The use of visualization and sketches of thin sections to encourage a better understanding of phase diagrams: Binary and ternary phase diagram exercises

Solutions

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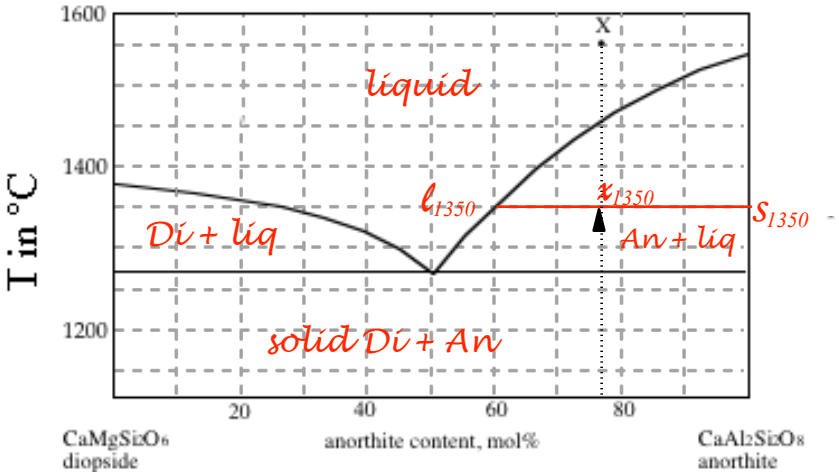
Simple eutectic phase diagram exercise
Igneous and Metamorphic Petrology



1. Label the fields and the eutectic and peritectic point(s) on this diagram. All of the following questions refer to composition X.

2. What is the first phase to crystallize from composition X?

   Anorthite

3. At what temperature does the first crystal form?

   approximately 1450°C

4. What is the liquid composition at T=1500°C?

   approximately 77% An, 23% Di

5. What is the liquid composition at T=1350°C?

   An_{60}

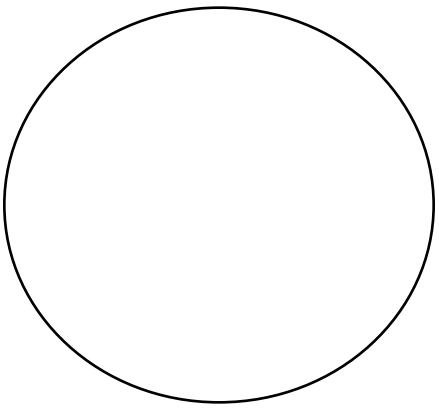
6. What is the solid composition at T=1350°C?

   100% Anorthite

7. What percent solid is present at T=1350°C?

$$\%\ solid = \frac{\overline{\ell_{1350} x_{1350}}}{\overline{\ell_{1350} s_{1350}}} \quad or \quad \%sol = \frac{1.4mm}{3.25mm} = 43\%$$

8. What would the thin section look like if you could freeze it at T=1350°C? Draw a picture below (label minerals and use colored pencils if necessary).



students should show approx. 43% euhedral (lath-shaped) plagioclase grains with a matrix of glass (of An_{60}).

9. How many degrees of freedom does the system have when T=1500°C?

f = c-p+1 (only varying T); f = 2-1+1= 2 (T and x)

10. How many degrees of freedom does the system have when T=1350°C?

f = c-p+1; f = 2-2+1= 1 (T OR x)

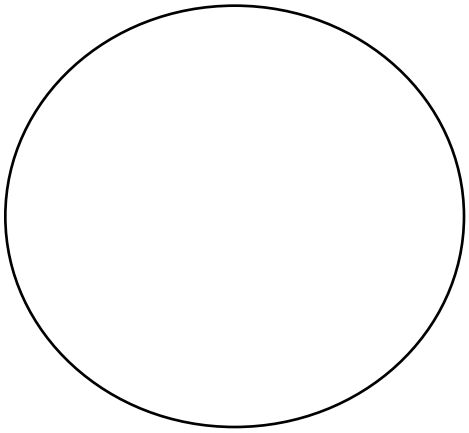
11. What is the composition of the liquid for bulk composition X when the first crystals of solid anorthite begin to form?

approximately 77% An, 23% Di

12. How many degrees of freedom does the system (composition X) have when crystals of anorthite begin to form? What phases are in equilibrium?

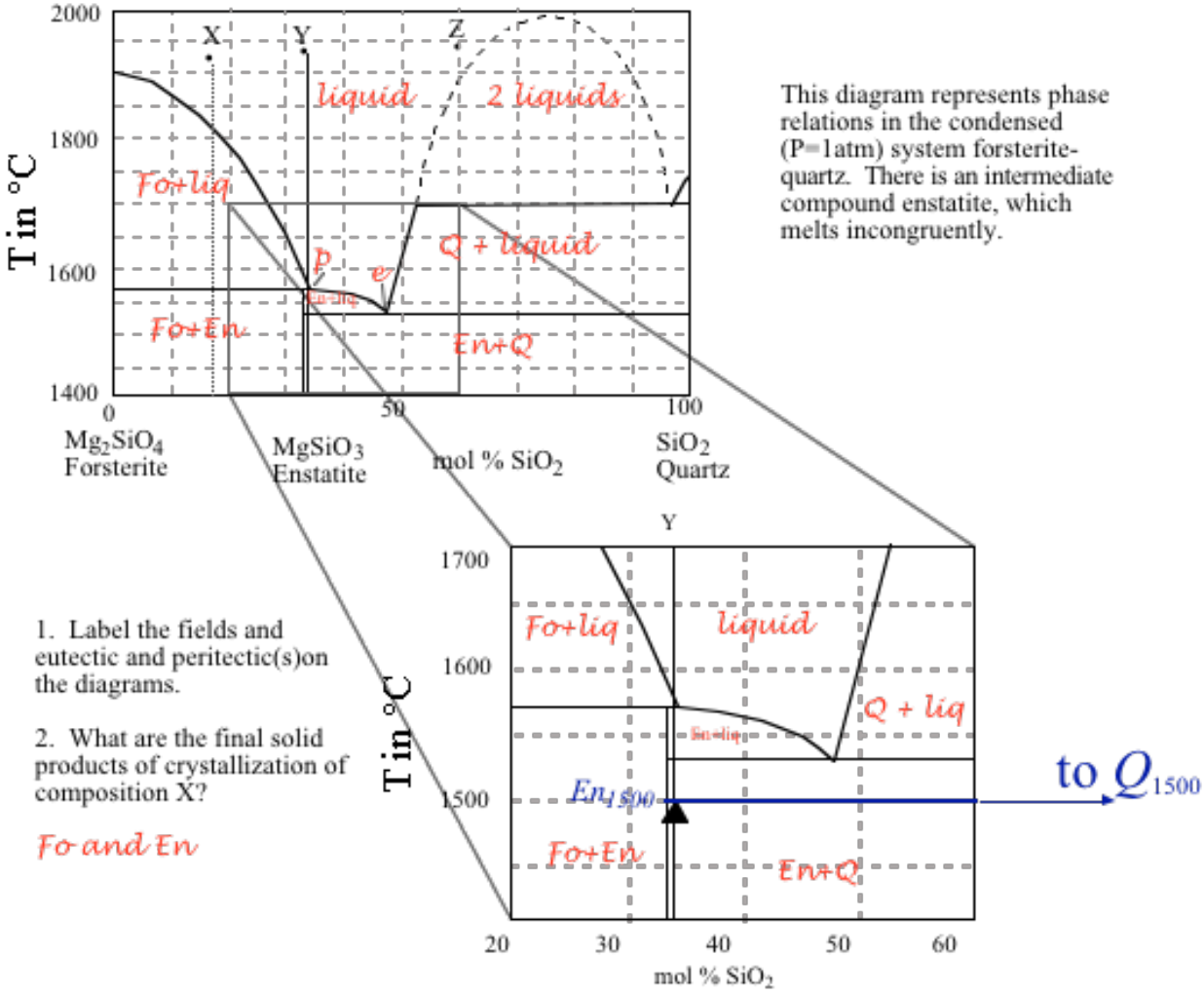
f = 2-2+1= 1; solid anorthite and liquid of composition in # 11

13. What would the thin section look like for a magma with An_{70} at 1200°C? Pay special attention to proportions of phases and crystal morphology.

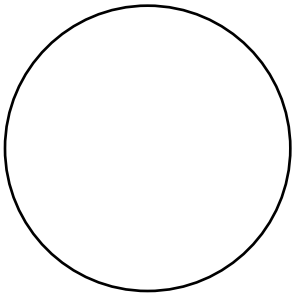


students should show approx. 70% euhedral (lath-shaped) plagioclase grains with 30% sub-anhedral grains of diopside

Simple peritectic phase diagram exercise
Igneous and Metamorphic Petrology



3. If you cooled a magma of composition X to a temperature of 1700°C and then froze it, what would the rock look like in thin section? Draw a picture below (label minerals and use colored pencils!).



Students should draw a thin section that has "euhedral" olivine crystals (63%) and glass (37%)

4. Give the proportions of the solids for composition X when T = 1500°C.

   approximately 1:1 Fo and En

5. Enstatite melts incongruently at 1557°C. What are the products of this incongruent melting? If there is a liquid, give its composition.

   Fo + liquid; liquid is peritectic composition

6. Give the composition and proportions of the phases at equilibrium at T = 1500°C for composition Y.

   En + Q; 1% Q, 99% En or $\%Q = \frac{\overline{En_{1500}Y_{1500}}}{En_{1500}Q_{1500}}; \%En = 100\% - \%Q$

7. What is the variance of the system for composition Y at T=1557°C? What happens to change the variance at this T after some time has elapsed?

   f = 2-3+1= 0; All the En must be converted to liq + Fo (during melting) or all the Fo must react with the melt to become En (during crystallization).

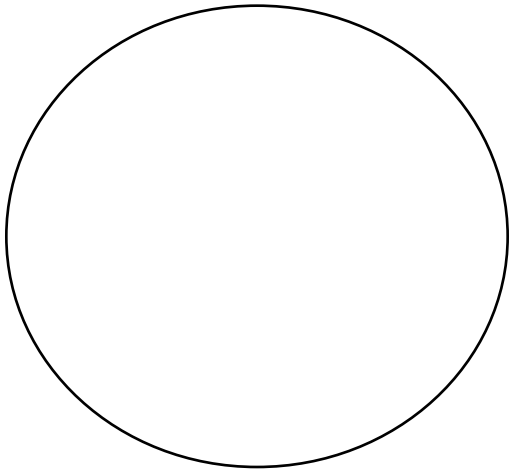
8. What is the first phase to crystallize from a liquid of composition Y? What are the final crystalline products?

   Fo crystallizes 1st; En+Q are final products

9. What are the final crystalline products of the crystallization of Z? At what temperature is the last drop of liquid used up?

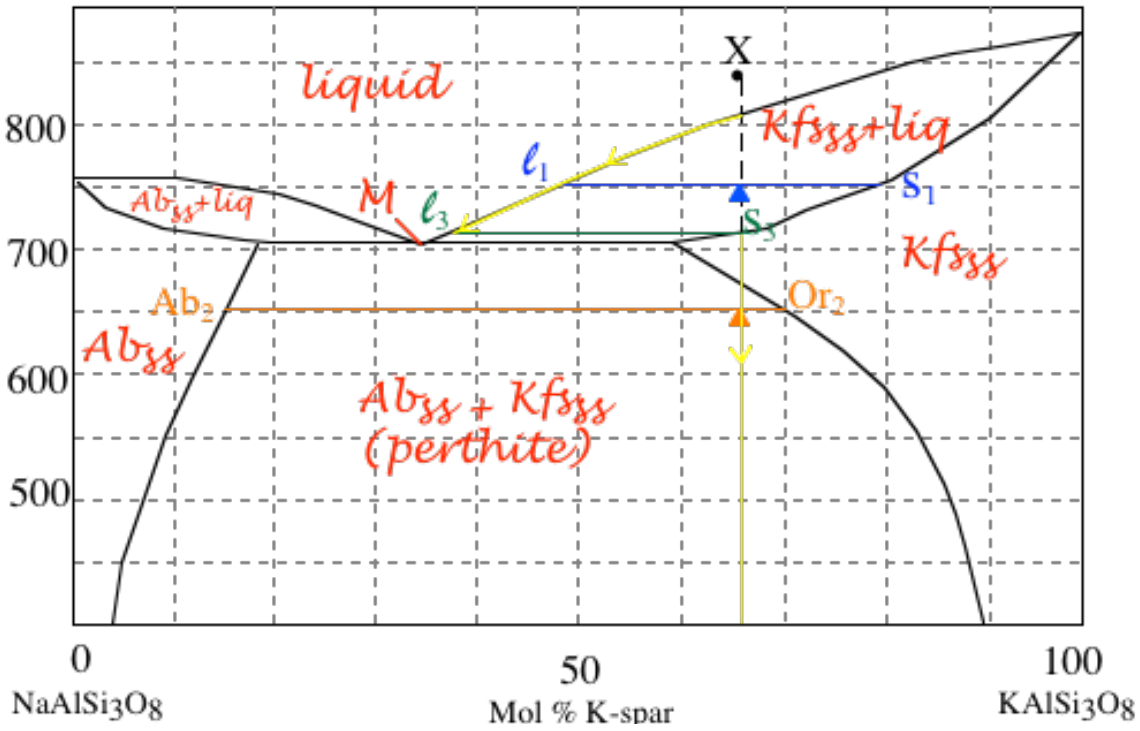
   En+Q are final products; eutectic temperature

10. What phases are in equilibrium at T=1900°C for composition Z? Draw a picture of what a thin section would look like if the magma immediately froze at this point.



two liquids are in equilibrium @ 1900°C. Should draw two mingled (but not mixed) liquids (sometimes students draw a completely black field of view to represent what they would see in XPL.

Alkali Feldspar Phase Diagram
Igneous and Metamorphic Petrology



This diagram represents phase relations at high P_{H2O}.

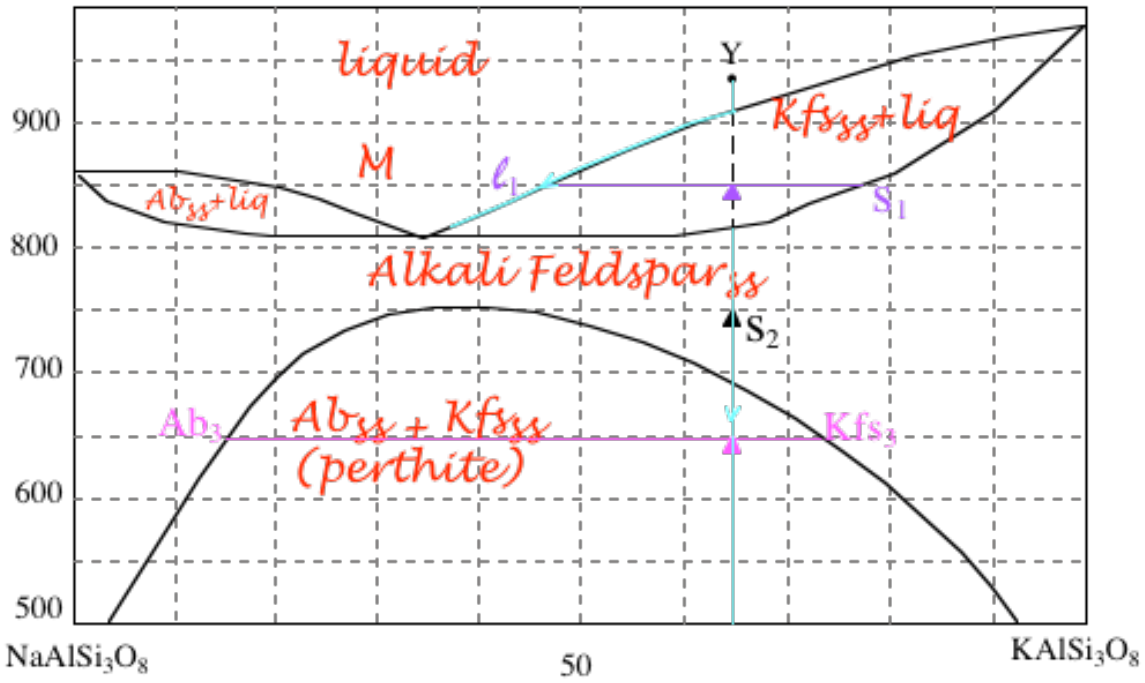
Modified from Philpotts, 1990

1. Label the fields and any peritectic(s) or eutectic(s).

2. Follow the crystallization path for composition X. What is the composition of the solid at 750°C? What is the liquid composition at 750°C? What are the proportions of solid and liquid at 750°C? *See yellow line above for crystallization path. Blue line represents compositions at 750˚C—s_1 is solid composition, l1 is liquid composition; %solid = $\frac{\overline{\ell_1 X}}{\overline{\ell_1 s_1}}$; %liq = 100% - %solid*

3. What phases are in equilibrium for the composition X at 650°C? What are their proportions?
orange line, Ab$_{ss}$ and Kfs$_{ss}$ % Or$_{ss}$ = $\frac{\overline{Ab_2 X}}{\overline{Ab_2 Or_2}}$; % Ab$_{ss}$ = 100% - %Or

4. At what temperature would composition X begin to melt? What is the composition of the melt? How about the solid? *about 715˚C, melt is l_3, solid is S_3*



5. \

6. This diagram represents phase relations at low P_{H2O} (Philpotts, 1990).

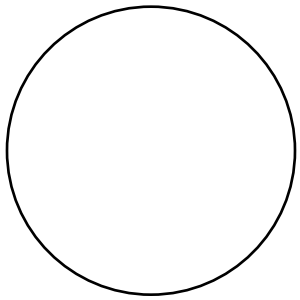
7. Label the fields and any peritectic(s) or eutectic(s).

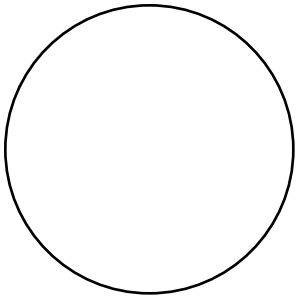
8. Follow the crystallization path for composition Y. What is the composition of the melt at 850°C? What is the composition of the solid? What is the proportion of solid to liquid?
See light blue line above for crystallization path. Purple line represents compositions at 750˚C—s_1 is solid composition, l1 is liquid composition; %solid = $\frac{\overline{\ell_1 Y}}{\overline{\ell_1 s_1}}$; %liq = 100% - %solid

9. What phases are at equilibrium at 750°C? What are their proportions? *See black triangle; only one alkali feldspar solid solution is in equilibrium -- composition is equal to s_2 (or Y) and 100% of system is s_2*

10. What phases are at equilibrium at 650°C? What are their compositions? What are their proportions? *See pink line; two alkali feldspars are in equilibrium -- compositions are equal to Ab_3 and Kfs_3 and their proportions are* $\%Kfs_3 = \frac{\overline{Ab_3 Y}}{\overline{Ab_3 Or_3}}$

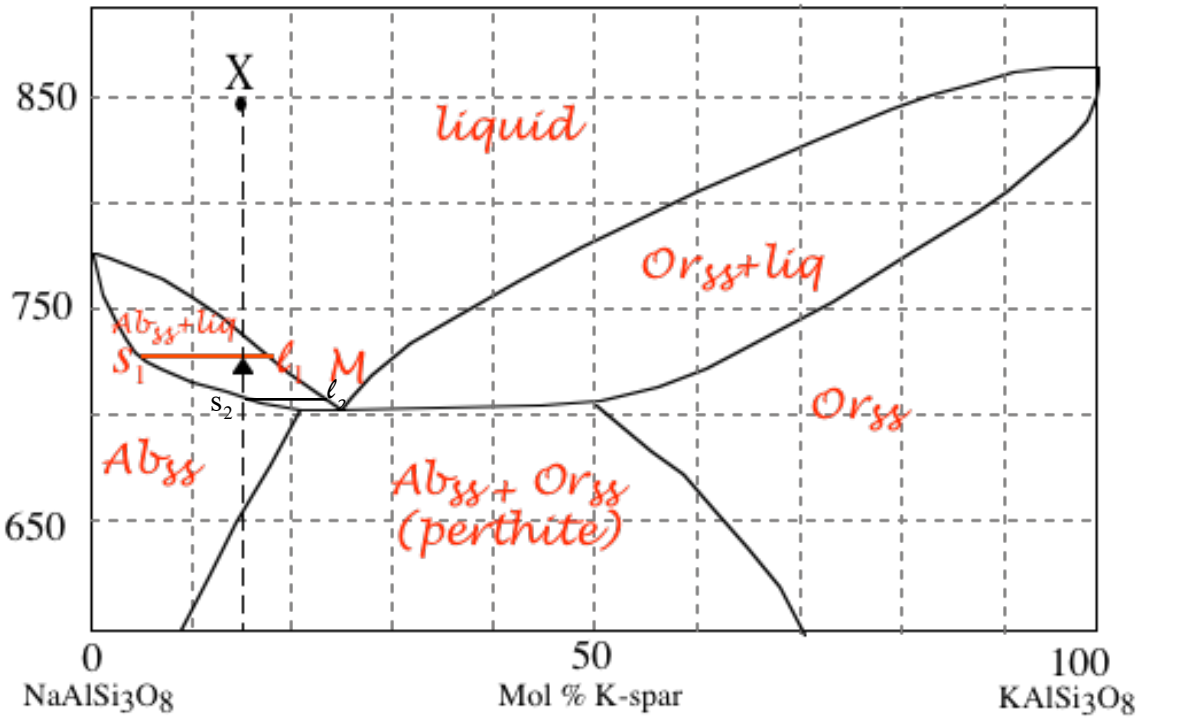
11. Draw a picture of a thin section (crystallized at equilibrium) for X and Y at T= 550°C.





Both should show perthite. Y should have only perthite and X should have perthite but only in some of the crystals.

Alkali Feldspar Phase Diagram
ES 424 -- Igneous and Metamorphic Petrology



Modified from Philpotts, 1990

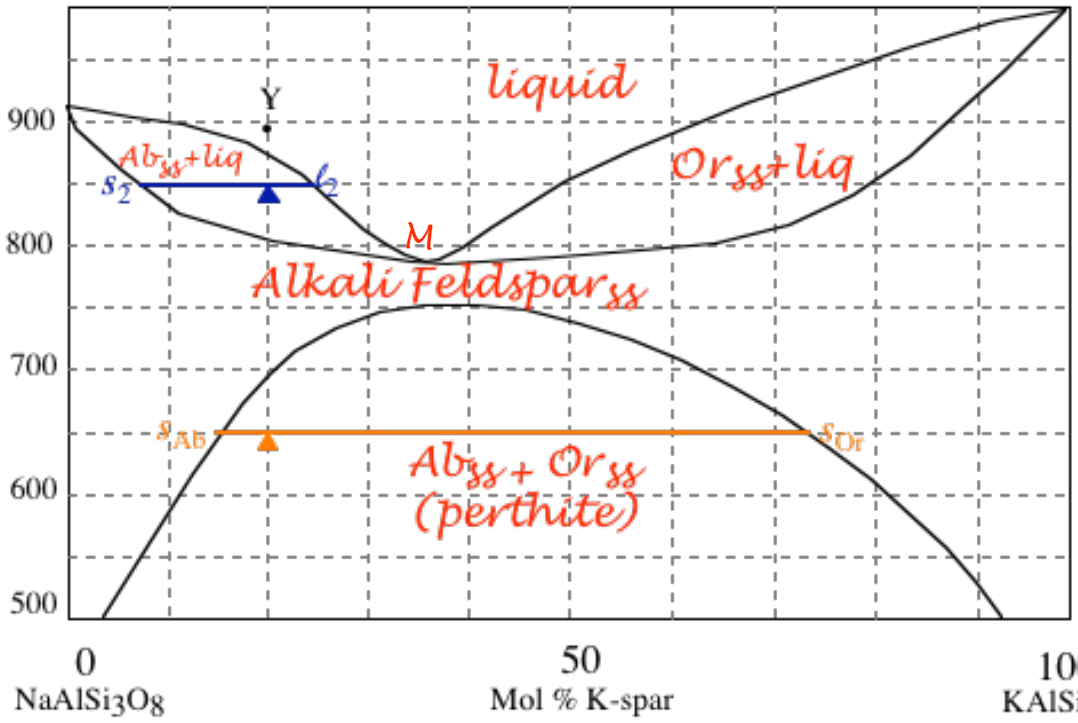
1. The diagram above represents the relationships of alkali feldspars at pressures of approximately 0.5GPa. Label the fields and any peritectic(s) or eutectic(s).

2. Follow the crystallization path for composition X. What is the composition of the solid at 725°C? What is the liquid composition at 725°C? What are the proportions of solid and liquid at 725°C? *Albite solid solution, composition s_1; ℓ_1 (see above); % liq = $\frac{\overline{s_1 x}}{s_1 \ell_1}$, % solid = 100% - % liq*

3. What phases are in equilibrium for the composition X at 650°C? What are their proportions?
   Albite solid solution and K feldspar solid solution; approximately 99% Ab$_{ss}$ and about 1% K-feldspar $_{ss}$

4. At what temperature would composition X begin to melt? What is the composition of the melt? How about the solid?

   Approximately 710°C; melt is approximately 23%Or, 77%Ab (ℓ; solid is Albite Solid solution approximately 85% Ab-15%Or. (s_2)



(After Philpotts, 1990)

5. The diagram above represents the relationships of alkali feldspars at low pressures (Philpotts, 1990). Label the fields and any peritectic(s) or eutectic(s). Questions 5-8 refer to comp. Y.

6. Follow the crystallization path for composition Y. What is the composition of the melt at 850°C? What is the composition of the solid? What is the proportion of solid to liquid?

liquid composition is ℓ_2 or approximately Or_{25} (see above);

solid comp = s_2 or Or_7; % liq = $\frac{\overline{s_2 x}}{\overline{s_2 \ell}}$, % solid = 100% - % liq

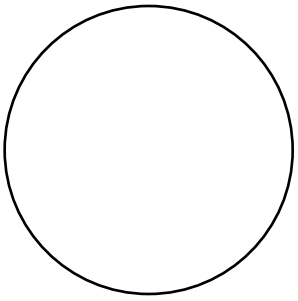
7. What phase(s) are at equilibrium at 750°C? What are their proportions?

Alkali feldspar solid solution (Or_{20}); 100%

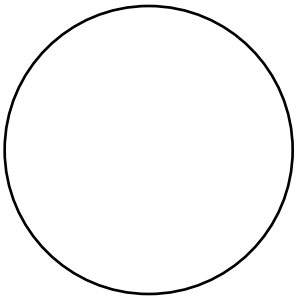
8. What phases are at equilibrium at 650°C? What are their compositions? What are their proportions?

Two alkali feldspars (solid solutions); s_{Ab} and s_{Or} or Ab_{85} and Or_{75}; about 91% Ab_{85} and 9% Or_{75}

9. Draw a picture of a thin section (crystallized at equilibrium) for X and Y at T= 600°C.



Both should show anti-perthite. Y should have more or exsolved in the anti-perthite but in general they should look very similar



Simple Ternary Phase Diagram
Igneous and Metamorphic Petrology

Q-Ab-Or system at high P_{H2O}

This phase diagram is at high P_{H2O} such that the relationship between albite and orthoclase is essentially a binary eutectic.

After Philpotts, 1990

1. Label the fields and any peritectics or eutectics on the diagram.

2. Draw the arrows on the cotectics or reaction lines.

3. What is the first phase to crystallize from composition X? (Label the diagram.)

   quartz

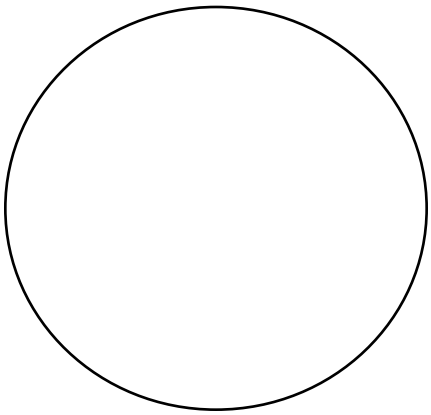
4. What are the final solid products of composition X?

   quartz, orthoclase and albite

5. Assume crystallization of X. What is the variance at point A? What phases are in equilibrium at point A? What is the composition of solid in equilibrium with liquid A? What is the instantaneous composition of the solid crystallizing from X at point A?

   f_A=3-3+1=1; quartz, orthoclase and liquid (of composition A); Solid in equilibrium = S_A (see orange line above) or approx. 90% Q + 10% Or; instantaneous composition is S_{instA} (see green line above) or approximately 40% Q + 60% Or.

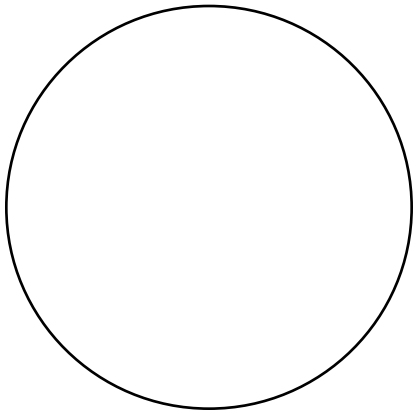
6. Draw what you would see in thin section if magma X froze at point A.



Students should draw approx. 50% eu- to subhedral crystals (composed of 90% Q + 10% Or) and 50% glass

7. What is the composition of the last drop of liquid when crystallizing magma X?
Eutectic composition

8. Draw a picture of the thin section after composition X has finished crystallizing.



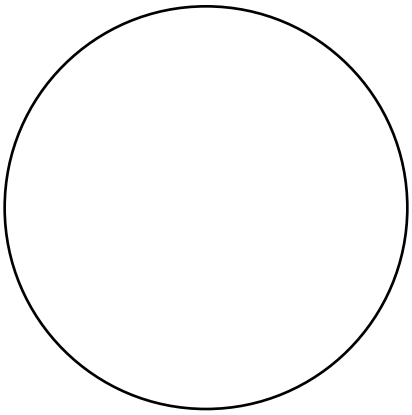
Students should draw approx. 60% Q, 30% Or and 10% Ab.

9. What is the first drop of liquid to form from melting composition Y?
eutectic composition

10. Draw the melting path of composition Y on the diagram. What phases are in equilibrium when the liquid is on the cotectic?
See purple lines on diagram above; Albite and Orthoclase

11. What is the variance at point B? Determine the proportions of phases melting instantaneously at point B. What is the total solid composition at point B?
f_A=3-3+1=1; %Ab melting = $\frac{Or_B S_{inst_B}}{Or_B Ab_B}$ = ~ 70% Ab; % Or melting = 100% solid - % Ab = 30% Or (See purple dashed line on diagram). Total Solid composition = 22% Or and 78% Ab (see blue line on diagram).

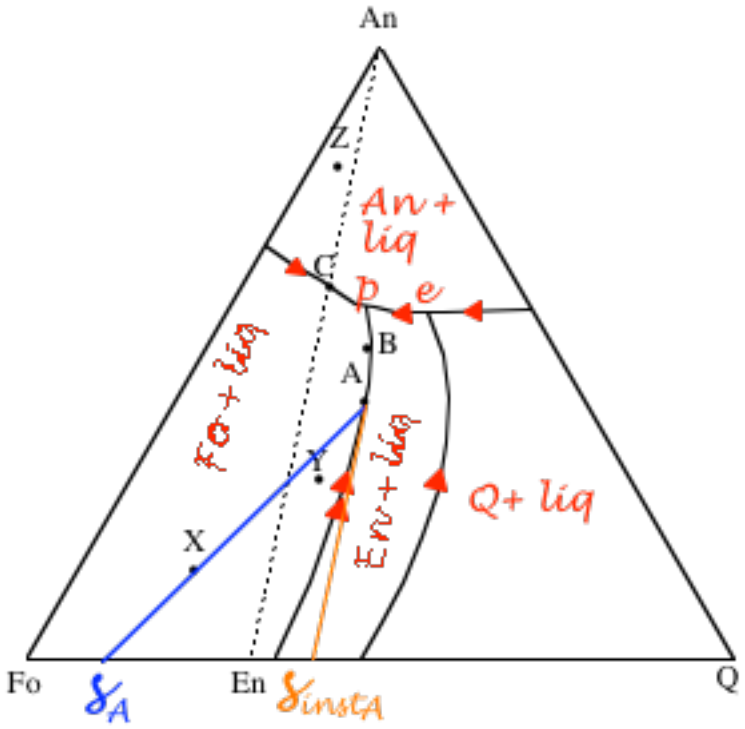
12. Draw a picture of a thin section if this magma were frozen at point B.



Students should draw approximately 60% crystals (22% of those crystals should be Or and 78% should be Ab) and 40% glass.

Ternary Phase Diagram
Igneous and Metamorphic Petrology

Fo-An-Q system



After Philpotts, 1990

1. Label the fields and any peritectics or eutectics on the diagram.

2. Draw the arrows on the cotectics or reaction lines.

3. What is the first phase to crystallize from composition X?

   forsterite

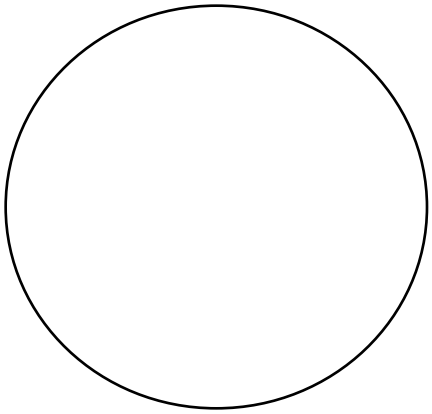
4. What are the final solid products of composition X?

   Forsterite, Enstatite and Anorthite

5. Assume that we are crystallizing X. What is the variance of composition X at point A? What phases are in equilibrium at point A? What is the composition of solid in equilibrium with liquid A? What is the instantaneous composition of the solid crystallizing from X at point A?

   f = c-p+1 = 3-3 (Fo+En+liq) +1 = 1; Fo+En+liq; s_z (or 33%En, 67%Fo) is in equilibrium with liquid A; s_{instA} is the instantaneous sold composition - this composition can be confusing to the students since (Fo is actually reacting thus a negative Fo composition for the instantaneous composition

6. Draw a picture of a thin section if the magma (of composition X) froze at point A.

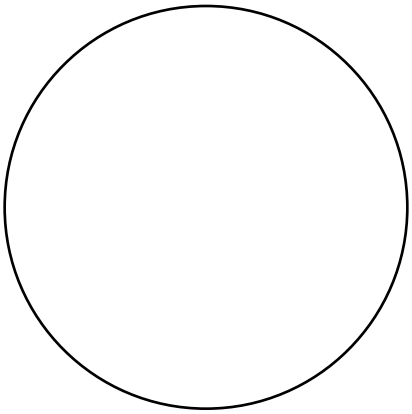


Students should show approximately 1/3 of the field of view as glass and the other 2/3 as about 33% En and 67%Fo (very anhedral because it is reacting).

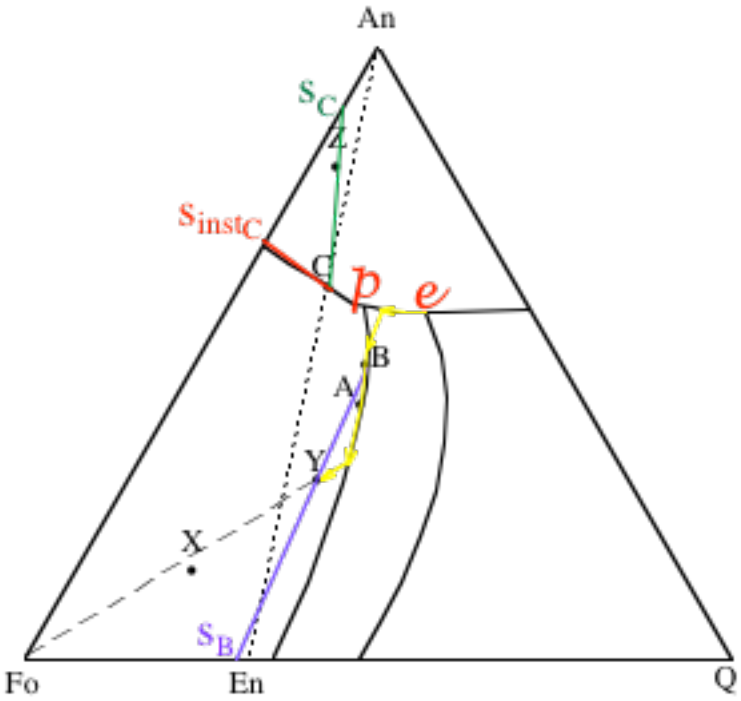
7. What is the composition of the last drop of liquid when crystallizing composition X?

Peritectic composition (p)

8. Draw a picture of the thin section after composition X has finished crystallizing.



Students should sketch approximately 26% anhedral (or reacted) Fo, 22% An and 52% En.



9. What is the first drop of liquid to form from melting composition Y?

Eutectic composition (e)

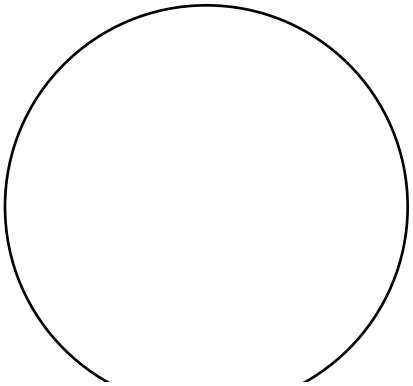
10. Draw the melting path of composition Y on the diagram. What phases are in equilibrium at point A?

See yellow line on diagram; En, Fo and Liquid

11. What is the variance of composition Y at point B? Determine what phases are in equilibrium at point B. What is the total solid composition at point B?

f = c-p +1 = 3-3+1 = 1; Fo+En+liq; S_B (see diagram) or approximately 5% Fo and 95% En.

12. Draw a picture of a thin section if composition Y was frozen **at** point B.



About 60% solid (5% of that is Fo and the other 95% is En) and 40% glass

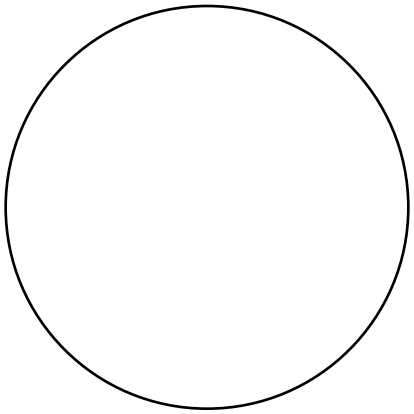
13. What is the composition of the first drop of liquid formed from melting composition Z?
peritectic composition (p)

14. Assume melting of composition Z. What phases are in equilibrium at point C?

Fo + An + melt

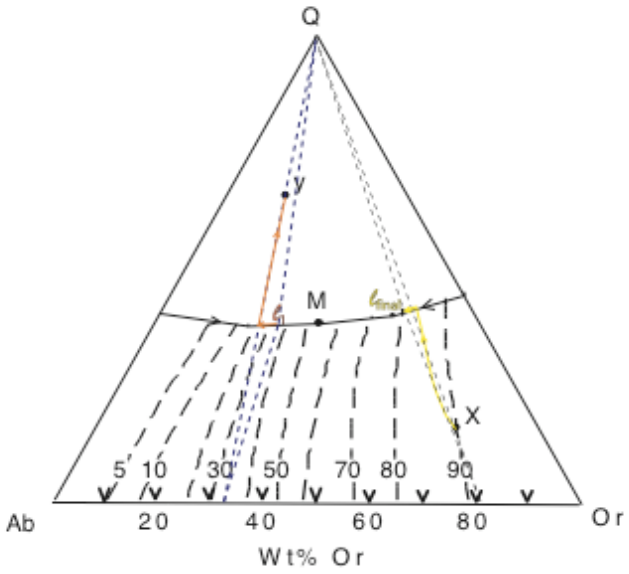
15. What is the variance of composition Z at point C? Determine the proportions of phases melting instantaneously at point C. What is the total solid composition at point C? f = c-p +1 = 3-3+1 = 1; S_{incC} or 68% An and 22% Fo is the instantaneous composition; total solid is S_C or 10% Fo and 90% An

16. Draw a picture of a thin section if composition Z was frozen at point C.



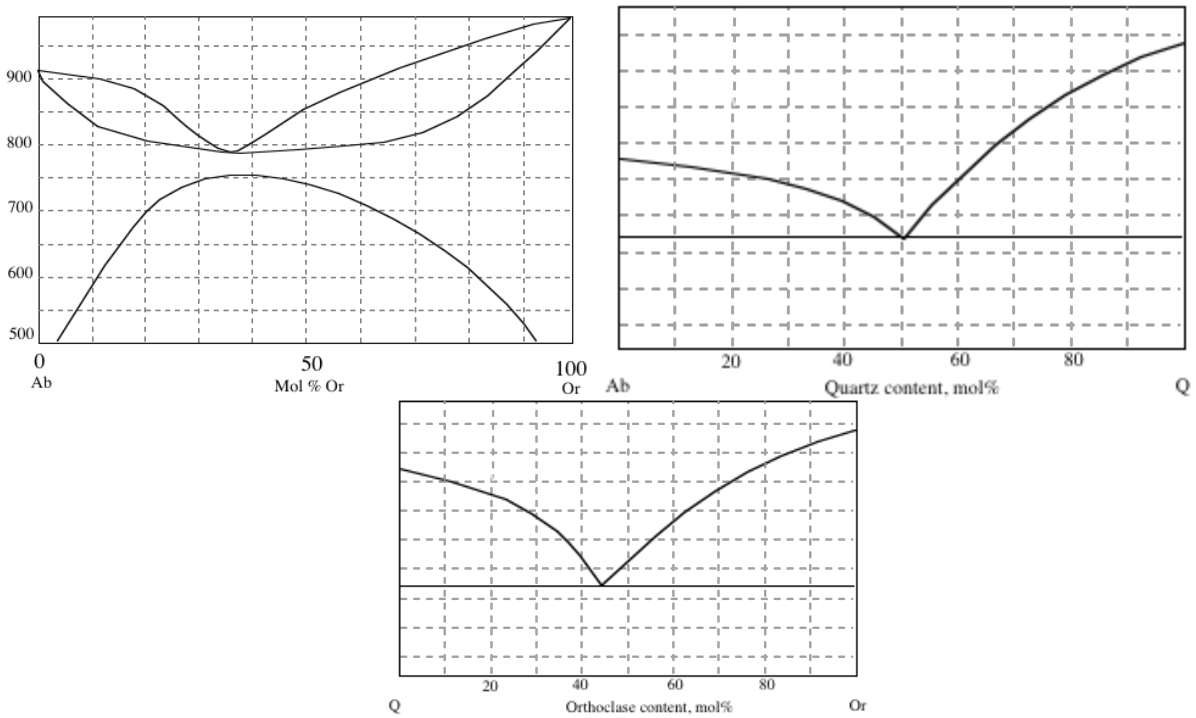
about 70% solid (10% Fo and 90% An) and 30 % glass.

Q-Ab-Or (at P_{H2O}=0) phase diagram exercise
Igneous and Metamorphic Petrology



(After Philpotts, 1990)

1. Draw binary phase diagrams for each side of the ternary phase diagram. Hint: manipulating this phase diagram will be much easier when you consider what is happening with each binary.



2. Assume crystallization conditions for ***x***. Show the crystallization path on the diagram above.
   See yellow line on diagram above

3. What is the composition of the first solid to crystallize from composition x?

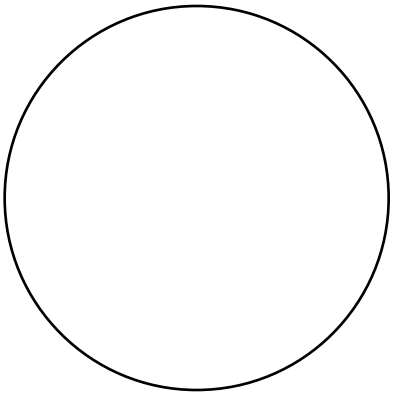
   Or_{90} is the first solid to crystallize

4. What is the composition of the last drop of liquid?
   l_{final} is the last drop of liquid

5. What happens at the cotectic? (Hint: Think again about what the phase diagrams on each side of the diagram look like.)

   compositions of the melt evolve toward "M" the minimum melt composition. Not all of them get there (as in the alkali Feldspar diagram)

6. Sketch a thin section with composition X if it crystallized in equilibrium.



Students should sketch a thin section with approx. 85% perthite (30% of which is exsolved Ab) and 15 % quartz.

7. Assume melting conditions for ***y***. Show the melting path on the diagram above.
   See orange line on diagram above

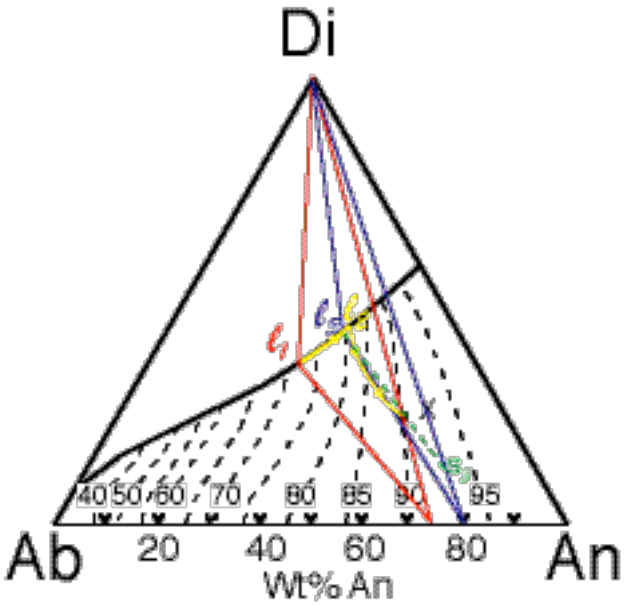
8. What is the composition of the first drop of liquid?

   l_1 is the first drop of liquid

9. What is the composition of the last solid to melt?
   Quartz is the last solid to melt

Di-Ab-An phase diagram exercise
Igneous and Metamorphic Petrology

Part 1: Melting ***X***



(After Philpotts, 1990)

1. Assume melting of composition ***x***. Draw the melting path.

   See yellow line above

2. What is the composition of the first drop of liquid when melting composition ***x***?

   ℓ_1

3. Draw a three-phase triangle when ***x*** generates the first drop of liquid. What phases are in equilibrium?

   See red triangle above; Di +An_{73} + liquid (of composition l_1)

4. What is the composition of the last drop of liquid (composition x) in equilibrium with both plagioclase and Di?

   ℓ_2 in yellow above

5. What happens to the assemblage that allows the liquid composition to leave the cotectic?

   All Di must be melted.

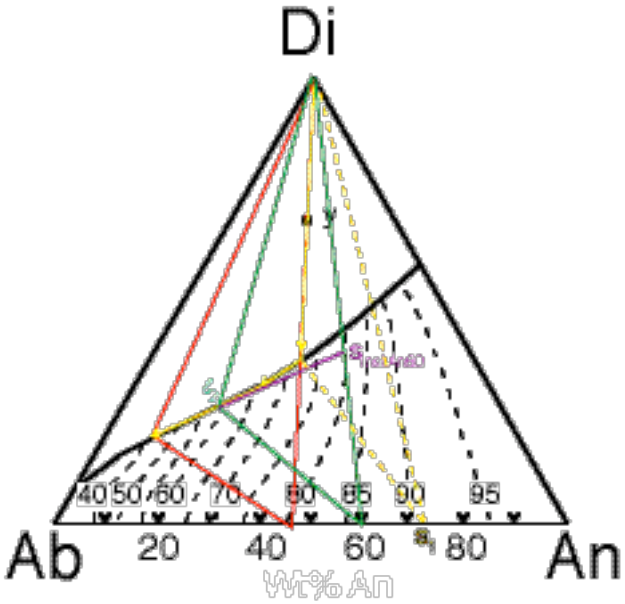
6. Draw a three phase triangle when melt is in equilibrium with plagioclase ***x*** = An_{80}. Show compositions of phases that are in equilibrium at that point. What are the proportions of solids in equilibrium at this point?

See Blue triangle above; An80 + Di + ℓ_2; % plag = $\frac{\overline{s_3 Di}}{\overline{An_{80} Di}}$ *; % Di = 1 -*

7. Draw a thin section of composition ***x*** if CRYSTALLIZED at equilibrium conditions.

Thin section should have approximately 25% Di +75% Plagioclase

Part 2: Crystallizing ***Y***.



(After Philpotts, 1990)

1. Now assume crystallization conditions for composition ***y***. Draw the crystallization path.

See yellow path above

2. What is the first phase to crystallize?

Di is first phase to crystallize from composition Y

3. What is the composition of plagioclase when the liquid first hits the cotectic?

Plagioclase is An_{72} (s_1; see yellow path and dotted triangle above)

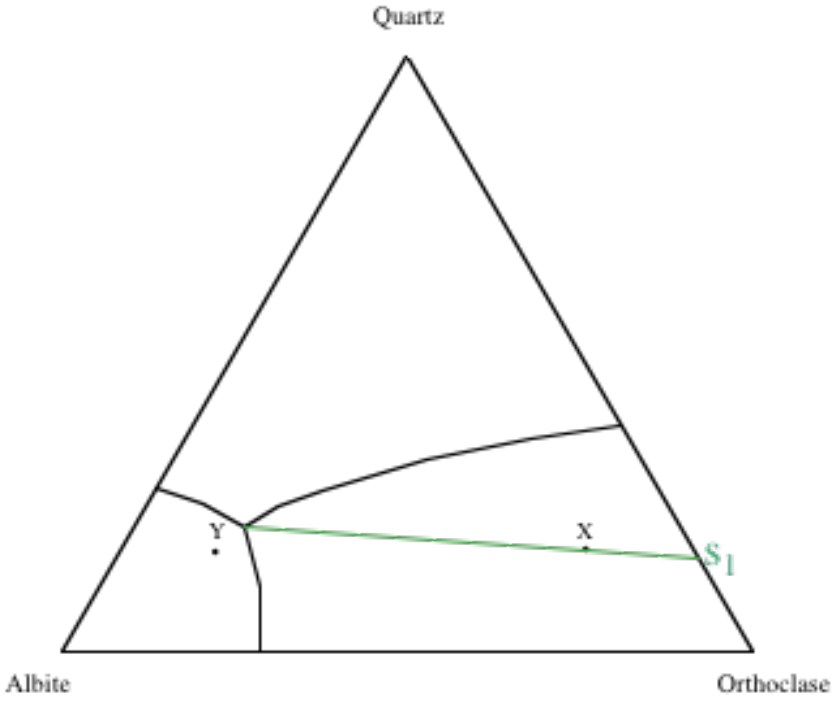
4. Show a three phase triangle when l is in equilibrium with plagioclase ***y*** =An_{60}. Show compositions of phases in equilibrium. What are the proportions of solids crystallizing at that point?

See Green triangle above. compositions in equilibrium are An_{60}, Di and l_2. %Di = $\frac{\overline{An_{60}S_{instAn_{60}}}}{\overline{An_{60}Di}}$. *$\%An_{60}$ = 100%-%Di*

5. Show a three-phase triangle when the last drop of liquid is left.

See red triangle above.

Q-Ab-Or at high P(H_2O)
Igneous and Metamorphic Petrology



(After Philpotts, 1990)

1. Consider fractional melting of composition X.
2. What is the composition of the first drop of liquid generated by meting X? Which rock (composition X or composition Y) is capable of generating more liquid of this composition? Explain.

   Eutectic composition. Y is capable of generating more liquid of eutectic composition because its composition is closer to the eutectic composition.

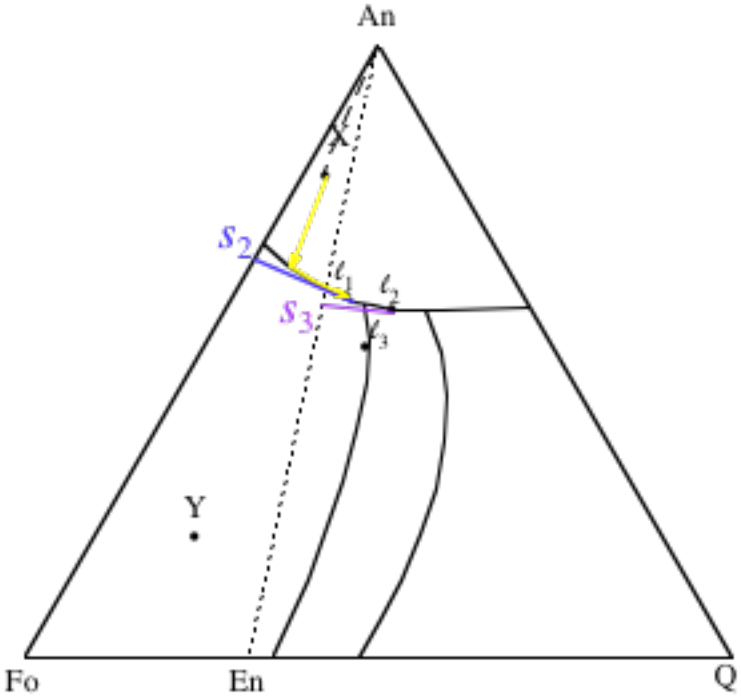
3. What solid phase will be the first to completely melt from composition X? Assume that this solid does completely melt and that the liquid and the solid are separated (fractional melting). What is the composition of the remaining solid? Draw a binary phase diagram that shows phase relations for the remaining solid.

   Albite will be the first to completely melt. The composition of the remaining solid is S_1. The phase diagram will be a eutectic phase diagram between quartz and orthoclase with a bulk composition of S_1.

4. Using this binary phase diagram, what is the composition of the first drop of liquid generated by melting the new solid?

   First drop of liquid will be l_1 or eutectic composition of binary phase diagram.

Fo-An-Q
Igneous and Metamorphic Petrology



1. Consider fractional crystallization of composition X.
2. What solid phases will exist after *equilibrium* crystallization of X?

   Fo + En + An

3. Consider *fractional crystallization* of X. Show the path of liquid compositions (use colored pencils!) assuming that all crystals that form in X are removed from the liquid until the liquid reaches composition l_1. What is the solid in equilibrium with l_1?

   See yellow arrows above. Solid is S_2 (An = 65%; Fo = 35%; blue line above)

4. Explain what happens at the peritectic point during *equilibrium* crystallization of l_1.

   Fo reacts with liquid to make En. Liquid composition stays there until all Fo is reacted away, then the liquid composition evolves toward the eutectic composition.

5. If l_1 crystallizes at *equilibrium* until it reaches composition l_2, then all solids are fractionated from the liquid, what is the first solid to crystallize from l_2?

   Solid is S_3 or about 60% An and 40%En (purple line above)

6. Consider *equilibrium* crystallization of Y until it reaches composition l_3. Explain how all the Fo could be fractionated from the liquid without *physically removing* the Fo and without removing *any* of the En. If this happens, where will l_3 finish crystallization? What phases will be present in the rock? Draw a thin section of Y crystallized under these conditions.

If En rims form on the Fo crystals the Fo is essentially "armored" and unable to react with the melt to generate En. When Fo is no longer able to react with the melt, the melt composition will move off the reaction line (directly away from En) toward the cotectic between En and An. The last melt composition will be eutectic composition and solid Fo, En, An AND Q will be present in the rock.

The thin section should have about 70% Fo with En rims, 10% Q and 20% An. Q should be interstitial and En and An should be subhedral.