

Predictive Assessment of Toxicants Migration from Technogenic Gold-Mining Wastes (Case Study of the Tailings Management Facility of Tokur Mill, Amur Region, Russia)

Valentina Ivanovna Radomskaya

Institut geologii i prirodopol'zovaniâ DVO RAN: Institut geologii i prirodopol'zovania DVO RAN

Lyudmila Mikhailovna Pavlova (✉ pav@ascnet.ru)

Institute of Geology and Nature Management Far Eastern Branch Russian Academy of Sciences

<https://orcid.org/0000-0002-3734-1445>

Lyudmila Pavlovna Shumilova

Institut geologii i prirodopol'zovaniâ DVO RAN: Institut geologii i prirodopol'zovania DVO RAN

Elena Nikolaevna Voropaeva

Institut geologii i prirodopol'zovaniâ DVO RAN: Institut geologii i prirodopol'zovania DVO RAN

Nina Aleksandrovna Osipova

Tomsk Polytechnic University: Nacional'nyj issledovatel'skij Tomskij politehnikeskij universitet

Research Article

Keywords: Elements , Gold-Mining , Wastes , TMF, Migration , Extraction , Fraction , Predictive Assessment , Acidogenic and Acid-Neutralising Potentials

Posted Date: March 15th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-202868/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Environmental Earth Sciences on November 8th, 2021. See the published version at <https://doi.org/10.1007/s12665-021-10077-y>.

1 **Predictive Assessment of Toxicants Migration from Technogenic Gold-Mining Wastes (Case**
2 **Study of the Tailings Management Facility of Tokur Mill, Amur Region, Russia)**

3

4 Radomskaya V.I.¹ • Pavlova L.M.¹ • Shumilova L.P.¹ • Voropaeva E.N.¹ • Osipova N.A.²

5 ¹ Institute of Geology & Nature Management Far Eastern Branch Russian Academy of Sciences; 675000, Amur region,
6 Blagoveshchensk, Relochniy line, 1, Russia,

7 ² National Research Tomsk Polytechnic University, 634050, Tomsk, Russia

8

9 Radomskaya V.I.

10 e-mail: radomskaya@ascnet.ru

11

12 Pavlova L.M. – correspondent

13 e-mail: pav@ascnet.ru

14

15 Shumilova L.P.

16 e-mail: shumilova.85@mail.ru

17

18 Voropaeva E.N.

19 e-mail: levorglav@mail.ru

20

21 Osipova N.A.

22 e-mail: osipova-nina@yandex.ru

23

24 **Abstract**

25 The results of the toxic elements behavior predicting in gold mining technogenic waste during their draining
26 with seasonal precipitation (case study of the tailings management facility of Tokur Mill, Amur Region, Russia)
27 present in this article. The predictive assessment was made on characteristics basis of the tailings management
28 facility material: the geochemical composition, migration ability of elements in model experiments using atomic
29 emission and mass spectral methods, calculation of acid-producing and acid-neutralizing potentials. The
30 substance of the tailing management facility has a high acid-neutralizing potential due to the carbonates in it,

31 which contributes to the neutral and slightly alkaline drainage flows formation. Under these conditions, the
32 migration of Cd, Bi, Pb, Sr, Co, Cu, Ni, Zn, Sb risk is low, and water migration of oxygen-containing As risk
33 anions is very high, since the share of its mobile compounds in the tailings management facility material is 90-
34 92%.

35
36 **Keywords** Elements • Gold-Mining • Wastes • TMF, Migration • Extraction • Fraction • Predictive Assessment
37 • Acidogenic and Acid-Neutralising Potentials

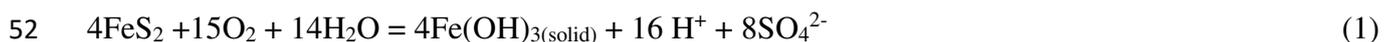
38

39 **Introduction**

40

41 Adverse impact of mining on the environment is consistently increasing world-wide due to boost of
42 production and processing of mineral resources. Mineral processing creates big amount of unusable
43 waste (overburden rock, mill tailings). The waste is stored in dumps or tailings management facilities
44 (TMFs) where it is kept for indeterminate time. As a rule, mining wastes contain compounds with toxic
45 and hazardous elements, such as As, Cd, Cr, Cu, Hg, Pb, Ni, Zn and others (Jambor et al. 2003; Kapaj
46 et al. 2006; Lottermoser 2007; Hoguet et al. 2013; Quansah et al. 2015). Being influenced by climatic
47 factors, the mineral compounds in the dumps are intensively weathered and transform quite rapidly.
48 When seasonal water flows (rainfall and snow-melt waters) interact with sulphide-bearing waste,
49 acidic (sulphate) drainage waters are formed due to oxidation of sulphide minerals (pyrite,
50 arsenopyrite, etc.) by the Eq. (1), (2):

51



53



55

56 The formed acids, in their turn, dissolve other waste components which increases migration
57 ability of toxic elements (Plyusnin and Gunin 2001; Corkhill and Vaughan 2009). In natural conditions,
58 sulphuric acid leaching as one of geochemical processes in hypergenesis of ore-caused sulphide-

59 bearing objects occurs imperceptibly. However, technogenesis steps them up tremendously.
60 Precipitation leaking through the waste gets into surface and ground waters. With the drainage waters
61 the released chemical elements and newly formed compounds migrate far beyond the dumps and
62 TMFs. Seasonal water flows contribute to distribution of toxic elements tens and hundreds kilometres
63 away from the source. It is difficult to predict how long the toxic elements of the stored waste will
64 arrive in the environment. According to Yanin (1993), the process may last tens or hundreds of years
65 depending on the quantity of sulphides, the rate of sulphide oxidation and the way the aggressive
66 wastes get into water.

67 In the Upper Amur Basin, gold has been mined for a long period of time (over 160 years) and
68 huge quantities of mining wastes, namely overburden rock dumps, tailing ponds and storages of slurry
69 tailings from gold processing plants have been amassed, often next to residential areas. For a long
70 time, up to 1988, gold mining in Russia was conducted with mercury to extract fine gold
71 (amalgamation). The process comprising selective wetting of gold particles with mercury used to be a
72 necessary part of traditional flow diagram/technological scheme of gold recovery. However, the
73 equipment and facilities of the mines were mostly artisanal and there was hardly any standardized
74 equipment (On termination... 1988). One of the most environmentally hazardous procedures was
75 evaporating of mercury out of amalgamated gold which was conducted in retort ovens without any
76 efficient condensing or mercury capturing system (Laperdina et al. 1995). Due to inferiority of the
77 capturing systems, the mercury vapours were drifted into the tailings. In the Tokur Mill (Amur Region)
78 gravity concentrate was amalgamated with mercury consumption 6–7 g per 1 tonne. In the period from
79 1969 to 1974 the mercury consumption in the mine amounted 3.070 kg (Koval et al. 2002). So, dumped
80 mining wastes may be the source of chemical elements of different hazard category.

81 The main objective of the study was experimental determination of toxic elements mobility in
82 technogenic gold-mining wastes (case study of the TMF of the Tokur Mill) in order to assess their
83 possible migration into adjacent environments.

84

85 **Materials and methods**

86 **Characteristics of the site**

87
88 The study object is the tailings of gold-bearing ore of the Tokur Mill. Waste like pulp had been
89 delivered to the TMF until the mine was suspended (2003). During years 1965–1996 2.548 thousand
90 tonnes of processed rock were dumped in the TMF (Pavlova et al. 2016). The TMF consists of two
91 plots (the old one and the new one) whose total length is 1.770 m. The plots lie along the right bank of
92 the Malyi Karaurak River, very close to the residential area of the settlement Tokur (Fig.1). In the north
93 and east, the TMF is bounded by piled dams, in the west, there is a natural slope. Permeability of the
94 dams rock is quite high as initially the dam was built with washed boulder and gravel deposits. As the
95 TMF reservoir was filled, the walls of the dam were piled up by wastes from the Mill. In spring and
96 summer the dam is intensively eroded by precipitation, the waters leak through the dam body into the
97 Malyi Karaurak. The TMF surface lacks humic layer, vegetation like wormwood and poplar
98 undergrowth is scarce.

99

100 **Fig. 1** Map-scheme of the Tokur Mill tailings area: ●2 – sample points

101

102 High permeability of the guard dam, formation of leakage channels and scours as well as
103 overloading of the tailings facility several times resulted in the dam failure and spread of man-made
104 waste as far as 3.5 km around the river valley. One of such failures caused flooding of lower and upper
105 floodplain forests of the Malyi Karaurak. Heavy (about 0.5–1 m depth) silt-loam layer was formed
106 which caused complete dieback of the forest stand. By now, the Mill wastes have spread with surface
107 waters down the river to the Barandzha Brook. Spreading of the wastes out of the TMF may cause
108 pollution of natural streams with not only suspensions but also highly-toxic elements.

109

110 **Natural and climatic characteristics of the area**

111

112 The TMF of the Tokur Mill is the integral part of technogenic ecosystem of the gold deposit Tokur.
113 The deposit is located in the north-east of Amur Region in the geographical region called Mountain
114 North. The landscape of the area is mountainous, having a lot of deep valleys and high hilly territories.
115 Altitudes of the hills reach 700–1500 m, relative excess of watersheds over the valley bottoms is 400–
116 480 m. The nearest mountain system is the Selemdzha Range. In hydrographic terms the area belongs
117 to the Selemdzha River basin and its tributaries.

118 The climate of the region is continental with monsoon features of the distribution of annual
119 precipitation. The hottest summer month is July, mean temperature reaches +15 to +20 °C, the highest
120 attainable temperature is +35 °C. The coldest month is January, the temperature may go down to -56
121 °C, 35-Centigrade temperatures last more than a month. Mean annual precipitation reaches 700 mm;
122 maximum precipitation (about 90%) is in summer period; winters are dry; the snow cover reaches 50
123 cm depth.

124 The area is characterized by permafrost which in some places reaches 70–80 or more metres
125 depth. The permafrost has regular distribution, insignificant melting spots occur in large river valleys
126 and on flat watersheds. In summer, frozen southern-slope ground melts 2–3 m depth, in poorly heated
127 and marshy areas as well as in bogs and swamps – 0.6–1.2 m depth. Seasonal melting forms in the
128 layer pore-stratal water whose impervious layer is permafrost. In the sites without drainage, the ground
129 water horizon reaches daylight surface. In relatively dry sites, after rainfall and at the end of the summer
130 season, 0.2–0.6 m depth soils are also water-abundant.

131 Hydrogeological conditions of the area are dependent on subpermafrost water of the seasonal
132 melting layer. Water-bearing soils of the layer are loose alluvial and deluvial deposits of small
133 thickness. All water-bearing subpermafrost horizons except alluvial soils freeze in the winter period.
134 The zonal soils of the region are mountain brown taiga illuvial-humic/Haplic Cambisols Dystric,
135 intrazonal – alluvial-sod soils which form in the river plains. Brown taiga illuvial-humic soils (Fig. 1
136 point No 1) are shallow marginal, there is a lot of rock debris in it. According to texture they belong to
137 gravel-stony loam with little percentage of silt. The main reason of stony texture is slow weathering of

138 the rock. Alluvial-sod soils (Fig. 1 point No 2) are common in river-side plain of the Malyi Karaurak
139 because while the placer was in progress the river plain landscape was damaged.

140

141 **Geology of Tokur deposit**

142

143 As ore composition and procedure of its recovery significantly influence element behavior in the TMF,
144 geological and geochemical characteristics of the deposit.

145 Geological structure of the deposit and mineral composition of its ore have been specified before
146 (Ejriş 2002; Ejriş et al. 2002; Ostapenko and Neroda 2007, 2016; Sorokin et al. 2011; Stepanov and
147 Melnikov 2017), so we may only give brief profile. The Tokur deposit is sited in the east of Mongol-
148 Okhotsk fold belt, in Selemdzha-Kerch gold zone. The deposit is confined to the southern wing of the
149 Chelogorsk anticline of latitudinal strike (near its dome-shaped arch), composed of weakly
150 metamorphosed sand-clay and siliceous deposits of the Tokur (PZ_{2-3tk}²) and Ekimchan (PZ_{2-3ek}) suite
151 of the Permian-Carboniferous age. Ore bodies are formed as a result of cementation and metasomatic
152 substitution by ore quartz of crushing materials for longitudinal, slightly consonant tectonic zones.
153 These are mineralized tectonites of breccia and banded texture. The fragments and lenses of the host
154 rocks are cemented by quartz of various generations. Native gold is genetically associated with quartz.
155 Besides quartz, the vein minerals present in the ores are adularia, sericite, chlorite and calcite. Ore
156 minerals, which make up 1–3% of the ore volume, are represented by pyrite and arsenopyrite;
157 sphalerite, galena, chalcopyrite, scheelite, pyrrhotite and fahl ores are less common, tin ore is very rare.
158 Part of the gold in the intergrown and emulsion impregnation forms was enclosed in pyrite,
159 arsenopyrite and galena. Primary ores, according to the mineralogical and geochemical composition,
160 power and gold content, do not change much with depth.

161

162 **Study methods**

163

164 **Soil sampling**

165
166 Sampling from the TMF was performed in the summer-autumn period from 2015 to 2016. Sampling
167 points (Fig. 1) were located like this: points No 1, 2 (soil) sited above the deposit and the TMF level,
168 and taken as background; points No 3, 4, 5, 6, 7 (industrial ground) are sited exactly in the old and new
169 plots of the TMF. The material was collected from the 0-10-cm top layer by ‘envelope’ technique (five
170 samples are collected in the shape of an envelope) on the 10×10 m area. Five samples were united into
171 1-kg sample. In points No 4 and 5 samples were collected layer-by-layer along the test pit to depths 80
172 and 230 cm respectively. The samples were thoroughly mixed to homogenize, quartered, one part was
173 grounded to 200 mesh to determine element composition.

174

175 **Method for predictive assessment of element mobility**

176

177 To determine possible consequences of drainage influence on natural components the predictive
178 assessment of toxic element mobility due to interaction of precipitation with the components of tailings
179 is applied. The method is based on the experiments aimed at getting a quantitative of element leaching,
180 element mobility in water and level of hazard which drainages cause to water reservoirs, water flows
181 and soils (Sobek et al. 1978; Paktunc 1999; Hageman et al. 2015; Dold 2017). One of the methods used
182 to predict drainage acidity is calculation of acidogenic and acid-neutralising potential of mining waste
183 and tailings matter (Paktunc 1999; Alekseev et al. 2011; Edelev 2009, 2013; Bortnikova et al. 2018).
184 Acidogenic value is widely used in environmental research (Skousen et al. 2002; Gaskova and
185 Bortnikova 2007; Edelev 2013).

186 Acidogenic potential (AP) is a value of acid maximum which may develop as a result of
187 hydrolytic oxidation of sulphites according to reactions 1–2 (Sobek et al. 1978). The value is calculated
188 basing on sulphur concentration in the form of sulphites. The measurement unit is relative amount of
189 calcium carbonate (kg per tonne of matter) required for acid neutralization according to the Eq. (3):

$$190 \quad AP = 10 \times \eta(S_{\text{sulphide}}) \times \frac{M(\text{CaCO}_3)}{M(\text{S})} \approx 10 \times \eta(S_{\text{sulphide}}) \times \frac{100}{32} = \eta(S_{\text{sulphide}}) \times 31.25, \quad (3)$$

191

192 where 10 is conversion coefficient kg/t into wt%; η (S_{sulphide}) – sulphide sulphur concentration in the
193 matter, wt%; $M(\text{CaCO}_3)$ and $M(\text{S})$ – calcium carbonate molar mass (100 g/mol) and sulphur (32 g/mol)
194 respectively (Edelev 2013).

195 To calculate AP values in soil samples, the content of total and sulphate forms of sulphur was
196 determined (Sulfur 1986). The sulphide sulphur content is calculated by the difference between total
197 and sulphate sulphur.

198 The value of the acid-neutralising potential (ANP) is used to quantify the ability of a substance
199 to neutralise acidic drainage (Sobek et al. 1978; Skousen et al. 2002) according to Eq. (4):



201 in which $\text{M} = \text{Ca}^{2+}, \text{Mg}^{2+}$.

202 Acid is mostly neutralised by carbonates, the most effective of which is calcite (Solomin and Krainov
203 1994). The value of ANP (kg CaCO_3/t) is calculated using the Eq. (5):

$$204 \quad \text{ANP} = n(\text{CaCO}_3) = 10 \times \eta(\text{CaCO}_3), \quad (5)$$

205 in which $n(\text{CaCO}_3)$ is the calcium carbonate content in the matter, kg/t; $\eta(\text{CaCO}_3)$ calcium carbonate
206 content in the matter, % (Paktunc 1999).

207 The content of carbonate minerals in the tailings samples was determined basing on the mineral
208 analysis data.

209 The difference between AP and ANP is called actual acidogenic potential (AAP) (Sobek et al.
210 1978; Ritcey 2005), $\text{AAP} = \text{ANP} - \text{AP}$. The AAP value gives us an idea of the resulting acidity of the
211 drainage in the future. Acidogenic is considered mineral matter of wastes with $\text{AAP} < -20 \text{ kg CaCO}_3/\text{t}$.
212 When the AAP value exceeds 20 kg CaCO_3/t , neutral and weakly alkaline waters are formed (Skousen
213 et al. 2002; Lengke et al. 2010; Edelev 2013). In the range $-20 \text{ kg CaCO}_3/\text{t} < \text{AAP} < 20 \text{ kg CaCO}_3/\text{t}$,
214 the uncertainty area lies.

215

216 **Determination of element migratory potential**

217

218 Migratory potential of tailings toxic elements in the Tokur Mill was determined experimentally, by
219 acting on it with different extractants. For the experiments, industrial ground from the old (point No 4)
220 and new (point No 7) plots of the TMF was used, the ground was dried in air to constant weight. In the
221 industrial ground samples, weak bounds in compounds of minerals and elements which under certain
222 conditions may migrate into adjacent environments (natural waters or soils) were determined by the
223 method of parallel extraction. The group of elements includes exchangeable, complex and specifically
224 sorbed forms of elements which are extracted with various extractants. Element compounds form the
225 following sequence according to the decrease of mobility within the group: water-soluble forms >
226 exchangeable forms > complex forms > specifically sorbed forms (Radomskaya et al. [2016](#), [2017](#)).

227 Water-soluble element compounds were extracted with snow-melted water (pH 7.09),
228 exchangeable – 1 M NH₄Ac with pH 4.8. The extraction was carried out for 18 hours at S/L = 1 : 5
229 with periodic stirring, the solution was separated by centrifugation (7000 rpm) for 15 min. In addition
230 to exchangeable, complex (organomineral) element compounds were extracted with 1% solution of
231 EDTA in ammonium acetate buffer (pH 4.8). Based on the difference between the content of elements
232 in 1% EDTA in 1 M NH₄Ac and 1 M NH₄Ac extracts, the quantity of elements in the composition of
233 organomineral complexes was calculated.

234 The content of elements in the hydrochloric acid extract (1 M HCl) shows potential reserve of
235 mobile element compounds in soils. Acid-soluble compounds are represented by exchangeable and
236 specifically sorbed forms of elements. Therefore, the number of specifically sorbed compounds was
237 found by the difference between the number of elements extracted by hydrochloric acid (1 M HCl) and
238 ammonium acetate (1 M NH₄Ac) extracts ([Madzhieva et al. 2014](#); [Minkina et al. 2018](#)). 1 M HCl
239 extraction was carried out for 1 hour with constant stirring and at the ratio S/L = 1 : 10. To assess the
240 potential reserve of toxic elements mobile compounds in industrial soils, their proportion in the gross
241 content was calculated.

242

243 **Instrumental methods**

244

245 The elemental composition of the samples, the content of the main cations and trace elements in the
246 extracts were determined by atomic emission (iCAP-6500, Thermo Scientific, USA) and mass-spectral
247 (X-7, Thermo Elemental, USA) methods in the Analytical Certification Test Centre at the Institute of
248 Microelectronics Technology and High Purity Metals of the Russian Academy of Sciences according
249 to the methods of NSAM №520-AES/MS and NSAM №499-AES/MS. In the calculations, in cases
250 when the element concentrations were below detection limit, the values equal half of the detection limit
251 were used (Golovin et al. 2002).

252 Open leaching experiments may include unrecorded mercury losses (Gladyshev et al. 1974).
253 Therefore, the thermoforms of mercury were determined in the initial material by atomic absorption
254 (pyrolysis) on the mercury analyzer “PA-915+” with the attachment “PIRO-915+” (Lumex, Russia).
255 This method allows us to identify the preferred forms of mercury in complex environments such as
256 mineral soils (Bloom et al. 2003; Pinedo-Hernández et al. 2015). Mercury thermoforms were
257 determined by increasing the temperature at an average heating rate of 0.8 °C/s. The detection limit of
258 the method was 5 ng/g.

259 Organic carbon in the samples was determined using a SHIMADZU TOC-V CPN (Shimadzu
260 Corp., Japan) carbon analyzer using the SSM-5000A module.

261

262 **Results and discussion**

263

264 **Characteristics of industrial ground elemental composition**

265

266 Industrial soil of the TMF is represented by a rather homogeneous finely dispersed mass of greyish-
267 brown colour. By texture, it is silty sand with predominant (79.9% on average) content of small and
268 fine particles (0.25–0.071 mm) (Table 1). The proportion of fine fractions increases with depth from
269 70.8 to 88.1%. Occurrence of the larger 1–0.5 mm fractions is minimal and decreases TMF, mechanical
270 degradation of large particles and their vertical fractional differentiation occurs in a sharply continental

271 climate. Almost complete absence of organic and mineral colloids, poor compactness, lack of cohesive
272 properties lead to high water permeability of the soil and contributes to its rapid erosion.

273

274 **Table 1** Granulometric composition of the Tokur Mill tailings material

275

276 In the soil mineralogical composition (Table 2), rock fragments predominate in volume,
277 consisting of intergrowths of quartz minerals, feldspar, amphibole, mica, and carbonate in various
278 proportions. The quartz content is 8–32%, feldspars – up to 21%, calcite – 4–11%, these minerals are
279 often associated with iron hydroxide films. The content of sludge, which is detached-in-water clayey-
280 dusty material of dark brown colour, reaches 32%. Ore minerals are insignificant.

281

282 **Table 2** Mineral composition of the Tokur Mill tailings material, %

283

284 The minimum and maximum contents of chemical elements in the tailings material do not have
285 significant variations (Table 3). The greatest scatter was found in the Hg and Bi concentrations, the
286 ratio of the maximum concentration to the minimum was 97 and 57.1 respectively. In conditionally
287 background soils, the greatest variability was noted in the CaO content.

288 Compared with the upper continental crust (Table 3), the bulk composition of the tailings of the
289 Tokur Mill is characterized by a relative deficiency of many elements – Na, Mg, Al, P, Ca, Sc, Co, Ni,
290 Rb, Ga, Sr, Y, Zr, Nb, Mo, Cd, Sn, Cs, Tl, Th, U and heavy lanthanides. Significantly high
291 concentrations of As, Sb, W, Bi were observed, their concentration coefficients, calculated as the ratio
292 of the average element content in soil samples to the conventional element clark in the upper
293 continental crust (according to Taylor and MacLennan 1988), are 1005.4, 36.1, 16.3 and 5.2
294 respectively Pb, Ba, Zn, Cu, Ni, Cr, V concentrations in some samples exceed bulk earth values.
295 Concentrations of other elements vary but insignificantly. Moreover, in some samples there was a
296 certain deficiency of these elements, in others – an excess.

297 The gross content of As and Sb in the soil is higher than similar indicators for conditionally
298 background soils and sanitary and hygienic standards. As concentration was 400–1640 times as high
299 as the maximum admissible, Sb concentration – 1.2–2.7 times.

300 Exuberant As concentration in the conditionally background sites (4.5–19.4 maximum
301 admissible) most likely indicates natural metallogenic features of the region. The calculated anomaly
302 coefficients (Saet et al. 1986) reflect increase of average element concentration in the soil compared to
303 the background soil. According to the obtained data (Table 3), anomaly level for As, W, Hg, Sb is
304 higher than for other elements.

305

306 **Assessment of acidogenic potential of the TMF industrial soil**

307

308 The hazard potential of tailings material for the environment determines the choice of environmental
309 measures, therefore, the investigation of the processes occurring during the long-term interaction of
310 waste and precipitation is of great importance. First of all, predictive assessment of drainage chemical
311 composition can be given in terms of acidogenic and acid-neutralising potentials. For the calculation,
312 data on the quantity of acidogenic (sulphides) and acid-neutralising (carbonates) mineral are used.
313 Table 4 presents the AP and ANP values of the tailings material in the Tokur Mill.

314

315 **Table 4** AP and ANP values (kg CaCO₃/t) in the tailings soil of the Tokur Mill

316

317 The results showed that all soil samples of the TMF are characterized by a high acid-neutralising
318 potential due to the presence of carbonates. The maximum ANP values are characteristic of the soil
319 from the tailings old site (106 kg CaCO₃/t), the average ANP values are 81 kg CaCO₃/t. AP values
320 obtained in tailings soils vary in a narrow range from 0.2 to 12 kg CaCO₃/t. Function of complex
321 variable value indicates that neutral and weakly alkaline waters will form due to drainage of industrial
322 soil in the TMF of the Tokur Mill by seasonal precipitation.

323 In the pH range 6.5–8.5 cationogenic toxicants (Pb, Cd, Cu, Ni, Co, Zn) have low migratory
324 ability as, according to the data (Shvartzev 1996), in the water with near-neutral pH, hydroxides whose
325 solubility is low, form. In the similar conditions, concentrations of toxicants which form oxygen-
326 bearing anions (Cr, As, Se and U) may reach much higher values. However, As takes a special position
327 among the elements. It is characterised by high mobility due to the formation of mobile forms not only
328 in oxidising, but also in reducing conditions (Charykova et al. 2008; Lindsay et al. 2015; Corkhill and
329 Vaughan 2009).

330

331 **Assessment of chemical elements migration potential from the Tokur Mill tailings**

332

333 Determining the gross content of chemical elements is essential for the composition analysis of
334 environmental objects. However, physicochemical mobility along with the element toxicity for natural
335 objects, largely depend on its chemical form and type of connection with the substrate matrix.
336 Contamination activity of the stored wastes for surface and ground waters is dependent on precipitation
337 and atmospheric oxygen exposure. These factors significantly contribute to the intensive leaching and
338 loss of elements. The number of weakly bound compounds of elements determines their volume that
339 can migrate to adjacent environments and pollute them (Radomskaya et al. 2006; Minkina et al. 2008;
340 Kulik and Radomskaya 2011a, 2011b). This group of elements includes water-soluble, exchangeable,
341 complex and specifically sorbed forms of elements.

342

343 **Water-soluble forms of elements in the industrial soil**

344

345 The water-soluble fraction of the elements is considered to be the most dangerous and aggressive, as
346 the rock matter is directly effected by precipitation and atmospheric oxygen. Subsequently,
347 hydrogeochemical processes occurring in stored mineral wastes affect the composition of drainage
348 water, ground and surface waters. Assay of water-soluble forms of toxic elements makes it possible to
349 predict the specific impact which the tailings have on the environment.

350 The acidity of aqueous solutions obtained during the extraction of elements with 7.09 pH snow-
351 melt water varied from 7.9 to 8.3 from the tailings soils in the Tokur Mill. In such conditions, according
352 to the data (Ryzhenko and Ryabenko 2013), dissolution reactions of minerals are the slowest, their rate
353 ranges from $n \times 10^{-3}$ mol/m² s (highly soluble salt minerals) to $n \times 10^{-20}$ mol/m² s (poorly soluble
354 minerals, oxides and silicates, phosphates, sulphides in a reducing environment, etc.). In addition,
355 elements from minerals do not dissolve simultaneously: the rate of dissolution depends on the position
356 of the element in the structure of the mineral. The interlayer cations are first to dissolve, then
357 isomorphically substituting ions and ions occupying the peripheral zone of particles come. The ions
358 that occupy the octahedral and tetrahedral fragments of the mineral structure migrate most slowly
359 (Czuryupa 1973). In aqueous solutions, the elements are predominantly in the form of highly soluble
360 secondary sulphates (Dold 2003; Bogush and Lazareva 2011), and soluble complex compounds with
361 fulvic acids and inorganic ligands (Ladonin 2002).

362 The range of major and trace elements in the aqueous extracts is quite wide (Table 5). There is
363 excess of MAC_{fw} (maximum admissible concentrations of contaminants in the fishery waters) for some
364 toxic elements (As, Cu, Pb, V and Hg). Maximum As and Hg concentrations are 20–30 times as high
365 as MAC_{fw}. In the solutions of all samples Al, Fe and Mn exceeded MAC_{fw}.

366 The proportion of water-soluble forms of toxic elements from their gross content in the soil is:
367 Cd 1.5–3.6%, Mo – 1.5%, Bi – 0.3-0.9% and Sb – 0.6–0.9%. Maximum content of water-soluble As
368 and Hg reaches 0.5%.

369 Thus, the drainage waters of the tailings can contain high concentrations of As, Hg, Cu, Mn,
370 exceeding the MAC standards for harmful substances in the fishery water bodies.

371

372 **Table 5** Content of elements in the water-soluble fraction

373

374 **Exchangeable forms of elements in the industrial soil of the TMF**

375

376 The fraction extracted with ammonium acetate (1 M NH₄Ac) simulates the effect of weakly acidic
377 solutions (weakly acidic drainage). Acid drainage can occur in those sites of the TMF where the rate
378 of acid formation and its mass are greater than the rate of the acid neutralisation with carbonates,
379 despite the higher content of carbonates in general. This process is possible in areas of passive and
380 active water exchange due to the finely divided waste texture. Passive water exchange is favourable
381 for the accumulation of products of sulphide sulphur oxidation, active – leaching of oxidation products
382 from the soil and formation of acid drainage. Long-term interaction of the rock and water facilitates
383 neutralisation processes.

384 Using a 1 M NH₄Ac (pH 4.8) solution, the exchangeable, most mobile, forms of elements, which
385 are represented by easily hydrolyzable compounds, are extracted (Kosheleva 2015). They pass into
386 solution due to ion exchange as well as hydrolysis under the influence of hydrogen ions and formation
387 of soluble acetate or ammonium complex compounds. The use of a slightly acidic buffer solution can
388 lead to partial dissolution of carbonates and to the transfer of carbonate-related elements into the
389 solution.

390 More trace (As, Ni, Cu, Co, Zn, Pb, Y, Ce, Hg) and major elements from the tailings soil (Table
391 6) passed into acetate-ammonium extracts than into the water-soluble fraction. In the fractional ratio,
392 only Li, Ga, V, W, Zr, Ti, Rb, and Nb have an insignificant part of exchangeable forms. For the
393 remaining elements, the share of exchangeable forms in the gross contents is large, which indicates a
394 high probability of their migration when exposed to acidic drainage solutions. Cd is one of the strongest
395 genotoxic and carcinogenic elements, whereas, the share of its exchangeable forms reaches 70% of
396 total Cd content in the soil. High extractability of Cd with ammonium acetate buffer has been reported
397 (Plekhanova et al. 2001; Minkina et al. 2016). The latter is related to the ability of Cd cations to be part
398 of very mobile chelate compounds that provide the transfer of this element. Major elements also have
399 large share of exchangeable forms: Ca – 45%, Mn – 32%, Sr – 36%.

400 Acidic drainage solutions may form while sulphur from sulphide minerals (e.g. pyrite FeS₂) is
401 being oxidised to sulphuric acid by Eq. (1). According to the data of elemental analysis, the sulphur
402 content in the tailings material ranges from 0.007 to 0.38 wt%. However, the presence of calcite in the

403 mill waste, the content of which varies from 4 to 11%, contributes to the neutralisation of acid solutions
404 by Eq. (4). The natural acid neutralisation will probably cause lower content of mobile forms of
405 elements in the drainage solutions of the tailings in natural conditions than in experimental data.

406

407 **Table 6** Average content of elements in exchangeable, organomineral and specifically sorbed fractions

408

409 **Organomineral forms of element in the industrial soil of the TMF**

410

411 Organomineral forms of elements (complex compounds) develop when organic matter interacts with
412 mineral components. This process facilitates the transition of chemical elements of minerals into
413 soluble, bioavailable forms. The number of organomineral forms is determined by the difference
414 between the numbers of elements recovered by 1% EDTA in 1 M NH₄Ac and 1 M NH₄Ac.

415 According to the quantitative content of complex compounds (% of gross content) in the tailings
416 of the Tokur Mill, the elements form the following variation series: As > Pb > Bi > Na > Co > Mn >
417 Cu > Ca > Cd > Fe > Sb > Ni > Zn > Sr > Ho > Y > Yb > Dy > Lu > Er > Tm > Mg > Mo > Tb > Th
418 > Eu > Gd. The share of organomineral As, Pb and Bi reaches 1/3 of their total content in the soil.
419 Large proportion of As compounds in the fraction indicates high migration ability of the element.
420 According to the data (Hess and Blanchard 1977), most soluble As compounds are found in flooded,
421 rich in organic matter soils with Eh = 25–100 mV. Organic molecules increase As bioavailability (Grafe
422 et al., 2001). The relative content of the complex forms of the remaining elements is much lower: the
423 proportions of Zn and Ni are 6–9% of the total content, which is explained by the weak complexing
424 properties of these elements with organic matter (Piccolo and Stevenson 1982). Insignificant number
425 of elements in the form of complex compounds can also be connected with low content of organic
426 carbon in the tailings material.

427

428 **Specifically sorbed forms of elements in the industrial soil**

429

430 Significant part of specifically sorbed compounds is represented by elements loosely bound with oxides
431 and hydroxides of Fe, Al, Mn and carbonates (Minkina et al. 2008). This form may be considered
432 intermediate or transitional to strongly bound compounds.

433 In the mineral matter of the TMF in the Tokur Mill among mobile compounds specifically sorbed
434 forms prevail (Table 6). The proportion of the fraction for As, Ca, Bi and Pb is more than 50% of the
435 gross content. Weakly bound compounds represent an important in ecological terms group. According
436 to the indicator, potential risks of element migration into adjacent environment may be estimated. To
437 assess the hazardous potential of the tailings from the Tokur Mill the proportion of mobile compounds
438 to their total content was calculated. Based on this, it was revealed that Ca, Pb, As, Mn, Bi, Sr and Co
439 led in the share of weakly bound compounds. Ca is passed into solutions by calcite whose concentration
440 in the tailings reaches 11%. Slightly acidic solutions may cause partial calcite dissolution and Ca
441 migration.

442 The total content of mobile forms of Pb, As is 85–90% of their gross content, Mn, Bi – 70–80%,
443 Cd – 64–99%, Co – 50–65%, Cu – about 45 %, Zn, Ni, Fe, Sb – 30–36%, Mo – 17–20%, Cr – 5–7%
444 of their gross content.

445 The proportion of specifically sorbed forms of Mn, As, Pb, Bi in the composition of weakly
446 bound compounds is 43–62%. The exchangeable forms of Cd and Sr dominate in the composition of
447 the compounds – up to 80% and 50%, respectively. Ecologically hazardous contaminations of adjacent
448 environments can be associated with both exchangeable and complex forms of Co, whose share among
449 loosely bound compounds is 40–59%.

450 The proportion of Hg mobile forms is 13-14%. Most Hg is contained in the bottom fraction which
451 indicates its poor solubility in the tailings soil. Despite of this, there is a high risk of the Hg mobile
452 forms getting into water intakes with ground waters while it is leached from technogenic dumps.

453

454 **Mercury forms in the industrial soil of the Tokur TMF**

455

456 The method of mercury thermal sublimation from solid samples makes it possible to determine the
457 potential forms of Hg on various matrices (Shuvaeva et al. 2008; Reis et al. 2012; Rumayor et al. 2013).
458 All Hg forms are divided into relative groups depending on the temperature of sublimation (maximum
459 yield temperature (T_m). At low T_m (150–160 °C) free mercury is sublimated. At $T_m = 250$ –290 °C,
460 physically sorbed Hg compounds are sublimated. The destruction of chemisorbed forms of Hg
461 according to thermal destruction data occurs at $T_m = 310$ –320 °C. At $T_m = 350$ –410 °C Hg sulphides
462 are sublimated (Tauson et al. 1992; Tauson et al. 1994). Shuvaeva et al. (2008) showed on the modelled
463 mixtures of individual mercury compounds (HgX_2 ($X = Cl^-$, N, S), HgO, CH_3HgCl and HgS) that HgX_2
464 and HgO during thermal destruction extract in the same temperature range (50–150 °C),
465 methylmercury – at 150–230 °C, Hg sulphide – at 190–280 °C. Rumayor et al. (2013) obtained thermal
466 desorption profiles of fifteen mercury compounds: HgI_2 (100 °C) < $HgBr_2$ (110 °C) < Hg_2Cl_2 (119 °C)
467 < $HgCl_2$ (138 °C) < $Hg(CN)_2$ (267 °C) < $HgCl_2O_8 \cdot H_2O$ (273 °C) < $Hg(SCN)_2$ (288 °C) < HgS (red)
468 (305 °C) < HgF_2 (234; 449 °C) < $Hg_2(NO_3)_2 \cdot 2H_2O$ (264; 427 °C) < $Hg(NO_3)_2 \cdot H_2O$ (215; 280; 460 °C)
469 < HgO (yellow, red) (284; 469 °C) < Hg_2SO_4 (295; 514 °C) < $HgSO_4$ (583 °C).

470 When determining the forms of Hg in complex, complicated in composition, objects, this method
471 has limitations since the thermal peaks of slightly different Hg compounds overlap, and T_m depends
472 on the composition of the sample matrix (Shuvaeva et al. 2008). Nevertheless, in the tailings material,
473 by the method of thermal sublimation, it was possible to determine three types of forms of mercury
474 (Fig. 2). The first type is represented by one thermoform, the second – contains two thermoforms, the
475 third – three. The content of mercury forms was determined by integration. With incomplete separation
476 of the peaks, the calculation was performed by doubling the area of the triangle, where one side is the
477 height of the poorly divided peak.

478

479 **Fig. 2** Types of mercury thermoforms

480

481 According to the data obtained (Fig. 2), mercury desorption was mainly observed in the
482 temperature range 130–460 °C. Maximum Hg desorption which amounts 75–100% was observed in

483 the range 190–230 °C. This peak corresponds to the form of physically adsorbed divalent mercury. The
484 range $T_m = 150\text{--}250$ °C is characteristic of thermal desorption methylmercury. However, low content
485 of organic carbon in the tailings material (0.09–0.3%) indicates the bound of Hg with mineral
486 components of the waste. Hg thermal form in the T_m range 250–270 °C is attributed to chemisorbed
487 mercury, its share is 5–17%. In some soil samples, small share of mercury was found (3–6%) in the
488 form of HgS (the peak with the maximum T_m ranges 370–410 °C). Thus, three forms of mobile Hg,
489 having unequal quantitative distribution, are determined in the tailings material of the Tokur Mill,
490 among which oxidised, physically sorbed, predominate.

491

492 **Conclusion**

493

494 The tailings material of the Tokur Mill is made up of soft, permeable silty sand. The concentration of
495 fine and small fractions (0.25–0.071 mm) makes up 80–88% whose proportion increases with depth.
496 In mineral composition of the soil, rock fragments dominate (up to 59%), there is quartz (up to 32%),
497 feldspars (up to 21%), calcite (11%) and insignificant quantity of ore minerals (up to 0.2%). In the
498 element composition of the soils compared to UCC high concentrations of As, Sb, W, Bi are found,
499 their concentration coefficients are 1005.1, 36.1, 16.3 and 5.2 respectively. Concentrations of Pb, Ba,
500 Zn, Cu, Ni, Cr, V in some samples are higher than bulk earth values. As for sanitation and hygiene
501 regulations, As is 400–1640 times higher and Sb is 1.2–2.7 times higher than MAC.

502 Assessment of the potential of chemical elements to migrate from a industrial soil of the TMF
503 showed that Cr, Mo, Sb, Zn, Ni, Cu in unstable compounds (water-soluble, exchangeable,
504 organomineral and specifically sorbed fractions) make up 7–46%, whereas Co, Sr, Pb, Bi, Cd, As –
505 60–90%. This fact indicates a high degree of risk that these elements will migrate to adjacent
506 environments during the draining of the tailings matter by seasonal precipitation.

507 Applying pyrolysis, three forms of mercury are identified in the tailings material, among which
508 75–100% are physically sorbed Hg^{2+} , 5–17% are chemisorbed, and 3–6% are mercury sulphide.
509 Assessment of the mercury migration potential shows that up to 87% of its compounds are in the

510 residual fraction. However, the insignificant (0.4–1.2%) proportion of water-soluble and exchangeable
511 compounds of mercury does not reduce its toxicity when it enters water flows.

512 The presence of a significant amount of carbonates (11%) in the tailings material causes a high
513 acid-neutralising potential of the industrial soil, due to which, the probability of acid drainage
514 formation is low. The formation of neutral and slightly alkaline effluents increases the risk of migration
515 of oxygen-containing As anions. The proportion of its mobile compounds in the tailings material is 90–
516 92%.

517

518 **Conflict of Interest** The authors declare that they have no conflict of interest.

519

520 **References**

521

522 Alekseev VA, Kochnova LN, Bychkova YaV, Krigman LV (2011) Experimental study of normalized
523 elements extraction by water from contaminated rocks. *Geochem Inter* 12:1317–1342

524 Bloom NS, Preus E, Katon J, Hiltner M (2003) Selective extractions to assess the biogeochemically
525 relevant fractionation of inorganic mercury in sediments and soils. *Anal Chim Acta* 479(2):233–
526 248. doi:10.1016/s0003-2670(02)01550-7

527 Bogush AA, Lazareva EV (2011) Behavior of heavy metals in sulfide mine tailings and bottom
528 sediment (Salair, Kemerovo region, Russia). *Environ Earth Sci* 64(5):1293–1302

529 Bortnikova SB, Silantyeva NV, Zapolsky AN (2018) Assessment of acid-base accounting of mine waste
530 rocks and mobility of potentially toxic elements of the Razdolinsky ore field (Krasnoyarsk
531 territory). *Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering* 329(12):55–
532 72. doi.org/10.18799/24131830/2018/12/20

533 Charykova MV, Krivovichev VG, Depmaejr V (2008) Physicochemical conditions for formation of
534 arsenic minerals in near-surface environments (in Russian). *Vestnik of Saint Petersburg*
535 *University, Ser 7 Geology, Geography* 4:62–81

536 Corkhill CL, Vaughan DJ (2009) Arsenopyrite oxidation – a review. *Appl Geochem* 24:2342–2361

537 Czuryupa IG (1973) Role of microorganisms in aluminosilicates weathering and the formation of
538 mobile easily migrating compounds (in Russian). *Weathering crust* Iss13:3–38

539 Dold B (2003) Speciation of the most soluble phases in a sequential extraction procedure adapted for
540 geochemical studies of copper sulfide mine waste. *J Geochem Explor* 80(1):55–68

541 Dold B (2017) Acid rock drainage prediction: a critical review. *J Geochem Explor* 172:120–132

542 Edelev AV 2009 Using of ore-processing industry waste solid matter analysis results to predict
543 chemical composition of drainage waters. *Chemistry for Sustainable Development* 17:487–494

544 Edelev AV (2013) Predictive assessment of drainage waters composition interacting with sulfide-
545 containing matter. *Russ Geol Geophys* 54(1):144–157

546 Ejrish LV (2002) Metallogeny of gold in the Amur Region (in Russian). *Dalnauka, Vladivostok*, p 194

547 Ejrish LV, Ostapenko NS, Moiseenko VG (2002) Tokur gold ore deposit (Far East, Russia). *Geology*
548 *of Ore Deposits* 44(1):50–52

549 Gaskova OL, Bortnikova SB (2007) On the quantitative determination of host rocks neutralizing
550 potential. *Geochem Inter* 45(4):461–464

551 Ginsburg A I (Ed) (1970) *Minerals and rocks of the USSR* (in Russian). *Thought, Moscow*, p 439

552 Gladyshev VP, Leviczka SA, Filippova LM (1974) *Analytical chemistry of mercury* (in Russian).
553 *Nauka, Moscow*, 231 p

554 GN 2.1.7.2041-06 (2006) *Maximum Permissible Concentration (MPC) of Chemical Substances in the*
555 *Soil* (in Russian). *Publishing Standards, Moscow*, 15 p

556 Golovin AA, Moskalenko NN, Achkasov AI et al (2002) Requirements for the production and results
557 of multipurpose geochemical mapping of 1: 200000 scale (in Russian). *IMGRE, Moscow*, p 92

558 Grafe M, Eick MJ, Gossel PR (2001) Adsorption of arsenate(V) and arsenite(III) on goethite in the
559 presence and absence of dissolved organic carbon. *Soil Sci Soc Am J* 65:1680–1687

560 Hageman PL, Seal RR, Diehl SF, Piatak NM, Lowers HA (2015) Evaluation of selected static methods
561 used to estimate element mobility, acid-generating and acid-neutralizing potentials associated
562 with geologically diverse mining wastes. *Appl Geochem* 57:125–139.
563 doi:10.1016/j.apgeochem.2014.12.007

564 Hess RE, Blanchar RW (1977) Dissolution of arsenic from water logged and aerated soil. Soil Sci Soc
565 Am J 41:861–865

566 Hoguet J, Keller JM, Reiner JL, Kucklick JR, Bryan CE, Moors AJ, Pugh RS, Becker PR (2013) Spatial
567 and temporal trends of persistent organic pollutants and mercury in beluga whales
568 (*Delphinapterus leucas*) from Alaska. Sci Total Environ 449:285–294

569 Jambor JL, Blowes DW, Ritchie AIM (Eds) (2003) Environmental aspects of mine wastes.
570 Mineralogical Assoc. of Canada, Short Course Series 31, 430 p

571 Kapaj S, Peterson H, Liber K, Bhattacharya P (2006) Human health effects from chronic arsenic
572 poisoning – a review. J of Environ Sci and Health. Part A: Toxic. Hazardous Substances and
573 Environ Engineering 41(10):2399–2428. doi:10.1080/10934520600873571

574 Kosheleva NE, Kasimov NS, Vlasov DV (2015) Factors of the accumulation of heavy metals and
575 metalloids at geochemical barriers in urban soils. Eur Soil Sci 48(5):476–492

576 Koval AT, Pavlova LM, Radomskaya VI, Radomskii SM, Kuimova NG, Krylov AV (2002) Mercury
577 in ecosystems of Amur Region (in Russian). Bulletin of the Far Eastern Branch of the Russian
578 Academy of Sciences 4:94–103

579 Kulik EN, Radomskaya VI (2011a) The study of modes of heavy metals occurrence in the brown forest
580 soil under anthropogenic impact (in Russian). Agricultural Research Magazine 7:12–15

581 Kulik EN, Radomskaya VI (2011b) Features of heavy metals translocation into legumes under
582 anthropogenic impact (in Russian). The Bulletin of KrasGAU 8 :83–88

583 Ladonin DV (2002) Heavy metal compounds in soils: problems and methods of study. Eur Soil Sci
584 35(6):605–613

585 Laperdina TG, Tupyakov AV, Egorov AI, Melnikova MV, Askarova OB, Bانشnikov VA, Xvostova
586 TE, Cybikdarzhiev Zh, Bochko OK (1995) Mercury pollution of environment in the zones of
587 Transbaikalia gold mining enterprises influence (in Russian). Chemistry for Sustainable
588 Development 3(1-2):57

589 Lengke MF, Davis A, Bucknam C (2010) Improving management of potentially acid generating waste
590 rock. Mine Water Environ 29(1):29–44

591 Lindsay MBJ, Moncur MC, Bain JG, Jambor JL, Ptacek CJ, Blowes DW (2015) Geochemical and
592 mineralogical aspects of sulfide mine tailings. *Appl Geochem* 57:157–177
593 doi:10.1016/j.apgeochem.2015.01.009

594 Lottermoser BG (2007) *Mine wastes: characterization, treatment and environmental impacts*. Springer,
595 Berlin, 314 p

596 Mandzhieva SS, Minkina TM, Motuzova GV, Golovatyj SE, Miroshnichenko NN, Lukashenko NK,
597 Fateev AI (2014) Fractional and group composition of zinc and lead compounds as an indicator
598 of the environmental status of soils. *Eur Soil Sci* 47(5):511–518

599 Minkina TM, Motuzova GV, Nazarenko OG, Kryshhenko VS, Mandzhieva SS (2008) Forms of heavy
600 metal compounds in soils of the steppe zone. *Eur Soil Sci* 41(7):708–716

601 Minkina TM, Fedorov YuA, Nevidomskaya DG, Mandzhieva SS, Kozlova MN (2016) Specific
602 features of content and mobility of heavy metals in soils of floodplain of the Don River. *Arid*
603 *Ecosystems* 6(1):70-79

604 Minkina TM, Mandzhieva SS, Burachevskaya MV, Bauer TV, Sushkova SN (2018) Method of
605 determining loosely bound compounds of heavy metals in the soil. *Methods X* 5 217–226.
606 doi:10.1016/j.mex.2018.02.007

607 On termination of mercury use (amalgamation) in technological processes during the gold-bearing ores
608 and sands beneficiation (in Russian) (1988) Order of the Main Directorate of Precious Metals
609 and Diamonds under the Cabinet of Ministers of the USSR N 124 dated 29.12.1988 (in Russian).

610 Ostapenko NS, Neroda ON (2007) Fluid pressure and hydrofracture of rocks in hydrothermal
611 mineralization (as exemplified by gold deposits). *Russ J Pacific Geol* 26(3):89–105

612 Ostapenko NS, Neroda ON (2016) Deposition conditions and features of distribution native gold
613 individuals in the veins of Tokur mesothermal deposit (Russia). *Geology of Ore Deposits*
614 58(3):239–250. doi: 10.7868/S0016777016030072

615 Paktunc AD (1999) Mineralogical constraints on the determination of neutralization potential and
616 prediction of acid mine drainage. *Environ Geol* 39(2):103–112. doi:10.1007/s002540050440

- 617 Pavlova LM, Radomskaya VI, Shumilova LP (2016) The biotic factor in the environmental assessment
618 of technogenic territory (on the example of tailing ponds of Tokur gold recovery plant). *Izvestia*
619 *RAS SamSC* 18(2-2):467–477
- 620 Piccolo A, Stevenson FJ (1982) Infrared spectra of Cu^{2++} , Pb^{2+} and Ca^{2+} complexes of soil humic
621 substances. *Geoderma* 27(3):195–208
- 622 Pinedo-Hernández J, Marrugo-Negrete J, Díez S (2015) Speciation and bioavailability of mercury in
623 sediments impacted by gold mining in Colombia. *Chemosphere* 119:1289–1295
624 doi:10.1016/j.chemosphere.2014.09.044
- 625 Plexanova IO, Klenova OV, Kutukova YuD (2001) Influence of sewage sludge on the content and
626 fractional composition of heavy metals in sandy loam and soddy-podzolic soils. *Eur Soil Sci*
627 4:496–503
- 628 Plyusnin AM, Gunin V I (2001) Natural hydrogeological systems, formation of the chemical composition
629 and response to technogenic impact (case study Transbaikalia) (in Russian). BNCz SO RAN, Ulan-
630 Ude, 137 p
- 631 Quansah R, Armah FA, Essumang DK, Luginaah I, Clarke E, Marfo K, Cobbina SJ, Nketiah-
632 Amponsah E, Namujju PB, Obiri S, Dzodzomenyo M (2015) Association of arsenic with adverse
633 pregnancy outcomes-infant mortality: a systematic review and meta-analysis. *Environ Health*
634 *Perspect* 123:412–421. <https://dx.http://dx.doi.org/10.1289/ehp.1307894>
- 635 Radomskaya VI, Moiseenko NV, Radomskii SM, Krylov AV, Katola VM, Moiseenko VG (2006) The
636 effect of sewage sludge on the behavior of heavy metals in the soil-plant system (in Russian).
637 *Agricultural Research Magazine* 1:77–84
- 638 Radomskaya VI, Radomskii SM, Kulik EN, Pavlova LM (2016) Distribution and migration of toxic
639 elements in soil-plant system at the Albynskoe gold deposit (Amur Region). *Geography and*
640 *Natural Resources* 3:62–69. doi: 10.21782/GiPR0206-1619-2016-3(62-69)
- 641 Radomskaya VI, Radomskii SM, Pavlova LM, Kulik EN (2017) Specific features of rare-earth
642 elements migration in natural and technogenic ecological systems. The case of Albynskoe gold

643 deposit, the Amur Region (in Russian). *Geokologiya. Inzhenernaya Geologiya. Hidrogeologiya.*
644 *Geokriologiya* 1:15-27

645 Reis AT, Coelho JP, Rodrigues SM, Rocha R, Davidson CM, Duarte AC, Pereira E (2012)
646 Development and validation of a simple thermo-desorption technique for mercury speciation in
647 soils and sediments. *Talanta* 99:363–368

648 Ritcey GM (2005) Tailings management in gold plants. *Hydrometallurgy* 78(1-2):3–20.
649 doi:10.1016/j.hydromet.2005.01.001

650 Rumayor M, Diaz-Somoano M, Lopez-Anton MA, Martinez-Tarazona MR (2013) Mercury
651 compounds characterization by thermal desorption. *Talanta* 114:318–322

652 Ryzhenko BN, Ryabenko AE (2013) Modeling the composition of mine (waste rock) water at the
653 deposits of the Balkhach gold-bearing field. *Geochem Int* 11:920–930

654 Saet YuE, Onishhenko TL, Yanin EP (1986) Methodological recommendations for geochemical
655 studies for environmental impact assessing of designed mining enterprises (in Russian). IMGRE,
656 Moscow, 99 p

657 Shuvaeva OV, Gustaytis MA, Anoshin GN (2008) Mercury speciation in environmental solid samples
658 using thermal release technique with atomic absorption detection. *Anal Chim Acta* 621:148–
659 154

660 Shvartsev SL (1996) *General Hydrogeology* (in Russian). Nedra, Moscow, 423 p

661 Skousen J, Simmons J, McDonald LM, Ziemkiewicz P (2002) Acid-base accounting to predict post-
662 mining drainage quality on surface mines. *J Environ Quality* 31(6):2034–2044

663 Sobek AA, Schuller WA, Freeman JR, Smith RM (1978) Field and laboratory methods applicable to
664 overburden and mine soils. U.S. EPA 600/2-78-054, 203 p

665 Solomin GA, Krajnov SR (1994) Acidic constituents of natural and acidic waste waters. The processes
666 of these waters neutralization with calcite. *Geochem Intern* 32(12):1755–1775

667 Sorokin AA, Ostapenko NS, Ponomarchuk VA, Travin AV (2011) $^{40}\text{Ar}/^{39}\text{Ar}$ age of adularia from veins
668 of the Tokur gold deposit, the Mongolian-Okhotsk orogenic belt, Russia. *Geology of Ore*
669 *Deposits* 53(3):264–271

670 Stepanov VA, Melnikov AV (2017) Tokur gold-bearing ore-placer cluster of the Amur province:
671 geological and structural features of deposits and prospects for their development. *Geology of*
672 *Ore Deposits* 59(2):113–123

673 Sulfur. Category III method. Chemical methods. Instructions N I-X, 2-X, 3-X (in Russian) (1986)
674 Moscow, 12 p

675 Tauson VL, Menshikov VI, Zubkov VS (1992) Application of the thermal atomic absorption analysis
676 of synthetic crystals to the determination of mercury speciation in minerals. *Geochem Intern*
677 8:1203–1208

678 Tauson VL, Zubkov VS, Menshikov VI (1994) Forms of finding mercury in mercury ore formation
679 minerals. *Russ Geol Geophys* 35(1):54–69

680 Taylor SR, McLennan SM (1988) Continental crust: its composition and evolution (in Russian). Mir,
681 Moscow, 384 p

682 Vinogradov AP (1957) Geochemistry of rare and trace chemical elements in soils (in Russian). AN
683 SSSR, Moscow, 234 p

684 Water quality standards for water bodies used for fishery, including standards on maximal allowable
685 concentrations of hazardous substances in water of water bodies used for fishery (in Russian).
686 Order of the Ministry of Agriculture of the Russian Federation N 552 of December 13, 2016 as
687 amended on March 10, 2020 (<http://www.pravo.gov.ru>, 16.06.2020, N 0001202006160052).
688 Access mode: <http://docs.cntd.ru/document/420389120>

689 Yanin EP (1993) Ecological geochemistry of mining areas (in Russian). *Geoinformmark*, Moscow, 50
690 p

Figures



Figure 1

Map-scheme of the Tokur Mill tailings area: 1, 2 – sample points Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

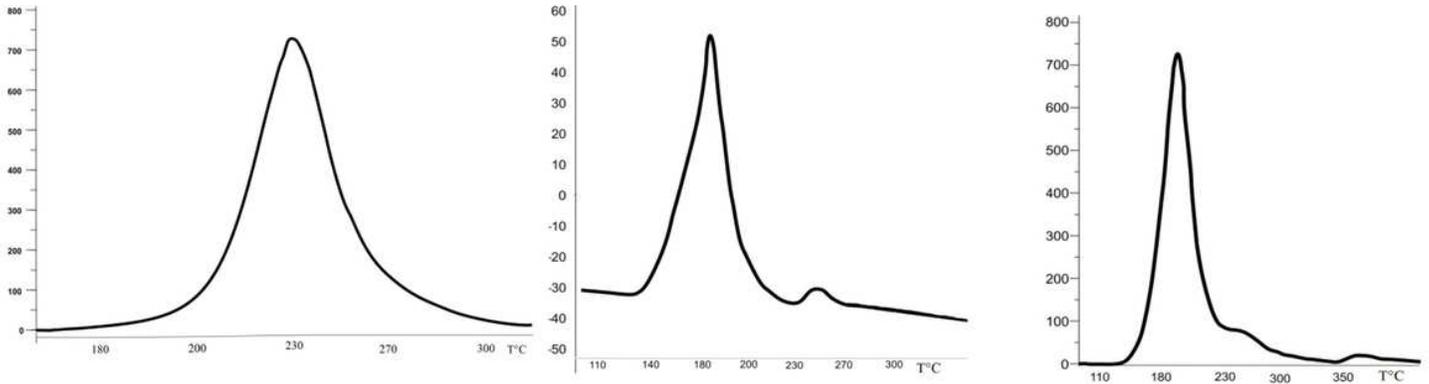


Figure 2

Types of mercury thermoforms