

1 Tracking metal pathways in magmas using volcanic gas fingerprints

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9 **As well as gases that regulate climate over geological time, volcanoes emit prodigious**  
10 **quantities of metals into the atmosphere, where they have key roles as catalysts,**  
11 **pollutants and nutrients. Here we compare arc basaltic volcano metal emissions**  
12 **measurements to those from hotspot settings. As well as emitting higher fluxes of metals**  
13 **(similar to those building ore deposits), these arc emissions possess a distinct**  
14 **compositional fingerprint, particularly rich in tungsten, arsenic, thallium, antimony and**  
15 **lead compared to those from hotspots. We propose volcanic metal emissions are**  
16 **controlled by magmatic water content and redox: hydrous arc magmas that do not**  
17 **undergo sulfide saturation yield metal-rich, saline aqueous fluid; shallow degassing and**  
18 **resorption of late-stage sulfides feeds volcanic gases at Hawai'i and Iceland. While**  
19 **global arc magma chemistries vary significantly, our findings suggest that volcanic**  
20 **emissions in arcs have a distinct fingerprint compared to other settings. A shift in global**  
21 **volcanic metal emissions may have occurred in Earth's past as more oxidized, water-**  
22 **rich magmas became prevalent, influencing the surface environment.**

23

24 An important, yet poorly quantified, part of the solid Earth metal cycle is the transport of  
25 dissolved metals by magmas, followed by their sequestration as crustal ore deposits or

26 outgassing into the surface environment during volcanic eruptions. Metals play key roles in a  
27 number of Earth processes. The flux of volcanically-mediated metals from submarine arc  
28 volcanoes into past euxinic oceans<sup>1</sup> may have been of key importance for the evolution of life.  
29 Transition metals outgassed by volcanoes catalyse the aqueous oxidation of sulfur<sup>2</sup>. Magmatic  
30 aqueous fluid is an important medium for transporting metals to sites of ore deposits<sup>3,4</sup>. With  
31 some notable exceptions, studies of volcanic metal emissions have been dominated by studies  
32 of condensates from low temperature fumaroles<sup>5</sup>, generated during shallow cooling of  
33 magmatic fluids. These fluids are generally metal-poor, owing to their low temperature  
34 (below most gaseous metal condensation temperatures) and low salinity at low pressures<sup>3</sup>.  
35 There are a number of datasets from the plumes of active basaltic volcanoes<sup>6-10</sup> however,  
36 which show that these volcanoes are emitting fluxes of metals<sup>6,8,11,12</sup> of similar scale to those  
37 from large industrial smelters<sup>13</sup> and those building crustal ore deposits<sup>3,6</sup>, making basaltic  
38 volcanoes a significant source of metals (and semi-metals) into the atmosphere and oceans.  
39 Studying basaltic volcanic systems, instead of their more evolved counterparts, brings  
40 advantages: high metal fluxes, safer sampling, a magma less affected by differentiation (and  
41 consequent metal fractionation) and a style of volcanism more representative of that prevalent  
42 on early Earth, possibly providing insights into metal fluxing into the early ocean and  
43 atmosphere. It is expected, from metal ratios in ore deposits<sup>14</sup> and sulfides<sup>15</sup> and metal  
44 systematics in glasses<sup>16,17</sup> that mid-ocean ridge, hotspot and arc basaltic volcanoes should  
45 have different assemblages of outgassing metals. This has been noted by previous studies<sup>9,18</sup>,  
46 but a systematic explanation for these differences has been lacking, until now.

47

#### 48 **Metal outputs of basaltic volcanoes into the atmosphere**

49 **Figure 1** presents a compilation of volcanic gas and aerosol metal data<sup>6-10,12</sup> (**Supplementary**  
50 **Material**) acquired at six active, basaltic volcanoes in a range of tectonic settings. Cu, Tl, Cd,

51 Zn, Pb, Se and Sn fluxes into the atmosphere can reach  $10^3$ - $10^4$  kg/day at basaltic arc  
52 volcanoes and fluxes of a number of other metals (e.g., In) and semi-metals (Bi, As) can  
53 exceed 100 kg/day (**figure 1A**), similar to metal fluxes involved in crustal ore deposit  
54 development<sup>3</sup>. Metal fluxes from hotspot volcanoes Kīlauea (Hawai'i, USA; during the 2008-  
55 2018 summit eruption) and Holuhraun (Iceland; during the 2014-2015 eruption) are lower,  
56 not exceeding 100 kg/day for any metal/semi-metal species (although upper error limits for  
57 Zn and Se exceed this). Further, the data in **figure 1A** indicate that the metal composition of  
58 volcanic emissions differs systematically between arc and hotspot settings. The emissions  
59 from Kīlauea and Holuhraun aerosols are dominated by Se, Cd, Te, Pb, Cu and Zn and there  
60 are markedly lower fluxes of W, In, As, Cs and Tl over arc volcanic aerosols. Arc volcanic  
61 aerosols, in contrast, have the highest fluxes of Pb, Cu, Zn, Tl, As, Sn, Se. The minor silicate  
62 contributions to most of the key elements In, As, Cs and Tl inferred from the data from  
63 Stromboli, Masaya, Etna and Ambrym (**Supplementary Material**) mean that a variable  
64 silicate ash fraction of the plumes is unlikely to account for these differences<sup>6,7,36</sup>. Further, the  
65 plume metal compositions do not mirror the composition of the lavas (**figure 1B**), which  
66 suggests that the gas compositions are not merely controlled by the initial compositions of the  
67 magmas in the different tectonic settings, although it is important to note that another recent  
68 study documented enrichments in Sb, As, Tl, W and Pb in Manus Basin submarine arc basalts  
69 over MORB<sup>19</sup>. Arc lavas (here exemplified by Stromboli and Etna) are, overall, richer in  
70 metals such as Sb, U, Te, W, Cs, but are not appreciably richer in the other metal species, in  
71 particular those which are so abundant in the plume, e.g., Pb, Cu, Sn and Zn. In fact, Cu, Sn  
72 and Zn have similar concentrations in erupted lavas from all of the volcanoes, even when  
73 degassing is accounted for (dashed lines in **figure 1B** show pre-degassing metal  
74 concentrations). The absolute flux of metals for a particular volcano is controlled by magma  
75 degassing rate and style of volcanic activity, which would elevate or depress metal fluxes, but

76 is not expected to change the distinctive patterns observed in the relative metal abundances  
77 shown in **figure 1A**. The ratios  $X/SO_2$ , where  $X$  is a metal (or semi-metal), also show  
78 differences between settings (**Supplementary Material**), with  $X/SO_2$  being generally lower  
79 for the hotspot volcanoes ( $<1 \times 10^{-4}$  for most metals and semi-metals, with many  $<1 \times 10^{-6}$ ),  
80 extending up to  $1 \times 10^{-3}$  for Pb, Zn and Cu for the arc volcanoes.

81

82 We propose that the metals measured in these volcanic plumes were transported in the  
83 exsolved magmatic volatile phase prior to and during eruption. A plot of enrichment factors  
84 (see **methods**) demonstrates the tendency of the metals to exist in the volcanic plume gas and  
85 aerosol phase over the silicate melt phase, relative to Cu (**figure 1C**). Enrichment factors  
86 reach overall higher values for the hotspot volcanic systems: greater than  $10^2$  for In, Bi and  
87 Cd (for both Kīlauea and Holuhraun) and As, Tl and Pb (for Holuhraun) and reaching  $10^4$ - $10^5$   
88 for Te and Se, the most volatile semi-metals. For the arc plumes, enrichment factors are in  
89 general lower but follow the same overall trends (**figure 1C**). Te, Se, Cd and Bi exhibit much  
90 lower enrichment factors referenced to Cu in high-temperature these arc volcanic gases over  
91 hotspot volcanic gases, despite similar or higher concentrations of these metals in the melt  
92 prior to degassing (**figure 1B**). Kinetic effects may be important under certain conditions; it  
93 has been shown that significant variation in, e.g., Tl/Pb is possible in silicate melt during  
94 degassing, due to diffusive fractionation<sup>20</sup>. These effects are poorly understood yet unlikely to  
95 explain the order of magnitude differences observed in Tl/Pb here (**figure 1A**).

96

### 97 **Metal pathways in magmas prior to eruption**

98 Explaining the systematic differences in trace metal emissions between these arc and hotspot  
99 volcanoes requires consideration of the processes that partition metals during magma ascent  
100 and eruption. In magmatic systems in the crust, metals partition between silicate melt, an

101 aqueous fluid phase (which may be a hypercritical phase or an aqueous liquid at mid-crustal  
102 pressures, or a vapor phase at low pressures, comprising CO<sub>2</sub>, water, sulfur and halogen  
103 species), and a sulfide phase (liquid sulfide, or monosulfide solid solution, depending on  
104 temperature), should they be present. Other phases, such as silicates, oxides and phosphates,  
105 may also take up metals, but are of subordinate importance. Both chalcophile and siderophile  
106 metals partition strongly into both aqueous fluid and sulfide phases over silicate melt over a  
107 range of temperatures and pressures. Aqueous fluid-melt partition coefficients are constant  
108 regardless of whether a sulfide phase is present; therefore the presence of sulfide sequesters  
109 metals such that both the melt and aqueous fluid phases become metal-depleted. Many  
110 experimental determinations of metal partitioning have been under conditions not directly  
111 relevant to volatile-rich magmas in the crust, e.g., at mantle pressures<sup>21,22</sup>. Little attention has  
112 been paid to those metals most prevalent in volcanic gases, such as Zn, Sn, Pb and Tl.  
113 Experiments at ~200 MPa on andesites and basalts with co-existing sulfide, silicate melt and  
114 aqueous fluid<sup>23-26</sup> show that aqueous fluid-melt partitioning is dependent on the composition  
115 of the aqueous fluid and on redox. High Au concentrations in silicate melt are promoted by  
116 conditions just below the sulfide-sulfate transition (which is gradual and occurs  
117 ~NNO+0.5)<sup>23</sup>. The fluid-melt partitioning of Au is enhanced at  $fO_2 < NNO+0.5$  and  
118 suppressed at higher  $fO_2$  and when SO<sub>2</sub> dominates the aqueous fluid phase, in contrast to the  
119 partitioning of Cu, which is much less dependent on S speciation<sup>26</sup>. A recent set of  
120 experiments on aqueous fluid-melt partitioning of a wide range of metals in mafic magma, in  
121 the presence of S- and Cl-bearing aqueous fluid (**Supplementary Material Table 2**), showed  
122 that Cu, Se, Te and Cd are most volatile, followed by Zn, As, Ag, Sb, Cs, W, Tl, and Bi<sup>24</sup>.  
123 This is broadly consistent with the volcanic emissions measurements shown in **Figure 1C**  
124 although W, Cs and Zn show lower enrichment factors compared to Cu than these  
125 experiments might predict.

126

127 To understand the balance between the silicate melt-aqueous fluid and silicate melt-sulfide  
128 partitioning further, a compilation of sulfide-silicate melt, and vapor-melt partition  
129 coefficients for metals is shown in **figure 2** (citations and experimental conditions in  
130 **Supplementary Material**). Also shown in **figure 2** are the calculated emanation coefficients  
131 (see **methods**) of the metals (and semi-metals) in the gas/aerosol plumes of the basaltic  
132 volcanoes, plotted in order of the Holuhraun data. These data show that the hotspot basaltic  
133 volcanic emissions plumes (Kīlauea and Holuhraun) are particularly poor in those metals that  
134 partition more strongly into aqueous saline fluid than the sulfide phase, such as U, Cs, W, Zn,  
135 Mo (left hand side of the plot). The plumes from Kīlauea and Holuhraun are particularly rich  
136 (with emanation coefficients of 1–100%) in those metals and semi-metals which partition  
137 strongly into sulfide over silicate melt (with partition coefficients of  $>100$ ; on the right-hand  
138 side of the plot), such as Cd, Se, Te (no data exists for Au in the gas plumes of Kīlauea or  
139 Holuhraun; **Figure 2**). In contrast, the data for these arc gases show that all metals have an  
140 emanation coefficient of  $>0.1\%$  (with the exception of U for Stromboli). These arc plumes are  
141 richer in U, Cs, W, Cu than hotspot volcanic plumes; these elements are associated with  
142 significantly higher aqueous fluid-melt partition coefficients (up to  $10^1$ – $10^2$ ; note the aqueous  
143 fluid-melt partition coefficient for Sn is for rhyolite melt<sup>27</sup> and the partition coefficient  
144 increases with the chlorine content of the aqueous fluid<sup>27</sup>) relative to their sulfide-silicate melt  
145 partition coefficients ( $<10$ , with the exception of Cu).

146

#### 147 **Effect of the timing of aqueous fluid and sulfide saturation**

148 Arc basalts contain, on average, 4 wt% H<sub>2</sub>O<sup>29</sup>, and 0.5–2.0 wt% CO<sub>2</sub><sup>30</sup>. Aqueous fluid  
149 saturation is expected to occur in the mid-crust, into which metals will partition, strongly in  
150 some cases (**figure 2**). Hotspot basalts, in contrast, contain 0.5-1.0 wt% H<sub>2</sub>O<sup>31</sup> and 0.5 to 1.0

151 wt% CO<sub>2</sub><sup>32</sup>, which results in the exsolved fluid becoming water-rich only at shallower depths.  
152 Importantly, the fluid phase will be strongly CO<sub>2</sub>-dominated until the magma reaches low  
153 pressures (<100 MPa) during magma ascent, when H<sub>2</sub>O and sulfur (as H<sub>2</sub>S or SO<sub>2</sub>) partition  
154 into the aqueous vapor phase<sup>33,34</sup>. The metal-carrying capacity of CO<sub>2</sub>-rich aqueous fluid has  
155 been shown to be poor<sup>35</sup>.

156

157 Models of sulfide saturation<sup>36,37</sup> show that while mid-ocean ridge basalts are likely saturated  
158 in sulfide on eruption, more oxidized basalts, where a greater proportion of sulfur is present as  
159 sulfate<sup>38,39</sup>, must fractionate to a greater degree to achieve sulfide saturation. Some basalts  
160 may not saturate in sulfide at all<sup>39,40</sup>. Sulfides are not commonly present (as quenched sulfide  
161 liquid or sulfide minerals), either in the groundmass or as inclusions, in the erupted products  
162 of Stromboli, Etna and Ambrym<sup>41</sup>. In contrast 2014–2015 Holuhraun Icelandic melts contain  
163 abundant sulfides on eruption; as do the matrix glass and melt inclusions of Laki<sup>42</sup>. At  
164 Kīlauea, basaltic tephra contain sulfides as inclusions in olivine. Sulfur systematics in the  
165 matrix glasses of basalts from Iceland and Kīlauea are consistent with sulfide saturation on or  
166 shortly before eruption<sup>43</sup>.

167

168 If sulfide saturates prior to an aqueous fluid in the deep crust (**figure 3, middle**), dense  
169 sulfides may be sequestered into cumulates, thus removing metals from the silicate-melt  
170 aqueous fluid system and generating chalcophile-poor melt (and aqueous fluid) upon further  
171 ascent and eruption of the magma; this has been suggested as an explanation for the lack of  
172 ore deposits in relatively water-poor ‘barren’ arc magmatic systems<sup>44</sup>. A chalcophile-poor arc  
173 volcanic gas is not a feature of the datasets presented here. If, however, an aqueous fluid  
174 phase forms before sulfide saturation, which is likely for a water-rich arc basalt (**figure 3,**  
175 **right**), metals will partition strongly into the saline aqueous fluid<sup>45</sup>. If the silicate melt does

176 not saturate with sulfide<sup>16</sup>, the aqueous fluid will remain metal-rich and will be outgassed  
177 during magma ascent and eruption at the surface with the metals in proportions controlled by  
178 their respective fluid-melt partition coefficients. If the melts are very chlorine-rich, a brine  
179 phase may form at low pressure, unmixing, along with a low density vapor, from a  
180 supercritical fluid described by the solvus in the NaCl-H<sub>2</sub>O system<sup>3</sup>. Brine formation may  
181 fractionate metals; however these effects are minimal for basalts degassing near atmospheric  
182 pressure, which are relatively poor in chlorine (compared to rhyolites) and are likely to  
183 transport a saline aqueous fluid phase up to the surface (including any minor brine phase)<sup>3</sup>.  
184 The vapor phase in the sulfide-free case will then be rich in a range of fluid-mobile  
185 metals/semi-metals, just as observed in the arc volcanic gas data presented here (**figure 1**).  
186 Note that primary melts in arc settings may also be variably enriched in fluid-mobile metals<sup>19</sup>,  
187 caused by fluid addition to the mantle wedge directly from the slab. However, the data  
188 presented here suggest that further partitioning into the aqueous fluid phase must also take  
189 place to explain the enrichment in fluid-mobile metals in the volcanic emissions over the  
190 silicate melt (**figures 1B, 2**).

191

192 If sulfide saturates after an aqueous fluid phase, the sulfides may play some role in metal  
193 partitioning during shallow eruption and degassing processes. The hotspot volcanic gases in  
194 **figure 1A** are rich in chalcophiles (e.g., Cd, Te, Se) and the emanation coefficients of the  
195 gases in these plumes broadly follows sulfide-silicate melt partition coefficients (**figure 2**),  
196 suggesting that metals are sourced from sulfides directly, either via a mantle melting process<sup>46</sup>  
197 or through the formation of a sulfide liquid droplet at the interface between a silicate melt and  
198 aqueous fluid bubble<sup>47,48</sup>, shown as “vapor-sulfide aggregates”, in **Figure 3 (left)**. Sulfides  
199 may become unstable due to oxidation during attachment to a vapor bubble and may then be  
200 resorbed during exsolution of an aqueous vapor phase<sup>49</sup>. In this way, metals that were bound



201 in sulfides<sup>17</sup> are released to the silicate melt-vapor system, and then to the atmosphere.  
202 Congruent dissolution of sulfides within these bubble-sulfide aggregates has been proposed to  
203 explain the similarity of metal outgassing ratios to metal ratios in sulfides at some  
204 volcanoes<sup>47,50</sup>.

205

### 206 **Implications of systematic volcanic metal emissions variations**

207 The four arc volcanoes presented here have a distinctive metal outgassing fingerprint, with  
208 higher concentrations of Cs, As, In, W and Tl over hotspot volcanoes (**Figure 1**). While  
209 global arc magma chemistries vary significantly, we propose that these characteristic metal  
210 enrichments will be a broad feature of global arc volcanic plumes due to their relatively  
211 oxidized nature, low degree of fractional crystallization and high magma water and chlorine  
212 contents. Together, these factors suppress sulfide saturation promoting partitioning of  
213 metals/semi-metal directly into aqueous/saline aqueous fluid rather than metal/semi-metal  
214 degassing being mediated by sulfides (**Figure 3**).

215

216 Saline aqueous fluids clearly play an important role in transporting large fluxes of metals  
217 from basaltic melts through the mid and upper crust, eventually either outgassing from  
218 volcanoes or being incorporated into ore deposits. Volcanic outgassing of metals and ore  
219 deposit formation may be effectively mutually exclusive in any particularly time period. In  
220 fact, the gases emitted from volcanoes are representative of the fluids that, under different  
221 conditions of magma supply or tectonic stress, might instead precipitate economically viable  
222 concentrations of metals and sulfur in shallow crustal porphyries. In arc magmatic systems,  
223 there is good evidence that mafic magmas of the type that we observe outgassing at the  
224 surface (**figure 1**) underplate felsic magmas in the crust<sup>53</sup>. Recharging mafic magmas clearly  
225 have potential to supply extensive fluxes of volatiles to overlying felsic magmas via an

226 aqueous fluid phase which might migrate efficiently through crystal-rich, near-solidus  
227 magmas<sup>54,55</sup>. Accumulation of aqueous fluid at the roof zones of such reservoirs may  
228 therefore trigger the shallow intrusion of stocks and then be the medium from which metals  
229 are precipitated in copper porphyry systems<sup>3</sup>, without the need to invoke reworking of  
230 magmatic sulfides to concentrate metals.

231

232 There may be broader implications of the important role of volcanoes in metal geochemical  
233 cycling. It has been proposed that arc basalts were not oxidized until the late Neoproterozoic,  
234 when extensive ocean bottom water sulfate led to subducted sulfate oxidizing the sub-arc  
235 mantle<sup>56</sup>, which coincides with copper and gold porphyries becoming prominent in the  
236 geological record<sup>56,57</sup>. Submarine arc volcanoes during the Archaean and much of the  
237 Proterozoic may hence have outgassed mixtures of metals very much like hotspot volcanoes  
238 today; with higher volcanic arc outgassing fluxes of W, Cs, As, Tl, Pb, Cu and Zn (similar to  
239 modern arc volcanoes) only becoming widespread in the earliest Phanerozoic, when shallow  
240 submarine arc vents may have become significant localized sources of these biologically  
241 important metals in the ocean<sup>58</sup>.

242

### 243 **Methods**

244 Enrichment factors were calculated by normalizing gas plume metal concentrations by Cu  
245 concentrations, and lava metal compositions by Cu concentrations and then dividing the former by the  
246 latter. This normalization step is necessary because plume dilution is variable between datasets.  
247 Enrichment factor (EF) is then a quantity that is comparable between sources and is given by:

248

249 
$$EF_{Cu} = \frac{\left( \frac{[X]}{[Cu]} \right)_{gas}}{\left( \frac{[X]}{[Cu]} \right)_{lava}} \quad (1)$$

250

251 We have used Cu as our normalizing element, rather than a more lithophile element such as a REE or  
252 Al, Mg, because the latter necessitates accounting far more accurately for the contamination of the  
253 samples by silicate material. Cu has been affected by contamination by ash, but only by up to 6%; see  
254 **supplementary material** for discussion). Cu is a poorly to moderately volatile element, which is  
255 reflected in the plot of enrichment factors; most metals plot at higher values than Cu.  $EF < 1$  means the  
256 element is less “volatile” than Cu;  $EF > 1$  means the element is more “volatile” than Cu. Ours is not the  
257 first study to use a moderately volatile element to normalize data to generate EF; Br has been used in  
258 several studies<sup>6</sup>.

259

260 The emanation coefficient,  $\epsilon_x$ , is calculated as the percentage of the metal  $x$  that has degassed from  
261 the silicate melt, equal to:

262

263 
$$\epsilon_x = \frac{(c_i - c_f)}{c_i} \quad (2)$$

264

265 where  $c_i$  is the initial concentration of element  $x$  in the magma and  $c_f$  is the final concentration of  
266 element  $x$  in the post-eruptive lava (as originally defined by<sup>59</sup>, who used this relation to describe  
267 the degassing of radionuclides <sup>222</sup>Rn, <sup>210</sup>Po, <sup>210</sup>Bi and <sup>210</sup>Pb).

268

269 We use two methods to calculate emanation coefficients shown in **Figure 2** (see Supplementary  
270 Material Table 1). The emanation coefficient  $\epsilon_x$  of these elements from the magma can be assessed  
271 from their mean enrichment factor (EF, see equation 1 above) and the emanation coefficient of Pb  
272 from molten basalt (which we assume to be constant at 0.01<sup>60</sup>), as<sup>6,8,61</sup>:

273

274 
$$\epsilon_x^{-1} = 1 + \left[ \frac{EF_{Pb}}{EF_x} \right] \left[ \frac{1 - \epsilon_{Pb}}{\epsilon_{Pb}} \right] \quad (3)$$

275

276 We also calculate the concentration of metals and semi-metals in the silicate melt prior to degassing  
277 and then the emanation coefficient using equation 2 above. The amount of metal (or semi-metal) in the  
278 gas plume was “added” back into to the degassed lava composition by converting the mass X/SO<sub>2</sub>  
279 ratio in the plume (**Supplementary Material figure 1**) to X/S and then multiplying by the mass of  
280 sulfur degassed (from melt inclusion and matrix glass sulfur concentrations<sup>41 9 39,62</sup>). This amount, in  
281 ppm, was added to the degassed lava composition to estimate an “un-degassed” magma composition  
282  $c_i$ . It is possible that sulfide saturation could occur prior to melt inclusion entrapment, which would  
283 cap the sulfur concentration and deplete chalcophile metal concentrations in the melt inclusions; these  
284 processes would introduce error on these estimates. The arc basalts show no evidence for sulfide  
285 saturation; there are no sulfide globules in the melt inclusions from Ambrym<sup>41</sup>, Stromboli and Etna<sup>39</sup>,  
286 but Kīlauea and Holuhraun melt inclusions show occasional sulfide<sup>62</sup>, although it is not clear whether  
287 these formed pre- or post-entrapment. We assume that sulfur is dominantly present as SO<sub>2</sub> in the gas  
288 plume and H<sub>2</sub>S is neglected. It is also possible that under some circumstances S degasses from a larger  
289 volume of magma than metals/semi metals due to its lower solubility at higher pressures or mediation  
290 of metal degassing by halogen species. In order to overcome the difficulties associated with using X/S  
291 ratios to calculate  $\epsilon_x$ , we repeat the calculation using X/Cl to calculate the pre-degassing metal (and  
292 semi-metal) concentrations for which data is available for most of the datasets used here (see  
293 **Supplementary Material**). We find there is good agreement between the  $\epsilon_x$  calculated using X/S and  
294 X/Cl (see **Supplementary Material**).

295

#### 296 **Data Availability Statement**

297 The authors declare that the data supporting the findings of this study, and the citations  
298 detailing data sources, are available within the article and its supplementary information files.

299

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480

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484

#### 485 **Author contributions**

486 All authors contributed equally to the concept and intellectual content of this article. ME took  
487 main responsibility for writing the article and for revising it after review.

488

#### 489 **Figures**

490

491 **Figure 1: Metal systematics in the gas plumes of active basaltic volcanoes in a range of**  
492 **settings.** A: Metal fluxes in kg/day, with uncertainties, from four arc (or “arc affinity”)  
493 volcanoes (blue) and two hotspot volcanoes (red)<sup>6,7,9,10,12,41</sup>.  $X/SO_2$  for each dataset are shown

494 in **figure 1** of the **supplementary material**. B: Lava compositions (ppm) (a volcanic bomb  
495 for Masaya; and scoria for Stromboli and Holuhraun) for the eruptions in each setting,  
496 citations as above. Solid lines are degassed lava compositions; dashed lines show the metal  
497 concentration prior to degassing (see **supplementary material** for data and methods). Note  
498 that these dashed lines are only resolvable for some elements; for others the amount depleted  
499 by degassing is relatively small. C: Enrichment factors relative to Cu for each volcano (see  
500 Methods). Fields for each setting are shaded for ease of visual evaluation.

501

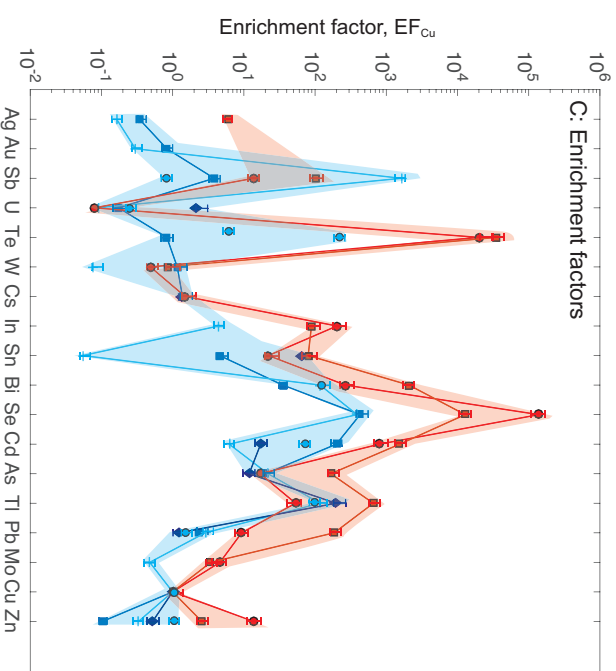
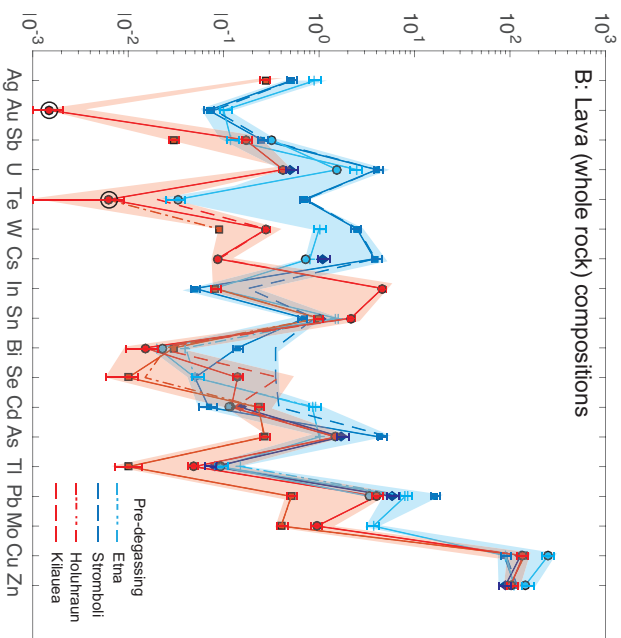
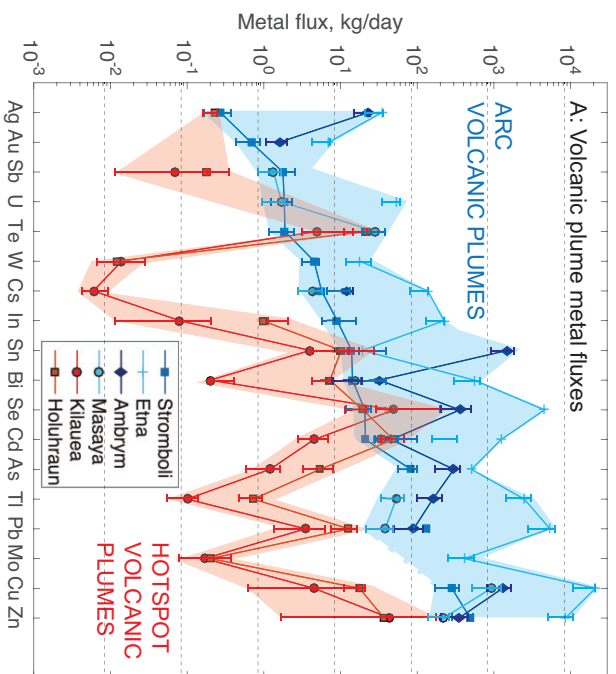
502 **Figure 2: Volcanic gas data compared to metal partitioning between silicate melt, sulfide**  
503 **and aqueous fluid**. Emanation coefficients for the range of metals and semi-metals are  
504 shown (see **methods** and **Supplementary Material**). Red shaded data are for volcanic gases  
505 from hotspot volcanoes Kīlauea and Holuhraun (Iceland); blue shaded data are for volcanic  
506 gases from arc basaltic eruptions Stromboli\*, Etna, Masaya and Ambrym. Dark green  
507 rectangles are sulfide-silicate melt partition coefficients and light green, aqueous fluid-melt  
508 partition coefficients (see **Supplementary Material** for citations).

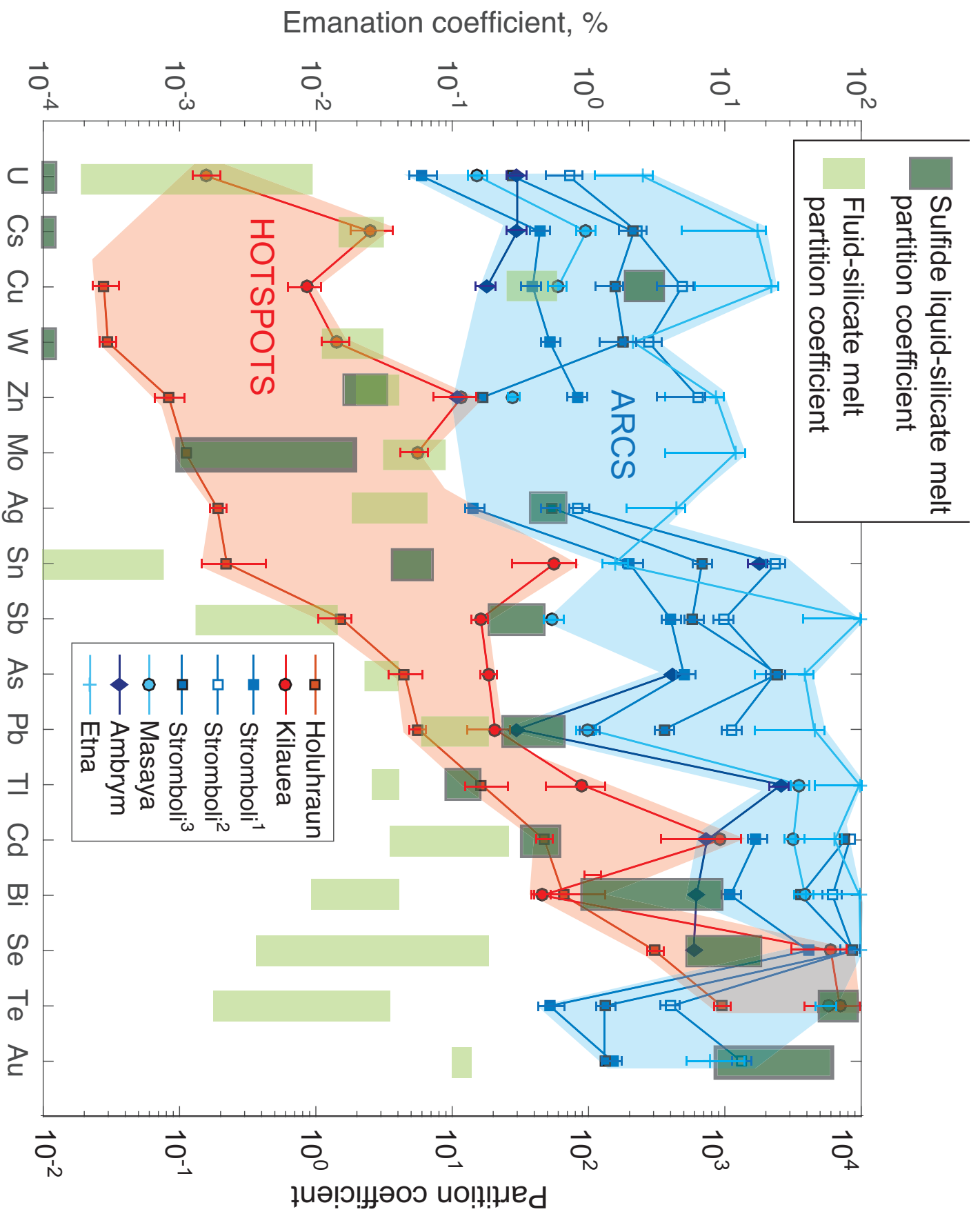
509 \*Three emanation coefficients are shown for Stromboli (see Methods and Supplementary Material): 1. From<sup>6</sup>  
510 calculated assuming  $\epsilon_{pb} \sim 1\%$ <sup>59,60</sup>; 2. calculated using plume  $X/SO_2$  and the mass of sulfur degassed. 3. calculated  
511 using plume  $X/Cl$  and the mass of chlorine degassed. Note that the  $X/SO_2$  values for Etna aerosol  
512 (**Supplementary Table 1**) are high compared with other arc volcanoes in this dataset and with other data from  
513 Etna<sup>8,28</sup>, which causes the emanation coefficients to be anomalously high when using this  $X/SO_2$  ratio, combined  
514 with the melt inclusion sulfur contents (see **methods**), to reconstruct the metal contents of the melts.

515

516 **Figure 3: Metal pathways through silicate melt, sulfide and aqueous fluid, and their**  
517 **impact on the metal composition of basaltic volcanic gas and aerosol**. We envisage  
518 Kīlauea and Holuhraun to correspond to the far left case, where much of the magmatic water  
519 exsolves at low pressures in the crust, coinciding with late stage sulfide saturation. Arc basalts

520 correspond to the far right case, where deep magmatic aqueous fluid phase saturation occurs  
521 with no sulfide saturation, allowing metal-rich aqueous fluid to form.







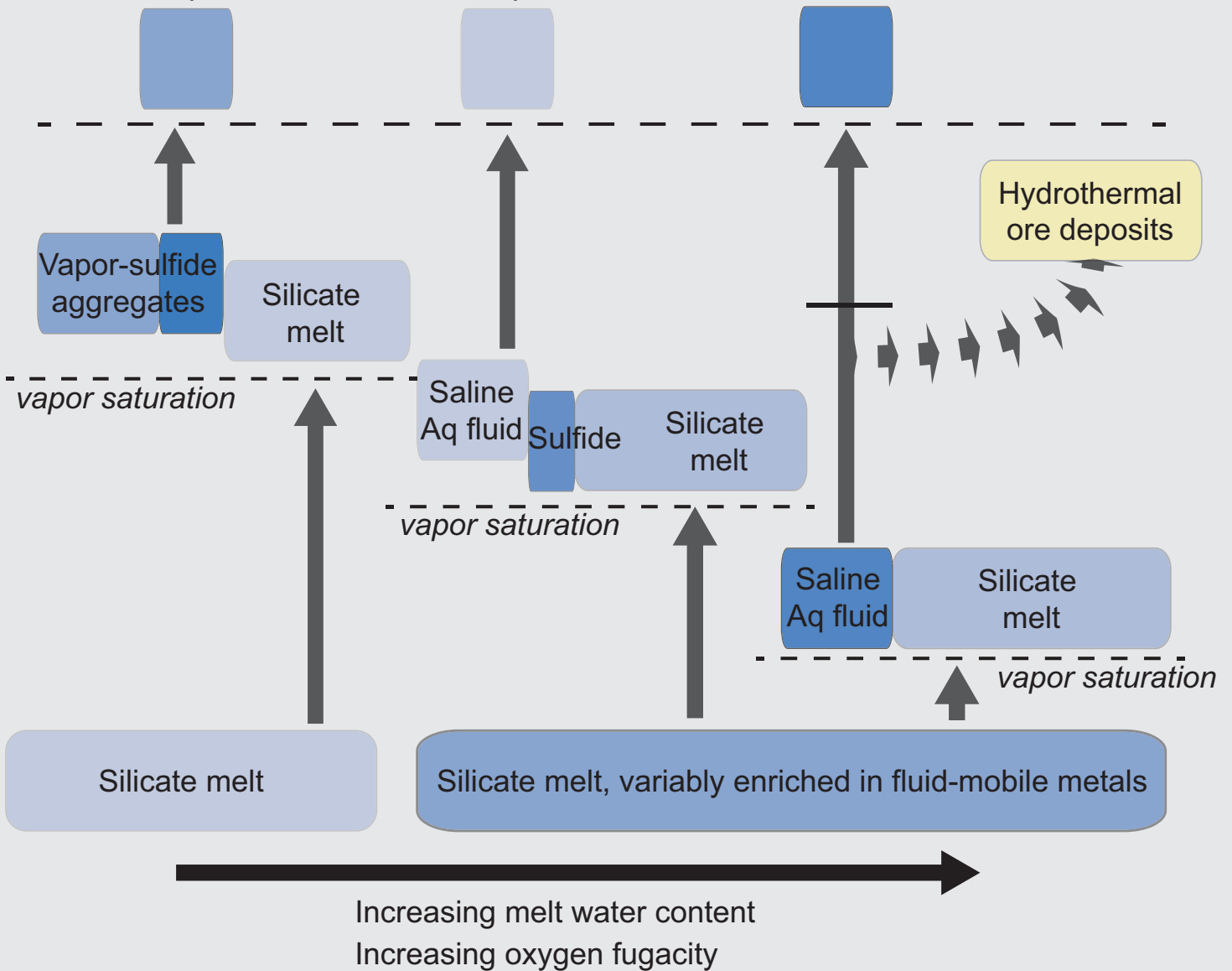
Ocean island volcanoes

Basaltic arc volcanoes

Volcanic gases enriched in chalcophiles

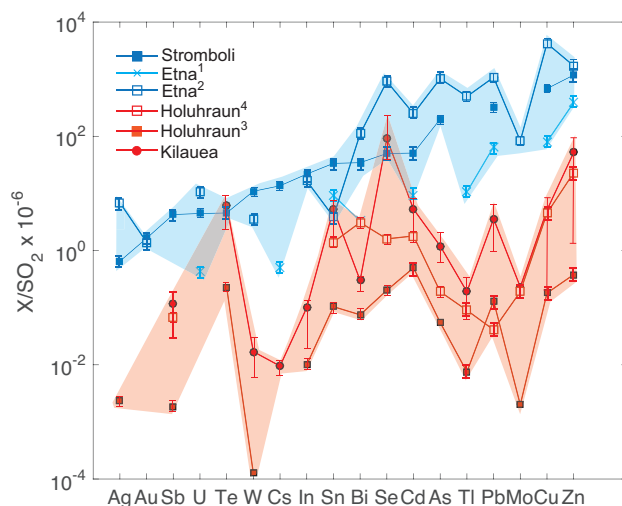
Volcanic gases depleted in chalcophiles

Volcanic gases enriched in fluid-mobile metals



## Supplementary Material

## Tracking metal pathways in magmas using volcanic gas fingerprints

*M. Edmonds, T. A. Mather, E. J. Liu*

**Supplementary figure 1: Ratios  $X/SO_2$ , in mg/kg, in the gas plumes volcanoes from arc (blue) and ocean island settings (red).** Volcanoes are Stromboli (solid blue squares), Etna (light blue crosses<sup>1</sup> and blue open squares<sup>2</sup>), Kīlauea (red circles) and Holuhraun, Iceland (red squares<sup>3</sup> and open squares<sup>4</sup>). Elements are ordered using the Stromboli dataset, as **Figure 1** of the main paper. See **table 1** for citations and errors on data.

### Contribution of metals to the volcanic plume as silicate ash particles

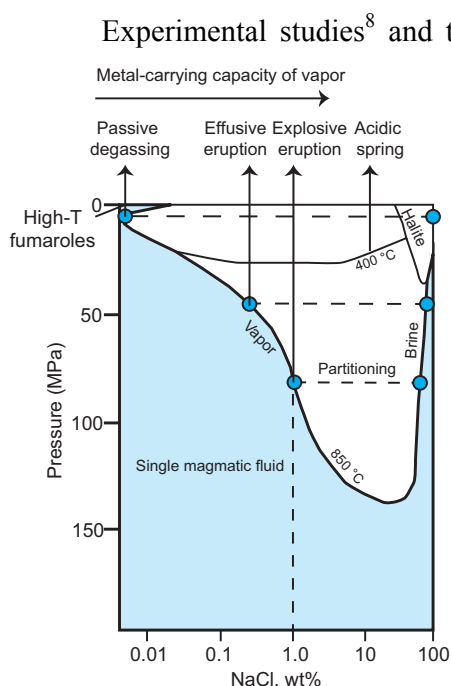
Volcanic particulates sampled by filter packs in plumes are made up of both aerosols (aqueous liquids with dissolved acid gases into which metals partition from high temperature magmatic vapor, before being condensed upon quenching in the atmosphere) and also silicate particles, fragments of bubble walls typically launched into the plume by bubble bursting. The bulk analysis of the particulate fraction then inevitably results in some of the metal budget being sourced from the silicate particles rather than metals that have been volatilized from the magma forming the aerosol and gas phases. This effect is most significant for the less mobile, more lithophile elements, and less important for the more volatile metals, with high vapor-melt partition coefficients. Here we discuss the magnitude of this effect.

At Stromboli a minor silicate contribution was inferred for Cr, Cs, Cu, Rb and W (0-5%), but a significant one for Te and Zn (10%) and corrected accordingly<sup>3</sup>. For Etna, it has been noted that significant concentrations of Al, Si, Na, K, and REE are present in the plume, which must be sourced from silicate material<sup>2</sup>. Elements such as Se, Cd and Sb, however, which are present only in trace amounts in silicate melts, are present in significant quantities in filter pack analyses (greater than more abundant lithophile trace elements such as Th, Sc), suggesting that these metals are volatile. The weight ash fraction (WAF) was calculated by these authors<sup>2</sup> using the abundance of REE. The calculated WAF is very low for Bi (0.1%), Sb (0.2%), Se and Tl (both 0.1%); slightly more significant for Pb (3%), As (2%) and Cu (6%) but significant for Mo, Zn, Te and W (33, 25, 59, 100% respectively), although Te is poorly constrained by its low abundance (close to detection, table 1) in lavas. There is abundant evidence from elsewhere that Te is highly volatile<sup>4</sup>. Another study used Th abundance to calculate the proportion contributed from ash and derived considerably lower estimates: zero for Tl, Bi, Cd; then 3% for Cu, 1% for Sn, 2% for Zn and 0.5% for Pb<sup>1</sup>. At Ambrym negligible ash contributions were inferred for Ag, Au, Sn, Bi, Se, Cd, As, Tl, with a slightly larger contribution for Cs (0-15%), Pb (~2%), Cu (0-17%) and Zn (7-40%)<sup>5</sup>. For Holuhraun the concentrations of Th and REE were used to estimate very low proportion of silicate ash (about 10  $\mu\text{g}$  of ash per filter on average) and therefore the effect of ash contamination was neglected<sup>6</sup>. An ash correction was not calculated for the Kīlauea dataset.

Solid sulfides, oxides, halides, and oxyhydroxides might also be present in the plume, given the dramatic fall in solubility of gaseous metal chloride, sulfide and other species during the drop in temperature from the basalt liquidus temperature to ambient conditions. The presence of these phases may impact the estimation of silicate ash fraction because even nominally "immobile" high field strength elements like Sn, Th or REE may have significant volatility in the presence of abundant gaseous F, as is well known from studies of greisen-forming ore-bearing hydrothermal systems e.g.[7].

We conclude that while in some cases up to 40% of a metal or semi-metal species might be supplied from ash, in general the metals we plot here are highly volatile and their abundance is controlled dominantly by transport initially in the magmatic vapor phase and later (at and away from the vent) in liquid aerosol.

### Metal-carrying capacity of magmatic vapor phase at low pressures

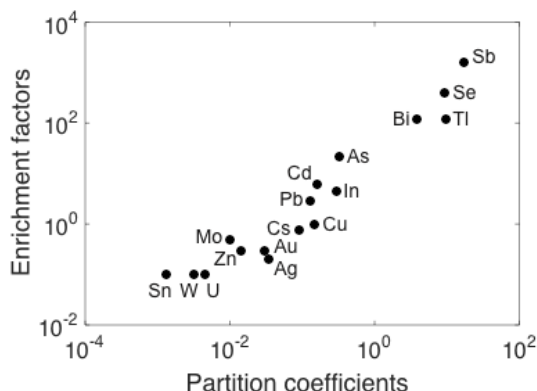


Experimental studies<sup>8</sup> and thermodynamic modeling have shown that metals form stable complexes with chloride, sulfate and fluoride in volcanic plumes<sup>9</sup>. Volcanic gas at the surface is the low density phase which is the result of separation of a brine phase from a saline supercritical fluid as it decompresses and cools (**supplementary figure 2**). Up to now, much of the literature on metals in volcanic environments has been gleaned from condensates<sup>10,11</sup>, deposited during shallow cooling of magmatic fluids, which have little relevance to the question of how mafic volcanic systems outgas metals to the atmosphere<sup>12</sup>. Little data exists for hot magmatic plumes outgassed directly from the magma column during eruptions, which are expected to contain a far higher load of metals dispersed into the atmosphere, either as gas or as sub micron-aerosols, owing to their higher temperature and chloride content<sup>13,14</sup>.

**Supplementary figure 2:** NaCl-H<sub>2</sub>O phase diagram plotted in pressure-composition space, modified after<sup>15</sup>.

The solvus will shrink significantly at high temperatures, increasing the salinity and metal-carrying capacity of outgassing vapor. It is possible that supercritical metal-rich fluids may reach the surface, avoiding immiscibility. Until recently<sup>16,17</sup>, it was assumed by some authors that low salinity volcanic gas would not have the capacity to dissolve large quantities of metals as chloride complexes, and the brine phase was therefore the favored ore-forming medium<sup>18</sup>. **Figure 1 (main paper)** shows that, on the contrary, volcanic gases are highly significant carriers of metals.

**Table 1**, below, shows the data used in this paper and its sources. We focus here on active basaltic volcanoes with data acquired using filter packs at the vent (*i.e.* not from fumaroles or lava flows, or as condensates and sublimates).



**Supplementary Figure 3:** Enrichment factors from **table 1** for elements in the plume of Etna (Italy), using Cu as a normalising element, plotted against "absolute" partition coefficients (defined as mass of element in the gas/mass of element in the melt phase) calculated by estimating a dilution factor for the plume<sup>12</sup>.

**Table 1:** Metal/semi-metals contents of degassed lavas and gas/aerosol samples; X/SO<sub>2</sub>, metal fluxes, volatilities and enrichment factors for the datasets presented in the main paper.

*Erupted lava metal content*, in ppm. Data sources: Stromboli Volcano (Italy)<sup>3</sup>, Holuhraun (Iceland)<sup>6</sup>, Etna (Italy)<sup>2</sup>, Ambrym Volcano (Vanuatu)<sup>5</sup>, Kīlauea (Hawaii, USA), standard BHVO<sup>19</sup> and Masaya Volcano (Nicaragua)<sup>20</sup>. Error typically <10% for ICP-MS, IMA with internal calibration using standards.

*Gas and aerosol metal data*, in µg/m<sup>3</sup>, from Stromboli Volcano (Italy)<sup>3</sup>, Holuhraun (Iceland)<sup>6</sup>, Etna (Italy)<sup>1</sup>, Ambrym Volcano (Vanuatu)<sup>5</sup>, Kīlauea Volcano (Hawaii, USA)<sup>14</sup> and Masaya Volcano (Nicaragua)<sup>20</sup>. Uncertainties are shown in brackets for each element within each dataset and are typically 5-25%.

*Flux* of element X in kg per day, calculated using the mass ratio X/SO<sub>2</sub>\* and the independently measured flux of SO<sub>2</sub> (data sources as above). The uncertainty on the flux measurement is 30-32%, propagated from errors on SO<sub>2</sub> flux (~30%) and errors on gas and aerosol measurements (5-10%).

\* X/SO<sub>2</sub> in mg/kg; errors on X/SO<sub>2</sub> are propagated from errors on analysis of S and X in gas/aerosol phase and including, where available<sup>21</sup>, the standard deviation of repeat analyses on the same day, amounting to 7-17% for the former and up to 95% for the latter<sup>21</sup>.

*Emanation coefficient*,  $\epsilon_x$ , is calculated as the percentage of the metal x that has degassed from the silicate melt, equal to:  $\epsilon_x = \left( \frac{c_i - c_f}{c_i} \right) / \frac{c_i}{c_f}$

where  $c_i$  is the initial concentration of element x in the magma and  $c_f$  is the final concentration of element x in the post-eruptive lava (as originally defined by<sup>22</sup>). The *emanation coefficients* given are estimated in a range of ways (which are indicated as footnotes for each sub-table). The *emanation coefficient*  $\epsilon_x$  of these elements from the magma can be assessed from their mean enrichment factor (EF) and the emanation coefficient of Pb from molten basalt (which may be assumed to be constant at 0.01<sup>23</sup>), as  $\epsilon_x^{-1} = 1 + \left[ \left( \frac{EF_{Pb}}{EF_x} \right) \left( \frac{1 - \epsilon_{Pb}}{\epsilon_{Pb}} \right) / \frac{c_i}{c_f} \right]$ . We also calculate the concentration of metals and

semi-metals in the silicate melt prior to degassing,  $c_i$ . The amount of metal (or semi-metal) in the gas plume was “added” back into the degassed lava composition by converting the mass X/SO<sub>2</sub> ratio in the plume and then multiplying by the pre-eruptive melt concentration of sulfur (from melt inclusion concentrations, corrected for matrix glass sulfur concentration<sup>5,6,25,26</sup>). This amount, in ppm, was added to the degassed lava composition to estimate a “un-degassed” magma composition  $c_i$ . For some datasets we also calculate emanation coefficients using X/Cl to estimate pre-degassing metal concentrations in the melt, using melt inclusion and matrix glass concentrations as shown in the footnotes. Errors on the *emanation coefficients* are propagated from typical errors on the individual electron microprobe analyses of sulfur, which is typically 5%, and errors on X/SO<sub>2</sub>. Total errors

$EF_{Cu}$  is the *enrichment factor* relative to copper (Cu), equal to

$$EF_{Cu} = \frac{\left( \frac{[X]}{[Cu]} \right)_{\text{gas}}}{\left( \frac{[X]}{[Cu]} \right)_{\text{rock}}}$$

. Errors are propagated from the individual metal analyses

and range from 14-17%.

*Note on propagation of errors:* X/SO<sub>2</sub>, enrichment factors and emanation coefficients are calculated using the measured concentration data as defined above, with individual errors as defined in the paper sources (see tables below). Errors on these quantities are propagated from the error on the individual measurements, where the uncertainty on quantity z (which is a function of independent variables x and y e.g. z = xy, or z = x/y) is the sum

of the squares of the fractional errors, or error percentages, of x and y:  $\frac{\delta z}{z} = \sqrt{\left( \frac{\delta x}{x} \right)^2 + \left( \frac{\delta y}{y} \right)^2}$ .

<i>Volcano</i>	<b>Stromboli<sup>3</sup></b>	<i>Gas, aerosol,</i> <i>Lava,</i> <i>ppm</i>	<i>Gas, aerosol,</i> <i>µg/m<sup>3</sup></i>	<i>Flux,</i> <i>kg/day</i>	<i>X</i> <sub>SO<sub>2</sub></sub> <i>mg/kg</i>	<i>X</i> <sub>Cl</sub> <i>mg/kg</i>	<i>Emanation</i> <i>coefficient</i> <i>ε (%)<sup>a</sup></i>	<i>Emanation</i> <i>coefficient</i> <i>ε (%)<sup>b</sup></i>	<i>Emanation</i> <i>coefficient</i> <i>ε (%)<sup>c</sup></i>	<i>EF<sub>Cl</sub></i>
S	40	4540 (±227)	4.15 × 10 <sup>5</sup> (±1.26 × 10 <sup>5</sup> )	1.40 × 10 <sup>5</sup> (±4.25 × 10 <sup>4</sup> )	0.65 (±0.05)	2.06 (±0.22)	98	99	98	
Cl	550	2910 (±146)			0.14	0.82	74	79	71	0.3 (±0.045)
Ag	0.51	6.0 × 10 <sup>3</sup> (±0.0003)		0.27 (±0.08)	1.64 (±0.18)	0.69 (±0.08)	0.14	0.82	0.54	0.8 (±0.14)
Au	0.07	2.0 × 10 <sup>-3</sup> (±2.0 × 10 <sup>-4</sup> )		0.68 (±0.22)	4.27 (±0.48)	11.3 (±1.2)	1.5	13	1.3	3.8 (±0.65)
Sb	0.25	3.3 × 10 <sup>-2</sup> (±3.3 × 10 <sup>-3</sup> )		1.77 (±0.56)	4.45 (±0.31)	8.25 (±0.90)	4	10	5.8	3.8 (±0.65)
U	4.0	2.4 × 10 <sup>-2</sup> (±1.2 × 10 <sup>-3</sup> )		1.85 (±0.56)	4.55 (±0.32)	6.87 (±0.76)	0.06	0.72	0.28	0.2 (±0.03)
Te	0.7	2.0 × 10 <sup>-2</sup> (±1.0 × 10 <sup>-3</sup> )		1.89 (±0.57)	4.55 (±0.32)	6.87 (±0.76)	0.52	4.1	1.3	0.8 (±0.12)
W	2.5	1.0 × 10 <sup>-1</sup> (±1.0 × 10 <sup>-2</sup> )		4.53 (±1.43)	10.9 (±1.22)	34.4 (±3.8)	0.52	2.8	1.8	1.2 (±0.21)
Cs	3.8	1.8 × 10 <sup>-1</sup> (±1.8 × 10 <sup>-2</sup> )		5.66 (±1.79)	13.6 (±1.52)	61.9 (±6.8)	0.44	2.3	2.2	1.4 (±0.24)
Sn	0.70	1.1 × 10 <sup>-1</sup> (±5.5 × 10 <sup>-3</sup> )		14.0 (±4.26)	33.6 (±2.38)	37.8 (±4.2)	2.0	24	6.8	4.6 (±0.69)
Bi	0.14	1.7 × 10 <sup>-1</sup> (±8.5 × 10 <sup>-3</sup> )		14.3 (±4.35)	34.5 (±2.44)	58.4 (±6.4)	11	62	36	35.2 (±5.3)
Se	0.05	7.4 × 10 <sup>-1</sup> (±7.4 × 10 <sup>-2</sup> )		20.8 (±6.58)	50.0 (±5.59)	254 (±28)	41	87	87	429 (±74)
Cd	0.07	4.8 × 10 <sup>-1</sup> (±2.4 × 10 <sup>-2</sup> )		21.1 (±6.42)	50.9 (±3.60)	165 (±18)	17	83	76	199 (±30)
As	4.30	3.0 (±0.3)		83.0 (±26.3)	200 (±22.4)	1030 (±110)	5	23	24	20.2 (±3.5)
Tl										
Pb	16.2	1.3 (±0.065)		132 (±40.2)	318 (±22.5)	447 (±49)	1	11	3.6	2.3 (±0.35)
Mo										
Cu	87	3.0 (±0.15)		283 (±86.1)	682 (±48.2)	1030 (±110)	0.39	4.8	1.6	1.0 (±0.15)
Zn	112	0.40 (±0.04)		491 (±155)	1180 (±132)	137 (±15)	0.83	6.4	0.17	0.1 (±0.017)

<sup>a</sup> *Emanation coefficient* calculated assuming  $\epsilon_{\text{Pb}} \sim 1\%_{\text{O}}^{22,23}$  (see table caption), from<sup>3</sup>.

<sup>b</sup> *Emanation coefficient* calculated using plume *X*/*SO<sub>2</sub>* and the mass of sulfur degassed (from matrix and melt inclusion glass analysis; see table caption and methods). Melt inclusion and matrix glass data from<sup>3,27</sup> (0.34 and 0.004 wt% sulfur).

<sup>c</sup> *Emanation coefficient* calculated using plume *X*/*Cl* and the mass of chlorine degassed (from matrix and melt inclusion glass analysis; see table caption and methods). Melt inclusion and matrix glass data from<sup>3,27</sup> (0.19 and 0.055 wt% chlorine).

<i>Volcano</i>	<b>Holuhraun<sup>6</sup></b>		<i>Gas, aerosol<sup>a</sup></i>	<i>Flux,</i>	<i>X/SO<sub>2</sub></i>	<i>Emanation</i>	<i>Emanation</i>	<i>EF<sub>cu</sub></i>
<i>Elements</i>	<i>Lava</i>		<i>µg/m<sup>3</sup></i>	<i>kg/day</i>	<i>mg/kg</i>	<i>ε (%)<sup>b</sup></i>	<i>ε (%)<sup>c</sup></i>	
	<i>ppm</i>							
S	400 <sup>28</sup>		185 (±19)				74	500 (±85)
Cl			3.64 (±0.36)				32	42 (±7.1)
Ag	0.28		1.54 × 10 <sup>-3</sup> (±1.5 × 10 <sup>-4</sup> )	0.23 (±0.04)	2.41 × 10 <sup>-3</sup> (±2.7 × 10 <sup>-4</sup> )	1.8 × 10 <sup>-3</sup>	1.9 × 10 <sup>-3</sup>	5.9 (±1.0)
Au								
Sb	0.026		2.47 × 10 <sup>-3</sup> (±2.5 × 10 <sup>-4</sup> )	0.18 (±0.06)	1.82 × 10 <sup>-3</sup> (±2.0 × 10 <sup>-4</sup> )	1.5 × 10 <sup>-2</sup>	1.5 × 10 <sup>-2</sup>	103 (±18)
U								
Te	0.0048		1.58 × 10 <sup>-1</sup> (±1.6 × 10 <sup>-2</sup> )	22.3 (±7.1)	2.28 × 10 <sup>-1</sup> (±2.5 × 10 <sup>-2</sup> )	9.2	9.5	35800 (±6200)
W	0.093		7.30 × 10 <sup>-5</sup> (±7.3 × 10 <sup>-6</sup> )	1.2 × 10 <sup>-2</sup> (±3.8 × 10 <sup>-3</sup> )	1.26 × 10 <sup>-4</sup> (±1.0 × 10 <sup>-5</sup> )	2.9 × 10 <sup>-4</sup>	3.0 × 10 <sup>-4</sup>	0.9 (±0.16)
CS								
Sn	0.99		7.28 × 10 <sup>-2</sup> (±7.3 × 10 <sup>-3</sup> )	10.2 (±3.2)	1.04 × 10 <sup>-1</sup> (±1.1 × 10 <sup>-2</sup> )	2.2 × 10 <sup>-2</sup>	2.2 × 10 <sup>-2</sup>	80.0 (±14)
Bi	0.025		4.80 × 10 <sup>-2</sup> (±4.8 × 10 <sup>-3</sup> )	7.28 (±2.3)	7.5 × 10 <sup>-2</sup> (±8.4 × 10 <sup>-3</sup> )	6.4 × 10 <sup>-1</sup>	6.6 × 10 <sup>-1</sup>	2080 (±360)
Se	0.014		1.68 × 10 <sup>-1</sup> (±1.7 × 10 <sup>-2</sup> )	19.6 (±6.2)	2.01 × 10 <sup>-1</sup> (±2.2 × 10 <sup>-2</sup> )	2.9	3.1	12800 (±2200)
Cd	0.23		3.30 × 10 <sup>-1</sup> (±3.3 × 10 <sup>-2</sup> )	48.7 (±15.4)	4.99 × 10 <sup>-1</sup> (±5.6 × 10 <sup>-2</sup> )	4.5 × 10 <sup>-1</sup>	4.8 × 10 <sup>-1</sup>	1540 (±270)
As	0.27		4.09 × 10 <sup>-2</sup> (±4.1 × 10 <sup>-3</sup> )	5.38 (±1.7)	5.50 × 10 <sup>-2</sup> (±6.2 × 10 <sup>-3</sup> )	4.4 × 10 <sup>-2</sup>	4.5 × 10 <sup>-2</sup>	167 (±30)
Tl	0.01		6.07 × 10 <sup>-3</sup> (±6.1 × 10 <sup>-4</sup> )	0.73 (±0.23)	7.46 × 10 <sup>-3</sup> (±8.3 × 10 <sup>-4</sup> )	1.6 × 10 <sup>-1</sup>	1.6 × 10 <sup>-1</sup>	658 (±14)
Pb	0.51		8.79 × 10 <sup>-2</sup> (±8.8 × 10 <sup>-3</sup> )	12.8 (±4.1)	1.31 × 10 <sup>-1</sup> (±1.5 × 10 <sup>-2</sup> )	5.4 × 10 <sup>-2</sup>	5.7 × 10 <sup>-2</sup>	186 (±32)
Mo	0.40		1.26 × 10 <sup>-3</sup> (±1.3 × 10 <sup>-4</sup> )	0.2 (±0.06)	2.01 × 10 <sup>-3</sup> (±2.2 × 10 <sup>-4</sup> )	1.1 × 10 <sup>-3</sup>	1.1 × 10 <sup>-3</sup>	3.4 (±0.6)
Cu	142		1.30 × 10 <sup>-1</sup> (±1.3 × 10 <sup>-2</sup> )	17.7 (±5.6)	1.80 × 10 <sup>-1</sup> (±2.0 × 10 <sup>-2</sup> )	2.7 × 10 <sup>-4</sup>	2.8 × 10 <sup>-4</sup>	1.0 (±0.2)
Zn	100		2.37 × 10 <sup>-1</sup> (±2.4 × 10 <sup>-2</sup> )	36.9 (±11.7)	3.79 × 10 <sup>-1</sup> (±4.2 × 10 <sup>-2</sup> )	8.0 × 10 <sup>-4</sup>	8.3 × 10 <sup>-4</sup>	2.6 (±0.5)

<sup>a</sup> sample name BAR-A from<sup>6</sup><sup>b</sup> *Emanation coefficient* (expressed in terms of a %) from<sup>6</sup>, calculated using a dilution factor (calculated using at-vent and downwind plume sulfur dioxide concentrations). Error propagated from gas measurements are in the range 10-20%.<sup>c</sup> *Emanation coefficient* calculated assuming the degassing of 1100 ppm sulfur, from 1500 ppm to 400 ppm<sup>28</sup> and using the X/SO<sub>2</sub> ratio of the plume to reconstruct the concentration of element X prior to degassing.

Volcano	Ena <sup>a</sup> Lava ppm	Gas aerosol <sup>a</sup> µg/m <sup>3</sup>	Flux, kg/day	X/SO <sub>2</sub> <sup>c</sup> , mg/kg	Emanation coefficient ε (%) <sup>b</sup>	Emanation coefficient ε (%) <sup>c</sup>	Emanation coefficient ε (%) <sup>d</sup>	EF <sub>Cu</sub>
<i>Elements:</i>								
S	150	181 (±19)	5.0 × 10 <sup>6</sup> (±1.7 × 10 <sup>6</sup> )	1.85 × 10 <sup>5</sup> (±2.0 × 10 <sup>4</sup> )	39.9	56.4	0.80	71 (±9)
Cl	1700	67 (±7)	9.2 × 10 <sup>5</sup> (±3.0 × 10 <sup>5</sup> )	6.91 (±0.77)	4.47	8.36	0.07	2.3 (±0.3)
Ag	0.9	2.5 × 10 <sup>-3</sup> (±2.5 × 10 <sup>-4</sup> )	35 (±12)	1.41 (±0.16)	7.91	14.3	0.10	0.2 (±0.035)
Au	0.1	5.1 × 10 <sup>-4</sup> (±5.1 × 10 <sup>-5</sup> )	7.0 (±2.3)	9.17 × 10 <sup>3</sup> (±1.0 × 10 <sup>3</sup> )	99.8	99.9	85	0.3 (±0.05)
Sb	0.12	3.32 (±0.33)	4.5 × 10 <sup>4</sup> (±1.5)	10.5 (±1.2)	2.50	4.75	0.035	1630 (±282)
U	2.5	3.8 × 10 <sup>-3</sup> (±3.8 × 10 <sup>-4</sup> )	52.5 (±17.3)					0.1 (±0.012)
Te								
W	1	1.3 × 10 <sup>-3</sup> (±1.3 × 10 <sup>-4</sup> )	18.0 (±5.94)	3.59 (±0.4)	2.14	4.09	0.035	0.1 (±0.017)
Cs	0.8	0.01 (±0.001)	138 (±46)	27.6 (±3.1)	17.4	29.1	0.26	0.74 (±0.13)
Sn	1.5	1.4 × 10 <sup>-3</sup> (±1.4 × 10 <sup>-4</sup> )	19.3 (±6.8)	3.87 (±0.43)	1.55	2.97	0.035	0.1 (±0.017)
Bi	0.02	4.0 × 10 <sup>-2</sup> (±4.0 × 10 <sup>-3</sup> )	552 (±182)	110 (±12)	97.1	98.5	29	118 (±20.4)
Se	0.05	3.3 × 10 <sup>-1</sup> (±3.3 × 10 <sup>-2</sup> )	4560 (±1500)	912 (±101)	99.1	99.5	58	388 (±67.2)
Cd	0.85	9.0 × 10 <sup>-2</sup> (±9.0 × 10 <sup>-3</sup> )	1243 (±435)	249 (±27)	64.1	77.7	2.1	6.2 (±1.1)
As	1	3.7 × 10 <sup>-2</sup> (±3.7 × 10 <sup>-3</sup> )	511 (±179)	102 (±11)	38.4	54.9	7.12	22 (±3.8)
Tl	0.09	1.8 × 10 <sup>-1</sup> (±1.8 × 10 <sup>-2</sup> )	2486 (±870)	497 (±55)	97.1	98.5	29	118 (±20.4)
Pb	8	3.9 × 10 <sup>-1</sup> (±3.9 × 10 <sup>-2</sup> )	5387 (±1890)	1077 (±120)	45.1	61.5	1.0	2.9 (±0.50)
Mo	3.7	3.0 × 10 <sup>-2</sup> (±3.0 × 10 <sup>-3</sup> )	414 (±145)	82.9 (±9.2)	12.0	21.0	0.17	0.5 (±0.09)
Cu	90	1.53 (±0.15)	2.11 × 10 <sup>4</sup> (±7.4 × 10 <sup>3</sup> )	4227 (±470)	22.3	35.8	0.35	1.0 (±0.17)
Zn	110	6.2 × 10 <sup>-1</sup> (±0.062)	8564 (±3000)	1710 (±1.90)	8.67	15.6	0.10	0.3 (±0.05)

<sup>a</sup> ET1 of<sup>2</sup><sup>b</sup> *Emanation coefficient* calculated using plume X/SO<sub>2</sub> and the mass of sulfur degassed (from matrix and melt inclusion glass analysis; see table caption and methods). Melt inclusion and matrix glass data from (0.32 and 0.015 wt% sulfur)<sup>26</sup>.<sup>c</sup> *Emanation coefficient* calculated using plume X/Cl and the mass of chlorine degassed (from matrix and melt inclusion glass analysis; see table caption and methods). Melt inclusion and matrix glass data from (0.28 and 0.17 wt% chlorine)<sup>26</sup>.<sup>d</sup> *Emanation coefficient* calculated assuming ε<sub>Pb</sub> ~ 1%<sup>22,23</sup> (see table caption and methods).<sup>e</sup> Note that these X/SO<sub>2</sub> values are high compared with other arc volcanoes in this dataset and with other data from Ena<sup>1,29</sup>, which causes the emanation coefficients to be anomalously high when using the X/SO<sub>2</sub> ratio, combined with the melt inclusion sulfur contents, to reconstruct the metal contents of the melts (main paper, figure 2).



<i>Volcano</i>	<b>Masaya<sup>20</sup></b> <i>Lava</i> <i>ppm</i>	<i>Gas aerosol,</i> <i>µg/m<sup>3</sup></i>	<i>X/SO<sub>2</sub>,</i> <i>mg/kg</i>	<i>Flux,</i> <i>kg/day</i>	<i>EF<sub>Ca</sub></i>
<i>Elements</i>					
S	150	0.11 (±0.006)	$5.0 \times 10^5 (\pm 6.0 \times 10^4)$	$5.0 \times 10^5 (\pm 1.65 \times 10^4)$	$2.8 \times 10^3 (\pm 0.4 \times 10^3)$
Cl					
Ag					
Au					
Sb	0.321	0.0074 (±0.00074)	0.35 (±0.04)	0.18 (±0.06)	0.92 (±0.12)
U	1.55	0.01 (±0.001)	0.48 (±0.05)	0.24 (±1.2)	0.26 (±0.034)
Te	0.033	0.19 (± 0.019)	9.0 (±1.0)	4.5 (±1.5)	230 (±29)
W					
Cs	0.711	0.029 (±0.0029)	1.38 (±0.15)	0.69 (±0.23)	1.6 (±0.21)
In					
Sn					
Bi	0.023	0.061 (±0.006)	2.90 (±0.32)	1.5 (±0.5)	110 (±14)
Se					
Cd	0.113	0.22 (±0.022)	20.9 (±2.3)	11 (±3.6)	77 (±10)
As					
Tl	0.092	0.21 (±0.021)	20.0 (±2.2)	10 (±3.4)	91 (±12)
Pb	3.36	0.142 (±0.014)	13.5 (±1.5)	6.7 (±2.2)	1.7 (±0.22)
Mo					
Cu	251	6.32 (±0.063)	600 (±67)	300 (±99)	1.0 (±0.33)
Zn	144	1.69 (±0.17)	160 (±18)	80 (±26)	0.47 (±0.06)

Volcano	Kilauea	Gas, aerosol <sup>14</sup>	Flux,	X/SO <sub>2</sub>	X/Cl	Emanation coefficient $\epsilon$ (%) <sup>a</sup>	Emanation coefficient $\epsilon$ (%) <sup>b</sup>	Emanation coefficient $\epsilon$ (%) <sup>c</sup>	EF <sub>Cl</sub>
	Lava <sup>19</sup>	$\mu\text{g}/\text{m}^3$	kg/day	mg/kg	mg/kg				
Elements:	ppm								
S	402	120 ( $\pm 13$ )	$7 \times 10^8$ ( $\pm 65 \times 10^6$ )	640 ( $\pm 45$ )		89	89	44	
Cl	$3.32 \times 10^{-1}$	16 ( $\pm 1.5$ )	448 ( $\pm 45$ )			0.42	30	3.3	
Ag	$1.5 \times 10^{-3}$								
Au									
Sb	$1.7 \times 10^{-1}$	$2.5 \times 10^{-3}$ ( $\pm 0.4 \times 10^{-4}$ )	0.07 ( $\pm 0.06$ )	0.12 ( $\pm 0.01$ )	$1.6 \times 10^2$ ( $\pm 20$ )	0.16	0.22	1.46	13.7 ( $\pm 2.1$ )
U	$4.2 \times 10^{-1}$	$3.6 \times 10^{-5}$ ( $\pm 5.0 \times 10^{-6}$ )		$0.0029$ ( $\pm 3 \times 10^{-4}$ )	$2.3$ ( $\pm 0.3$ )	0.0016	0.16	0.0087	0.080 ( $\pm 0.02$ )
Te	$6.3 \times 10^{-3}$	$1.34 \times 10^{-1}$ ( $\pm 1.5 \times 10^{-2}$ )	4.8 ( $\pm 3.0$ )	6.3 ( $\pm 0.7$ )	$8.4 \times 10^3$ ( $\pm 1 \times 10^3$ )	70	99	96	$1.98 \times 10^4$ ( $\pm 3.8 \times 10^3$ )
W	$2.80 \times 10^{-1}$	$1.46 \times 10^{-4}$ ( $\pm 2.6 \times 10^{-5}$ )	$1.4 \times 10^{-2}$ ( $\pm 8.0 \times 10^{-3}$ )	0.017 ( $\pm 2 \times 10^{-3}$ )	9.1 ( $\pm 1.3$ )	0.014	0.97	0.053	$4.86 \times 10^{-1}$ ( $\pm 0.11$ )
Cs	$8.6 \times 10^{-2}$	$1.38 \times 10^{-4}$ ( $\pm 3.0 \times 10^{-5}$ )	$6.0 \times 10^{-3}$ ( $\pm 2.0 \times 10^{-3}$ )	$9.5 \times 10^{-3}$ ( $\pm 1 \times 10^{-3}$ )	8.6 ( $\pm 1.3$ )	0.025	2.92	0.16	1.50 ( $\pm 0.4$ )
In	4.6	$1.00 \times 10^{-2}$ ( $\pm 1.0 \times 10^{-4}$ )	$8.0 \times 10^{-2}$ ( $\pm 7.0 \times 10^{-2}$ )	0.1 ( $\pm 1 \times 10^{-2}$ )	63 ( $\pm 10$ )	0.0050	0.41	18	202 ( $\pm 37$ )
Sn	2.15	$5.1 \times 10^{-2}$ ( $\pm 9.0 \times 10^{-3}$ )	4.5 ( $\pm 2.3$ )	$5.3$ ( $\pm 6 \times 10^{-1}$ )	$3.2 \times 10^3$ ( $\pm 5 \times 10^2$ )	0.56	31	2.3	22.1 ( $\pm 5.2$ )
Bi	$1.5 \times 10^{-1}$	$4.3 \times 10^{-3}$ ( $\pm 1.9 \times 10^{-4}$ )	0.21 ( $\pm 0.07$ )	$0.3$ ( $\pm 3 \times 10^{-2}$ )	$2.7 \times 10^2$ ( $\pm 40$ )	0.46	35	22	267 ( $\pm 43$ )
Se	$1.4 \times 10^{-1}$	1.49 ( $\pm 0.15$ )	62.5 ( $\pm 4.5$ )	91 ( $\pm 10$ )	$9.3 \times 10^4$ ( $\pm 1 \times 10^4$ )	60	99	99	$1.39 \times 10^5$ ( $\pm 2.5 \times 10^4$ )
Cd	$1.2 \times 10^{-1}$	$1.03 \times 10^{-1}$ ( $\pm 1.2 \times 10^{-2}$ )	3.8 ( $\pm 2.3$ )	5.3 ( $\pm 0.6$ )	$6.4 \times 10^3$ ( $\pm 1 \times 10^3$ )	9.2	94	46	800 ( $\pm 150$ )
As	1.5	$2.73 \times 10^{-2}$ ( $\pm 2.0 \times 10^{-3}$ )	1.1 ( $\pm 0.5$ )	1.2 ( $\pm 0.1$ )	$1.7 \times 10^3$ ( $\pm 3 \times 10^3$ )	0.18	25.4	1.8	17.0 ( $\pm 2.9$ )
Tl	$4.9 \times 10^{-2}$	$2.8 \times 10^{-3}$ ( $\pm 0.4 \times 10^{-3}$ )	0.13 ( $\pm 0.07$ )	0.19 ( $\pm 0.02$ )	$1.8 \times 10^2$ ( $\pm 30$ )	0.88	52	5.5	53.3 ( $\pm 11$ )
Pb	4.0	$4.0 \times 10^{-2}$ ( $\pm 0.3 \times 10^{-2}$ )	3.1 ( $\pm 2.3$ )	3.6 ( $\pm 0.4$ )	$2.5 \times 10^3$ ( $\pm 400$ )	0.21	16	1	9.32 ( $\pm 1.6$ )
Mo	$9.50 \times 10^{-1}$	$4.7 \times 10^{-3}$ ( $\pm 0.5 \times 10^{-3}$ )	$1.7 \times 10^1$ ( $\pm 0.1$ )	0.23 ( $\pm 0.03$ )	$2.9 \times 10^2$ ( $\pm 50$ )	0.056	8.5	0.50	4.61 ( $\pm 0.86$ )
Cu	137	$1.5 \times 10^{-1}$ ( $\pm 9.0 \times 10^{-3}$ )	4.5 ( $\pm 4.0$ )	5.1 ( $\pm 0.06$ )	$9.4 \times 10^3$ ( $\pm 1.5 \times 10^3$ )	0.0086	2.0	0.11	1.00 ( $\pm 0.16$ )
Zn	102	1.50 ( $\pm 0.17$ )	45 ( $\pm 44$ )	52 ( $\pm 6$ )	$9.4 \times 10^4$ ( $\pm 1.3 \times 10^4$ )	0.12	22	1.5	13.7 ( $\pm 2.6$ )

<sup>a</sup> *Emanation coefficient* calculated using plume X/SO<sub>2</sub> and the mass of sulfur degassed (from matrix and melt inclusion glass analysis; see table caption and methods). Melt inclusion and matrix glass data: 0.13 and 0.015 wt% sulfur<sup>31</sup>.

<sup>b</sup> *Emanation coefficient* calculated using plume X/Cl and the mass of chlorine degassed (from matrix and melt inclusion glass analysis; see table caption and methods). Melt inclusion and matrix glass data: 0.05 and 0.035 wt% chlorine<sup>25</sup>. Note that the uncertainty on this emanation coefficient is high owing to the low concentration of Cl in the plume and the uncertainty associated with estimating the chlorine budget from melt inclusions and matrix glasses<sup>21,32</sup>.

<sup>c</sup> *Emanation coefficient* calculated assuming  $\epsilon_{\text{Pb}} \sim 1\%^{22,23}$  (see table caption and methods).

<i>Volcano</i>	<b>Ambrym<sup>5</sup></b> <i>Lava<sup>5</sup>, ppm</i>	<i>Gas, aerosol<sup>5</sup>, µg/m<sup>3</sup></i>	<i>Flux, kg/day</i>	<i>Emanation coefficient ε (%)<sup>6</sup></i>	<i>EF<sub>Cl</sub></i>
<i>Elements</i>					
S	0.015			95	
Cl	0.07			30	
Ag		3.20 (±0.19)	23 (±4.0)		
Au		3.1 × 10 <sup>-3</sup> (±1.9 × 10 <sup>-4</sup> )	1.6 (±0.5)		
Sb					
U	0.5	1.3 × 10 <sup>-2</sup> (±5.2 × 10 <sup>-4</sup> )		0.3	2.1 (±0.33)
Te					
W					
Cs	1.1	1.8 × 10 <sup>-2</sup> (±1.1 × 10 <sup>-3</sup> )	12 (±3.7)	0.3	1.3 (±0.21)
Sn	1	0.8 (±0.08)	1500 (±470)	18	64.5 (±1.8)
Bi		4.1 × 10 <sup>-2</sup> (±1.6 × 10 <sup>-3</sup> )	32 (±9.7)	6.2	
Se		3.1 × 10 <sup>-1</sup> (±0.03)	360 (±114)	5.9	
Cd	0.15	3.2 × 10 <sup>-2</sup> (±3.2 × 10 <sup>-3</sup> )	46 (±15)	7.4	17.2 (±3.2)
As	1.7	0.25 (±0.025)	300 (±95)	4.1	11.9 (±2.2)
Tl	0.08	0.195 (±0.012)	160 (±49.0)	26	197 (±32.4)
Pb	5.9	0.09 (±0.004)	90 (±27)	0.3	1.2 (±0.19)
Mo					
Cu	129.00	1.60 (±0.10)	1300 (±400)	0.18	1.00 (±0.16)
Zn	89.5	0.58 (±0.035)	350 (±110)	0.11	0.52 (±0.086)

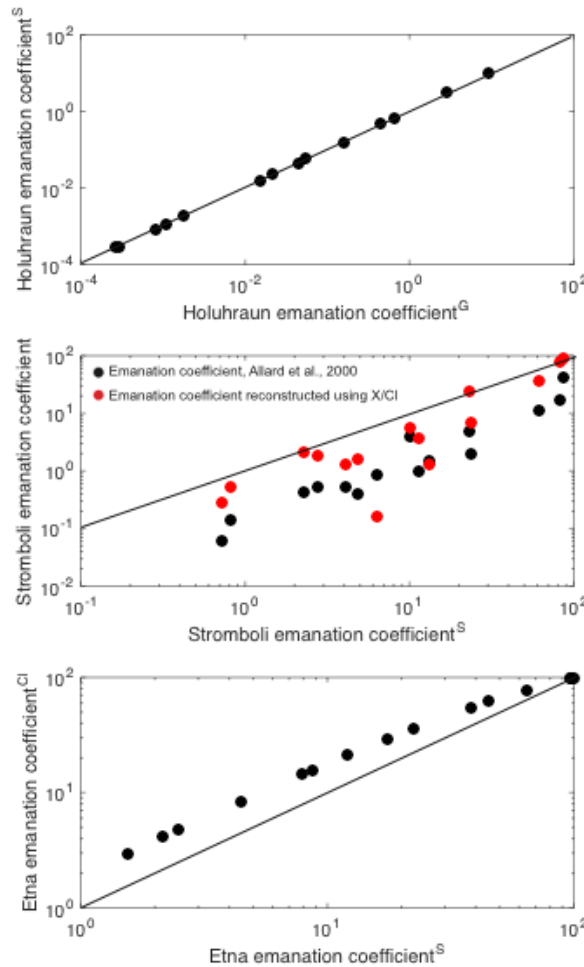
<sup>a</sup> *Emanation coefficient* calculated using measurements of ε<sub>pb</sub> from <sup>5</sup> (see table caption and methods).

### Comparison of different ways to calculate emanation coefficients

The tables above show various different ways to estimate the emanation coefficient,

$$\varepsilon_x = \frac{(c_i - c_f)}{c_i} \quad \text{where } c_i \text{ is the initial concentration of element } x \text{ in the magma and}$$

concentration of element  $x$  in the post-eruptive lava (as originally defined by<sup>22</sup>). The **supplementary figure 4** show how they compare to one another. The emanation coefficients calculated using the various methods are broadly consistent with one another in terms of volatility, with the methods using  $X/SO_2$  and  $X/Cl$  to “add back” metals in the proportions of these ratios to calculate  $c_i$  and thus emanation coefficient yielding higher emanation coefficients than the methods based on measurement of the emanation coefficient of  $^{210}Pb^{23}$ , by



**Supplementary Figure 4:** top: emanation coefficient for metals and semi-metals at Holuhraun calculated by<sup>6</sup> by using factor calculated from their measurements of sulfur in vent and plume gases (x-axis) and emanation coefficient calculated using the mass of sulfur outgassed (from melt inclusion and matrix gas microanalysis<sup>28</sup>) and  $X/SO_2$  ratios to calculate  $c_i$  (y axis). Middle: emanation coefficient for Stromboli metals calculated in this study using  $X/S$  to reconstruct  $c_i$  (x axis) plotted versus emanation coefficient from<sup>3</sup> using measurement of emanation coefficient of  $^{210}Pb^{23}$  (y axis) using  $X/Cl$  (this study) to calculate  $c_i$  (this study) to calculate  $c_i$  (y axis). Bottom: comparison between emanation coefficient calculated using  $X/SO_2$  (x axis) versus emanation coefficient calculated using  $X/Cl$  (y axis) to calculate  $c_i$  (this study) to calculate  $c_i$  (y axis) for Mt Etna (Italy). Black solid line is 1:1 relationship.

## Metal partition coefficients

**Table 2:** Vapor-melt ( $D_{\text{vapor-melt}}$ ) and sulfide-silicate melt ( $D_{\text{sulfide-silicate melt}}$ ) partition coefficients used in this paper. Sources are shown either in column header or in individual cells.

	$D_{\text{vapor-melt}}^{33}$	$D_{\text{vapor-melt}}$	$D_{\text{sulfide-silicate melt}}$	$D_{\text{sulfide-silicate melt}}^{34}$	$D_{\text{sulfide-silicate melt}}^{35}$
U		0.002 to 0.45 <sup>36</sup>	0.001 <sup>37</sup>		
Cs	2.3 to 5.9	0.5 to 10 <sup>38</sup>			
W	1.8 to 4.5	3 to 16 <sup>39</sup>		0.003 to 0.1	
Cu	33 to 70	1 to 80 <sup>40</sup>	260 to 447 <sup>41</sup>	540 to 1040	1042 to 1624
Zn	2.3 to 5	9 to 70	1.9 to 3.1 <sup>41</sup>	0.28 to 0.94	2.4 to 4.7
Mo	5.5 to 9.8	9.3 to 523 <sup>39</sup>		0.1 to 2.58	
Ag	1.9 to 7	7 to 10 <sup>38</sup>	360 to 617 <sup>41</sup>	300 to 700	853 to 1528
Sn		0.002 to 0.078 <sup>40</sup>		2.4 to 6.0	9 to 13
Sb	0.14 to 2.6	1 to 10 <sup>38</sup>	15 to 34 <sup>41</sup>	1.4 to 11.2	
As	3 to 6.2	1 to 2.5 <sup>42</sup>		0.3 to 19.7	
Pb	8.4 to 15	2 to 14 <sup>39</sup>	26 to 54 <sup>41</sup>	13 to 48	45 to 71
Tl	3.1 to 6	3.5 to 12.4 <sup>39</sup>	10 to 17 <sup>41</sup>		
Cd	6.5 to 30		45 to 82 <sup>41</sup>		61 to 193
Bi	1 to 5.3	7 to 30 <sup>38</sup>		110 to 1130	
Se	0.59 to 12		790 to 1500 <sup>41</sup>		
Au		12 to 15 <sup>42</sup>		930 to 5500	
Te	0.22 to 6.7		6000 to 16000 <sup>41</sup>		

### Notes on experimental conditions.

<sup>33</sup> Partitioning of metals between vapor and basalt silicate melt at 850 °C, 2 kbar, Cl- and H<sub>2</sub>O-bearing fluids.

<sup>34</sup> Partitioning between basanite melt, sulfide liquid and monosulfide solid solution, at 1175 to 1300 °C, 1.5-3.0 GPa, 3 units below to 1 unit above FMQ buffer, relevant to mantle conditions.

<sup>35</sup> Mid-ocean ridge basalts at FMQ to FMQ-1.

<sup>36</sup> Haplogranite melt composition, aqueous fluid with HCl and HF, 2 kbar, 750 C.

<sup>37</sup> 1-10 GPa, 1750–2100 °C, 0–28 wt% S, and  $f_{\text{O}_2}$  2 log units below IW (core conditions).

<sup>38</sup> Granitic and peralkaline melts, melts with high chlorinities (1-14 mole/kg),  $\log f_{\text{O}_2} = \text{NNO}-1.7$  to  $\text{NNO}+4.5$ .

<sup>39</sup> Haplogranite melt composition, with H<sub>2</sub>O-HCl and H<sub>2</sub>O-HF vapor phase. For Cu, lowest  $D_{\text{vapor-melt}}$  for H<sub>2</sub>O-only and highest for Cl-rich case; for Sn highest  $D_{\text{vapor-melt}}$  for Cl-rich case, but poorly constrained.

<sup>40</sup> Haplogranite melt composition, aqueous fluid with HCl and HF, 2 kbar, 750 C.

<sup>41</sup> The silicate constituent was either a MORB or a composition close to the 1.5 GPa eutectic composition in the system anorthite–diopside–forsterite (An<sub>50</sub>Di<sub>28</sub>For<sub>22</sub>). FeO was added to vary FeO activity.

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