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

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Introductory Statement:

We developed these exercises to put the concepts of igneous phase diagrams into a practical context. Our objective was to relate the phase diagrams that students manipulated for homework to things that they were seeing in lab. And, not coincidentally, igneous phase diagrams pop up in lab exercises; students are asked to relate what they are seeing in the rocks to a phase diagram. By making the students think about what is actually happening with the magma/crystals, they seem to make connections better and to understand why a basic comprehension of phase diagrams is crucial to our understanding of igneous rocks.

In order to complete these exercises, students need at least an introduction to the concepts of basic thermodynamics, Gibb's Free Energy, Gibbs Phase Rule (and the condensed phase rule), the lever rule, equilibrium vs. fractional melting/crystallization and some petrography (to make their sketches realistic). We have included a handout that introduces many of these ideas (see supporting material – in-class handout developed by Wenner and Daniel Brabander). Wenner uses this handout as an in class exercise (the class works through it together) to introduce phase diagrams. Phase diagrams are an important part of the course and, thus, quite a bit of time is spent examining diagrams.

In general, most of these phase diagram exercises deal with equilibrium crystallization or melting. However, the last two exercises are designed to have students deal with fractional crystallization and partial melting. These are rather advanced concepts and exercises and may not be appropriate for some courses. However, when dealing with these difficult concepts in a course, these exercises might be put to use as an in-class exercise. The Q-Ab-Or exercise is particularly useful for illustrating the generation of granites.

The primary objective of all of these exercises is for students to recognize that phase diagrams have relevance to real rocks, that they can use phase diagrams to understand the evolution of a given rock and that phase diagrams are the ONLY way to tell "what crystallizes first" from a given composition. [Students are amazed to find out that (despite what they think Bowen said) quartz may actually crystallize first in some magmas!] Other learning objectives include honing of some quantitative skills (such as calculating proportions and setting up ratio problems), development of skills in estimation of percentage, ability to sketch realistic thin sections (i.e., make the minerals representative of what they would actually see) and a basic comprehension of the relationship of thermodynamics to geology.

Each of the exercises is "stand-alone" (1-3 pages of diagram(s) and questions) and 10 exercises follow this introductory statement. Each exercise begins with a **bold** title describing the diagram that is to be interpreted.

Simple eutectic phase diagram exercise
Igneous and Metamorphic Petrology

CaMgSi₂O₆
diopside

anorthite content, mol%

CaAl₂Si₂O₈
anorthite
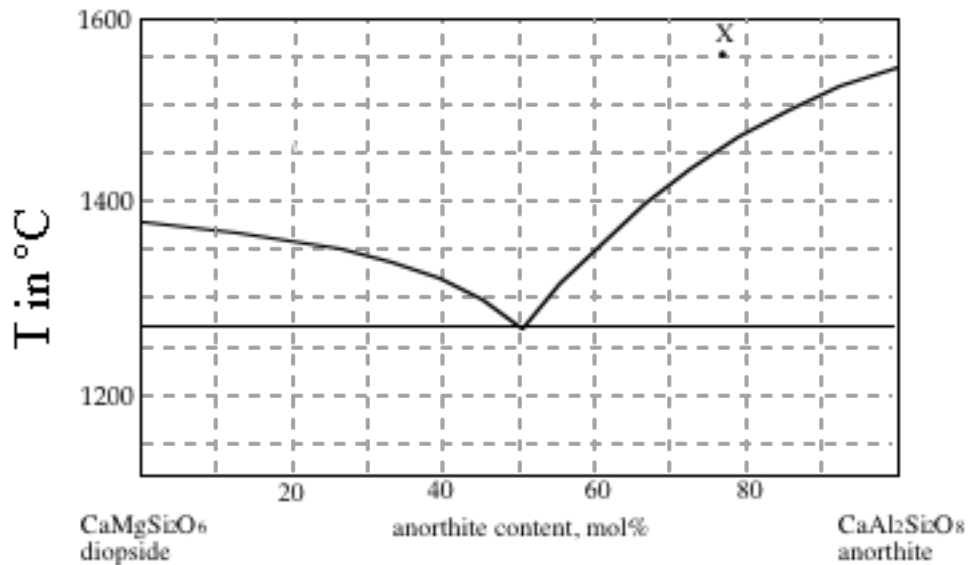
After Philpotts, 1990

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?

3. At what temperature does the first crystal form?

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

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

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

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

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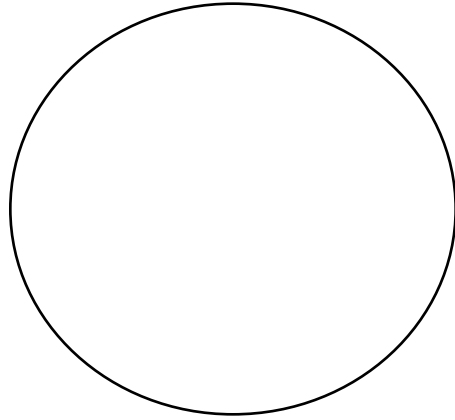
9. How many degrees of freedom does the system have when T=1500°C?

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

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

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

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.
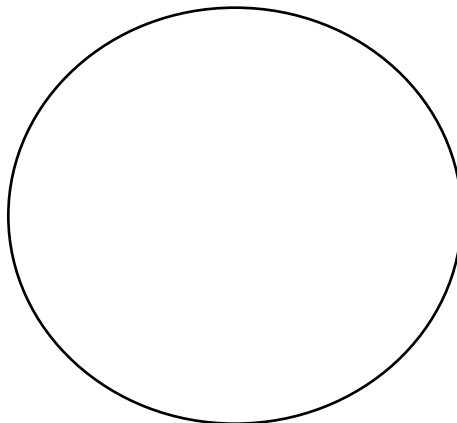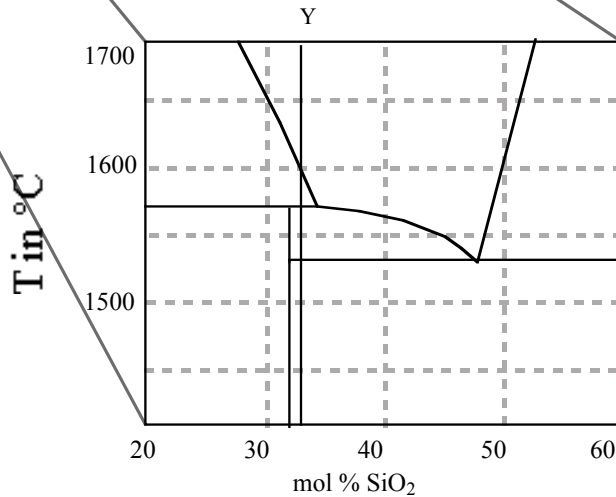
Name:_____

Simple peritectic phase diagram exercise
Igneous and Metamorphic Petrology
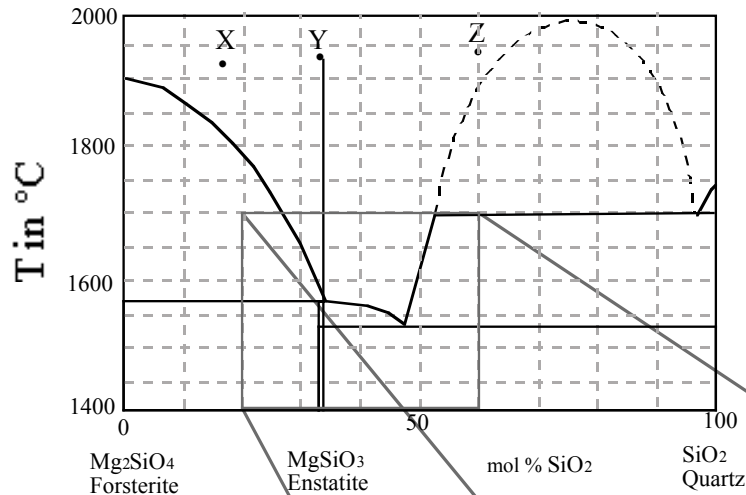
This diagram represents phase relations in the condensed (P=1atm) system forsterite-quartz.
The intermediate compound enstatite melts incongruently.

Graph (T in °C vs mol % SiO₂):
- Y-axis: T in °C, from 1400 to 2000
- X-axis: mol % SiO_2, from 0 to 100
- 0: Mg_2SiO_4 Forsterite
- 50: $MgSiO_3$ Enstatite
- 100: SiO_2 Quartz
- Points labeled X, Y, Z

Lower-right diagram: T in °C (1500–1700) vs mol % SiO_2 (20–60), labeled Y.

This diagram represents a portion of the diagram above and shows the crystallization of composition Y. Use it to answer questions 5-8.

1. Label the fields, eutectic and peritectic(s)on the diagrams.

2. What are the final solid products of crystallization of composition X?

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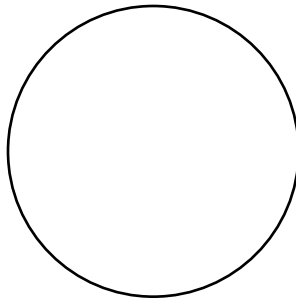
4. Give the proportions of the solids for composition X when T = 1500°C.

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

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

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?

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

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

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.
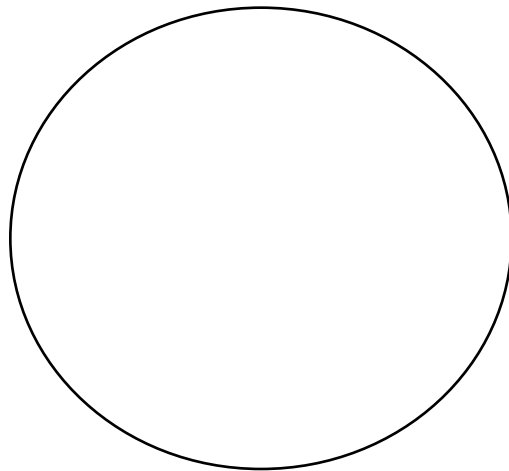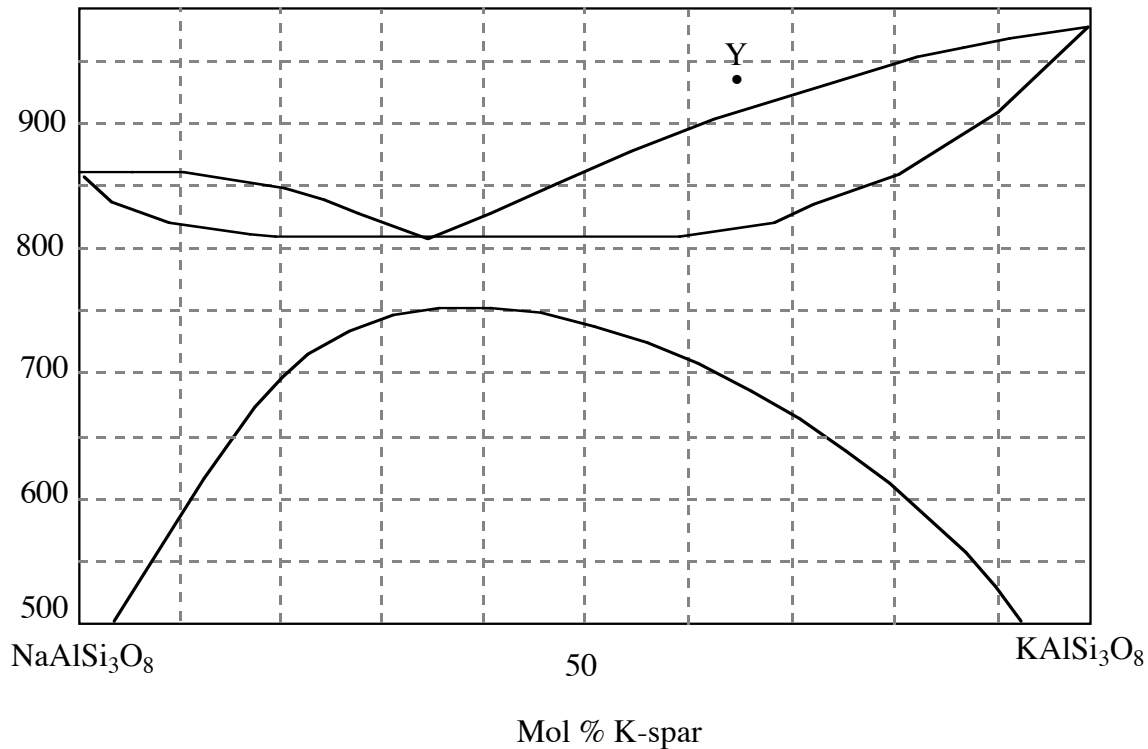
Alkali Feldspar Phase Diagram
Igneous and Metamorphic Petrology
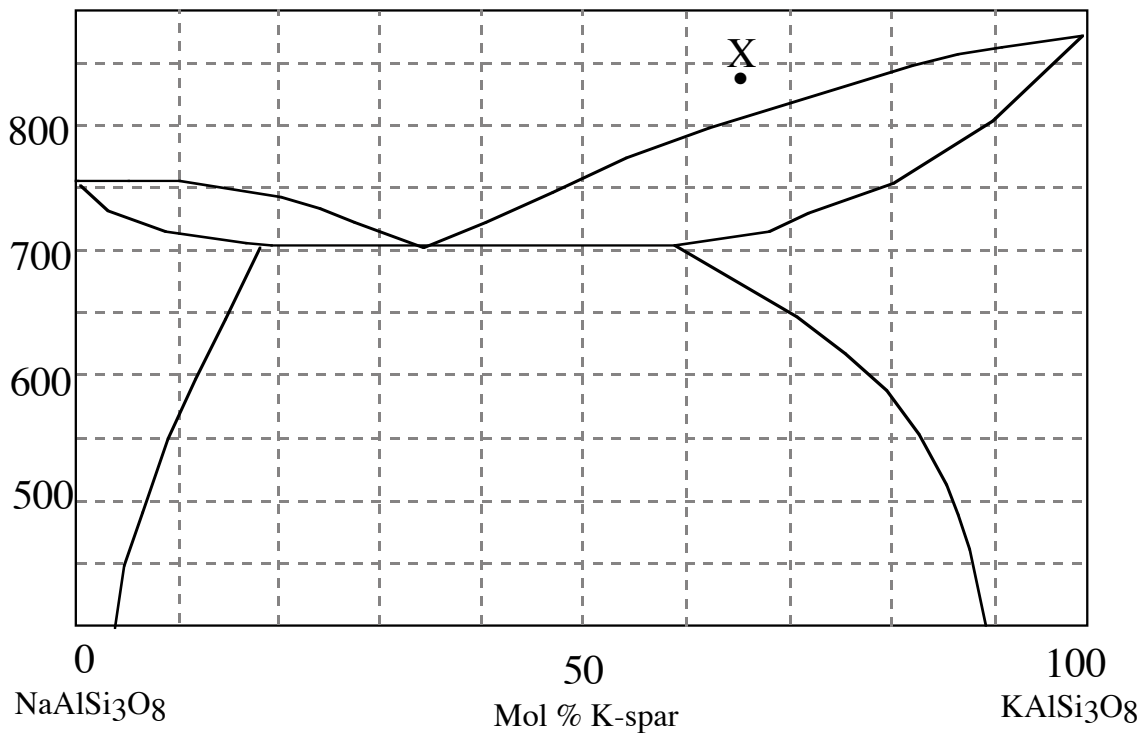
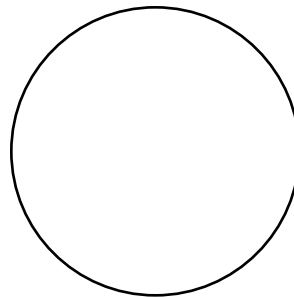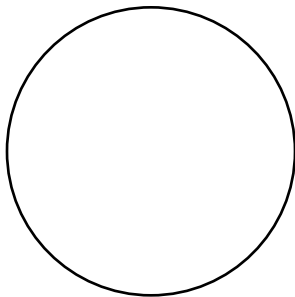**This diagram represents phase relations at high P_{H2O} (Philpotts, 1990).**

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?

3. What phases are in equilibrium for the composition X at 650°C? What are their proportions?

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

Y
•

900

800

700

600

500

NaAlSi$_3$O$_8$ 50   KAlSi$_3$O$_8$

Mol % K-spar

This diagram represents phase relations at low P$_{H2O}$ (Philpotts, 1990).

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

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?

7. What phases are at equilibrium at 750°C? What are their proportions?

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

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

Alkali Feldspar Phase Diagram
**Igneous and Metamorphic Petrology**
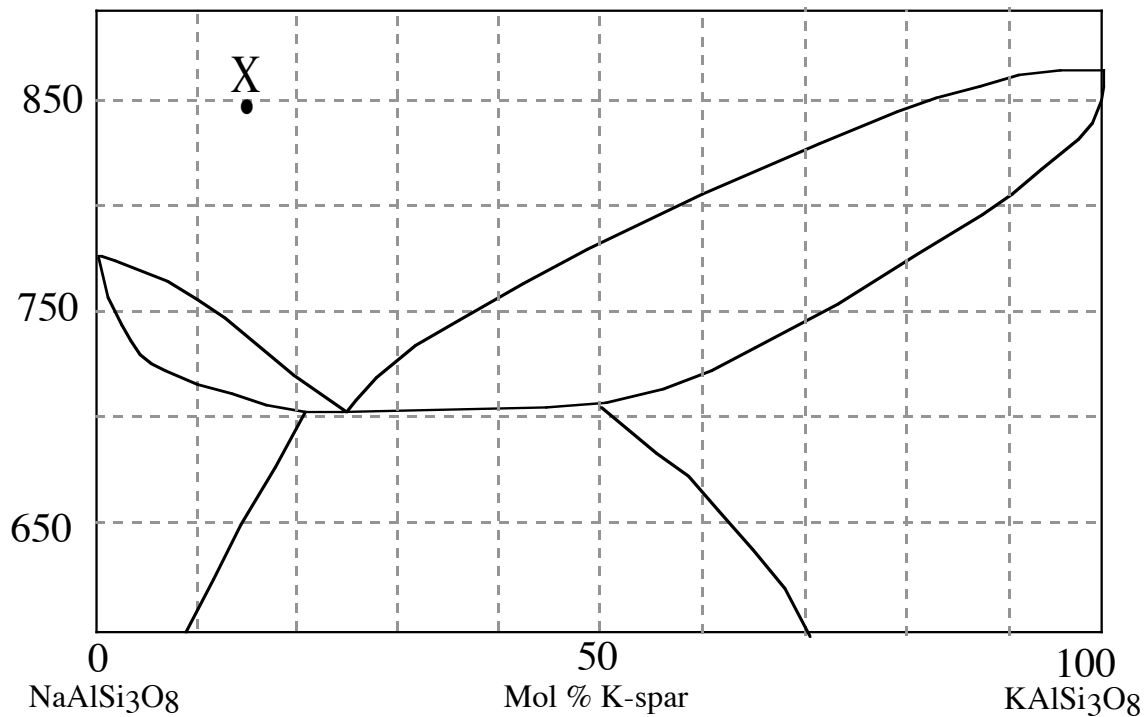
Modified from Philpotts, 1990

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?

3. What phases are in equilibrium for the composition X at 650°C? What are their proportions?

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

900

800

700

600

500

0
NaAlSi$_3$O$_8$

Y

50
Mol % K-spar

100
KAlSi$_3$O$_8$
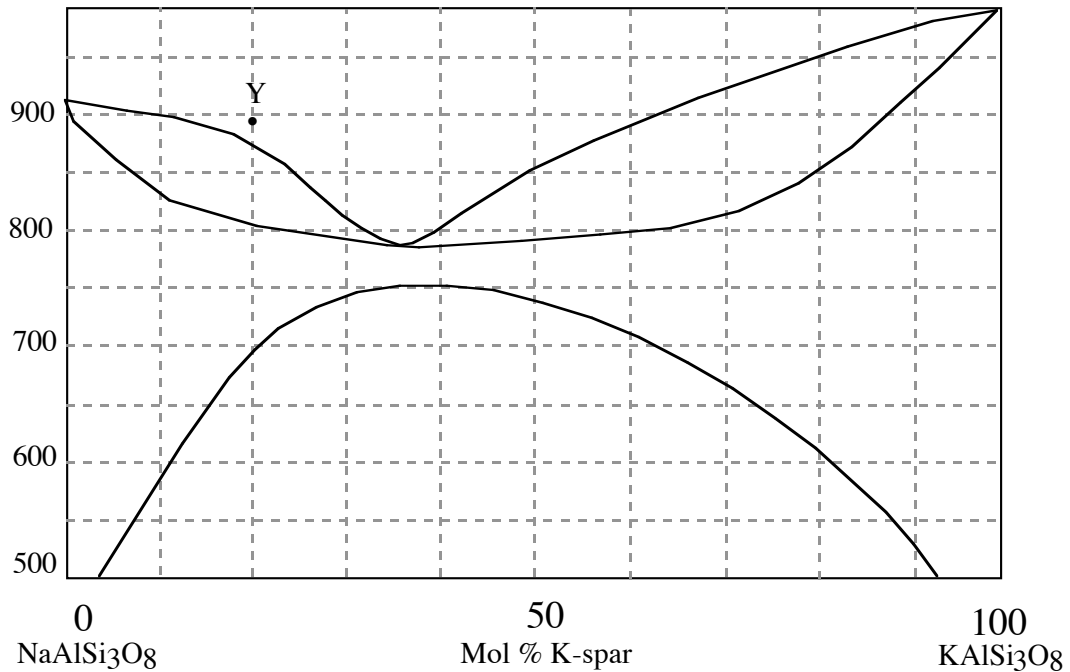
(After Philpotts, 1990)

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?

7. What phases are at equilibrium at 750°C? What are their proportions?

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

9. Draw a picture of thin sections (crystallized at equilibrium) for X and Y at T= 550°C.
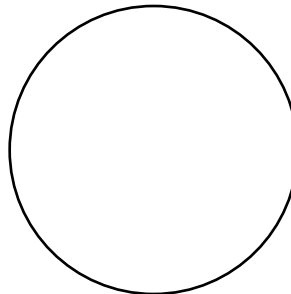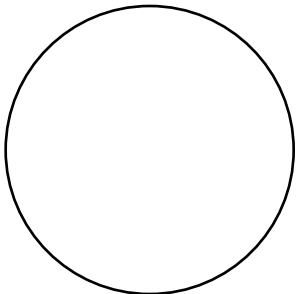
Simple Ternary Phase Diagram
**Igneous and Metamorphic Petrology**

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

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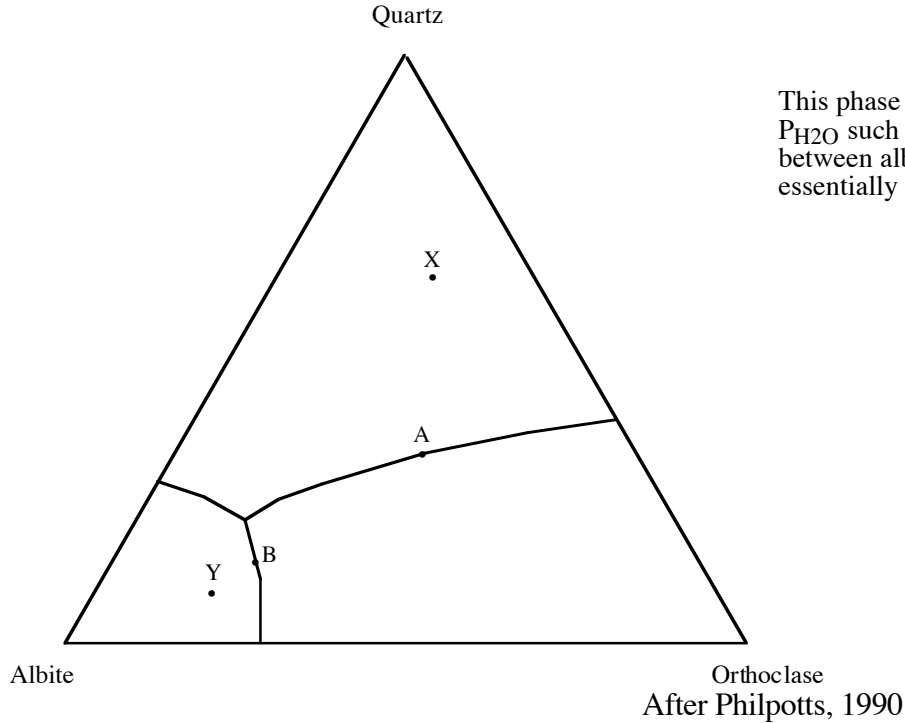
This phase diagram is at high
P_{H2O} such that the relationship
between albite and orthoclse is
essentially a binary eutectic.

X
•

A
•

B
Y
•

Albite

Orthoclase
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.)

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

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?
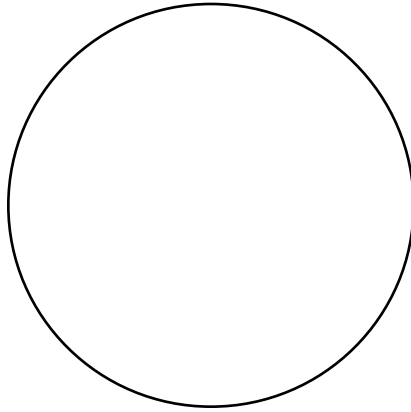
6. Draw what you would see in thin section if the magma froze at point A.
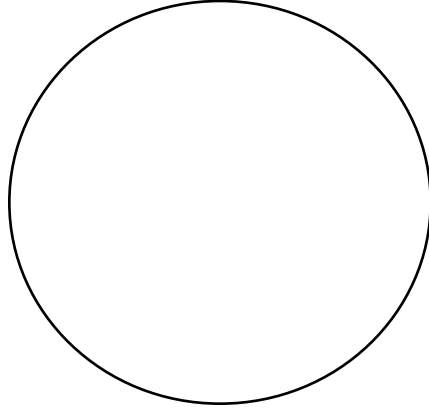
7. What is the composition of the last drop of liquid when crystallizing composition X?

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

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

10. Draw the melting path of composition Y on the diagram. What phases are in equilibrium when the liquid is on the cotectic?

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?
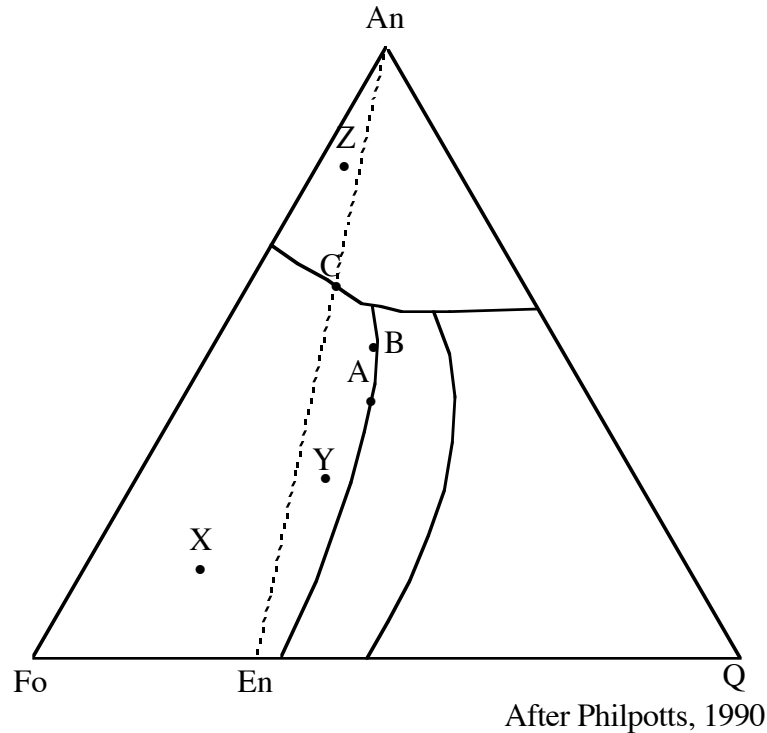
12. Draw a picture of a thin section if this magma were frozen at point B.
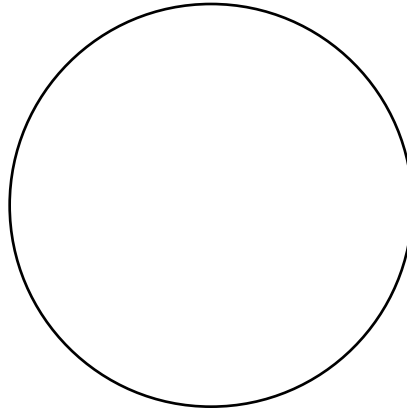
Ternary Phase Diagram
Igneous and Metamorphic Petrology

Fo-An-Q system

An

Z

C

B

A

Y

X

Fo   En   Q

After Philpotts, 1990

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

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

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

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

15. 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?
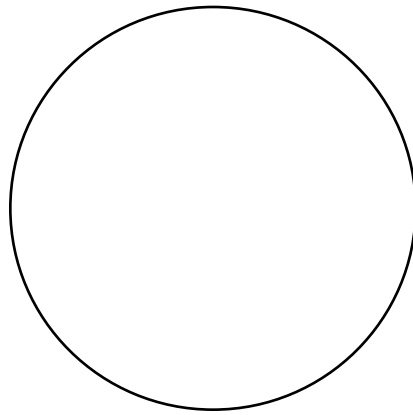
16. Draw a picture of a thin section if the magma (of composition X) froze at point A.
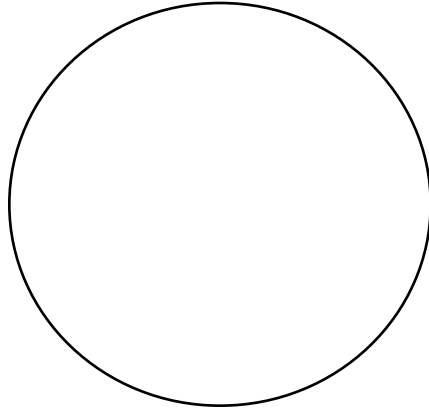
17. What is the composition of the last drop of liquid when crystallizing composition X?

18. Draw a picture of the thin section after composition X has finished crystallizing.
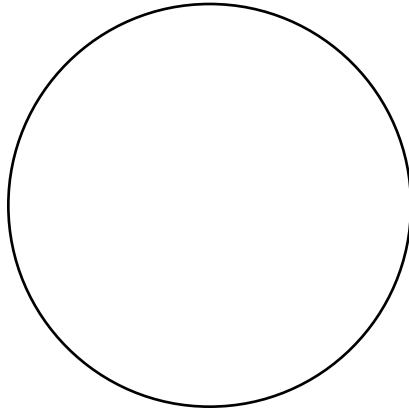
19. What is the first drop of liquid to form from melting composition Y?

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

21. What is the variance of composition Y at point B? Determine the proportions of phases melting instantaneously at point B. What is the total solid composition at point B?

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

23. What is the composition of the first drop of liquid formed from melting composition Z?

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

25. 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?

26. Draw a picture of a thin section if composition Z was frozen at point C.
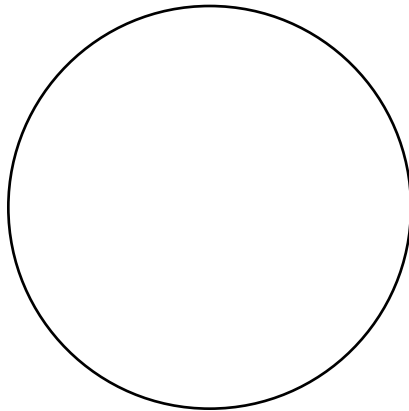
Q-Ab-Or (at P$_{H2O}$=0) phase diagram exercise
Igneous and Metamorphic Petrology


(Modified from Philpotts, 1990)
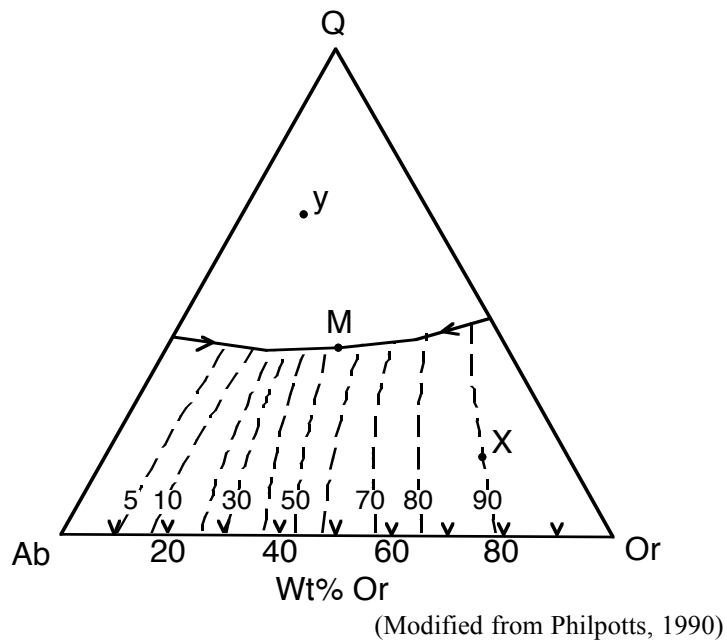
1. Draw binary phase diagrams for each side of the ternary phase diagram. Hint: manipulating this phase diagram will be much easier when you consider what is happening with each binary.

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

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

4. What is the composition of 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.)

6. Sketch a thin section with composition X if it crystallized in equilibrium.
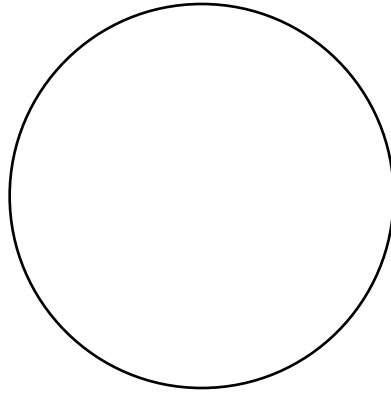
7. Assume <u>melting</u> conditions for *y*. Show the melting path on the diagram above.
8. What is the composition of the first drop of liquid?

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

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

<u>Part 1: Melting X</u>

Di

• y

• X

40 50 60 70   80 85 90   95

Ab   20   40   60   80   An
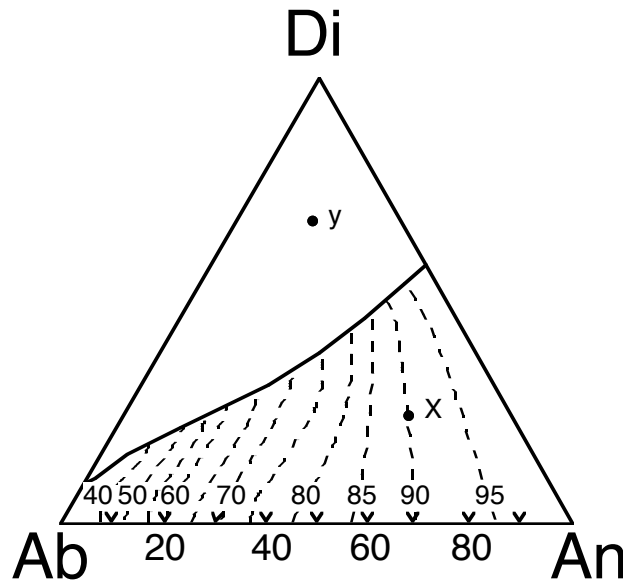
(After Philpotts, 1990)

1. Assume <u>melting</u> of composition x. Draw the melting path.

2. What is the composition of the first drop of liquid when <u>melting</u> composition x?

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

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

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

6. Draw a three phase triangle when in l is in equilibrium with plagioclase $x = An_{75}$. Show compositions of phases that are in equilibrium at that point. What are the proportions of solids in equilibrium at this point?

7. Draw a thin section if <u>crystallizing</u> x at equilibrium after final drop of liquid is consumed.

Part 2: Crystallizing **Y**.
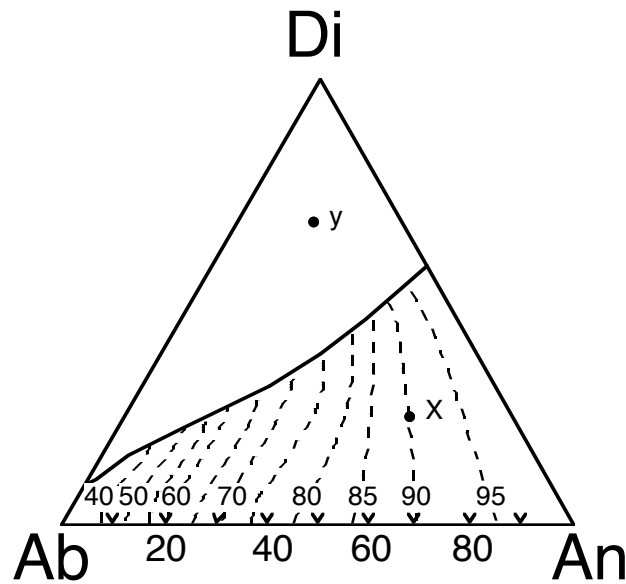
1. Now assume <u>crystallization</u> conditions for composition **y**. Draw the crystallization path.

2. What is the first phase to crystallize?

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

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?

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

Name:_____

Q-Ab-Or at high P(H₂O)
Igneous and Metamorphic Petrology

Quartz

Y
·

X
·

Albite   Orthoclase
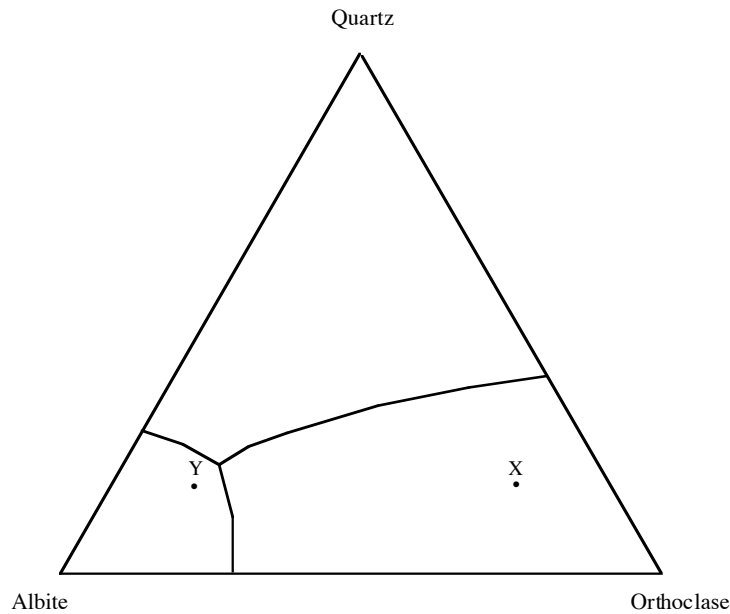
1. Consider fractional melting of composition X.
2. What is the composition of the first drop of liquid generated by meting X? Which rock (composition X or composition Y) is capable of generating more liquid of this composition assuming that both begin with the same volume? Explain.

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.

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

Fo-An-Q
Igneous and Metamorphic Petrology

An

X

ℓ_1 ℓ_2

ℓ_3

Y

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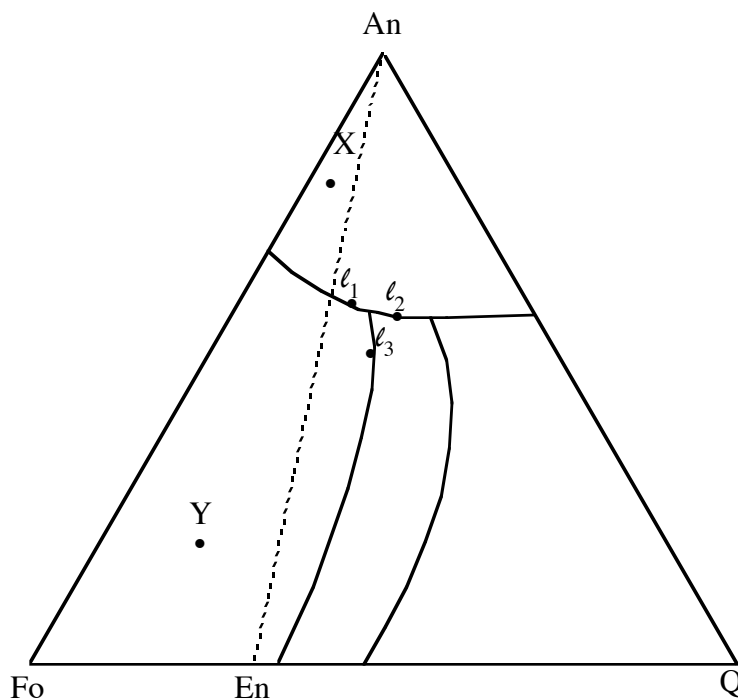
1. Consider fractional crystallization of composition X.
2. What solid phases will exist after *equilibrium* crystallization of X?

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?

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

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?

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.