Magma to Rock: M&M's, CIPW Norms, and MELTS

Lab 3: M&M Magma Chamber

Basis for the lab:
*Karl Wirth's advanced M&M Magma Chamber exercise
-http://serc.carleton.edu/NAGTWorkshops/petrology/teaching_examples/24646.html

Skills / knowledge needed by the students:
*lab 1 in the course names a broad range of igneous rocks with the IUGS classification
*lab 2 works through a sequence of phase diagrams (modified from Winter's single, binary, and ternary exercises) and addresses fractional vs. equilibrium crystallization
*Harker diagrams were covered in the lecture about various types of diagrams frequently used in conjunction with igneous chemistry data
*Bowen's reaction series was covered in the Physical Geology class and the students may or may not have used Karl Wirth's introductory M&M Magma Chamber exercise
-http://serc.carleton.edu/NAGTWorkshops/gsa03/activities/2028.html
*all of the students had at least a minimal introduction to Excel from another class

Goals:
*give students a solid understanding of fractional crystallization that they will be able to refer back to over the course of the semester
*reinforce use of Harker diagrams to analyze igneous systems
*reinforce IUGS classification of igneous rocks
*give students practice with manipulating data in Excel
*shift from lecture-based to learner-centered teaching

Modifications to the original Wirth lab:
*I introduce the lab by having the students draw Bowen's reaction series on the board where each student writes the name of one mineral in the appropriate location and then passes on the chalk/marker to the next student
*I purposely divide the class into 3-4 person groups -- with more students, I find they do not all equally participate in the activity
*I don't ask the students to draw a circled area on a large white sheet of paper & mix all of the M&Ms together to start; instead I ask the students to divide their poster board into 10 approximately equal layers (see pictures below for example)
*students are handed a data sheet and asked to construct the an equivalent Excel spreadsheet on their own
*I encourage the students to discuss their Analysis and Reflection answers with their classmates before handing in their own individual write-ups
*change some wording to clarify points / match vocabulary used in my lectures

Caveats (which the students will hopefully identify in the reflection section):
*no water or hydrous minerals included
*very limited solid solution (only plagioclase & olivine)
*some missing phases (e.g. opx, apatite, rutile)
*unrealistically high modes of oxide minerals at some points

Sucesses & Pitfalls:
*students LOVE this lab (even though it involves Excel, which is not their favorite computer activity)
*when discussing layered mafic intrusions two months later, the students immediately remembered this lab and how it applied to the topic at hand
*even with students who don't traditionally work well together, this lab works fine, but group dynamics varied quite a bit every time I've used this activity
*some groups choose to cluster the M&Ms by cation and others by mineral (see below); both methods illustrate certain parts of questions in the reflection portion of the lab, so I usually just allow both to go forward, but it makes it harder for one group to directly compare with another using the other method
*if you count the M&M's wrong, it may cause you great amounts of grief
*this may be difficult to use with large classes simply to the massive number of M&M's you would have to purchase & count out

Options:
*count out all of the M&Ms prior to class -- saves quite a bit of hassle
*took students 2-3 hours to construct magma chamber, produce Harker diagrams, and answer questions, but <50 minutes just to construct the magma chamber
-one lab period for entire exercise, but they'll either need to bring laptops or have access to computers
-first part can be done in the classroom and the analysis / reflection assigned as homework or worked on during a 2nd class
*addition of two steps to demonstrate magma mixing and assimiliation
-works best when students originally produced >2 chambers
-with 3 chambers, I do magma mixing, assimilation of a limestone, and assimilation of a shale
-students work through the entire fractional crystallization exercise before going back to remove steps 7-10 to work through either the mixing or assimilation directions
-this takes ~45 minutes, so it may be a squeeze in a 3 hour lab
-compositions I use for these options:

Rock type	*starting magma (Wirth)*	*added magma (adapted from Wirth)*	*limestone (Gao et al., 1998)*	*shale (Shaw, 1956)*
SiO2	46.00	46.00	13.00	61.37
TiO2	1.25	1.00	0.06	0.98
Al2O3	17.75	18.00	2.22	19.25
FeO	9.50	9.50	0.85	6.91
MgO	10.00	10.00	14.89	2.03
CaO	8.25	8.50	31.13	0.46
Na2O	5.75	5.50	0.37	1.30
K2O	1.50	1.50	0.72	3.58
total	100.00	100.00	63.24	95.88

Gustavus 2010 Petrology class: Sam, Andi, and Todd (left to right) who chose to group by element

Gustavus 2010 Petrology class: Jonathan, Carson, and Mike (left to right) who chose to group by mineral

Prelab 4: CIPW Norm Calculations

Basis for the lab:
*James Brophy pre-lab assignment for his 2001 Magmatic Processes MELTS lab

Skills / knowledge needed by the students:
*lab 1 in the course names a broad range of igneous rocks with the IUGS classification
*lab 3 - fractional crystallization via M&M's lab
*AFM diagrams (needed for lab portion) covered in the igneous chemistry plot lecture
*conversion from wt% oxide to molecular proportions was covered and practiced in mineralogy

Goals:
*to have the students realize that the M&M model is simplistic
*start the students considering how magma composition affects the modal mineralogy
*reinforce the studetnts skills at converting from wt% oxide to molecular proportions
*reinforce IUGS classification of igneous rocks
*successfully calculate a CIPW Norm by hand

Layout of assignment:
*calculate BY HAND the CIPW Norm of the five given compositions (see below)
*for each composition, determine what the IUGS name would be
*reflection questions:
-compare & contrast the norm calculated for composition #1 with the minerals that we chose to crystallize out for the M&M lab
-compare & contrast the norms calculated for composition #2-5 and try to come up with several general statements about why the normative minerals are different for each composition
-using your book and the internet, what are the four constraints on the CIPW norm?
*discuss your results and the reflection questions with your classmates before starting lab 4

Sucesses & Pitfalls:
*this is probably the activity the students wish most I would leave out of the course -- I would gladly take suggestions on how to make norms more interesting!
*once they have worked there way through both this pre-lab and the MELTS lab, the students tend to understand the controls on what minerals may occur in an igneous rock
*in the last round, I walked through the majority of the first calculation (for the M&M basalt) with the students -- it cut down on the frustrated head-banging
*there are a number of resources available online that will calculate the norm for the students -- difficult to tell if they did it by hand or not
*I believe by calculating the norm by hand, the composition control on mineralogy is reinforced

Options:
*none of the magma compositions are really "wild" and don't result in some of the stranger normative minerals; I've considered changing one magma to be stranger
*allow the students to use a program to calculate the norm instead of by hand

	1	2	3	4	5
SiO2	46.00	45.50	49.50	49.30	50.88
TiO2	1.25	3.44	1.50	1.60	0.72
Al2O3	17.75	15.71	14.60	15.60	18.18
Fe2O3	0.00	3.61	2.50	3.50	2.10
FeO	9.50	8.64	9.40	7.80	6.94
MnO	0.00	0.22	0.22	0.20	0.16
MgO	10.00	5.37	7.10	6.50	7.20
CaO	8.25	9.43	10.80	10.30	11.22
Na2O	5.75	3.47	2.90	2.70	2.36
K2O	1.50	1.38	0.45	0.50	0.54
P2O5	0.00	0.29	0.27	0.30	0.01

1. Basalt from Wirth's M&M lab; use FeO = 8.25 and Fe2O3 = 1.06
2. Alkali Basalt, St. Helena Island
3. Continental Flood Basalt, Columbia River Plateau
4. Contental Flood Basalt, Columbia River Plateau
5. Hi Alumina Basalt, New Hebrides Arc

Normative minerals	Weight % Norm				
	1	2	3	4	5
Quartz	0	0	0	0.95	0
Plagioclase	25.89	46.58	50.03	51.82	57.39
Orthoclase	8.86	8.16	2.66	2.95	3.19
Nepheline	22.19	3.25	0	0	0
Leucite	0	0	0	0	0
Kalsilite	0	0	0	0	0
Corundum	0	0	0	0	0
Diopside	18.42	17.61	21.57	16.39	14.77
Hypersthene	0	0	11.5	17.39	19.62
Wollastonite	0	0	0	0	0
Olivine	20.84	9.03	6.39	0	0.91
Larnite	0	0	0	0	0
Acmite	0	0	0	0	0
K2SiO3	0	0	0	0	0
Na2SiO3	0	0	0	0	0
Rutile	0	0	0	0	0
Ilmenite	2.37	6.53	2.85	3.04	1.37
Magnetite	1.54	5.23	3.62	5.07	3.04
Hematite	0	0	0	0	0
Apatite	0	0.67	0.63	0.7	0.02
Zircon	0	0	0	0	0
Perovskite	0	0	0	0	0
Chromite	0	0	0	0	0
Sphene	0	0	0	0	0
Pyrite	0	0	0	0	0
Halite	0	0	0	0	0
Fluorite	0	0	0	0	0
Anhydrite	0	0	0	0	0
Na2SO4	0	0	0	0	0
Calcite	0	0	0	0	0
Na2CO3	0	0	0	0	0
Total	100.11	97.06	99.25	98.31	100.31

Lab 4: MELTS

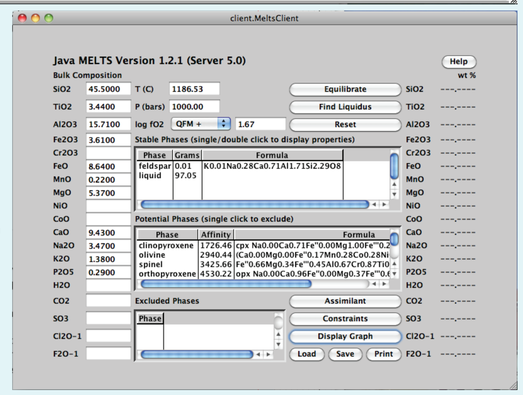
Basis for the lab:
*James Brophy 2001 Magmatic Processes MELTS lab

Goals:
*give students a solid understanding of how magma composition affects the modal mineralogy
*reinforce use of AFM diagrams to analyze igneous systems
*reinforce IUGS classification of igneous rocks
*shift from lecture-based to learner-centered teaching

Layout of the assignment:
*students explore the MELTS applet via some leading questions
*perform the following calculations using MELTS using the same five basalt compositions as for the prelab:
-find liquidus T & 1st mineral to crystallize at 1 kbar and QFM for each basalt; compare new vs. original liquid composition
-find liquidus T & 1st mineral to crystallize at 1 kbar and HM / NNO / IW for each basalt
-find liquidus T & 1st mineral to crystallize at QFM and 5 / 10 / 15 / 20 kbar for each basalt
-find liquidus T & 1st mineral to crystallize at 1 kbar, QFM, and H_2O = 0.25 / 0.50 / 0.75 / 1.00 wt % for each basalt
-for each basalt, crystallize the entire magma in 25 C increments at 1 kbar, QFM, and H_2O = 0.00; plot all five liquid composition paths on an AFM diagram and record the sequence of minerals that crystallize at each step
-choose one basalt from #2-5 for the following section:
*crystallize the entire magma in 25 C increments at QFM, H_2O = 0.0, and 5 / 10 / 15 / 20 kbar
*crystallize the entire magma in 25 C increments at 1 kbar, H_2O = 0.0, and NNO / HM / IW
*crystallize the entire magma in 25 C increments at 1 kbar, QFM, and H_2O = 0.25 / 0.50 / 0.75 / 1.00 wt %
*reflection questions:
-what is the affect of fO_2 / H_2O / pressure on the liquidus temperature and mineral crystallization sequence?
-compare and contrast your results from 1 kbar, QFM, and H_2O = 0.00 with the CIPW norm
-is there a pattern that relates the path of an AFM diagram to the starting composition of a magma?

Sucesses & Pitfalls:
*the Java applet means the students can attempt this lab on their own computers or on any lab computer
*students may become frustrated if the applet starts to behave slightly strangely
*once they have worked there way through the MELTS lab, the students tend to have a reasonable understanding about why norms & Bowen's reaction series are too simplistic (though this may make them question WHY I had them calculate a norm...)
*I've used the reflection questions in a modified format on Petrology exams and the classes as a whole have done fairly well, which I taken as a sign that they understand the material (not addressed in lecture beyond answering questions that arose from the reflection)

Options:
*if you have a computer lab with Macs / UNIX boxes, you could download MELTS and run it on your own machines -- the applet can freeze, the internet connection is occasionally questionable, and some of the tools are hard to access in the applet
*some of the students chose to download MELTS onto their personal machines
*I occasionally feel like I could reduce the number of steps and get similar results...



Above: Mac version of MELTS (requires X11 to run); complete version does require students to understand the program better since there are a wider range of variables that can be modified

Right: Java applet of MELTS as seen on a Mac; no software required beyond a Java plugin (that most browsers already have) & internet access