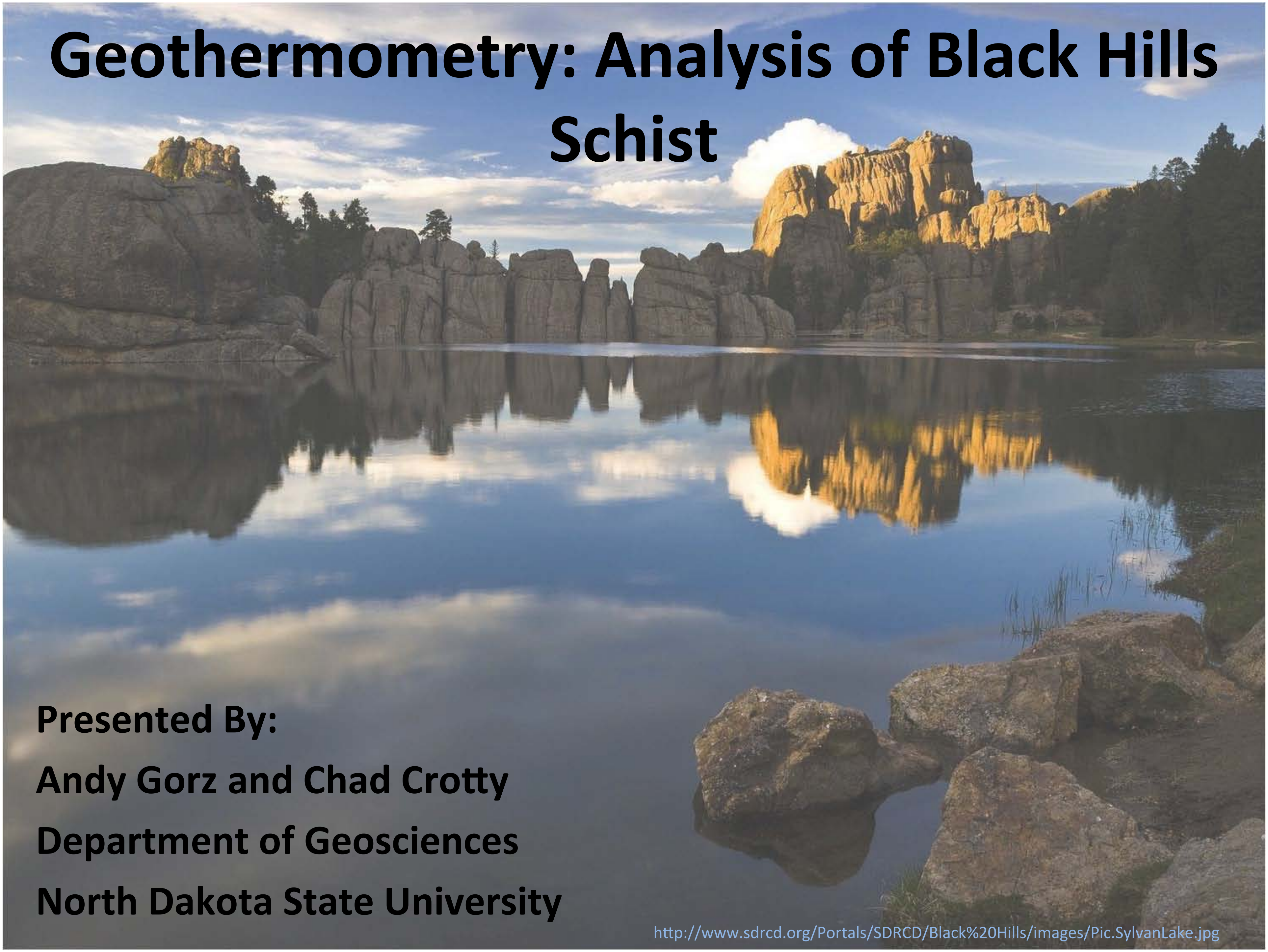
Geothermometry: Analysis of Black Hills Schist



Presented By:

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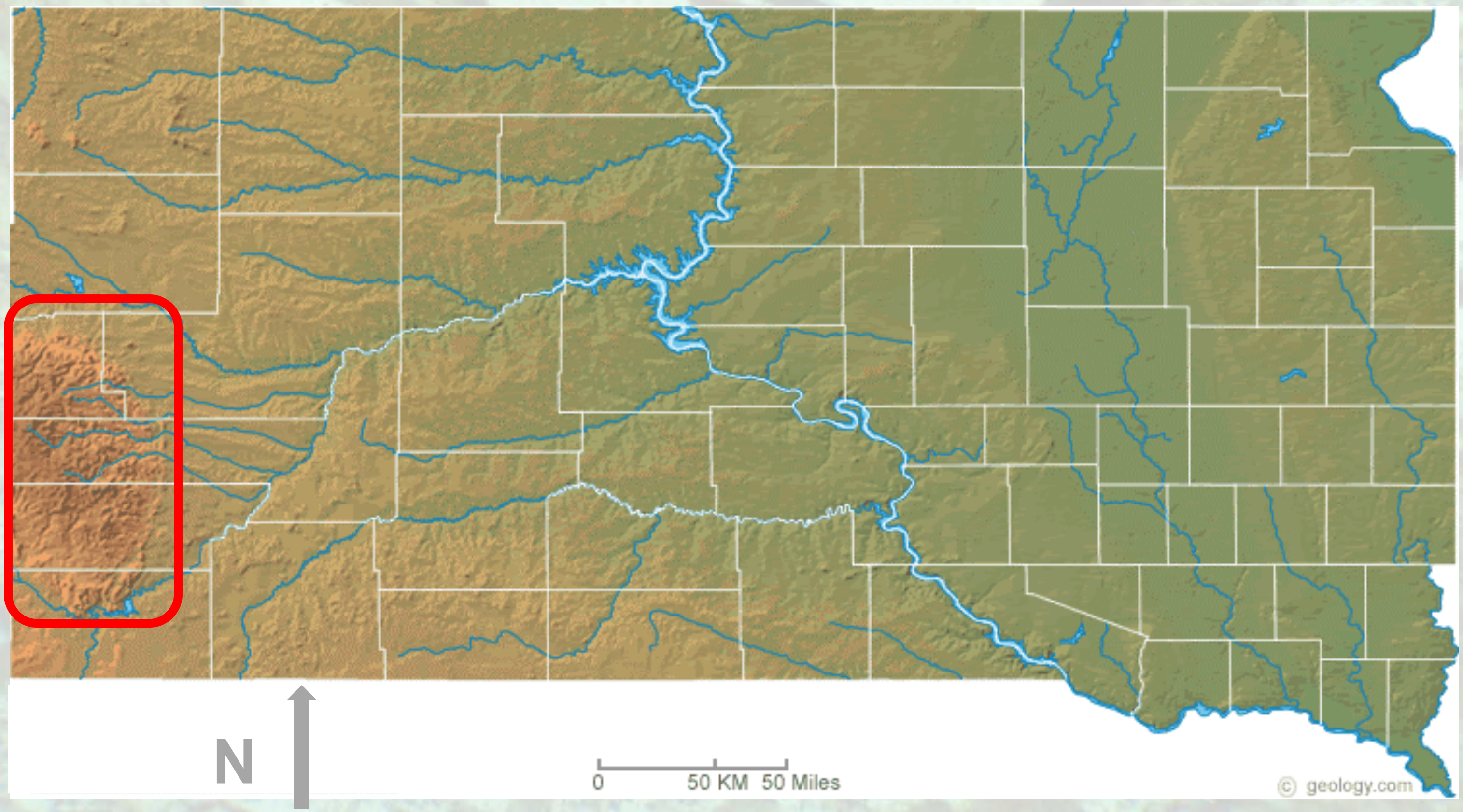
North Dakota State University

http://www.sdrcd.org/Portals/SDRCD/Black%20Hills/images/Pic.SylvanLake.jpg

Overview

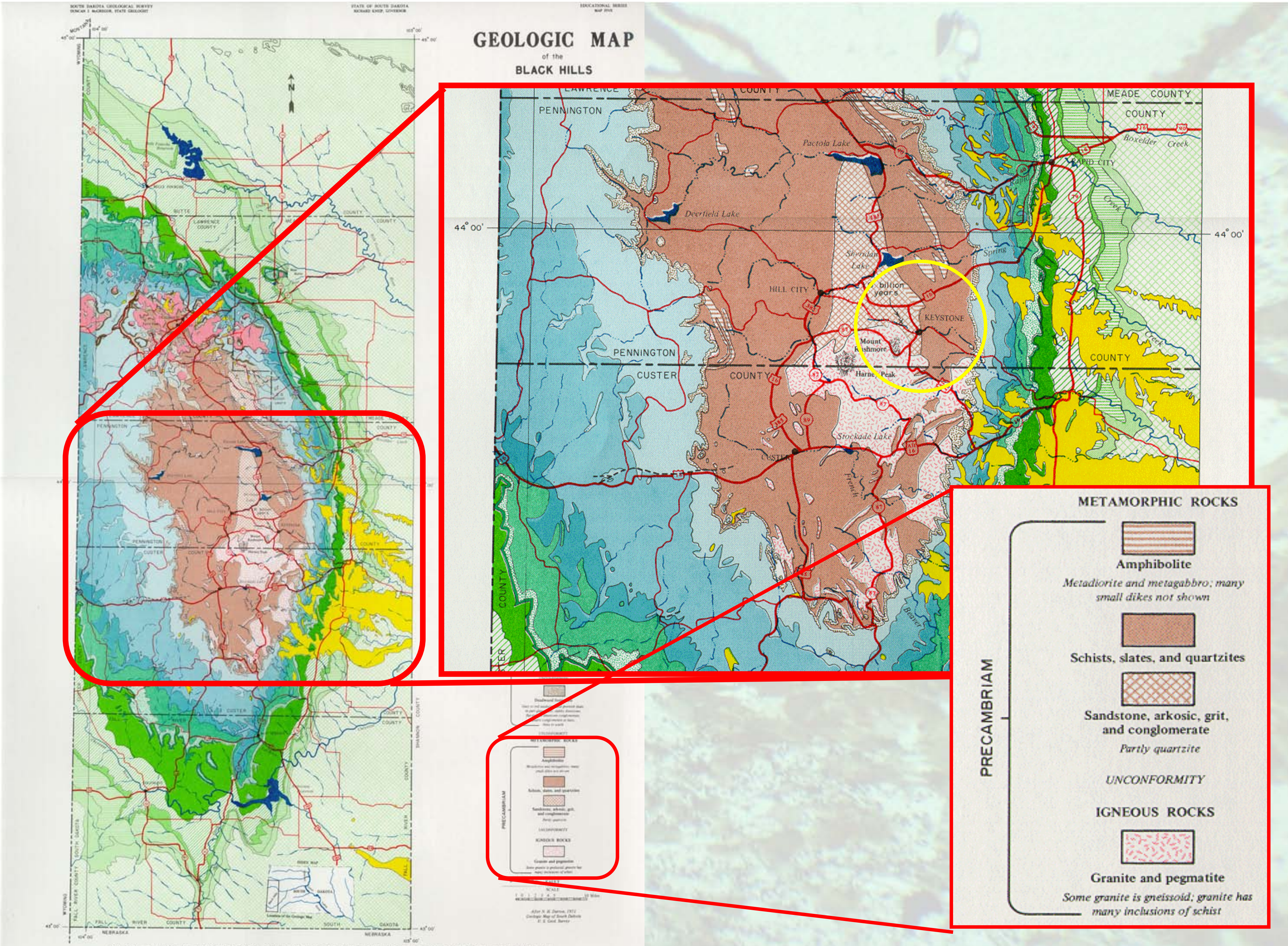
- Background of Black Hills
- Methods
- Geothermobarometry
- Conclusion

Black Hills of South Dakota



Geologic History

- Trans-Hudson Orogen (2.5–2.0 Ga)
  - deformation events
- Emplacement of Harney Peak Granites (1.7Ga)
  - contact metamorphism
  - deformation event
- Laramide Orogeny Uplift (80-35 Ma)



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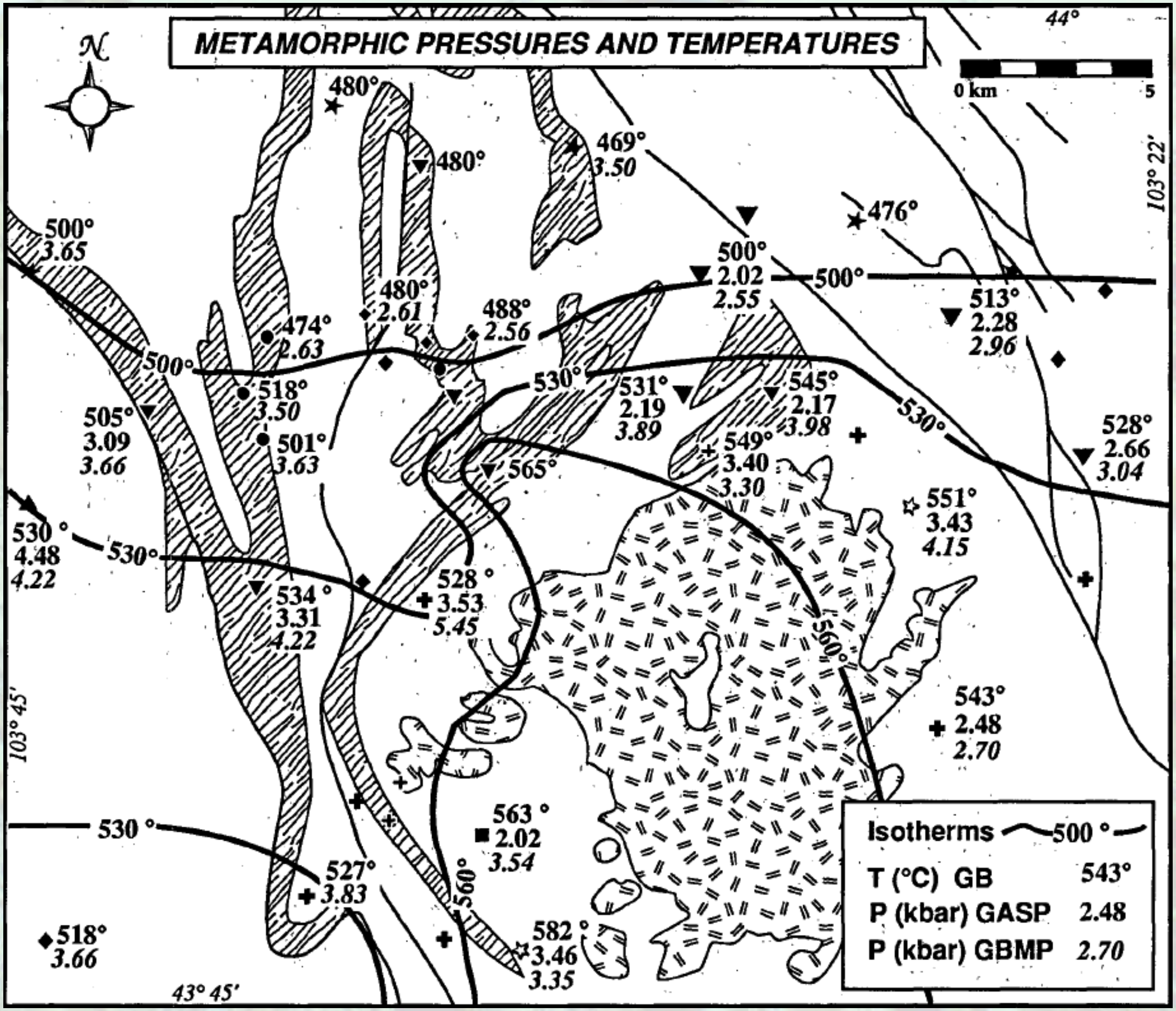
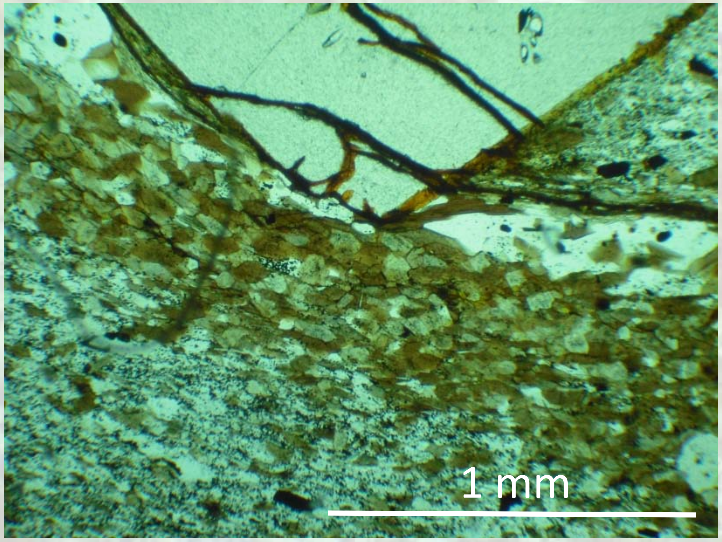


(Helms and Labotka, 1991)

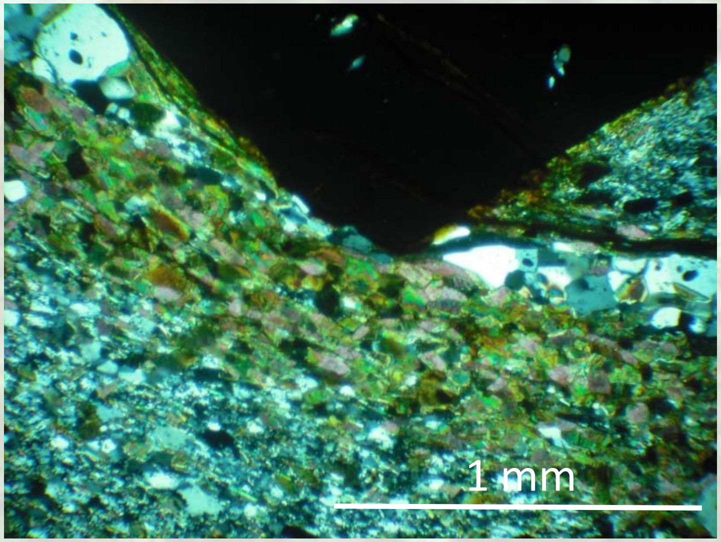
Hand Specimen

Fine grained groundmass, displaying metamorphic schistosity, supporting Garnet phenocrysts.

Thin Sections



PPL



XP

Scanning Electron Microscopy (SEM)

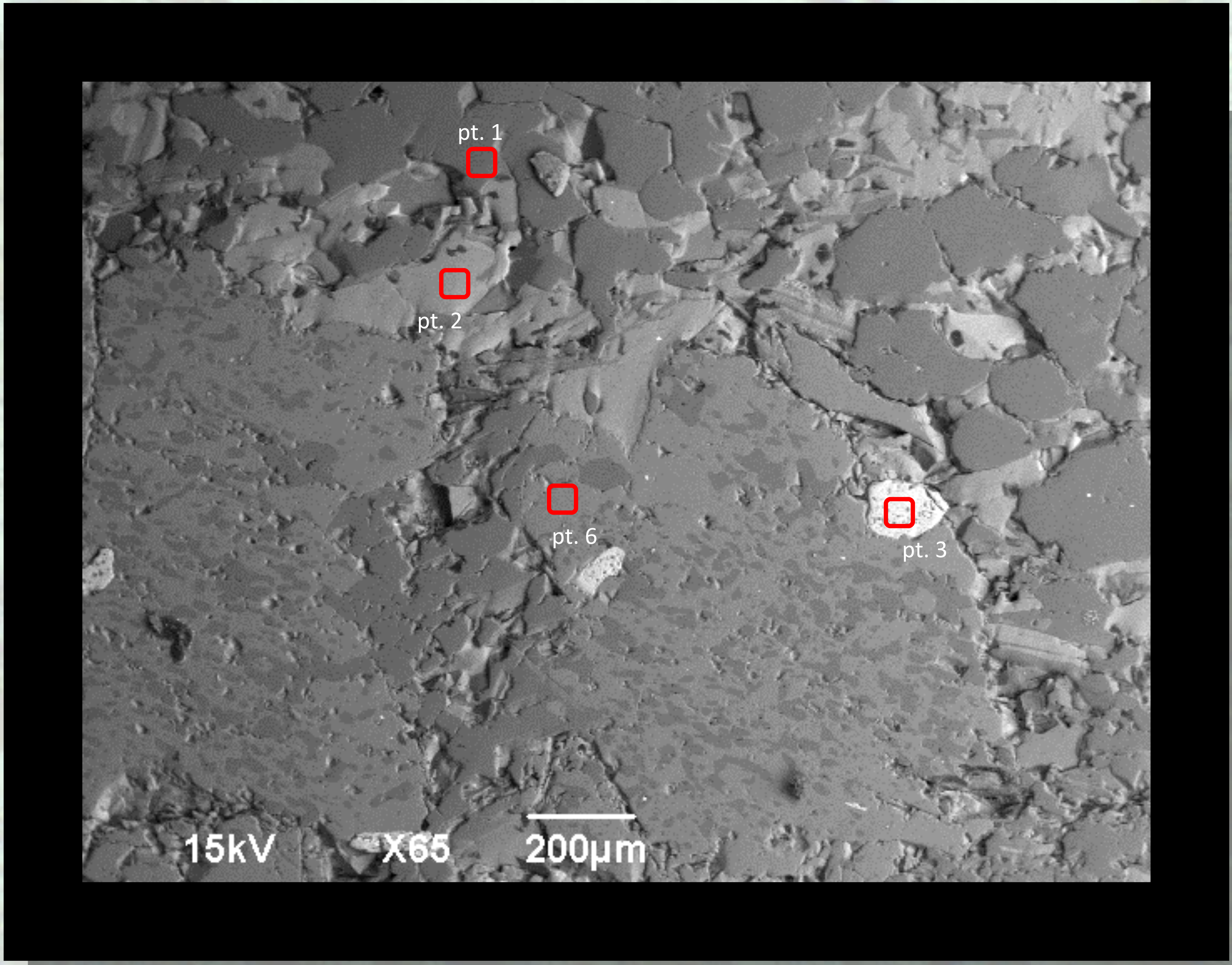
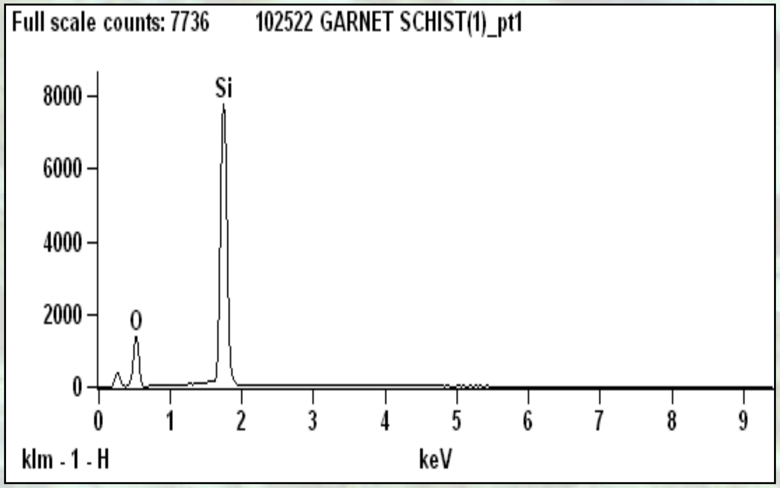
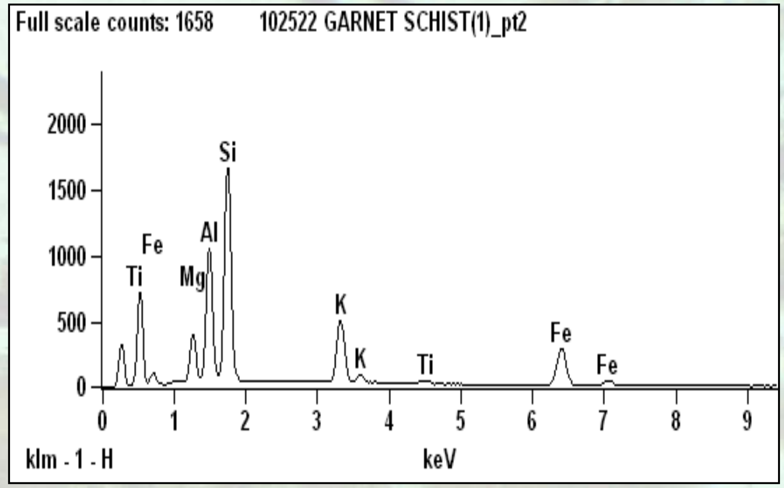


Image courtesy of NDSU Electron Microscopy Center (2010)

SEM cont.


Full scale counts: 7736
102522 GARNET SCHIST(1)_pt1
8000
6000
4000
2000
0
O
Si
0 1 2 3 4 5 6 7 8 9
klm - 1 - H
keV


Full scale counts: 1658
102522 GARNET SCHIST(1)_pt2
2000
1500
1000
500
0
Ti
Fe
Mg
Al
Si
K
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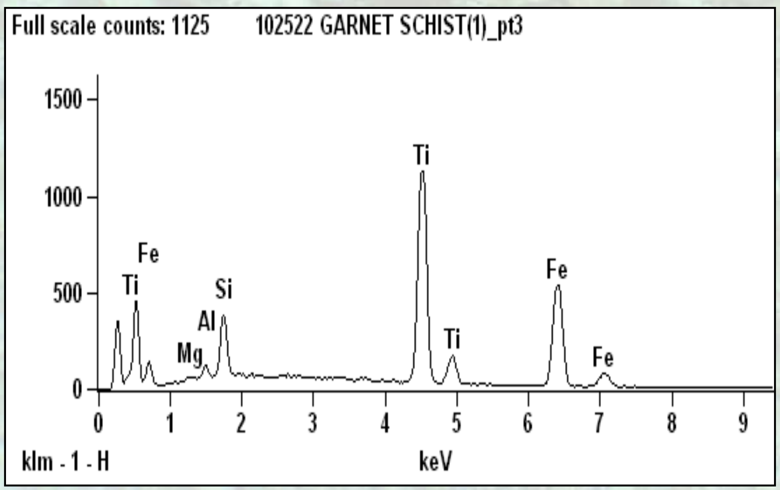
Ti
Fe
Fe
0 1 2 3 4 5 6 7 8 9
klm - 1 - H
keV


Full scale counts: 1125
102522 GARNET SCHIST(1)_pt3
1500
1000
500
0
Ti
Fe
Mg
Al
Si
Ti
Ti
Fe
Fe
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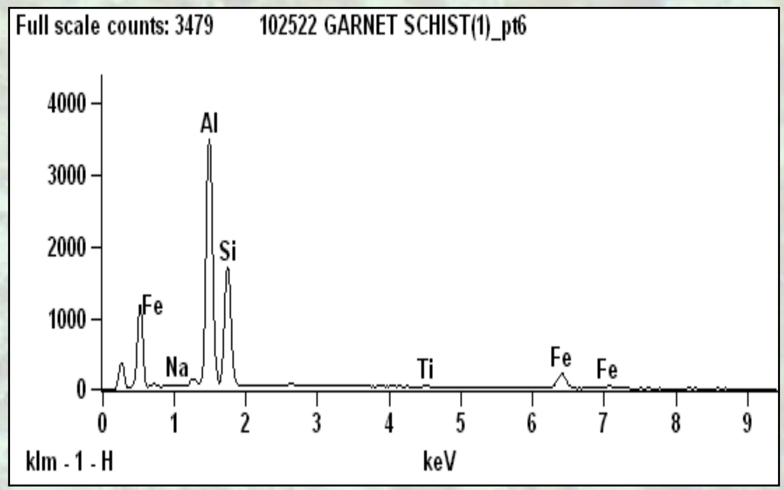
klm - 1 - H
keV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4000
3000
2000
1000
0
Fe
Na
Al
Si
Ti
Fe
Fe
0 1 2 3 4 5 6 7 8 9
klm - 1 - H
keV

SEM cont.

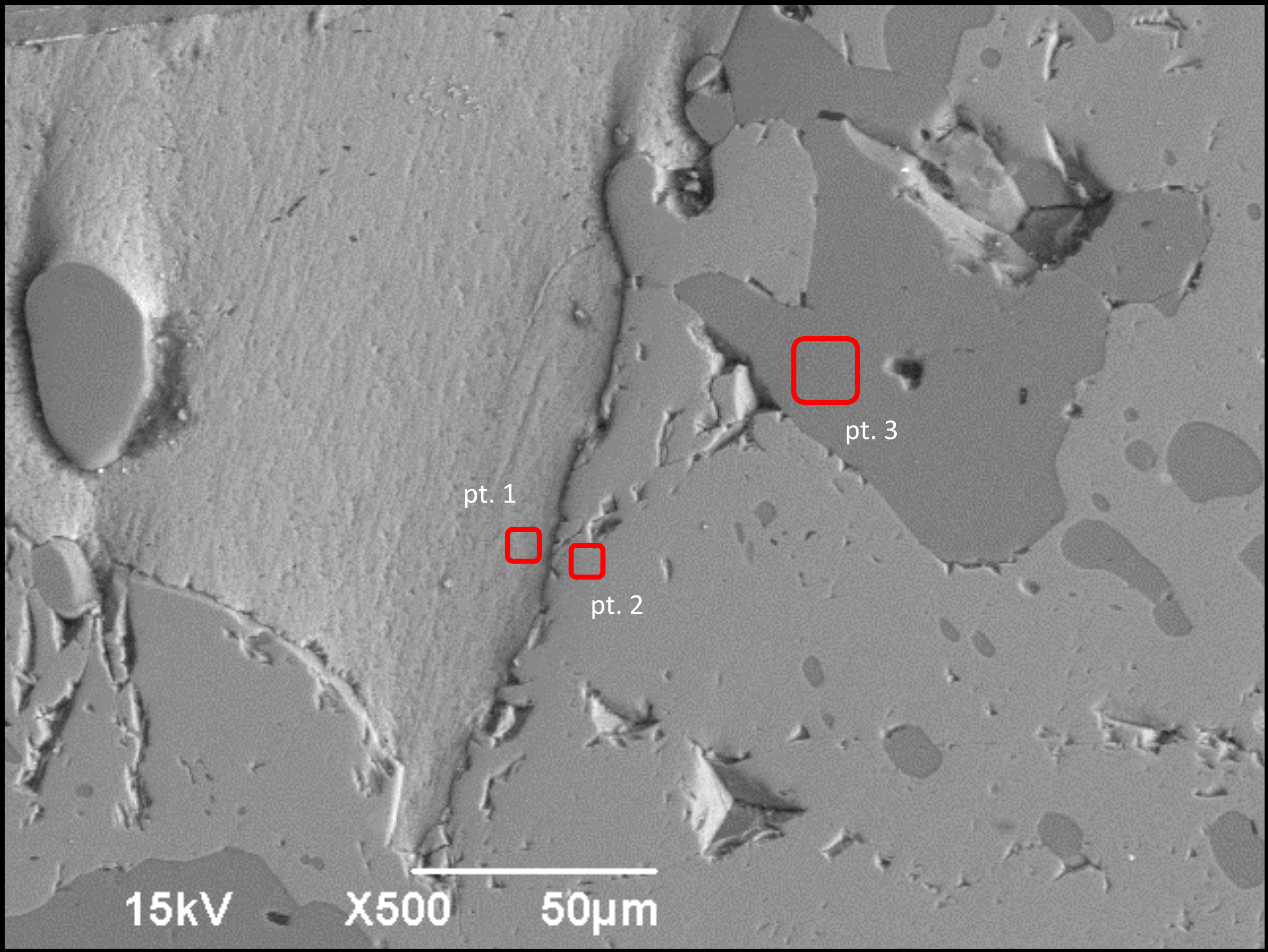
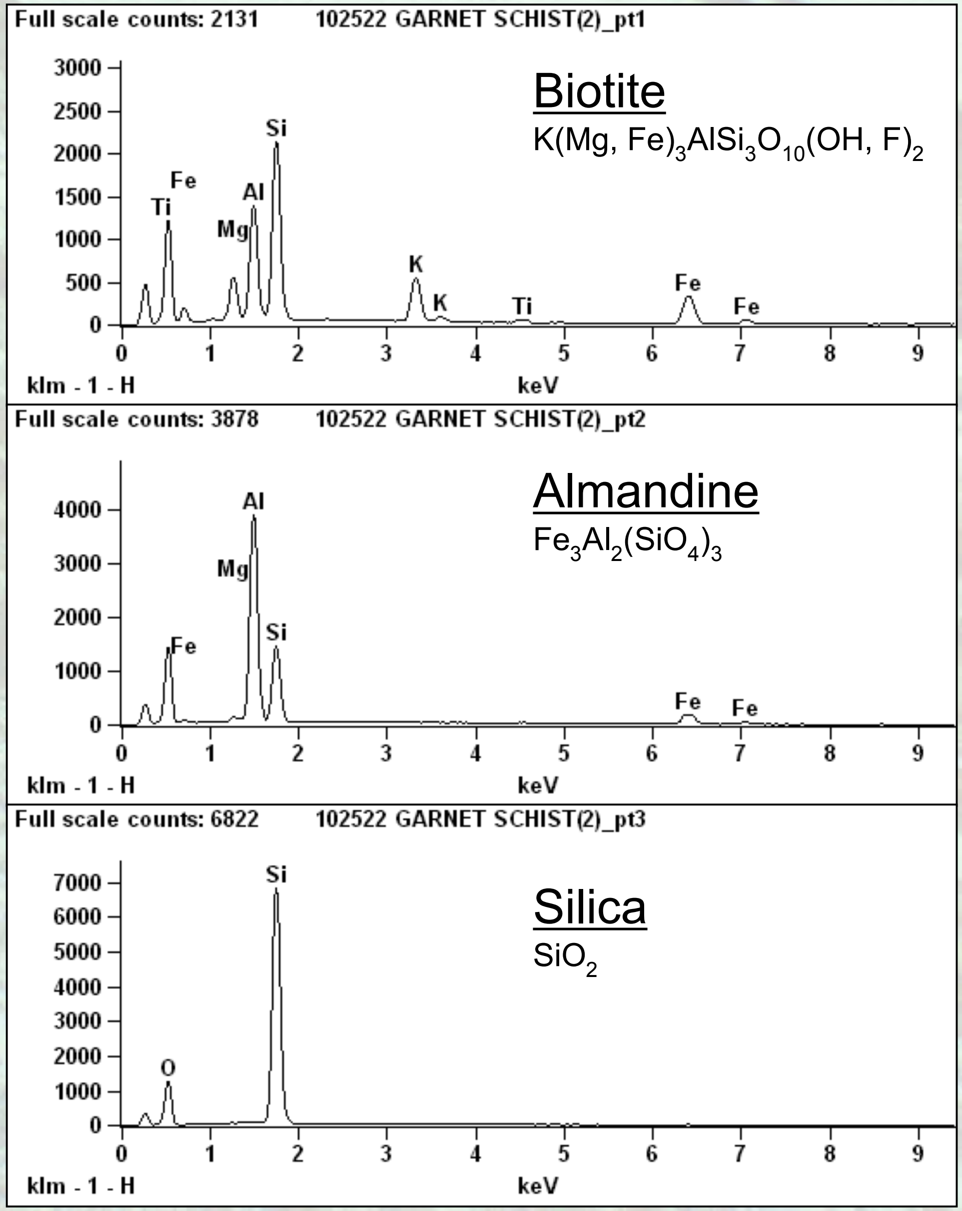


Image courtesy of NDSU Electron Microscopy Center (2010)

SEM cont.



Full scale counts: 2131
102522 GARNET SCHIST(2)_pt1
Biotite
$K(Mg, Fe)_3AlSi_3O_{10}(OH, F)_2$
Ti
Fe
Mg
Al
Si
K
K
Ti
Fe
Fe
klm - 1 - H
keV
Full scale counts: 3878
102522 GARNET SCHIST(2)_pt2
Almandine
$Fe_3Al_2(SiO_4)_3$
Fe
Mg
Al
Si
Fe
Fe
klm - 1 - H
keV
Full scale counts: 6822
102522 GARNET SCHIST(2)_pt3
Silica
SiO_2
O
Si
klm - 1 - H
keV

SEM Data

Weight %

	O-K	Mg-K	Al-K	Si-K	K-K	Ti-K	Fe-K
102522 GARNET SCHIST(2)_pt1		5.87	17.00	30.31	13.20	1.74	31.88
102522 GARNET SCHIST(2)_pt2		0.51	47.89	27.11			24.50
102522 GARNET SCHIST(2)_pt3	37.34			62.66			

Atom %

	O-K	Mg-K	Al-K	Si-K	K-K	Ti-K	Fe-K
102522 GARNET SCHIST(2)_pt1		5.87	17.00	30.31	13.20	1.74	31.88
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Geothermobarometry

- **Geobarometry**
  - The evaluation of the pressure at which a rock was formed

- **Geothermometry**
  - The evaluation of the temperature at which a rock formed

(Winter, 2010)

Who is ready for Equations!

Geothermobarometry

$$G = H - TS$$

G = Gibbs Free Energy (Measure of energy content of chemical systems)

H = Enthalpy (Heat Content)

T = Temperature (in Kelvins)

S = Entropy (Most easily preceived as randomness)

(Winter, 2010)

Geothermobarometry

- When applied to reaction with constant pressure:

$$\Delta G = \Delta H - T\Delta S$$

- When $\Delta G = 0$:

$$\Delta G = 0 = \Delta G^0 + RT\ln K$$

R = Gas Constant = 8.3144 J/mol K

K = Equilibrium Constant

Δ = Change in variable as result of reaction

(Winter, 2010)

Geothermobarometry

- Combining and rearranging these equations…

$$\ln K = -\Delta H^0/RT + \Delta S^0/R - (\Delta V/RT)dP$$

V = Volume

P = Pressure

d = finite change in variables of state (Ex: T & P)

- If ΔH^0, ΔV, and ΔS^0 are kept constant
  - Can use measurable K to find T (P almost insignificant)

(Winter, 2010)

Geothermometry:
The Garnet-Biotite Exchange

- Exchange Fe and Mg with changing temperatures and pressures
- Trying to reach equilibrium (Depends on T)
- Can infer temperature at formation of rock by measuring the ratio of Mg/Fe in both

(Winter, 2010)

Geothermometry

Ferry and Spear (1978)

•Performed Series of Experiments on Fe-Mg exchange between Biotite and Ca-free Garnet:

$$\underset{\text{Almandine}}{Fe_3Al_2Si_3O_{12}} + \underset{\text{Phlogopite}}{KMg_3Si_3AlO_{10}(OH)_2} = \underset{\text{Pyrope}}{Mg_3Al_2Si_3O_{12}} + \underset{\text{Annite}}{KFe_3Si_3AlO_{10}(OH)_2}$$

•Constant P = 0.207 Gpa

•T = 500-800° C

(Winter, 2010)

Ferry and Spear, 1978

- $X^{Grt} = Alm_{90}Prp_{10}$
- X_{Fe}= molar Fe / (Fe + Mg) = 0.9
- Two different X^{Bt}
  - Approach equilibrium from both sides
- Grt and Bt molar proportions of 98:2
  - Bt would have to change far more to accommodate Grt composition in attaining equilibrium K_D value

(Winter, 2010)

Ferry and Spear, 1978

•Experiments lasted 13 to 56 days to give time for equilibration to be reached

TABLE 27.2 Experimental Results of Ferry and Spear (1978) on a Garnet–Biotite Geothermometer

T°C	Initial X_{Bt}^{Fe}	Final X_{Bt}^{Fe}	Final X_{Grt}^{Fe}	Final $(Mg/Fe)_{Grt}$	Final $(Mg/Fe)_{Bt}$	*K*	T kelvins	1/T kelvins
799	1.00	0.750	0.905	0.105	0.333	0.315	1072	0.00093
799	0.50	0.710	0.896	0.116	0.408	0.284	1072	0.00093
749	0.50	0.695	0.896	0.116	0.439	0.264	1022	0.00098
738	1.00	0.730	0.906	0.104	0.370	0.281	1011	0.00099
698	0.75	0.704	0.901	0.110	0.420	0.261	971	0.00103
698	0.50	0.690	0.896	0.116	0.449	0.258	971	0.00103
651	0.75	0.679	0.901	0.110	0.473	0.232	924	0.00108
651	0.50	0.661	0.897	0.115	0.513	0.224	924	0.00108
599	0.75	0.645	0.902	0.109	0.550	0.197	872	0.00115
599	0.50	0.610	0.898	0.114	0.639	0.178	872	0.00115
550	0.75	0.620	0.903	0.107	0.613	0.175	823	0.00122
550	0.50	0.590	0.898	0.114	0.695	0.163	823	0.00122

Table from (Winter, 2010) p. 588, originally from (Ferry and Spear,

Ferry and Spear, 1978

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799	0.50	0.710	0.896	0.116	0.408	0.284	1072	0.00093

ΔX_{Fe}^{Grt}= (2/98)ΔX_{Fe}^{Bt}= (2/98) * (1.0 – 0.750) = 0.005

So final X_{Fe}^{Grt}= 0.90 + 0.005 = 0.905

Table from (Winter, 2010) p. 588, originally from (Ferry and Spear,

Ferry and Spear, 1978

- Can use these final compositions to find K_D
- Assuming an ideal solution:

$$K = K_D = \frac{(Mg/Fe)^{Grt}}{(Mg/Fe)^{Bt}}$$

$$\ln K = \ln K_D = -\Delta H^0/RT + \Delta S^0/R - (\Delta V/RT)dP$$

Measurable

Trying to find

Ferry and Spear, 1978

- Rearranging previous equations:

$$\ln K_D = \frac{-\Delta H - P\Delta V}{3R} * (1/T) + \frac{\Delta S}{3R}$$

<u>Experimentally derived constants:</u>

ΔS = 19.506 J/K mol
ΔV = 2.494 J/Mpa (Robbie and Hemingway, 1995)
ΔH = 52.09 kJ/mol

Ferry and Spear, 1978

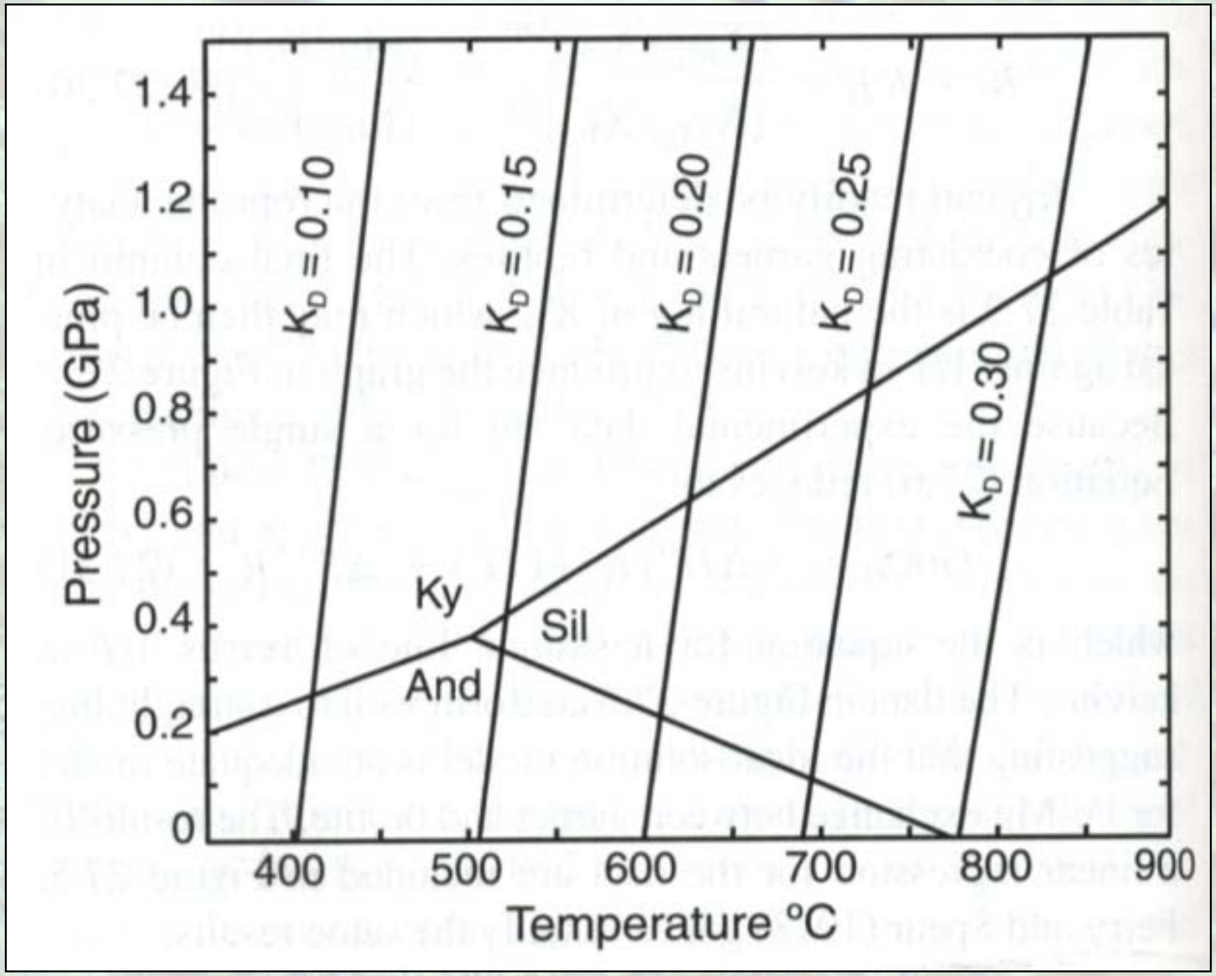
- Rerranging previous equation & substituting in constant values:

$$T^{\circ}\mathrm{C} = \frac{52{,}090 + 2.494\,P(\mathrm{MPa})}{19.506 - 24.943\,\ln K_D} - 273$$

•P only variable left…

Spear, 1993

- Change in P almost insignificant.



KD values for the garnet-biotite exchange.
Diagram from (Winter, 2010) p. 590, originally from (Spear,

Our SEM Data

Atom %

	O-K	*Mg-K*	*Al-K*	*Si-K*	*K-K*	*Ti-K*	*Fe-K*
Biotite		8.34	21.76	37.27	11.66	1.26	19.72
~Almandine		0.65	55.47	30.16			13.71

$$K_D = \frac{(0.65/13.71)^{Grt}}{(8.34/19.72)^{Bt}} = 0.112$$

Assuming an average P of 4 kilobars = 400 Mpa…

$$T^{\circ}C = \frac{52{,}090 + 2.494*400}{19.506 - 24.943 \ln(0.112)} - 273 = \mathbf{443.31^{\circ}C}$$

Conclusion

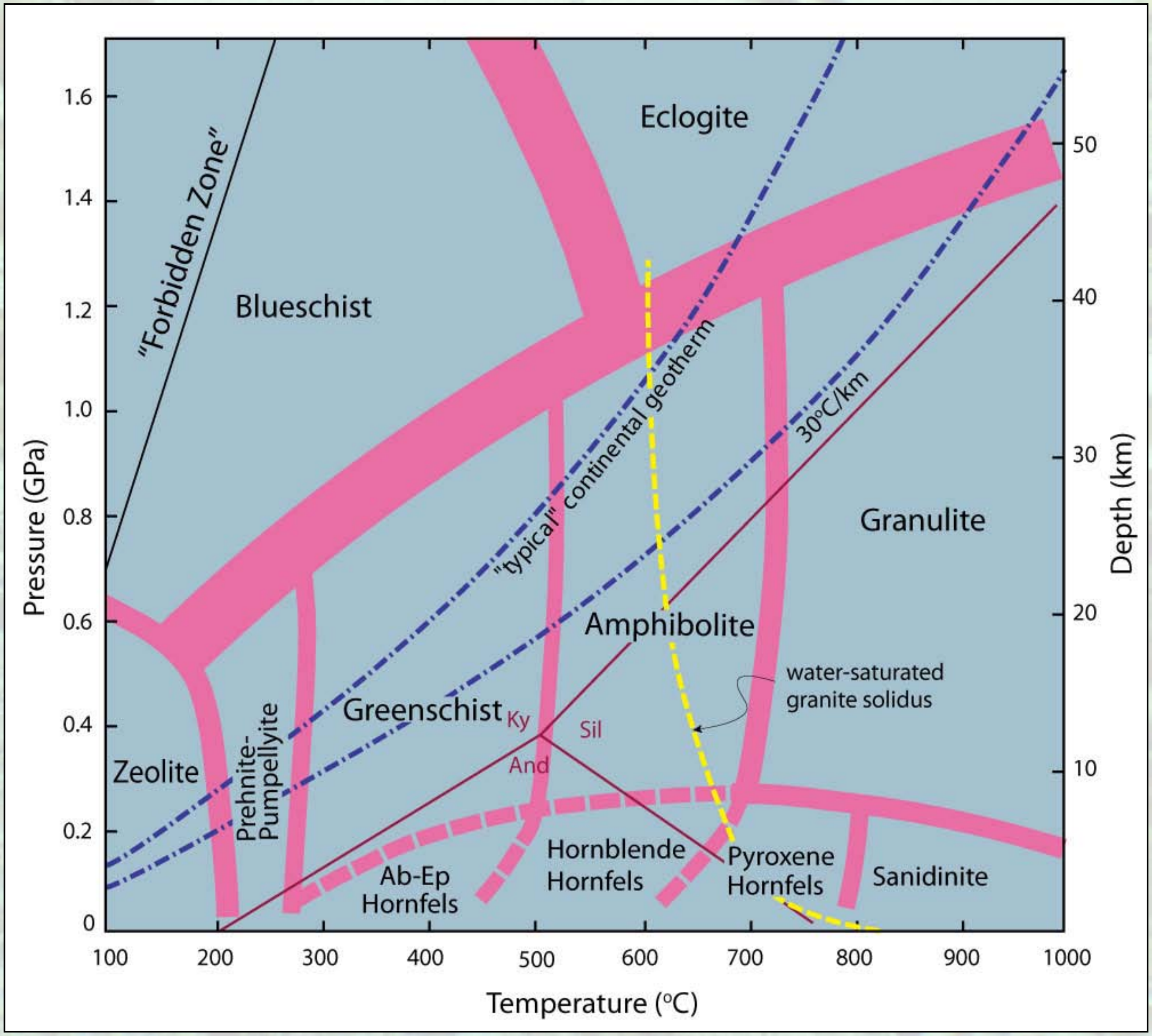
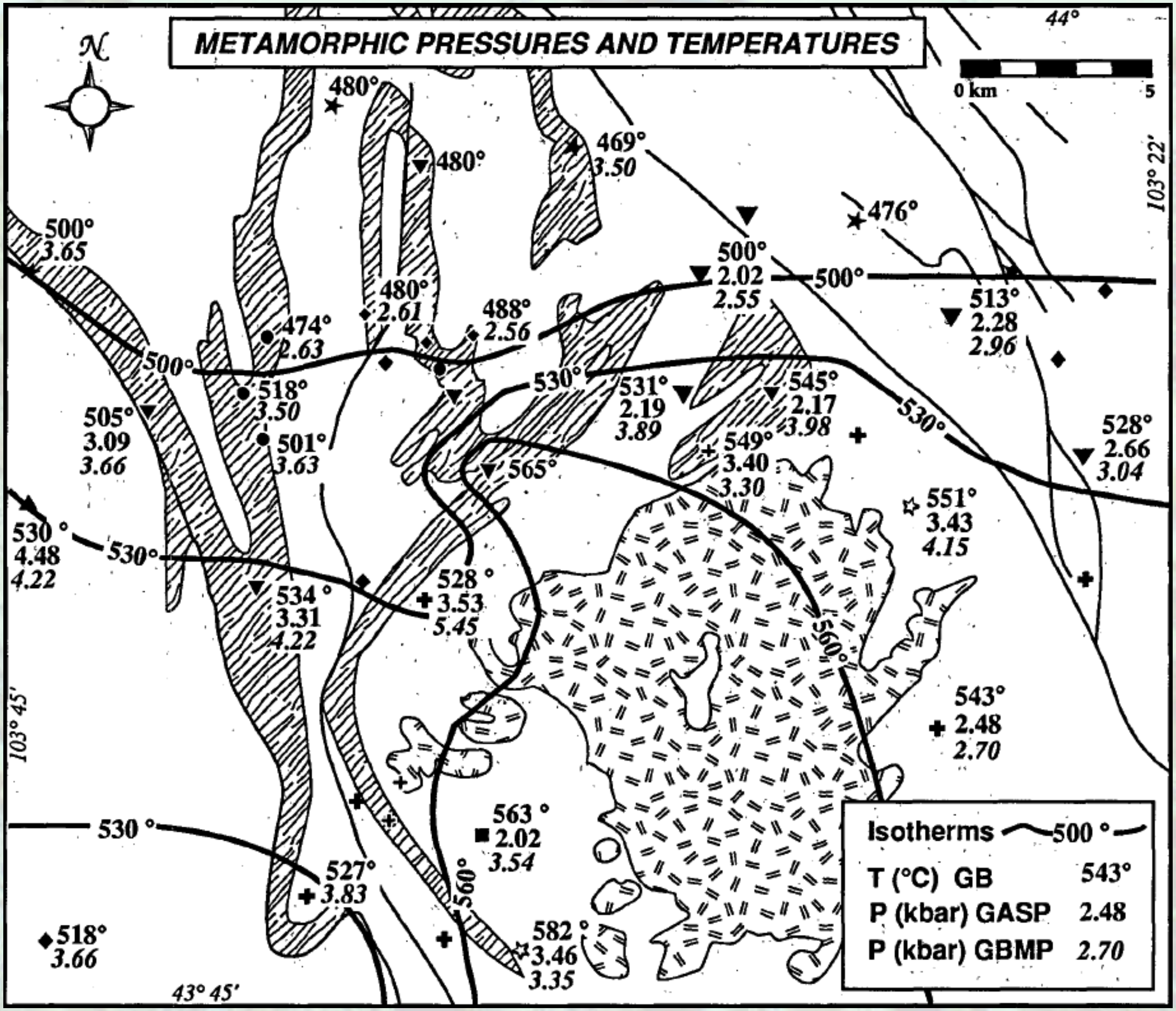


Diagram from (Winter, 2010) p. 588



(Helms and Labotka, 1991)

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