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Olgeir Sigmarsson

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1 **Reply to comment on “Long or short silicic magma residence time beneath**
2 **Hekla volcano, Iceland?” by Sigmarsson O, Bergþórsdóttir I A, Devidal J-L,**
3 **Larsen G, Gannoun A.**

4

5 **Olgeir Sigmarsson**

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10

11 **Abstract**

12 We would like to thank Geist et al. (2023) for the opportunity to further discuss the arguments
13 presented in our paper “Long or short silicic magma residence time beneath Hekla volcano,
14 Iceland?” (Sigmarsson et al. 2022). The disagreement centres around the origin of the silicic
15 magmas at Hekla, namely whether it is by (i) fractional crystallisation and a long crustal
16 residence time before eruption or (ii) partial melting of altered basaltic crust and short transfer
17 time to the surface. We disagree with the arguments presented by Geist et al. (2023) against the
18 model for the origin of dacite at Hekla from dehydration melting of amphibolite, a model that
19 still explains most if not all results obtained so far on the Hekla magma suite.

20

21 **Introduction**

22 The origin of silicic rocks at Hekla volcano, Iceland, has been discussed for more than a century.
23 The German chemist Robert Wilhelm Bunsen (the one that improved the Bunsen-burner), the
24 French mineralogist Des Cloizeaux and the Danish naturalist J. C. Schythe visited Mt. Hekla
25 after its 1845-1846 eruption (i.e., Wentrup 2021). They proposed a classification of two rock
26 types, a felsic and a mafic type originating from two different magma chambers (Bunsen 1851).
27 A century later in 1947-1948, Hekla had one of its largest historical eruptions that prompted
28 many detailed studies published by the Icelandic Science Society (the “Hekla Series”). For
29 instance, based on Harker-diagrams, Einarsson (1950) proposed that fractional crystallization
30 explained the compositional diversity of the tephra and lava produced. Also by combining
31 accounts from written annals and experience drawn from the 1947-1948 eruption, Thorarinsson
32 (1967) established the linear correlation between the length of the foregoing quiescent period and
33 the initial SiO₂ concentrations in the first emitted tephra, however without proposing a specific
34 mechanism for the observed relationship. The 1970 eruption (Thorarinsson and Sigvaldason
35 1972) drew the first attention of American researchers to Hekla with the study of Baldrige et al.
36 (1973). They published electron-probe micro-analyses (EPMA) of Hekla products and concluded

37 that its magma followed an evolution similar to the tholeiitic trend that had been established for
38 the Thingmuli magma suite (Carmichael 1964). In marked contrast, Sigvaldason (1974), building
39 upon the paper of Yoder (1973) on the concept of contemporaneous silicic and mafic magma,
40 discussed the need for crustal origin of the more evolved rocks. By this time, all the hypotheses
41 proposed for the origin of silicic magma at Hekla were based on major element criteria.
42 However, major element variations cannot distinguish between a final silicic melt formed by
43 extensive fractional crystallisation and a first melt generated by partial crustal melting. Both
44 melts plot close to the eutectic in the “petrogenic residual system” (e.g., Johannes & Holtz 1996),
45 where the final mineral assemblage controls the residual or the initial melt composition close to
46 the solidus.

47 The utility of isotope ratios for discerning petrogenic processes and magma source compositions
48 in Iceland was demonstrated by Muehlenbachs et al. (1974). They showed that silicic magma
49 generally has lower $\delta^{18}\text{O}$ than basalt from the same volcano or volcanic system, later interpreted
50 by Óskarsson et al. (1982) to reflect partial melting of the hydrated basaltic crust in amphibolite
51 facies. However, Hekla dacite and rhyolite turned out to have similar $\delta^{18}\text{O}$ as its basaltic andesite
52 (or icelandite), and not as low as silicic magma from the rift-zones. Soon thereafter, significantly
53 lower ($^{230}\text{Th}/^{232}\text{Th}$) was measured in the silicic Hekla magma compared to the basalt and basaltic
54 andesite, interpreted to reveal the crustal origin of Hekla dacite, consistent with higher Th/U in
55 the silicic magma (Condomines et al. 1981; Sigmarsson et al. 1992). Geist et al. (2021)
56 challenged that interpretation for Hekla silicic magma and preferred to return to the fractional
57 crystallisation model that was first proposed by Einarsson (1950). They followed Chekol et al.
58 (2011) by explaining higher Th/U in the silicic magma by apatite fractionation and magma
59 dwelling timescales of tens of thousands of years beneath the volcano. How such a silicic magma
60 chamber could have escaped all the Holocene magmatism and volcanic activity at Hekla is hard
61 to understand. A few months later, Sigmarsson et al. (2022) published the partition coefficients
62 of U and Th between several mineral phases and glass of basaltic andesite, dacite and rhyolite
63 composition from Hekla. The D_{U} and D_{Th} between apatite and melt turned out to be within error
64 ($D_{\text{U}}/D_{\text{Th}}=1$), a result that precludes apatite as a phase capable of fractionating the Th/U of the
65 melt in the case of Hekla.

66 In the following, we will address all the comments by Geist et al. (2023) on our paper and
67 demonstrate that they do not change the hypothesis of an origin of dacite at Hekla from
68 dehydration melting of amphibolite.

69

70 **Discussion**

71 *Comment #1: Metaluminous vs peraluminous silicic magma:*

72 Geist et al. (2023) argue that the aluminium saturation index (ASI), presumably calculated as the
73 molar ratio $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$, for glasses of amphibolite melting experiments are
74 different from those of Hekla silicic rocks. They compare whole-rock analyses from their Hekla
75 study ($\text{ASI} < 1$) with EPMA of experimental glasses ($\text{ASI} > 1$) obtained in diverse melting
76 experiments of different amphibolites (see Geist et al. (2023) for references), metaluminous vs

77 peraluminous silicic melt, respectively. Because of this difference they conclude that silicic
78 magma of Hekla cannot be derived from partial melting of amphibolite. However, comparing
79 whole-rock analyses to EPMA may lead to erroneous inferences. It is well known that spot
80 analyses of Na₂O concentrations in hydrous Si-rich glasses by EPMA may underestimate the
81 concentrations. For instance, Beard and Lofgren (1991), one of the study cited by Geist et al.
82 (2023), estimated that the Na₂O loss during analyses of their experimental glass could have been
83 as high as 32%. Moreover, small beam sizes may lead to overestimation of aluminium
84 concentrations according to Acosta-Vigil et al (2003). Furthermore, the partial melting model of
85 amphibolite discussed by Sigmarsson et al. (2022) for the generation of dacite beneath Hekla
86 volcano is a fluid-absent, or dehydration, melting model where amphibole melts out and the
87 residuum is free of amphibole.

88 Figure 1 shows the aluminium saturation index (ASI) of glass analyses of the Hekla 1104 CE
89 pumice and melt inclusions from Geist et al. (2021) plotted against SiO₂ concentrations
90 demonstrating the variability of ASI of the 1104 CE glass. The glass analyses of the 1104 CE
91 pumice straddle the boundary between-per- and metaluminous divide. Similarly dehydration
92 melting experiments of amphibolite (Beard and Lofgren 1991) with amphibole-free residuum
93 produce dacitic melts that have both per- and metaluminous compositions. The experimental
94 melts extensively overlap with the composition of the silicic Hekla melt. A comparison of Hekla
95 products with experimental results with amphibole still present should be considered irrelevant
96 when discussing the proposed model of crustal origin of silicic melts beneath Hekla (Sigmarsson
97 et al. 1992; 2022).

98 *Comment #2: Torfajökull vs Hekla*

99 Silicic magma with high ⁸⁷Sr/⁸⁶Sr (0.70334-0.70386) at Torfajökull (20 km east of Hekla) has
100 been interpreted to reflect melting of compositionally evolved crustal material (with elevated
101 Rb/Sr, e.g. Gunnarsson et al. 1998), whereas lower Sr isotope ratio at Hekla are consistent with
102 melting of fairly young amphibolite with low Rb/Sr (Sigmarsson et al. 1992). In their comments,
103 Geist et al. (2023) take the lower ⁸⁷Sr/⁸⁶Sr of Hekla rocks (0.70315), as an evidence against
104 crustal anatexis. Such an argument would only be valid if the crust, in general, had higher Sr
105 isotope ratio than basalt erupted around Hekla, which is unlikely for the following reasons. The
106 ⁸⁷Sr/⁸⁶Sr of the basaltic crust will remain largely within the range of rift-zone basalt (where the
107 crust is formed) because of its young age and the slow decay of ⁸⁷Rb generating ⁸⁷Sr. Therefore,
108 partial crustal melt of amphibolite beneath Hekla will lead to silicic melts with similar or
109 marginally higher ⁸⁷Sr/⁸⁶Sr compared to the basalt. The high ⁸⁷Sr/⁸⁶Sr at Torfajökull suggests
110 partial crustal melts from different lithologies than amphibolite formed from rift-zone basalt,
111 namely lithologies with elevated Rb/Sr as a magma source as discussed by Gunnarsson et al.
112 (1998).

113 *Comment #3: Mobile vs immobile elements*

114 Geist et al. (2023) state that “mobile elements show similar variations as immobile elements ...,
115 and ratios of mobile to immobile elements in the dacites are precisely as predicted for
116 crystallization differentiation of a basaltic andesite parent”. Such a strong statement is surprising

117 given their earlier statement “that mineral/melt partition coefficients are uncertain”. Geist et al.
118 (2023) prefer to compare Hekla silicic rocks with those of Torfajökull using a ratio that turns out
119 to be indistinguishable between the two volcanos (Rb/Zr of 0.0463-0.0689 for Hekla compared
120 to 0.028-0.232 for Torfajökull). Sigmarsson et al. (1992; 2022) concluded that dacite formation
121 by either crustal anatexis or extreme fractional crystallisation could not be distinguished using
122 conventional major- and trace element analyses in the case of Hekla. High-precision trace
123 element analyses by isotope dilution mass spectrometry (with analytical errors less than 1%) are
124 needed to unravel the natural variations such as that of Th/U for the different magma types.
125 Fractional crystallisation alone cannot explain the increase from approximately 3.2 in basalt and
126 basaltic andesite to 3.4 in dacite without crustal contribution. The D_U/D_{Th} indistinguishable from
127 1 between apatite and melt and the highly incompatible behaviour of U and Th request a
128 magmatic process in addition to simple fractional crystallisation, namely an assimilation-
129 fractional crystallisation (AFC) with crustal-derived dacite as an assimilant (Sigmarsson et al.
130 1992; 2022; Chekol et al. 2011).

131 *Comment #4: Absence or presence of amphibole in crustal melting residue*

132 Melting experiments should not be expected to mimic exactly natural compositions due to
133 inherent experimental difficulties but rather to hint at likely magmatic processes or source rock
134 compositions. In their effort to disprove the partial crustal melting model for the formation of
135 Hekla dacite, Geist et al. (2023) pick results from run #1583 of Sisson et al. (2005) with 39%
136 amphibole still in the residue, and calculate a trace element spectrum very different to those of
137 Hekla dacite. Whether amphibole is exhausted or remains in the melting residue controls both the
138 major- and trace element composition of the melt formed. Thy et al. (1990) showed that only
139 dehydration-amphibolite melts with amphibole-free residuum have major-element composition
140 comparable to silicic magmas in Iceland. Furthermore, Beard and Lofgren (1991) and Sisson et
141 al. (2005) discussed the effect of the amphibolite source rock composition on the silicic melt
142 produced during partial melting.

143 Systematic melting experiments at lower crustal conditions of amphibolite produced from the
144 Icelandic rift-zone basalt could shed further light on Hekla dacite formation. Given the
145 uncertainty regarding the exact source rock composition, hydrothermally altered basalt from a
146 volcano (such as Krafla) in the middle of the rift-zone, where the crust of Iceland is being
147 generated, must be considered a better source rock than diverse amphibolite from elsewhere in
148 the world.

149 In a nutshell, calculations of trace element contents from the residue mode of melting
150 experiments with abundant amphibole still present, have little bearing on the model for
151 dehydration melting of amphibolite producing the silicic magma at Hekla.

152 *Comment #5: Hybrid origin for the andesites or not*

153 Geist et al. (2023) state that andesite at Hekla cannot be a hybrid between basaltic andesite and
154 dacite melts. Figure 3 shows the Sr versus Th concentrations and a straight line representing
155 binary mixing is drawn between basaltic andesite and dacite. Most points plot close to that line
156 and the scatter is likely to reflect additional mineral-melt fractionation. It should be noted,

157 however, that the compositions of the mingling endmembers can rapidly vary with time as has
158 been observed during single eruptions, for example Eyjafjallajökull 2010 (Sigmarsson et al.
159 2011). Consequently, a single mixing line is not a proof for or against magma hybridisation,
160 especially since the dacite crustal melt composition is expected to vary with time if the crustal
161 source varies.

162 *Comment #6: Crystallisation differentiation or not*

163 Geist et al. (2023) discuss trace element modelling using their published results and come to the
164 conclusion that fractional crystallisation (FC) can account for all trace elements. Sigmarsson et
165 al. (1992 and 2022) stressed that, in the case of Hekla, conventional trace element analysis does
166 not have the resolving power to distinguish between dacite melt origin by FC or partial
167 amphibolite melting. High-precision analyses of U and Th demonstrate a significantly higher
168 Th/U in the silicic magma of Hekla, which cannot be explained by the partition coefficients
169 measured for basaltic andesite, dacite or rhyolite of Hekla. Once again, apatite-melt D^U/D^{Th} is
170 indistinguishable from unity in the case of Hekla and other minerals in the basaltic andesite and
171 the andesite have U and Th nearly perfectly incompatible.

172 *Comment #7: Krafla rhyolite?*

173 Geist et al. (2023) conclude their discussion by comparing rhyolite from Krafla volcano to silicic
174 rocks of Hekla. In both cases, the silicic rocks have much lower ($^{230}\text{Th}/^{232}\text{Th}$) than the basaltic
175 magma produced at both volcanoes, a fact that should not be ignored. In addition, $\delta^{18}\text{O}$ is much
176 lower in the Krafla rhyolite than in the basalt while $^{87}\text{Sr}/^{86}\text{Sr}$ remains uniform (Nicholson et al.
177 1991). In both cases, the silicic magma with lower ($^{230}\text{Th}/^{232}\text{Th}$) is best explained by crustal
178 anatexis. Ageing Th isotope ratio by tens to hundred of thousands of years in a Si-rich magma
179 chamber beneath Hekla volcano would not explain linear decrease of ($^{230}\text{Th}/^{232}\text{Th}$) versus $1/\text{Th}$
180 shown in Fig. 4, but is fully explained by mixing of Si-rich crustal melt with incoming basaltic
181 andesite. The extensive magmatic activity at Hekla during the Holocene would hardly escape a
182 silicic melt waiting in a magma chamber beneath the volcano to be remobilised.

183 *Future research needed to better understand Hekla magmatism*

184 The general dehydration melting model with amphibolite protolith explains most silicic magma
185 composition where the geothermal gradient of the Icelandic crust is elevated. The exact nature of
186 the protolith composition is, however, challenging to assess although rift-zone tholeiite remains
187 the best analogue being the most abundant rocks of the Icelandic crust. The crust is not only
188 composed of basalt but also of an unknown proportion of silicic rocks, isostatically buried
189 dacite-rhyolite and granite. These latter rock types may have formed by fractional crystallisation
190 away from the rift-zones where the geothermal gradient is low, or by crustal anatexis where it is
191 high (e.g. Martin & Sigmarsson 2007).

192 Sigurdsson (1977) suggested that plagiogranite melting could explain the abundance of silicic
193 volcanic rocks in Iceland and Gunnarsson et al. (1998) used a variant of that model to account
194 for the abundance of rhyolite at Torfajökull volcano. Hekla volcano frequently erupts a few light-
195 coloured xenoliths of different composition than the eruptive products. These xenoliths have not

196 been studied in much details yet but have been ascribed to products from Torfajökull that may
197 underlie the young Hekla volcano (Sigvaldason 1974; Sigmarsson et al. 1992; Chekol et al.
198 2011; Geist et al. 2021). Similarly zircons from Hekla of heterogeneous composition (Carley et
199 al. 2011) have been suggested to represent entrained crystal cargo of diverse origin (Bindeman et
200 al. 2012). The zircons must be younger than 0.3 Ma, since they are in ^{238}U - ^{230}Th radioactive
201 disequilibrium, but much older than all known silicic tephra from Hekla (Carley et al. 2011).
202 How relevant their model age is for the Hekla volcanism remains to be clarified but, in principle,
203 they may be derived from Si-rich crustal melts of different age and origin, remobilized by the
204 ascending Hekla magma. The presence of silicic crustal formations interbedded within the
205 overall amphibolitic deeper crust, can also account for low $\delta^{37}\text{Cl}$ in Hekla pumice thought to
206 represent crustal brine (Ranta et al. 2021). Indeed, almost complete melting of an old silicic
207 protolith in U-Th radioactive equilibrium with zircon remaining in the residue withholding U
208 relative to Th could be seen as a possible explanation for the low ($^{230}\text{Th}/^{232}\text{Th}$) in Hekla dacite-
209 rhyolite magma. However, this possibility was rejected by Sigmarsson et al. (1992) and must be
210 considered unlikely due to the rapid renewal of silicic magma beneath Hekla and the large
211 Plinian eruptions forming the well-known prehistoric tephra layers.

212

213 **Conclusion**

214 In conclusion, we discuss the points criticised by Geist et al. (2023) and show that none of them
215 provide compelling evidence against the dehydration melting of amphibolite, a model that still
216 explains most if not all results obtained so far on the Hekla magma suite.

217

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222

223 **References:**

224 Acosta-Vigil A, London D, Morgan VI GB, Dewers TA (2003) Solubility of excess alumina in
225 hydrous granitic melts in equilibrium with peraluminous minerals at 700–800 °C and 200 MPa,
226 and applications of the aluminum saturation index. *Contr Mineral Petrol* 146:100-119.

227 Baldrige SW, McGetchin TR, Frey FA (1973) Magmatic Evolution of Hekla, Iceland. *Contr*
228 *Mineral Petrol* 42:245-258.

229 Beard JS, Lofgren GE (1991) Dehydration melting and water-saturated melting of basaltic and
230 andesitic greenstones and amphibolites at 1, 3, and 6.9 kb. *J Petrol* 32:365-402.

231 Bindeman I, Gurenko A, Carley T, Miller C, Martin E, Sigmarsson O (2012) Silicic magma
232 petrogenesis in Iceland by remelting of hydrothermally altered crust based on oxygen isotope

233 diversity and disequilibria between zircon and magma with implications for MORB. *Terra Nova*
234 24:227-232.

235 Bunsen R (1851) Ueber die Prozesse der vulkanischen Gesteinsbildung Islands. *Poggendorffa*
236 *Annalen* 83:197-272.

237 Carley TL, Miller CF, Wooden JL, Bindeman IN, Barth AP (2011) Zircon from historic eruptions
238 in Iceland: reconstructing storage and evolution of silicic magmas. *Miner Petrol* 102:135–161.

239 Carmichael ISE (1964) The petrology of Thingmuli, a tertiary volcano in Eastern Iceland. *J*
240 *Petrol* 5:435–460.

241 Chekol TA, Kobayashi K, Yokoyama T, Sakaguchi C, Nakamura E (2011) Timescales of magma
242 differentiation from basalt to andesite beneath Hekla Volcano, Iceland: Constraints from U-series
243 disequilibria in lavas from the last quarter-millennium flows. *Geochim Cosmochim Acta* 75:256-
244 283.

245 Condomines M, Morand P, Allègre CJ, Sigvaldason G (1981) ^{230}Th - ^{238}U disequilibria in
246 historical lavas from Iceland. *Earth Planet Sci Lett* 55: 393-406.

247 De Paolo DJ (1981) Trace element effects of combined wallrock assimilation and fractional
248 crystallization. *Earth Planet Sci Lett* 53: 189-202.

249 Einarsson T (1950) Chemical analyses and differentiation of Hekla's magma. *Eruption of Hekla*
250 1947-1948, 4. *Soc Sci Islandica*, Reykjavik.

251 Geist D, Harpp K, Oswald P, Wallace P, Bindeman I, Christensen B (2021) Hekla revisited:
252 fractionation of a magma body at historical timescales. *J Petrol* 10.1093/petrology/egab001.

253 Geist D, Wallace P, Harpp K, Oswald P (2023) A Discussion of: Long or short silicic magma
254 residence time beneath Hekla volcano, Iceland? *Contrib Mineral Petrol*

255 Gunnarsson B, Marsh B Taylor Jr H (1998) Generation of Icelandic rhyolites: silicic lavas from
256 the Torfajökull central volcano. *J Volcanol Geotherm Res* 83:1–45.

257 Johannes W, Holtz F (1996) *Petrogenesis and Experimental Petrology of Granitic Rocks.*
258 *Minerals and Rocks* 22, Springer, Berlin, 115-275. <https://doi.org/10.1007/978-3-642-61049-3>.

259 Kokfelt TK, Hoernle K, Hauff F, Fiebig J, Werner R, Garbe-Scönberg D (2006) Combined trace
260 element and Pb–Nd–Sr–O isotope evidence for recycled oceanic crust (upper and lower) in the
261 Iceland mantle plume. *J Petrol* 47:1705-1749.

262 Martin E, Sigmarsson O (2007) Geographical variations of silicic magma origin in Iceland: the
263 case of Torfajökull, Ljósufjöll and Snæfellsjökull volcanoes. *Contrib Mineral Petrol* 153:593-
264 605.

265 Muehlenbachs K, Anderson AT, Sigvaldason GE (1974) Low 180 basalts from Iceland. *Geochim*
266 *Comochim Acta* 38:577-588.

267 Nicholson H, Condomines M, Fitton JD, Fallick AE, Grönvold K, Rogers G (1991) Geochemical
268 and isotopic evidence for crustal assimilation beneath Krafla, Iceland. *J Petrol* 32:1005–1020.

269 Óskarsson N, Sigvaldason GE, Steinthórsson S (1982) A dynamic model of rift zone
270 petrogenesis and regional petrology of Iceland. *J Petrol* 23:28-74.

271 Ranta E, Halldórsson SA, Barnes JD, Jónasson K, Stefánsson A (2021) Chlorine isotope ratios
272 record magmatic brine assimilation during rhyolite genesis. *Geochem Persp Let* 16:35–39. doi:
273 10.7185/geochemlet.2101.

274 Sigmarsson O, Condomines M, Fourcade S (1992) A detailed Th, Sr, and O isotope study of
275 Hekla: differentiation processes in an Icelandic volcano. *Contrib Mineral Petrol* 112:20-34.

276 Sigmarsson O, Vlastelic I, Andreassen R, Bindeman I, Devidal J-L, Moune S, Keiding JK,
277 Larsen G, Höskuldsson A, Thordarson Th (2011) Remobilization of silicic intrusion by mafic
278 magmas during the 2010 Eyjafjallajökull eruption. *Solid Earth* 2:271–281.

279 Sigmarsson O, Bergþórsdóttir I A, Devidal J-L, Larsen G, Gannoun A (2022) Long or short
280 silicic magma residence time beneath Hekla volcano, Iceland? *Contrib Mineral Petrol* 177:13.
281 <https://doi.org/10.1007/s00410-021-01883-5>.

282 Sigurðsson H (1977) Generation of Icelandic rhyolites by melting of plagiogranites in the
283 oceanic layer. *Nature* 269:25-28.

284 Sigvaldason GE (1974) The petrology of Hekla and origin of silicic rocks in Iceland. Eruption of
285 Hekla 1947-1948. *Soc Sci Islandica* 5:1-44.

286 Sisson, T. W., Ratajeski, K., Hankins, W. B., & Glazner, A. F. (2005). Voluminous granitic
287 magmas from common basaltic sources. *Contrib Mineral Petrol* 148, 635-661.

288 Thorarinsson S (1967) The eruptions of Hekla in historical times. In: Einarsson T, Kjartansson G,
289 Thorarinsson S (Eds). *The eruption of Hekla 1947-48. I*, Soc Sci Islandica, Reykjavík. pp 1-177.

290 Thorarinsson S, Sigvaldason GE (1972). The Hekla eruption of 1970. *Bull Volcanol* 36:269–
291 288.

292 Thy P, Beard JS, Lofgren GE (1990) Experimental constraints on the origin of Icelandic
293 rhyolites. *J Geology* 98:417-421.

294 Wentrup C (2021) Bunsen the Geochemist: Icelandic Volcanism, Geyser Theory, and Gas, Rock
295 and Mineral Analyses. *Angew Chem Int Ed Engl.* 60:1066-1081. doi: 10.1002/anie.202008727.

296 Yoder HSJr (1973) Contemporaneous basaltic and rhyolitic magmas *Am Mineral* 58:153-171.

297

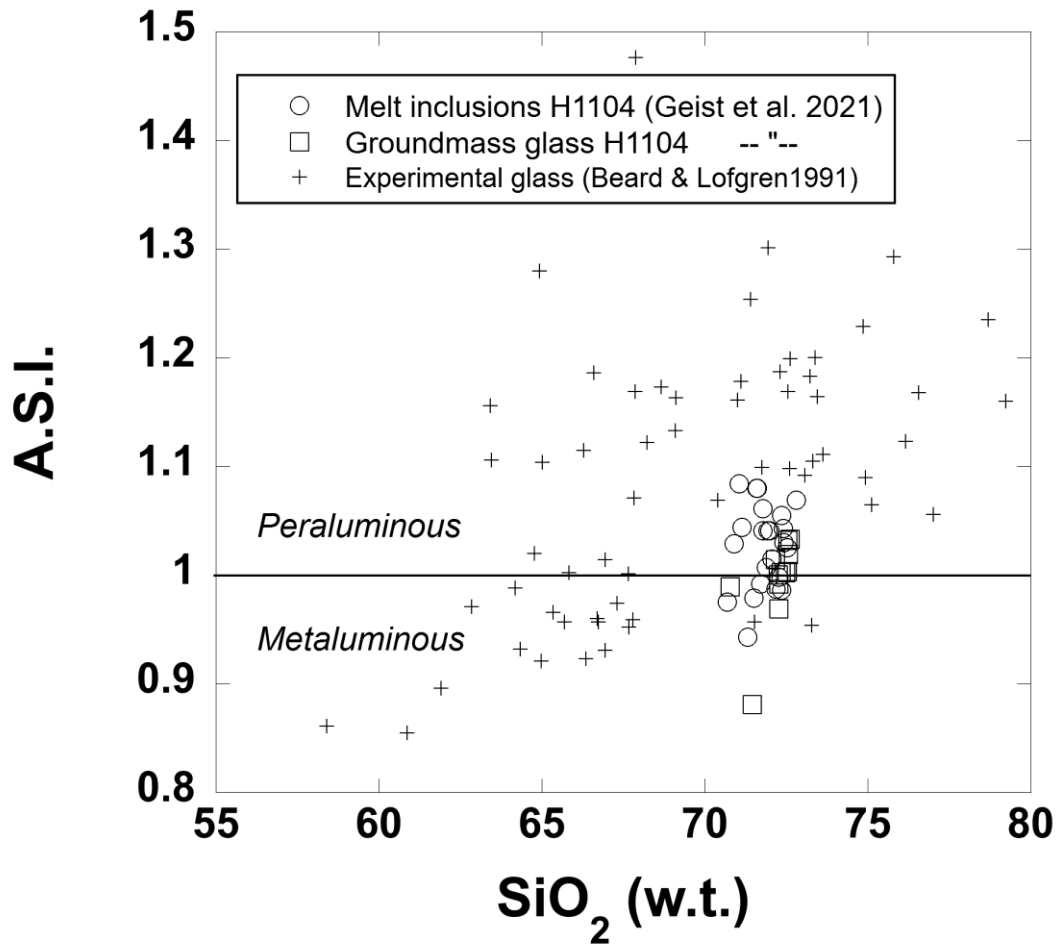
298 **Figure legends:**

299 **Figure 1.** Aluminium Saturation Index (A.S.I.) versus **silica** oxide concentrations from electron
300 microprobe glass analyses of the Hekla 1104 CE pumice (results from Geist et al. 2021). **Also**
301 **plotted are experimental glass from amphibolite dehydration melting experiments with**
302 **amphibole-free residuum (Beard and Lofgren 1991). The overlap between the Hekla silicic**
303 **glass and the experimental glass support the model of dehydration amphibolite melting for**
304 **silicic magma at Hekla (see text for further discussion).**

305 **Figure 2.** Concentrations of U and Th measured with the isotope dilution technique
306 demonstrating uniform Th/U from basalt to basaltic andesite due to fractional crystallisation,
307 increase from Th/U of 3.2 to 3.4 from basaltic andesite through andesite to dacitic crustal melts
308 and further increase in Th/U caused by zircon fractionation (further information is given in
309 Sigmarsson et al. 1992 and 2022).

310 **Figure 3.** Strontium versus Th variation (Chekol et al. 2011; Geist et al. 2021; Sigmarsson et al.
311 2022).

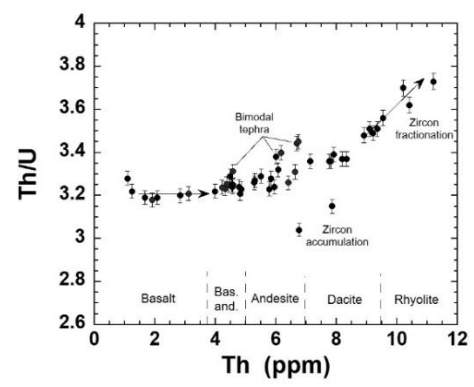
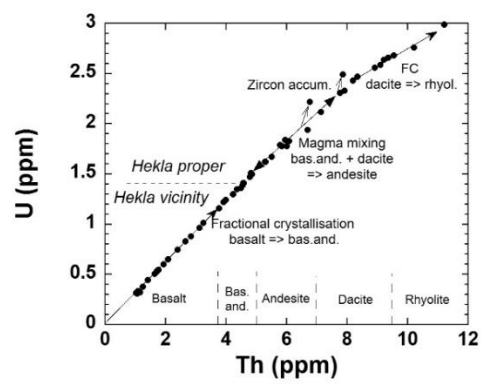
312 **Figure 4.** Thorium isotope systematics of Hekla magma erupted last thousand years versus Th
313 concentrations. Arrows for fractional crystallisation (FC) and assimilation fractional
314 crystallisation (AFC; **De Paolo 1981**) with R being the ratio of crystallising mass over mass of
315 assimilant (silicic crustal melt) with R of 0 representing a binary magma mixing. Here, the
316 assimilant is silicic crustal melt (further details can be found in Sigmarsson et al. 1992 and
317 2022).



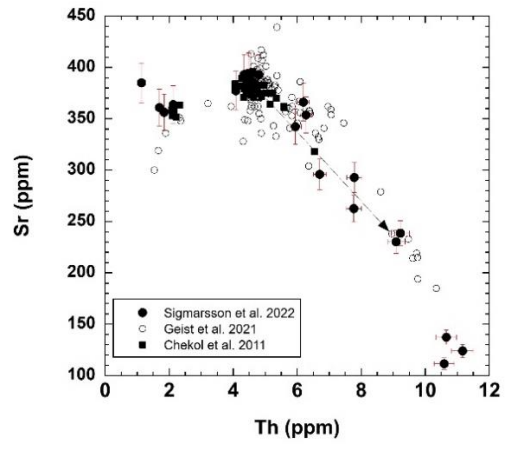
319

320 Figure 1.

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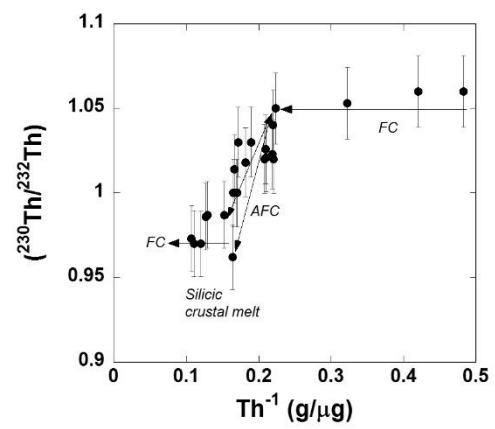
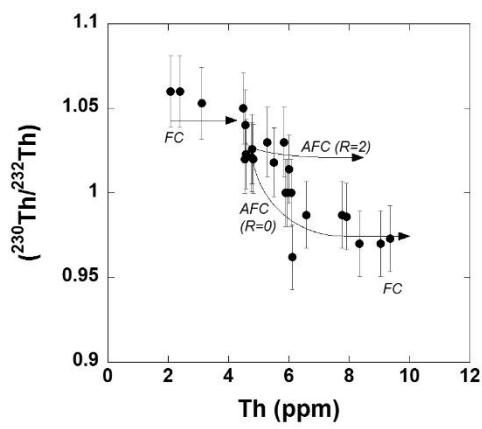


322
323 Figure 2.



324

325 Figure 3.



326
 327 Figure 4.

