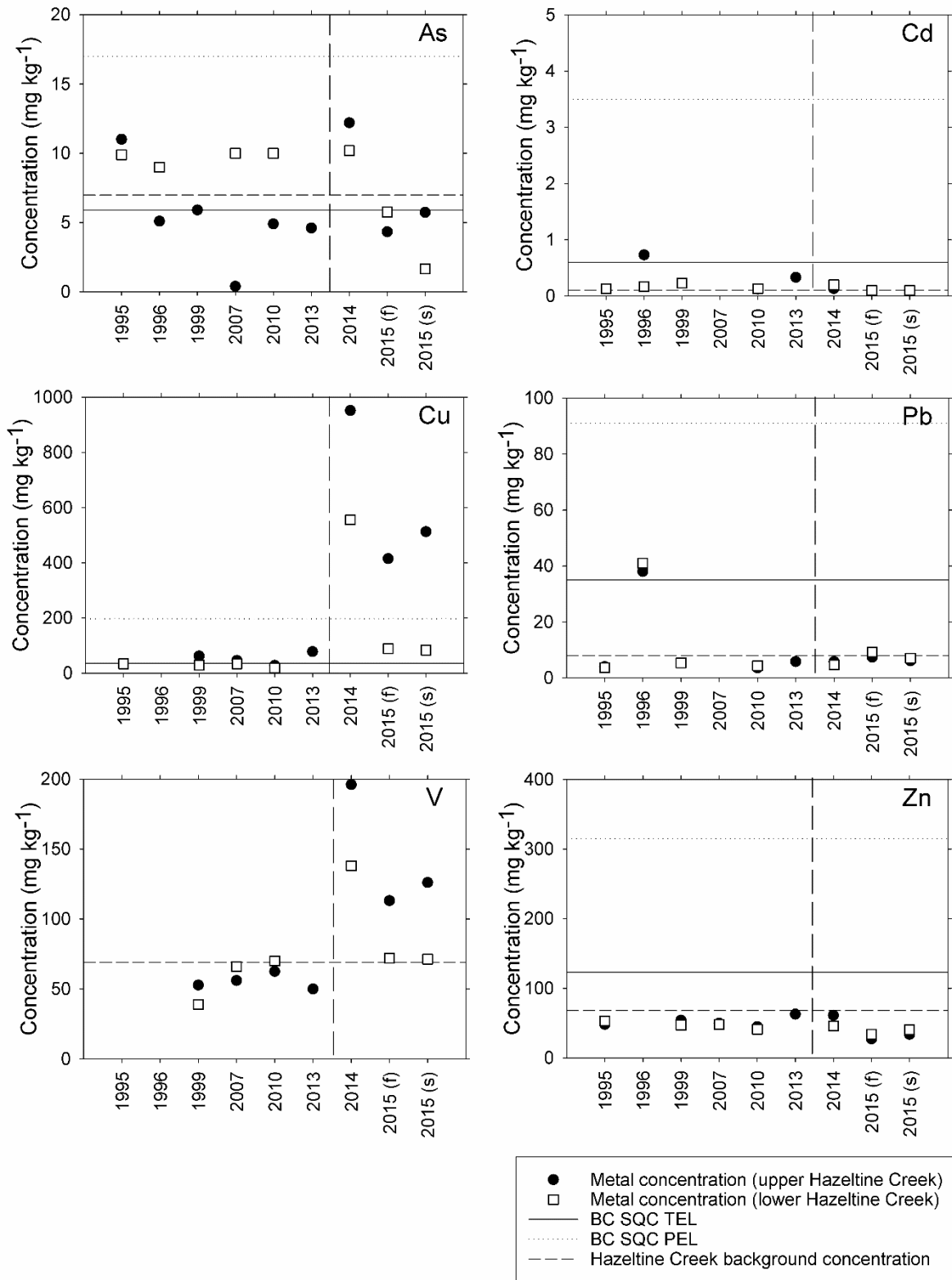
323 The steeper, confined bedrock gorges in the lower half of Hazeltine Creek will have seen the highest
324 stream powers during the flood event, which would have resulted in the winnowing of the silt-rich
325 sediment fraction, notably during the falling limb of the flood event. This will have left stream
326 sediments in those reaches relatively rich in sand-rich material, shown to contain higher Cu
327 concentrations in both the stored tailings (Figure 2) (SRK Consulting (Canada) Inc., 2015) and channel
328 sediments (Figure 3). The sand-rich sediments sampled in the bedrock gorges contain the highest Cu
329 concentrations in channel sediments measured along Hazeltine Creek, with Cu concentrations in
330 sand-rich sediments being lower at sample sites between the two gorges. This results in the
331 previously noted lack of a clear distance-concentration relationship for Cu in sand-rich sediments.
332 The influence of stream power and similar grain-size effects in influencing distance-concentration
333 relationships has been previously noted by Graf (1990) following the Church Rock tailings spill.
334 These results indicate the potential complex geomorphologically-, hydraulically- and
335 sedimentologically-influenced controls on the dispersal and storage of material released by the
336 tailings spill and on subsequent spatial trends in channel sediment metal concentrations.

337

338 To further evaluate the impact of the spill on channel sediment geochemistry, metal concentrations
339 determined in 2014 (immediately post-spill) and 2015 (one year after the spill) are plotted alongside
340 concentrations measured in the 9 years prior to the dam failure from samples collected at two sites,
341 one in the upper, and one in the lower reaches of Hazeltine Creek (Figure 5). Sample site locations

342 are shown in Figure 1. Concentrations of metals and As within river channel sediments indicate that
343 Cu and V showed the largest enhancement compared to pre-spill levels in Hazeltine Creek . For
344 example, maximum post-spill Cu concentrations are 17 and 19 times more enriched in the upper and
345 lower Hazeltine Creek, respectively. In comparison, the maximum enrichment for As (2.3 times), Pb
346 (2 times) and Zn (1.2 times) are much lower. The concentrations measured in samples collected in
347 2014 and 2015 indicate that the upper reaches of Hazeltine Creek were more affected by the spill.
348 Concentrations of Cu reduced from 952 to 512 mg kg⁻¹ at the upper site (Figure 5), but
349 concentrations at the lower site had reduced to 88 mg kg⁻¹ in 2015 compared to 556 mg kg⁻¹ in 2014
350 (Figure 5). The concentrations present in samples collected after the spill, and differences between
351 upper and lower Hazeltine Creek, reflect, at least in part, the influence of grain-size effects and
352 hydraulic sorting noted previously. However, these patterns are also to likely reflect the spatially-
353 variable nature of post-spill remediation works. For example, in the lower part of Hazeltine Creek
354 (upstream of the lower Hazeltine Creek sample site), it potentially reflects the influence of settling
355 ponds, constructed. Copper concentrations in the lower Hazeltine Creek sample site (downstream
356 of the settling pond) in 2015, were 89 % (silt-rich sediment) and 84 % (sand-rich sediment) lower
357 than those measured at the same location in 2014, after the spill but prior to the ponds'
358 construction (Figure 5).

359



360

361 Figure 5. Metal and As concentrations pre- and post-spill in Hazeltine Creek channel sediments. The
 362 upper and lower Hazeltine Creek data sampled from locations equating to sites MP32 and MP72,
 363 respectively. Data for 1995-2013 from Minnow Environmental Inc. (2015), data for 2014 from SRK
 364 Consulting (Canada) Inc. (2015) and for 2015 from this study. Data for 2015 is provided for both
 365 fine-grained silt rich (f) and coarser-grained, sand-rich (s) sediments. Metal and As concentrations

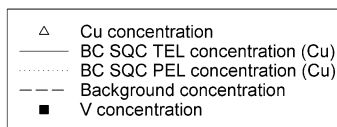
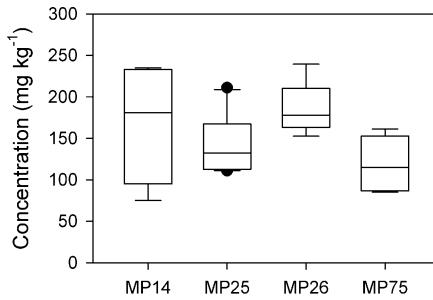
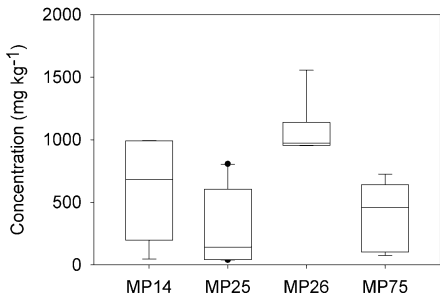
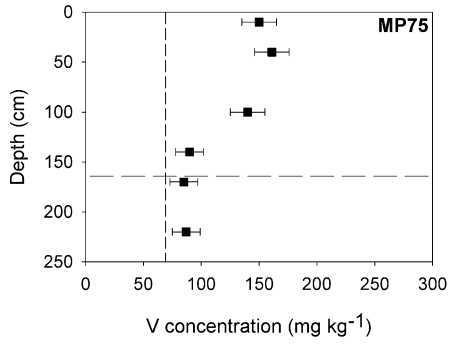
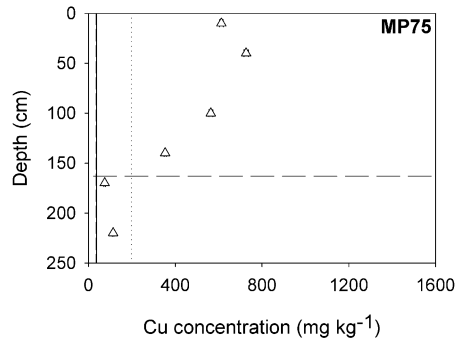
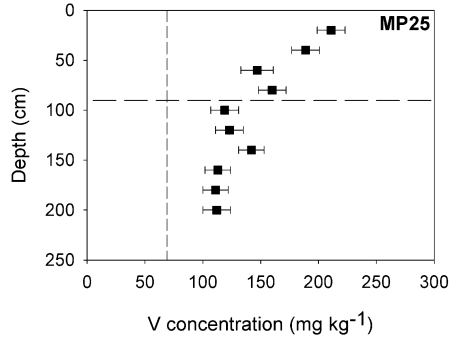
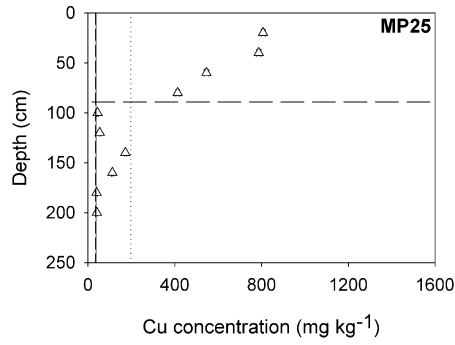
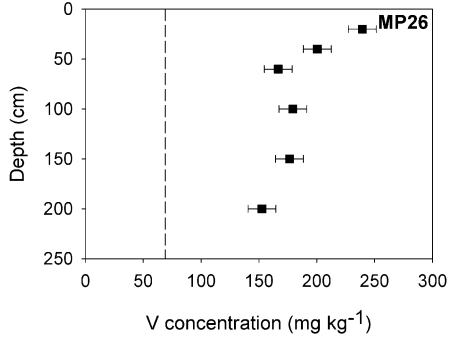
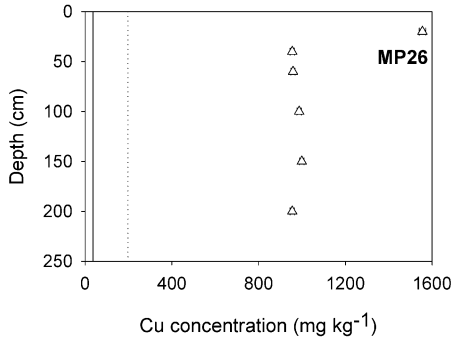
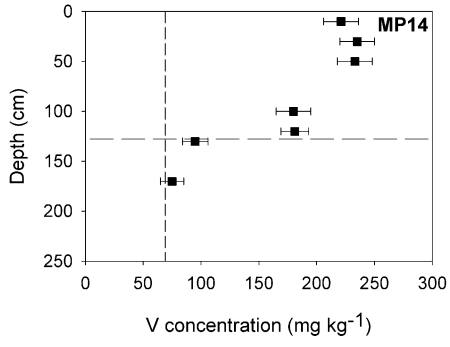
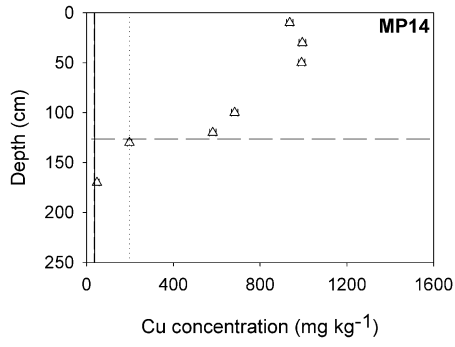
366 determined following aqua regia digestion. The vertical dashed line separates pre- and post-spill
367 samples. Note: for Cu, the BC SQC TEL (36 mg kg⁻¹) and background concentration (35 mg kg⁻¹) are
368 very similar and overlap.

369 **Metals in floodplain sediments**

370 Metal concentrations in exposed floodplain profiles at sites MP14, MP25 and MP75 show pre-spill
371 stream sediments overlain by between 0.9 – 1.6 m of Cu- and V-rich material released by the spill
372 (Figure 6). At site MP26, the Cu- and V-rich spilled material is more than 2 m thick. The thickness of
373 metal-rich material deposited and currently stored on the floodplain following the spill is spatially
374 heterogeneous; a pattern that was also recorded following the 1998 Aznalcóllar tailings spill in Spain
375 (Gallart et al., 1999). Concentrations of Cu are generally above the BC SQG PEL in the upper meter
376 of these deposits with concentrations ranging from 560 to 1550 mg kg⁻¹. With the exception of site
377 MP26, from c. 1 m below ground level, Cu concentrations are lower (40-581 mg kg⁻¹), below the BC
378 SQG PEL, and reflect the background Cu concentration determined for Hazeltine Creek (Table 2).
379 Similarly, site MP26 excepted, V concentrations in floodplain sediments deeper than 1m below
380 ground level (75-180 mg kg⁻¹) are also similar to the upper range of background concentrations,
381 whereas concentrations above this depth are higher (120-235 mg kg⁻¹). Arsenic concentrations
382 (Supplementary Material 2) display a similar down-profile pattern to Cu and V, and although
383 concentrations in the upper meter are above the BC SQG TEL, all concentrations with the exception
384 of one, fall below the BC SQG PEL. Lead and Zn are below BC SQG TEL concentrations in all samples
385 (Supplementary Material 2), and display no clear down-profile trends.

386

387



389 Figure 6. Copper and V concentrations from four floodplain profiles in Hazeltine Creek.
390 Concentrations determined by ICP-MS following aqua regia digestion. British Columbia (BC)
391 Sediment Quality Guidelines (SQG) and background concentrations are also plotted. Note: no SQG
392 has been determined for V, and for Cu, the BC SQC TEL (36 mg kg^{-1}) and background concentration
393 (35 mg kg^{-1}) are very similar and overlap. The horizontal line denotes the boundary between spill
394 material and the pre-spill floodplain material (note all samples at site MP26 were within spill
395 material). Cu and V concentrations in the four profiles are also compared using a boxplot.

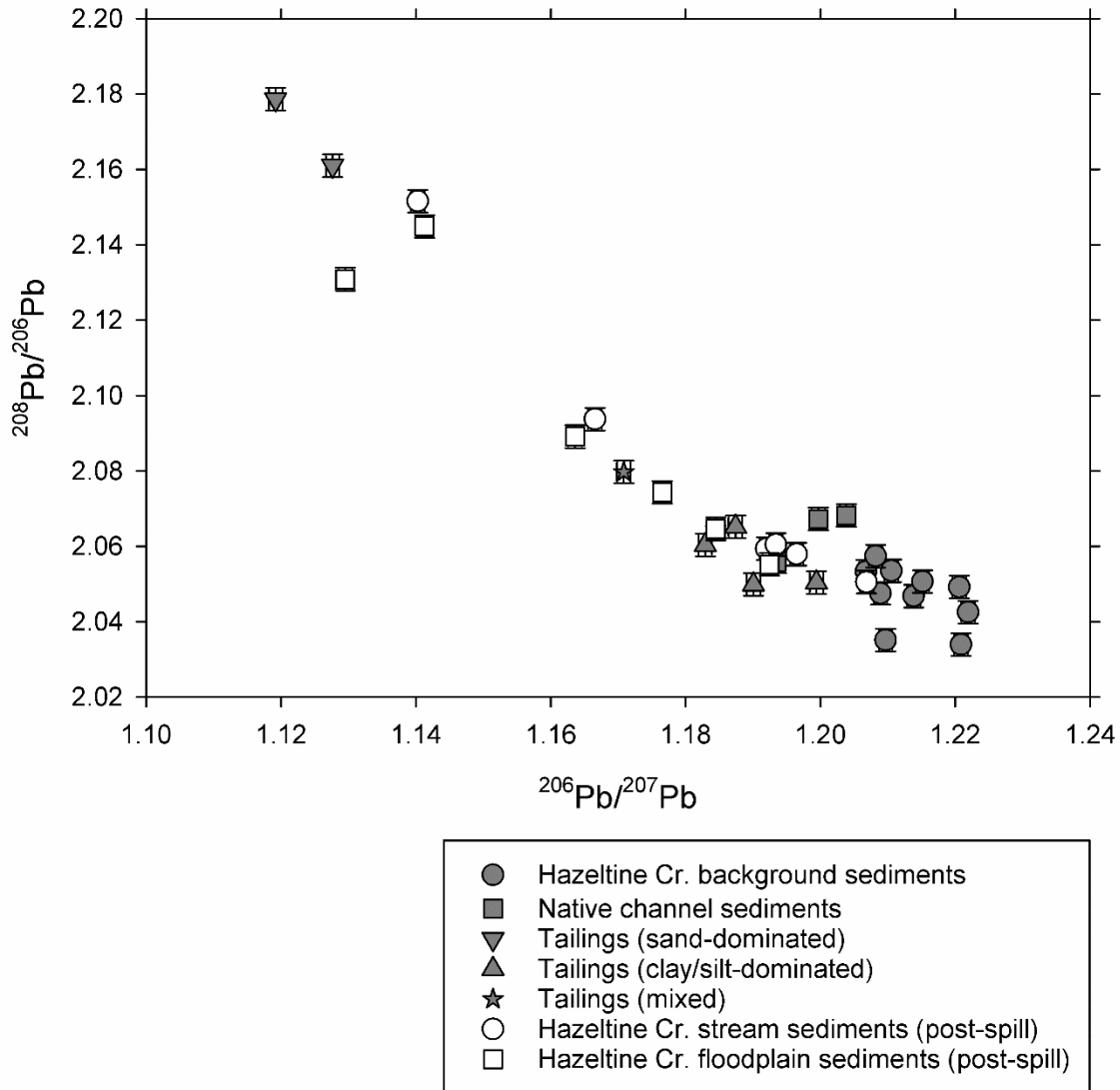
396 Concentrations of Cu and V in the floodplain profiles at site MP75, in lower Hazeltine Creek (c. 8.5
397 km channel distance), are generally lower than those at site MP14, in upper Hazeltine Creek (c. 1.5
398 km channel distance). Median and peak Cu concentrations are 682 mg kg^{-1} and 990 mg kg^{-1} ,
399 respectively at site MP14, and 458 mg kg^{-1} and 730 mg kg^{-1} at site MP75. However, the floodplain at
400 site MP26 (c. 6 km channel distance), approximately half-way between Polley Lake and Quesnel
401 Lake, contains the highest concentrations of Cu and V (median and peak Cu concentrations are 970
402 mg kg^{-1} and 1550 mg kg^{-1} , respectively). This suggests that, although there is a general down-profile
403 reduction in Cu and V concentrations at most sites, there is not a simple down-stream trend of
404 generally reducing metal concentrations in the floodplain deposits. Indeed, highest concentrations
405 occur in material deposited in the middle part of the study reach. This may be related to the bedrock
406 gorge reaches between 5.5 and 8 km channel distance (Figure 3) creating a backwater effect and
407 enhancing floodplain sedimentation, and the deposition of metal-rich material immediately
408 upstream.

409 **River sediment provenance**

410 Lead isotope signatures have been used to establish the provenance of river channel and floodplain
411 sediments in Hazeltine Creek and to quantify the contribution from key sediment sources (Table 1)
412 within the catchment to these sediments following the tailings spill.

413 Ratios for $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ in these potential source materials form a linear mixing linear
414 trend with the signatures for sand-rich tailings and background sediments (indicative of geogenic Pb
415 isotope signatures) forming the end members (Figure 7). Native channel sediments that pre-date the
416 spill, silt and clay-rich tailings and mixed tailings plot between these end-members (Figure 7). The
417 signatures for river channel and floodplain sediments deposited by the spill plot between the end-
418 members at varying points along the linear trend and show that they are derived from a mixture of
419 these source materials. Similar trends are also apparent in plots for $^{208}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and
420 $^{206}\text{Pb}/^{204}\text{Pb}$ (Supplementary Material 3).

421



422

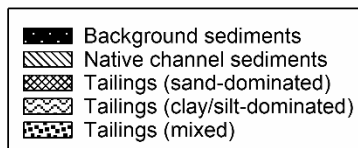
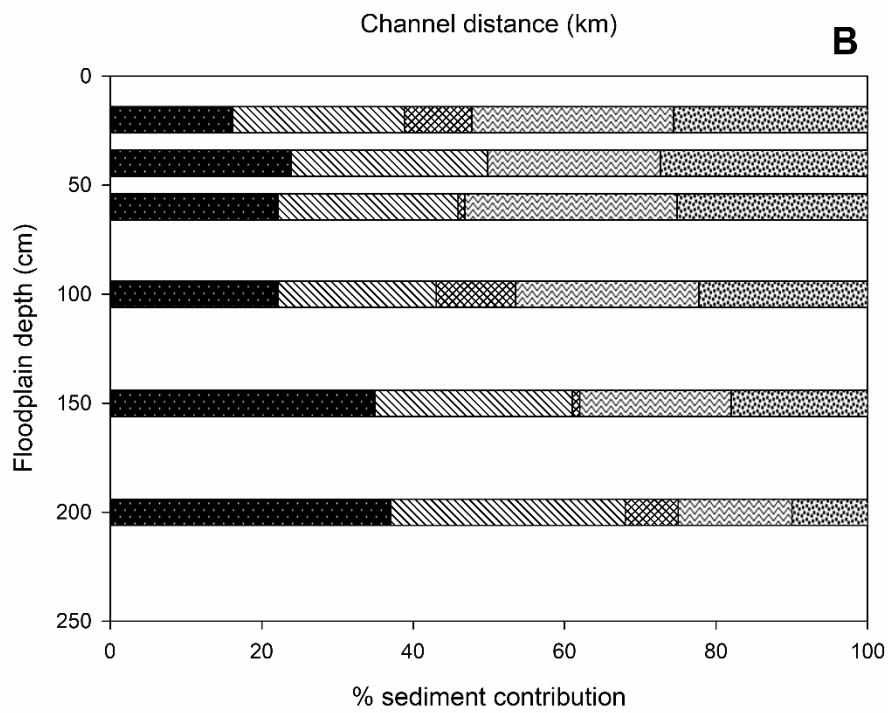
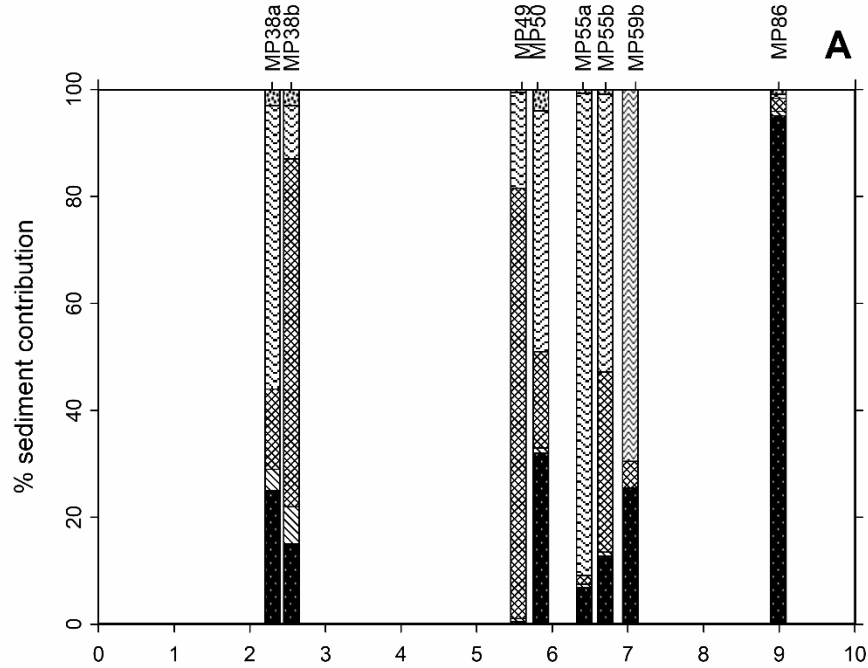
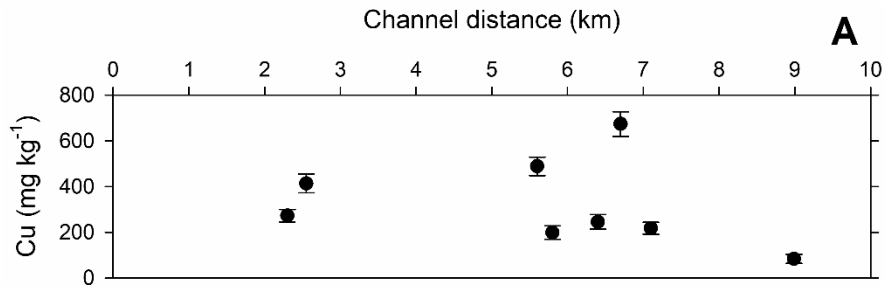
423 Figure 7. Ratios of $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ determined in river channel and floodplain sediments
 424 and tailings material from Hazeltine Creek.

425

426 The proportion of river channel sediment presently in Hazeltine Creek sourced from native channel
 427 sediments and mixed tailings is very low (both on average <2%) across all sample sites for which the
 428 mixing model was run (Figure 8a). However, the proportion of river channel sediment sourced from
 429 background sediments unaffected by mining, and sand-rich and silt/clay-rich tailings is greater, but
 430 also spatially variable. This indicates that the river channel sediments present within Hazeltine Creek
 431 following the spill reflect a mixture of background sediment (average = 27%), eroded from the valley
 432 floor during and following the accident, and tailings (on average, 28% sand-rich and 42% clay/silt-rich)
 433 released by the accident. River channel sediment samples with higher Cu concentrations (samples

434 MP38b, MP49, MP55b [430-670 mg kg⁻¹]) contain a greater proportion (34-80%) of sand-rich tailings
435 released by the spill (Figure 8a). Samples collected from approximately 6.5-7 km channel distance
436 (samples MP38a, MP55a, MP55b and MP59b) are primarily composed of clay/silt-rich tailings (52-
437 90%) and have generally lower, but still enriched, Cu concentrations (200-270 mg kg⁻¹).

438



440 Figure 8. Cu concentrations and percentage sediment contribution in stream sediments (A) and
441 percentage sediment contribution in floodplain sediment at site MP26 (B).

442

443 At the end of the study reach, river channel sediments at site MP86, draining out of the second of two
444 settling ponds that were constructed post-spill to reduce sediment fluxes to Quesnel Lake, contained
445 Cu, Pb and Zn at levels below the respective BC SQG PEL concentrations. This material comprised 95%
446 background sediments and indicates the success of the settling ponds in trapping sediments, and
447 particularly tailings-rich material. This is in notable contrast to sites upstream of the settling ponds
448 which contain channel sediments estimated to be composed of 67-99% of tailings material (of any
449 type), and therefore associated with mining-related sources.

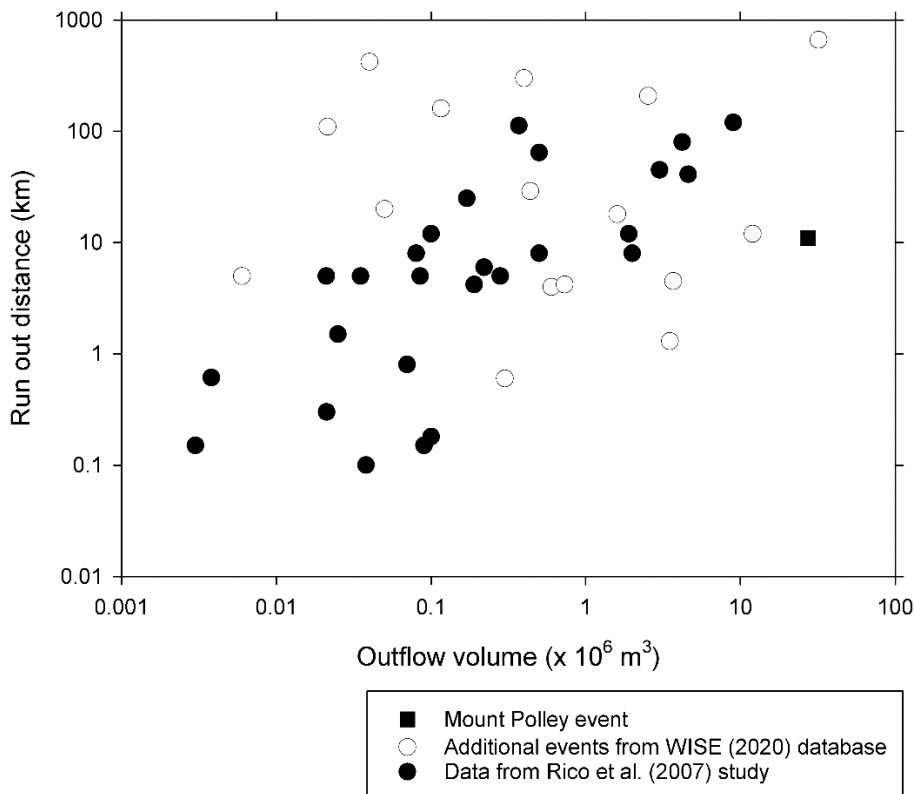
450 With respect to floodplain material (Figure 8b), it is evident that samples up to 100 cm depth contain
451 a greater proportion of tailings (50-61%) than samples at 150 cm (39%) or 200 cm (32%). Material at
452 150 and 200 cm depth contains a greater proportion of background and native channel sediments (up
453 to 68 % combined) compared to the upper 100 cm (up to 49% combined). The fingerprinting indicates
454 that this material deposited on the floodplain contains a mixture of released tailings and material
455 eroded by the flood wave that resulted from the TSF failure (Figure 8b). The downprofile changes in
456 the relative proportions of material derived from mining and non-mining sources indicates that the
457 proportion of these materials varied during deposition.

458 Concentrations in material at site MP26 are above guideline and background values, especially in the
459 upper profile (Figure 6). However, given that 38-68% of this material is derived from non-mining
460 sources, this highlights that there has potentially been a degree of physical dilution of mine waste by
461 large-scale erosion of 'clean' valley floor soil and sediment during the spill, and common during
462 exceptionally large tailings dam failures (Macklin et al., 2006). This is especially true in cases similar to
463 Mount Polley, where metal and As concentrations are low in the unmineralised parts of catchment
464 and where there have been no historical mining or metallurgical activities resulting in watercourse
465 contamination prior to the construction of the TSF (see Macklin et al., 2006).

466 **Implications for management of river systems impacted by TSF failures**

467 Previous studies have sought to compile chronologies of TSF failures, to analyse the spatial and
468 temporal trends in occurrence (Martin and Davies, 2000; Rico et al., 2008), and the cause of failures
469 (e.g. Lyu et al., 2019). From these studies, and from information held in databases such as WISE
470 (2020), it is evident that the magnitude of impact, both environmentally and socio-economically are
471 very varied. It is also apparent that there is a lack of consistent data collected on TSF failures. Each
472 failure is unique, in terms of the volume and composition of spilled material and the physical

473 environmental setting into which that material is released (Kossoff et al., 2014). For example, work
 474 by Rico et al. (2007) demonstrated a correlation ($r^2 = 0.56$) between the volume of spilled material
 475 and the run-out distance of that material for 28 TSF failures. However, as the authors note, the
 476 scatter within the data demonstrates the importance of the characteristics of the spill and the
 477 topography of the recipient environment. Of particular note in influencing the dispersal, storage and
 478 longer-term fate of spilled tailings will be the geomorphology of the recipient river system (Macklin
 479 et al., 2006; Kossoff et al., 2014). Figure 9 plots the relationship between volume of spilled material
 480 and run out distance for the 28 TSF failures included in Rico et al.'s (2007) study, plus an additional
 481 16 failures for which the data are available in the WISE (2020) database, including the Mount Polley
 482 event (Supplementary Material 4). It is apparent that the analysis of the larger number of events
 483 reduces the strength of the correlation relation ($r^2 = 0.25$), further highlighting the influence of
 484 event-specific characteristics. It is also apparent that the Mount Polley event has a relatively low
 485 run-out distance in relation to the volume of tailings released (Figure 9), determined by the relatively
 486 short distance between the TSF failure and Quesnel Lake.



487

488 Figure 9. Relationship between the volume of spilled material and run out distance for 44 TSF
 489 failures 1965-2020.

490 This study has demonstrated substantial contribution of eroded catchment materials to the volume
491 of material deposited within river systems following a tailings spill. Therefore, consideration of the
492 potential geochemical and geomorphological disruption within recipient river systems needs to
493 factor in the potential influence of these erosion process that may be initiated by the spill, but will
494 themselves be influenced by the characteristics of the spill event (e.g. water volume, flow, tailings
495 load). The initiation of erosive processes, as exemplified at Mount Polley, will also influence the
496 volume of particulate material (tailings and eroded sediments) that are deposited within river
497 systems and may need to be handled as part of remediation or reclamation works.

498 In the case of the Mount Polley TSF failure, although non-mining sediments helped to reduce overall
499 metal and As concentrations, the physical impacts of the spill on Hazeltine Creek and Quesnel Lake
500 were substantially amplified as a consequence of the flood wave eroding and remobilising very large
501 volumes of pre-mining valley floor and tributary deposits. So while the concentrations of metals and
502 As released into Hazeltine Creek were significantly smaller than in some other recent TSF failures
503 (Bird et al., 2008; Macklin et al., 2003), the scale of habitat, river and lake environment damage was
504 very substantial indeed. If unprecedented rates of sediment delivery to a catchment system by
505 mining activity is considered to be an act of pollution, and the destruction of pristine river
506 ecosystems in the 21st century viewed as being unacceptable, then the Mount Polley TSF failure
507 represents one of North America's most significant recent environmental disasters.

508 **CONCLUSIONS**

509 Analysis of river channel sediments following the Mount Polley tailing spill show concentrations of
510 Cu in Hazeltine Creek exceed the British Columbia Sediment Quality Guideline Probable Effect Level.
511 Concentrations were found to be highest in coarser-grained, sand-rich sediments and tailings. Spatial
512 trends in metal concentrations in sand-rich and clay/silt-rich river channel sediments reflect the
513 influence of hydraulic sorting, notably the differential transport and deposition of finer and coarser
514 material on the rising and falling limbs of flood wave caused by the TSF failure. Deposition of
515 material on the floodplain of Hazeltine Creek resulted in 1-2 m of Cu- and V-rich material burying the
516 former floodplain surface. Lead isotope analysis and multivariate mixing modelling indicated that
517 river channel sediments predominantly comprise a mixture of released tailings and catchment soils
518 and sediments eroded by the flood wave. The dominance of spilled tailings was also seen in the
519 material deposited on the floodplain surface, but up to 50% of material was derived from the
520 erosion of catchment soils and sediments. The fingerprinting of river channel and floodplain
521 sediments highlights the importance of erosive processes caused by TSF failures and of the
522 contribution of eroded catchment soils and sediments to the sediment loads transported and

523 deposited following the failure. These data indicate that the response to tailings spills by mining
524 companies and/or governments needs to consider the volumes and composition of spilled and
525 eroded material in the strategy.

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529 providing site information and data, and for field support.

530

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670 **SUPPLEMENTARY MATERIAL 1**

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673 Table 1. Analytical quality control data for aqua regia analyses.

	GSD-6 Certified ^a (mg kg ⁻¹)	Analysed (mg kg ⁻¹)	% Precision ^b	Duplicate analyses ^c
As	13.6 ± 1.0	12.4	9.5	2.1-32.8 (18.3)
Cd	0.43 ± 0.03	0.36	16.2	1.1-56.7 (27.7)
Cu	383 ± 12	350	8.4	1.1-23.1 (9.3)
Pb	27 ± 4	29	5.2	3.4-9.5 (9.7)
V	142 ± 8	131	7.8	1.6-28.8 (15.2)
Zn	144 ± 7	130	6.9	2.1-32.8 (18.3)

674 ^aCertified values are available from:

675 https://www.ncrm.org.cn/English/CRM/pdf/GBW07302_20160301_134249108_1713109.pdf

676 ^bDetermined from replicate analysis (n = 10) of the GSD-6 CRM.

677 ^cAnalyses to monitor the comparability of datasets provided by the Mount Polley Mining
 678 Corporation and those generated by this study. Twenty randomly selected samples previously
 679 analysed by the Mount Polley Mining Corporation, were reanalysed by this study. Data presented
 680 are the range of percentage differences between the analysis of duplicates, with mean in
 681 parentheses.

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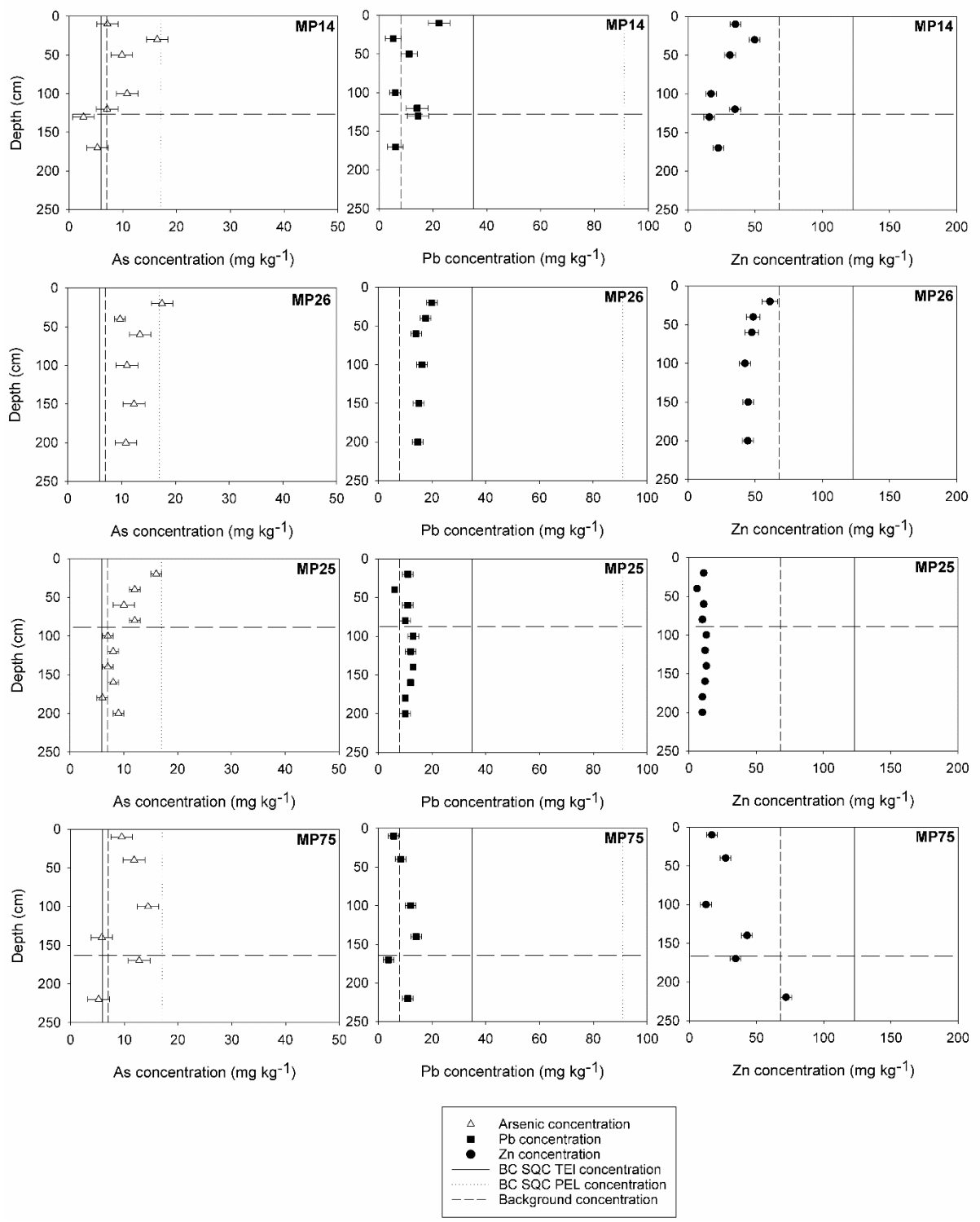
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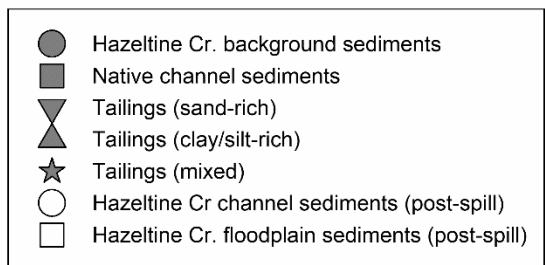
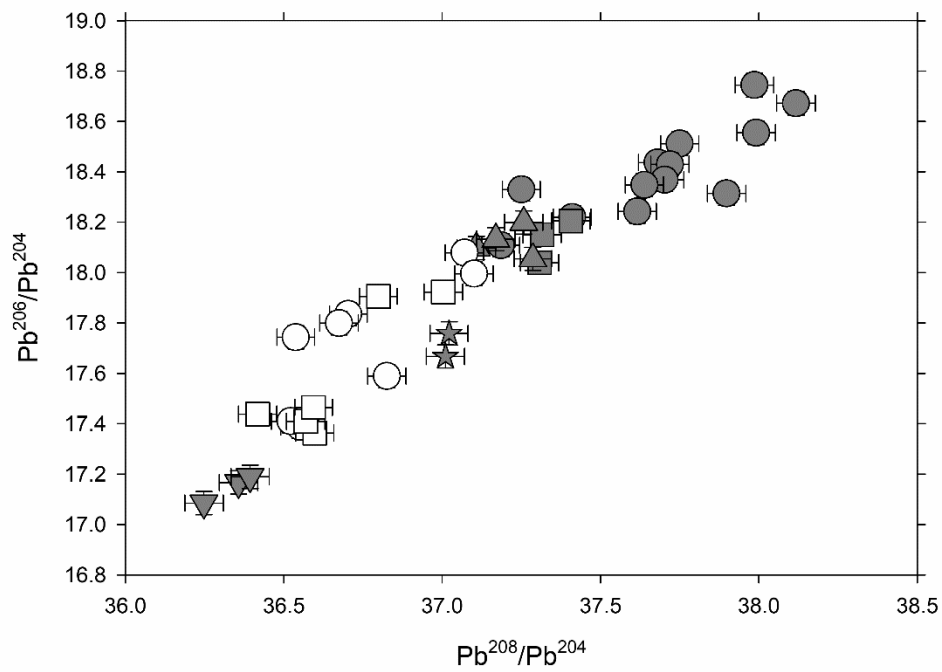
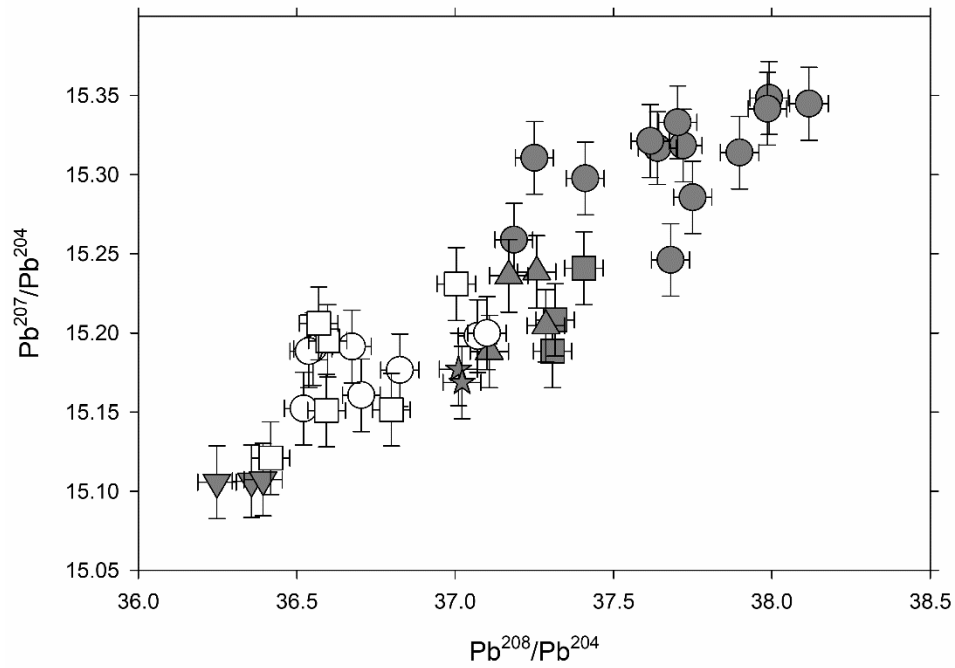
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721 **SUPPLEMENTARY MATERIAL 4**

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723 Table 1. Data for volume of material released (tailings and water) and run out distance for TSF
 724 failures 1965-2020. Data from Rico et al. (2007) are italicized and data for other events (including
 725 Mount Polley [**bold**]) are taken from WISE (2020).

Event, Location	Date	Volume of material released (x10 ⁶ m ³)	Run out distance (km)
San José de Los Manzanos, Mexico	2020	0.006	5
Tieli, China	2020	2.53	208
Córrego de Feijão, Brazil	2019	12	12
Cieneguita , Mexico	2018	0.439	29
Germano, Brazil	2015	32	663
Mount Polley, Canada	2014	27.4	11
Buenavista del Cobre, Mexico	2014	0.04	420
Huancavelica, Peru	2010	0.02142	110
Cerro Negro, Chile	2003	0.05	20
Sasa Mine, Macedonia	2003	0.1	12
Amatista, Nazca, Peru	1996	0.3	0.6
El Porco, Bolivia	1996	0.4	300
Marcopper, Philippines	1996	1.6	18
Harmony, Merriespruit, South Africa	1994	0.6	4
Niujaolong, China	1985	0.73	4.2
Balka Chuficheva, Russia	1981	3.5	1.3
Silverton, USA	1975	0.116	160
Huogudu, China	1962	3.68	4.5
<i>Baia Mare, Romania</i>	<i>2000</i>	<i>0.1</i>	<i>0.18</i>
<i>Los Frailes, Spain</i>	<i>1998</i>	<i>4.6</i>	<i>41</i>
<i>Omai, Guyana</i>	<i>1995</i>	<i>4.2</i>	<i>80</i>
<i>Stancil, USA</i>	<i>1989</i>	<i>0.038</i>	<i>0.1</i>
<i>Itabirito, Brazil</i>	<i>1986</i>	<i>0.1</i>	<i>12</i>
<i>Stava, Italy</i>	<i>1985</i>	<i>0.19</i>	<i>4.2</i>
<i>Cerro Negro No.4, Chile</i>	<i>1985</i>	<i>0.5</i>	<i>8</i>
<i>Veta del Agua N°1, Chile</i>	<i>1985</i>	<i>0.28</i>	<i>5</i>
<i>Ollinghouse, USA</i>	<i>1985</i>	<i>0.025</i>	<i>1.5</i>
<i>Phelps-Dodge, USA</i>	<i>1980</i>	<i>2</i>	<i>8</i>
<i>Churchrock, USA</i>	<i>1979</i>	<i>0.37</i>	<i>112.6</i>
<i>Mochikoshi No.1, Japan</i>	<i>1978</i>	<i>0.08</i>	<i>8</i>
<i>Mochikoshi No.2, Japan</i>	<i>1978</i>	<i>0.003</i>	<i>0.15</i>
<i>Arcturus, Zimbabwe</i>	<i>1978</i>	<i>0.0211</i>	<i>0.3</i>
<i>Bafokeng, South Africa</i>	<i>1974</i>	<i>3</i>	<i>45</i>
<i>Galena Mine, USA</i>	<i>1974</i>	<i>0.0038</i>	<i>0.61</i>
<i>Unidentified, USA</i>	<i>1973</i>	<i>0.17</i>	<i>25</i>
<i>Buffalo Creek, USA</i>	<i>1972</i>	<i>0.5</i>	<i>64.4</i>
<i>Cities Service, USA</i>	<i>1971</i>	<i>9</i>	<i>120</i>
<i>Hokkaido, Japan</i>	<i>1968</i>	<i>0.09</i>	<i>0.15</i>

<i>Sgurigrad, Bulgaria</i>	<i>1966</i>	<i>0.22</i>	<i>6</i>
<i>Bellavista, Chile</i>	<i>1965</i>	<i>0.07</i>	<i>0.8</i>
<i>Cerro Negro No.3, Chile</i>	<i>1965</i>	<i>0.085</i>	<i>5</i>
<i>El Cobre Old Dam, Chile</i>	<i>1965</i>	<i>1.9</i>	<i>12</i>
<i>La Patagua New Dam, Chile</i>	<i>1965</i>	<i>0.035</i>	<i>5</i>
<i>Los Maquis, Chile</i>	<i>1965</i>	<i>0.021</i>	<i>5</i>

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