

## T-X Diagrams

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*T-X diagrams are most often used for describing metamorphism of carbonate-rich rocks (marbles or marls) or ultramafic rocks. In these kinds of rocks, both CO<sub>2</sub> and H<sub>2</sub>O can be very important fluid species. In the many other kinds of metamorphic rocks, fluid is typically H<sub>2</sub>O is the only significant fluid present or, sometime, fluid only has a negligible effect.*

### Minerals, Abbreviations, and Compositions Used in This Handout

An	anorthite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>
Br	brucite	Mg(OH) <sub>2</sub>
Cc	calcite	CaCO <sub>3</sub>
Co	corundum	Al <sub>2</sub> O <sub>3</sub>
CO <sub>2</sub>	CO <sub>2</sub> vapor	CO <sub>2</sub>
Di	diopside	CaMgSi <sub>2</sub> O <sub>6</sub>
Do	dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>
En	enstatite	MgSiO <sub>3</sub>
Fo	forsterite	Mg <sub>2</sub> SiO <sub>4</sub>
Ge	gehlenite	CaAl <sub>2</sub> SiO <sub>7</sub>
Gr	grossular	Ca <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>
H <sub>2</sub> O	H <sub>2</sub> O vapor	H <sub>2</sub> O
Kfs	K-feldspar	KAlSi <sub>3</sub> O <sub>8</sub>
Mg	magnesite	MgCO <sub>3</sub>
Mnt	montecellite	CaMgSiO <sub>4</sub>
Pe	periclase	MgO
Ph	phlogopite	KMg <sub>3</sub> AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub>
Qz	quartz	SiO <sub>2</sub>
Tc	talc	Mg <sub>3</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>
Tr	tremolite	Ca <sub>2</sub> Mg <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>
Wo	wollastonite	CaSiO <sub>3</sub>

T-X diagrams are, in many ways, similar to P-T diagrams. All the same kinds of rules apply. There is one significant difference. When we look at a T-X diagram, it is assumed that a fluid phase is present. The fluid may be pure H<sub>2</sub>O or pure CO<sub>2</sub> or anything between. The X-axis on the diagram represents fluid composition.

To see why we need T-X diagrams, let's start first by looking at a classic P-T diagram.

Figure 1 (next page) shows some reactions involving phases in the CaO-MgO-SiO<sub>2</sub>-H<sub>2</sub>O-CO<sub>2</sub> system plotted on a P-T diagram. The locations of these reactions were calculated using an internally consistent thermodynamic data base but, as we shall see, this leads to complications.

*Reaction 1* is a solid-solid reaction. The others involve H<sub>2</sub>O, CO<sub>2</sub>, or both.

*Reaction 2, a dehydration reaction,* shows where tremolite will break down to form quartz, enstatite, diopside and (pure) H<sub>2</sub>O.

*Reaction 3, a decarbonation reaction,* shows where calcite and quartz will react to produce wollastonite and (pure) CO<sub>2</sub>.

The H<sub>2</sub>O and CO<sub>2</sub> involved in these reactions will be released as an intergranular fluid in the rock. Typically, intergranular fluids are neither pure H<sub>2</sub>O nor pure CO<sub>2</sub>. They are solutions of the two, and may even contain other components.

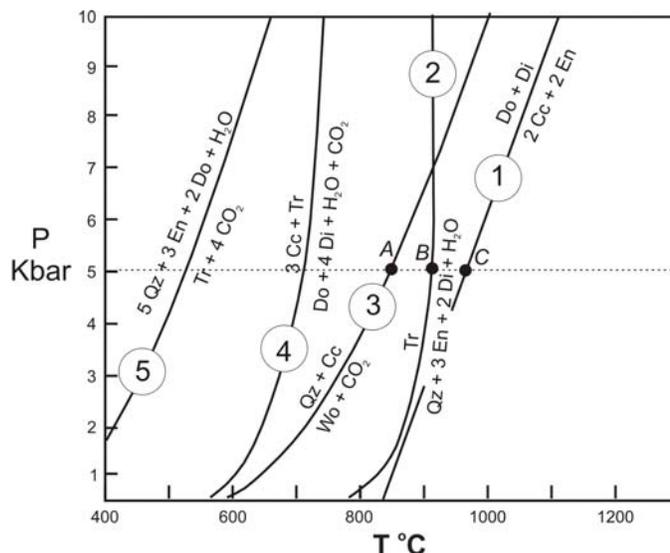


Figure 1. Some reaction in the CaO-MgO-SiO<sub>2</sub>-H<sub>2</sub>O-CO<sub>2</sub> system

Dehydration and decarbonation reactions are very sensitive to the composition of the fluid in a rock. For normal dehydration (or decarbonation) reactions, if the H<sub>2</sub>O (or CO<sub>2</sub>) are diluted, the reaction takes place at lower temperature.

This is a standard rule of thermodynamics: ***if you dilute a phase, or dilute one phase in a phase assemblage, you extend the stability of the phase or assemblage.*** In Figure 1, the H<sub>2</sub>O and CO<sub>2</sub> are on the high temperature side of *Reactions 2, 3, and 4.* If you dilute them, the reactions shift to lower temperature.

So, *Reaction 2* will only take place at the conditions shown in Figure 1 if the fluid is pure H<sub>2</sub>O; otherwise it will take place at lower temperature. *Reaction 3* will only take place at the conditions shown if the fluid is pure CO<sub>2</sub>; otherwise it will shift to lower temperature, as well.

Things become even more complicated for *Reactions 4 and 5.* They involve both pure H<sub>2</sub>O and pure CO<sub>2</sub>. However, the two fluids cannot exist together and be pure because they will always mix and dilute each other. So, the locations shown in Figure 1 are *metastable.* They are consistent with the thermodynamic properties of the pure phases involved but in nature will never occur because in nature H<sub>2</sub>O and CO<sub>2</sub> mix together and do not act like separate phases.

*Reaction 4,* which is a combination of a dehydration and decarbonation reaction, will shift to lower temperatures when H<sub>2</sub>O and CO<sub>2</sub> mix, since the effect is to dilute both. However, for reactions such as *Reaction 5,* which have a different fluid on each side, it is not always clear what will happen if fluid composition changes.

### T-X Diagrams Work Better

Because reactions involving  $H_2O$  and  $CO_2$  are so sensitive to fluid compositions, we often plot them on T-X diagrams, such as the one shown in Figure 2. T-X diagrams show the temperature at which a reaction will occur, depending on fluid composition.

To construct a T-X diagram, we must assume a pressure. For Figure 2, the pressure is 5 Kbar.

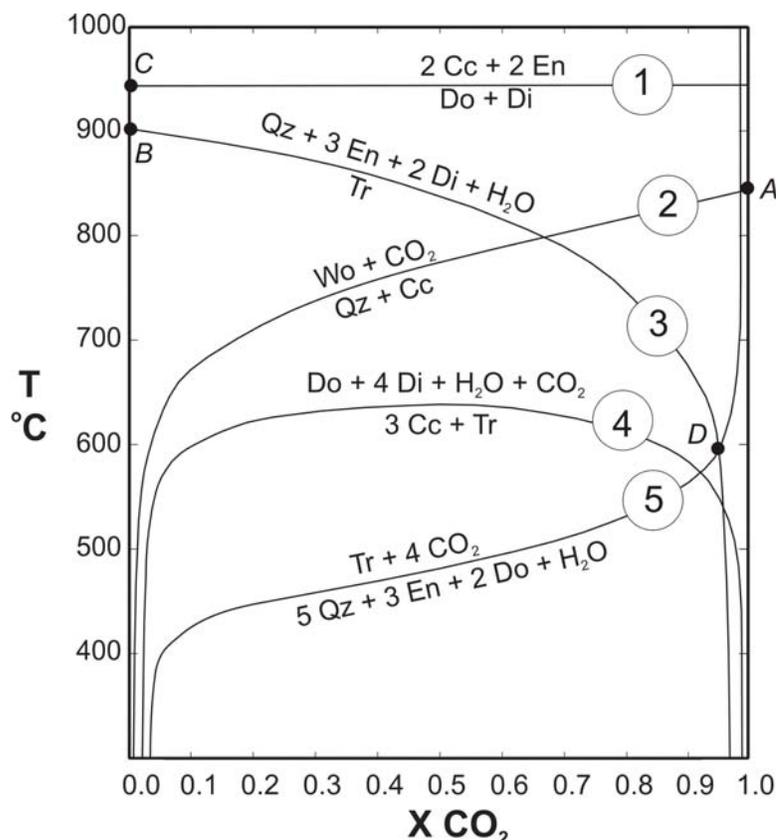
Figure 2 shows the same reactions as in Figure 1, but at constant pressure. The X-axis shows the composition of the fluid present in the system from  $X_{CO_2}=0$  (pure  $H_2O$ ) to  $X_{CO_2}=1$  (pure  $CO_2$ ).

*Reaction 1* involves neither  $H_2O$  nor  $CO_2$ . So, in Figure 2, it plots as a straight line. It is not affected by changing fluid composition. Point C in Figure one shows the temperature at which this reaction occurs at 5 Kbar. It corresponds to point C and the reaction curve labeled 1, in Figure 2.

Similarly, points A and B in Figure 1 are the same as points A and B in Figure 2. They represent the conditions at which the decarbonation *Reaction 2* (or the dehydration *Reaction 3*) will take place if the fluid is pure  $CO_2$  (or pure  $H_2O$ ).

Several things are worth pointing out about T-X diagrams:

- Solid-solid reactions plot as straight lines (see *Reaction 1*).
- If  $H_2O$  or  $CO_2$  appear on one side only of a reaction, they are on the high temperature side (*Reactions 2 and 3*).
- The reaction curves for decarbonation reactions terminate on the pure  $CO_2$  side of the diagram but are asymptotic to the pure water ( $X_{CO_2}=0$ ) side. The temperature of reaction goes down as more  $H_2O$  is added to the fluid (see *Reaction 2*).



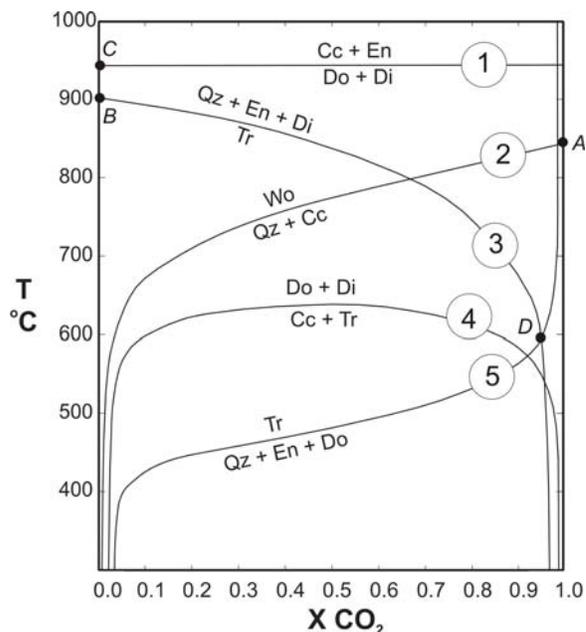
**Figure 2.** Some reactions in the system  $CaO-MgO-SiO_2-H_2O-CO_2$  at 5 Kbar. *Reaction 1* is a solid-solid reaction. *Reaction 2* is a decarbonation reaction. *Reaction 3* is a dehydration reaction. The other two involve both  $H_2O$  and  $CO_2$ . The intersection of *Reactions 3* and *5* creates an invariant point. The other crossing reactions contain too many phases between the two of them, and so are "indifferent crossings."

- The reaction curves for dehydration reactions terminate on the pure water side of the diagram but are asymptotic to the pure CO<sub>2</sub> side ( $X_{CO_2} = 1$ ). The temperature of reaction goes down as more CO<sub>2</sub> is added to the fluid (see *Reaction 3*).
- Reactions involving both H<sub>2</sub>O and CO<sub>2</sub> are asymptotic on both sides of the diagram. If H<sub>2</sub>O is on the low-temperature side of the reaction, the curve is asymptotic downward on the H<sub>2</sub>O side of the diagram. If H<sub>2</sub>O is on the high-temperature side of the reaction, the curve is asymptotic upward on the H<sub>2</sub>O side of the diagram. Similar relationships hold for CO<sub>2</sub> and the CO<sub>2</sub> side of the diagram.
- A dehydration reaction will always take place if the fluid is pure CO<sub>2</sub>. For example, *Reaction 3* (Figure 2) will proceed to the right at all temperatures if fluid is 100% CO<sub>2</sub>.
- A decarbonation reaction will always take place if the fluid is pure H<sub>2</sub>O. For example, see *Reaction 2* in Figure 2.

### Fluid Assumed Present

Because fluid is assumed present, and because the X-axis tells the composition of the fluid, reactions on T-X diagrams are generally labeled with H<sub>2</sub>O and CO<sub>2</sub> omitted. Additionally, it is seldom useful to include the reaction coefficients. So, Figure 3 is a more typical version of the diagram in Figure 2.

Although in reality, an H<sub>2</sub>O-CO<sub>2</sub> fluid is one phase (because the two components mix), when we balance and write reactions, we assume that H<sub>2</sub>O and CO<sub>2</sub> are separate. This leads to some problems/complications. Recall the two metastable reactions in Figure 1 (because the fluid cannot be both pure CO<sub>2</sub> and pure H<sub>2</sub>O.) For reactions involving fluids, the temperature (and pressure) of reaction depend on fluid composition. That is why such reactions are best depicted on a T-X diagram instead of a T-X diagram.



**Figure 3.** T-X diagram showing the same reactions as in the previous diagrams. In this figure, the H<sub>2</sub>O and CO<sub>2</sub> have been omitted from the reaction labels, as have the reaction coefficients.

## T-X Diagrams and the Phase Rule

Because we only have two dimensions on a piece of paper, T-X diagrams are constructed at a fixed pressure. Similarly, less-commonly-used P-X diagrams are constructed for a fixed temperature. For both, there is only one *intensive parameter* that can vary. So, the phase rule for these diagrams (if fluid is considered to be 1 phase) is modified to be:

$$C + 1 = P + F$$

According to this (revised) version of the phase rule, for a 5-component system, a normal univariant reaction should involve 5 phases. Let's count the phases involved in the reactions shown on Figure 2. The five reactions involve:

*Reaction 1:* calcite, enstatite, dolomite, diopside (4 phases)

*Reaction 2:* wollastonite, quartz, calcite, fluid (4 phases)

*Reaction 3:* quartz, enstatite, diopside, tremolite, fluid (5 phases)

*Reaction 4:* dolomite, diopside, calcite, tremolite, fluid (5 phases)

*Reaction 5:* tremolite, quartz, enstatite, dolomite, fluid (5 phases)

The first two reactions are degenerate—they contain fewer than the number of phases allowed.

Note: It is more difficult to see that reactions are consistent with the phase rule when they are depicted without H<sub>2</sub>O and CO<sub>2</sub> labeled, as in Figure 3.

Invariant points in T-X diagrams are similar to invariant points in P-T diagrams. Look at Figure 3. There are three points where reaction lines cross. However, only the intersection of *Reactions 3* and *5* (at point *D*) creates an invariant point. At this point, 6 phases (quartz, enstatite, diopside, tremolite, dolomite, and fluid coexist). The other two reaction crossings are *indifferent crossings* because they involve 7 phases.

Four reactions intersect at the invariant point D, although only two are shown in Figures 2 and 3. The original two reactions are (with phases absent shown in parentheses):

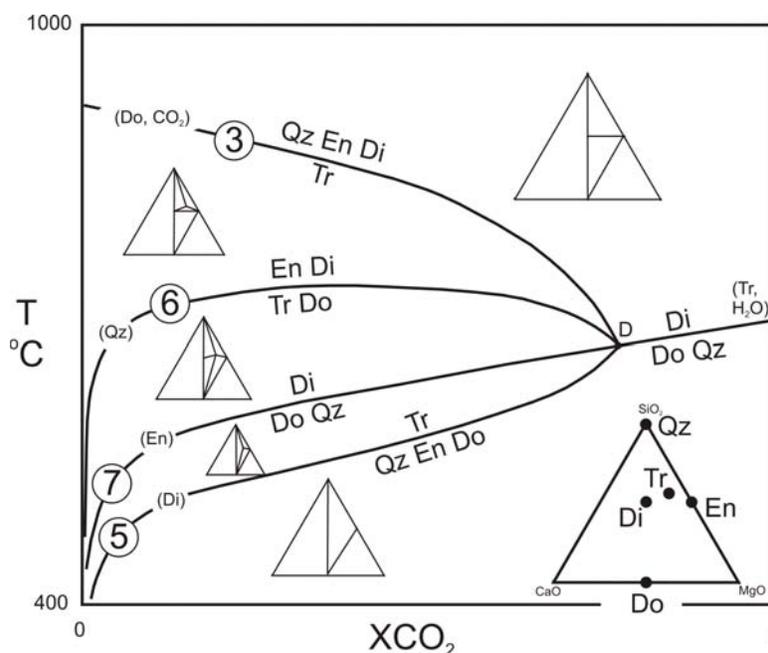


The other two are:



The first of these reactions is *degenerate* (missing 2 phases), and the last is *doubly degenerate* (missing 3 phases).

Conducting a *Schreinemakers analysis* (figuring out which reactions are stable or metastable at an invariant point) of an invariant point on a T-X diagram is the same as for a T-X diagram, except that fluid is assumed to be present. All four reactions are shown intersecting in Figure 4.



**Figure 4.** The invariant point (D) at which quartz, enstatite, diopside, tremolite, dolomite and fluid coexist. The chemical system being considered is CaO-MgO-SiO<sub>2</sub>-H<sub>2</sub>O-CO<sub>2</sub>. This diagram only involves 5 minerals; if other minerals are considered, some of the reactions shown become metastable. The diagram was calculated for a pressure of 8 Kbar. However, the invariant point has been shifted slightly to the left for clarity.

The reactions at the invariant point obey all the Schreinemakers rules. Note that one of the degenerate reactions (*Reaction 7*) passes through the invariant point. The other three reactions (including the other degenerate reaction) terminate there.

### Error in Textbook?

Figure 5 comes from John Winter's book *An Introduction to Igneous and Metamorphic Petrology*. It depicts reactions in a 5-component system, CaO-MgO-SiO<sub>2</sub>-CO<sub>2</sub>-H<sub>2</sub>O.

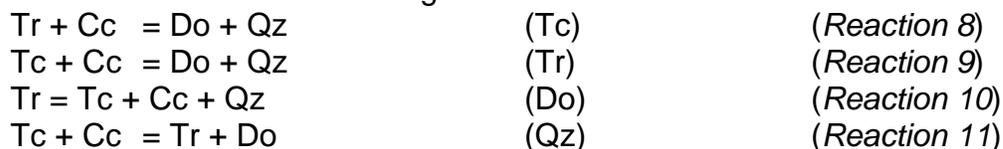
According to the (*revised*) phase rule, univariant reactions will involve 5 phases (unless they are degenerate). So, reactions can involve 4 solid phases and a fluid, or 5 solid phases and no fluid (but notice that no solid-solid reactions are shown on this particular diagram - Figure 5.)

11 phases are involved in reactions in Figure 5: Tr, Tc, Cc, Qz, Do, Fo, Di, Wo, Pe, Mnt, and fluid. However, fluid is NOT shown as a product or reactant on any of the reactions in this figure, because *it is assumed that fluid must be present whenever we use T-X diagrams*.

Take a closer look at the invariant point labeled A. Here, we have the following 6 phases coexisting: tremolite, quartz, talc, calcite, dolomite, fluid.

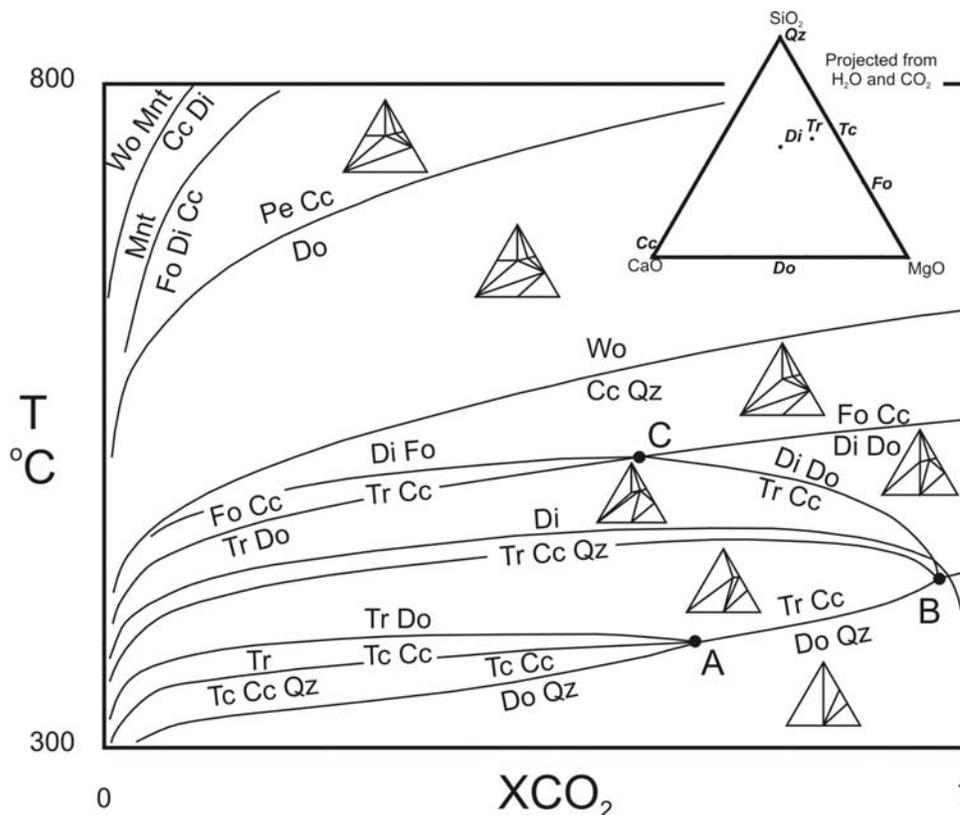
If we separate the fluid into both species, we have: tremolite, quartz, talc, calcite, dolomite, H<sub>2</sub>O, and CO<sub>2</sub> (7 phases).

The 4 reactions shown on the diagram are:



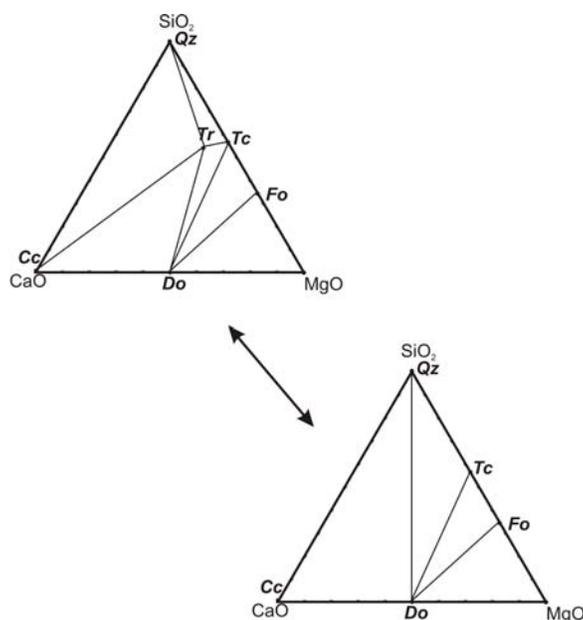
So, what about the reactions "missing" Cc, H<sub>2</sub>O, and CO<sub>2</sub>? Why were they left off the diagram? Winter may have made a goof when he drafted this figure.

Another way to see that reactions are missing is to note that you cannot get from the compositional triangle up and to the left of point A to the triangle down and to the right of point A simply by crossing the reaction  $\text{Tr} + \text{Cc} =$



**Figure 5.** Phase relationships in the system CaO-MgO-SiO<sub>2</sub>-CO<sub>2</sub>-H<sub>2</sub>O at 0.1 GPa (1 Kbar). This figure is copied from Winter's *An Introduction to Igneous and Metamorphic Petrology*.

Do + Qz. Try it and see. To get from one of the compatibility diagrams to the other means changing more than one tie line.

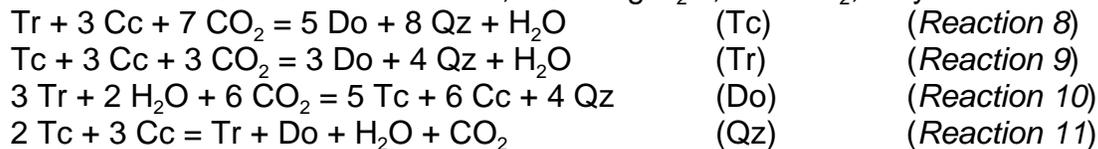


**Figure 6.** Two of the compatibility diagrams from Figure 5. It is impossible to get from one to the other without crossing more than 1 reaction.

Or, notice that, at the invariant point, there is a reaction labeled (Do) on the previous page. It limits tremolite's stability. (Remember, we are assuming that  $H_2O$  and  $CO_2$  are present.) It comes into point A and stops. If one reaction limits tremolite's stability. Either this reaction must pass through the invariant point or some other reaction must leave point A that limits tremolite's stability too.

The above is an example of a  $180^\circ$  rule violation: *a phase or assemblage (in this case we are talking about tremolite) cannot be stable for more than  $180^\circ$  around an invariant point unless it is stable everywhere.*

If we wish to balance the four reactions, including  $H_2O$ , and  $CO_2$ , they are:



We can add/subtract any two of the above to get the other reactions:

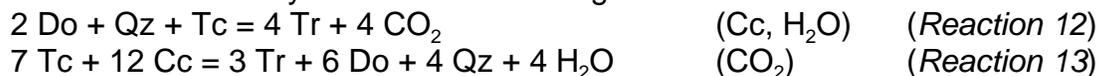


Figure 7 shows the original 4 reactions. If we carry out a Schreinemakers analysis, we find that the missing reactions plot as shown in Figure 8.

If we were looking at an invariant point on a T-X diagram, then Figure 8 would be correct. However, for T-X diagrams to apply, fluid must be present. Consequently, the (CO<sub>2</sub>) reaction must be metastable (because it involves phases that cannot exist where it is shown if fluid is present.)

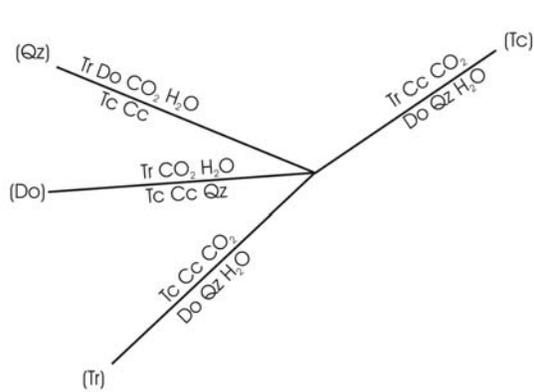


Figure 7. Some reactions involving Tc-Tr-Do-Qz-Cc around the invariant point.

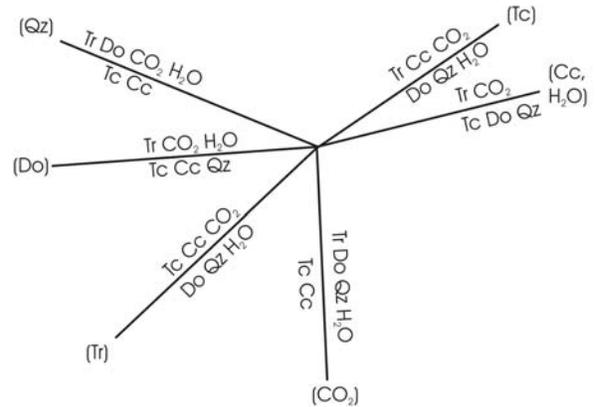


Figure 8. The same invariant point as in the previous figure, but with the two missing reactions added.

If we eliminate the (CO<sub>2</sub>) reaction, remove H<sub>2</sub>O and CO<sub>2</sub> from the reaction labels, and add compatibility triangles, we get the result in Figure 9. So, we see that Winter did mistakenly omit one reaction from his figure. The other missing reaction, however, is metastable everywhere.

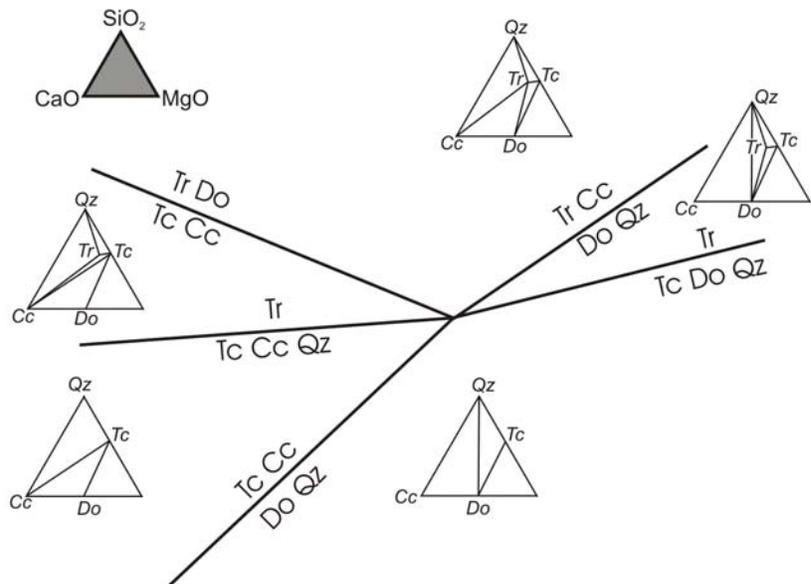


Figure 9. The same invariant point as in the previous two figures, but with all metastable reactions omitted.

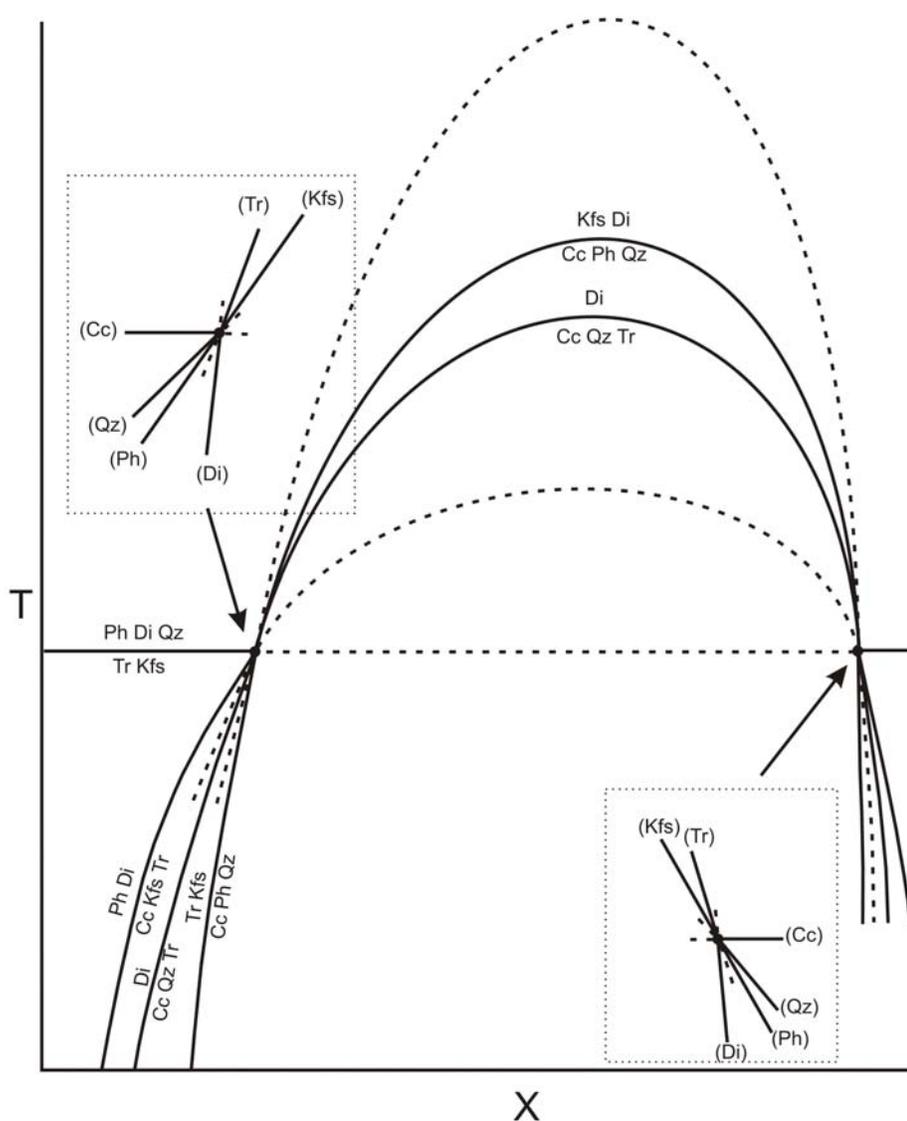
### The Same Invariant Point Twice

Figure 10 shows another interesting aspect of some T-X diagrams: the same invariant point can exist at two places.

While it is theoretically possible to have this happen on a P-T diagram, it rarely does. On T-X diagrams involving multiple components, it is quite common. Note that the two invariant points form an *enantiomorphic pair*.

Figure 10 also serves to remind us of how important fluid composition is. If the fluid is very H<sub>2</sub>O rich or very CO<sub>2</sub> rich, the stable mineral assemblages will be the same. They don't change much with changes in temperature.

At intermediate fluid compositions, however, the assemblages Cc-Qz-Tr and Cc-Ph-Qz (which are never stable for fluids close to pure H<sub>2</sub>O or pure CO<sub>2</sub>) are stable to high temperature. Note also that an assemblage containing Tr-Kfs is stable only for very H<sub>2</sub>O or very CO<sub>2</sub> rich fluids. It is never stable for intermediate fluid compositions.

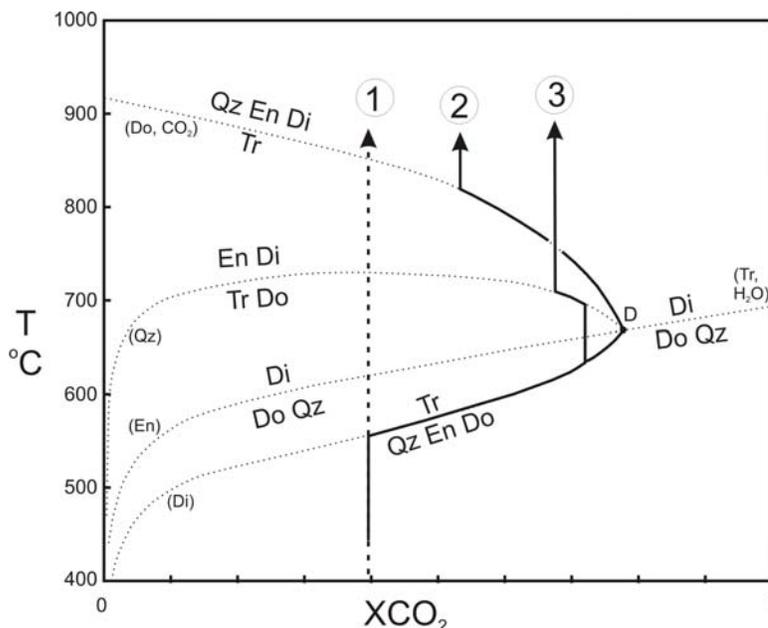


**Figure 10.** T-X diagram showing some reactions in the  $K_2O$ - $CaO$ - $MgO$ - $Al_2O_3$ - $SiO_2$ - $H_2O$ - $CO_2$  system. Metastable reactions are shown as dashed lines. The two invariant points are mirror images of each other.

## Reactions Can Buffer Fluid Composition

When reactions involving H<sub>2</sub>O or CO<sub>2</sub> occur, they may change the composition of fluid in a rock.

Decarbonation reactions, for example, release CO<sub>2</sub>, so the fluid will become richer in CO<sub>2</sub>. Dehydration reactions release H<sub>2</sub>O, making the fluid more H<sub>2</sub>O rich. Reactions that release both CO<sub>2</sub> and H<sub>2</sub>O may drive the fluid composition in either direction, depending on which species is released in the greatest amount. Fluid composition will only remain constant if the rock is an *open system* – if fluid of some fixed composition is flowing through the rock so that fluid composition is externally controlled.



**Figure 11.** Reactions involving tremolite, quartz, enstatite, dolomite and diopside. The numbered lines show how mineral reactions may buffer fluid composition. This is the same phase diagram as Figure 4.

**Case 1.** Consider the diagram in Figure 11 (the same reactions as in Figure 4).

Consider a rock containing Qz-En-Do and a fluid that is about 40% CO<sub>2</sub>. If it starts out at low temperature and is heated, it will follow the vertical dashed line shown (and labeled #1), provided fluid composition is externally controlled and remains constant.

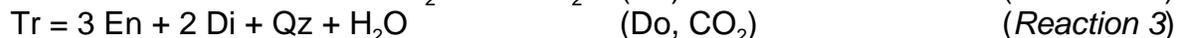
So, Tr will begin to form at about 550 °C by the reaction:



As this reaction takes place, Qz, En and Do will disappear. Eventually one of them will be completely gone. The reaction will cease and temperature will once again increase until the next reaction is reached at about 610 °C:



The process will continue. temperature will increase, and the next two reactions will be crossed at about 715 and 870 °C:



In the end, the final mineral assemblage depends on the fluid and minerals that were there in the first place.

**Case 2.** Suppose the fluid composition is not externally controlled -- that it is entirely controlled by reactions taking place in the rock. In this case, once *Reaction 5* starts to take place, the fluid will change to a more CO<sub>2</sub> rich composition. As temperature increases, tremolite will form and the fluid will follow the line for *Reaction 5* (Di), as shown on Figure 11 (curve labeled #2). So, the fluid composition is *buffered* by the mineral assemblage.

Eventually the fluid composition may reach the invariant point (D) where diopside will begin to form. Diopside will continue to grow until either dolomite or tremolite are gone.

The line labeled #2 in Figure 11, shows what happens if dolomite runs out first. From point D, the fluid follows the (Do, CO<sub>2</sub>) curve (to higher temperatures and more water-rich compositions) while tremolite breaks down. Eventually, when all the tremolite is gone, reaction will stop and temperature will increase with no change in fluid composition or mineral assemblage. (If, at point D, all the tremolite had been used up before dolomite, the fluid composition would have followed the (Tr, H<sub>2</sub>O) curve up and to the right of the invariant point.)

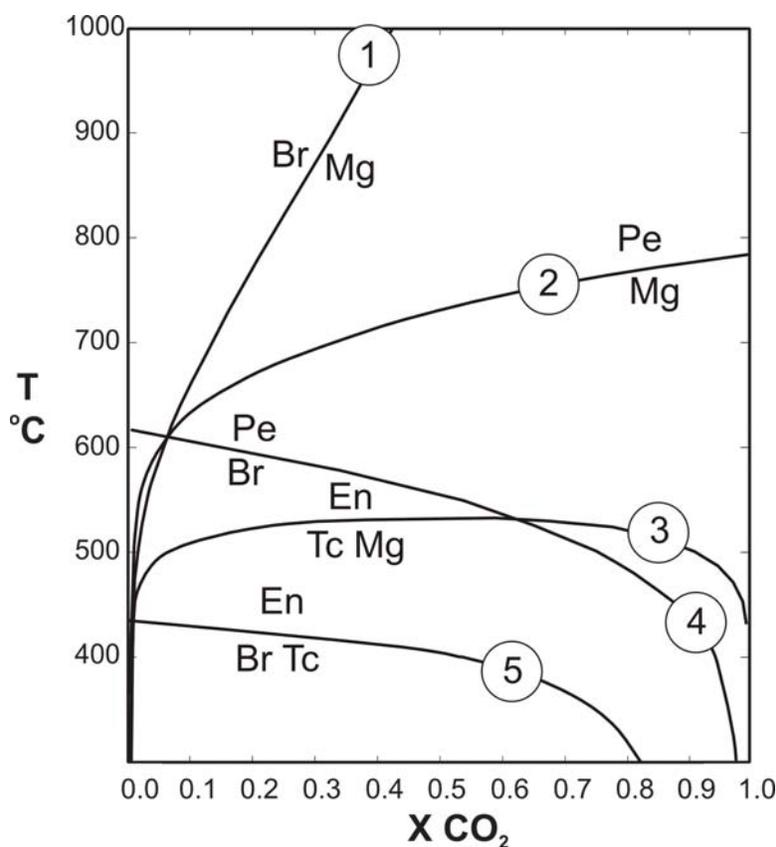
**Case 3.** The line labeled #3 in Figure 11 shows a third possibility, intermediate to the two described above. In this case, as *Reaction 5* (Di) takes place, quartz runs out before the fluid reaches the invariant point (D). Temperature then increases with no change in fluid composition until the (Qz) reaction is reached. Then Tr+Do react to form En+Di, driving fluid to more water-rich compositions. Soon, however, the Tr is all gone, so reaction stops and temperature increases with no subsequent change in fluid composition or mineral assemblage.

There are many more possibilities than the three described above. Different mineral assemblages will be produced in different parts of T-X space, depending on composition (see the triangular compatibility diagrams in Figure 4). The controlling factors are the minerals present in the original rock, the original composition of the fluid, and the ratio of fluid to solid.

### Problems

**Problem 1.** Look at Figure 10. One reaction (that plots as a horizontal line) is a *solid-solid reaction*. The others all have about the same shape, and are very dependent on fluid composition. What kinds of reactions are these? Do they involve H<sub>2</sub>O or CO<sub>2</sub> and, if so, are H<sub>2</sub>O and CO<sub>2</sub> on the high temperature or low-temperature side of these reactions?

**Problem 2.** a. On the diagram shown below, add the H<sub>2</sub>O and CO<sub>2</sub> to the reaction labels, taking care to put them on the correct side of the reaction curves. Reactions may involve both H<sub>2</sub>O and CO<sub>2</sub>, one or the other of them, or neither.



**Figure 12.** Reactions involving some phases in the system MgO-SiO<sub>2</sub>-H<sub>2</sub>O-CO<sub>2</sub> at 1 Kbar.

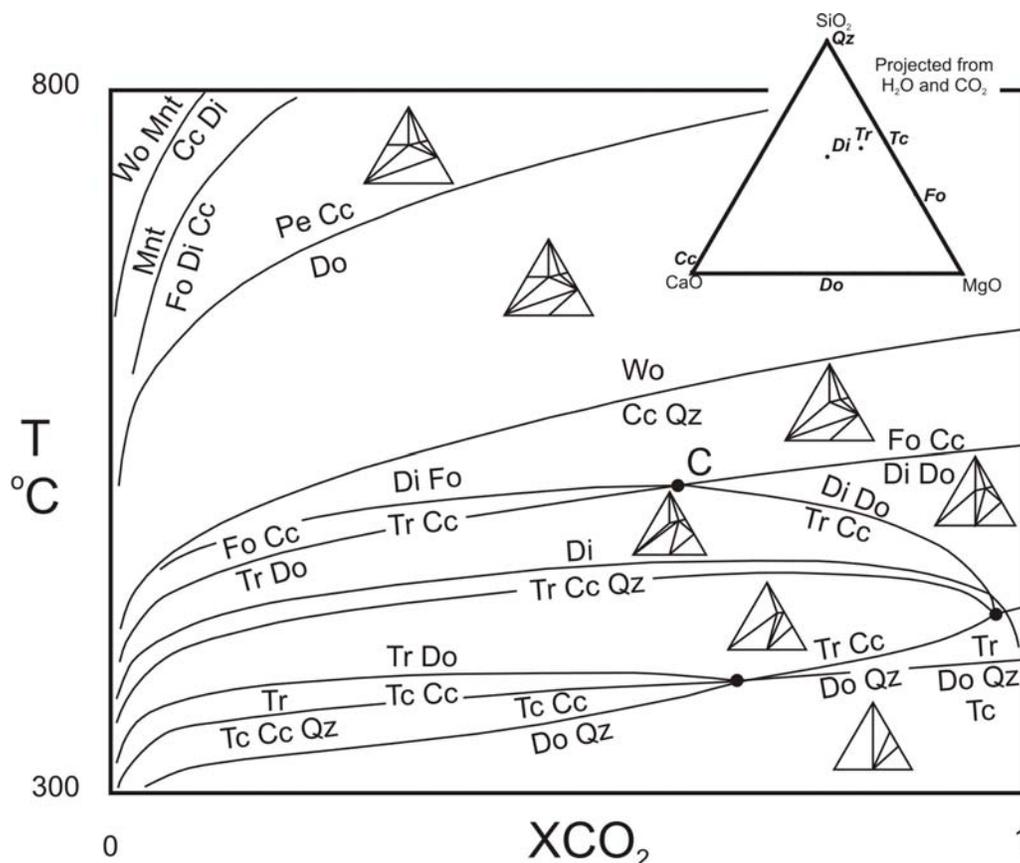
b. There is an invariant point in Figure 12 where *Reactions 1,2 and 4* intersect, and Br-Mg-Pe coexist. Make an enlarged view of that invariant point and show the stable and metastable parts of the three reactions.

**Problem 3.** Consider the diagram below. Where on this diagram are the following minerals/assemblages stable?

*Note, this is the same diagram that was missing a reaction before (Figure 5). I added the missing reaction that was already identified. Perhaps you will find another missing reaction? If so, explain.*

- talc
- dolomite
- tremolite
- diopside + dolomite
- forsterite + diopside
- diopside + tremolite + quartz
- talc + quartz + dolomite
- talc+ quartz + calcite + tremolite
- talc + calcite + wollastonite + dolomite
- tremolite + calcite + forsterite + diopside + dolomite
- tremolite + calcite + forsterite + diopside + periclase

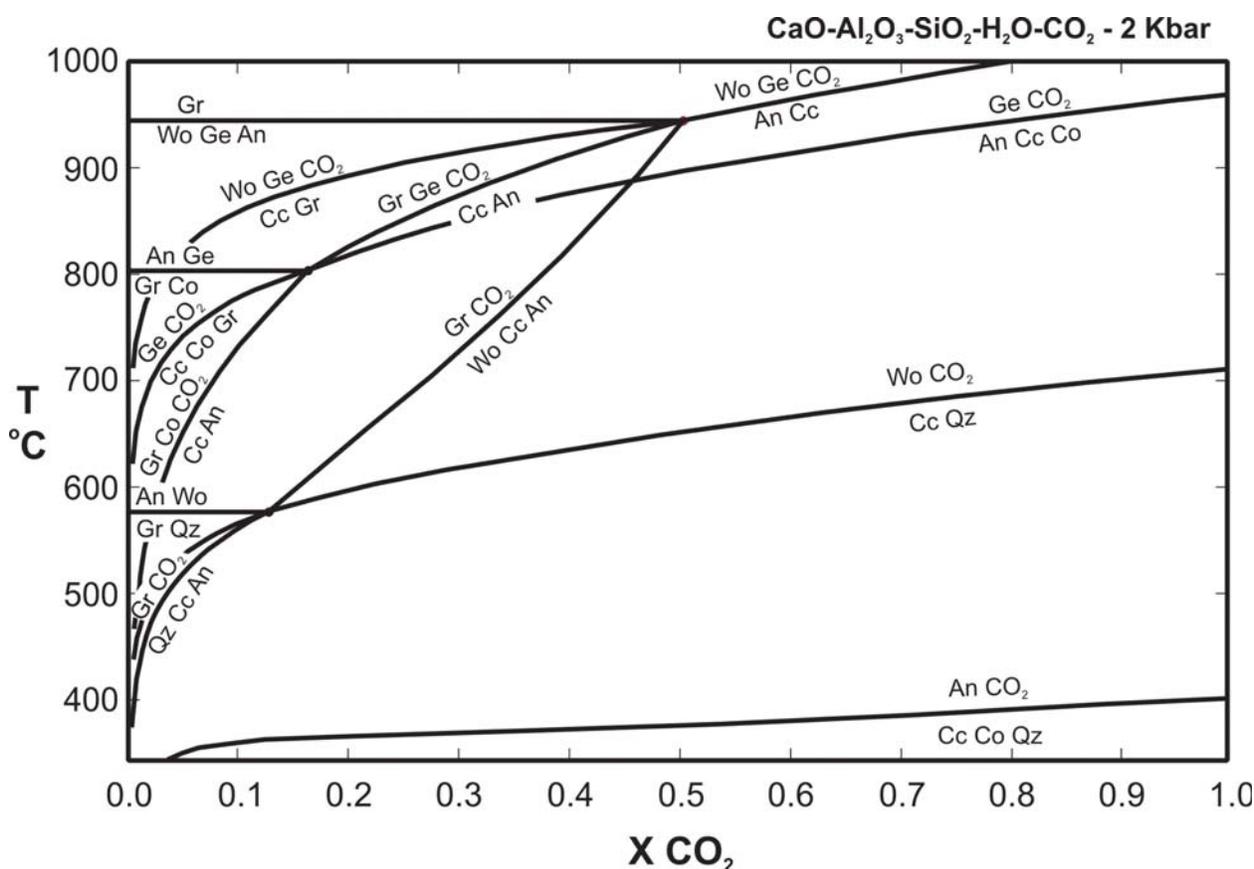
Use arrows or shading or whatever you wish to show your answer. But, make your answers clear.



**Figure 13.** Phase relationships in the system CaO-MgO-SiO<sub>2</sub>-CO<sub>2</sub>-H<sub>2</sub>O at 0.1 GPa (1 Kbar). This figure is copied from Winter's *An Introduction to Igneous and Metamorphic Petrology*.

**Problem 4.** Consider the phase diagram below. It shows important reactions that occur in a low-Mg carbonate rock during metamorphism.

- Suppose the original rock is a limestone that contains only calcite. According to the phase diagram, how will the mineralogy of the rock change during metamorphism? Will the results be the same for both relatively H<sub>2</sub>O-rich fluids and relatively CO<sub>2</sub>-rich fluids?
- Suppose the original rock is not so pure. It contains 90% calcite and 10% quartz. According to the phase diagram, how will the mineralogy of the rock change during metamorphism? Will the results be the same for both relatively H<sub>2</sub>O-rich fluids and relatively CO<sub>2</sub>-rich fluids?



**Figure 14.** Phase diagram showing reactions at 2 Kbar that involve calcite and a number of silicates. Note that the reaction  $Cc + Qz = Wo + CO_2$  is degenerate and passes through the invariant point in the lower left part of the diagram.

- Suppose that the original rock contains 80% calcite, 15% quartz, and 5% anorthite. (This is close to many natural carbonate rocks.) According to the above phase diagram, how will the mineralogy of the rock change during metamorphism? Will the results be the same for both relatively H<sub>2</sub>O-rich fluids and relatively CO<sub>2</sub>-rich fluids?

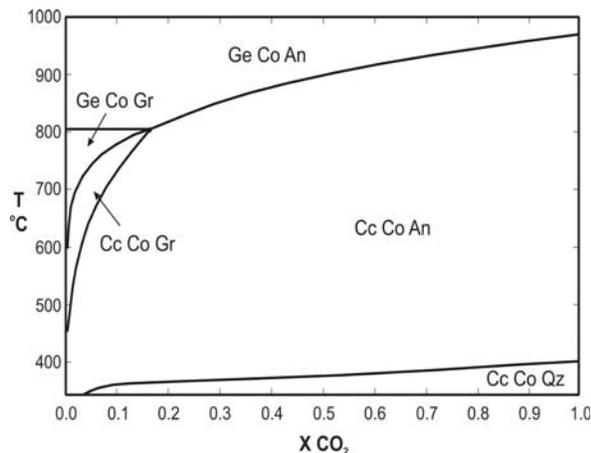
This problem (part C) is more complicated than the last two. You can logic it out by looking at the phase diagram and reactions, but you may find it easier to look at the

animated pdf file available at:

[http://serc.carleton.edu/files/research\\_education/equilibria/cashtx\\_animation.pdf](http://serc.carleton.edu/files/research_education/equilibria/cashtx_animation.pdf)

In particular, look at the triangular compatibility diagrams there and figure out where the 80-15-5% composition plots.

d. *Construct a pseudosection:* Consider only your result to part c, above. Make a new drawing of the phase diagram that only includes reactions that affect a rock that starts out as 80% calcite, 15% quartz, and 5% anorthite. Instead of labeling the reaction curves, label the stable mineral assemblages that are present in the different parts of T-X space. The drawing below (for a rock of a different composition) will give you an idea of what your results should look like, but your diagram will have different fields and curves.



**Figure 15.** A 2 Kbar pseudosection for a rock that contains about equal amounts of  $\text{CaO}$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{SiO}_2$ . If pressure was different, or if composition was different, the fields and field boundaries would not be as shown here.

If you complete your drawing correctly, you will have a *pseudosection* for a rock that started with 80% calcite, 15% quartz, and 5% anorthite.

e. For the 80-15-5% composition being considered, is the stable metamorphic assemblage the same for fluids of all compositions? Are the assemblages different if the fluid is  $\text{H}_2\text{O}$ -rich or if it is  $\text{CO}_2$ -rich? If not, explain why not. If so, explain in a general sense what is going on that makes the difference.

f. Under what conditions will this rock contain garnet?

**Problem 5.** Consider the phase diagram in Figure 16, below. It includes two reactions:  $Cc + Co + 2 Qz = An + CO_2$  and  $Cc + Qz = Wo + CO_2$ .

Assume you have a rock that contains 90% minerals (70% calcite, 15% quartz, and 5% corundum) and 10% fluid. The fluid composition is  $X_{CO_2}=0.45$ .

The rock starts at room temperature and is metamorphosed. Heat is added, and the rock encounters the first reaction at about 440°C. Eventually, after more reactions, the temperature reaches 800°.

- On the phase diagram, draw a line/curve to show how the composition of fluid changes as metamorphism occurs. You can be very specific. See Figure 11 for examples.
- At what temperature will anorthite appear in the rock?
- At what temperature will wollastonite appear in the rock?
- What will be the final composition of the fluid?
- What will be the final mineral assemblage?

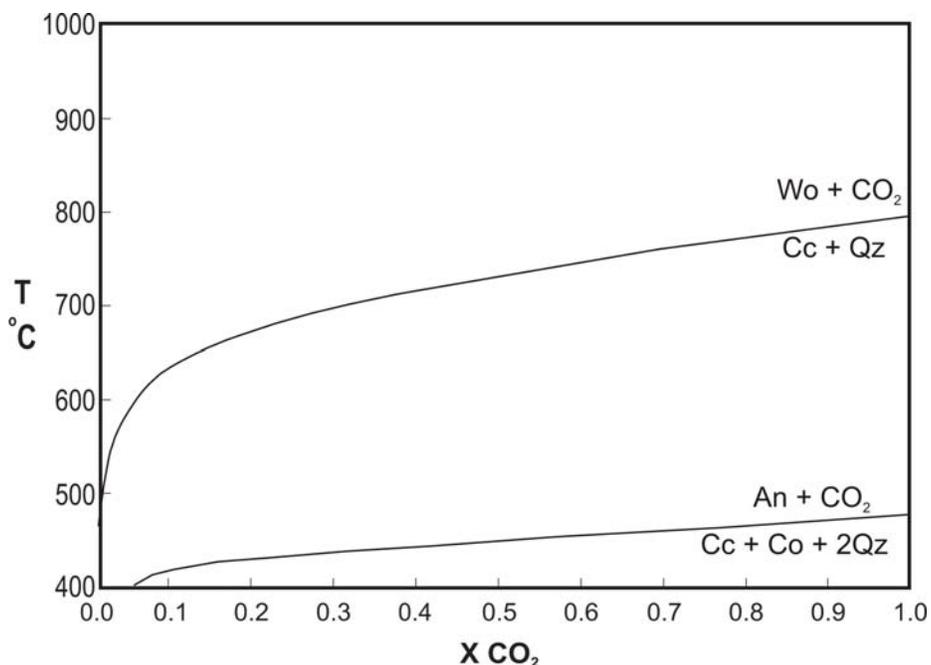
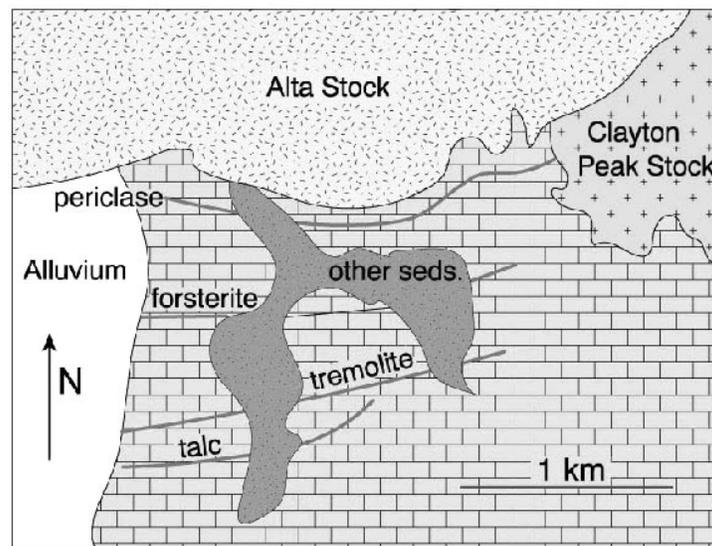


Figure 16. Two reactions in the  $CaO-Al_2O_3-SiO_2-CO_2$  system

- Suppose that the rock contains significantly more than 10% fluid. How will the results differ?
- Suppose that the rock contains  $\ll 1\%$  fluid. How will the results differ?

**Problem 6.** Metamorphic petrologists use *index minerals* to estimate metamorphic grade. Some minerals form at low temperature, some require higher temperature.

a. Look at Figure 13 (Problem 3). In what order do minerals appear as temperature increases. You may assume that calcite, dolomite and quartz are present in the original rock. The question is, in what order do the other minerals appear? Of course, fluid composition plays a role. But, in general, which minerals are low temperature minerals,



**Figure 17.** Isograds near Alta, Utah. This figure is modified from one on D.J. Henry's Geology 3041 web page: <http://www.geol.isu.edu/henry/Geology3041/lectures/29MetaCalcUm/Fig29-2.jpg>

etc.? Make a list in order from low-temperature to high-temperature minerals.

Figure 17 shows geology of a *contact aureole* near Alta, Utah. Four isograds are mapped – these are lines showing the first appearance of talc, tremolite, forsterite, and periclase. The person who made this map interpreted these isograds to mean that heat from the Alta Stock was responsible for metamorphosing the original limestone.

b. Do the minerals at Alta appear in the same order that you listed in the first part of this question? Discuss differences and/or similarities. If the agreement is good, explain why. If not, why not?

c. Can you tell from the order of the isograds at Alta, whether the metamorphism occurred in the presence of an H<sub>2</sub>O-rich fluid or a CO<sub>2</sub>-rich fluid, or somewhere between? Explain.

d. Do you agree with the geological interpretation? Did heat from the Alta Stock cause the metamorphism?

**Problem 7.** On the phase diagram in Problem 5, the two curves become asymptotic to the left-hand side. So, the high temperature assemblages ( $Wo+CO_2$  or  $An+CO_2$ ) are stable to very low temperature if the fluid is nearly 100%  $H_2O$ . Why is this? Explain, in layman's terms, using logic, why this makes sense. Why do the lines typically go asymptotic on one or both sides of a T-X diagram? (Don't just tell me it is because something is unstable there, etc. Tell me why things are the way they are.)

**Problem 8.** On all the T-X diagrams you have seen, the stability of carbonate phases (e.g., calcite) is decreased if the fluid contains little  $CO_2$ , compared to a fluid that is rich in  $CO_2$ . The stability of hydrous phase is decreased if the fluid contains little  $H_2O$ , compared to a fluid that is rich in  $H_2O$ . Why? Explain, in layman's terms, using logic, why this makes sense.