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1 Cumulate formation and melt extraction from mush-dominated magma reservoirs: the melt  
2 flush process exemplified at mid-ocean ridges

3

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10

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12 crystallization, oceanic crust

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26 **ABSTRACT**

27 Volcanism is the surface expression of extensive magmatic systems, with their  
28 intrusive counterpart representing ~80% of the total magma budget. Our knowledge of  
29 igneous processes therefore largely relies on our understanding of deep plutonic processes. In  
30 continental or oceanic environments, most of the intrusive igneous rocks bear geochemical  
31 cumulate signatures (e.g., depletion in incompatible elements and enrichment in compatible  
32 ones) that are commonly explained by mineral-melt segregation during differentiation.  
33 Deformation-assisted compaction aided by melt buoyancy is usually referred to as the main  
34 process involved in melt extraction. However, buoyancy alone is not sufficient, and a number  
35 of cumulative rocks are lacking any compaction evidence, opening the potential for the  
36 involvement of other processes. In addition, our view of magmatic systems has shifted in the  
37 last decades from large melt-rich bodies to crystal-rich magma reservoirs. This paradigm shift  
38 challenges some of the long-established first-order igneous concepts like the idea that melt  
39 differentiation at depth is mainly governed by (fractional) crystallization; alternatively, the  
40 presence of mush potentially favors additional processes such as melt-mush reactions.

41 We propose a novel igneous process for the formation of igneous cumulates,  
42 consistent with the mushy nature of oceanic igneous reservoirs, their continuous/cyclic  
43 replenishment by primitive melts, and the widespread occurrence of reactive porous flow  
44 (RPF) during magma differentiation identified in a growing number of magmatic systems.  
45 The “*melt flush*” process relies on melt-mush reactions between the primitive recharge melt(s)  
46 and crystal mush. Replacement of the more evolved interstitial melt by the primitive recharge  
47 melt leading to reactions (dissolution+crystallization), and concomitant extraction of the more  
48 evolved melt from the cumulate by buoyancy participate in the acquisition of the final  
49 cumulate signature.

50 This process relying on oceanic igneous systems considers for the first time melt  
51 inputs and not only melt extraction, and matches the petrographic (e.g., mineral dissolution  
52 evidence) and geochemical constraints (trace element signatures) brought by natural oceanic  
53 samples. We tested various melt-mush reactions likely involved in the early stages of the *melt*  
54 *flush* process during RPF to investigate their thermodynamic feasibility with the Magma  
55 Chamber Simulator. First-order results show that one-step equilibration of primitive melts  
56 with primitive to moderately differentiated mush crystals triggers mineral assimilation.  
57 Together with the constraints established from the natural rock record, it strengthens the idea  
58 that RPF is a potential key process for magma differentiation in magma reservoirs at different  
59 evolution stages. The proposed *melt flush* process eventually adds to other processes involved  
60 in cumulate formation like magma compaction or crystal settling, and is likely to apply to any  
61 other magmatic system from various settings sharing similar reservoir characteristics.

62

## 63 INTRODUCTION

64 In both continental and oceanic settings, magma reservoir formation is the  
65 consequence of the cyclic injection of primitive melts from the mantle into the crust (e.g.,  
66 Annen *et al.*, 2006, 2015; Rannou *et al.*, 2006; Godard *et al.*, 2009; Cordier *et al.*, 2010;  
67 Cashman *et al.*, 2017; Sparks *et al.*, 2019; Boulanger *et al.*, 2020). Melt differentiation paths  
68 within reservoirs, hence their evolution, are a function of several parameters such as the  
69 primitive melt composition and flux, the physical conditions of crystallization (e.g., pressure,  
70  $fO_2$ ), or the reservoir architecture and thermal state and evolution. The physical behavior of a  
71 magma *sensu lato* depends largely on its crystal load (Costa *et al.*, 2009; Cashman *et al.*,  
72 2017), and we will hereafter consider that a magma *sensu stricto* is an unlocked system where  
73 the crystal load allows magma migration, whereas a mush is locked, and cannot be mobilized  
74 for extensive mush migration and potential eruption without involving, for example, a

75 rejuvenation episode, tectonic events, second boiling, etc (e.g., Tait et al., 1989; Woods and  
76 Cardoso, 1997; Bachmann and Bergantz, 2003; Till et al., 2015; Seropian et al., 2021).  
77 Although still controversial (e.g., Latypov *et al.*, 2020), most current models of crustal  
78 reservoirs describe mush-dominated environments (Cashman *et al.*, 2017; Bachmann and  
79 Huber, 2019; Lissenberg *et al.*, 2019; Sparks *et al.*, 2019). Melt emplacement and migration  
80 mechanisms, and the efficiency and timing of melt extraction are dictated by the medium  
81 (melt viscosity and density, and crystal load fraction) that contains within a mush only a few  
82 volume percent of liquid within a crystal framework (Lejeune and Richet, 1995; Vigneresse *et*  
83 *al.*, 1996; Cheadle *et al.*, 2004; Costa *et al.*, 2009). In general, the magma-to-mush transition  
84 is attained between 40 and 60% crystals (e.g., Mainprice, 1997; Cashman *et al.*, 2017) and  
85 depends on the shape of the mush forming minerals. The exact amount of melt in the  
86 reservoirs is difficult to determine (Paulatto *et al.*, 2022) but is likely variable, as imaged  
87 seismically and with other geophysical methods (Singh *et al.*, 1998; Zandt *et al.*, 2003;  
88 Canales *et al.*, 2009, 2017; Desissa *et al.*, 2013; Comeau *et al.*, 2015; Dunn, 2015; Magee *et*  
89 *al.*, 2018; Laumonier *et al.*, 2019 and references therein). Magma dynamics, in turn, control  
90 the processes operating during melt differentiation (e.g. Meurer and Boudreau, 1989a; Picard  
91 *et al.*, 2011; Leuthold *et al.*, 2014; Lissenberg and MacLeod, 2016; Boulanger *et al.*, 2020,  
92 2021; Ferrando *et al.*, 2021a): crystallization could proceed at equilibrium, be fractionated or  
93 involve in situ crystallization (Langmuir, 1989), melt eventually could be trapped or  
94 segregated, and disequilibrium interactions between the melt and their surroundings could  
95 potentially occur (e.g. Spera and Bohrsen, 2004; see definitions in Box 1). The latter tend to  
96 be of particular interest when considering mush-dominated magma reservoirs, and reactive  
97 porous flow (RPF) appears to be likely widespread and critical to melt differentiation in  
98 oceanic and potentially continental environments (Lissenberg and Dick, 2008; Cooper *et al.*,  
99 2016; Jackson *et al.*, 2018; Hepworth *et al.*, 2020).

100 The textures and the geochemical signatures of igneous rocks are commonly used to  
101 identify and quantify the differentiation processes that take place during their formation. One  
102 key signature is the cumulate character of many plutonic lithologies, which were historically  
103 interpreted as evidence for crystal-melt segregation and melt differentiation by fractional  
104 crystallization (FC) and deformation (Bowen, 1915, 1920; Irvine, 1982). Here, we examine  
105 the recent petrological and geophysical developments and the latest architecture models of  
106 igneous plumbing systems, together with an overview of the different models of melt-mush  
107 reactions and reactive porous flow that have been developed in various settings. We  
108 particularly focus on oceanic magma reservoirs where the study of these processes is most  
109 advanced. Together with a new test of the thermodynamic feasibility of characteristic melt-  
110 mush reactions, we examine in light of all these elements the potential impact of RPF on the  
111 development of cumulate geochemical signatures in magma reservoirs. We suggest the  
112 involvement of a novel integrated igneous process: the *melt flush* process. We finally discuss  
113 the potential for the application of this process to magmatic systems from other geodynamic  
114 settings.

115

## 116 **CUMULATE FORMATION PROCESSES**

### 117 **Processes and limitations**

118 The term cumulate was first proposed by Wager *et al.* (1960) and referred to igneous  
119 rocks formed by crystal accumulation. In this case, the formation of cumulates involves  
120 crystal segregation and FC, as previously described by Bowen (1915). The removal of the  
121 most evolved melt fraction from cumulate minerals results in whole-rock compositions that  
122 are characteristically depleted in incompatible trace elements compared to the primitive melt  
123 composition (e.g., with a positive Eu anomaly if the cumulate assemblage includes  
124 plagioclase; Fig. 1; Meurer and Boudreau, 1989a). The main processes considered for crystal

125 accumulation and melt extraction are linked to melt buoyancy and gravitationally-driven  
126 viscous compaction (e.g., Mckenzie, 1984; Meurer and Boudreau, 1989b; Holness *et al.*,  
127 2017b; Lissenberg *et al.*, 2019), the latter of which can be assisted by tectonic stresses (e.g.;  
128 Bowen, 1920; Kohlstedt and Holtzman, 2009; Holness *et al.*, 2017b; Lissenberg *et al.*, 2019;  
129 Zhang *et al.*, 2020). Cumulates can also form by compositional convection that is governed by  
130 the density contrast between intercumulus melts and an overlying magma chamber melt,  
131 without involving complete physical separation of intercumulus melts from crystals and  
132 without considering melt-mush reactions (Tait *et al.*, 1984; Toplis *et al.*, 2008; Namur and  
133 Charlier, 2012). However, the efficiency of these processes in the lower crust has been  
134 challenged, especially in mushy systems in the absence of any large magma chamber  
135 (Holness, 2018; Krättli and Schmidt, 2021). Buoyancy alone is likely insufficient for efficient  
136 and rapid crystal-melt segregation in mushes where the melt flux is resisted by the strength of  
137 the crystal matrix and the viscosity of the percolating melt (Daines and Pec, 2015; Bachmann  
138 and Huber, 2019). Basaltic and picritic melts with low viscosities have more potential for  
139 segregation, yet the thickness of the mush layer is critical and additional concurrent processes  
140 are required for small (~100 m-scale) systems (Daines and Pec, 2015). Viscous compaction is  
141 favored in reservoirs with thick mush columns subject to low cooling rates and comprising  
142 relatively dense crystallizing mineral assemblages such as mafic systems (e.g., Holness *et al.*,  
143 2017b; Lissenberg *et al.*, 2019), although the lack of textural evidence such as intracrystalline  
144 deformation in many mafic cumulates from continental and oceanic settings questions the  
145 importance of this process (Cheadle and Gee, 2017; Holness *et al.*, 2017b; Holness, 2018;  
146 Ferrando *et al.*, 2021a). An alternative process is crystal repacking or mechanical compaction  
147 by grain rearrangement (e.g., Holness *et al.*, 2017b; Bachmann and Huber, 2019, and  
148 references therein). The efficiency of the process is constrained to a limited crystallinity  
149 range, yet the amount of melt extracted is potentially significant depending on the

150 morphology of the minerals (Bachmann and Huber, 2019). Crystal repacking is caused at the  
151 reservoir scale by differential stresses generated by processes such as recharge or tectonic  
152 forces, and is likely to lead to the development of a crystal fabric or to be accompanied by  
153 dissolution-precipitation aiding compaction without crystal deformation (Holness *et al.*,  
154 2017b; Bachmann and Huber, 2019). Alternatively, gas or fluid percolation through the melt  
155 can aid its extraction from the (here passive) crystal matrix (Boudreau, 2016; Bachmann and  
156 Huber, 2019). The models detailed above only consider melt extraction from the systems and  
157 do not consider the potential impact of recharge melts migrating within the crystal mush from  
158 lower levels, as currently suggested for magma reservoirs in different settings (e.g., Jackson *et*  
159 *al.*, 2018; Dick *et al.*, 2019). Hence, most of these models do not consider any primitive melt  
160 inputs and, when occurring, the potential crystal-melt disequilibrium and the impact RPF to  
161 the formation of rocks bearing geochemical cumulate signatures.

162

### 163 **Implications for melt extraction**

164 In addition to their implications for cumulate formation, processes associated with  
165 melt migration and segregation in magma reservoirs are key to a better understanding of the  
166 volcanic-plutonic connection, which is the link between extracted melts, involved in the  
167 genesis of erupted magmas, and their crystal-rich reservoirs that ultimately cool to form  
168 plutons (e.g., Bachmann *et al.*, 2007; Schaen *et al.*, 2021). For example, the modes of  
169 extraction of large volumes of crystal-poor magma from silicic crystal mushes are critical to  
170 comprehend the dynamics of large continental volcanic systems (100 to 1000 km<sup>3</sup>), their  
171 mobilization to produce eruption, and related monitoring. Yet, as shown in the above section  
172 they remain controversial for both silica-rich and silica-poor systems, especially regarding the  
173 efficiency and timescales of melt extraction (e.g., Bachmann and Bergantz, 2004; Burgisser  
174 and Bergantz, 2011; Holness, 2018; Bachmann and Huber, 2019; Sparks *et al.*, 2019). On



175 another scale, mid-ocean ridge basalts (MORBs) and related products are often studied for  
176 their interest in constraining the mantle compositions and heterogeneities, taking into account  
177 potential processes occurring between mantle melting and eruption (e.g., Rubin *et al.*, 2009;  
178 O'Neill and Jenner, 2012; Lambart *et al.*, 2019; Neave *et al.*, 2019). These processes depend  
179 on the volumes and fluxes of melts emplaced within the crust that in turn control the magma  
180 reservoir's structure, thermal architecture, composition, and evolution (e.g., Dunn *et al.*, 2005;  
181 Coogan, 2014; Dunn, 2015; Chen *et al.*, 2021). MORBs, especially at slow-spreading ridges,  
182 record geochemical signatures consistent with an evolution of melts by RPF or assimilation of  
183 gabbroic lithologies, which is also supported by textural evidence for assimilation recorded in  
184 crustal gabbros (e.g., Lissenberg and Dick, 2008; Lissenberg *et al.*, 2013; Lissenberg and  
185 MacLeod, 2016; Leuthold *et al.*, 2018; Shimizu *et al.*, 2019; Boulanger *et al.*, 2020;  
186 Sanfilippo *et al.*, 2020). This suggests that significant volumes of reacted melts can segregate  
187 from high-crystallinity mushes where RPF might occur, yet this segregation is still a matter of  
188 debate. However, olivine gabbro cumulates from a magmatic crustal section drilled at the  
189 Atlantis Bank oceanic core complex (OCC; IODP hole U1473A, Southwest Indian Ridge;  
190 SWIR) present recurrent fine-grained domains also found in other crustal sections (Bloomer  
191 *et al.*, 1991). They are interpreted as areas of interstitial reactive melts collection from the  
192 crystal mush, supporting the melt segregation hypothesis (Ferrando *et al.*, 2021a).

193

## 194 **EVOLUTION OF OCEANIC IGNEOUS RESERVOIRS**

### 195 **Impact of reactive porous flow**

196 Magma reservoirs at oceanic spreading ridges were long suspected to be mush-  
197 dominated environments (e.g., Sinton and Detrick, 1992), a reservoir structuring with strong  
198 implications on the differentiation path of magmas. Indeed, heterogeneous modal proportions  
199 and mineral compositions observed at all scales in the oceanic crust suggest that melts are

200 unlikely to maintain local chemical equilibrium with the crystal framework through which  
201 they percolate, and rather interact with it (Lissenberg *et al.*, 2019; Yang *et al.*, 2019).  
202 Providing sufficient melt flux, protracted interactions with (or assimilation of) the crystal  
203 framework could ultimately result in a state of equilibrium and homogenization of the system  
204 (Blundy, 2022). Several studies have proposed the ubiquitous involvement of RPF and its  
205 strong control on the melt and crystal compositions. It has been suggested either at the  
206 mineral scale (Sanfilippo *et al.*, 2020), the scale of a mush column (Ferrando *et al.*, 2021a),  
207 the scale of a magma reservoir (Boulangier *et al.*, 2020), or the scale of the entire crustal  
208 section (Zhang *et al.*, 2020) drilled at the Atlantis Bank OCC (Dick *et al.*, 2000, 2019). These  
209 results are in agreement with previous studies conducted at Atlantis Bank and other spreading  
210 ridges, which predicted the strong control of RPF on the lithologies and differentiating melt  
211 composition (e.g., Coogan *et al.*, 2000; Kvassnes, 2004; Gao *et al.*, 2007; Lissenberg and  
212 Dick, 2008; Lissenberg and MacLeod, 2016; Ferrando *et al.*, 2018; Leuthold *et al.*, 2018;  
213 Lissenberg *et al.*, 2019, and references therein). In detail, two main lines of evidence support  
214 the RPF hypothesis (see Table 1). First, the gabbro cumulates (*sensu lato*; Fig. 1) present  
215 modal compositions that usually deviate from the typical thermodynamically constrained  
216 tholeiitic liquid line of descent (e.g., Dick *et al.*, 2019; Boulangier *et al.*, 2020). The gabbro  
217 cumulates also present minerals with characteristic textures that, despite the strong  
218 heterogeneity described in all crustal sections and oceanic crust samples, can be found on a  
219 recurrent basis. Olivine (Ol) textures are often characterized by round shapes (Fig. 2f, k, r),  
220 especially Ol chadacrysts engulfed in poikilitic plagioclase (Pl) or clinopyroxene (Cpx, Fig.  
221 2b, f, o), or irregular and wavy contacts with surrounding minerals suggesting resorption of  
222 the grains (Fig. 2d, i). Pl present very irregular grain boundaries that often crosscut the twins  
223 of the grain with dissolution fronts (Fig. 2j), and are found as chadacrysts in both Pl (Fig. 2n)  
224 or Cpx oikocrysts (Fig. 2c, e, f, h, m, p). They can also present complex zoning patterns,

225 reversed or normal, with resorbed core remnants (Fig. 2g, i). The first Cpx textures that were  
226 associated with RPF are the large (sometimes pegmatitic) poikilitic grains that contain  
227 numerous Ol and/or Pl chadacrysts with resorbed grain boundaries (Fig. 2e). Cpx-Amphibole  
228 symplectites (or Cpx-Orthopyroxene symplectites) are regularly found in oceanic samples but  
229 their RPF origin is debated (Fig. 2a, h). In addition to symplectites, Cpx-Cpx intergrowths are  
230 also frequently found in samples presenting other RPF textures, and are suspected to result  
231 from this process (Fig. 2a, j, l; summary available in Table 1; e.g., Lissenberg and Dick, 2008;  
232 Lissenberg *et al.*, 2013; Sanfilippo *et al.*, 2015; Lissenberg and MacLeod, 2016; Leuthold *et*  
233 *al.*, 2018; Boulanger *et al.*, 2020; Zhang *et al.*, 2020; Ferrando *et al.*, 2021b). However, the  
234 disequilibrium reactions can also be more cryptic and the second line of evidence, the in situ  
235 mineral compositions, is also critical to identify the occurrence of RPF within the systems  
236 (Lissenberg and MacLeod, 2016; Sanfilippo *et al.*, 2020). There are two main components to  
237 the RPF geochemical signatures, initially described as enrichments in incompatible elements  
238 compared to the compositions expected after simple crystallization. First, the incompatible  
239 trace element contents of minerals from various gabbroic rocks are indeed higher than  
240 expected for their corresponding major element contents, which characterizes a decoupling  
241 between major and trace elements observed in the natural samples. For example, TiO<sub>2</sub>  
242 contents in Cpx reaches up to 1.5 wt% in minerals at very high Mg# of about 90 (Boulanger *et*  
243 *al.*, 2020), or the range of La contents is the same for Pl with An contents ranging between 45  
244 and 85. This decoupling is likely due to the progressive enrichment in incompatible trace  
245 elements with concomitant major element reequilibration of the melt with the crystal  
246 framework during RPF (e.g., towards higher Mg# for Cpx during percolation of Ol-rich  
247 crystal frameworks). The second characteristic signature is the strong fractionation between  
248 trace elements with variable degrees of incompatibility that has only been reconciled so far  
249 with an evolution modelled by AFC (DePaolo, 1981; Fig. 3A). Other processes likely to occur

250 in oceanic systems have failed to reproduce these signatures (e.g., Sanfilippo *et al.*, 2020;  
251 Boulanger *et al.*, 2021; Ferrando *et al.*, 2021b). Equilibrium or FC do not lead to the  
252 formation of assimilation textures, and completely fail to explain the fractionation of the  
253 incompatible trace elements of the minerals. Trapped melt crystallization was first mentioned  
254 to be the cause of the trace element enrichments in a variety of samples (Ross and Elthon,  
255 1997; Borghini and Rampone, 2007), yet the process by itself cannot be the cause for the  
256 assimilation textures, systematic normal zoning of minerals is lacking in many samples, in  
257 addition to accessory phases that should result from trapped melt crystallization. Finally,  
258 trapped melt alone cannot account for the significant decoupling between major and trace  
259 elements observed in samples, nor for the fractionation between incompatible trace elements  
260 (especially REE) with different degrees of incompatibility found in most natural samples  
261 (Sanfilippo *et al.*, 2020; Boulanger *et al.*, 2021; Ferrando *et al.*, 2021b). Additional effects of  
262 sub-solidus diffusion on the geochemical signatures, or associated with variations of the  
263 temperature-dependent partition coefficients of trace elements during the processes mentioned  
264 before also do not sufficiently impact the signatures to account for the observed natural  
265 sample record, nor explain the assimilated textures (Sanfilippo *et al.*, 2020). Instead, these  
266 signatures tend to be interpreted as resulting from RPF with the support of the textural  
267 evidence found in the same sample (summarized in Table 1). Fig. 4 presents the comparison  
268 between Pl, Cpx and MORB compositions from various fast-spreading (FSR) and slow-  
269 spreading (SSR) ridges, and geochemical models of FC and AFC for incompatible rare earth  
270 elements (REE). It shows that FC falls short to explain the range of compositions of these  
271 systems, and that the potential impact of RPF (modeled here by AFC) on incompatible  
272 elements is found in all components of the oceanic crust and may significantly impact oceanic  
273 crustal accretion. The incompatible element contents of Pl and Cpx seem to require both the  
274 assimilation of Ol and/or Pl, but they do not record the same crystallization events. While

275 crystallization of Cpx help reproduce the composition of Pl, Ol crystallization help reproduce  
276 the composition of Cpx (Fig. 4). This effect is likely the result of Pl and Cpx asynchronous  
277 crystallization in the reservoirs. MORB data also document the assimilation of at least Ol  
278 and/or Pl together with the crystallization of Cpx  $\pm$  Ol. This result suggests that the extraction  
279 of MORB melts from the mush reservoirs proceeds once Cpx has started to crystallize within  
280 the mush. It is consistent with the results of Lissenberg *et al.* (2019) who highlighted such a  
281 chronology.

282 The majority of these gabbros, apart from the more evolved lithologies such as oxide  
283 gabbros, are described as cumulates based on the whole rock geochemical signatures and  
284 especially their incompatible trace element contents which result to some extent from RPF  
285 (Fig. 1). Yet, despite several lines of evidence arguing for the occurrence of RPF and some  
286 experimental constraints (Leuthold *et al.*, 2015; Yang *et al.*, 2019), the question of the  
287 thermodynamic feasibility of RPF process is still pending due to the lack of applied  
288 thermodynamic modelling.

### 290 **Characteristics of the reactions**

291 In detail, the melt-mush reactions described as involved during RPF can vary with the  
292 magmatic system considered. On one hand, the reaction characteristics can be estimated  
293 relying on the textures and the composition of the studied samples. On the other hand, their  
294 impact on the chemistry of a system can be approximated by numerical models. The  
295 correspondence between natural chemical compositions and the models then allows adding  
296 constraints parameters controlling the reactions, such as the nature and fraction of the  
297 reactants and products (melt and minerals). The most commonly used model for RPF relying  
298 on trace elements is the assimilation-fractional crystallization model (AFC; DePaolo, 1981).  
299 Overall, the reactions mostly involve assimilation and/or crystallization of the main cumulate-

300 forming minerals (i.e., Ol, Pl and Cpx) in various proportions, usually in favor of Ol and Pl  
301 assimilation, and crystallization of Pl and Cpx (Fig. 3A, Table 1). This is directly supported  
302 by the evidence for Ol and Pl resorbed textures, and evidence for Pl and Cpx crystallization  
303 after a first mineral dissolution step (poikilitic minerals engulfing resorbed grains, Fig. 2,  
304 Table 1). We present in Fig. 4 different theoretical reactions involving Ol, Pl or Cpx, which  
305 are either assimilated or crystallized, both generations of minerals having different  
306 compositions. The results show the sensibility of the AFC models to the nature of the phases  
307 involved, leading to both enrichment and fractionation between incompatible trace elements  
308 that significantly vary with the minerals considered. The composition of the reactive melt is  
309 almost systematically more primitive compared to the liquid in equilibrium with the mush  
310 crystals involved during the reactions (e.g., (Boulangier et al., 2020)) and, overall, induces  
311 reactions in favor of crystallization compared to assimilation, as described by the  $r$  ratio in the  
312 AFC models from the literature. This  $r$  value is described by DePaolo (1981) as the ratio  
313 between the rate of assimilation and “the rate at which fractionating phases are being  
314 effectively separated from the magma”. This ratio is always comprised between 0.5 and ~0.9  
315 in AFC model related to oceanic igneous reservoirs, and usually a range of  $r$  is needed to  
316 explain the entire range of compositions recorded in a single sample or magmatic system  
317 (examples shown in Fig. 3B; literature synthesis present in Table 1; e.g., Coogan *et al.*, 2000;  
318 Kvassnes, 2004; Boulangier *et al.*, 2020; Zhang *et al.*, 2020; Ferrando *et al.*, 2021b). The  
319 upper limit of  $r = 0.3$  mentioned by DePaolo (1981) for the model applies only to the  
320 assimilation of cold country rocks, and  $r$  can reach values up to 1 during the assimilation of  
321 minerals relatively closer to their liquidus than their solidus temperatures. The range  $r = 0.2$ –  
322 0.99 summarized in Table 1 therefore likely indicates that melts crystallize and thus tend to  
323 reduce the porosity of the system during RPF. It does not ensure, however, that the  
324 assimilation and crystallization steps are fully synchronous during melt-mush reaction, even

325 though both are described at the same time by the AFC equation and recorded together in  
326 natural samples (Lissenberg and Dick, 2008; Boulanger *et al.*, 2020). The characteristics of  
327 the main reactions (type, proportions and compositions of assimilated and crystallized  
328 minerals, melt composition) based on the study of natural oceanic crust samples are supported  
329 by the results of the few available experimental studies for melt-mush reactions (Leuthold *et*  
330 *al.*, 2015; Yang *et al.*, 2019). They are also consistent with the melt dynamics within magma  
331 reservoirs that predict multiple primitive melt injections within crystal mushes and potential  
332 large-scale melt percolation (e.g., Grimes *et al.*, 2008; Godard *et al.*, 2009; Sanfilippo and  
333 Tribuzio, 2013; Dick *et al.*, 2019; Boulanger *et al.*, 2020; Zhang *et al.*, 2020). Hence, the  
334 geochemical signatures of many gabbroic cumulates recovered from the oceanic crust seem to  
335 be directly linked to RPF processes, that likely exert a strong control on melt differentiation.  
336 We provide in the following a thermodynamic modeling of the potential reactions occurring  
337 in gabbroic magma reservoirs to discuss further the implication of melt-mush reactions  
338 involved during RPF.

#### 340 **Thermodynamic feasibility test**

##### 341 *Aim of the AFC model*

342 We present here an attempt to discuss the thermodynamic feasibility of melt-mush  
343 reactions associated with RPF that so far were mostly approached by mass-balance models  
344 relying on trace elements and petrographic descriptions (e.g., Sanfilippo *et al.*, 2020;  
345 Boulanger *et al.*, 2021; Ferrando *et al.*, 2021b). Our approach complements the work of  
346 Collier and Kelemen (2010) that focused on reactive crystallization in the mantle. In our case,  
347 the reactions occur in the earliest stages of evolution of a mush in contact with a primitive  
348 melt. In this scenario, the mineral assemblage of the mush involved in the reaction(s) formed  
349 most likely by FC from a primitive melt (similar to the reactive primitive melt) during a melt-

350 rich evolution phase of the reservoir. The small composition difference and close equilibrium  
351 temperatures of the two components (melt and minerals) questions the assimilation capacity  
352 of the melt. The thermodynamic model rhyolite-MELTS (Gualda *et al.*, 2012; Ghiorso and  
353 Gualda, 2015) allows to model assimilation of a determined mass of material in a melt under  
354 isenthalpic conditions. It does not however consider any heat input from the assimilated  
355 material on the system. The Magma Chamber Simulator (MCS; Bohron *et al.*, 2014, 2020),  
356 which relies on the rhyolite-MELTS engine, allows to track the enthalpy and both  
357 compositions and temperatures of up to three components in a magmatic system : the main  
358 magma subsystem, a subsystem assimilated by the magma and a recharge subsystem. Here,  
359 we used the AFC mode of the MCS to model the evolution of a mush equivalent when in  
360 contact with and assimilated by a primitive melt, with no additional melt input (recharge)  
361 during the reaction. The model allows to track the compositional and thermal evolution of  
362 both the primitive melt (*Magma*) and of the potentially assimilated material (hereafter called  
363 *Mush*) until both are in thermal equilibrium (this is a limit of the MCS AFC model). It also  
364 allows to track if any assimilation of the *Mush* was induced.

#### 365 *Model inputs for oceanic crustal reservoirs*

366 We adapted the model to a slow-spreading oceanic environment and used the Atlantis  
367 Bank OCC as reference (Boulangier *et al.*, 2020). The *Magma* corresponds to a primitive  
368 MORB equivalent suspected to feed the magma reservoirs by cyclic intrusions (SWIR MORB  
369 from Coogan *et al.*, 2004 ; described in Boulangier *et al.*, 2020). The *Mush* equivalents (to be  
370 assimilated) for the Atlantis Bank system are taken as the mineral assemblages (crystals  
371 without melt) obtained by FC of the same primitive MORB equivalent or *Magma* at different  
372 temperatures (determined by rhyolite-MELTS). The pressure of the system is set at 2 kbar,  
373 with redox conditions at FMQ with ~0.2 wt% H<sub>2</sub>O in the *Magma*, which correspond to  
374 average estimates for magma reservoirs at slow-spreading ridges (Lissenberg *et al.*, 2015;



375 Koepke *et al.*, 2018). Other parameters for the AFC runs are the enthalpy convergence step  
376 optimized by MCS modelers at 30, and the FmZero that we set here at 0.05 as we consider a  
377 mineral assemblage from a mush where melt extraction is favored. FmZero describes the  
378 proportion of melt to reach in the *Mush* so that partial melts start being extracted from the  
379 *Mush* and assimilated in the *Magma*. A decisive input parameter for the system is the  
380 temperature set for the different components. The possible input temperatures of the *Mush*  
381 using the MCS is either equal or lower than the solidus temperatures of the selected phase  
382 assemblages. Two mush compositions were tested, a first early stage cumulate obtained after  
383 17.6% FC by MELTS at 1202°C (18.3% Ol, 61.3% Pl and 20.4% Cpx), and a second  
384 advanced stage cumulate obtained at 50.6% FC at 1162°C (11.4% Ol, 52.4% Pl and 36.2%  
385 Cpx). The corresponding modal compositions of the considered mushes are consistent with  
386 the range of olivine gabbros from Atlantis Bank (Boulangier *et al.*, 2021; Ferrando *et al.*,  
387 2021b). The two corresponding input *Mush* temperatures are taken as their crystallization  
388 temperatures of 1202°C for the early stage cumulate and of 1162°C for the advanced stage  
389 cumulate. In relation with MCS limitations, the assimilated material had to be fully solidified  
390 and we therefore took an adcumulate equivalent to the mush presented above (dry assemblage  
391 devoid of melt). This represents an extreme case where the interstitial melt is entirely replaced  
392 by the assimilating melt. This extreme case is disadvantageous for assimilation. In a least  
393 extreme case, the interstitial melt of a mush could partially to fully mix with the injected  
394 primitive melt. The temperature of the melt at the launch of the temperature equilibration  
395 between the *Magma* and the *Mush* is the liquidus, here at 1256.8°C. We consider a  
396 temperature decrement step of 5°C (like the FC model). Finally, and to test the efficiency of  
397 the reactions, five ratios of the *Mush/Magma* masses of 0.25, 0.5, 1, 1.5 and 2 were  
398 considered. They allow to test the reactions for either mush-dominant or melt-dominant  
399 regimes and how this parameter influences the temperature equilibrium, and hence the

400 capacity of assimilation of the melt. The inputs and main outputs of the models are presented  
401 in the Supplementary Materials Table S3 and in the following section *Results of the melt-*  
402 *mush reaction models.*

403 The aim of this model is not to reproduce the complete RPF process, but only to test  
404 with these endmember reactions if the (small) degree of disequilibrium between the *Magma*  
405 and the *Mush* is sufficient to induce assimilation. An integrated RPF model would require a  
406 time component and consider the evolution of the permeability within the system during the  
407 reactions, which is not possible via the MCS AFC model. The occurrence of assimilation  
408 however is often debated and remains a strong argument against melt-mush reactions and RPF  
409 process. The inputs presented above were carefully selected to represent the first increment of  
410 reaction occurring in the initial phase of the RPF involving a primitive melt and two mineral  
411 assemblages that both contain all three main cumulate forming minerals (Ol, Pl and Cpx)  
412 suspected to be involved in melt-mush reactions described in natural samples, and on which  
413 the models rely.

#### 414 *Results of the melt-mush reaction models*

415 The results of the models are presented in Fig. 5. Fig. 5A details the amount of  
416 material from the *Mush* assimilated into the *Magma* and the amount of material crystallized  
417 from the *Magma* for each AFC run. The ratio between the total assimilated mass and the total  
418 crystallized mass is taken as a proxy to the  $r$  ratio discussed earlier in the literature (see  
419 **Characteristics of the reaction**). Fig. 5B compares the initial and final state of the *Mush* for  
420 each AFC model, in terms of mass of each mineral present. For example, in Fig. 5B no spinel  
421 is present in the initial *Mush* and spinel only crystallizes from the *Magma* during the  
422 reactions, as shown in Fig. 5A. The equilibrium temperature between the *Mush* and *Magma*  
423 reached at the end of the models is between 1219-1242°C for the early stage cumulates and  
424 between 1197-1231°C for the advanced stage cumulates. The amount of crystallized and

425 assimilated material is higher for the most evolved *Mush* and increases when the initial  
426 amount of *Mush* involved in the reaction is higher (Fig. 5). Overall, the reactions are in favor  
427 of assimilation for melt-dominated reactions ( $Mush/Magma < 1$ ), with equivalent  $r$  ratios  
428 between 2.66 and 3.65. For higher  $Mush/Magma$  ratios, no assimilation occurs during the  
429 reactions with the early stage (primitive) *Mush*, only crystallization is induced by the decrease  
430 in temperature during equilibration with the mush. For the advanced stage (evolved) *Mush*,  
431 mush-dominated reactions lead to partial assimilation of the *Mush* but overall, the reactions  
432 are in favor of crystallization (with  $r$  ratios between 0.65 and 0.90). All three minerals present  
433 in the *Mush* are assimilated, mostly Pl, then Cpx, and to lesser extent Ol. This is consistent  
434 with Pl and Cpx being in greater disequilibrium with the primitive melt around 1197-1242°C  
435 as they form at lower temperature than Ol in this system, and hence are more likely to be  
436 assimilated during the temperature equilibration. All minerals crystallize in at least one of the  
437 reactions (Spinel, Ol and Pl), except Cpx that is only assimilated in all reactions. Spinel and  
438 Ol crystallize in all reactions (the former due to the presence of Cr in the *Magma*), and Pl  
439 crystallizes for  $Magma/Mush$  ratios superior or equal to 1. As mentioned earlier, the amount  
440 of crystallized and assimilated material increases when the initial amount of *Mush* involved in  
441 the reaction is higher (Fig. 5) until no assimilation is possible, which is the case during mush-  
442 dominated reactions for the primitive *Mush*. There are two competing mechanisms at play:  
443 higher  $Mush/Magma$  ratios imply larger *Mush* mass available for assimilation which seem to  
444 favor higher  $r$  values ( $Mush/Magma$  up to 1), but at the same time higher initial mass of *Mush*  
445 leads to equilibration down to lower temperatures that favor crystallization ( $Mush/Magma$   
446 superior to 1).

447 Overall, the main results of the new models is that reactions between a mush  
448 (primitive or more evolved) and a primitive melt are thermodynamically feasible. For melt-  
449 dominated reactions they lead to partial assimilation of the mush crystals with predominant

450 assimilation over crystallization compared to the reactions described in the literature and  
451 relying on natural samples (Fig. 3B). Assimilation is also possible during mush-dominated  
452 reactions, but it seems to be efficient only for lower-temperature or more evolved  
453 assemblages. The associated  $r$  values (0.65, 0.72 and 0.9) are more consistent with the range  
454 of values described in the literature (Table 1). However, it is difficult to establish with MCS  
455 models whether temperature or composition is the controlling parameter. Overall, between ~6  
456 and 21% of the initial *Mush* mass is assimilated during these one-step reactions. The  
457 proportion of minerals involved differs from the reactions described in the literature (Table 1).  
458 Ol and Pl mainly crystallize in the models whereas in the natural samples Pl and mostly Cpx  
459 seem to crystallize during reactions. In addition, Cpx is systematically assimilated during the  
460 reactions even though in natural samples ubiquitous textural evidence for such assimilation  
461 are so far lacking. These discrepancies could be explained by the fact that our models using  
462 the MCS only reproduce one step of melt-mush reactions (until thermal equilibration between  
463 *Magma* and *Mush*) in a thermally isolated system, whereas natural samples record the entire  
464 protracted RPF process. Also, they do not account for the global progressive cooling of  
465 magma reservoirs within the oceanic crust, which eventually lead to complete mush  
466 crystallization during which most of Cpx crystallization might occur. These models however  
467 support the idea that, as previously suspected (Lissenberg and Dick, 2008; Boulanger *et al.*,  
468 2020), RPF related assimilation and crystallization as recorded in natural samples are partially  
469 decoupled. Most of the assimilation likely occurs in the earliest stages of RPF while the melt  
470 input is sustained (melt-dominated reactions with  $r < 1$ ). This also means that the permeability  
471 of the system can be maintained during the melt-dominated stage of RPF while a new  
472 generation of minerals forms at the expense of the initial mush forming minerals. The one-  
473 step AFC models provided here to study crystal-melt interactions are quite decisive as they

474 show for the first time the thermodynamic sustainability of the reactions on which the RPF  
475 described relies within oceanic igneous reservoirs.

476

## 477 **THE MELT FLUSH PROCESS**

### 478 **Description of the process**

479 We propose here an alternative process for the formation of igneous rock bearing  
480 cumulate signatures, which combines the main characteristics of RPF processes with melt  
481 dynamics in igneous reservoirs. The *melt flush* process considers the most recent  
482 developments on the nature of oceanic reservoirs (mush-dominated), their formation  
483 (repetitive cycles of melt intrusions), and associated melt dynamics (melt percolation through  
484 the porosity of a mush column). It also relies on the studies of natural samples that show the  
485 ubiquitous occurrence of melt-mush reactions and help to precise the main characteristics of  
486 these reactions through the textural record and geochemical signatures (see section **Impact of**  
487 **reactive porous flow** above). The process is also strengthened by the new thermodynamic  
488 models for melt-mush reactions presented herein, which confirm the thermodynamic  
489 feasibility of those reactions.

490 Overall, the *melt flush* process applies to open system magma reservoirs, in mush-  
491 dominated environments continuously fed by primitive melts, subject to global upward melt  
492 migration and extraction. Buoyancy associated with the continuous injection of primitive melt  
493 in the system appears as the main favorable driving force for melt percolation through a  
494 crystal-rich matrix, considering that the bulk density of the cumulate assemblages are denser  
495 than the melt (here crystallized from a primary MORB; Lissenberg *et al.*, 2019). Within the  
496 considered mush, and because of this internal melt migration, RPF seems to exert a strong  
497 control on melt differentiation. As described earlier (**EVOLUTION OF OCEANIC IGNEOUS**  
498 **RESERVOIRS**), most of the reactions occur between already formed mush crystals and a

499 percolating, primitive melt (Fig. 6). The more primitive character of the injected melt relative  
500 to the last increment of crystallized minerals implies its thermodynamic disequilibrium with  
501 the percolated crystal matrix resulting in interactions (Fig. 6). A simplified view of the *melt*  
502 *flush* process could be summarized by the initial crystallization of a relatively primitive melt  
503 ( $L_n$ ) to form a mush composed of crystals ( $C_{n+1}$ ) that are in equilibrium with a slightly more  
504 evolved melt ( $L_{n+1}$ ) following the reaction ( $L_n \rightarrow C_{n+1} + L_{n+1}$ ). During the first increment of  
505 the reactive process,  $L_n$  is recharged and percolates through the mush, replacing the interstitial  
506 melt ( $L_{n+1}$ ) that percolates further up in the surrounding mush. At that stage, the interstitial  
507 melt ( $L_{n+1}$ ) is either totally flushed out or partially mixes with the recharge melt ( $L_n$ ). This  
508 triggers a thermodynamic disequilibrium ( $C_{n+1}$  is in contact with  $L_n$  instead of  $L_{n+1}$ ) and melt-  
509 mush reaction proceeds (Fig. 6). According to our model results, up to 21% of the initial mush  
510 crystals ( $C_{n+1}$ ) is assimilated while a new generation of minerals form ( $C_{n+2}$ ). These minerals  
511 crystallize from the new, more primitive interstitial melt ( $L_{n+2}$ ) in comparison to the previous  
512 interstitial melt ( $L_{n+1}$ ).  $L_{n+2}$  will be similarly flushed out in its turn by a new injection of  $L_n$  at  
513 the second increment of the reactive process. At the scale of the mush column melt  
514 percolation proceeds upwards, and at each level interstitial melts are being progressively  
515 flushed up by more primitive melts that evolve through local melt-mush reactions, which  
516 defines RPF (Fig. 7A). Crystallization being overall predominant over assimilation in natural  
517 cooling reservoirs (Table 1), RPF leads to a progressive record of the primitive character of  
518 the recharge melt(s) in the newly formed minerals until the process eventually stops at  
519 porosity closure of the system.

#### 520 **Melt flush as a cumulate forming process**

521 The *melt flush* process eventually represents a new endmember to form cumulus rocks.  
522 The continuous replacement of the evolved interstitial melt ( $L_{n+1}$ ) by a more primitive (and  
523 thus more depleted in incompatible elements)  $L_n$  melt during the *melt flush* process represents

524 a key element to acquire a depleted bulk rock composition typical of the cumulate signature.  
525 Indeed, incompatible elements that concentrate in the interstitial melt phase during the  
526 increment of crystallization are flushed out of the mush and replaced by the more primitive  
527 (relatively poorer in incompatible elements)  $L_n$  recharge melt. The following crystallization  
528 stage being associated with the recharge melt, the depleted cumulate signature is ultimately  
529 recorded in the plutonic rock's bulk chemical composition.

### 530 **Impact on differentiating mush columns and magma reservoirs**

531 The *melt flush* process translates petrographic and geochemical observations from  
532 oceanic systems, and together with our new thermodynamic constraints, reconciles the  
533 emerging vision of magma reservoirs and their formation dynamics with the widespread  
534 record of RPF in plutonic (and volcanic) rocks. The process is also consistent in terms of melt  
535 dynamics with the complex replenish-mix-tap-crystallize model (RMTX, O'Neill and Jenner,  
536 2016) that would, in the *melt flush* case, integrate an additional assimilation component. In  
537 fact, even in the RMTX model, assimilation is likely to proceed as this model considers a  
538 recharge stage within a partially crystallized system. No direct physical constraints are  
539 established at this stage, apart from the density characterization of the solid and liquid phases  
540 of the magmatic systems driving melt buoyancy and migration through the mush. The  
541 question of the feasibility and stability of the flow involved during RPF can be a matter of  
542 debate, which we do not aim to fully address here, but recent numerical simulations in  
543 continental settings seem to highlight the viability of this process at the crustal scale. Again  
544 there, the process is triggered by continuous melt recharge and buoyancy (Jackson *et al.*,  
545 2018). The results of the melt-mush reaction models presented here are also consistent with  
546 the *melt flush*: if the porous flow is sustained through the mush, preventing cooling of the  
547 magma reservoir at the large scale, the melt-mush reactions leading to both assimilation and  
548 crystallization should locally stay in favor of assimilation, hence preventing total porosity

549 closure and maintaining permeability in the system. The physical conditions associated with  
550 melt migration likely vary with and within the system considered, which would also partially  
551 explain the variability in textures and geochemical signatures recorded within gabbro  
552 cumulates (e.g., Ferrando *et al.*, 2021b). The efficiency of melt replacement and extraction  
553 associated with *melt flush* is also important to consider, especially in the presence of melts  
554 (interstitial and replacing) with high viscosity contrasts. High viscosity differences generate  
555 instabilities (Saffman-Taylor, e.g., Whitehead and Helfrich, 1991; Perugini and Poli, 2005)  
556 that lead to viscous fingering structures and "focused" flow of low viscosity melts in high  
557 viscosity ones. Considering the *melt flush* process, the iterative melt migration from one level  
558 to the next one in a mush column likely proceeds on relatively short distances (meter scale,  
559 see Ferrando *et al.*, 2021b, who highlighted the presence of reactive melt extraction every 3 to  
560 4 m in the studied plutonic section), and viscosity variations are therefore very limited on a  
561 local scale. In this perspective, Saffman-Taylor instabilities are unlikely to occur, even less so  
562 if mixing occurs between melts. As an example, for tholeiitic systems, after 60%  
563 crystallization the viscosity of the differentiating melt only increases by a factor of 1.3  
564 (MELTS FC of the primitive MORB composition from the SWIR (Gualda *et al.*, 2012).  
565 Protracted differentiation of melts is not excluded by *melt flush* but would occur at the scale  
566 of the entire mush column with differentiation and viscosity increasing gradually towards the  
567 top of the system and melt density progressively decreasing and sustaining buoyancy flow.

568

## 569 **GENERALIZATION AND LIMITS OF THE PROCESS**

570 The *melt flush* process potentially applies to any magmatic system that shares the same  
571 characteristics considered here for oceanic magma reservoirs and presented in the following.  
572 As described earlier (INTRODUCTION), 1/ the incremental formation of magma chambers or  
573 reservoirs thanks to multiple melt injections is almost consensual (e.g., Annen *et al.*, 2015;



574 Hepworth *et al.*, 2018; Sparks *et al.*, 2019). The other fundamental characteristic of magma  
575 reservoirs where *melt flush* is potentially occurring is 2/ the presence of mush. The mush-  
576 dominated character of the reservoirs is sometimes debated in other settings than at oceanic  
577 spreading centers, and evidence for melt evolution in mostly liquid chamber or sills were  
578 presented and long suspected in different systems (e.g., most recently in the Bushveld  
579 Complex, Holness *et al.*, 2017a; Kruger and Latypov, 2020; and elsewhere, Holness *et al.*,  
580 2019). However, many models suggest that at least part or most of melt storage and/or  
581 evolution at depth occurs on long timescales in a mushy medium (e.g., Bachmann and  
582 Bergantz, 2008; Cashman *et al.*, 2017; Cooper, 2017; Jackson *et al.*, 2018; Edmonds *et al.*,  
583 2019, and references therein). This is especially the case for transcrustal magmatic systems  
584 where the presence of mush is supported by geophysical evidence (Huang *et al.*, 2015; Kiser  
585 *et al.*, 2016), and in which 3/ reactive melt flow is expected to be a critical process for melt  
586 differentiation (Cashman *et al.*, 2017; Jackson *et al.*, 2018; Blundy, 2022). The process would  
587 lead to a decoupling between major and trace elements (Solano *et al.*, 2014; Blundy, 2022),  
588 which is similar to the evolution of the geochemical signatures described as characteristic of  
589 RPF in oceanic systems. A growing number of evidence for the occurrence of melt-mush  
590 reactions is described in various magmatic systems apart from mid-ocean ridges. In the Rum  
591 Layered Intrusion (Scotland), the layered structure represents crosscutting sills formed by  
592 repeated intrusion of picritic melts (Holness *et al.*, 2007; Hepworth *et al.*, 2018; Troll *et al.*,  
593 2020). Several lines of evidence for melt-mush reactions (or infiltration metasomatism) were  
594 found in Units 7 to 12 linked to these intrusive events within pre-existing cumulates, with  
595 wavy reaction fronts associated with upward reactive melt infiltration or laterally orientated  
596 metasomatism (Holness *et al.*, 2007; O'Driscoll *et al.*, 2010; Leuthold *et al.*, 2014, 2015;  
597 Hepworth *et al.*, 2020). At Skaergaard Intrusion (East Greenland), evidence for RPF has not  
598 been identified directly within the layered sequence but within the Marginal Border Series,

599 which represent the mushy inner margin of the intrusion where infiltration of reactive melts  
600 and progressive margin growth occurred (Namur *et al.*, 2013). Geochemical maps of P in Ol  
601 from the Sept Iles layered intrusion show evidence of complex zoning with intense dissolution  
602 features highlighting intense interactions between the crystals and a disequilibrium melt (Xing  
603 *et al.*, 2022). Evidence for melt-mush reactions was also found in the arc crust. Within the  
604 lower arc crust exposed at the Sapat Complex (Pakistan), Bouilhol *et al.* (2015) identified  
605 feeder pipes of mantle melts concomitantly evolving and reacting with previous cumulates  
606 while arising through the km-scale structures. On another scale, plutonic xenoliths from  
607 Martinique sampling mid-crust crystal mushes reveal the occurrence of melt-mush reactions  
608 within the system, yet this information appears to be lacking within lavas (Cooper *et al.*,  
609 2016). Finally, ocean island systems are not exempt from RPF, as Gleeson *et al.* (2021)  
610 detected evidence for melt-mush reactions in both xenoliths and erupted magmas from the  
611 low melt input mushy magma reservoir beneath Isla Floreana (Galapagos, Ecuador). The  
612 characteristics of the reactions detailed in those various studies are summarized in Table 1.  
613 Compared to mid-ocean ridges, the reactions associated with RPF are nevertheless not yet  
614 characterized to the same extent or resolution in other crustal magmatic systems. The impact  
615 of RPF on melt differentiation is key to assess the potential implications of the *melt flush*  
616 process in those systems and is still challenged. Hence, a better comprehension of the  
617 potential implication of RPF is required before any attempt to generalize the *melt flush*  
618 process to other magmatic systems, even though the other main characteristics of the  
619 magmatic systems involved are met.

620 The *melt flush* process also has potential implications on the collection, aggregation  
621 and accumulation of melt-rich bodies at or close to the top of mush columns. At fast-  
622 spreading oceanic ridges, or in some continental series like in the Ivrea-Verbano zone, where  
623 plumbing systems have been interpreted to be transcrustal, the cumulative series are topped

624 by relatively evolved plutonics when compared to the underlying more mafic series (e.g.,  
625 Voshage *et al.*, 1990; MacLeod and Yaouancq, 2000; France *et al.*, 2009). Similar features are  
626 observed at the top of mushy igneous reservoirs from slow-spreading oceanic centers  
627 (Boulanger *et al.*, 2020) on which the *melt flush* process relies. Although detailed models  
628 dedicated to each of those settings would be required to fully apprehend the corresponding  
629 processes, this common feature could potentially be explained by the numerical models  
630 presented by Jackson *et al.* (2018) who highlighted that incrementally formed transcrustal  
631 igneous systems tend to develop more evolved melt-rich bodies in their relatively shallow  
632 levels through reactive melt flow. In continental settings, where transcrustal plumbing  
633 systems are likely thicker than in oceanic settings, differentiation is potentially more  
634 pronounced, and the *melt flush* process, if effective, could be protracted with the intrusion of  
635 significantly higher volumes of primitive melt at the bottom of the system, and over longer  
636 periods of time. The production of larger volumes of potentially more evolved melts in the  
637 upper part of the mush column could be amplified, and the assimilation component of RPF  
638 could also assist crystal repacking that is the most likely process inducing silicic melt  
639 extraction from a crystal matrix (Bachmann and Huber, 2019). The *melt flush* process and  
640 associated evolved melt extraction close to shallow levels, thus potentially relates to the  
641 process of formation of large volumes of silica-rich melts feeding large silicic eruptions.

642

### 643 **PERSPECTIVES**

644 The *melt flush* process does not aim to replace other cumulate forming processes, and  
645 where occurring, it likely acts concomitantly to crystal settling, mush compaction or  
646 deformation, and reinforces the geochemical cumulate signatures recorded in plutonic rocks  
647 (Fig. 7B). The scale in both time and space at which the *melt flush* process applies is also  
648 likely to vary depending on the magmatic system considered (size of the reservoir, melt input

649 volumes and fluxes, duration of the magmatic activity, localization of the mush zones). The  
650 process as presented here relies on our current knowledge of RPF, and mostly considers  
651 petrographic, geochemical and new thermodynamic constraints, yet the latter only regards the  
652 feasibility of end-member melt-mush reactions in a static way. The modelling of RPF itself,  
653 that is necessary to test the implications of *melt flush* for magmatic systems, requires the  
654 consideration of physical parameters to constrain the evolution of the system during the  
655 reactions: the evolution of the porosity, its impact on the permeability of the system, the  
656 viscosity and relative buoyancy of the melt(s) compared to the mineral assemblages, and the  
657 deformability of the mush matrix. Indeed, these parameters control the capacity of the melt(s)  
658 to percolate through the mush, and hence the occurrence and efficiency of RPF. Time, and  
659 melt flux constraints will also have to be implemented if we are to better apprehend the  
660 kinematics of the *melt flush* process, the degree of reequilibration between newly injected  
661 melt(s) and the percolation matrix, and thus the final mineral (and melt) compositions.

662 Although additional physical constraints will be required to better apprehend the *melt*  
663 *flush* process, it represents a novel, first-order igneous process integrating for the first time (1)  
664 the emerging vision of magmatic reservoirs as mush-dominated environments, (2) their  
665 formation dynamics as open magmatic systems subject to repeated melt intrusions, and (3) the  
666 widespread record of RPF in both plutonic and volcanic rocks and the chemical contribution  
667 of migrating melts during cumulate formation.

668

## 669 CONCLUSION

670 The current concept of magma reservoirs has been shifting over the past decades from  
671 liquid- to mush-dominated environments. The implication of mush as the predominant  
672 differentiation medium of crustal melts is potentially significant but not yet integrated at the  
673 scale of magma reservoirs or crustal accretion. In slow-spreading mid-oceanic ridge

674 reservoirs, the occurrence and significance of crystal-melt interactions within mushes have  
675 been described in multiple samples, magmatic systems, and at multiple scales. The summary  
676 of the RPF models shows similarities between the reactions, which often involve a primitive  
677 melt interacting with the main mush minerals (Ol, Pl, Cpx) under a prevailing crystallization  
678 regime over assimilation. Modeling of those melt-mush reactions using here the Magma  
679 Chamber Simulator shows their thermodynamic feasibility and supports their widespread  
680 occurrence in nature. The RPF characteristics that are determined by the petrology and  
681 compositions of natural samples are also consistent with the global melt dynamics within  
682 oceanic magma systems, formed by cyclic melt intrusions at depths during the main magmatic  
683 events. Altogether, this opens the potential for revisiting some concepts for the formation of  
684 igneous reservoirs, and especially here for the formation of igneous cumulates. Classical  
685 formation processes (melt buoyancy, crystal-mush compaction) are either insufficient on their  
686 own or not observed in many oceanic igneous cumulates, and we attempt here to propose a  
687 novel igneous process that accounts for the widespread occurrence of RPF, and for melt  
688 dynamics within reservoirs: the *melt flush* process. During the *melt flush*, the cyclic inputs of  
689 primitive melts at the base of a mush column together with buoyancy (of melts relative to  
690 crystals) prompt the flushing out of the interstitial, more evolved melt out of the system.  
691 Primitive melts interact with the mush crystals in disequilibrium, which are partially  
692 assimilated during melt-mush reactions while a new generation of minerals forms from the  
693 reactive melt. These minerals record a cumulative geochemical signature through the  
694 replacement of interstitial evolved melt by the reinjected more primitive one, together with  
695 the record of the associated RPF signatures. The *melt flush* process does not aim at replacing  
696 other processes for the formation of cumulates that likely acts jointly to some degree, but is a  
697 reconciliation with our current understanding of oceanic igneous reservoirs by taking into  
698 account primitive melt inputs in the systems, and the widespread occurrence of RPF. The *melt*

699 *flush* opens the way for new discussion for example on the physics of the reservoirs and  
700 mushes, in addition to the completion of integrated thermodynamic models at the scale of  
701 magma reservoirs. The process is potentially applicable to some degree to magmatic systems  
702 sharing the same characteristics as slow-spreading mid-ocean ridge reservoirs, i.e. the  
703 presence of mush, cyclic melt recharges, and the widespread occurrence of RPF.

704

#### 705 **SUPPLEMENTARY DATA**

706 Supplementary data are available at Journal of Petrology online.

707

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ORIGINAL UNEDITED MANUSCRIPT

716 **References**

- 717 Annen, C., Blundy, J. D., Leuthold, J. & Sparks, R. S. J. (2015). Construction and evolution  
718 of igneous bodies: Towards an integrated perspective of crustal magmatism. *Lithos*.  
719 Elsevier B.V. **230**, 206–221.
- 720 Annen, C., Scaillet, B. & Sparks, R. S. J. (2006). Thermal constraints on the emplacement rate  
721 of a large intrusive complex: The Manaslu Leucogranite, Nepal Himalaya. *Journal of*  
722 *Petrology* **47**, 71–95.
- 723 Bachmann, O. & Bergantz, G. W. (2003). Rejuvenation of the Fish Canyon magma body: A  
724 window into the evolution of large-volume silicic magma systems. *Geology* **31**, 789–  
725 792.
- 726 Bachmann, O. & Bergantz, G. W. (2004). On the origin of crystal-poor rhyolites: Extracted  
727 from batholithic crystal mushes. *Journal of Petrology* **45**, 1565–1582.
- 728 Bachmann, O. & Bergantz, G. W. (2008). Rhyolites and their Source Mushes across tectonic  
729 Settings. **49**, 2277–2285.
- 730 Bachmann, O. & Huber, C. (2019). The Inner Workings of Crustal Distillation Columns; The  
731 Physical Mechanisms and Rates Controlling Phase Separation in Silicic Magma  
732 Reservoirs. *Journal of Petrology* **60**, 3–18.
- 733 Bachmann, O., Miller, C. F. & de Silva, S. L. (2007). The volcanic-plutonic connection as a  
734 stage for understanding crustal magmatism. *Journal of Volcanology and Geothermal*  
735 *Research* **167**, 1–23.
- 736 Bédard, J. H. (1994). A procedure for calculating the equilibrium distribution of trace  
737 elements among the minerals of cumulate rocks, and the concentration of trace elements  
738 in the coexisting liquids. *Chemical Geology* **118**, 143–153.
- 739 Bloomer, S. H., Meyer, P. S., Dick, H. J. B., Ozawa, K. & Natland, J. H. (1991). Textural and  
740 mineralogic variations in gabbroic rocks from Hole 735B. *Proceedings of the Ocean*

- 741 *Drilling Program.*
- 742 Blundy, J. (2022). Chemical Differentiation by Mineralogical Buffering in Crustal Hot Zones.  
743 *Journal of Petrology* **63**, 1–36.
- 744 Bohron, W. A., Spera, F. J., Ghiorso, M. S., Brown, G. A., Creamer, J. B. & Mayfield, A.  
745 (2014). Thermodynamic model for energy-constrained open-system evolution of crustal  
746 magma bodies undergoing simultaneous recharge, assimilation and crystallization: The  
747 magma chamber simulator. *Journal of Petrology* **55**, 1685–1717.
- 748 Bohron, W. A., Spera, F. J., Heinonen, J. S., Brown, G. A. & Scruggs, M. A. (2020).  
749 Diagnosing open - system magmatic processes using the Magma Chamber Simulator (   
750 MCS ): part I — major elements and phase equilibria. *Contributions to Mineralogy and*  
751 *Petrology*. Springer Berlin Heidelberg.
- 752 Borghini, G. & Rampone, E. (2007). Postcumulus processes in oceanic-type olivine-rich  
753 cumulates: The role of trapped melt crystallization versus melt/rock interaction.  
754 *Contributions to Mineralogy and Petrology* **154**, 619–633.
- 755 Boudreau, A. (2016). Bubble migration in a compacting crystal-liquid mush. *Contributions to*  
756 *Mineralogy and Petrology*. Springer Berlin Heidelberg **171**, 1–17.
- 757 Bouilhol, P., Schmidt, M. W. & Burg, J.-P. (2015). Magma Transfer and Evolution in  
758 Channels within the Arc Crust: the Pyroxenitic Feeder Pipes of Sapat (Kohistan,  
759 Pakistan). *Journal of Petrology* **56**, 1309–1342.
- 760 Boulanger, M. (2020). Le devenir des liquides au sein de la croûte océanique des dorsales à  
761 expansion lente. *Université de Lorraine*.
- 762 Boulanger, M. *et al.* (2021). Magma-Mush Interactions in the Lower Oceanic Crust: Insights  
763 From Atlantis Bank Layered Series (Southwest Indian Ridge). *Journal of Geophysical*  
764 *Research: Solid Earth* **126**.
- 765 Boulanger, M., France, L., Deans, J. R. L., Ferrando, C., Lissenberg, C. J. & von der Handt,



- 766 A. (2020). Magma Reservoir Formation and Evolution at a Slow-Spreading Center  
767 (Atlantis Bank, Southwest Indian Ridge). *Frontiers in Earth Science* **8**.
- 768 Bowen, N. L. (1915). The later stages of the evolution of the igneous rocks. *journal of*  
769 *geology* **XXIII**.
- 770 Bowen, N. L. (1920). Differentiation by deformation. *Proceedings of the national academy of*  
771 *sciences* **6**, 59–62.
- 772 Bowen, N. L. (1928). *The evolution of the igneous rocks*. .
- 773 Burgisser, A. & Bergantz, G. W. (2011). A rapid mechanism to remobilize and homogenize  
774 highly crystalline magma bodies. *Nature*. Nature Publishing Group **471**, 212–217.
- 775 Canales, J. P., Dunn, R. A., Arai, R. & Sohn, R. A. (2017). Seismic imaging of magma sills  
776 beneath an ultramafic-hosted hydrothermal system. *Geology* **45**, 451–454.
- 777 Canales, J. P., Nedimovi, M. R., Kent, G. M., Carbotte, S. M. & Detrick, R. S. (2009).  
778 Seismic reflection images of a near-axis melt sill within the lower crust at the juan de  
779 fuca ridge. *Nature* **460**, 89–93.
- 780 Cashman, K. V., Sparks, R. S. J. & Blundy, J. D. (2017). Vertically extensive and unstable  
781 magmatic systems: A unified view of igneous processes. *Science* **355**.
- 782 Cheadle, M. J., Elliott, M. T. & McKenzie, D. (2004). Percolation threshold and permeability  
783 of crystallizing igneous rocks: The importance of textural equilibrium. *Geology* **32**, 757–  
784 760.
- 785 Cheadle, M. J. & Gee, J. S. (2017). Quantitative textural insights into the formation of gabbro  
786 in mafic Intrusions. *Elements* **13**, 409–414.
- 787 Chen, J., Cannat, M., Tao, C., Sauter, D. & Munsch, M. (2021). 780 Thousand Years of  
788 Upper-Crustal Construction at a Melt-Rich Segment of the Ultraslow Spreading  
789 Southwest Indian Ridge 50°28'E. *Journal of Geophysical Research: Solid Earth* **126**.
- 790 Collier, M. L. & Kelemen, P. B. (2010). The case for reactive crystallization at mid-ocean

791 ridges. *Journal of Petrology* **51**, 1913–1940.

792 Comeau, M. J., Unsworth, M. J., Ticona, F. & Sunagua, M. (2015). Magnetotelluric images of  
793 magma distribution beneath Volcán Uturuncu, Bolivia: Implications for magma  
794 dynamics. *Geology* **43**, 243–246.

795 Coogan, L. A. (2014). *The Lower Oceanic Crust. Treatise on Geochemistry: Second Edition*.  
796 Elsevier Ltd.

797 Coogan, L. A., Saunders, A. D., Kempton, P. D. & Norry, M. J. (2000). Evidence from  
798 oceanic gabbros for porous melt migration within a crystal mush beneath the Mid-  
799 Atlantic Ridge. *Geochemistry, Geophysics, Geosystems* **1**.

800 Coogan, L. A., Thompson, G. M., MacLeod, C. J., Dick, H. J. B., Edwards, S. J., Hosford  
801 Scheirer, A. & Barry, T. L. (2004). A combined basalt and peridotite perspective on 14  
802 million years of melt generation at the Atlantis Bank segment of the Southwest Indian  
803 Ridge: Evidence for temporal changes in mantle dynamics? *Chemical Geology* **207**, 13–  
804 30.

805 Cooper, G. F., Davidson, J. P. & Blundy, J. D. (2016). Plutonic xenoliths from Martinique,  
806 Lesser Antilles: evidence for open system processes and reactive melt flow in island arc  
807 crust. *Contributions to Mineralogy and Petrology*. Springer Berlin Heidelberg **171**.

808 Cooper, K. M. (2017). What does a magma reservoir look like? the “crystal’s-eye” view.  
809 *Elements* **13**, 23–28.

810 Cordier, C., Benoit, M., Hémond, C., Dymont, J., Gall, B. Le, Briaux, A. & Kitazawa, M.  
811 (2010). Time scales of melt extraction revealed by distribution of lava composition  
812 across a ridge axis. *Geochemistry, Geophysics, Geosystems* **11**.

813 Costa, A., Caricchi, L. & Bagdassarov, N. (2009). A model for the rheology of particle-  
814 bearing suspensions and partially molten rocks. *Geochemistry, Geophysics, Geosystems*  
815 **10**, n/a-n/a.

- 816 Daines, M. J. & Pec, M. (2015). Migration of Melt. *The Encyclopedia of Volcanoes* 49–64.
- 817 DePaolo, D. J. (1981). Trace element and isotopic effects of combined wallrock assimilation  
818 and fractional crystallization. *Earth and Planetary Science Letters* **53**, 189–202.
- 819 Desissa, M., Johnson, N. E., Whaler, K. A., Hautot, S., Fisseha, S. & Dawes, G. J. K. (2013).  
820 A mantle magma reservoir beneath an incipient mid-ocean ridge in Afar, Ethiopia.  
821 *Nature Geoscience*. Nature Publishing Group **6**, 861–865.
- 822 Dick, H. J. B. *et al.* (2000). A long in situ section of the lower ocean crust: results of ODP  
823 Leg 176 drilling at the Southwest Indian Ridge. *Earth and Planetary Science Letters*  
824 **179**, 31–51.
- 825 Dick, H. J. B. *et al.* (2019). Dynamic Accretion Beneath a Slow-Spreading Ridge Segment:  
826 IODP Hole 1473A and the Atlantis Bank Oceanic Core Complex. *Journal of*  
827 *Geophysical Research: Solid Earth* **124**, 12631–12659.
- 828 Dunn, R. A. (2015). Crust and Lithospheric Structure - Seismic Structure of Mid-Ocean  
829 Ridges. *Treatise on Geophysics*. Elsevier, 419–451.
- 830 Dunn, R. A., Lekić, V., Detrick, R. S. & Toomey, D. R. (2005). Three-dimensional seismic  
831 structure of the Mid-Atlantic Ridge (35°N): Evidence for focused melt supply and lower  
832 crustal dike injection. *Journal of Geophysical Research B: Solid Earth* **110**, 1–17.
- 833 Edmonds, M., Cashman, K. V., Holness, M. & Jackson, M. (2019). Architecture and  
834 dynamics of magma reservoirs. *Philosophical Transactions of the Royal Society A:*  
835 *Mathematical, Physical and Engineering Sciences* **377**.
- 836 Ferrando, C., Basch, V., Ildefonse, B., Deans, J. R., Sanfilippo, A., Barou, F. & France, L.  
837 (2021a). Compaction-driven melt extraction and accumulation in a slow-spreading  
838 oceanic crust: microstructures of olivine gabbros from Atlantis Bank (IODP Hole  
839 U1473A, SWIR). *Tectonophysics* **815**.
- 840 Ferrando, C., France, L., Basch, V., Sanfilippo, A., Tribuzio, R. & Boulanger, M. (2021b).

- 841 Grain size variations record segregation of melts residual from reactive migration in  
842 slow-spreading oceanic crust (Atlantis Bank ; 57°E Southwest Indian Ridge). *J.*  
843 *Geophys. Res.-Solid Earth*.
- 844 Ferrando, C., Godard, M., Ildefonse, B. & Rampone, E. (2018). Melt transport and mantle  
845 assimilation at Atlantis Massif (IODP Site U1309): Constraints from geochemical  
846 modeling. *Lithos*. Elsevier B.V. **323**, 24–43.
- 847 France, L., Ildefonse, B. & Koepke, J. (2009). Interactions between magma and hydrothermal  
848 system in Oman ophiolite and in IODP Hole 1256D: Fossilization of a dynamic melt lens  
849 at fast spreading ridges. *Geochemistry, Geophysics, Geosystems* **10**, 1–30.
- 850 Gale, A., Dalton, C. A., Langmuir, C. H., Su, Y. & Schilling, J. G. (2013). The mean  
851 composition of ocean ridge basalts. *Geochemistry, Geophysics, Geosystems* **14**, 489–518.
- 852 Gao, Y., Hoefs, J., Hellebrand, E., von der Handt, A. & Snow, J. E. (2007). Trace element  
853 zoning in pyroxenes from ODP Hole 735B gabbros: Diffusive exchange or synkinematic  
854 crystal fractionation? *Contributions to Mineralogy and Petrology* **153**, 429–442.
- 855 Ghiorso, M. S. & Gualda, G. A. R. (2015). An H<sub>2</sub>O–CO<sub>2</sub> mixed fluid saturation model  
856 compatible with rhyolite-MELTS. *Contributions to Mineralogy and Petrology*. Springer  
857 Berlin Heidelberg **169**, 53.
- 858 Gleeson, M. L. M., Gibson, S. A. & Stock, M. J. (2021). Upper Mantle Mush Zones beneath  
859 Low Melt Flux Ocean Island Volcanoes : Insights from Isla Floreana, Galapagos.  
860 *Journal of Petrology* 1–26.
- 861 Godard, M. *et al.* (2009). Geochemistry of a long in-situ section of intrusive slow-spread  
862 oceanic lithosphere: Results from IODP Site U1309 (Atlantis Massif, 30°N Mid-  
863 Atlantic-Ridge). *Earth and Planetary Science Letters*. Elsevier B.V. **279**, 110–122.
- 864 Grimes, C. B., John, B. E., Cheadle, M. J. & Wooden, J. L. (2008). Protracted construction of  
865 gabbroic crust at a slow spreading ridge: Constraints from <sup>206</sup>Pb/<sup>238</sup>U zircon ages from

866 Atlantis Massif and IODP Hole U1309D (30°N, MAR). *Geochemistry, Geophysics,*  
867 *Geosystems* **9**.

868 Gualda, G. A. R., Ghiorso, M. S., Lemons, R. V. & Carley, T. L. (2012). Rhyolite-MELTS: A  
869 modified calibration of MELTS optimized for silica-rich, fluid-bearing magmatic  
870 systems. *Journal of Petrology* **53**, 875–890.

871 Harris, P. G. (1957). Zone refining and the origin of potassic basalts. *Geochimica et*  
872 *Cosmochimica Acta*, **12**(3), 195–208. [https://doi.org/10.1016/0016-7037\(57\)90032-7](https://doi.org/10.1016/0016-7037(57)90032-7)

873 Hepworth, L. N., Kaufmann, F. E. D., Hecht, L., Gertisser, R. & O’Driscoll, B. (2020).  
874 Braided peridotite sills and metasomatism in the Rum Layered Suite, Scotland.  
875 *Contributions to Mineralogy and Petrology*. Springer Berlin Heidelberg **175**, 1–25.

876 Hepworth, L. N., O’Driscoll, B., Gertisser, R., Daly, J. S. & Emeleus, C. H. (2018). Linking  
877 in situ crystallization and magma replenishment via sill intrusion in the Rum Western  
878 Layered Intrusion, NW Scotland. *Journal of Petrology* **59**, 1605–1642.

879 Hildreth, W., & Moorbath, S. (1988). Crustal contributions to arc magmatism in the Andes of  
880 Central Chile. *Contributions to Mineralogy and Petrology*, **98**(4), 455–489.  
881 <https://doi.org/10.1007/BF00372365>

882 Holness, M. B. (2018). Melt segregation from silicic crystal mushes : a critical appraisal of  
883 possible mechanisms and their microstructural record. *Contributions to Mineralogy and*  
884 *Petrology*. Springer Berlin Heidelberg **173**, 1–17.

885 Holness, M. B., Cawthorn, R. G. & Roberts, J. (2017a). The thickness of the crystal mush on  
886 the floor of the Bushveld magma chamber. *Contributions to Mineralogy and Petrology*.  
887 Springer Berlin Heidelberg **172**, 1–20.

888 Holness, M. B., Hallworth, M. A., Woods, A. & Sides, R. E. (2007). Infiltration  
889 metasomatism of cumulates by intrusive magma replenishment: The wavy horizon, Isle  
890 of Rum, Scotland. *Journal of Petrology* **48**, 563–587.

- 891 Holness, M. B., Stock, M. J. & Geist, D. (2019). Magma chambers versus mush zones:  
892 Constraining the architecture of sub-volcanic plumbing systems from microstructural  
893 analysis of crystalline enclaves. *Philosophical Transactions of the Royal Society A:  
894 Mathematical, Physical and Engineering Sciences* **377**.
- 895 Holness, M. B., Vukmanovic, Z. & Mariani, E. (2017b). Assessing the role of compaction in  
896 the formation of adcumulates: A microstructural perspective. *Journal of Petrology* **58**,  
897 643–674.
- 898 Huang, H.-H., Lin, F.-C., Schmandt, B., Farrell, J., Smith, R. B. & Tsai, V. C. (2015). The  
899 Yellowstone magmatic system from the mantle plume to the upper crust. *Science* **348**,  
900 773–776.
- 901 Irvine, T. N. (1982). Terminology for Layered Intrusions. *Journal of Petrology* **23**, 127–162.
- 902 Jackson, M. D., Blundy, J. & Sparks, R. S. J. (2018). Chemical differentiation, cold storage  
903 and remobilization of magma in the Earth's crust. *Nature*. Springer US **564**, 405–409.
- 904 Kiser, E., Palomeras, I., Levander, A., Zelt, C., Harder, S., Schmandt, B., Hansen, S., Creager,  
905 K. & Ulberg, C. (2016). Magma reservoirs from the upper crust to the Moho inferred  
906 from high-resolution  $V_p$  and  $V_s$  models beneath Mount St. Helens, Washington State,  
907 USA. *Geology* **44**, 411–414.
- 908 Koepke, J., Botcharnikov, R. E. & Natland, J. H. (2018). Crystallization of late-stage MORB  
909 under varying water activities and redox conditions: Implications for the formation of  
910 highly evolved lavas and oxide gabbro in the ocean crust. *Lithos*. Elsevier B.V. **323**, 58–  
911 77.
- 912 Kohlstedt, D. L. & Holtzman, B. K. (2009). Shearing melt out of the earth: An  
913 experimentalist's perspective on the influence of deformation on melt extraction. *Annual  
914 Review of Earth and Planetary Sciences* **37**, 561–593.
- 915 Krättli, G. & Schmidt, M. W. (2021). Experimental settling, floatation and compaction of

916 plagioclase in basaltic melt and a revision of melt density. *Contributions to Mineralogy*  
917 *and Petrology*. Springer Berlin Heidelberg **176**, 1–27.

918 Kruger, W. & Latypov, R. (2020). Fossilized solidification fronts in the Bushveld Complex  
919 argues for liquid-dominated magmatic systems. *Nature Communications*. Springer US  
920 **11**, 1–11.

921 Kvassnes, A. J. S. (2004). The evolution of oceanic gabbros : in situ and ancient examples.  
922 MIT - Woods Hole Joint Progra in Oceanography, Woods Hole.

923 Lambart, S., Koornneef, J. M., Millet, M. A., Davies, G. R., Cook, M. & Lissenberg, C. J.  
924 (2019). Highly heterogeneous depleted mantle recorded in the lower oceanic crust.  
925 *Nature Geoscience*. Springer US **12**, 482–486.

926 Langmuir, C. H. (1989). Geochemical consequences of in situ crystallization. *Nature* **340**,  
927 199–205.

928 Latypov, R. M., Chistyakova, S. Y., Namur, O. & Barnes, S. (2020). Dynamics of evolving  
929 magma chambers : textural and chemical evolution of cumulates at the arrival of new  
930 liquidus phases. *Earth-Science Reviews*. Elsevier **210**, 103388.

931 Laumonier, M., Karakas, O., Bachmann, O., Gaillard, F., Lukács, R., Seghedi, I., Menand, T.  
932 & Harangi, S. (2019). Evidence for a persistent magma reservoir with large melt content  
933 beneath an apparently extinct volcano. *Earth and Planetary Science Letters*. Elsevier  
934 B.V. **521**, 79–90.

935 Lejeune, A. M. & Richet, P. (1995). Rheology of crystal-bearing silicate melts: an  
936 experimental study at high viscosities. *Journal of Geophysical Research* **100**, 4215–  
937 4229.

938 Leuthold, J., Blundy, J. D. & Brooker, R. A. (2015). Experimental petrology constraints on  
939 the recycling of mafic cumulate: a focus on Cr-spinel from the Rum Eastern Layered  
940 Intrusion, Scotland. *Contributions to Mineralogy and Petrology*. Springer Berlin

- 941 Heidelberg **170**, 12.
- 942 Leuthold, J., Blundy, J. D., Holness, M. B. & Sides, R. (2014). Successive episodes of  
943 reactive liquid flow through a layered intrusion (Unit 9, Rum Eastern Layered Intrusion,  
944 Scotland). *Contributions to Mineralogy and Petrology* **168**, 1–27.
- 945 Leuthold, J., Lissenberg, C. J., O’Driscoll, B., Karakas, O., Falloon, T., Klimentyeva, D. N. &  
946 Ulmer, P. (2018). Partial Melting of Lower Oceanic Crust Gabbro: Constraints From  
947 Poikilitic Clinopyroxene Primocrysts. *Frontiers in Earth Science* **6**.
- 948 Lissenberg, C. J. & Dick, H. J. B. (2008). Melt-rock reaction in the lower oceanic crust and its  
949 implications for the genesis of mid-ocean ridge basalt. *Earth and Planetary Science*  
950 *Letters* **271**, 311–325.
- 951 Lissenberg, C. J. & MacLeod, C. J. (2016). A reactive porous flow control on mid-ocean  
952 ridge magmatic evolution. *Journal of Petrology* **57**, 2195–2220.
- 953 Lissenberg, C. J., MacLeod, C. J., Howard, K. A. & Godard, M. (2013). Pervasive reactive  
954 melt migration through fast-spreading lower oceanic crust (Hess Deep, equatorial Pacific  
955 Ocean). *Earth and Planetary Science Letters*. Elsevier **361**, 436–447.
- 956 Lissenberg, C. J., Riou, M., MacLeod, C. J., Bowring, S. A. & Shimizu, N. (2015).  
957 Crystallization depth beneath an oceanic detachment fault (ODP Hole 923A, Mid-  
958 Atlantic Ridge). *Geochemistry, Geophysics, Geosystems* **17**, 162–180.
- 959 Lissenberg, J. C., MacLeod, C. J. & Bennett, E. N. (2019). Consequences of a crystal mush-  
960 dominated magma plumbing system: A mid-ocean ridge perspective. *Philosophical*  
961 *Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*  
962 **377**.
- 963 MacLeod, C. J. & Yaouancq, G. (2000). A fossil melt lens in the Oman ophiolite:  
964 Implications for magma chamber processes at fast spreading ridges. *Earth and Planetary*  
965 *Science Letters* **176**, 357–373.



- 966 Magee, C. *et al.* (2018). Magma plumbing systems: A geophysical perspective. *Journal of*  
967 *Petrology* **59**, 1217–1251.
- 968 Mainprice, D. (1997). Modelling the anisotropic seismic properties of partially molten rocks  
969 found at mid-ocean ridges. **279**, 161–179.
- 970 Mckenzie, D. (1984). The generation and compactation of partially molten rock. *Journal of*  
971 *Petrology* **25**, 713–765.
- 972 Meurer, W. P. & Boudreau, A. E. (1989a). Compaction of Igneous Cumulates Part I:  
973 Geochemical Consequences For Cumulates and Liquid Fractionation Trends. *The*  
974 *Journal of Geology* **106**, 281–292.
- 975 Meurer, W. P. & Boudreau, A. E. (1989b). Compaction of Igneous Cumulates Part II:  
976 Compaction and the Development of Igneous Foliations. *The Journal of Geology* **106**,  
977 293–304.
- 978 Meyer, P. S., Dick, H. J. B. & Thompson, G. (1989). Cumulate gabbros from the Southwest  
979 Indian Ridge, 54°S-7°16' E: implications for magmatic processes at a slow spreading  
980 ridge. *Contributions to Mineralogy and Petrology* **103**, 44–63.
- 981 Namur, O. & Charlier, B. (2012). Efficiency of compaction and compositional convection  
982 during mafic crystal mush solidification: The Sept Iles layered intrusion, Canada.  
983 *Contributions to Mineralogy and Petrology* **163**, 1049–1068.
- 984 Namur, O., Humphreys, M. C. S. & Holness, M. B. (2013). Lateral reactive infiltration in  
985 avertical gabbroic crystal mush, skaergaard intrusion, east greenland. *Journal of*  
986 *Petrology* **54**, 985–1016.
- 987 Neave, D. A., Namur, O., Shorttle, O. & Holtz, F. (2019). Magmatic evolution biases basaltic  
988 records of mantle chemistry towards melts from recycled sources. *Earth and Planetary*  
989 *Science Letters*. Elsevier B.V. **520**, 199–211.
- 990 O'Driscoll, B., Emeleus, C. H., Donaldson, C. H. & Daly, J. S. (2010). Cr-spinel seam

- 991 petrogenesis in the rum layered suite, NWScotland: Cumulate assimilation and in situ  
992 crystallization in a deforming crystal mush. *Journal of Petrology* **51**, 1171–1201.
- 993 O'Neill, H. S. C. & Jenner, F. E. (2012). The global pattern of trace-element distributions in  
994 ocean floor basalts. *Nature*. Nature Publishing Group **491**, 698–704.
- 995 O'Neill, H. S. C. & Jenner, F. E. (2016). Causes of the compositional variability among ocean  
996 floor basalts. *Journal of Petrology* **57**, 2163–2194.
- 997 Paulatto, M., Hooft, E. E. E., Chrapkiewicz, K., Heath, B., Toomey, D. R. & Morgan, J. V  
998 (2022). Advances in seismic imaging of magma and crystal mush. 1–31.
- 999 Perugini, D. & Poli, G. (2005). Viscous fingering during replenishment of felsic magma  
1000 chambers by continuous inputs of mafic magmas: Field evidence and fluid-mechanics  
1001 experiments. *Geology* **33**, 5–8.
- 1002 Picard, D., Arbaret, L., Pichavant, M., Champallier, R. & Launeau, P. (2011). Rheology and  
1003 microstructure of experimentally deformed plagioclase suspensions. *Geology* **39**, 747–  
1004 750.
- 1005 Rannou, E., Caroff, M. & Cordier, C. (2006). A geochemical approach to model periodically  
1006 replenished magma chambers: Does oscillatory supply account for the magmatic  
1007 evolution of EPR 17-19°S? *Geochimica et Cosmochimica Acta* **70**, 4783–4796.
- 1008 Ross, D. K. & Elthon, D. (1997). Cumulus and postcumulus crystallization in the oceanic  
1009 crust: major- and trace-element geochemistry of Leg 153 gabbroic rocks. *Proceedings of*  
1010 *the Ocean Drilling Program, Scientific Results* **153**, 333–353.
- 1011 Rubin, K. H., Sinton, J. M., MacLennan, J. & Hellebrand, E. (2009). Magmatic filtering of  
1012 mantle compositions at mid-ocean-ridge volcanoes. *Nature Geoscience*. Nature  
1013 Publishing Group **2**, 321–328.
- 1014 Sanfilippo, A., Macleod, C. J., Tribuzio, R., Lissenberg, C. J. & Zanetti, A. (2020). Early-  
1015 Stage Melt-Rock Reaction in a Cooling Crystal Mush Beneath a ( IODP Hole U1473A ,

- 1016 Atlantis Bank , Southwest Indian Ridge ). *Frontiers in Earth Science* **8**, 1–21.
- 1017 Sanfilippo, A. & Tribuzio, R. (2013). Building of the deepest crust at a fossil slow-spreading  
1018 centre (Pineto gabbroic sequence, Alpine Jurassic ophiolites). *Contributions to*  
1019 *Mineralogy and Petrology* **165**, 705–721.
- 1020 Sanfilippo, A., Tribuzio, R., Tiepolo, M. & Berno, D. (2015). Reactive flow as dominant  
1021 evolution process in the lowermost oceanic crust: evidence from olivine of the Pineto  
1022 ophiolite (Corsica). *Contributions to Mineralogy and Petrology*. Springer Berlin  
1023 Heidelberg **170**, 1–12.
- 1024 Schaen, A. J., Schoene, B., Dufek, J., Singer, B. S., Eddy, M. P., Jicha, B. R. & Cottle, J. M.  
1025 (2021). Transient rhyolite melt extraction to produce a shallow granitic pluton. *Science*  
1026 *Advances* **7**, eabf0604.
- 1027 Seropian, G., Kennedy, B. M., Walter, T. R., Ichihara, M. & Jolly, A. D. (2021). A review  
1028 framework of how earthquakes trigger volcanic eruptions. *Nature Communications*.  
1029 Springer US **12**, 1–13.
- 1030 Shimizu, K., Saal, A. E., Hauri, E. H., Perfit, M. R. & Hékinian, R. (2019). Evaluating the  
1031 roles of melt-rock interaction and partial degassing on the CO<sub>2</sub>/Ba ratios of MORB:  
1032 Implications for the CO<sub>2</sub> budget in the Earth's depleted upper mantle. *Geochimica et*  
1033 *Cosmochimica Acta* **260**, 29–48.
- 1034 Singh, S. C., Kent, G. M., Collier, J. S., Harding, A. J. & Orcutt, J. A. (1998). Melt to mush  
1035 variations in crustal magma properties along the ridge crest at the southern East Pacific  
1036 Rise. *Nature* **394**, 874–878.
- 1037 Sinton, J. M. & Detrick, R. S. (1992). Mid-ocean ridge magma chambers. *Journal of*  
1038 *Geophysical Research* **97**, 197–216.
- 1039 Solano, J. M. S., Jackson, M. D., Sparks, R. S. J. & Blundy, J. (2014). Evolution of major and  
1040 trace element composition during melt migration through crystalline mush: Implications

- 1041 for chemical differentiation in the crust. *American Journal of Science* **314**, 895–939.
- 1042 Sparks, R. S. J., Annen, C., Blundy, J. D., Cashman, K. V., Rust, A. C. & Jackson, M. D.
- 1043 (2019). Formation and dynamics of magma reservoirs. *Philosophical Transactions of the*
- 1044 *Royal Society A: Mathematical, Physical and Engineering Sciences* **377**.
- 1045 Spera, F. J. & Bohron, W. A. (2004). Open-system magma chamber evolution: An energy-
- 1046 constrained geochemical model incorporating the effects of concurrent eruption,
- 1047 recharge, variable assimilation and fractional crystallization (EC-E'RA $\chi$ FC). *Journal of*
- 1048 *Petrology* **45**, 2459–2480.
- 1049 Tait, S., Jaupart, C. & Vergnolle, S. (1989). Pressure, gas content and eruption periodicity of
- 1050 a shallow, crystallising magma chamber. *Earth and Planetary Science Letters* **92**, 107–
- 1051 123.
- 1052 Tait, S. R., Huppert, H. E. & Sparks, R. S. J. (1984). The role of compositional convection in
- 1053 the formation of adcumulate rocks. *Lithos* **17**, 139–146.
- 1054 Till, C. B., Vazquez, J. A. & Boyce, J. W. (2015). Months between rejuvenation and volcanic
- 1055 eruption at Yellowstone caldera, Wyoming. *Geology* **43**, 695–698.
- 1056 Toplis, M. J., Brown, W. L. & Pupier, E. (2008). Plagioclase in the Skaergaard intrusion. Part
- 1057 1: Core and rim compositions in the layered series. *Contributions to Mineralogy and*
- 1058 *Petrology* **155**, 329–340.
- 1059 Troll, V. R., Mattsson, T., Upton, B. G. J., Emeleus, C. H., Donaldson, C. H., Meyer, R.,
- 1060 Weis, F., Dahrén, B. & Heimdal, T. H. (2020). Fault-Controlled Magma Ascent
- 1061 Recorded in the Central Series of the Rum Layered Intrusion, NW Scotland. *Journal of*
- 1062 *Petrology* **61**.
- 1063 Vigneresse, J. L., Barbey, P. & Cuney, M. (1996). Rheological transitions during partial
- 1064 melting and crystallization with application to felsic magma segregation and transfer.
- 1065 *Journal of Petrology* **37**, 1579–1600.

- 1066 Voshage, H., Hofmann, A. W., Mazzucchelli, M., Rivalenti, G., Sinigoi, S., Raczek, I. &  
1067 Demarchi, G. (1990). Isotopic evidence from the Ivrea Zone for a hybrid lower crust  
1068 formed by magmatic underplating. *Nature* **347**, 731–736.
- 1069 Wager, L. R., Brown, G. M. & Wadsworth, W. J. (1960). Types of Igneous Cumulates.  
1070 *Journal of Petrology* **1**, 73–85.
- 1071 Whitehead, J. A. & Helfrich, K. R. (1991). Instability of flow with temperature-dependent  
1072 viscosity: A model of magma dynamics. *Journal of Geophysical Research: Solid Earth*  
1073 **96**, 4145–4155.
- 1074 Woods, A. W. & Cardoso, S. S. S. (1997). Triggering basaltic volcanic eruptions by bubble-  
1075 melt separation. *Nature* **385**, 518–520.
- 1076 Xing, C. M., Wang, C. Y., Charlier, B. & Namur, O. (2022). Ubiquitous dendritic olivine  
1077 constructs initial crystal framework of mafic magma chamber. *Earth and Planetary*  
1078 *Science Letters*. Elsevier B.V. **594**, 117710.
- 1079 Yang, A. Y., Wang, C., Liang, Y. & Lissenberg, C. J. (2019). Reaction between MORB  
1080 magma and lower oceanic crust: An experimental study. *Geochemistry Geophysics*  
1081 *Geosystems*.
- 1082 Zandt, G., Leidig, M., Chmielowski, J., Baumont, D. & Yuan, X. (2003). Seismic detection  
1083 and characterization of the Altiplano-Puna magma body, Central Andes. *Pure and*  
1084 *Applied Geophysics* **160**, 789–807.
- 1085 Zhang, W.-Q., Dick, H. J. B., Liu, C.-Z., Lin, Y.-Z. & Angeloni, L. M. (2021). MORB Melt  
1086 Transport Through Atlantis Bank Oceanic Batholith (SW Indian Ridge). *Journal of*  
1087 *Petrology*.
- 1088 Zhang, W.-Q., Liu, C.-Z. & Dick, H. J. B. (2020). Evidence for Multi-stage Melt Transport in  
1089 the Lower Ocean Crust: the Atlantis Bank Gabbroic Massif (IODP Hole U1473A, SW  
1090 Indian Ridge). *Journal of Petrology* **61**.

Magma or igneous reservoir:

Structure that comprises a porous and permeable framework of crystals (mush) with melt present in the pore space (low-melt-fraction mush reservoir from Jackson *et al.*, 2018).

Magma chamber:

Structure that stores at depth melts liquid-rich regions (high-melt-fraction mush reservoir from Jackson *et al.*, 2018).

Magma:

System of melt containing crystals (and gases) where the crystal load forms a discontinuous or unlocked framework that allows magma migration (Sparks *et al.*, 2019).

Mush:

“Any system of crystals and melt (and gases) in which the crystals form a continuous framework through which melt is distributed” (Cashman *et al.*, 2017).

Melt-rock reaction:

Reaction between a rock and melts in contact.

Melt-mush reaction:

Reaction between preexisting cumulate minerals from an active mush and melts in contact.

Reactive porous flow (RPF):

Series of reactions of a melt with the rock or mush through which it is percolating.

Differentiation:

Any process whereby a magma, without foreign contamination, forms either a mass of rock that has different compositions in different parts or separate masses that differ from one another in composition (Bowen 1915).

Assimilation-Fractional Crystallization:

Model considering the evolution of a magma by concurrent assimilation of lithologies and differentiation by fractional crystallization (Bowen, 1928; DePaolo, 1981).

Trapped melt crystallization:

Extreme differentiation of residual interstitial melt trapped within the porosity remnant of a rock by fractional crystallization (Meyer *et al.*, 1989; Bédard, 1994; Sanfilippo *et al.*, 2020).

In situ crystallization:

Crystallization of a magma at the magma chamber margins with various fractions of the interstitial melt of the mush boundary layer returning to the main magma body (Langmuir, 1989).

1092 Table 1A. Summary of the main geochemical and textural evidence for the occurrence of RPF in natural mid-  
 1093 ocean ridge and other crustal magmatic systems.

MOR systems	Studied area	Sample type	Geochemical evidence	Textural evidence
Coogan et al. (2000)	Kane Megamullion (MAR)	Poikilitic and brown-pyroxene gabbros	Zoned Cpx crystals with enrichments in Zr relative to REE	Equidimensional PI with interdigitated grain boundaries in Cpx oikocrysts
Kvassnes (2003)	Atlantis Bank OCC (SWIR)	Clinopyroxenes from ODP Hole 735B gabbros	Increasing LREE/HREE ratios in augites with fractionation	-
Gao et al. (2007a)	Atlantis Bank OCC (SWIR)	Clinopyroxene from an olivine gabbro	Profiles in TEs in a Cpx grain (strong enrichments and fractionation between LREE and HREE towards the grain boundary)	-
Lissenberg & Dick (2008)	Kane Megamullion (MAR)	MORB	High-Mg# low-pressure Cpx with high Cr <sub>2</sub> O <sub>3</sub> or high TiO <sub>2</sub> contents	Crosscutting Cpx oikocrysts defining bands, enclosing PI chadacrysts with irregularly curved grain boundaries (resorbed)
Lissenberg et al. (2013)	Hess Deep (EPR)	Gabbroic rocks	Large PI An range for given Cpx Mg#, poor correlation between Cpx Mg# and TiO <sub>2</sub> and Cr <sub>2</sub> O <sub>3</sub> , enrichment and fractionation of incompatible TEs in Cpx, TEs	Dissolution fronts in PI (An maps)

			disequilibrium between Ol, Pl and Cpx	
Leuthold et al. (2018)	Kane Megamullion (MAR)	Poikilitic gabbro and troctolite	Complex Cr, Ti, REE, Zr and Y zoning in coarse-grained Cpx oikocrysts	Large Cpx oikocrysts with resorption textures between zoned areas, Pl chadacrysts resorption textures
Zhang et al. (2020)	Atlantis Bank OCC (SWIR)	Olivine gabbros and oxide gabbros	Mineral HFSE/REE fractionations	Irregular contacts between Cpx oikocrysts and Pl chadacryst, resorbed Ol textures against Pl grains, corroded Ol chadacrysts in Pl or Cpx
Boulanger et al. (2020)	Atlantis Bank OCC (SWIR)	Troctolites, olivine gabbros, gabbros	High-Mg# and TiO <sub>2</sub> Cpx, decoupling between major and trace elements in Pl and Cpx, LREE/HREE fractionation of Pl	Cpx intergrowths, Cpx symplectite, complex Pl zoning, discordant Pl twins on irregular grain boundaries, rounded (resorbed) Ol grains
Sanfilippo et al. (2020)	Atlantis Bank OCC (SWIR)	Olivine gabbro	TEs zoning in Pl and Cpx, progressive fractionation between LREE and HREE towards grain boundaries of Pl and Cpx grains	Ox-rich gabbro patches and veinlets crosscutting the primitive Ol gabbros with resorbed Pl core relicts
Ferrando et al. (2021a)	Atlantis Bank OCC (SWIR)	Olivine gabbros	Pl and Cpx chemical zoning, LREE/HREE fractionation, TEs enrichment in rims	Pl grains (+/- chadacrysts) with lobate grain boundaries against Cpx, Ol with corroded contacts against Cpx or Pl
Boulanger et al.	Atlantis Bank OCC (SWIR)	Layered olivine gabbros	Corroded grain boundaries or	REE and TiO <sub>2</sub> enrichment



(2021)			rounded grains of Ol, Cpx intergrowths, locally resorbed Pl and overgrown Cpx grain boundaries	in Cpx compared to an evolution by FC, LREE/HREE fractionation in Cpx
Other systems	Studied area	Sample type	Geochemical evidence	Textural evidence
Namur et al. (2013)	Skaergaard (East Greenland)	Inner Banded Division of the Marginal Border Series	-	(Colloform banding at intrusion margins)
Leuthold et al. (2014)	Rum Layered Intrusion (Scotland)	Allivalites	Cr and Al zoning in poikilitic Cpx	Troctolite replacement by anorthosite, complex zoning of poikilitic Cpx grains with dissolution evidence
Bouihol et al. (2015)	Sapat Complex (Pakistan)	Dunite and pyroxenites	-	Hornblende replacing Cpx textures, Opx replacing and Hbl replacing Ol textures, structural organization of lithologies
Cooper et al. (2016)	Martinique (France)	Plutonic xenoliths	Amp and Cpx variability in incompatible trace element signatures, REE enrichments in amphiboles with flat REE profiles	Reacted Pl rims, two generations of Amph (early and late appearance), interstitial amphiboles associated with Cpx
Hepworth et al. (2020)	Rum Layered Intrusion (Scotland)	Cpx-rich wherlites	-	Large poikilitic Cpx, zoned Cpx oikocryst with small rounded Ol chadacrysts
Gleeson et al. (2021)	Isla Floreana (Ecuador)	Wehrlites, dunites and gabbro xenoliths	TE disequilibria (cumulus phases - erupted melts) LREE fractionation	Poikilitic Cpx and lack of evidence for trapped melt crystallization

			(La/Sm, Ce/Y) in Cpx xenoliths	
Xing et al. (2022)	Sept Iles layered intrusion (Canada)	Ol primocrysts	P zoning patterns in Ol	Dendritic, hopper and sector patterns of high-P zones corroded by P-poor Ol domains

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1131 Table 1B. Summary of the main reactions characteristic of RPF in natural mid-ocean ridge and  
 1132 other crustal magmatic systems and associated numerical models parameters.

MOR systems	Studied area	Assimilated material	Reactive melt	Reaction(s)	Model	r = Ma/Mc
Coogan et al. (2000)	Kane Megamullion (MAR)	Primitive clinopyroxene	-	Cpx + melt1 -> Cpx + melt2	AFC (DePaolo 1981)	0,7 - 0,8 - 0,9
Kvassnes (2004)	Atlantis Bank OCC (SWIR)	Olivine gabbro	-	Ol <sub>15</sub> + Pl <sub>50</sub> + Cpx <sub>35</sub> + melt1 -> Ol + Pl + Cpx + melt2	AFC (DePaolo 1981)	0,5 - 0,8 - 0,9
Gao et al. (2007a)	Atlantis Bank OCC (SWIR)	Primitive clinopyroxene	Primitive melt (Cpx core equilibrium melt)	Cpx + melt1 -> Pl <sub>100-60</sub> + Cpx <sub>0-40</sub> + melt2	AFC (DePaolo 1981)	[0,5 ; 0,9]
Lissenberg & Dick (2008)	Kane Megamullion (MAR)	Troctolitic mush	Primitive MORB and more evolved MORB	Ol <sub>86/80/67</sub> + Pl <sub>14/20/33</sub> + melt1 -> Pl <sub>56</sub> + Cpx <sub>44</sub> + melt2	Major element mass balance	2 - 0,75
Lissenberg et al. (2013)	Hess Deep (EPR)	Gabbroic mush		Ol <sub>[0-60]</sub> + Pl <sub>[0-80]</sub> + Cpx <sub>[0-100]</sub> + melt1 -> Ol <sub>[10-50]</sub> + Pl <sub>[10-70]</sub> + Cpx <sub>[10-70]</sub> + melt2	AFC (DePaolo 1981)	[0,75; 0,95]
Leuthold et al. (2018)	Kane Megamullion (MAR)	Gabbroic protolith	Primitive mantle-derived melt	Ol + Pl + Cpx + melt1 -> Ol + Pl + Cpx + melt2 Ol + Pl + Cpx + melt3 -> Ol + Pl + Cpx + Sp + melt4	MASH (Hildreth & Moorbat h (1988))	-
Zhang et al.	Atlantis Bank OCC	Gabbroic mush	Primitive melt (Cpx	Ol <sub>15</sub> + Pl <sub>50</sub> + Cpx <sub>35</sub> +	AFC (DePaolo	[0,6; 0,9]

(2020)	(SWIR)		equilibrium melt)	melt1 -> Ol <sub>6</sub> + Pl <sub>56</sub> + Cpx <sub>38</sub> + Opx <sub>1</sub> + melt2 Ol <sub>15</sub> + Pl <sub>50</sub> + Cpx <sub>35</sub> + melt1 -> Ol <sub>6</sub> + Pl <sub>56</sub> + Cpx <sub>38</sub> + Opx <sub>1</sub> + Ilm <sub>0,6/1,4</sub> + melt2	1981) AFC (DePaolo 1981)	[0,6; 0,9]
Boulanger et al. (2020)	Atlantis Bank OCC (SWIR)	Troctolitic mush	Primitive MORB (SWIR) and reactive melts	Ol <sub>45</sub> + Pl <sub>55</sub> + melt1 -> Pl <sub>100</sub> + melt2 Ol <sub>45</sub> + Pl <sub>55</sub> + melt1 -> Ol <sub>5</sub> + Pl <sub>50</sub> + Cpx <sub>45</sub> + melt2 Ol <sub>45</sub> + Pl <sub>55</sub> + melt1 -> Pl <sub>55</sub> + Cpx <sub>45</sub>	AFC (DePaolo 1981) AFC (DePaolo 1981) AFC (DePaolo 1981)	[0,9; 0,99] [0,5; 0,9] [0,6; 0,99]
Sanfilippo et al. (2020)	Atlantis Bank OCC (SWIR)	Gabbroic mush	Primitive melt (Cpx ad Pl equilibrium melt)	Ol <sub>10</sub> + Pl <sub>50</sub> + Cpx <sub>40</sub> + melt1 -> Pl <sub>60</sub> + Cpx <sub>40</sub> + melt2	AFC (DePaolo 1981)	0,99
Ferrando et al. (2021a)	Atlantis Bank OCC (SWIR)	Troctolitic mush and gabbroic mush	N-MORB (SWIR) and reactive melts	Ol <sub>40</sub> + Pl <sub>60</sub> + melt1 -> Ol <sub>10</sub> + Cpx <sub>30</sub> + melt2 Ol + Pl + Cpx + melt2 -> Pl + Cpx + melt3	AFC (DePaolo 1981) AFC (DePaolo 1981)	[0,6; 0,85] [0,6; 0,85]
Boulanger et al. (2021)	Atlantis Bank OCC (SWIR)	Gabbroic mush	Primitive melt (intrusion and Pl equilibrium melt)	Ol <sub>11</sub> + Pl <sub>50</sub> + Cpx <sub>39</sub> + melt1 -> Pl <sub>50</sub> + Cpx <sub>50</sub> + melt2	AFC (DePaolo 1981) Plate Model	[0,2; 0,85]

				Pl <sub>40/30/20</sub> + Cpx <sub>60/70/80</sub> + melt1 -> Pl <sub>70/50</sub> + Cpx <sub>30/50</sub> + melt2	(Vernières et al., 1997)	
Other systems	Studied area	Assimilated material	Reactive melt	Reaction(s)	Model	$r = \frac{Ma}{Mc}$
Namur et al. (2013)	Skaergaard (East Greenland)	Gabbroic crystal mush	Dry mafic silicate melt	Ol1 + Cpx1 + melt1 -> Ol2 + Cpx2 + melt2	-	-
Leuthold et al. (2014)	Rum LI (Scotland)	Gabbro pile	Differentiated picritic magma	-	-	-
Bouihol et al. (2015)	Sapat Complex (Pakistan)	Lower crustal metagabbro	Mantle basaltic melts	Cpx + melt1 -> Hbl + melt2, Ol + melt3 -> Opx + Hbl + melt4	-	-
Cooper et al. (2016)	Martinique (France)	Mush with Cpx and early formed Amph	Water-rich Pl-undersaturated melts	Cpx + melt1 -> Amp + melt2	-	-
Hepworth et al. (2020)	Rum LI (Scotland)	Feldspathic peridotite protolith	Cpx-oversaturated melt	-	-	-
Gleeson et al. (2021)	Isla Floreana (Ecuador)	Ol-dominated mush	Cpx-saturated melts	Ol + melt1 -> Cpx + melt2	Zone refining (Harris, 1957)	-
Xing et al. (2022)	Sept Iles layered intrusion (Canada)	Early-formed Ol grains	Primary magma recharge(s)	-	-	-

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1137 FIGURE 1. Cumulate geochemical signatures. Mean rare earth element (REE) compositions of  
1138 oceanic plutonic rocks from (a) the mid-Atlantic ridge ('MAR'; Atlantis Massif, IODP Hole  
1139 U1309D; from Godard *et al.*, 2009) and (b) the Southwest Indian Ridge ('SWIR'; Atlantis Bank,  
1140 ODP Hole 735B; from Dick *et al.*, 2000). Elemental concentrations are normalized to a primary  
1141 MORB magma, calculated as the melt formed after 10% fractional melting of the Depleted  
1142 MORB Mantle following the procedure of Godard *et al.* (2009). MORB compositions are from  
1143 the PetDB database (Aug. 2020) and Coogan *et al.* (2004). Plutonic rocks with REE contents  
1144 lower than those of the primary MORB (normalized concentrations <1) display characteristic  
1145 cumulate signatures (e.g., Eu enrichment, Supplementary Materials Table S1).

1146  
1147 FIGURE 2. Petrographic evidence of reactive porous flow. Microphotographs (cross-polarized  
1148 light), and chemical map (g) of oceanic plutonic samples presenting characteristic reactive  
1149 textures. (a) Clinopyroxenes (Cpx) intergrowths in an olivine gabbro (ODP Hole 735B,  
1150 Lissenberg *et al.*, 2013). Scale bar: 1mm. (b) Rounded olivine (Ol) grains within a poikilitic  
1151 anhedral Cpx (Erro Tobio troctolites, Borghini and Rampone, 2007). Scale bar: 0.5mm. (c)  
1152 Partially resorbed plagioclase grains (Pl) in a poikilitic coarse grained Cpx (scale bar: 2.5mm)  
1153 and (d) Ol with rounded resorbed shapes in contact with Pl and Cpx in olivine gabbros from  
1154 IODP Hole U1473A (Ferrando *et al.*, 2021b). Scale bar: 0.5mm. (e) Plagioclase dissolution  
1155 textures in a poikilitic Cpx from the Kane Megamullion (Lissenberg and Dick, 2008). Scale bar:  
1156 3mm. (f) Detailed thin section in ODP Hole 735B-91R-1 sample with numerous rounded olivine  
1157 grains and plagioclase grains with irregular boundaries engulfed in cm-wide clinopyroxene  
1158 oikocrysts (red grain boundaries). Scale bar: 1 cm. (Boulanger *et al.*, 2020). (g) Anorthite (molar  
1159 fraction  $An = Ca/(Ca+Na+K) \times 100$ ) map showing dissolution fronts in Pl (Hess Deep gabbro,  
1160 Lissenberg *et al.*, 2013). Scale bar: 0.5mm. (h) Pl grain with resorbed grain boundary included in

1161 a Cpx crystal presenting symplectite textures, (i) Pl grain with complex zoning and irregular grain  
1162 boundaries, (j) Pl with irregular grain boundaries crosscutting twins and Cpx intergrowths and (k)  
1163 rounded-shape Ol crystals and plagioclase presenting complex zoning from ODP Hole 735B  
1164 (Boulanger et al., 2020). Scale bars: 0.5mm. (l) Cpx intergrowths, small resorbed Pl chadacrysts  
1165 in a large Cpx (m) and Pl (n) crystal, and (o) round-shaped Ol chadacryst within a larger Cpx  
1166 (IODP Hole U1473A, Boulanger et al., 2021). Scale bars: 0.5mm. (p) Pl grains enclosed by a  
1167 large Cpx oikocryst with irregular contacts, (q) irregularly-shaped Ol with resorbed textures, (r)  
1168 highly corroded small Ol grains enclosed by Cpx and Pl and (s) Pl grain with deformation twins  
1169 and irregular contacts with surrounding minerals (IODP Hole U1473A, Zhang et al., 2020). Scale  
1170 bars for (p), (q) and (r): 2mm. Scale bar for (s): 1mm.

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1172 FIGURE 3. Geochemical evidence for reactive porous flow and characteristics. (a)  $La_N/Sm_N$   
1173 ratios versus  $La_N$  analyzed in plagioclases from oceanic cumulates (olivine gabbros from ODP  
1174 Hole 735B; Boulanger *et al.*, 2020), and expected composition of Pl after fractional  
1175 crystallization (FC) and assimilation-fractional crystallization (AFC). Values normalized to the  
1176 average primitive MORB composition in the Atlantis Bank area (MORBs from Coogan *et al.*,  
1177 2004). Red and yellow trends: modeled plagioclase compositions after FC from two different  
1178 parental melts (melts in equilibrium with plagioclases bearing the most primitive signatures from  
1179 the Upper - red star - and Lower - yellow star - units of the section). Natural Pl compositions, FC  
1180 and AFC models from Boulanger *et al.* (2020). (b) Summary of literature  $r$  values (the ratio of  
1181 mass assimilated to that crystallized during AFC) obtained by fitting natural data with AFC  
1182 models in oceanic plutonic sections where RPF has been quantified.  $r$  values are here compared  
1183 to clinopyroxene Mg# of the studied oceanic sections (Coogan *et al.*, 2000; Kvassnes, 2004; Gao  
1184 *et al.*, 2007; Boulanger *et al.*, 2020; Sanfilippo *et al.*, 2020; Zhang *et al.*, 2020, 2021; Ferrando *et*

1185 *al.*, 2021b). Values of  $r$  below 1 indicate preferential crystallization during reactive porous flow,  
1186 whereas values above 1 indicate preferential assimilation. For additional  $r$  values from the  
1187 literature, see Table 1.

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1189 FIGURE 4. Comparison of minerals and melt compositions obtained by theoretical models of  
1190 AFC (*DePaolo, 1981*) with natural minerals and melt (MORB) compositions. The models  
1191 presented in a given row of the figure consider crystallization of one single oceanic cumulate  
1192 forming mineral, either Ol, Pl or Cpx. The models presented in a given column of the figure show  
1193 the resulting compositions in either Pl, Cpx or melts after AFC. For each graph, assimilation of  
1194 Ol (green lines), Pl (blue lines) or Cpx (red lines) are considered for different  $r = M_a/M_c$  ratios  
1195 ranging from 0 (equivalent to fractional crystallization) to 0.99. Additional black lines correspond  
1196 to pure assimilation modelled by mixing between the mineral composition (Ol, Pl or Cpx) and the  
1197 composition of the melt used in the AFC models (yellow star). Natural Pl and Cpx compositions  
1198 are from Lissenberg *et al.*, 2013 (L13), Lissenberg and MacLeod, 2016 (L&M16), Ferrando *et*  
1199 *al.*, 2021b (F21), Boulanger *et al.*, 2021 (B21), Boulanger *et al.*, 2020 (B20) and Boulanger, 2020  
1200 (this study). MORB melts from fast-spreading ridges (FSR) and slow-spreading ridges (SSR)  
1201 from Gale *et al.* (2013). Input parameters of the AFC models available in Supplementary  
1202 materials (Table S2).

1203  
1204 FIGURE 5. Results of AFC thermodynamic models using the Magma Chamber Simulator  
1205 (Bohrson *et al.*, 2014). All results are given as equivalent mass (g). The initial mass of Magma is  
1206 100 g for all models. (a) Amount of material from the *Mush* assimilated into the *Magma* and  
1207 amount of material crystallized from the *Magma* during the AFC process.  $r$  = ratio between the  
1208 total assimilated mass and the total crystallized mass. (b) Initial and final state of the *Mush* for



1209 each AFC process modeled, after assimilation and crystallization. For more details, see  
1210 **Thermodynamic feasibility test** and Supplementary Materials Table S3.

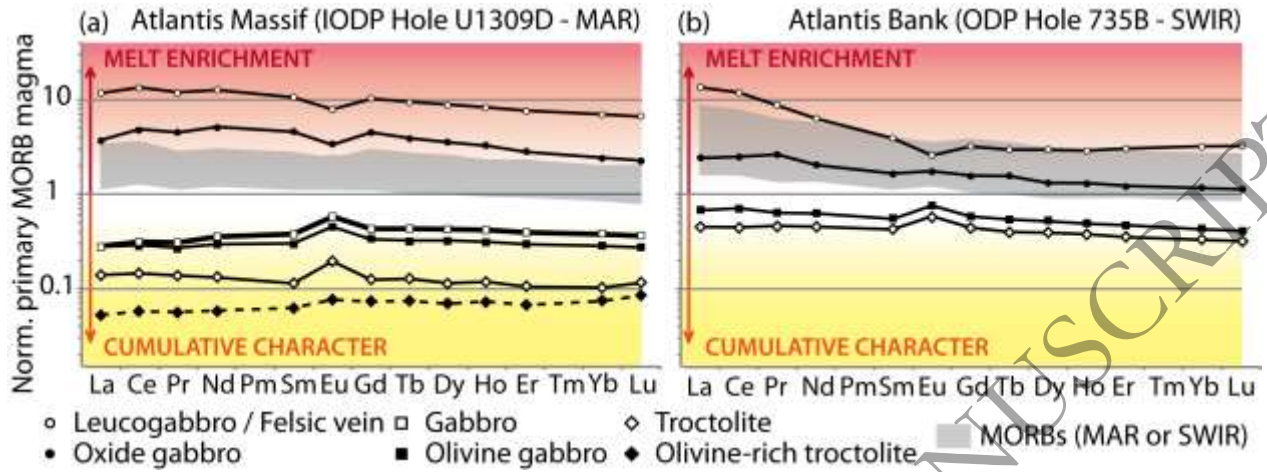
1211  
1212 FIGURE 6. Simplified view of a mush where *melt flush* occurs. This figure shows the progressive  
1213 removal of interstitial evolved melt ( $L_{n+1}$ ) from the crystal matrix replaced by the primitive melt  
1214 ( $L_n$ , *Magma* in the MCS models) that partially assimilates the minerals before crystallization of a  
1215 new generation recording both the average more primitive character of the melt and textural and  
1216 chemical evidence for RPF.

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1218 FIGURE 7. The *melt flush* process. Schematic diagram of the *melt flush* process, and a summary  
1219 of the processes occurring during the formation of cumulate igneous rocks from a petrologic  
1220 perspective. Continuous and cyclic replenishment refers to oscillatory melt replenishment cycles  
1221 by melt intrusions that vary through time (see Boulanger *et al.*, 2020, for further details). RPF:  
1222 reactive porous flow.

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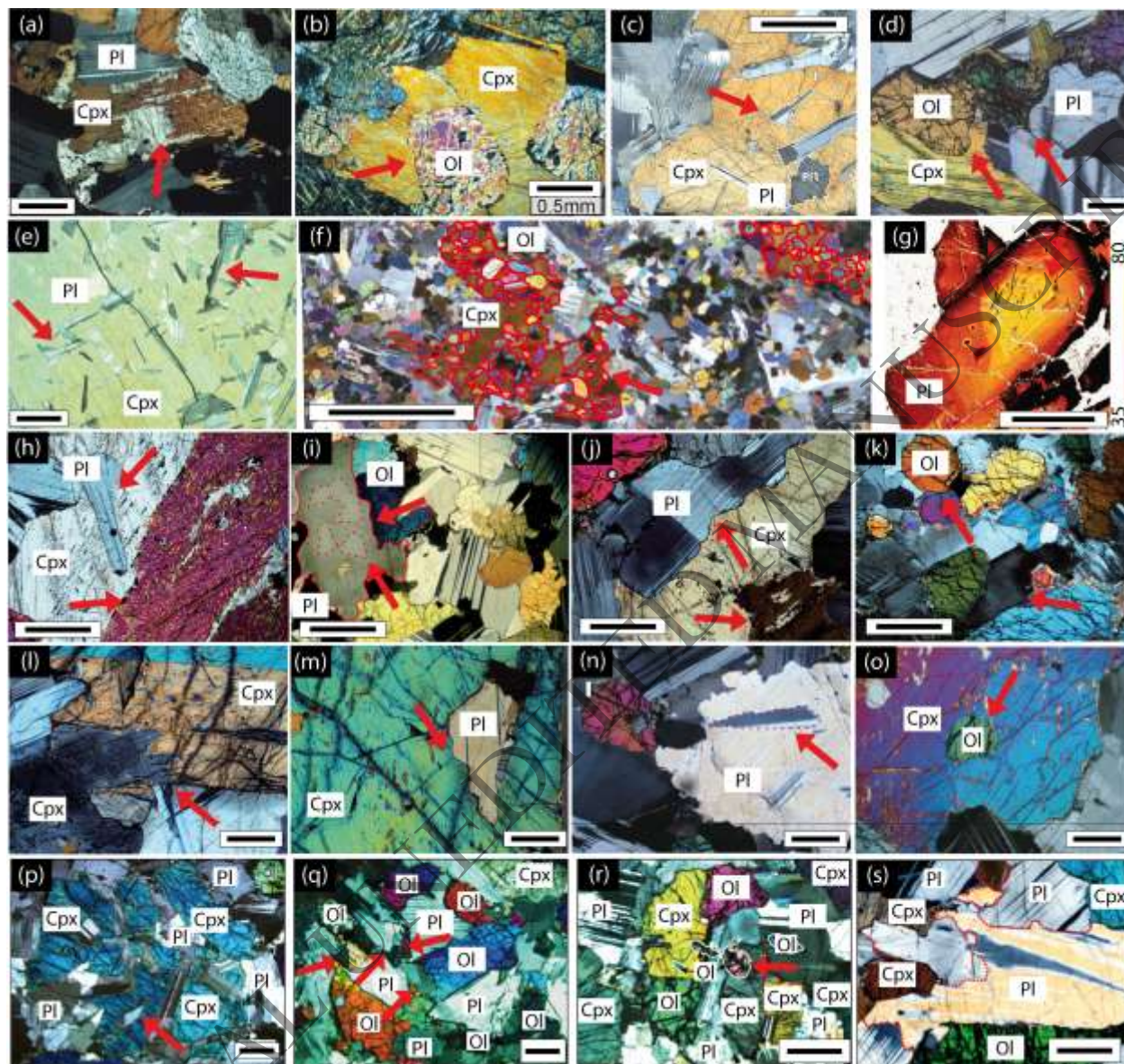
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1224 **Fig. 1.**  
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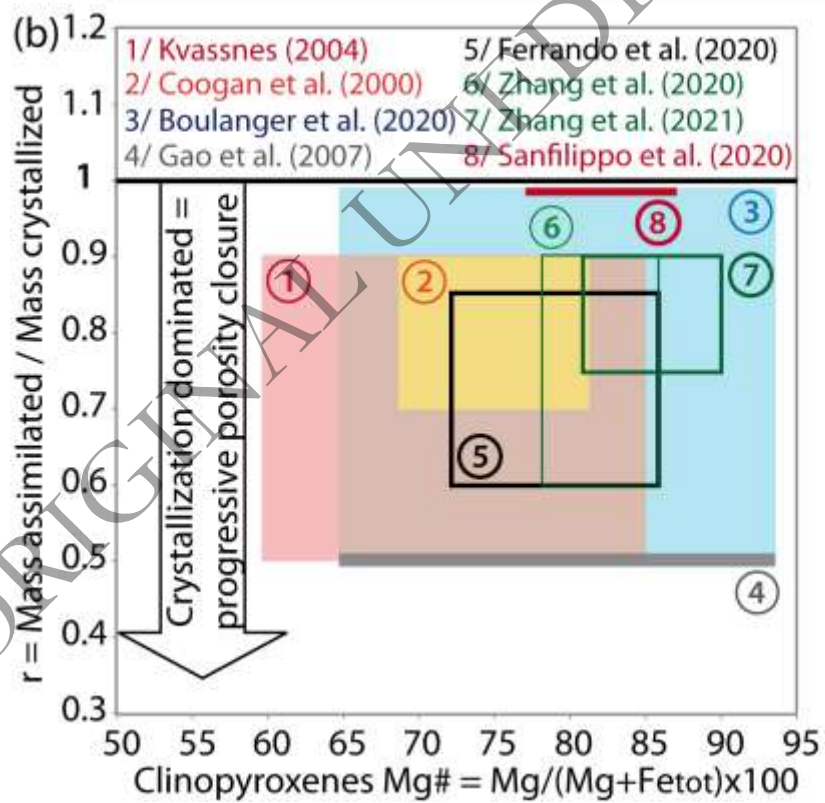
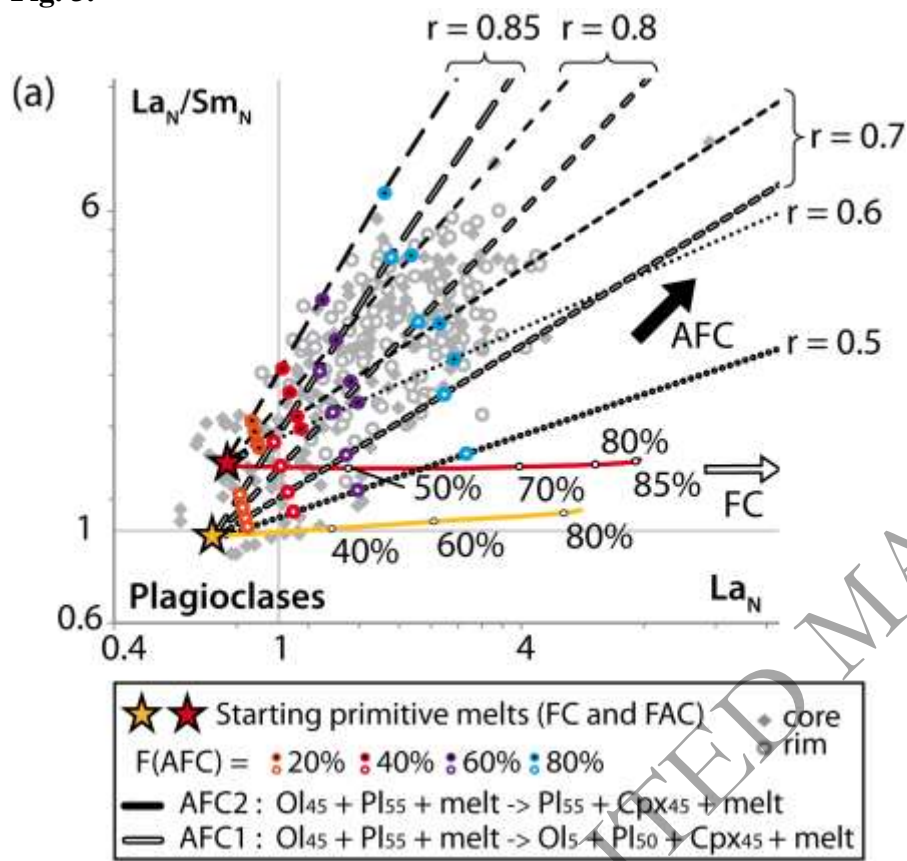
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1259 **Fig. 2.**  
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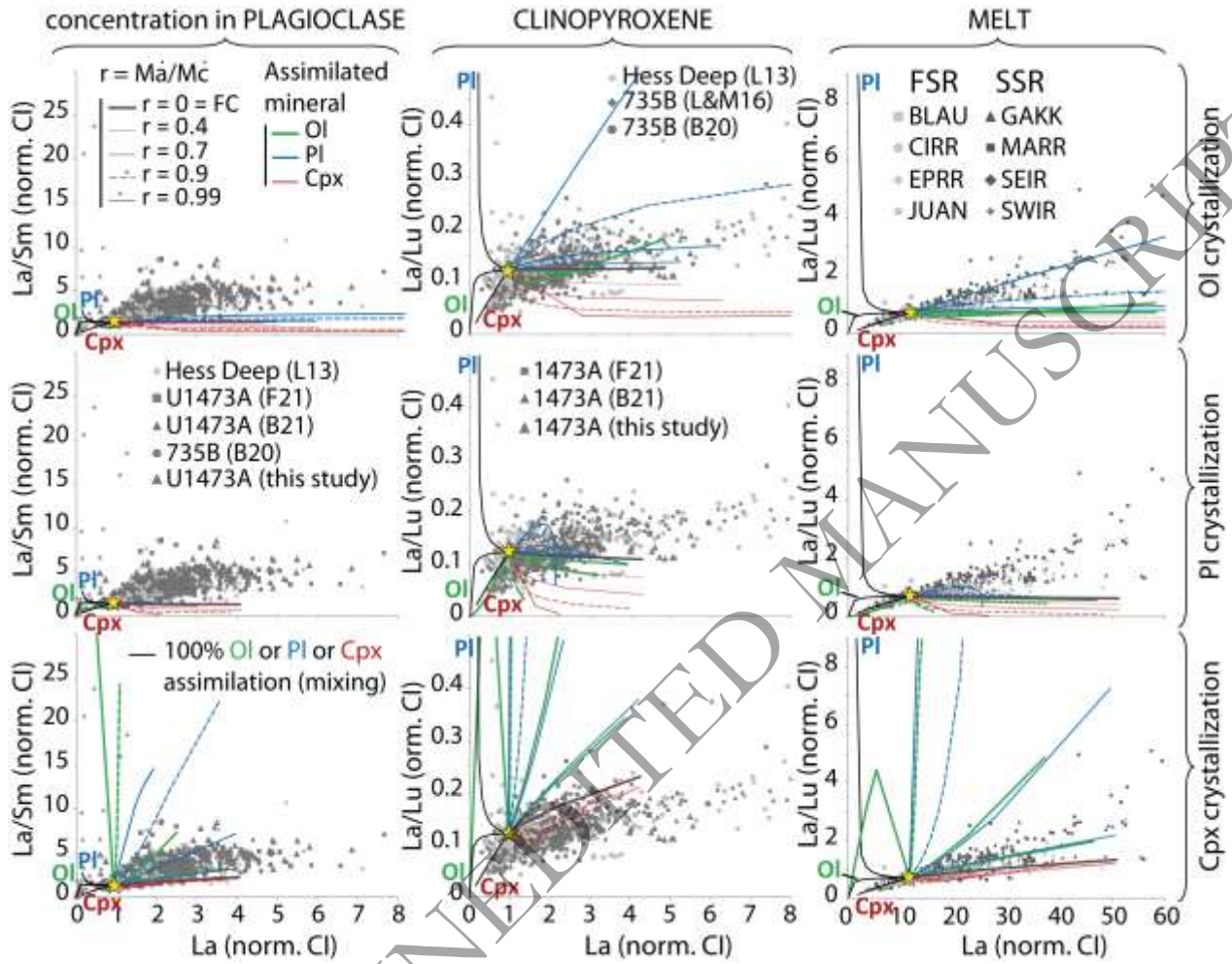


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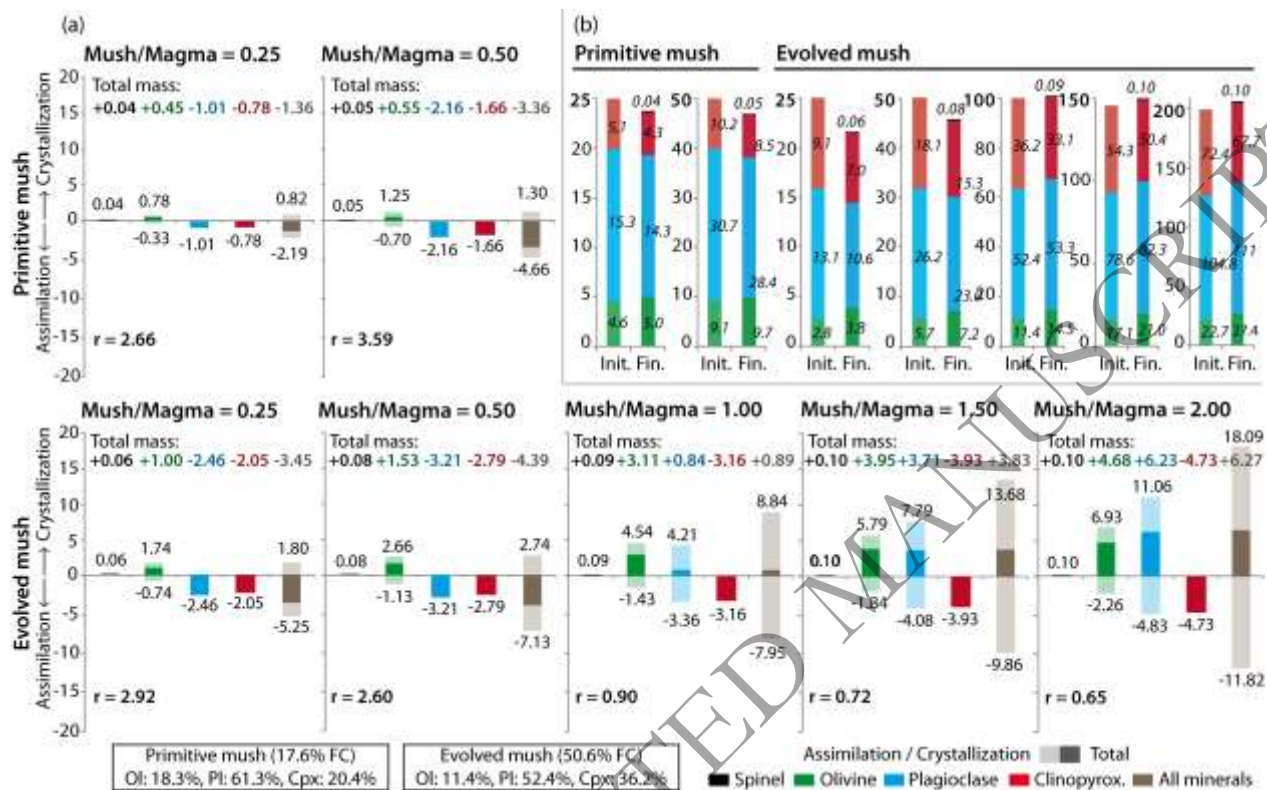


1277 **Fig. 4.**  
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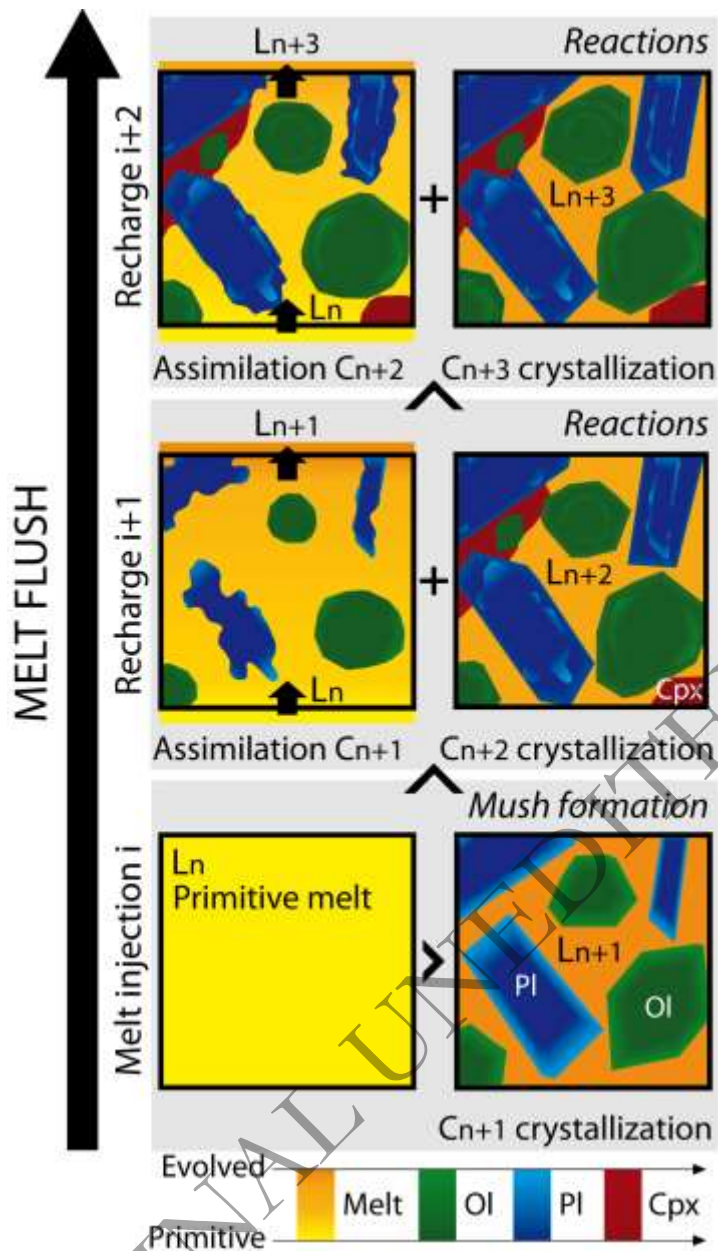
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1298 Fig. 5.  
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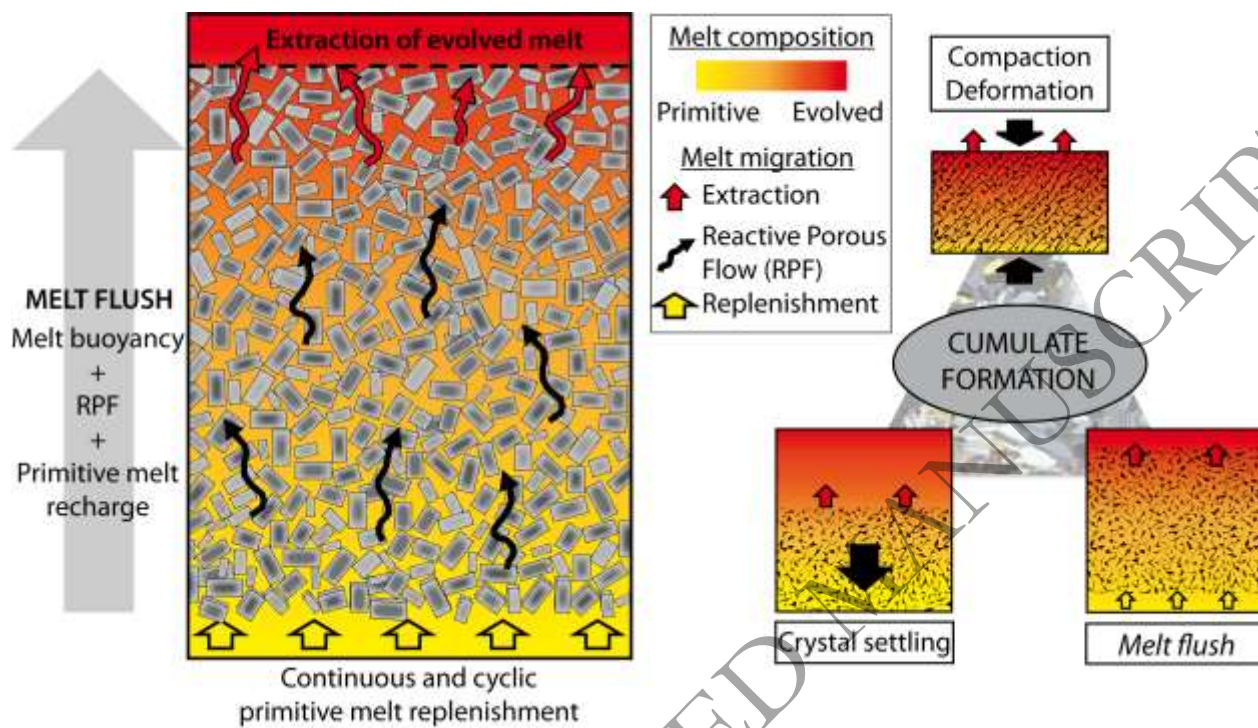
1324 **Fig. 6.**  
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1338 **Fig. 7.**  
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