Differentiation of Magmas By Fractional Crystallization

Modified from Karl Wirth, rev. July 2011

Objective

The objective of this exercise is to gain first-hand knowledge of the process of magmatic differentiation by fractional crystallization. The activity also provides an opportunity to utilize your knowledge of mineral stoichiometry, the IUGS classification system, and spreadsheets.

A Bit of History and Terminology

In the introductory geology course you learned about Bowen’s reaction series and the importance of crystal-melt fractionation in generating the spectrum of observed igneous rock compositions (e.g., basalt, andesite, rhyolite). *Magmatic differentiation* is the process by which diverse rock types are generated from a single magma. Differentiation is accomplished by *crystal-melt fractionation*, a two-stage process that involves the formation and mechanical separation of compositionally distinct phases. In 1844 Charles Darwin described flows from the Galápagos Islands in which the lowest flows contained greater proportions of feldspar crystals. These observations led Darwin to propose that density differences between crystals and melt would result in mechanical separation of these two phases and the formation of different magma types. This process, known today as gravity settling, was the focus of detailed experimental studies by N.L. Bowen. Today, several additional mechanisms of crystal-melt fractionation are also recognized, including: flow segregation, filter pressing, and convective melt fractionation.

Constructing the Magma Chamber

1. In this exercise each major cation (e.g., Si, Ti, Al) will be represented by a different colored M&M® (e.g., brown, purple, red, respectively). Mark on your data sheet which color of M&M’s® is appropriate for each cation. Divide the provided poster board into ten approximately equal sections (divide lengthwise, not widthwise). Each section will represent a new layer of your crystallizing magma chamber.

Crystallization and Fractionation of the Magma

1. Before you begin, determine the composition and stoichiometry of each of the minerals involved in the crystallization process.

2. For the first increment of crystallization, move the appropriate number of M&M’s® from the magma chamber to the “floor” of the magma chamber (*e.g.* the lowest division on your poster board). For each cation, record the number that remains in the magma chamber.

3. For each increment of crystallization, move the appropriate number of cations (M&M’s®) into the next layer up. In this manner you will crystallize the M&M’s® magma chamber from the bottom on up. At each step, remember to record the number of remaining cations in the magma chamber.

4. Take a moment prior to moving on to the analysis section of the lab and describe the general trends that you observed during the fractional crystallization of the magma. Compare your preliminary results with the other group(s).

5. Before your experiment is dismantled (or consumed), finish the analysis and reflection sections of the lab.

Analyzing the Results

1. Construct an Excel spreadsheet that is laid out in the same fashion as the data sheet that has been provided.

2. For each crystallization step, complete the calculations of the:
   a. modes of the minerals being removed to the chamber floor (cumulus minerals)
   b. normalized modes of the minerals used for IUGS classification
   c. number of cations remaining and the cation composition of the remaining liquid
   d. fraction of liquid remaining (*F*), an
   e. Mg# = ([Mg]/[Mg+Fe])

3. Next, use your data to determine the following:
   a. IUGS rock name for the cumulus layer formed during each crystallization event
   b. the rock name for the residual liquid remaining after each crystallization event based on the TAS (Na_2O+K_2O vs. SiO_2) diagram [name both taking & ignoring Na & K into consideration]

4. Generate x-y plots of the following in Excel:
   a. fraction of liquid remaining (*F*) and Mg# versus Si
   b. a sequence of Harker diagrams (*e.g*. Ti, Al, Fe, Mg, Ca, Na, K vs. Si)
   c. indicate the arrival of minerals on the liquidus on each of the plots

Reflecting on What You Have Learned

1. Describe the effect each mineral has on the liquid line of descent. (*e.g*. olivine caused __ and __ to decrease while the percent of __, __, __, __, and __ increased)

2. How are the terms compatible and incompatible defined (both mathematically and qualitatively)? From your results, which elements behaved compatibly during crystallization of this magma? Which behaved incompatibly? Do all of the elements exhibit the same behavior throughout the duration of crystallization? Explain.

3. Describe the changes in rock composition (proportions of cumulus minerals) that result from each increment of crystallization. Use IUGS rock terms and plots in your answer.

4. Describe the chemical changes that result in the residual magma after each increment of crystallization.

5. At what melt fraction (*F*) does the magma approximate andesite composition? Rhyolite composition?

6. Is the parental basaltic magma in this experiment also a "primitive liquid?" Explain.

7. Which aspects of this model magma chamber are realistic? Which are not? Discuss the ways that the model might be made more realistic.

8. Contrast the results of this model (fractional crystallization) with those of a model involving equilibrium crystallization.

You may want to compare and discuss your findings with your classmates, but each student will be responsible for handing in their own lab. You should hand in:

- your Excel version of the data sheet (scaled to fit on one page)
- all of your diagrams (which should all fit on two pages)
- typed answers to the reflection questions
- a work cited, acknowledgement, and/or further work section if appropriate (typed)

If optional assimilation / magma mixing included:

- separate data sheets for each mixing and assimiliation example (scaled to each fit on one page)
- all of your diagrams for each scenario (two pages per scenario)
- typed answers to (d), (e), and (g)

Optional Assimilation / Magma Mixing scenarios

(We're only going to do this section of the lab if time permits.)

1. Instead of allowing fractional crystallization to continue until the end, we're going to explore two other options for what might occur to change the composition of our magma chamber. Remove layers 7-10 from your crystallized magma chamber and put them to the side (but still don't eat them!). Assume these layers are back in the magma body.

2. Join with one or two other magma chamber groups – with one chamber we're going to explore magma mixing and with the other one/two assimilation.

3. Magma mixing example:
    a. Create a new sheet in your Excel spreadsheet and copy all of the data sheet information from the fractional crystallization example into the new sheet. Remove the information from step 7 through 10, but keep steps 1 through 6. Insert an "added magma" step and a "mixed magma" step between 6 and 7 on your data sheet.
    b. A new, undifferentiated magma will be provided by your instructor. Enter the information in the "added magma" step. Based on the number of cations, determine the composition of the new magma and give it a TAS name.
    c. Mix the new magma with the liquid that remained after layer 6 crystallized (layers 7-10 plus the last gasp of liquid) and enter the data in the "mixed magma" step. Determine the new number of cations, the composition of the new magma, and its TAS name.
    d. Compare the mixed magma composition with the liquid that remained after crystallization of steps 1 through 6—which liquid does it most closely resemble?
    e. If crystallization occurred after the magma mixing, what minerals would you expect to crystallize and in what proportions?

f. Check with your instructor for your answer to (e) and then proceed to crystallize step 7 and 8 with the new mineral proportions.
g. Plot steps 1-6 and 7-8 on the same series of diagrams as above. How did the injection of a new magma affect the general trends for each of the diagrams?

4. Assimilation example(s):
    a. Create another new sheet in your Excel spreadsheet and lay it out the same as the magma mixing sheet excpet "added magma" = "melted shale" or "melted limestone" depending on what the instructor hands you. (Depending on the number of groups that joined, you may have to repeat these steps for a different melted country rock.)
    b. The instructor will hand you the appropriate M&M's® to represent either limestone or shale that will be melted and assimilated by your magma chamber. Based on the number of cations, try to apply a TAS name. Is the new melted material compositionally similar to a "typical" volcanic rock? Why or why not?
    c. Mix the new melted rock with the liquid that remained after layer 6 crystallized (layers 7-10 plus the last gasp of liquid) and enter the data in the "mixed magma" step. Determine the new number of cations, the composition of the new magma, and its TAS name (if you can).
    d. Compare the mixed magma composition with the liquid that remained after crystallization of steps 1 through 10 of your original magma chamber—which liquid does it most closely resemble?
    e. If crystallization occurred after the assimilation, what minerals would you expect to crystallize and in what proportions?
    f. Check with your instructor for your answer to (e) and then proceed to crystallize step 7 and 8 with the new mineral proportions.
    g. Plot steps 1-6 and 7-8 on the same series of diagrams as above. How did the melting of the country rocks affect the general trends for each of the diagrams?

Cation	M&M Color	fractionating minerals								
		Forsterite	*Fayalite*	*Diopside*	*Anorthite*	*Albite*	*K-feldspar*	*Quartz*	*Ilmenite*	*Magnetite*
Si										
Ti										
Al										
Fe										
Mg										
Ca										
Na										
K										

Minerals Formed at Each Step

Mineral	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Fo	2	3	4	3	2					
Fa			1	1	1	1				
Di				1	1	4	2	2	1	1
An		1	2	3	3	4	3	3	1	1
Al						1	3	6	5	7
Ksp									2	2
Qtz									1	4
Ilm							1	2	1	1
Mag					1	3	1	1	1	1
total										

Cumulus Mineral Modes

Mineral	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Fo										
Fa										
Di										
An										
Al										
Ksp										
Qtz										
Ilm										
Mag										

Normalized Mineral Modes for IUGS

Mineral	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
ol										
cpx										
pl (An >50)										
pl (QAPF)										
alk										
qtz										
Name rock										

What's left in the magma

element	*original #*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Si	184										
Ti	5										
Al	71										
Fe	38										
Mg	40										
Ca	33										
Na	23										
K	6										
total	400										
% Liquid	100.00%										

Composition of the magma

element	*original %*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Si	46.00										
Ti	1.25										
Al	17.75										
Fe	9.50										
Mg	10.00										
Ca	8.25										
Na	5.75										
K	1.50										
total	100										
F (liq. Fract.)	1										
Mg #	0.512821										
Na2O+K2O	7.25										
TAS classification	tephrite basanite										
TAS (ignore Na+K)	basalt										

element	*original #*	*added magma*	*added limestone*	*added shale*
Si	184	92	26	121
Ti	5	2	0	2
Al	71	36	4	39
Fe	38	19	2	14
Mg	40	20	30	4
Ca	33	17	64	1
Na	23	11	0	2
K	6	3	1	7
total	400	200	127	190