THERMOBAROMETRY HOMEWORK

You collect a rock that contains the assemblage *Garnet + Biotite + Muscovite + Kyanite + Plagioclase + Quartz* from an area that you think was involved in **continent-continent collision followed by rapid unroofing**. In order to evaluate this hypothesis, you analyze the minerals with the electron microprobe and use the compositions to calculate *P-T* conditions of equilibration for the rock. You are lucky enough to find garnets with inclusions of biotite, plagioclase, kyanite, and quartz, and hence are able to determine an early set of *P-T* conditions as well as the conditions of final equilibration. See the attached page for a sketch of the sample and for the mineral analyses.

(a) Look at the compositions of the garnet and plagioclase grains. Does garnet get more or less calcic from core to rim? What about the plagioclase? Based on the **calcium data**, make a prediction: will the pressure calculated for Area 2 be higher or lower than the value for Area 1? What is the basis for your answer?

(b) Determine the pressure and temperature at which the **inclusion phases were entrapped** within the garnet, using the garnet-biotite thermometer and the garnet-plag-kya-qtz barometer and the compositional data from Area 1.

(c) Determine the conditions of **final equilibration** of the rock using the compositional data from Area 2, with the same thermometer and barometer as in (a).

(d) Comment on whether or not the calculated conditions of final equilibration are likely to be **representative of T_{max}** – what is the basis for your answer?

Choose **one** of the two methods outlined below to solve the thermometer and barometer equations. Regardless of which method you use, present your results on a **single *P-T* graph**, showing the early and late conditions of equilibration. Once you have graphed your results, use the *P-T* data to **evaluate the original tectonic hypothesis**. If you reject the original hypothesis, please **present an alternative explanation**. In either case, please **justify your answer!**
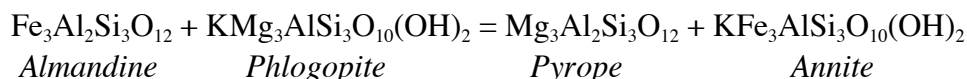
Method I. Using the equations given on the next page, solve for *P* and *T* by hand or using the math program of your choice. Note that you will need to solve the thermometer and barometer equations simultaneously, i.e., two equations in two unknowns. You will need to do this twice – once using the Area 1 compositions to get the early *P-T* conditions, and once using the Area 2 compositions to get the conditions of final equilibration. *Pay attention to the numbers that you calculate* – if they seem geologically unreasonable, you probably made a math error somewhere along the way! The simultaneous solution should not require more than about 10 lines of math.

Method II. Solve for *P* and *T* using the Excel program **GPTmodified.xls** (the program has been simplified from an original version written by J. Reche and F. Martinez). In order to determine *P-T* conditions, you will start by entering cation values for the different minerals in the yellow-shaded cells. Next, you will enter a reference *P* in order to calculate *T*, and a reference *T* in order to calculate *P* – your reference values go in the pink boxes near the bottom of the spreadsheet. The calculated *T* and *P* values will appear in the blue boxes. The easiest way to calculate *P-T* points for the inclusion and rim conditions is to do each set of calculations twice at different reference conditions, and then plot the resulting K_d lines and graphically determine their intersections. Example: Using the Area 1 compositions, do the temperature calculation at reference pressures of 4 and 12 kbar and note the resulting temperature in each case. Draw a straight line connecting (T_1, 4 kbar) and (T_2, 12 kbar). Then do the pressure calculation at temperatures of 400 and 800°C, and draw a straight line connecting (400°, P_1) and (800°C, P_2). The point where your two lines intersect represents the *P-T* conditions of equilibration of the inclusion assemblage. Alternatively, you can iterate *P* and *T* until your answers converge. Now repeat the process in order to determine the *P-T* conditions of final equilibration using the Area 2 compositions.

EXTRA CREDIT: Use both methods to solve the problem. Note that the answers you get differ. Speculate on **why** the two methods yield somewhat different calculated *P-T* conditions. There are several potential reasons….

Garnet-Biotite thermometer

The distribution of Fe and Mg between garnet and coexisting biotite is controlled by the temperature-sensitive reaction:

$$Fe_3Al_2Si_3O_{12} + KMg_3AlSi_3O_{10}(OH)_2 = Mg_3Al_2Si_3O_{12} + KFe_3AlSi_3O_{10}(OH)_2$$
$$\textit{Almandine} \qquad \textit{Phlogopite} \qquad \textit{Pyrope} \qquad \textit{Annite}$$

This distribution is described by the following equation:

$$\ell n K_{Fe-Mg}^{Gt-Bt} = -\left(\frac{52,108}{3R}\right)\frac{1}{T} + \frac{19.51}{3R} - P\left(\frac{0.238}{3R}\right)\frac{1}{T}$$

where

$$K_{Fe-Mg}^{Gt-Bt} = \frac{X_{Fe}^{Bt}/X_{Mg}^{Bt}}{X_{Fe}^{Gt}/X_{Mg}^{Gt}} = \frac{(Fe/Mg)^{Bt}}{(Fe/Mg)^{Gt}}$$

Use cation values, not oxides!!

Garnet-Plagioclase-Kyanite-Quartz barometer

The distribution of Ca between garnet and plagioclase, in the presence of kyanite and quartz, is controlled by the pressure-sensitive reaction:

$$3\,CaAl_2Si_2O_8 = Ca_3Al_2Si_3O_{12} + 2\,Al_2SiO_5 + SiO_2$$
$$\textit{Anorthite} \qquad \textit{Grossular} \qquad \textit{Kyanite}\;\;\textit{Quartz}$$
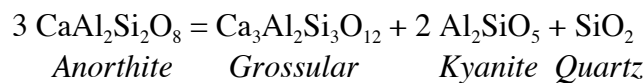
This distribution is described by the following equation:

$$\ell n K_{Ca}^{Gt-Pl} = \left(\frac{55,865}{R}\right)\frac{1}{T} - \frac{153.59}{R} + P\left(\frac{6.608}{R}\right)\frac{1}{T}$$

where

$$K_{Ca}^{Gt-Pl} = \frac{\left(a_{grs}^{Gt}\right)}{\left(a_{An}^{Pl}\right)^3}$$

$$a_{grs}^{Gt} = \left(\gamma_{grs}^{Gt}X_{grs}^{Gt}\right)^3 = \left[1.03\left(\frac{Ca}{Ca+Fe+Mg+Mn}\right)_{Gt}\right]^3$$

Use cation values!!

$$a_{An}^{Pl} = 1.35\left(X_{Ca}^{Pl}\right) = 1.35\left(\frac{Ca}{Ca+Na+K}\right)_{Pl}$$
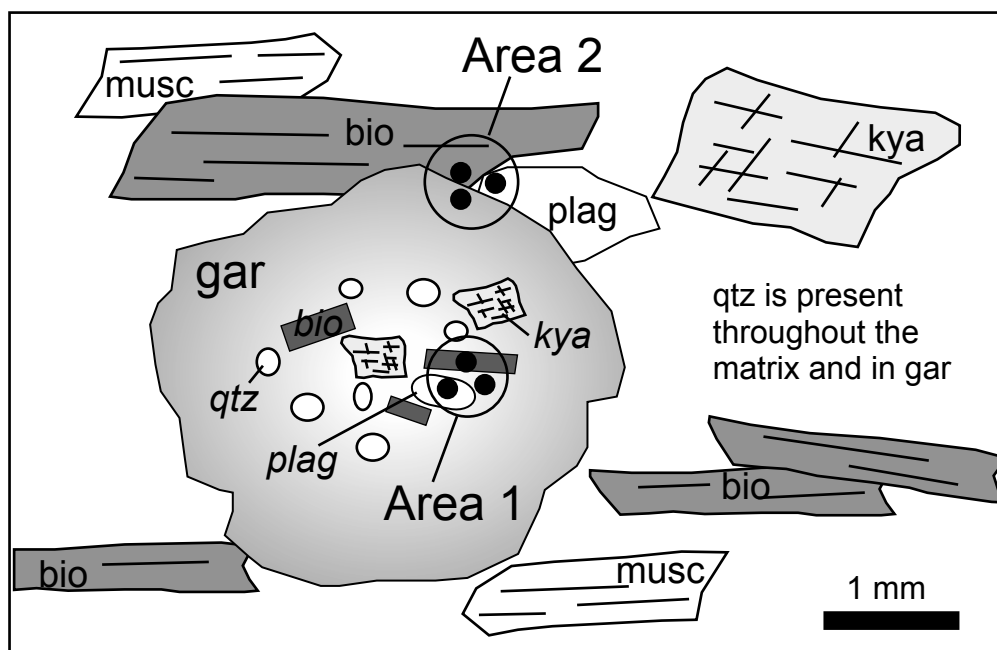
For both equations:

R = 8.314 J mol^{-1} K^{-1} (gas constant)
P is in bars, not kilobars!!
T is in Kelvins, not °C!! Make sure you convert. Please present your results in °C.
Please show all of your work so that I can follow each step.

(**Note**: the activity terms are simplified forms that are *approximately* correct for the conditions of this problem; in reality, the γ values are themselves functions of composition and temperature).

Area 2

musc

bio

kya

plag

gar

bio

kya

qtz is present throughout the matrix and in gar

qtz

plag

Area 1

bio

musc

1 mm

Area 1: inclusions in garnet
Area 2: garnet edge and adjacent minerals

	Garnet1 interior	Garnet2 rim	Biotite1 inclusion	Biotite2 matrix	Plag1 inclusion	Plag2 matrix
SiO2	37.38	36.85	35.33	37.65	61.55	58.79
Al2O3	21.45	21.76	18.76	16.57	24.41	26.70
TiO2	0	0	1.84	2.18	0	0
FeO	26.52	33.17	20.92	19.28	0	0
MgO	1.84	3.95	10.46	12.46	0	0
MnO	7.55	1.15	0	0	0	0
CaO	5.02	2.48	0	0	5.19	7.89
Na2O	0	0	0.21	0.09	8.41	7.23
K2O	0	0	8.44	8.49	0.28	0.12
total	99.87	99.43	95.96	96.73	99.85	100.83

wt% oxides

Cations

Si	3.00	2.96	2.68	2.80	2.73	2.61
Aliv	0	0	1.32	1.20	0.27	0.40
Alvi	2.03	2.06	0.36	0.25	1.00	1.00
Ti	0	0	0.10	0.12	0	0
Fe	1.78	2.23	1.32	1.20	0	0
Mg	0.23	0.47	1.18	1.38	0	0
Mn	0.51	0.08	0	0	0	0
Ca	0.43	0.21	0	0	0.25	0.38
Na	0	0	0.03	0.01	0.72	0.62
K	0	0	0.82	0.80	0.02	0.01

cations: use in calculations