

Petrography and Petrogenesis of a Mid-Ocean Ridge Lava Suite
Answer Key and author comments
 Matthew C. Smith
 University of Florida Department of Geological Sciences

Figure 5: Photomicrographs of example textures.

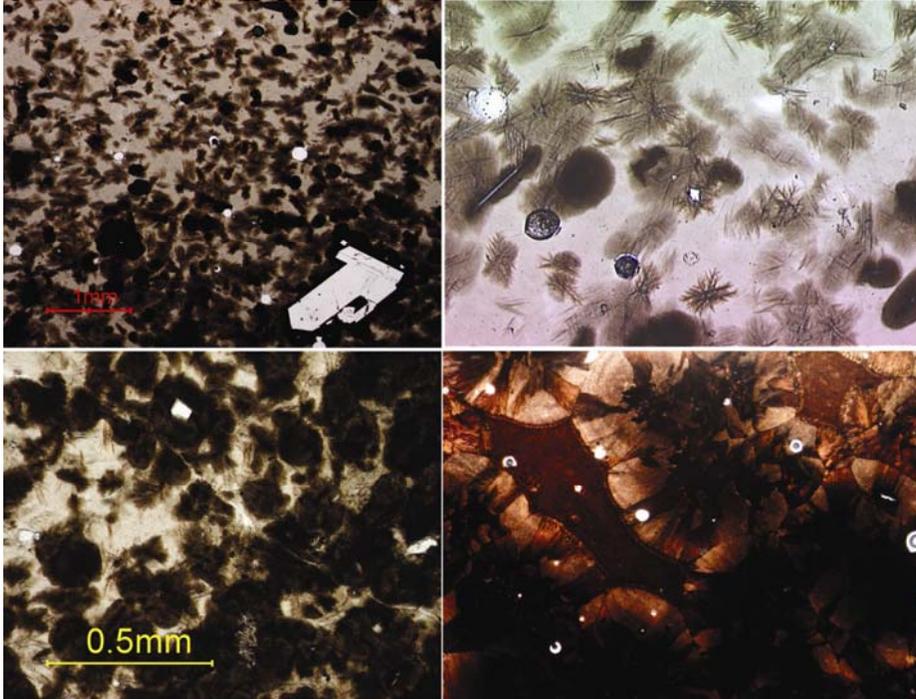


Figure 5a. (Top left) Quenched microlites in glass (Top Right) High magnification view of the top left photo. (Bottom Left) Quenched glass and microlites of plagioclase forming a variolitic texture. (Bottom Right) High magnification view of a variolitic texture.

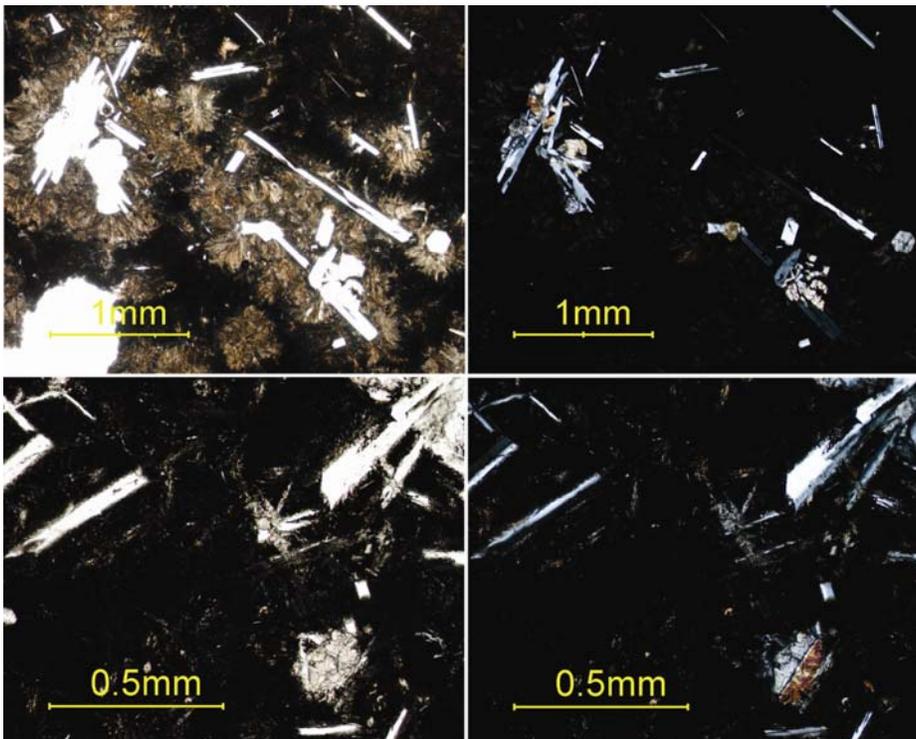


Figure 5b. (Top) Fascicular to variolitic textures surrounding cotectically formed intergrowths of plagioclase feldspar and olivine. Shown in both plain-polarized light (right) and cross-polarized light (left).

(Bottom) FeTi basalt showing cotectic intergrowth of clinopyroxene and plagioclase feldspar. Shown in both plain-polarized light (right) and cross-polarized light (left). Pigeonite is visible in the lower right hand corner as a twinned grain.

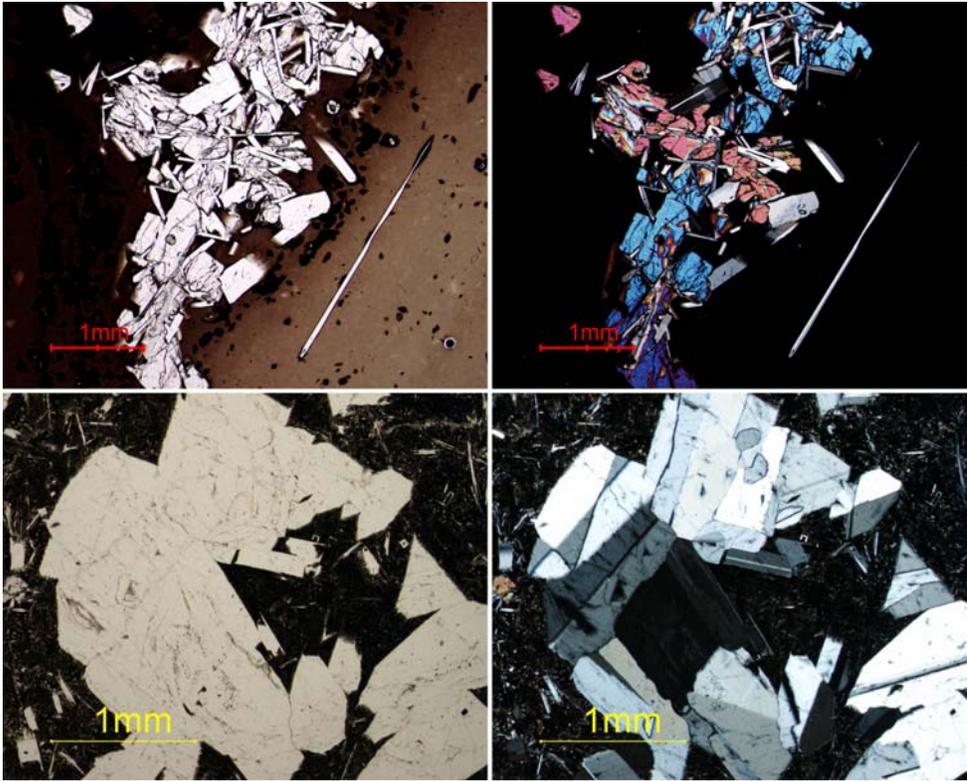


Figure 5c. (Top) Crystal clots showing cotectically intergrown olivine and plagioclase in both plane polarized light (left) and cross-polarized light. Olivine grains show embayments and grain shape indicative of resorption and disequilibrium.

(Bottom) Glomeroporphyritic crystal clots of plagioclase feldspar. Plain-polarized light shown at left and cross-polarized light shown at right.

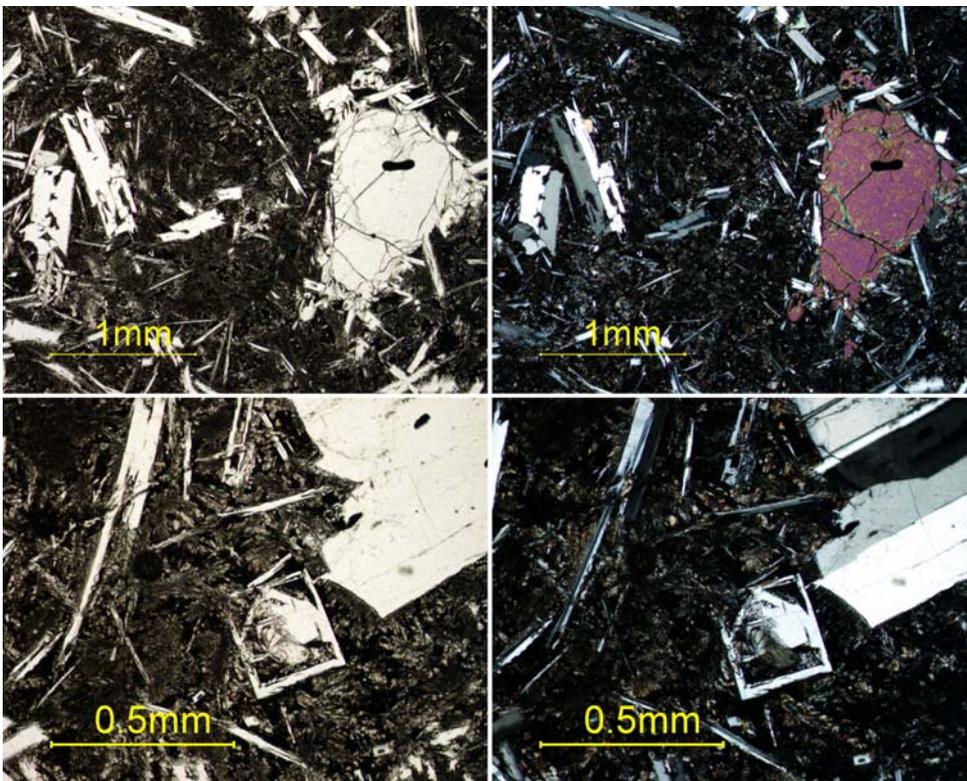


Figure 5d. (Top) Olivine and plagioclase feldspar showing minor disequilibrium textures. Plain-polarized light shown at left and cross-polarized light shown at right.

(Bottom) Swallowtail and skeletal plagioclase feldspar indicative of rapid undercooling and quench. Groundmass shows a fascicular to variolitic texture. Plain-polarized light shown at left and cross-polarized light shown at right.

Disclaimer: The answers and comments included here are the result of examination of several thin-sections from each sample and limited pilot testing in our classroom. Textures vary slightly among thin-sections of the same sample

Exercise: Thin-section Analysis of lavas from the southern Juan de Fuca Ridge (JdFR).

Comment: Students should work under the assumption that these samples could be a genetically related suite of lavas. All (except DR12a-12) are from a limited area of ridge axis and related to relatively recent magmatism. DR12A samples were dredged from the Vance segment (the next segment to the North) and has been used as a parent composition in modeling the petrogenesis of Cleft segment MORB [Smith et al, 1994]. The range of compositions/lava types we have included is somewhat unusual for a mid-ocean ridge environment, having only been documented in 4-5 other MOR locations. However, extremely fractionated tholeiitic lava series are common on oceanic islands such as Iceland where the crust is thicker than normal oceanic crust and detailed field work is easier to do than on the seafloor. This suite of rocks includes MOR lavas that would be classified as basalt, ferrobasalt, FeTi basalt, ferroandesite (or icelandite), and tholeiitic dacite.

Samples

JdF90-DR12A-2

ALV-2268-1

T179-G7 or G8

JDF-90-DR13-3

T178-G4

T735-G12

Note that it can be very useful to first examine and describe the slide macroscopically by putting it on a sheet of white paper. It is generally a good idea to start your examination at the lowest magnification and proceed towards higher magnification. When examining the slide microscopically be sure to use both plain- and crossed-polars. Additionally, the provided chemistry can be used as a guide to probable mineral content.

1. ALV-2268-1
 - a. What are the two major microphenocryst phases? Detail the observations you made to draw this conclusion.

The two phenocryst phases are olivine (ol) and plagioclase (pl).

Comment: Students will likely site the twinning, low birefringence and low relief in identifying the plagioclase. Forsteritic olivine is distinguished from augitic clinopyroxene by its optic sign (typically negative) and 2V angle (v. high). By comparison, augitic clinopyroxene (cpx) is biaxial positive with a moderate 2V angle. Other distinctions include body color in plain-polarized light (ppl) and birefringence, though the distinctions between cpx and ol are often not great. Students commonly

confuse these two mafic minerals in fresh basalts unless they take an interference figure. It is also worth noting to students that if a sample has an abundance of mafic crystals they are more likely to be cpx than ol because only the most primitive of basalts (e.g. picrites) have more than ~20% modal olivine.

- b. Several phenocrysts show a texture of cotectic (simultaneous) crystallization. Find an example of this and draw it.

For examples of cotectic textures see Figure 5. Drawings should indicate intergrowth of mineral grains. If students are inexperienced in petrography they will likely need some guidance in what to look for in analyzing the textures in the samples.

- c. Examine the overall population of phenocrysts. Which of these phases do you think may have started crystallizing first? Explain the observation(s) that led you to this conclusion. (Tip: Consider differences in crystal morphology the associations in which crystals occur relative to one another when trying to determine the sequence of crystallization.)

Plagioclase formed first (was the liquidus phase) followed by plagioclase+olivine.

Comment: In this sample, olivine only occurs as a microphenocryst phase together in association with plagioclase. Evidence of cotectic intergrowth for these phases is abundant as are quench textures indicating they were forming at the time of eruption. Plagioclase occurs (rarely) as a larger solitary phenocryst phase (or in small glomeroporphyritic clusters; see Figure 5c). Students will likely site this or note the larger plagioclase grains in establishing it formed first. Students may have to look around for one of the larger plagioclase crystals. They are typically visible macroscopically if one sets the slide on a piece of white paper.

- d. Examine the groundmass texture. You may want to increase the light intensity to get a good view. Describe (draw) and identify the most prevalent texture you observe.

Students should site some level of quenched texture. Degree of quenching varies from place to place within the slide and can range from nearly pure glass to varying degrees of fascicular to variolitic (often called spherulitic in more felsic rocks) texture (see Figure 5). Most slides are oriented to capture some part of the glassy surface of the lava flow.

Comment: In our pilot study some students became confused by the gradational nature of these groundmass textures, fixating on how to unambiguously classify them. Classification of the textures should not be the focus. You may want to point out that basalts are more typically holocrystalline (or nearly so) and merely detecting quench-related textures in the groundmass and microphenocryst assemblage provides information about the environment of lava emplacement and the phases crystallizing from the liquid (glass) at the time of eruption.

2. JDF-90-Dr12a-2

- a. Examine the groundmass mineral phases and matrix (when examining the groundmass, you may want to intensify the transmitted light or engage the condenser lens and also utilize medium to high magnification). Describe and draw any textural features that are indicative of rapid quenching of this lava.

As above.

Comment: You may wish to omit this question if your sample 2268-1 illustrates good examples of quench textures. However, under medium to high magnification inspection of the groundmass reveals plagioclase microlites intergrown with a fine grained mafic mineral (ol). This observation can help with part C.

- b. This sample only has one phenocryst phase. What is it?

Plagioclase

- c. Olivine occurs as a fine-grained groundmass phase. Is the sequence of crystallization in this sample consistent with the sequence you determined for sample ALV-2268-1? Why or why not?

Yes. Plagioclase is the only phenocryst phase. The groundmass has both olivine and plagioclase. If these lavas are genetically related the interpretation is consistent with a plagioclase then plagioclase+olivine crystallization sequence.

Comment: If students don't find the large plagioclase grains in the previous sample (2268-1), this sample provides a clue to the proper crystallization sequence.

3. T179-G7, 8 or 10: This MORB is composed primarily of three silicate mineral phases, opaque minerals and glass (both of the latter as part of the groundmass).
 - a. Identify the three silicate phases that occur as phenocrysts or microphenocrysts. You may need to work a bit to distinguish the two mafic phases from one another. Be sure to note the observations you made to correctly identify the phases; an interference figure may be diagnostic in distinguishing the two mafic phases. (Tip: The best interference figures are seen in grains that don't change their appearance and color greatly with stage rotation in cross-polars. Look for a grain that is big enough and has low-order interference colors. Your high power objective should be fairly well centered to get a good interference figure on a small grain.)

Olivine, augitic clinopyroxene, and plagioclase all occur as phenocryst/microphenocryst phases. See above comments re: distinguishing cpx from ol.

- b. Describe the textural relationship(s) that exist between the phenocryst phases? What might you infer about the relative timing of crystallization of these phases?

All show evidence of simultaneous crystallization

- c. Describe and draw any textural features that are indicative of rapid quenching of this lava.

See above comments

Comment: This question is repetitive of others and may be skipped if desired.

- d. How does the crystallinity and relative abundance of phenocrysts in this sample compare to that of JDF-90-DR12a-2? What might you infer about these two rocks from your observations? (Hint: think pre-eruption cooling history, not so much post eruption cooling history. You might also consider how the chemical compositions of these two samples differ, and a possible cause of that difference.)

The sample has more abundant phenocrysts/microphenocrysts. Students may note this concluding that this sample has cooled and crystallized more.

Comment: This sample also has a lower MgO content than DR12A-2, indicating a greater degree of chemical fractionation; a concept introduced later in this investigation.

4. T735-G12: This rock is also from the Juan de Fuca Ridge, but it is quite rare and unusual. Examine the major element chemistry in Table 1.
 - a. Classify the rock type for this lava using Figure 6 and the given rock chemistry.

Dacite – but it should be pointed out that these types of “dacites” are significantly different from those typically associated with arcs. In particular the anhydrous mineralogy should be noted.

- b. Would you expect to find olivine in this rock? Explain?

Students' answers will vary. Noting the high silica content and low MgO content of this rock, students will likely suggest that olivine would not be found (based on simple understanding of magma crystallization, e.g. Bowen's Reaction Series), or, if found, will be in a state of disequilibrium (showing resorption features).

Comment: Note: This sample does contain olivine, and if students have examined the slide before answering the question their answers may reflect this. The olivine in this dacite, however, is fayalitic not forsteritic as those previously viewed. If students are familiar with binary peritectic diagrams this question is an opportunity to examine the

MgO-SiO₂ system. The ternary system discussed below includes a peritectic (reaction) point.

- c. Describe the mineralogy of this lava. Using optical techniques, try to determine the composition of plagioclase present in this sample. Compare this plagioclase composition to the composition observed (or presumed) in one of the previously examined basalt samples. (Tip: The Michel-Levy Technique can be used to determine the composition of plagioclase feldspar. A description of this technique can be found in most Optical Mineralogy Textbooks.)

Comment: These dacites are dominated by elongate microphenocrysts of ferroaugite and oxides set in a glassy matrix. More crystalline zones have intersertal glass that has tiny quenched crystallites. Subtrachytic texture is commonly observed and they are uncommonly vesicular for MOR lavas.

- d. Examine the vesicles. How do they compare in size and overall modal percent to the more primitive MORB samples? Are your observations consistent with the chemistry of this rock? Why or why not?

Vesicles are larger and more abundant in this sample compared to previous samples in this suite. This is consistent with the highly chemically-evolved nature of this sample, as the volatiles that formed the vesicles behave incompatibly and increase in abundance with continued differentiation. Most of the dacites have relatively high H₂O contents in the glass and little or no CO₂ indicating that it was CO₂ degassing that created the vesicles.

Comment: MORB typically have low vesicularity due to the low volatile contents of these magmas and the hydrostatic pressure in their eruptive environment (these lavas were erupted at greater than 2 km depth = ~ 0.05 GPa). However, even at these pressures the CO₂ can degas.

- e. Examine the groundmass. Note that overall it appears to be glassier compared to the more variolitic and fascicular textures seen in the basalts. Hypothesize a possible explanation for this observation?

Student answers may vary. Many may site a more rapid cooling and/or different flow morphology (thickness). Some who recognize that felsic volcanics are more commonly glassy than are mafic volcanics may site the high silica content of this sample as a possible explanation.

Comment: High silica content in these lavas increases viscosity and slows chemical diffusion rates, decreasing the rate of crystal formation and increasing the tendency to form glass. This sample demonstrates this and provides an opportunity to discuss these effects with students.

- f. This lava has a number of xenoliths and xenocrysts included in it. Find one (or more, preferably) and examine it. What is the mineralogy of the xenoliths? What do you think these xenoliths represent and where did they originate?

Two populations of xenoliths can be found in the evolved samples. 1). Rounded xenoliths of basaltic composition (mostly ferrobasalts) with chilled margins and finely crystalline interiors comprised of plagioclase and clinopyroxene and 2). Coarse-grained xenoliths/xenocrysts composed entirely of larger crystals, $\geq 1\text{mm}$, with irregularly shaped margins. These xenocrysts of plagioclase and clinopyroxene have “basaltic” compositions rather than crystals that are in equilibrium with the andesitic-dacitic glasses. Crystals of fayalite (high relief, high birefringence, clear), ferroaugite-hedenburgite (moderate relief and birefringence, green), and zircon may also be out of equilibrium with the dacitic glass because they also have rounded and embayed edges suggesting some resorption. However, their composition indicates that they must have crystallized from very evolved and Fe-rich magma.

Comment: Although thin-sections from this sample vary, most include basaltic xenoliths. Xenoliths can typically be found by macroscopically examining the thin section on a piece of white paper

- g. Compare the textures observed in the xenoliths compared to the host rock. Describe each. Also closely examine the texture along the contacts between xenoliths and host rock. Note any observations you make.

Boundaries between the xenoliths of volcanic rock and host rock are crisp and more fine-grained than the interior of the xenoliths themselves, though in places a little disaggregated/irregular. The irregular, fine-grained (quenched?) rims suggest they might have been liquid rather than crystalline when they were incorporated in the evolved melt.

Comment: Ask students why these observations might be important, leading them to the conclusion that the contact texture provides information into the origin of the xenolith (disaggregated crystal mush material, fully solidified rock, melt etc.) and the level to which it may have been assimilated into the host magma.

- h. Hypothesize a possible origin for the xenoliths.

There are a number of reasonable responses: Basaltic rock from the surrounding seafloor, basalt from the crust, basaltic melt that mixed with the dacite magma.

5. Complete full thin-section descriptions for JDF-90-13-3 and T178-G4. Be sure to note the following in your descriptions: phenocryst mineralogy, your best guess of the groundmass mineralogy, the approximate modal % of each phenocryst phase, and any textures indicating disequilibrium, condition/timing of crystallization or post eruptive cooling. Remember, it can be very useful to first

examine and describe the slide macroscopically by putting it on a sheet of white paper. It is generally a good idea to start your examination at the lowest magnification and proceed towards higher magnification. When examining the slide microscopically be sure to use both plain- and crossed-polars.

Comment: The above are suggestions. Guide students to describe the samples in whatever manner is consistent with your course practices and goals.

JdF-90-13-3 is a FeTi basalt (highly evolved basalt rich in Fe and Ti) from the intersection of the JdFR with the Blanco fracture zone. It contains plagioclase, clinopyroxene, rare pigeonite (a low-calcium pyroxene), and abundant oxides (mostly titanomagnetite with lesser ilmenite) making the groundmass appear darker than in most of the previous samples. Photos of this sample as shown in Figure 5b

Sample T178-G4 is a ferroandesite that varies from glassy to variolitic to microcrystalline. In places, flow banding can be seen. It is subtrachytic and slightly phyrlic with phenocrysts of clinopyroxene and lesser plagioclase and pigeonite. It contains rarer xenocrysts of olivine and large plagioclase (both show resorption textures). This sample has been interpreted to be the result of mixing between basaltic and dacitic(?) magmas. Photos of this sample are shown in Figure 5c.

6. The P-T phase diagram in Figure 7 shows the crystallization sequence for primitive basalt. In this kind of diagram, phase relationships of a single starting magma composition (in this case, that of primitive basalt) are investigated as variables of both pressure and temperature.
 - a. Starting from the “all liquid” field of this diagram (a temperature greater than the liquidus temperature), draw a cooling/crystallization path on the diagram for a magma that crystallizes at low pressure (less than 1 GPa), and one at higher pressure. Describe the predicted sequence of crystallization for each cooling/crystallization path.

Crystallization paths should proceed from right to left, possibly angling down if the student presumes the magma is rising in the oceanic crust during crystallization. High-pressure crystallization sequence begins with clinopyroxene on the liquidus, low pressure begins with either olivine (<~0.5 GPa) or plagioclase (between ~0.5 and 1 GPa)

- b. Describe how the crystallization history of a primitive basalt differs in these two different cooling pathways?

The timing of the entrance of the different mineral phases into the crystallizing assemblage differs. Specific differences depend on the paths that students draw.

- c. Using the mineral and textural observations from your thin-sections (and your interpreted sequence of crystallization), at what range of pressures do you think the thin-section samples crystallized? Justify your answer.

Between about 0.5 and 0.75 GPa (to result in the interpreted sequence: plagioclase then plagioclase + olivine, then plagioclase + olivine + clinopyroxene)

7. Figure 8 is the four-component (Anorthite-Forsterite-Clinopyroxene-Quartz) phase diagram projected from the plane of plagioclase saturation [after Walker, 1979]. Plagioclase is assumed to be saturated and crystallizing in all fields. (Note that this is a different kind of phase diagram than that of Figure 7.) In this diagram composition and temperature are the variables and the pressure is held constant. Point A and B represent starting compositions for liquid lines of descent (LLD) discussed below. Points P and E are invariant reaction (P) and eutectic (E) points, respectively.
- a. Draw onto Figure 8 the liquid line of descent that you would expect from magma that crystallizes, starting from either point A or point B. (Draw one LLD from each point.) Describe the sequence of crystallization for each LLD? (Remember, plagioclase is assumed to be crystallizing in all cases on this diagram.)

Liquid lines of descent follow a pathway from the parent melt composition to the cotectic line. That portion of the LLD is defined by a line between the olivine apex and the starting composition. The LLDs continue down the cotectic (controlled by the co-crystallization of ol+cpx (+plag) for composition A) at which point they proceed to point P. Composition A will produce the following crystallization sequence: plagioclase followed by plagioclase + olivine, followed by plagioclase + olivine + clinopyroxene, followed by plagioclase + clinopyroxene + low-Ca pyroxene (pigeonite or orthopyroxene)

Comment: At point P (in either LLD) olivine is on the way out at point P, as it is a reaction point that consumes olivine.

Composition B produces this crystallization sequence: plagioclase followed by plagioclase + olivine, followed by plagioclase + olivine + low Ca-clinopyroxene, followed by plagioclase + clinopyroxene + low-Ca pyroxene (pigeonite or orthopyroxene).

- b. Use the phase relations you observed in the thin-sections to approximate where each of the samples would plot on your proposed liquid line of descent, and plot them on Figure 8. Note that although you may not have found it, the mineral pigeonite (sub-calcic clinopyroxene) occurs in sample JdF-90-DR13-3.

Students should plot their samples along the pathway defined by point A. Locations should be consistent with the observed phenocryst mineralogy and the predicted crystallizing phases on the diagram.

- c. From this information, place the samples in order from most primitive to most evolved.

Dr12-2A, 2268-1, T179-G7 or G8, JDF-90-DR13-3, T178-G4, T735-G12

Comment: Sample T178-G4 is interpreted as a mixed magma and therefore likely may fall off of the predicted LLD. A mix between sample 179-G7 (first one on the cotectic) and T735-G12 (which is the most evolved dacite) produces a composition that falls in the clinopyroxene (plus plagioclase) field, explaining the disequilibrium olivine that is cotectically intergrown with plagioclase. It should be noted, however, that while 179-G7 has been interpreted as a mixed magma, these two other samples have not been modeled as the end members that mixed. Still, this provides an opportunity to qualitatively investigate the petrographic and chemical consequences of magma mixing.

- d. Consider the chemistry and petrography of sample T178-G4; it is a basaltic andesite. One possible petrogenetic origin for this sample could be a mix between a basaltic melt and a silicious melt. Draw a mixing line onto Figure 8 that connects samples T179-G7 and T735-G12. Predict the mineralogy of a sample produced by a mix of these two compositions. How does your prediction compare to the observed mineralogy of sample T179-G4? Hypothesize at least two petrographic observations that might be indicative of magma mixing and found in a sample formed by mixing of these two end-member magmas.

See above comment. Two possible petrographic observations include the resorption of olivine and chemical zoning in plagioclase (and some cpx grains).

8. Using the program Excel® and Table 1, plot the major oxide compositions of your samples against the MgO wt.%, and the total alkali content vs. the SiO₂ wt.%. Then answer the following questions.

Comment: Encourage students, if plotting multiple oxides on one graph, to group oxides according to their overall compositional range onto the same graph. This will minimize the range of the Y-axis scale, increasing students' ability to discern the relative geochemical trends

- a. On most regular Harker diagrams the major oxides are plotted against SiO₂ wt. %. Why is MgO plotted on the x-axis for MORB lava suites instead?

SiO₂ varies very little in the basalts of this suite. In fact in many MORB suites, SiO₂ can decrease a bit before starting to increase after the onset of oxide crystallization. MgO varies more greatly and is a better indication of the extent of magma evolution.

- b. Using your Excel diagrams and the information from your petrographic analysis of the thin-sections, how does MgO change with increasing evolution (differentiation) of the magma?

MgO decreases with increasing degrees of magma chemical evolution.

- c. Describe the manner in which each of the other major oxide concentrations change with increasing chemical evolution of the melt. Hypothesize why these particular trends exist in the data ?

As MgO decreases Al₂O₃ decreases and CaO decrease while K₂O, Na₂O, and MnO increase. FeO and TiO₂ increase in abundance up through sample DR13-3, but then decrease when oxides (mag+ilm) start to crystallize.

Comment: Students may not note the decreasing trend in FeO and TiO₂, as the most evolved samples are not well-connected in geochemical space to the others on the trend (not a lot of intermediate compositions to fill out the trend at this point). However, this pathway is an important part of tholeiitic differentiation trend and students should be encouraged to consider how the chemical trends must have changed if the dacite is related to the basalts via fractional crystallization of a common parent. This activity is intended to introduce chemical evolution via fractional crystallization, and sets up a follow-up exercise in which students use the data presented here in conjunction with data retrieved from the PetDB database and modeled LLDs to investigate chemical evolution of MORB via fractional crystallization and the relationship of those chemical changes to the fractionating mineral assemblages. This follow-on investigation will be posted later this summer.

Table 1

Sample	DR12A-2	T179-G7	2268-1	DR13-3	T178-G4	735-12
¹ Type	DR	TIB	ALV	DR	TIB	TIB
Latitude	45 10.5	44 34.88	44 39.48	44 26.3	44 34.88	44 30.00
Longitude	-130 9.6	-130 21.60	-130 21.37	-130 28.2	-130 24.28	-130 28.42
SiO ₂ (wt.%)	50.1	50.8	50.3	49.9	53.7	66.9
TiO ₂	1.21	2.13	1.58	2.98	1.89	0.786
Al ₂ O ₃	15.7	13.7	14.6	12.6	14.0	12.1
² FeO*	9.39	12.8	10.8	15.4	11.6	7.64
MnO	0.21	0.25	0.20	0.27	0.22	0.15
MgO	8.23	6.43	7.47	5.17	4.89	0.585
CaO	12.5	10.7	12.4	9.74	8.82	3.41
Na ₂ O	2.33	2.88	2.43	2.98	3.29	4.55
K ₂ O	0.08	0.16	0.10	0.22	0.49	1.16
Total	99.7	100.1	99.9	99.2	99.3	98.6

notes:

1. Dr=sampled by dredge, ALV=sampled using the submersible ALVIN, TIB=sampled using the ROV Tiburon

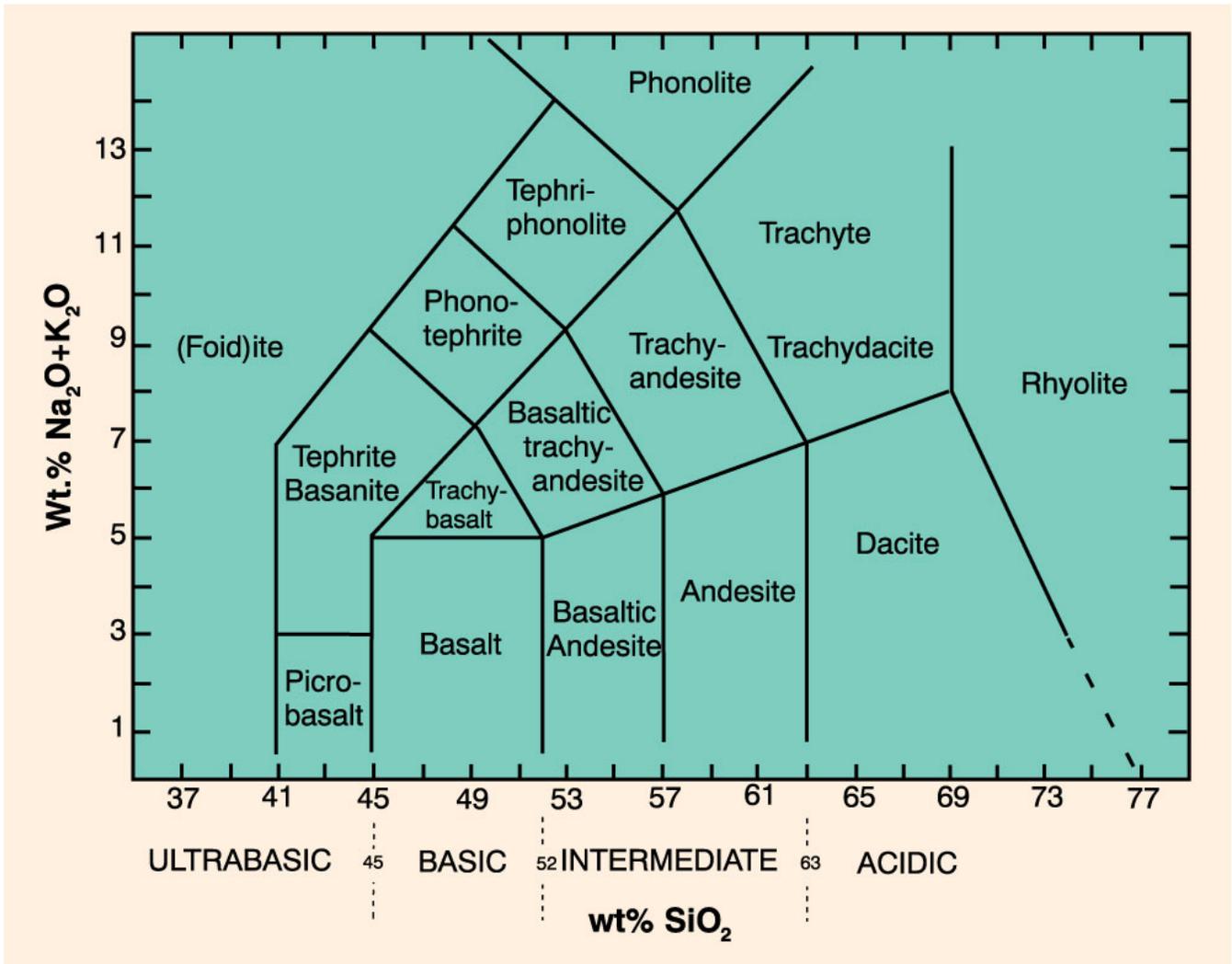


Figure 6. Total alkali vs silica classification diagram (IUGS Classification)

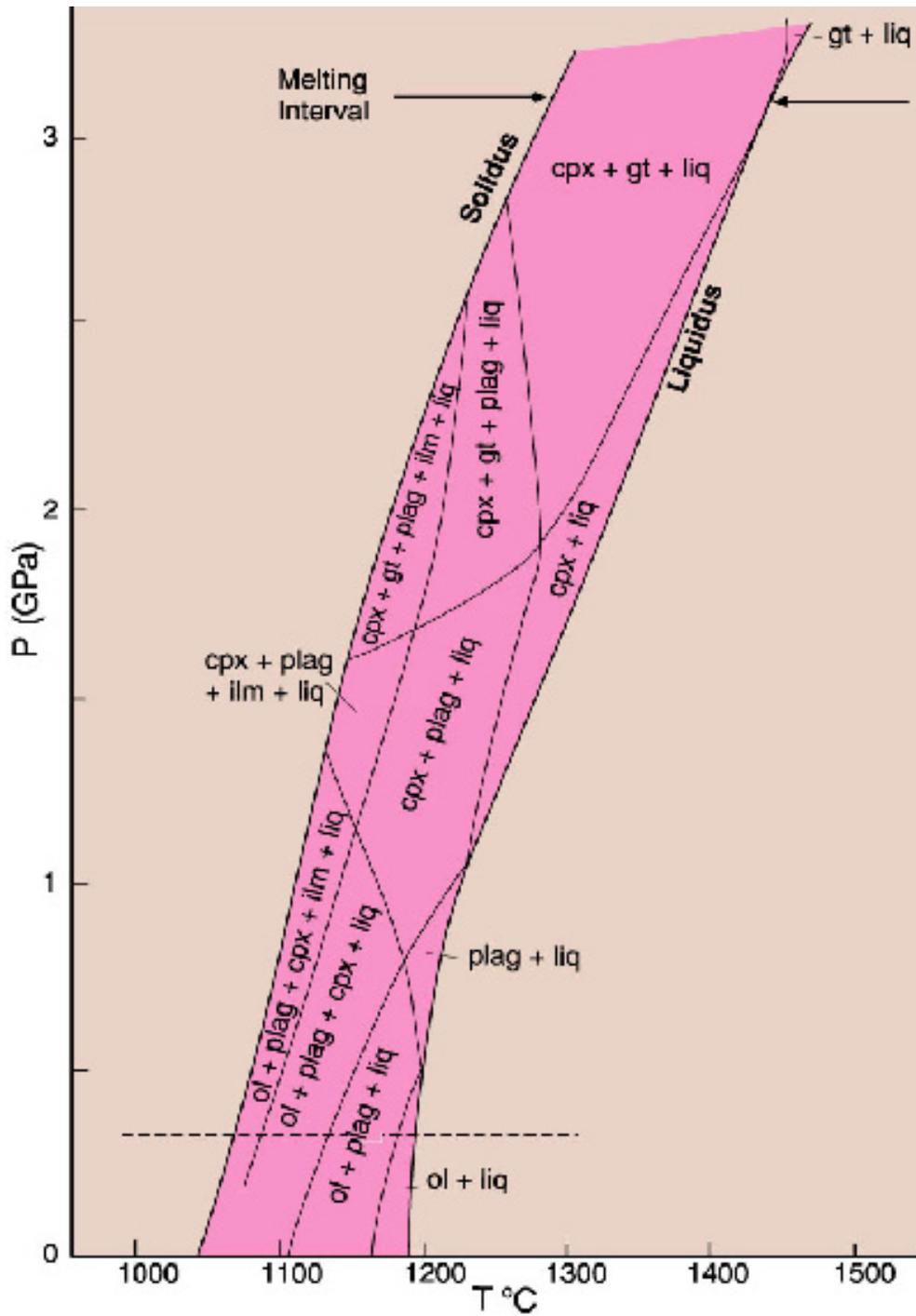


Figure 7. Pressure-Temperature phase diagram for crystallization of a Primitive MORB (composition is a constant in this diagram). [after Thompson, 1973]

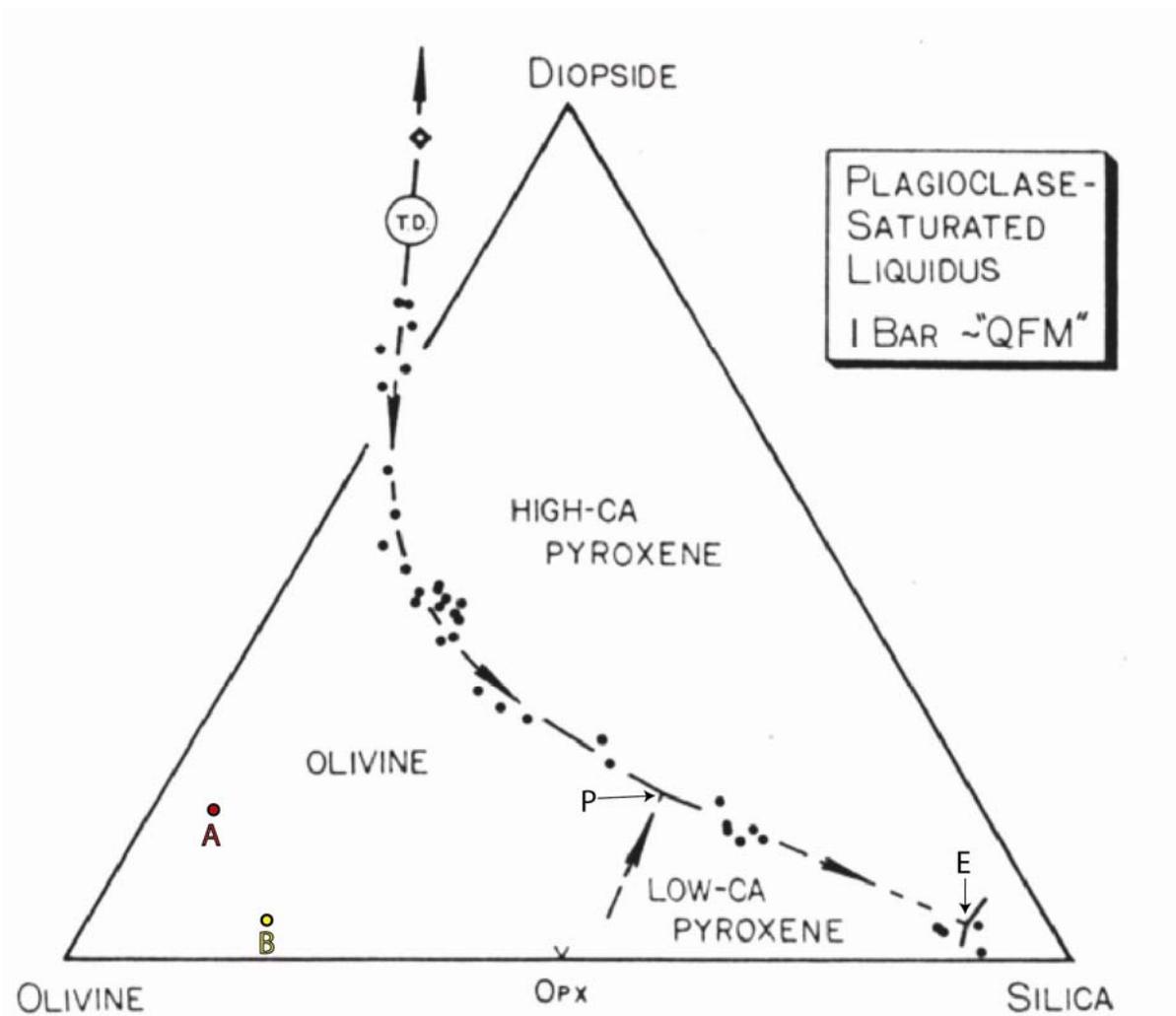


Figure 8. Diagram of the olivine-plagioclase-quartz-augite quaternary system, projected from the plane of plagioclase saturation onto the plane Olivine-quartz-augite [Walker et al., 1979]. System is plotted in mole components. Points A and B are starting compositions referred to in the text. Point P is a peritectic point in this system while Point E is a eutectic point. Note that since this publication of this diagram refined (and slightly more complex) phase-relations have been determined for this system and published (see Grove and Bryan, 1983, for example). This older version was chosen for ease of interpretation, however, more recently determined phase relations are used in modern research.