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1 **Antimony in paints and enamels of everyday items**

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12 **Abstract**

13 Concentrations of antimony have been determined for paints and enamels that are available to
14 the consumer or accessible to the public by x-ray fluorescence spectrometry. The metalloid was
15 only present in consumer paints of a speciality (e.g. artistic) nature, but was common in old
16 household paints as an anti-chalking agent and in brightly-coloured contemporary exterior
17 paints (on roads, street furniture and playground equipment, for example) as a colour fastener
18 with concentrations ranging from a few hundred to about 25,000 $\mu\text{g g}^{-1}$. Antimony was also
19 found in contemporary container glass and ceramic products as an additive or opacifier and as
20 a colour fastener in enamels at concentrations up to a few thousand $\mu\text{g g}^{-1}$. Overall, the yellow
21 pigment, lead antimonite, was only evident in two ceramic products, with Sb concentrations
22 exceeding 62,800 $\mu\text{g g}^{-1}$. Available data in the literature suggests that, while Sb concentrations
23 up to 30 $\mu\text{g g}^{-1}$ are bioaccessible in exterior paints and that concentrations of up to 20 mg L^{-1}
24 are migratable in some ceramicware, no relevant regulations are currently in place. Given our
25 lack of understanding of the health impacts of Sb, more studies on its toxicity and mobility from
26 commonly encountered products are required.

27

28 **Keywords:** antimony; paints; enamels; ceramics; glass; XRF

29 **1. Introduction**

30 Antimony (Sb) has been used as a pigment, and mainly as antimony sulphide and lead
31 antimonite, for several thousand years (Aldersey-Williams, 2011; Schwarz-Schampera, 2014).
32 Currently, Sb has the status of a technologically-critical element that is essential for economic
33 development, and although the principal present uses are in antimonial lead, as a flame retardant
34 synergist in textiles and plastics and as a catalyst (e.g. in the production of polyethylene
35 terephthalate, PET), the element is still used in pigments, ceramic glaze and glass (Orisakwe,
36 2012; Dupont et al., 2016). The most recent European data available indicate that Sb employed
37 as an additive in glass manufacture represents 1% (250 t) of total use while application in
38 pigments, paints and ceramics constitutes about 4.5% (1100 t); these values compare with 3.9%
39 in PET production and 32.9% in flame retardant synergist manufacture (European
40 Communities, 2008). In addition to these applications, Sb readily and widely contaminates
41 many contemporary consumer plastics at low levels through the recycling of electronic and
42 PET-based products (Turner and Filella, 2017).

43 While the behaviour of Sb in different environmental compartments is relatively well-known,
44 or at least has been extensively studied (Filella et al., 2009), the toxicological implications of
45 its pervasiveness in everyday products are far less understood. Specifically, the occurrence and
46 fate of Sb as a catalyst or synergist have received recent attention (Haldimann et al., 2013;
47 Snedeker, 2014; Turner and Filella, 2017), with concentrations migratable from the matrix
48 regulated for (PET) food containers (European Commission, 2005) and children's toys
49 (European Parliament and the Council of the European Union, 2009). However, its occurrence,
50 function, mobility and potential impacts in contemporary paints, consumer glass and
51 ceramicware are poorly documented, despite the obvious exposure routes arising from these
52 applications.

53 In this study, we examined the occurrence of Sb in the paints and enamels of various consumer
54 goods and everyday items that have been purchased new or that are in circulation and in extant
55 applications on structures which the public are exposed to and where the presence and/or
56 mobility of other elements, like Cd, Cr(VI) and Pb, are highly regulated on environmental and
57 health grounds (Sheets, 1999; Turner, 2019). Measurements of Sb were made *in situ* or in the
58 laboratory by energy dispersive x-ray fluorescence (XRF) spectrometry and relevant
59 information in the literature on its migration from any applications was reviewed. The
60 investigation complements an earlier study that determined the occurrence and distribution of
61 Sb as catalytic residue or a flame retardant synergist in consumer plastics using the same
62 protocols and techniques (Turner and Filella, 2017).

63 **2. Materials and methods**

64 About 400 measurements of Sb have been performed on distinct regions (in terms of colour or
65 texture) of 335 samples acquired from or located within south west England. Many of the
66 samples had been measured as part of independent research projects (Turner et al., 2015; Turner
67 et al., 2016; Turner and Solman, 2016; Turner, 2019a) and here published and unpublished data
68 on Sb have been compiled, while other samples were analysed specifically for the purposes of
69 the present study. The painted and enameled samples are described and categorised below.

- 70 (1) “Interior extant paint” on interior walls, doors, frames, skirting boards and floors of
71 various private households in the city of Plymouth ranging in age from 50 to 100 years;
- 72 (2) “Exterior extant paint” on the exteriors of these and other private households and
73 including walls, guttering and timber;
- 74 (3) “Municipal extant paint” on external wooden, tarmacked and metallic structures and
75 street furniture accessible to the public in the city of Plymouth, including roads, post
76 boxes, phone boxes, benches, gates and playground equipment;

- 77 (4) “Extant boat paint” applied to the hull, decking and cabin of pleasure craft or small
78 commercial vessels located on the coastal foreshores in the vicinity of Plymouth and
79 that were either abandoned or in use;
- 80 (5) “Consumer paint” for internal and external decoration or for artwork and that had been
81 purchased within the past five years;
- 82 (6) “Painted toys/equipment”: the paint on wooden and metallic toys and other consumer
83 items (e.g. tools, storage tins, artefacts) around the household;
- 84 (7) “Consumer bottle enamel”: the decorated enamels on glass for the containment and sale
85 of wine, beer and food products;
- 86 (8) “Drinking glass enamel”; the enamels on glassware for drinks and other food-contact
87 items purchased new or secondhand;
- 88 (9) “Ceramicware enamel”: the enameled decorations and glaze of (mainly food-contact)
89 ceramicware in circulation and purchased new or secondhand or loaned from
90 colleagues.

91 For each sample, the condition and principal colour (or colours) were noted, along with any
92 distinguishing signage (e.g. place of manufacture). For intact extant paints, and to avoid
93 disturbance or damage to the surface, Sb and other elements that included Br, Cl, Ni, Pb, Ti and
94 Zn, were measured *in situ* and on each distinctive colour and, where possible, the undecorated
95 substrate of structures using a battery-operated Niton XL3t 950 He GOLDD+ portable XRF
96 spectrometer. Here, the 8-mm diameter detector window of the instrument, containing the 200
97 μA -50 kV x-ray source and large area drift detector, was pointed directly over the area to be
98 measured with the aid of real-time video footage projected on to the touchscreen display
99 through a charged-couple device camera. Counting was activated by the trigger mechanism of
100 the XRF spectrometer for a period of between 30 and 60 seconds in a “plastics” mode, whose
101 performance has been verified by independent measurements of acid digests by inductively

102 coupled plasma spectrometry (Turner, 2019b). Successive measurements were made at 50 kV-
103 40 μ A and 20 kV-100 μ A and employing a thickness correction of between 0.05 and 0.1 mm.
104 For flakes of paint carefully retrieved from structures, new paints purchased in hardware stores
105 that had been applied by brush to a series of glass or cardboard slides and air-dried for 24 to 48
106 h, and new and secondhand ceramic and glass products of less than 200 mm in length, the XRF
107 was operated under the same conditions but in the laboratory while housed nose-upwards in an
108 accessory stand and activated remotely via USB. To discriminate Sb present in any décor of
109 these products from Sb in the glass or ceramic glaze, readings were also taken on undecorated
110 regions of the substrate, where possible. For products greater than 200 mm in length the surface
111 to be measured was cradled in a radiation apron on a stainless steel table and the XRF operated
112 likewise but handheld.

113 Elemental concentrations (in $\mu\text{g g}^{-1}$) were derived from secondary (fluorescent) x-ray spectral
114 peaks using standardless fundamental parameters software. Polyethylene Niton reference discs
115 impregnated with various elements (including Sb) were analysed at regular intervals throughout
116 each measurement session and returned concentrations that were within 15% of certified values.
117 The limit of detection for Sb, defined as three standard counting errors of background intensity
118 (and derived from errors in samples that did not return a signal for Sb) varied according to the
119 precise matrix and thickness but was generally in the range 40 to 100 $\mu\text{g g}^{-1}$. Precision, derived
120 from quintuplicate measurements of the same location on a range of samples, was always better
121 than 20%.

122

123 **3. Results and discussion**

124 *3.1. Occurrence, sources and concentrations of Sb*

125 Table 1 shows the number of samples considered in each category and the number of cases in
126 which Sb was detected by XRF spectrometry, along with summary statistics of Sb
127 concentrations. Note that where Sb was detected at multiple locations of a sample (for example,
128 on distinctly different colours), the average detectable concentration and principal colour have
129 been recorded. Also shown in Table 1 for each category are the colours of the samples that
130 returned the highest Sb concentrations and the most common colours that returned detectable
131 Sb, as well as the number of cases in which Sb was detected with Pb at a concentration above
132 $100 \mu\text{g g}^{-1}$.

133 Overall, Sb was detected in at least one region of about a third of all samples tested and detection
134 frequency exceeded 30% for extant paints (with the exception of those on boats), the enamels
135 on drinking glasses and ceramicware products. Detection frequency was lowest on painted toys
136 and household equipment and the enamels of consumer bottles. Antimony was detected in all
137 colours, and including the colourless or lightly coloured glass of some products, but most
138 commonly occurred in articles coloured yellow, red (including pink) or shades of white.
139 Significantly, Pb was present at concentrations above $100 \mu\text{g g}^{-1}$ in nearly 90% of samples
140 where Sb was detected and across all sample categories and among all colours.

141 The highest concentrations of Sb (above $50,000 \mu\text{g g}^{-1}$) were encountered with concentrations
142 of Pb above $100,000 \mu\text{g g}^{-1}$ in two bright yellow ceramic items (a tea cup and plate, with the
143 XRF spectra of the former illustrated in Figure 1a). These are the only clear cases in which the
144 pigment, lead antimonite or Naples yellow (whose theoretical molecular formula is $\text{Pb}_2\text{Sb}_2\text{O}_7$),
145 appears to have been used, and where excess Pb can be attributed to its additional use in the
146 glazing of these products. The pigment may have been used in some older interior and exterior
147 paints (where Sb concentrations exceeded $20,000 \mu\text{g g}^{-1}$) but here concentrations of Pb were
148 lower than the required stoichiometry of the compound and results and any relationships with

149 colour may have been confounded by the effects of multiple layers of different paint
150 formulations measured *in situ*.

151 Regarding paints available to the contemporary consumer, Sb was present at concentrations of
152 a few thousand $\mu\text{g g}^{-1}$ in two artists paints containing the bright red pigment, cadmium
153 sulphoselenide (CI Pigment Red 108), and exemplified by the XRF spectrum in Figure 1b, and
154 a speciality leaded paint coloured by lead chromate molybdate sulphate red (CI Pigment Red
155 104), but was not detected in any paints for internal or external decoration. This suggests that
156 Sb detected in extant paints of private properties arises from its presence in older applications,
157 and a co-association with Pb may simply reflect the historical use of leaded paints in the same
158 era. Antimony trioxide (CI Pigment White 11) was added to anatase titanium dioxide (CI
159 Pigment White 6) to reduce chalking of the primary pigment before inherently antichalking
160 formulations were available (Abel, 2000) and this may explain the presence of Sb in white
161 extant paints in association with high concentrations of Ti (see XRF spectrum in Figure 1c).
162 Antimony trioxide is, however, unlikely to be present (additionally) as a flame suppression
163 synergist because concentrations of Cl and Br (indicators of halogenated flame retardants) were
164 always too low to provide any form of fire retardancy (typically a few percent w/w; National
165 Materials Advisory Board, 1970).

166 In extant municipal paints and boat paints, Sb was usually present at concentrations ranging
167 from 1000 to 10,000 $\mu\text{g g}^{-1}$ in formulations that were brightly coloured, and in particular in reds
168 and yellows. In most cases, the XRF spectrum suggested that the primary pigment for colour
169 was lead chromate (CI Pigment Yellow 34), lead chromate molybdate sulphate or bismuth
170 vanadate (CI Pigment Yellow 184) (Figure 1d). Clearly, Sb is not used in these cases for colour
171 itself but appears to be used as a fastener where colour protection from UV radiation is required
172 (USAC, 2017).

173 Among the glass containers and drinking vessels, including newly-purchased articles, Sb was
174 present in the glass itself in three products, presumably as a fining component or decolourising
175 agent (Grund et al., 2010), and appeared to be used as a colour fastener on the brightly coloured
176 enamels of ten products, with maximum Sb concentrations in the glass and enamel of about
177 $4000 \mu\text{g g}^{-1}$ and $8000 \mu\text{g g}^{-1}$, respectively. Multiple measurements of ceramicware in circulation
178 suggested that Sb was present in the glaze and uncoloured enamels of 12 products and at
179 concentrations ranging from about 1000 to $3000 \mu\text{g g}^{-1}$, possibly as an opacifier in articles fired
180 at low temperatures (Demont et al., 2012), and in the coloured enamels of 15 products. As
181 above, Sb was present as a pigment (lead antimonite) in two cases but appeared to be more
182 commonly encountered in significantly lower concentrations (1000 to $4500 \mu\text{g g}^{-1}$), presumably
183 as a colour fastener for other pigments.

184 *3.2. Migration and potential environmental and health impacts of Sb*

185 Given concerns about the toxicity of Sb (IARC, 1989; NTP, 2018), the lack of regulations that
186 directly apply (or that have been applied) to the sample types considered herein and the data
187 presented in Table 1 is surprising. The most relevant regulation concerns material like paint,
188 that can be scraped off children's toys, where a maximum migratable limit (mobilised by 0.07
189 M HCl) is $560 \mu\text{g g}^{-1}$ according to the amended EU Toy Safety Directive (European Parliament
190 and the Council of the European Union, 2009). However, the results reported in Table 1 suggest
191 that the type of paint used on children's toys and other household wooden and metallic artefacts
192 rarely contains detectable Sb. Whether this reflects attempts to avoid Sb in such products or
193 simply results from no requirement for the metalloid in these applications is unclear. Perhaps
194 of greater concern to human health in this perspective is the use of Sb as a fastener in brightly
195 coloured paints used on public playground equipment. The highest concentration of Sb returned
196 for such equipment was about $6000 \mu\text{g g}^{-1}$, with an earlier study revealing that up to 0.56% of
197 Sb in these formulations was accessible to dilute HCl (Turner et al., 2016). This suggests about

198 30 $\mu\text{g g}^{-1}$ of Sb in playground paint could be accessible to children through inadvertent
199 ingestion. While this concentration is well below the limit stipulated by the Toy Safety
200 Directive, it should be noted that, in the majority of cases considered here, Sb was co-associated
201 with high concentrations of lead and that any synergistic effects of these elements on human
202 health are unknown.

203 Much recent attention has focussed on the migration of Sb from single-use PET food-contact
204 items like water bottles and ready meal trays. Regardless of storage conditions, measured
205 concentrations of Sb in bottled water have not exceeded the European Commission limit for
206 natural mineral water of 5 $\mu\text{g L}^{-1}$ or the US Environmental Protection Agency maximum
207 contaminant level of 6 $\mu\text{g L}^{-1}$ (Shotyk et al., 2006; Greifenstein et al., 2013; Payan et al., 2017;
208 Roje and Sutalo, 2019). While concentrations of Sb reported in food contained and cooked in
209 PET packaging sometimes exceed the 40 $\mu\text{g kg}^{-1}$ limit specified by European Union Regulation
210 10/2011, typical food consumption results in intakes of Sb that are significantly below the
211 World Health Organization (WHO) tolerable daily intake (TDI) of 6 $\mu\text{g kg}^{-1}$ (Haldimann et al.,
212 2007; Whitt et al., 2016). Antimony concentrations in contemporary PET as residual catalyst
213 (typically 200 to 300 $\mu\text{g g}^{-1}$; Westerhoff et al., 2008) are, however, an order of magnitude lower
214 than concentrations in many articles of ceramicware and glassware reported in the present study.
215 Moreover, the latter are subject to sustained or long-term use and to foodstuffs that may be
216 relatively acidic.

217 Despite the occurrence of Sb in historical and contemporary food-contact ware, the degree of
218 its migration from such articles is poorly documented. Burns (1935) studied the migration of
219 Sb compounds from the enamel (and glaze) of a ceramic jug that contained 9800 $\mu\text{g g}^{-1}$ Sb
220 using various preparations of 0.5% citric acid solution. Antimony concentrations of up to 5.6
221 mg L^{-1} were detected colorimetrically in successive 18-hour extracts of the original article in
222 which the acid was introduced while boiling, but extraction rose to 20 mg L^{-1} when the jug had

223 been scoured. Although the author was unable to definitively state that such concentrations were
224 toxic, the prohibition of Sb in enamelware was called for. More recently, Demont et al. (2012)
225 studied the mobilisation of Sb and other elements from customised ceramicware that had been
226 treated with various pigments (including Sb_2O_3 as an opacifier, but of unspecified
227 concentration) and glazed. Extraction after 24 h was greatest, and up to about 0.2 mg L^{-1} , for
228 4% acetic acid but tests were not performed after disturbing the glaze to simulate sustained
229 usage and washing. Given the high levels of Sb in some of the ceramicware and enamels studied
230 herein and regulations limiting both the concentrations and migration of lead and cadmium
231 from ceramicware and the lip area (within 2 cm of the rim) of decorated drinking glasses
232 (Council of the European Communities, 1984; Rebeniak et al., 2014) it would seem prudent to
233 investigate the rates and mechanisms of Sb migration from food-contact articles more
234 systematically. The potential risks arising from migration should also be evaluated with respect
235 to the WHO $6 \text{ } \mu\text{g kg}^{-1}$ TDI for the metalloid.

236 Unlike Sb-containing electronic plastics and PET food packaging, and, with the exception of
237 container glassware, the products and applications described herein are not generally recycled.
238 Thus, the use of Sb in ceramics, enamels and paints requires its disposal through landfill or
239 incineration, both of which are challenging because of regulatory or environmental constraints
240 on the metalloid in the waste stream. For example, in Europe the limit value for Sb leaching
241 from granular solid waste (by deionised water and according to standard batch test EN 12457)
242 is among the lowest for all elements reported, and above $5 \text{ } \mu\text{g Sb g}^{-1}$ waste is classified as
243 hazardous (Environment Agency, 2013). With regard to incineration, and despite the volatility
244 of many antimony compounds, about 50% of the metalloid remains in bottom ashes due to
245 interactions with other chemicals in the fuel bed and the consequent formation of thermally
246 stable antimonates (Paoletti et al., 2001). Because of the leaching of Sb from incinerator bottom

247 ashes, the EU considers the element to be the most problematic in terms of the reuse and
248 recovery potential of waste material (European Communities, 2008).

249

250 **4. Conclusions**

251 Antimony has a variety of applications in paints, glass and ceramicware that are available to
252 the consumer and accessible to the public. It is commonly encountered in old domestic paints
253 as an anti-chalking agent but appears to be limited to contemporary consumer paints of a
254 speciality nature where the metalloid is used as a fastener for brightly coloured, and often toxic,
255 primary pigments. It is more likely to be found in contemporary paints applied to exterior
256 municipal structures, like roads, boats, playground equipment and telephone kiosks, where it
257 serves as a fastener to reduce the deterioration of bright colours. Antimony is present in glass
258 and glazed ceramics and appears to be added as a fastener for pigments in enamels but clear
259 evidence of its occurrence as the primary pigment, lead antimonite, was restricted to two bright
260 yellow articles of ceramicware. Little information exists on the migration or accessibility of Sb
261 in paints, glass and ceramicware but given concerns about its health risks and that regulations
262 exist for other metals in such products, more systematic research into Sb mobility is called for.

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Table 1: Occurrence, distribution and concentrations of Sb in paints, ceramicware and container glass. Categories are shown with the number of samples analysed, n (column 2) is the number of cases in which Sb was detected, mean, median, minimum and maximum concentrations are in $\mu\text{g g}^{-1}$, colour_{max} is the colour of the article returning the highest Sb concentration, colour_{com} is the colour where Sb was most commonly detected, and Sb-Pb denotes the number of cases in which Sb co-existed with Pb above a concentration of $100 \mu\text{g g}^{-1}$.

	n	mean	median	min	max	colour _{max}	colour _{com}	Sb-Pb
Interior extant paint ($n = 25$)	10	8670	7630	2610	24500	yellow	white ($n = 6$)	10
Exterior extant paint ($n = 25$)	9	2530	1020	260	8540	brown	white ($n = 3$)	9
Municipal extant paint ($n = 93$)	38	2220	1190	147	27500	grey	yellow ($n = 18$)	32
Extant boat paint ($n = 21$)	6	3000	993	176	8080	red	red ($n = 3$)	4
Consumer paints ($n = 18$)	3	2070	2670	520	3020	red	red ($n = 3$)	3
Painted toys/equipment ($n = 33$)	2	318	318	215	420	red	red ($n = 2$)	1
Consumer bottle enamel ($n = 20$)	3	1290	1610	629	1640	green	various ($n = 1$)	2
Drinking glass enamel ($n = 31$)	10	2310	1510	507	7790	yellow	green ($n = 2$)	8
Ceramicware enamel ($n = 69$)	23	6430	933	308	62800	yellow	yellow ($n = 6$)	22
Total ($n = 335$)	104	3360	1180	147	62800	yellow	yellow ($n = 29$)	91

Figure 1: XRF spectra of four samples and shown as counts per second versus energy from 0 to 35 keV. (a) A second hand teacup pigmented with lead antimonate and glazed with lead oxide and tin oxide; (b) an artists' paint pigmented with cadmium sulphoselenide and where Sb is present, presumably, as a fastener; (c) the exterior paint of a private household where Sb is likely present as an anti-chalking agent with titanium dioxide and lead; (d) a galvanised steel playground gate coloured by bismuth vanadate and where Sb is present as a colour fastener.

