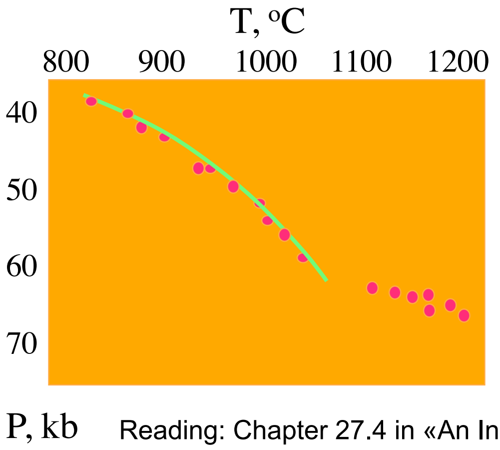
Geothermobarometry

Geothermobarometry-Calculation of equilibrium P and T from the measured distribution of elements between coexisting phases



Major tool that makes petrology into quantitative discipline

Enables understanding of metamorphic facies and tectonic regimes

Provides an absolute reference frame for comparison of different igneous rocks, igneous and metamorphic rocks

Reading: Chapter 27.4 in «An Introduction to Igneous and Metamorphic Petrology» by J. Winter (2000)

Geothermobarometry

Geothermobarometry-Calculation of equilibrium P and T from the measured distribution of elements between coexisting phases

1. Principles of geothermobarometry. Types of geothermobarometers
2. Thermodynamic foundation of thermobarometry
3. Step-by-step guide on how to make a geothermometer
4. Accuracy and Precision. Application of thermobarometers.

1. Types of thermobarometers:

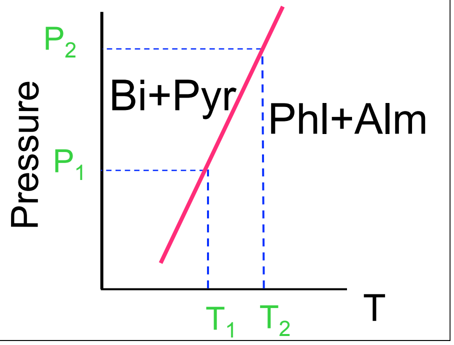
Fe in garnet + Mg in mica ⟺ Fe in mica + Mg in garnet

1. Exchange geothermometers involve the reciprocal exchange of components between minerals

- the modal amount of the phases involved remain constant; only their composition changes as a result of the exchange.
- the reactants and the products are similar, => a small ΔV and small dependence on P => the steep slope on the Clapeyron equation => good thermometer

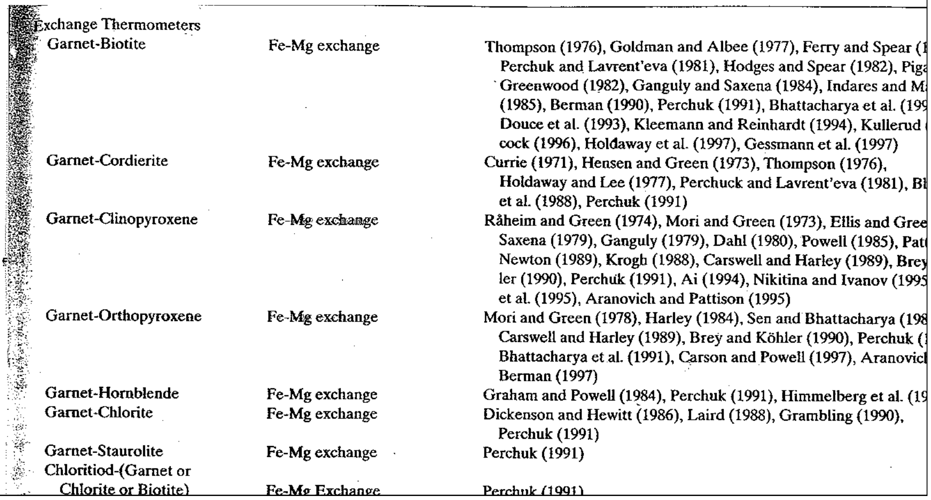
The Clapeyron Equation:

$$\frac{\Delta P}{\Delta T} = \frac{\Delta S}{\Delta V}$$



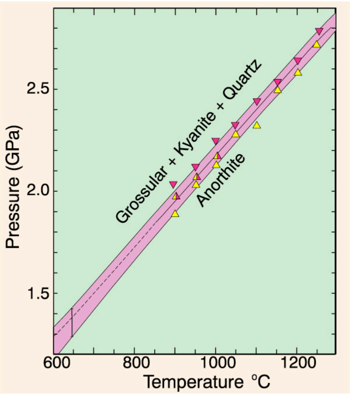
1A. Exchange geothermometers

- Developed in the past 30 years -> EMP
- Drawback: exchange reaction can occur readily, even during retrograde metamorphism, a process that can significantly upset geothermobarometry



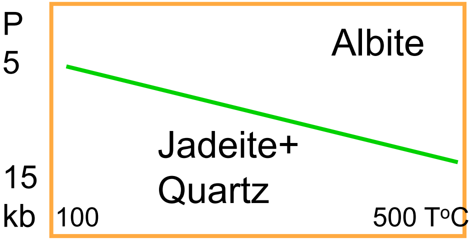
Exchange Thermometers		
Garnet-Biotite	Fe-Mg exchange	Thompson (1976), Goldman and Albee (1977), Ferry and Spear (Perchuk and Lavrent'eva (1981), Hodges and Spear (1982), Pig Greenwood (1982), Ganguly and Saxena (1984), Indares and M (1985), Berman (1990), Perchuk (1991), Bhattacharya et al. (19 Douce et al. (1993), Kleemann and Reinhardt (1994), Kullerud cock (1996), Holdaway et al. (1997), Gessmann et al. (1997)
Garnet-Cordierite	Fe-Mg exchange	Currie (1971), Hensen and Green (1973), Thompson (1976), Holdaway and Lee (1977), Perchuck and Lavrent'eva (1981), B et al. (1988), Perchuk (1991)
Garnet-Clinopyroxene	Fe-Mg exchange	Råheim and Green (1974), Mori and Green (1973), Ellis and Gree Saxena (1979), Ganguly (1979), Dahl (1980), Powell (1985), Pat Newton (1989), Krogh (1988), Carswell and Harley (1989), Brey ler (1990), Perchuk (1991), Ai (1994), Nikitina and Ivanov (199 et al. (1995), Aranovich and Pattison (1995)
Garnet-Orthopyroxene	Fe-Mg exchange	Mori and Green (1978), Harley (1984), Sen and Bhattacharya (19 Carswell and Harley (1989), Brey and Köhler (1990), Perchuk (Bhattacharya et al. (1991), Carson and Powell (1997), Aranovic Berman (1997)
Garnet-Hornblende	Fe-Mg exchange	Graham and Powell (1984), Perchuk (1991), Himmelberg et al. (1
Garnet-Chlorite	Fe-Mg exchange	Dickenson and Hewitt (1986), Laird (1988), Grambling (1990), Perchuk (1991)
Garnet-Staurolite	Fe-Mg exchange	Perchuk (1991)
Chloritiod-(Garnet or Chlorite or Biotite)	Fe-Mg Exchange	Perchuk (1991)

1B. Net Transfer Thermobarometers: based on reactions that result in a change in the modal amounts of the phases involved

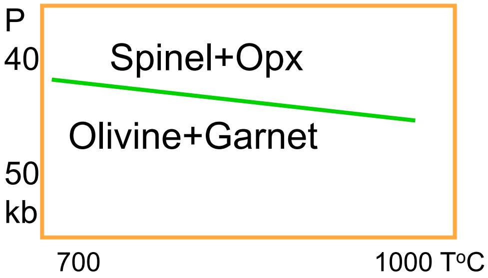


Solid-Solid

$$\frac{\Delta P}{\Delta T} = \frac{\Delta S}{\Delta V}$$ larger



Should these reactions be used as thermometers or barometers? Importance of this reactions?



1B. Net Transfer Thermometers

Solid-Solid

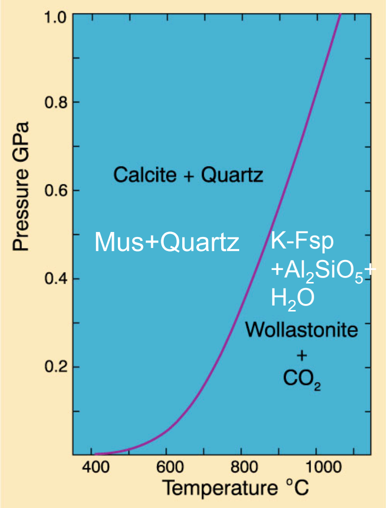
Solid-Gas

Dehydration Decarbonation

The concave upward shape - the slope varies

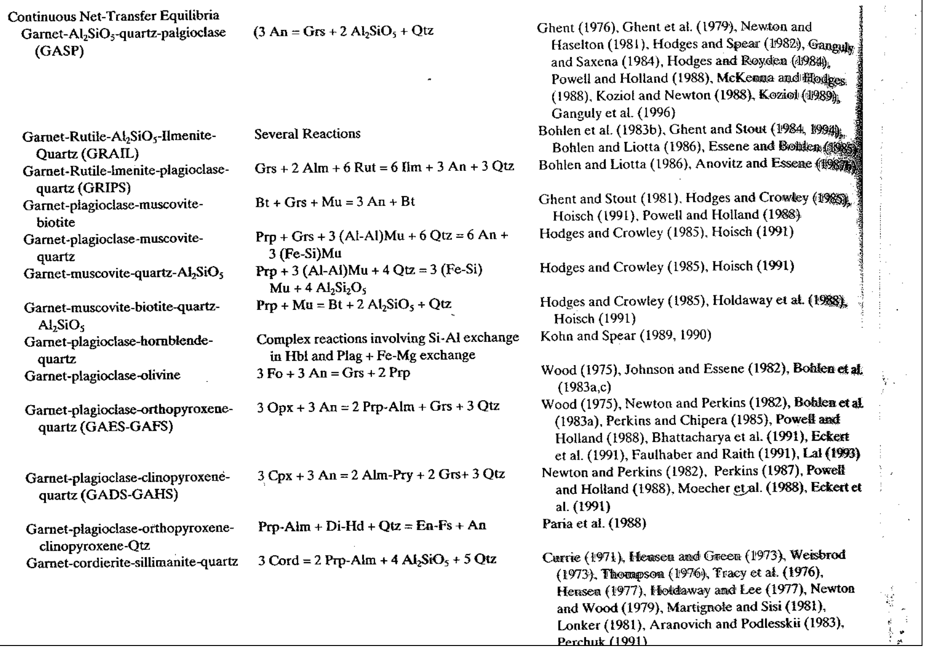
$$\frac{\Delta P}{\Delta T} = \frac{\Delta S}{\Delta V}$$

ΔV large at low T and then decreases <= the vapor phase is very compressible



Good thermometers at greater P

1B. Net Transfer Thermometers



Continuous Net-Transfer Equilibria		
Garnet-Al_2SiO_5-quartz-palgioclase (GASP)	(3 An = Grs + 2 Al_2SiO_5 + Qtz	Ghent (1976), Ghent et al. (1979), Newton and Haselton (1981), Hodges and Spear (1982), Ganguly and Saxena (1984), Hodges and Royden (1984), Powell and Holland (1988), McKenna and Hodges (1988), Koziol and Newton (1988), Koziol (1989), Ganguly et al. (1996)
Garnet-Rutile-Al_2SiO_5-Ilmenite-Quartz (GRAIL)	Several Reactions	Bohlen et al. (1983b), Ghent and Stout (1984, 1994), Bohlen and Liotta (1986), Essene and Bohlen (1985)
Garnet-Rutile-lmenite-plagioclase-quartz (GRIPS)	Grs + 2 Alm + 6 Rut = 6 Ilm + 3 An + 3 Qtz	Bohlen and Liotta (1986), Anovitz and Essene (1987b)
Garnet-plagioclase-muscovite-biotite	Bt + Grs + Mu = 3 An + Bt	Ghent and Stout (1981), Hodges and Crowley (1985), Hoisch (1991), Powell and Holland (1988)
Garnet-plagioclase-muscovite-quartz	Prp + Grs + 3 (Al-Al)Mu + 6 Qtz = 6 An + 3 (Fe-Si)Mu	Hodges and Crowley (1985), Hoisch (1991)
Garnet-muscovite-quartz-Al_2SiO_5	Prp + 3 (Al-Al)Mu + 4 Qtz = 3 (Fe-Si) Mu + 4 $Al_2Si_2O_5$	Hodges and Crowley (1985), Hoisch (1991)
Garnet-muscovite-biotite-quartz-Al_2SiO_5	Prp + Mu = Bt + 2 Al_2SiO_5 + Qtz	Hodges and Crowley (1985), Holdaway et al. (1988), Hoisch (1991)
Garnet-plagioclase-hornblende-quartz	Complex reactions involving Si-Al exchange in Hbl and Plag + Fe-Mg exchange	Kohn and Spear (1989, 1990)
Garnet-plagioclase-olivine	3 Fo + 3 An = Grs + 2 Prp	Wood (1975), Johnson and Essene (1982), Bohlen et al. (1983a,c)
Garnet-plagioclase-orthopyroxene-quartz (GAES-GAFS)	3 Opx + 3 An = 2 Prp-Alm + Grs + 3 Qtz	Wood (1975), Newton and Perkins (1982), Bohlen et al. (1983a), Perkins and Chipera (1985), Powell and Holland (1988), Bhattacharya et al. (1991), Eckert et al. (1991), Faulhaber and Raith (1991), Lal (1993)
Garnet-plagioclase-clinopyroxene-quartz (GADS-GAHS)	3 Cpx + 3 An = 2 Alm-Pry + 2 Grs+ 3 Qtz	Newton and Perkins (1982), Perkins (1987), Powell and Holland (1988), Moecher et al. (1988), Eckert et al. (1991)
Garnet-plagioclase-orthopyroxene-clinopyroxene-Qtz	Prp-Alm + Di-Hd + Qtz = En-Fs + An	Paria et al. (1988)
Garnet-cordierite-sillimanite-quartz	3 Cord = 2 Prp-Alm + 4 Al_2SiO_5 + 5 Qtz	Currie (1971), Hensen and Green (1973), Weisbrod (1973), Thompson (1976), Tracy et al. (1976), Hensen (1977), Holdaway and Lee (1977), Newton and Wood (1979), Martignole and Sisi (1981), Lonker (1981), Aranovich and Podlesskii (1983), Perchuk (1991)

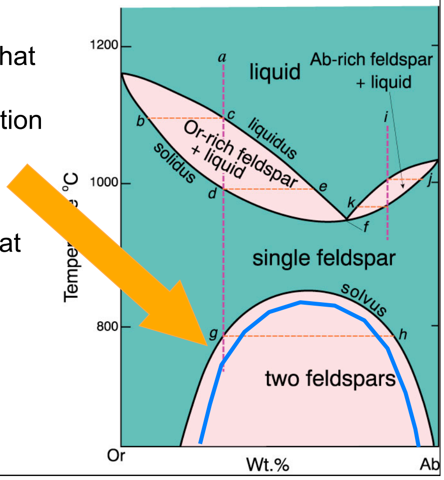
1.Types of thermobarometers:

A. Exchange Thermobarometers
B. Net-Transfer Thermobarometers
C. Solvus Thermobarometers

Solvus:The curved P-T-X line of surface that separates the field of homogeneous solid solution from the field of limited solid solution

- Based on the miscibility gap expanding at lower T's

- Miscibility gaps serve mainly as thermometers, but very often there is a pressure dependence as well

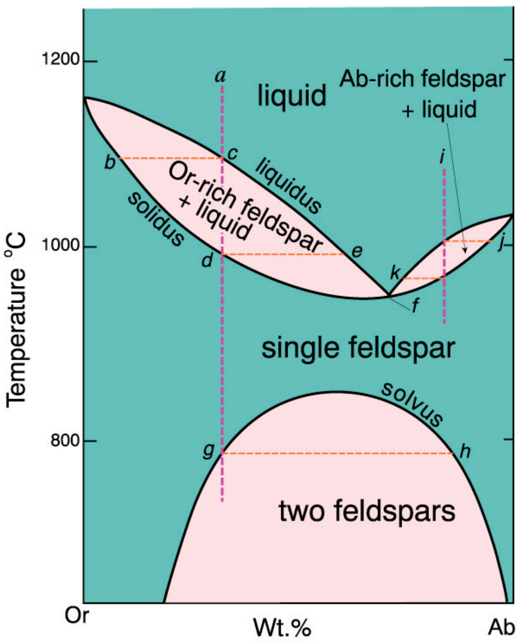


1C. Solvus Thermobarometers

- Different sensitivity in different T ranges

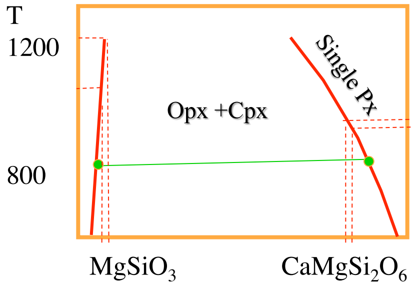
Widely used mineral pairs:

- Ksp and Plag (partitioning of Na)
- Calcite and dolomite (partitioning of Mg)
- Opx-Cpx



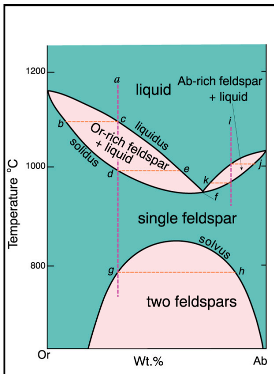
1C. Solvus Thermobarometers
Opx-Cpx solvus thermometer

- Ca/(Ca+Mg) in cPx was initially the measure of T
  Is Ca-rich Cpx more high-T or more low-T than low-Ca Cpx?
- The simple ratio Ca/(Ca+Mg) may not always be an adequate measure of T in natural pyroxenes because they rarely belong to the binary join Mg-MgCa.
- T range – 800 - 1300°C. Equally sensitive as the slope does not change
- Asymmetric. What limb should be a better measure of T?



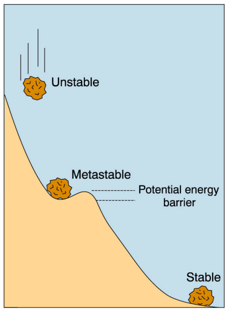
* Lindsley 1983: experiments in the Ca-Mg-Fe Px joins up to P=15 kb. The effect of pressure was found to be minor

2. Thermodynamic foundation of thermobarometry



Compositions of Or and Ab depend on T because K and Ab are in continuous chemical reaction that goes on between Or and Ab as T drops.

It's important to predict how this reaction will proceed. It can be done with a special energy parameter - Gibbs free energy.



- Potential energy controls the behavior of an object
- The object will always proceed to a state that minimizes its potential energy
- The potential energy cannot be measured directly

Gibbs free energy = chemical equivalent of potential energy

2. Thermodynamic foundation of thermobarometry

System - any part of the universe that is interesting to us.

$$NaAlSi_2O_6 + SiO_2 = NaAlSi_3O_8$$

Jadeite Quartz Albite

Our system - a set of 3 minerals. Two possible states for this system:
Jad+Qz or Albite

2. Thermodynamic foundation of thermobarometry

$$G=H-TS$$

the Gibbs free energy of a phase at a specified P and T

Enthalpy, or heat content

Entropy - the measure of randomness

T - always absolute, always in K

Why do we need another separate variable that describes heat content (apart from T)?

What is higher:
S of quartz or S of SiO_2 glass?
S of microcline or S of orthoclase?

2. Thermodynamic foundation of thermobarometry

Spl+ 4Opx = Ol+Gar

The goal – to assign correct Ps and Ts to the line of this equilibrium,
to assign P and T to a rock that contains all these 4 phases

Rocks of what paragenesis (Spl+Opx or Gar+Ol) should we see at this P, or T or bulk composition?

I.e. What is the stable side of the reaction at a given P and T?

ΔG for a reaction:

$$\Delta G = \Sigma\,(n\,G)_{products} - \Sigma(n\,G)_{reactants}$$
$$= G_{Ol} + G_{Gar} - \boxed{4}G_{Opx} - G_{Spl}$$

Extensive?

Gibbs free energy - extensive parameter

2. Thermodynamic foundation of thermobarometry

From now on - will always work with one mole of components in the system.

If the reaction is written for one mole of material:

ΔG for a reaction:

Spl+ 4Opx = Ol+Gar

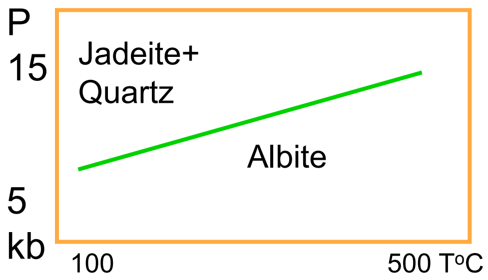
$$\Delta G = \mu_{Ol} + \mu_{Gar} - 4\mu_{Opx} - \mu_{Spl}$$

2. Thermodynamic foundation of thermobarometry

$$NaAlSi_2O_6 + SiO_2 = NaAlSi_3O_8$$

Jadeite Quartz Albite

Write an expression for ΔG for this reaction



How do we know the chemical potentials?

G=H-TS

Calculated for pure phases based on tabulated H and S (experimentally measured by calorimetry and presented in handbooks on thermodynamic properties of materials)

2. Thermodynamic foundation of thermobarometry

Calculation of the Gibbs free energy for solid solution minerals

$NaAlSi_2O_6 + SiO_2 = NaAlSi_3O_8$

Jadeite Quartz Albite

$NaAlSi_2O_6\text{-}CaMgSi_2O_6 + SiO_2 =$

Addition of Ca

Omphacite Quartz

$=NaAlSi_3O_8\text{-}CaAl_2Si_2O_8$

Plag

We must find a way to include composition of the phase in the G calculations.

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2. Thermodynamic foundation of thermobarometry

$NaAlSi_2O_6\text{-}CaMgSi_2O_6 + SiO_2 = =NaAlSi_3O_8\text{-}CaAl_2Si_2O_8$

Omphacite + Quartz = Plag

Chemical potential of albite in plagioclase:

$$\mu_{Ab}^{Plag} = \mu \text{ pure Ab} + RT\,ln\,a_{Ab}^{Plag}$$

Activity is thermodynamically effective concentration

Special compositional term that depends on concentration and T

R?

$NaAlSi_2O_6$ -$CaMgSi_2O_6$ + SiO_2 = $NaAlSi_3O_8$ -$CaAl_2Si_2O_8$

$$\mu^{Plag}_{Ab} - \mu^{Qtz}_{SiO_2} - \mu^{Cpx}_{Jad} = \Delta G = 0$$

$$\mu^{A}_{i} = \mu_i^{o} + RT\,ln\,a^{A}_{i}$$

$$\mu^{o}_{Ab} + RTln\,a^{Plag}_{Ab} - \mu^{o}_{Jad} - RTln\,a^{Cpx}_{Jad} - \mu^{o}_{SiO_2} - RTln\,a^{Qtz}_{SiO_2} = \Delta G = 0$$

$$\mu^{o}_{Ab} - \mu^{o}_{Jad} - \mu^{o}_{SiO2} = \Delta G^{0} = -RT\ln\left(\frac{a^{Plag}_{Ab}}{a^{Cpx}_{Jad}\;a^{Qtz}_{SiO2}}\right)$$

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2. Thermodynamic foundation of thermobarometry

Spl+ 4Opx = Ol+Gar

$MgAl_2O_4 + 4MgSiO_3 = Mg_2SiO_4 + Mg_3Al_2[SiO_4]_3$

Fe

Equilibrium: Sums of chemical potentials of Mg end-members in solid solutions on both side of the reactions should be equal

Write the analogous equation for ΔG for this reaction

2. Thermodynamic foundation of thermobarometry

$$\Delta G^o = -RT \ln \left(\frac{a^{Ol}_{Fo} \quad a^{Gar}_{Pyr}}{a^{Spl}_{MgAl2O4} \quad (a^{Opx}_{En})^4} \right)$$

K

(equilibrium constant)

The stochiometric coefficients must act as a multiplier to the appropriate terms and must appear as an exponent in the log function

$$\Delta G^o = -RT\,lnK$$

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2. Thermodynamic foundation of thermobarometry

To calculate T for a reaction:

$$\Delta G^o = -RT\,lnK$$

Known for pure phases based on tabulated H and S

Must know equilibrium constant K

Must know activities

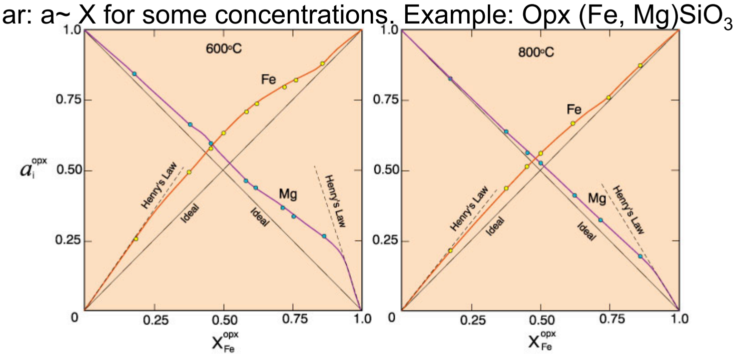
Activity - Thermodynamically effective analog of concentration

- Concentration adjusted for interactions between molecules and cations in solid solutions.

2. Thermodynamic foundation of thermobarometry

Solutions: a-X relationships

- Ideal Solution with substitution on one crystallographic site: a = X (molar fraction)
- Regular: a~ X for some concentrations. Example: Opx (Fe, Mg)SiO_3



- Asymmetric, quasi-regular etc. More empirically based terms are required to describe a-X relationships and more exterimental data needed to constrain these.

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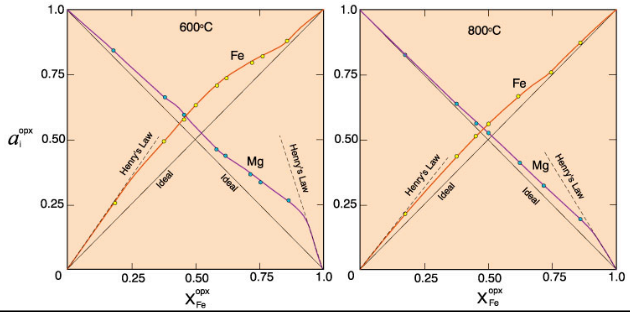
2. Thermodynamic foundation of thermobarometry

Wake-up practice

1. Molar fraction of an element is calculated as a cation amount of this element divided to the sum of cation amounts for all elements that can substitute for it in the mineral crystal lattice. What is the molar fraction of Ca in garnet with composition $Ca_{0.9}Fe_{0.3}Mg_{1.8}Cr_{0.5}Al_{1.5}Si_4O_{12}$?

2. What is the activity of Ab in Plagioclase with composition $Ab_{30}An_{70}$?

3. From the diagram on the right, read the activity of ferrosilite at 600°C in orthopyroxene with X_{Fe}=0.5 assuming the regular solid solution model



$$\Delta G^{o} = -RT\,ln K$$

Calculated for pure phases based on tabulated H and S

Done by authors of a thermobarometer and given in a source paper

Calculation of the reaction constant

Calculation of the activity of a component

Data on the solid solution

Calculation of a mole fraction of a component

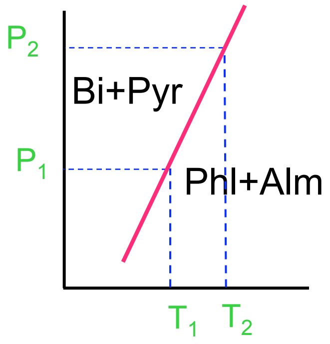
EMP analyses of mineral compositions

Geothermobarometry- Calculation of equilibrium P and T from the measured distribution of elements between coexisting phases

What it takes to make a new thermobarometer

Graphic representation of Gar - Bi geothermobarometer

Barometer or thermometer?
What type?



$Fe_3Al_2Si_3O_{12} + KMg_3Si_3AlO_{10}(OH)_2 =$
$Mg_3Al_2Si_3O_{12} + KFe_3Si_3AlO_{10}(OH)_2$

3. What it takes to make a new thermobarometer

$Fe_3Al_2Si_3O_{12} + KMg_3Si_3AlO_{10}(OH)_2 = Mg_3Al_2Si_3O_{12} + KFe_3Si_3AlO_{10}(OH)_2$

A series of experiments at 2 kb, 500-800°C

$Alm_{90}Pyr_{10}$

An interrupted approach toward the true equilibrium value?

Table 27-2. Experimental results of Ferry and Spear (1978) on a Garnet-Biotite Geothermometer

Reversed experiments

T °C	Initial X(Fe-Bt)	Final X(Fe-Bt)	Final X(Fe-Grt)	Final (Mg/Fe)Grt	Final (Mg/Fe)Bt	K	T Kelvins	1/T Kelvins	lnK
799	1.00	0.750	0.905	0.105	0.333	0.315	1072	0.00093	-1.155
799	0.50	0.710	0.896	0.116	0.408	0.284	1072	0.00093	-1.258
749	0.50	0.695	0.896	0.116	0.439	0.264	1022	0.00098	-1.330
738	1.00	0.730	0.906	0.104	0.370	0.281	1011	0.00099	-1.271
698	0.75	0.704	0.901	0.110	0.420	0.261	971	0.00103	-1.342
698	0.50	0.690	0.896	0.116	0.449	0.258	971	0.00103	-1.353
651	0.75	0.679	0.901	0.110	0.473	0.232	924	0.00108	-1.459
651	0.50	0.661	0.897	0.115	0.513	0.224	924	0.00108	-1.497
599	0.75	0.645	0.902	0.109	0.550	0.197	872	0.00115	-1.623
599	0.50	0.610	0.898	0.114	0.639	0.178	872	0.00115	-1.728
550	0.75	0.620	0.903	0.107	0.613	0.175	823	0.00122	-1.741
550	0.50	0.590	0.898	0.114	0.695	0.163	823	0.00122	-1.811
601	0.50	0.500	0.800	0.250	1.000	0.250	874	0.00114	-1.386
601	0.25	0.392	0.797	0.255	1.551	0.164	874	0.00114	-1.807
697	0.75	0.574	0.804	0.244	0.742	0.329	970	0.00103	-1.111
697	0.25	0.468	0.796	0.257	1.137	0.226	970	0.00103	-1.487

3. What it takes to make a new thermobarometer

$Fe_3Al_2Si_3O_{12} + KMg_3Si_3AlO_{10}(OH)_2 =$
$Mg_3Al_2Si_3O_{12} + KFe_3Si_3AlO_{10}(OH)_2$

Write the reaction constant and express activities as concentrations assuming the ideal solid solution

$$K_D = \qquad = \frac{(Mg/Fe)^{Gar}}{(Mg/Fe)^{Bi}}$$

3. What it takes to make a new thermobarometer

The Garnet - Biotite geothermometer

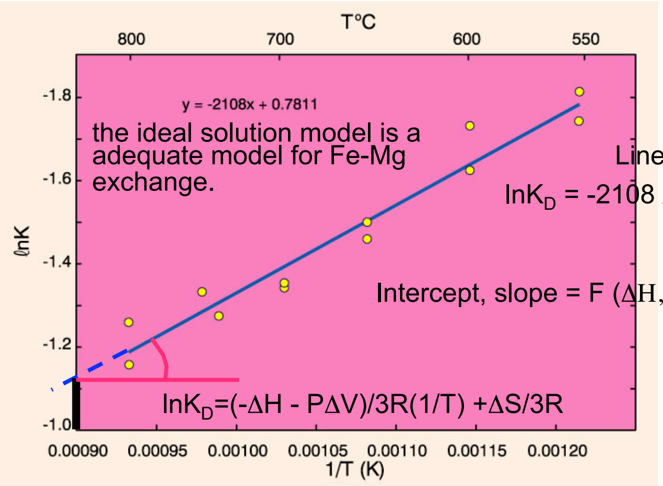
Table 27-2. Experimental results of Ferry and Spear (1978) on a Garnet-Biotite Geothermometer

T °C	Initial X(Fe-Bt)	Final X(Fe-Bt)	Final X(Fe-Grt)	Final (Mg/Fe)Grt	Final (Mg/Fe)Bt	K	T Kelvins	1/T Kelvins	lnK
799	1.00	0.750	0.905	0.105	0.333	0.315	1072	0.00093	-1.155
799	0.50	0.710	0.896	0.116	0.408	0.284	1072	0.00093	-1.258
749	0.50	0.695	0.896	0.116	0.439	0.264	1022	0.00098	-1.330
738	1.00	0.730	0.906	0.104	0.370	0.281	1011	0.00099	-1.271
698	0.75	0.704	0.901	0.110	0.420	0.261	971	0.00103	-1.342
698	0.50	0.690	0.896	0.116	0.449	0.258	971	0.00103	-1.353
651	0.75	0.679	0.901	0.110	0.473	0.232	924	0.00108	-1.459
651	0.50	0.661	0.897	0.115	0.513	0.224	924	0.00108	-1.497
599	0.75	0.645	0.902	0.109	0.550	0.197	872	0.00115	-1.623
599	0.50	0.610	0.898	0.114	0.639	0.178	872	0.00115	-1.728
550	0.75	0.620	0.903	0.107	0.613	0.175	823	0.00122	-1.741
550	0.50	0.590	0.898	0.114	0.695	0.163	823	0.00122	-1.811
601	0.50	0.500	0.800	0.250	1.000	0.250	874	0.00114	-1.386
601	0.25	0.392	0.797	0.255	1.551	0.164	874	0.00114	-1.807
697	0.75	0.574	0.804	0.244	0.742	0.329	970	0.00103	-1.111
697	0.25	0.468	0.796	0.257	1.137	0.226	970	0.00103	-1.487

$\Delta G^o = -RT\,lnK$ $\quad$ $lnK = -\Delta G^o/RT$

3. What it takes to make a new thermobarometer

The Garnet - Biotite geothermometer



the ideal solution model is a adequate model for Fe-Mg exchange.

Linear regression

$lnK_D = -2108 / T(K) + 0.781$

Intercept, slope = F (ΔH, ΔV, ΔS, P)

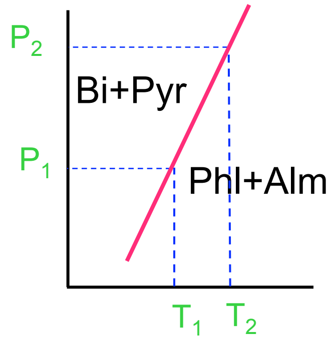
$lnK_D = (-\Delta H - P\Delta V)/3R(1/T) + \Delta S/3R$

- Deriving ΔS and ΔH from these experiments is an alternative to calorimetric derivation of t/d data at room conditions
- Knowing ΔV, ΔS we can then write down the general equation that takes into account varying pressure

3. What it takes to make a new thermobarometer

Graphic representation of Gar - Bi geothermometer

$$T^{o}C = \frac{52,090 + 2.494P(MPa)}{19.506 - 12,943\ln K_D} - 273$$



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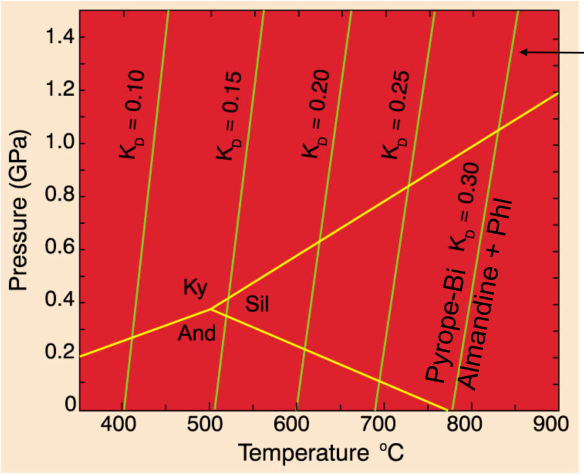
3. What it takes to make a new thermobarometer

Graphic representation of Gar - Bi geothermometer



Isopleths - lines of equal values for chemical parameters, in our case a distribution coefficient

To read T off the plot:
- analyze mica and garnet,
- calculate K_D,
- assume pressure

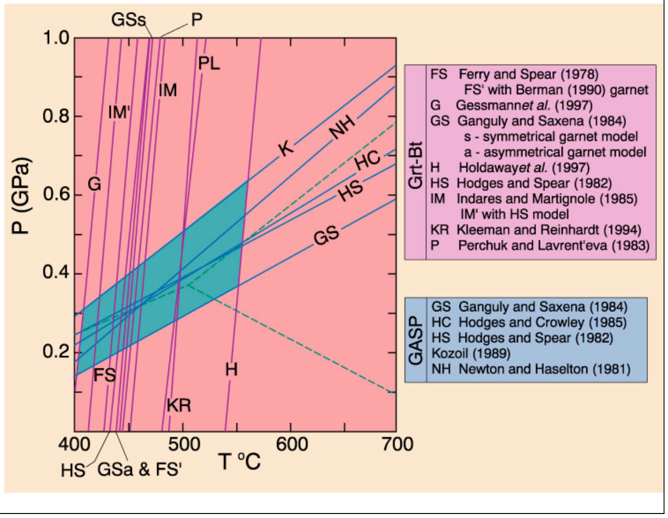
4. Application of Geothermobarometry to Rocks

Metamorphic rock with the assemblage
Gros - Al-silicate - Silica - Plagioclase- Biotite.

Thermometry

Barometry

Several calibrations of a single equilibrium



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4. Application of Geothermobarometry to Rocks: How to choose the best thermobarometers

1. Most geothermobarometers are based on experiments using simple mineral systems. In natural rocks - additional components that affect the ratio of other components in a mineral

Ca in garnet - strong and non-ideal effect on Mg-Fe

The most common and significant errors resulting from the application of geothermobarometry are related to applying a system beyond the compositional range over which it has been calibrated.

Thermobarometer must be empirically calibrated for your rock type, or calibrated for a simple mineral system that best approximates your natural paragenesis.

2. Thermobarometer must be calibrated for your range of P and T's. The longer the extrapolation in T or P from the experiments to the application, the larger the possible error.

3. A good thermobarometer must be based on reversed experiments

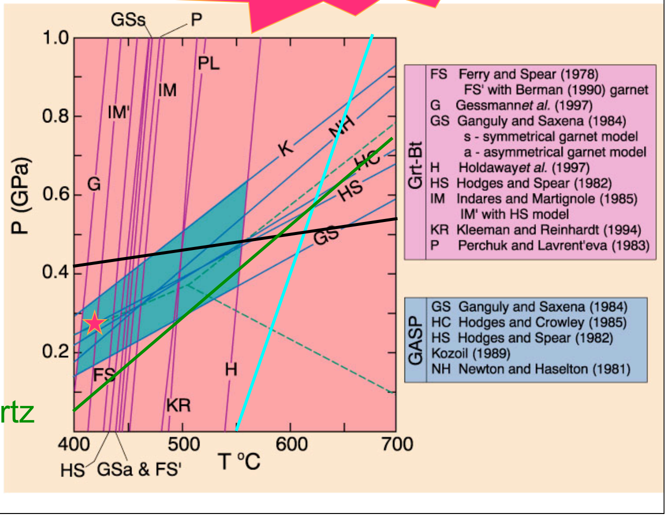
4. Application of Geothermobarometry to Rocks

Internally-consistent sets of thermobarometers

Gar-Cord

Gar-Rut-Ilm-Plag-Quartz

Gar-Cord-Sil-Quartz

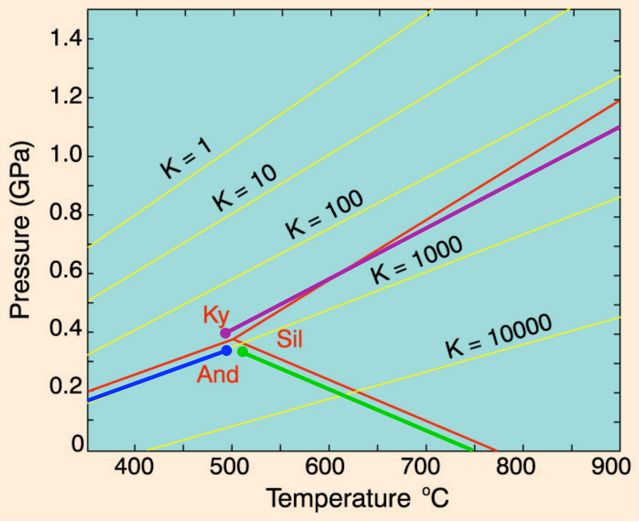


4. Application of Geothermobarometry to Rocks: Internally-consistent thermobarometry

Internally consistent data are data that have been compared with all other data in the database and adjusted for mutual conformity.

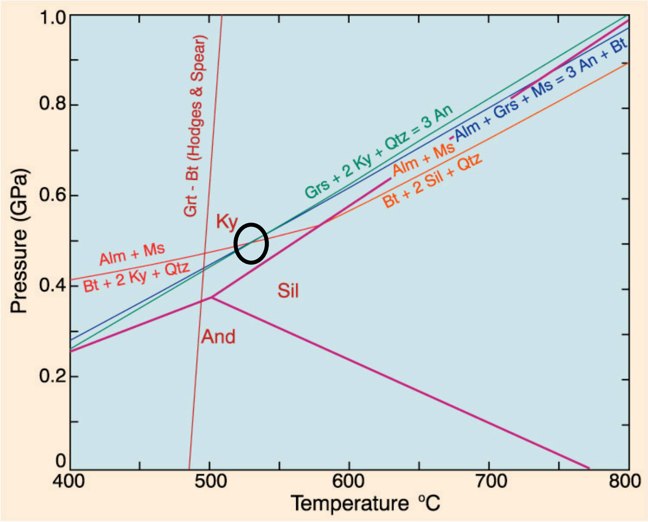
3 Labs:
Ky-Sil
And-Sil
Ky-And

adjust the values of thermodynamic data within the limits of experimental uncertainty



4. Application of Geothermobarometry to Rocks:

Internally-consistent thermobarometry



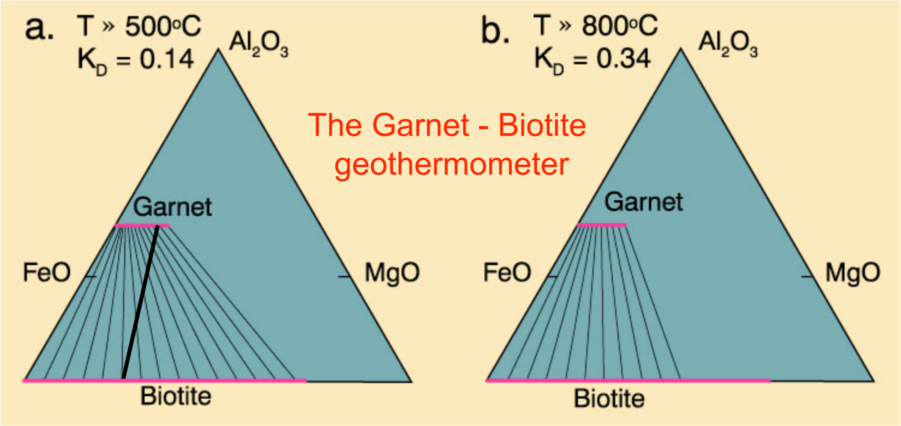
- TWQ Rob Berman's thermodynamic database for metamorphic phase equilibria has been applied to the rock

- The Gar-Bi line is off. Exchange and solvus reactions generally involve only 2 coexisting minerals and internally consistent data cannot correct or improve upon individual exchange or solvus thermometers

4. Pitfalls of practical geothermobarometry

1. Application to mineral assemblages not in equilibrium

- Absence of disequilibrium textures and consistent distribution of elements
- Inconsistent distribution of elements can result from retrograde effects that selectively affect only some minerals, or from subsolidus transformations

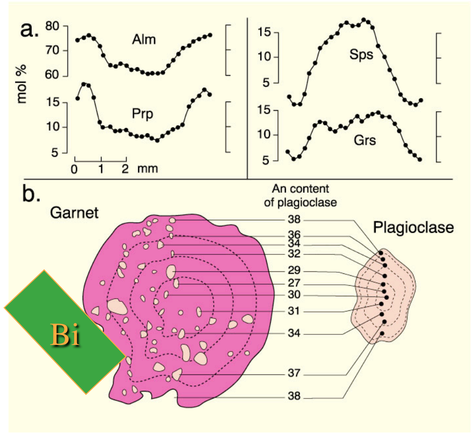


The Garnet - Biotite geothermometer

4. Pitfalls in practical geothermobarometry

2. Application to chemically zoned crystals

- Use compositions of adjacent zones of crystals
- Mineral cores may not represent earlier simultaneous equilibrium states because one mineral may have nucleated and grown before another became stable



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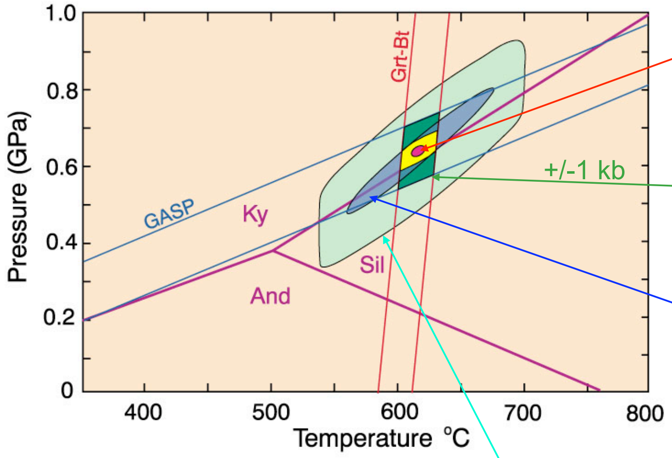
4. Pitfalls in practical geothermobarometry

3. Application to rocks formed under drastically different redox state

- The Fe^{3+}/Fe^{2+} ratio will be different and will disturb Mg/Fe^{2+}

4. Comparing results from several different thermobarometers that are not internally consistent

4. If you did not fall in any of the pits, how good are your P-T values?



analytical precision of the microprobe

the a-X models for the minerals (Plag and Gar)

the uncertainty that can be treated statistically (uncertainty in experimental calibration and DV

Total uncertainty : +/-3 kb and +/-150°C dominated by uncertainty of the mineral activity models

For ultramafic rocks: +/- 2 kb, +/- 25°

Conclusions

- Geothermobarometry-Calculation of equilibrium P and T from the measured distribution of elements between coexisting phases
- Thermometers and barometers must be experimentally calibrated
- Knowledge of thermodynamic properties of simple end-members of natural solid solution minerals and the type of solution is essential to making accurate thermobarometers
- There are several types of chemical reactions that can be used for thermobarometry
- Exchange reactions, solid-gas net transfer reactions at high T and solvus reactions are good thermometers
- Solid-solid net transfer reactions are good barometers
- Use only thermobarometers calibrated for your bulk chemical composition of rock and for your expected P and T range
- Careful petrographic work should always precede thermobarometric studies