

Appendix B: Petrogenetic Calculations

A key result of our work is that the fine-grained intermediate Meladiorite samples within the GIC formed by in situ crystallization fractionation of more mafic (and fine-grained) Gabbro samples, and that medium-grained Meladiorites are cumulate relicts of this process. To test such a hypothesis, it is of course essential to examine whether the major oxide variations of these units can be described by crystallization differentiation, using observed mineral modes. In the absence of extensive mineral composition determinations, it is impossible to determine a unique fractionation path, but our models do allow us to explore some testable possibilities. Here we provide details regarding how we calculated our fractional crystallization paths.

We found that a fractional crystallization model was more successful than a batch equilibrium model at describing major oxide variations at the pluton scale. Following Hanson and Langmuir (1978) and Langmuir and Hanson (1981) (see Methods) we thus applied the Rayleigh distillation equation:

$$C_i^{liq} = C_i^o F^{[D_i-1]} \quad (B1)$$

where C_i^{liq} is the concentration of i in a fractionated liquid, C_i^o is the concentration of i in the original un-fractionated liquid, F is melt fraction, and D_i is the bulk distribution coefficient between minerals and melt of i .

Below we provide details about how the inputs to these models were derived, but before doing so, some caveats are warranted. Because our main concern was pluton-scale major oxide variations, there can be no doubt that curves that describe pluton-scale variations are an oversimplification of actual fractionation processes. For example, the bulk distribution coefficient in Eqn. (B1) is calculated as $D_i = \sum X_j K_d^{xtl/liq}$, where X_j is the weight fraction of mineral j in a crystallizing assemblage, and $K_d^{min/liq}$ is the partition coefficient for element i between mineral j and a coexisting liquid (*liq*) phase. Both of these inputs (X_i , and $K_d^{min/liq}$), which are used to obtain D_i are certain to vary significantly, as liquids evolve from a Gabbro parent magma (with 49% SiO₂ and 8-9% MgO) to an evolved Meladiorite residual liquid (with 59% SiO₂ and 3% MgO). The An contents of plagioclase, the Fo contents of olivines, and the various components of hornblende are very sensitive to an every changing T and melt composition. A single curve that purports to describe pluton scale variations necessarily represents an “average process”, reflecting mean values of X_i , and $K_d^{min/liq}$, averaged over a range of intermediate temperatures, mineral modes and liquid compositions. In addition, it is also rather clear that no single curve can account for all major oxide arrays within the GIC. This does not mean that such modeling is useless. Since the lower units in the GIC are replete with rocks that are variously rich in pyroxene, olivine and plagioclase and hornblende, it is important to determine whether fractionation of such phases could plausibly explain pluton-scale major oxide trends, presuming that at least some of the rocks of the lower units are cumulates. In the main text, we presented curves that bracket the range of observed GIC compositions, and so in this way provide some cursory limits on the ranges of D_i that

would be needed to describe pluton-scale fractionation processes. Clearly, mineral compositions and outcrop-scale modeling is required to test these ideas.

For our fractionation models D_i values were calculated as follows: (a) for the input X_i , we used observed mineral modes (linear combinations of modes in Table B1), relying on medium-grained samples especially, as these are expected to possibly represent cumulates, and (b) for $K_d^{min/liq}$, we used mineral compositions from Best and Mercy (1967), and where analyses were not available we used mineral stoichiometry (olivine), and compositions from Deer et al. (1992) (plagioclase, magnetite and apatite). These mineral compositions were paired with fine-grained samples from the Gabbro and Meladiorite units, which we assumed to be liquids (e.g., samples JC_H6_bot, MDJC-2E, -3C, -3E, IG-4, G1A11B, G1A-6). To augment our models in the main text, we show in Table B2 sample calculations that fit the middle of GIC major oxide trends for Fe-Si-Ca-Na-K at $F = 1.0$ to 0.3 (shown as values of C_i^{liq} in Table B2). The mineral modes for these results are not matched by any particular rock sample, but are closely approximated by linear combinations of samples GIF-1B, 2807-8-BS, and G1A-8; the modes for any given mineral are also bracketed by a number of different samples present throughout the Gabbro and Meladiorite units (Table B1). The combined amounts of olivine clinopyroxene may indicate that olivine- and pyroxene-rich cumulates observed at the base of the section (much of which is not exposed) likely rivals the Meladiorite in terms of importance as crystal cumulates.

This model is far from unique, however. For example, if we use the much more Fe-rich orthopyroxene composition reported in Best (1963; his Table2, sample 106), substituting just that orthopyroxene composition alone (so as to calculate a new set of partition coefficients for orthopyroxene/liquid) allows us to obtain effectively the same liquid compositions as presented in Table B2, but with a cpx mode decreases from 20% to 5%, an opx mode that is increased from 0 to 20%, and a hornblende mode that is decreased by 5%. Similarly, we can substitute different compositions for plagioclase, hornblende and olivine and derive very different modal abundances. As another example of partition coefficient sensitivity, in model FC2 in the main text (see Fig. 7, and caption), the partition coefficient for K_2O exceeds that of FeO (both are <1); selection of even a very slightly different feldspar composition (with, say, half the amount of K_2O) would reverse the magnitude of the two partition coefficients, as would the selection of a more Fe-rich orthopyroxene. So can such modeling provide any constraints upon fractionation processes? To a degree, “yes”. We favor the model presented in B2 as an “average” process because our thin section analysis is in agreement with Best (1963), in that few if any rocks reveal 20% modal orthopyroxene (Table B1). In contrast, many Gabbro samples have clinopyroxene modes in range 15 – 35%, and hornblende and plagioclase-rich rocks are abundant in the Meladiorite (Table B1). We caution that a significant fraction of the GIC Gabbro unit is not exposed, so an opx-rich (or olivine-rich) fractionation model cannot be ruled out entirely. But these analyses allow an important test of whether exposed rock samples qualify as potential cumulates.

Table B1. Examples of Mineral modes for select Gabbros and Meladiorites (excluding minor phases).

Gabbro					
plagioclase	hornblende	clinopyroxene	olivine	Biotite	Fe-Ti oxides

G1A_8	48	25	25	0	0	2
IG 6	64.5	0	10.8	21.5	0	3.2
Ig 3	68.4	3.2	15.8	10.5	0	2.1
IG 4	42.9	4.8	35.1	9.5	1	6.7

Meladiorite

	plagioclase	hornblende	clinopyroxene	olivine	Biotite	Fe-Ti oxides
H4	45.9	25.5	20.4	0	5.1	3.1
H6	18	75	0	0	5	2
h7	35.4	60.6	0.5	0	0.5	3
H8	63.1	19.4	2.9	0	9.7	4.9
H13	27.8	66.7	0	0	3.3	2.2
21	39	50	7	0	3	1
22	44.8	39.7	5	0.5	8	2
MDJC-2A	22	70	0	0	5	3
140-1	47	40	7	0	2	4
140-1-GD	51	35.7	8.2	0	1	4.1
140-1-GD	0	89.7	0	0	0	10.3
140-2	64	20	7	0	2	7
md4	14.2	85.2	0	0	0	0.6
2807-3-BS-bot	0	93.7	0	0	1.6	4.7
2807-5-1-BS-bot	15	75	0	0	8	2
2807-8-2-z	36.1	46.3	0	0	15.5	2.1
G1F-1B SEG	100	0	0	0	0	0
G1F-1B	31	60	3	0	4	2
G1A_9	50	30	19	0	0	1
MDJC-2B	25	0	0	0	41.7	33.3
H2-JC	70.6	2.3	9.4	0	11.8	5.9
H3	66.4	0	0	0	0.4	33.2
H5	62.1	12.5	0	0	24.8	0.6
Best 6	86.7	3.3	0	0	6.7	3.3
FS-1	100	0	0	0	0	0
FS2B-C	34.9	54.9	0	0	10	0.2
FS2B-C seg	100	0	0	0	0	0
H12 v	100	0	0	0	0	0
MDJC2F	83.3	6.3	0	0	2.1	8.3

Table B2. Sample model inputs and results for GIC fractional crystallization model

Mineral ¹	Mineral Compositions									
	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
Olivine (Fo83.8)	39.8			15.4		44.8				
Clinopyroxene (140c)	52.3	0.6	2.0	6.8	0.2	15.8	21.3	0.3		
Orthopyroxene (140)	53.6	0.4	1.5	18.3	0.4	24.7	1.6	0.0	0.0	
Plagioclase (DHZ)	49.1		32.1	0.3		0.2	15.4	2.6	0.2	

Hornblende (128)	46.1	2.4	9.3	12.5	0.1	14.0	11.6	1.6	0.5	
Apatite (DHZ)				0.2		0.1	55.0			44.8

Liquid Composition for calculation of $K_d^{xtl/liq}$

Sample ²	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
Basalt (JC_H6_bot)	51.8	1.2	16.3	9.0	0.2	7.4	10.6	3.0	0.8	0.13

Mineral-liquid distribution coefficients ($K_d^{xtl/liq}$)

	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
Olivine	0.8	0.0	0.0	1.7	0.0	6.0	0.0	0.0	0.0	0.0
Clinopyroxene	1.0	0.5	0.1	0.8	1.1	2.1	2.0	0.1	0.0	0.0
Orthopyroxene	1.0	0.4	0.1	2.0	2.7	3.3	0.2	0.0	0.0	0.0
Plagioclase	0.9	0.0	2.0	0.0	0.0	0.0	1.4	0.9	0.2	0.0
Hornblende	0.9	2.1	0.6	1.4	0.7	1.9	1.1	0.5	0.7	0.0
Apatite	0.0	0.0	0.0	0.0	0.0	0.0	5.2	0.0	0.0	349.6
Magnetite ³	0.0	0.0	0.0	24.1	0.0	0.0	0.0	0.0	0.0	0.0

Mineral Proportions (X_i)

	Ol	Cpx	Opx	Plag	Hbl	Ap	Mt			
	0.1	0.2	0	0.4	0.279	0.001	0.02			
	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
D_i	0.9	0.7	1.0	1.2	0.4	1.6	1.3	0.5	0.3	0.3
C_i^o ³	51.8	1.2	16.3	9.0	0.2	7.4	10.6	3.0	0.8	0.1

Calculated fractionated liquid compositions (C_i^{liq})

F	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
0.01	79.4	5.2	18.8	3.3	2.1	0.6	2.8	29.3	22.7	2.6
0.1	64.1	2.5	17.5	5.4	0.6	2.1	5.4	9.4	4.3	0.6
0.2	60.1	2.0	17.1	6.3	0.4	3.0	6.7	6.7	2.6	0.4
0.3	57.9	1.7	16.9	6.9	0.3	3.8	7.5	5.5	1.9	0.3
0.4	56.4	1.6	16.8	7.4	0.3	4.5	8.1	4.7	1.6	0.2
0.5	55.2	1.5	16.7	7.7	0.2	5.1	8.7	4.2	1.3	0.2
0.6	54.3	1.4	16.6	8.1	0.2	5.6	9.2	3.9	1.2	0.2
0.7	53.5	1.3	16.5	8.3	0.2	6.1	9.6	3.6	1.0	0.2
0.8	52.8	1.2	16.4	8.6	0.2	6.6	10.0	3.4	0.9	0.1
0.9	52.3	1.2	16.4	8.8	0.2	7.0	10.3	3.2	0.9	0.1
1	51.8	1.2	16.3	9.0	0.2	7.4	10.6	3.0	0.8	0.1

¹Numbers beneath mineral names indicate either a calculated mineral stoichiometry (olivine; here assuming equilibrium with mafic Gabbro samples, assuming and Fe-Mg exchange coefficient of 0.30; Roeder and Emslie, 1970), a composition from Deer et al. (1992), indicated as DHZ, or sample numbers from mineral analyses from Best and Mercy (1967). ²The starting liquid composition is a high MgO sample (number JC_H6_bot) from Table A1. ³The partition coefficient for magnetite is from Ewart and Griffin (1994), a value obtained from the GERM partition coefficient database (<http://earthref.org/KDD/>), for the most mafic of liquids available (andesite; magnetite/melt partition coefficients for Fe, for more felsic compositions, range from 11 to 202). ³Values for C_i^o use the same liquid composition as used for the calculation of mineral/melt partition coefficients, i.e., sample JC_H6_bot.

References Cited (not cited in main text)

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