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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

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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 SiO<sub>2</sub> 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  $D_{\text{U}}$  and  $D_{\text{Th}}$  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 Na<sub>2</sub>O 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 Na<sub>2</sub>O 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 SiO<sub>2</sub> 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 <sup>87</sup>Sr/<sup>86</sup>Sr (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 <sup>87</sup>Sr/<sup>86</sup>Sr 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 <sup>87</sup>Sr/<sup>86</sup>Sr 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 <sup>87</sup>Rb generating <sup>87</sup>Sr. Therefore,  
108 partial crustal melt of amphibolite beneath Hekla will lead to silicic melts with similar or  
109 marginally higher <sup>87</sup>Sr/<sup>86</sup>Sr compared to the basalt. The high <sup>87</sup>Sr/<sup>86</sup>Sr 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 ( $^{230}Th/^{232}Th$ ) than the basaltic  
175 magma produced at both volcanoes, a fact that should not be ignored. In addition,  $\delta^{18}O$  is much  
176 lower in the Krafla rhyolite than in the basalt while  $^{87}Sr/^{86}Sr$  remains uniform (Nicholson et al.  
177 1991). In both cases, the silicic magma with lower ( $^{230}Th/^{232}Th$ ) 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 ( $^{230}Th/^{232}Th$ ) versus 1/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  $^{238}\text{U}$ - $^{230}\text{Th}$  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

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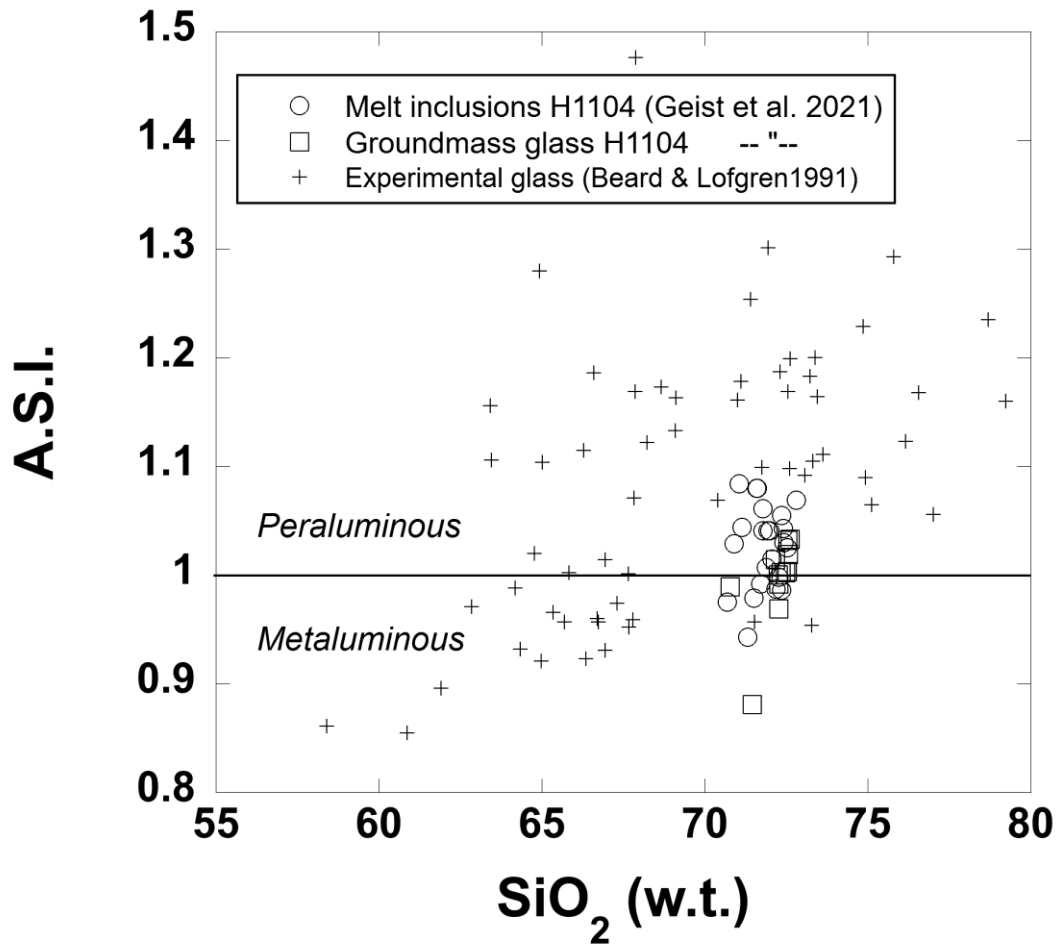
298 **Figure legends:**

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).

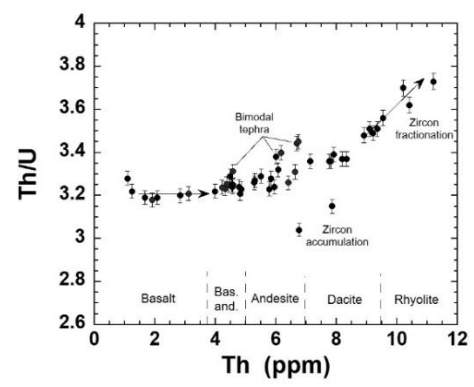
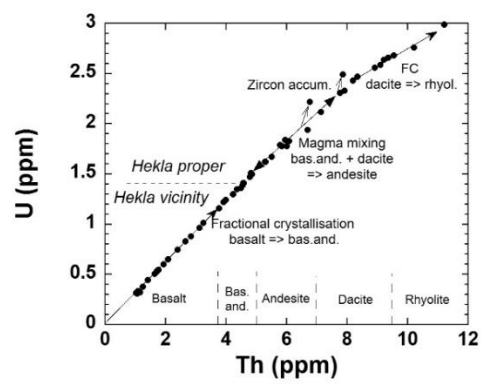
312 **Figure 4.** Thorium isotope systematics of Hekla magma erupted last thousand years versus Th  
313 concentrations. Arrows for fractional crystallisation (FC) and assimilation fractional  
314 crystallisation (AFC; **De Paolo 1981**) with R being the ratio of crystallising mass over mass of  
315 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).



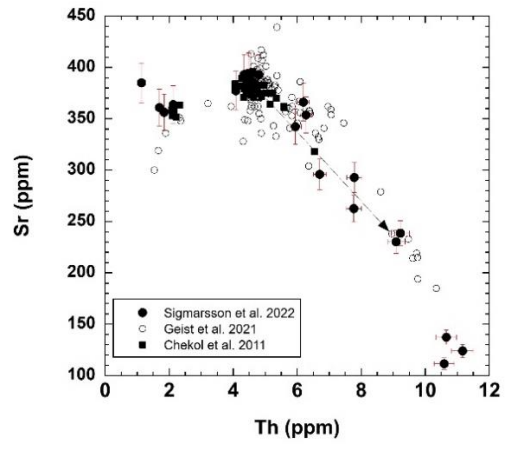
319

320 Figure 1.

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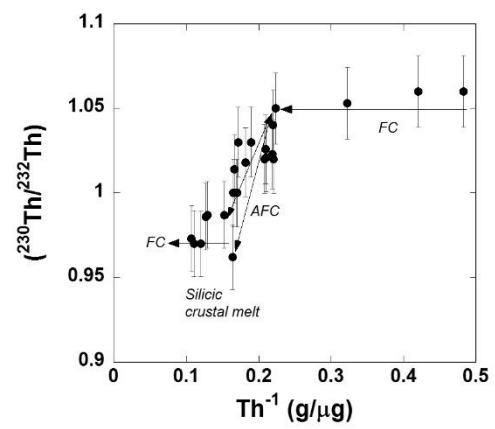
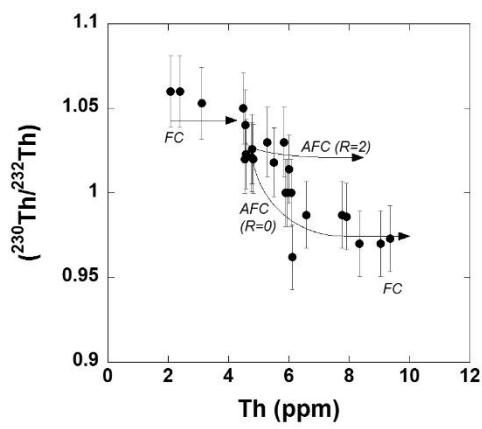


322  
323 Figure 2.



324

325 Figure 3.



326  
327 Figure 4.

