

Geothermometry

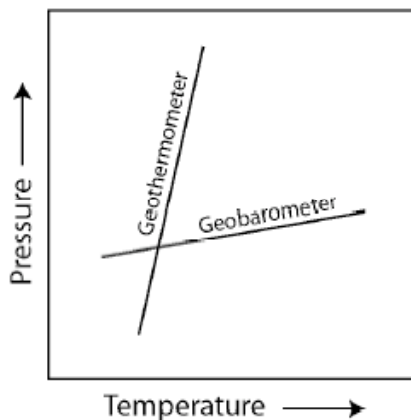
Introduction to thermobarometry

Geothermometers and geobarometers are mineral systems that may be used to estimate the absolute temperature and pressure that produced an equilibrium mineral assemblage in a metamorphic rock. Thermobarometry, or the determination of temperatures and pressures which occurred during metamorphism, represents a practical application of geochemical thermodynamics to petrology. Although time does not permit a thorough discussion of the principles and assumptions involved in applying thermobarometry, an example will hopefully serve to give you an appreciation for the possibilities.

For further investigation into this topic there are number of published sources; a place to start should involve a review of the theory behind thermobarometry as well as discuss different applications and/or limitations of various thermobarometers such as:

Essene, E.J., 1989, The current status of thermobarometry in metamorphic rocks, in: (J.S. Daly, R.A. Cliff, and B.W.D. Yardley, eds.) Evolution of Metamorphic belts, Geological Society Special Publication No. 43, p. 1-44.

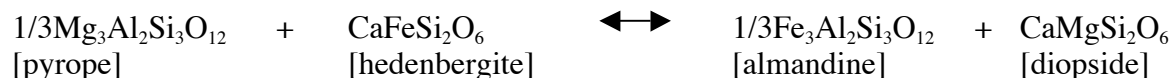
In general, for a particular reaction to be used as a geothermometer, it must be a strong function of temperature but be nearly independent of pressure. Conversely, a reaction that serves as a useful geobarometer is sensitive to pressure but not to temperature. See the diagram below:



Equilibrium curves for reactions that would make a good thermometer and a good barometer. The position of each of these curves is fixed at a given value of the distribution coefficient K_D . The geothermometer curve will be translated to the left, parallel to its present position, with increasing K_D . The geobarometer curve will be translated upward with increasing K_D , but it too will retain the same slope (after Faure, 1996).

Garnet-clinopyroxene thermometry: an example

For garnet-clinopyroxene thermometry, a commonly used geothermometer relies on using mineral assemblages that are involved in an Fe-Mg exchange reaction such as:



The partitioning of Fe and Mg between coexisting garnet and clinopyroxene is a function of temperature (and to a lesser extent) pressure. See the diagrams below:

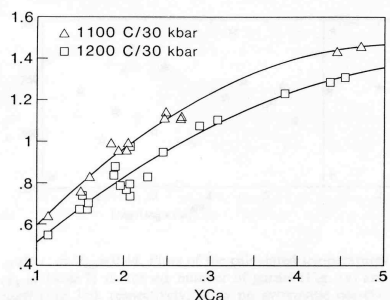


Fig. 1. X_{Ca} vs. ln K_d for experimental data at 1100 and 1200° C and 30 kbar, showing curvilinear relationships

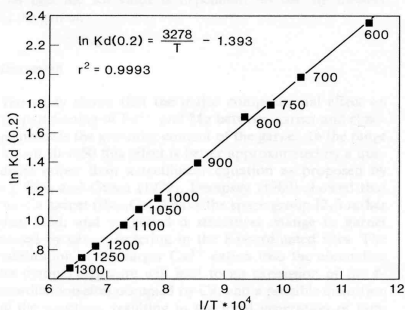


Fig. 2. 1/T vs. ln K_d normalised to X_{Ca}=0.20 and P=30 kbar, based on data from Table 1

(From Krogh, 1988)

You will use three different calibrations for Fe-Mg exchange in garnet and clinopyroxene based on different experimental data:

From Krogh (1988):

$$T = (1879 + (-6173(X_{Ca})^2) + 6731X_{Ca} + 10P)/(\ln K_d + 1.393) \tag{1}$$

From Powell (1985):

$$T = (2790 + 3140X_{Ca} + 10P)/(\ln K_d + 1.735) \tag{2}$$

From Ellis and Green (1979):

$$T = (3030 + 3140X_{Ca} + 10.86P)/(\ln K_d + 1.9034) \tag{3}$$

where,

T = temperature (in Kelvin);

P = pressure (kbar);

X_{Ca} = mole fraction of Ca in garnet; and

K_d = distribution coefficient = (X_{Fe2+}/X_{Mg})^{grt} / (X_{Fe2+}/X_{Mg})^{cpx}

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Create an Excel spreadsheet into which you can plug in data from chemical analyses of garnet and clinopyroxene and using the formulas given above. Here is an example:

Sample: xxxxx				
	<i>Garnet (mol)</i>	<i>Cpx (mol)</i>	<i>ln (K_D)</i>	<i>X_{Ca} in grt</i>
<i>Mg</i>	xxxx	xxxx	xxxx	xxxx
<i>Fe⁺²</i>	xxxx	xxxx		
<i>Ca</i>	xxxx	xxxx		
<i>P (kbar)</i>	xx			
	Krogh (1988) Powell (1985) Ellis and Green (1979)			
<i>T (K)</i>	xxxx	xxxx	xxxx	
<i>T (°C)</i>	xxxx	xxxx	xxxx	

For this assignment, you will assume a metamorphic pressure between 11 and 14 kbar, appropriate for granulite- to eclogite-facies metamorphism based on the mineralogy of the analyzed rocks. Be sure to convert your final calculated temperatures to °C.

Below are actual electron microprobe analyses (collected by me) showing moles of garnet-clinopyroxene pairs in thin sections of granulite- to eclogite-facies gabbros (collected by me) from the Lofoten Islands, Norway. These are the actual numbers that are generated by the program running the electron microprobe. Use these analyses for your calculations and interpretations:

Summary of the geology of the Lofoten Islands (for those who are interested)

The Lofoten Islands contains variably retrogressed eclogites within granulite-facies Proterozoic basement in northern Norway. These eclogites are often related to shear and mylonite zones suggesting that deformation and fluid access was important for their formation. The eclogitic rocks are restricted to gabbroic or troctolitic rock compositions and show, in the least retrogressed samples, the typical assemblage garnet + omphacite + rutile. The widespread occurrence of eclogite shows that the whole group of the Lofoten Islands was affected by high-pressure metamorphism; eclogites have been found on three of the five major islands so far (Flakstadøy, Vestvågøy, and Austvågøy). Geological, petrological and geochemical data suggest the following succession of events: (a) intrusion of mafic to mangeritic magmas (~1.8 Ga); (b) incomplete recrystallization under high-pressure granulite-facies conditions (locally complete recrystallization in intensely deformed zones); (c) eclogites formed in response to a significant pressure increase in the same high strain zones; and (d) post-eclogite retrogression occurred under intermediate- to high-pressure amphibolite-facies conditions (~1.1 Ga). Eclogite formation was related to crustal thickening during the final stages of Early Proterozoic magmatism and granulite-facies metamorphism. (Taken liberally from Markl and Bucher, 1997)

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Sample no.	Si Formula Atoms	Ti Formula Atoms	Al Formula Atoms	Fe Formula Atoms	Mn Formula Atoms	Cr Formula Atoms	Mg Formula Atoms	Ca Formula Atoms	Na Formula Atoms	K Formula Atoms	Formula Totals
VL-5b CPX	1.97656	0.003065	0.0862331	0.261691	0.0045581	0.0000365	0.726993	0.884287	0.0676342	0	10.0111
VL-5b GRT	3.0251	0.0010743	1.91147	1.81377	0.0498757	0.0003487	0.520922	0.695357	0	0	20.0179
FL-1d GRT	3.0202	0.001682	1.93616	1.67974	0.0243467	0.0014666	0.341371	1.00434	0	1.67974	20.0093
FL-1d CPX	1.9391	0.0009147	0.106611	0.516469	0.0060407	0	1.42906	0.0079287	0.0011356	0.516469	10.0073
FL-9 GRT	3.03398	0.0017876	1.91967	1.66174	0.0390164	0	0.544115	0.804098	0	1.66174	20.0044
FL-9 CPX	1.96426	0.004437	0.115193	0.247501	0.0047841	0.0006028	0.718142	0.866986	0.103003	0.247501	10.0249

VL-5b: Collected from near Vågje, Vestvågøya, Norway — Eclogitized gabbro

FL-1d: Collected from Flakstad, Flakstadøya, Norway — Eclogitized shear zone

FL-9: Collected near Nusfjord, Flakstadøya, Norway — Gabbro from shear zone

In addition to completing the temperature calculations for three mineral pairs in your Excel spreadsheet, answer the following questions about your temperature calculations on a separate sheet of paper or include your responses on your Excel spreadsheet:

- 1) Are the temperatures you calculated reasonable given the metamorphic grade of the rocks analyzed? Why?
- 2) How might you explain the variation of the calculated temperatures based on experimentally-determined formulas 1-3?
- 3) Look again at the exchange reaction between garnet and clinopyroxene above. What simplifying assumptions have been made about the compositions of garnet and clinopyroxene (i.e., what might have affected the distribution of Fe and Mg between coexisting garnet and clinopyroxene pairs)?