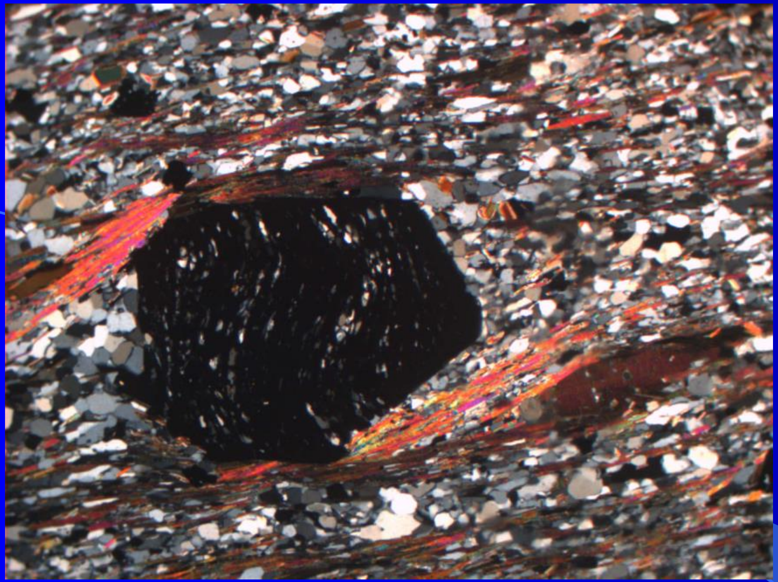
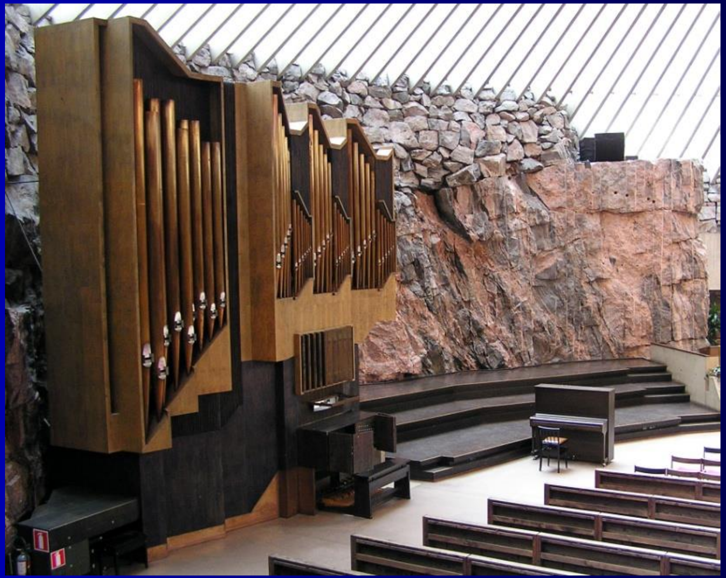
Metamorphic Rocks

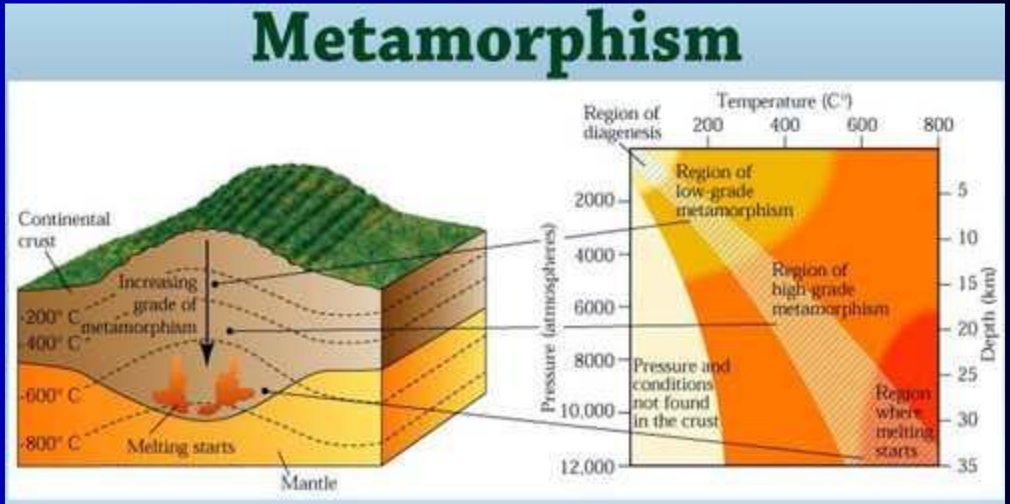


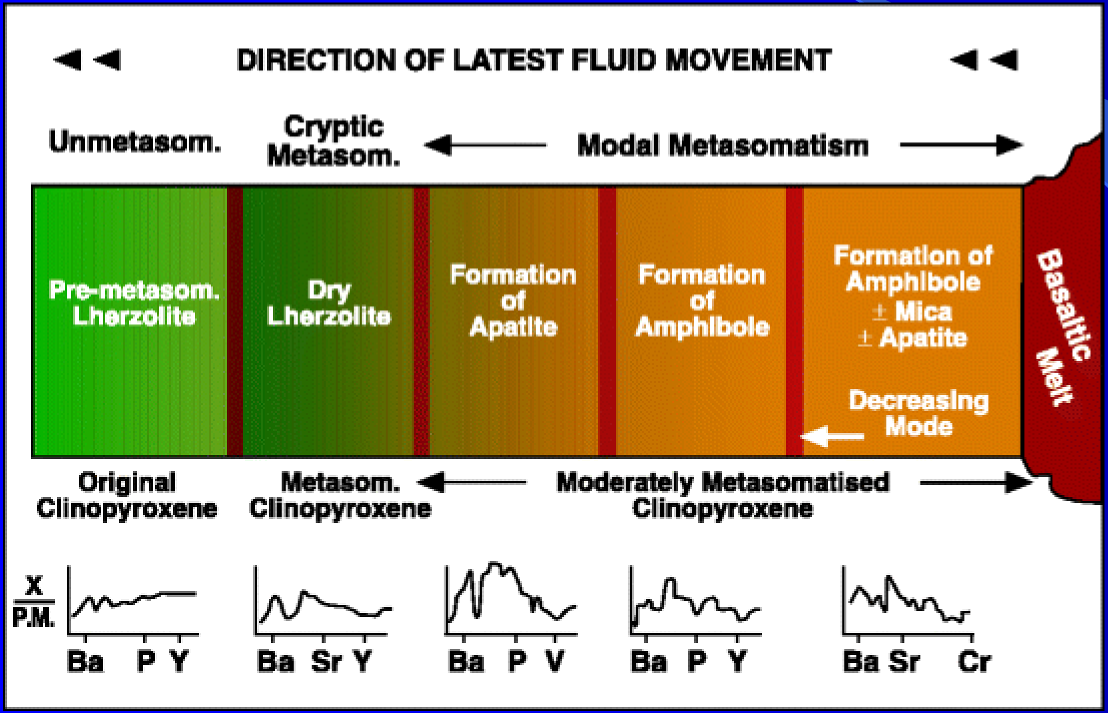


Reminder notes:

- Metamorphism
- Metasomatism
- Regional metamorphism
- Contact metamorphism
- Protolith
- Prograde
- Retrograde
- Fluids – dewatering and decarbonation – volatile flux
- Chemical change vs textural changes
- Mud to gneiss

Metamorphism – changes in mineralogy and texture of a rock due to changes in pressure and temperature. The bulk chemical composition of the rock doesn't change.





Metasomatism – changes in mineralogy and texture of a rock due to changes in pressure, temperature, and ***chemistry***. Chemically active fluids move ions from one place to another which changes the bulk chemistry of the rock. These fluids come from the breakdown of hydrous and carbonate minerals.

Contact versus Regional metamorphism

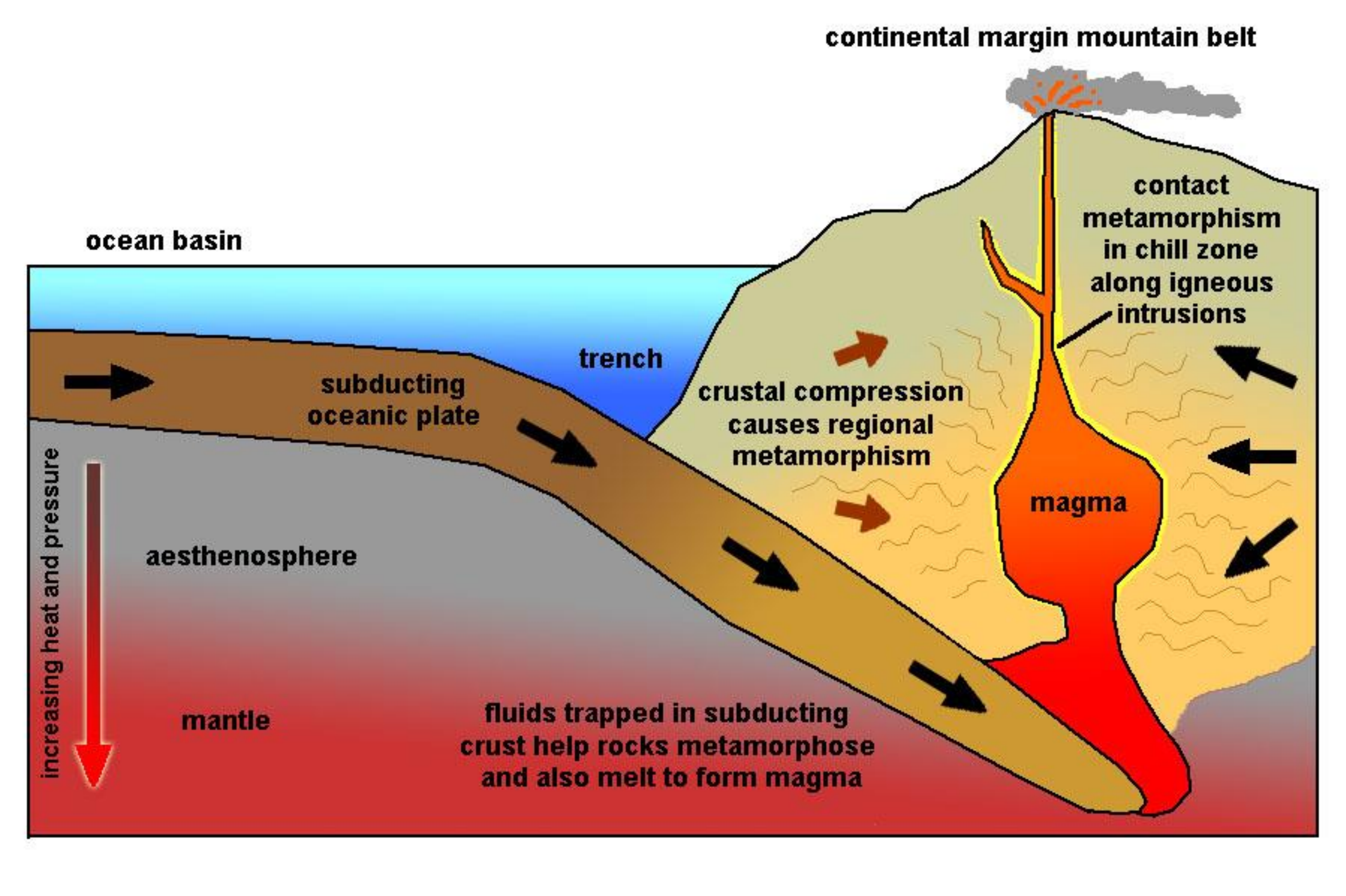
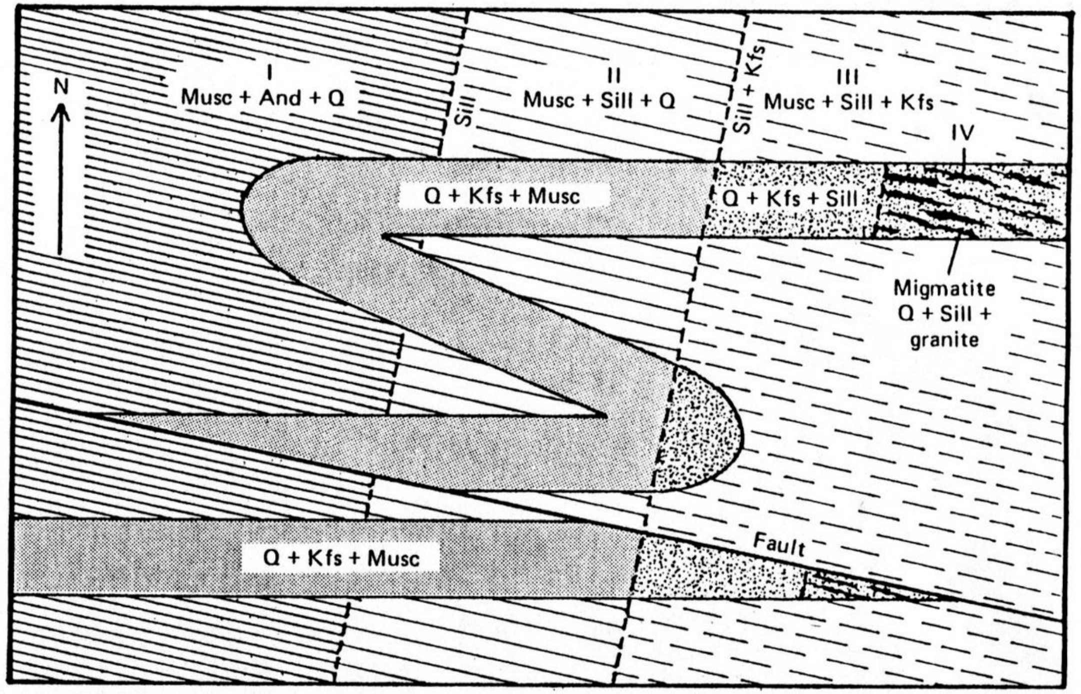


FIGURE 15-1 Idealized geologic map of a model metamorphic terrane containing two protoliths, sandstone (stippled) and shale (lined). These rocks were folded and faulted prior to metamorphism. The shale was converted to a muscovite schist and the sandstone to a quartzite during metamorphism. The intensity of metamorphism increases from west to east, with four metamorphic zones being developed (Roman numerals), each with its own characteristic mineral assemblages, as shown on the map. The boundaries between zones, which are called isograds, mark the intersection of reaction surfaces in P–T–a_{H_2O} space with the erosion surface. The isograds are labeled with the new mineral or mineral assemblage appearing on the high-temperature side of the isograd.



Metamorphic Facies

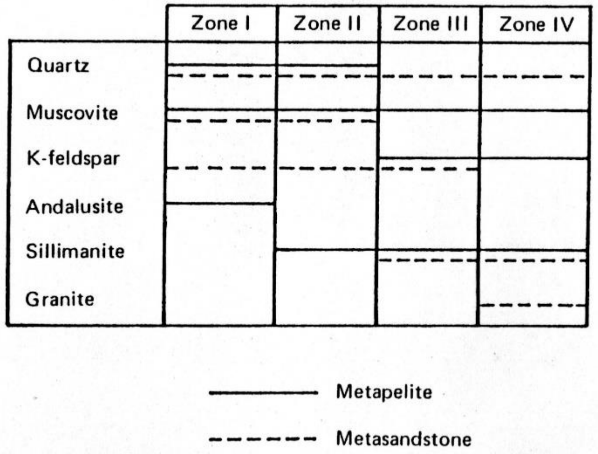
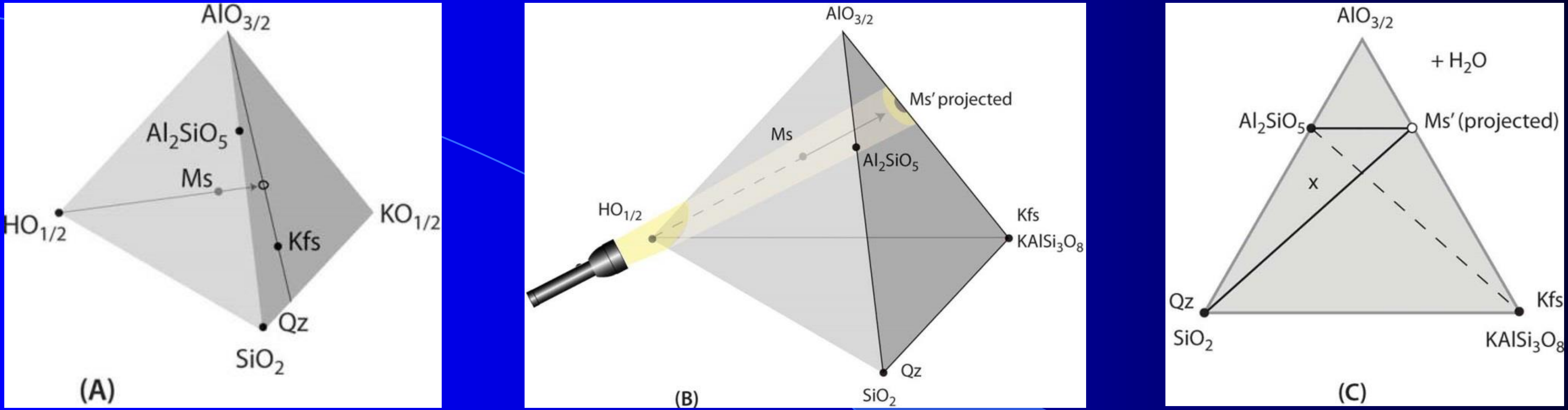


FIGURE 15-2 Minerals present in the metapelite and metasandstone in the four different metamorphic zones of the area shown in Figure 15-1.

Plotting metamorphic mineral diagrams



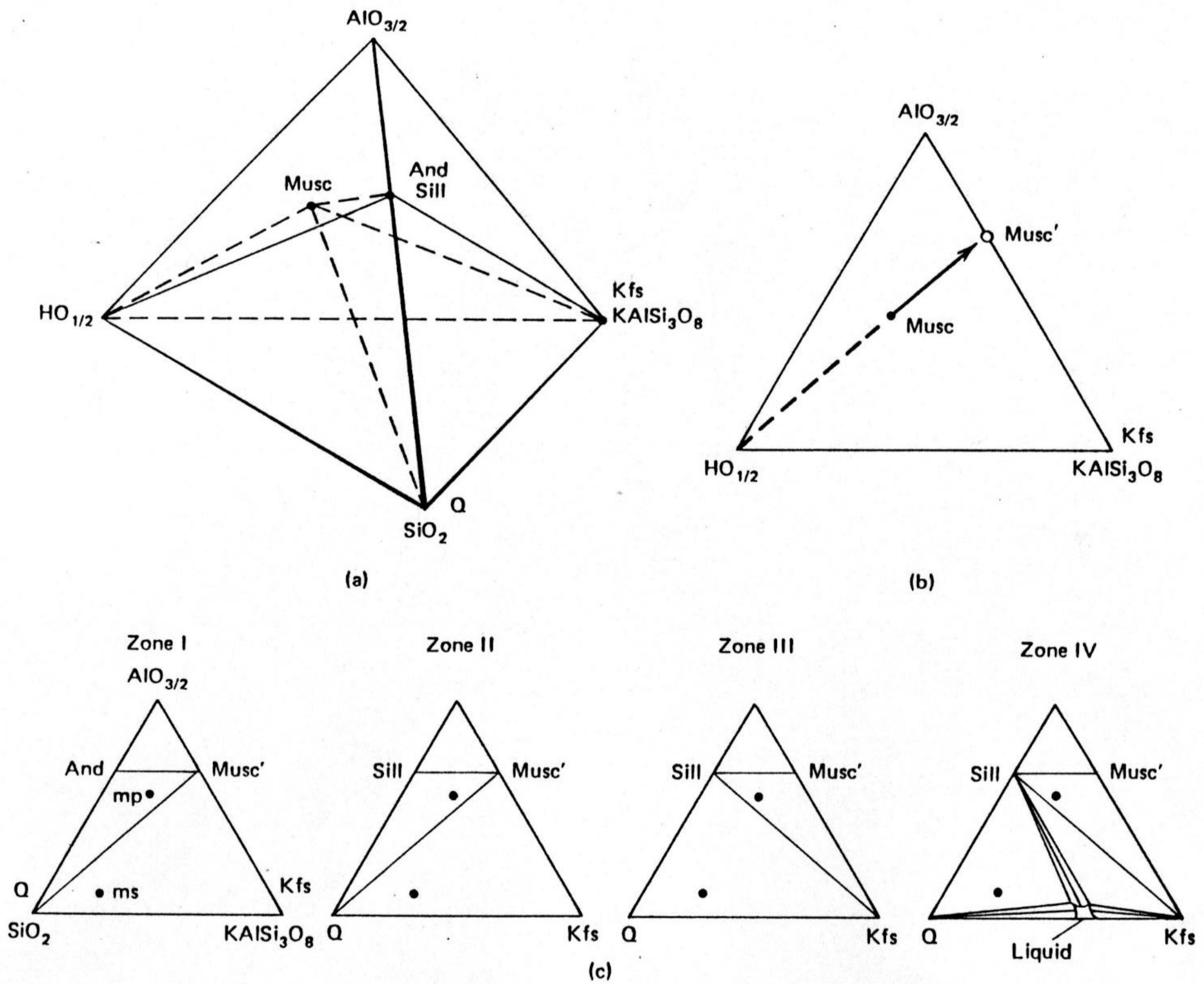
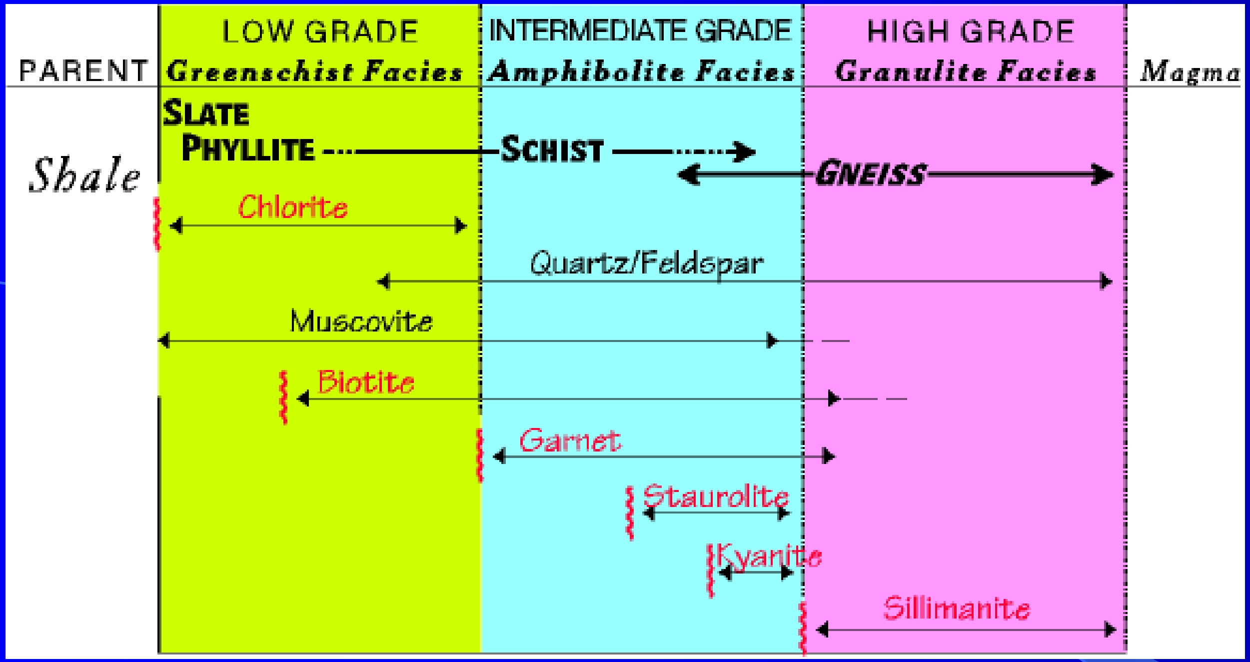
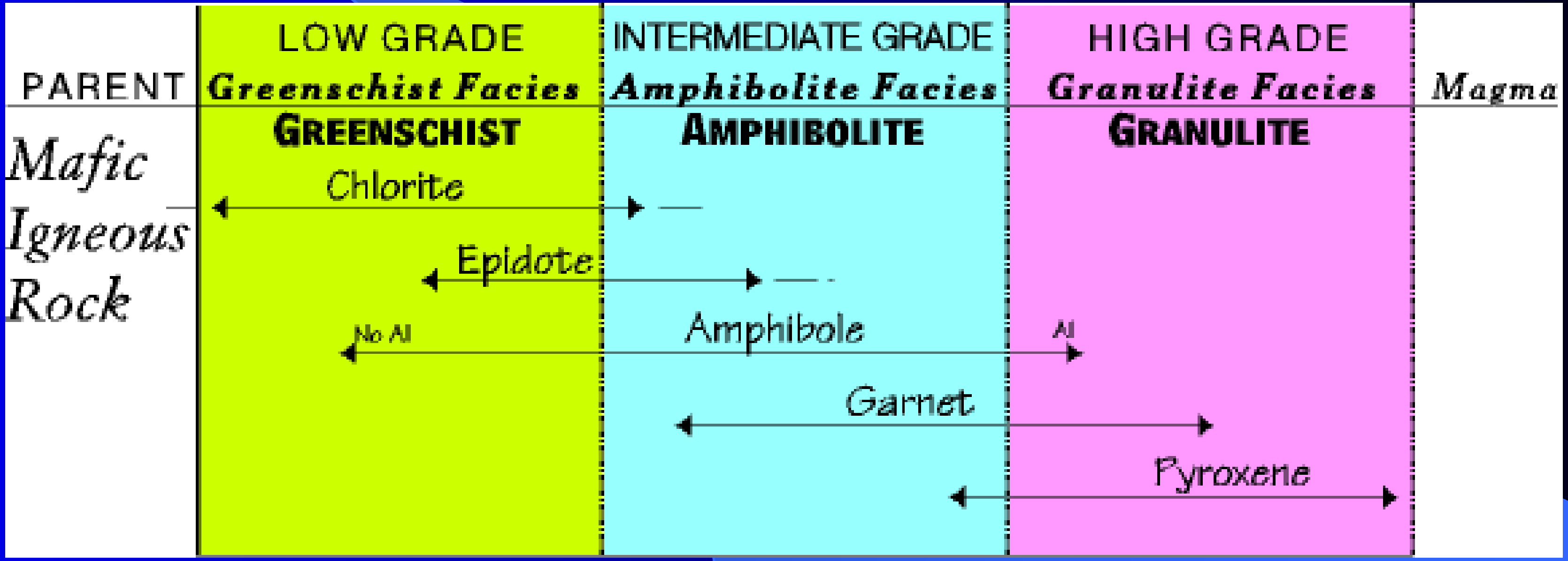


FIGURE 15-3 (a) Tetrahedral mole fraction plot of the mineral assemblages in zone I of the model metamorphic terrane shown in Figure 15-1. Muscovite plots on the back face of the tetrahedron. (b) Projection of the composition of muscovite across the back face of the tetrahedron onto the water-free join $AlO_{3/2}$–$KAlSi_3O_8$. (c) Mineral facies diagrams for each of the metamorphic zones. Compositions within the tetrahedron of (a) are projected onto the triangular face $AlO_{3/2}$–$KAlSi_3O_8$–SiO_2 from the water apex, assuming that the activity of water was buffered at some fixed value by the environment. The bulk composition of the metapelite is indicated by the point marked mp and the metasandstone by ms.

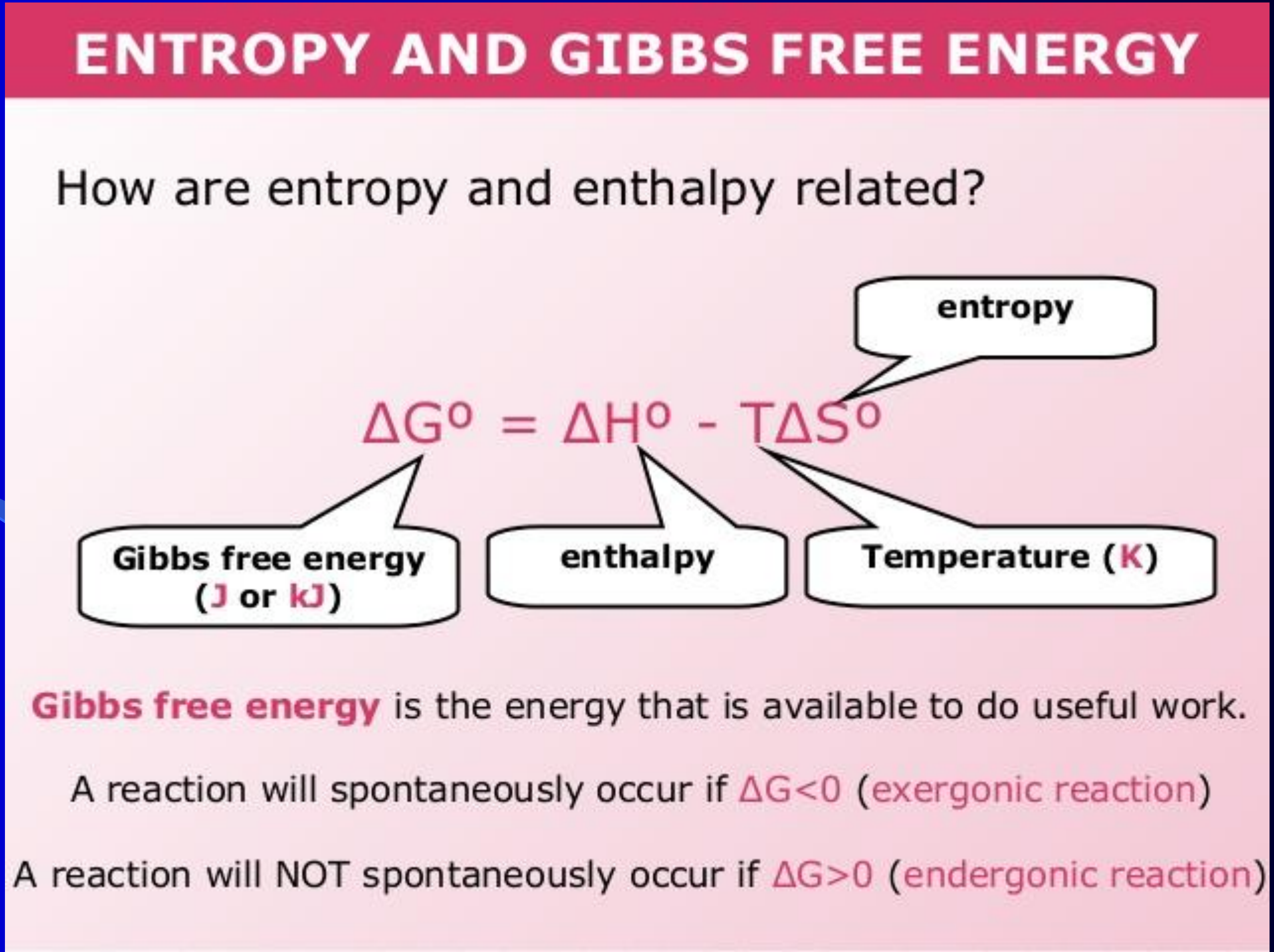
Barrovian metamorphic sequences



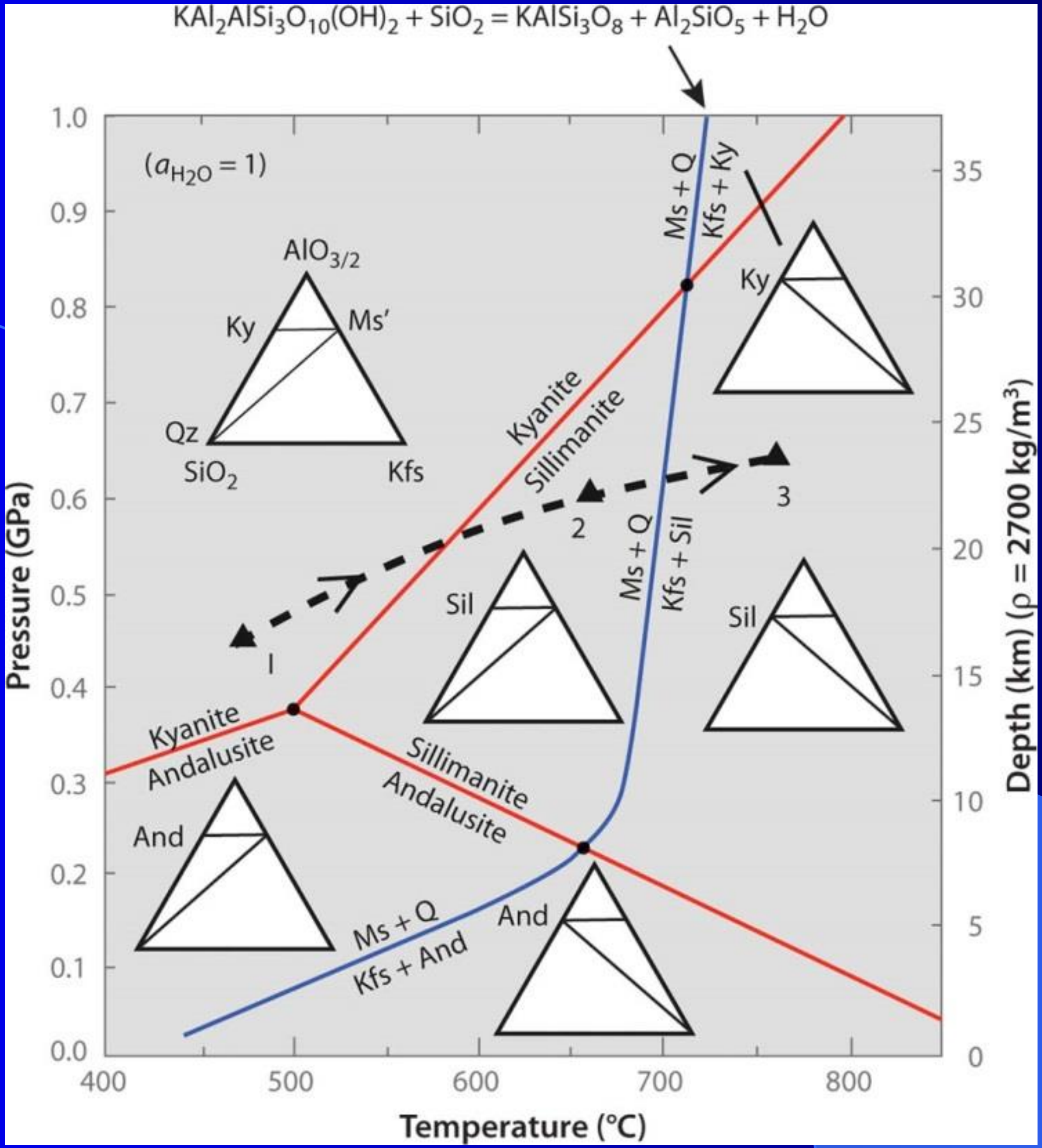


Thermodynamics and Gibbs free energy

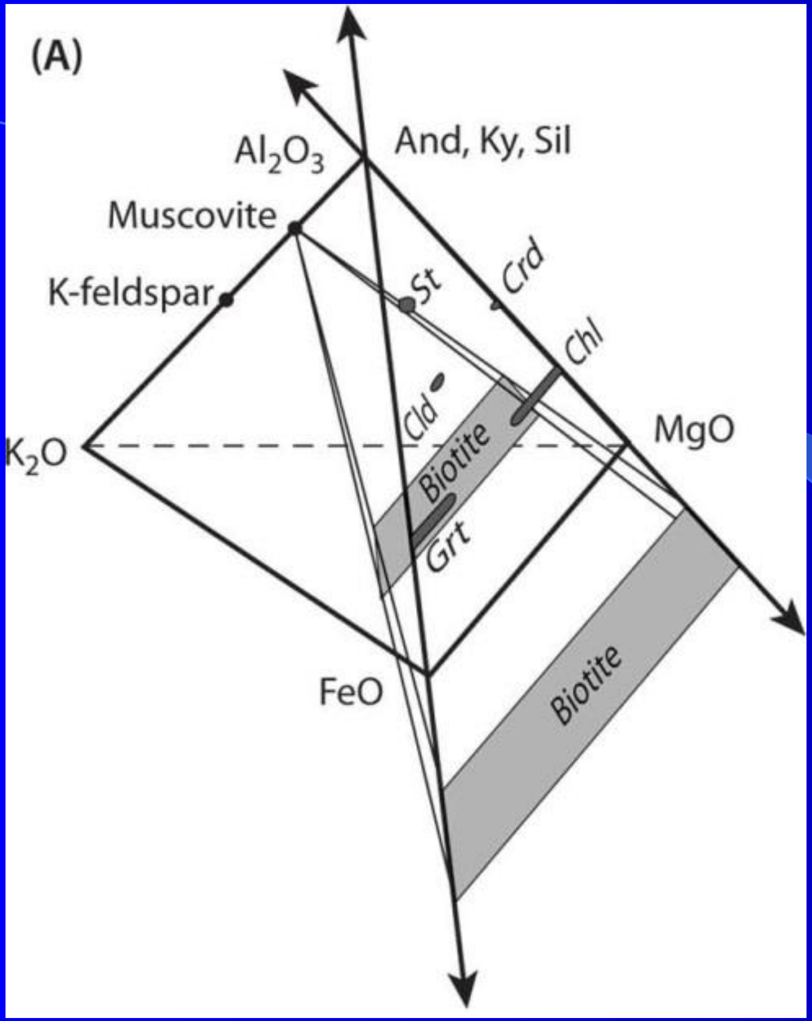
- Reactions take place in a direction that lowers Gibbs free energy
- Equilibrium is achieved only when Gibbs free energy reaches a minimum
- At equilibrium, temperature, pressure, and chemical potentials of all components must be the same throughout
- Equilibrium thermodynamics and kinetics. Thermodynamics tells us what can happen, kinetics tells us if it does happen

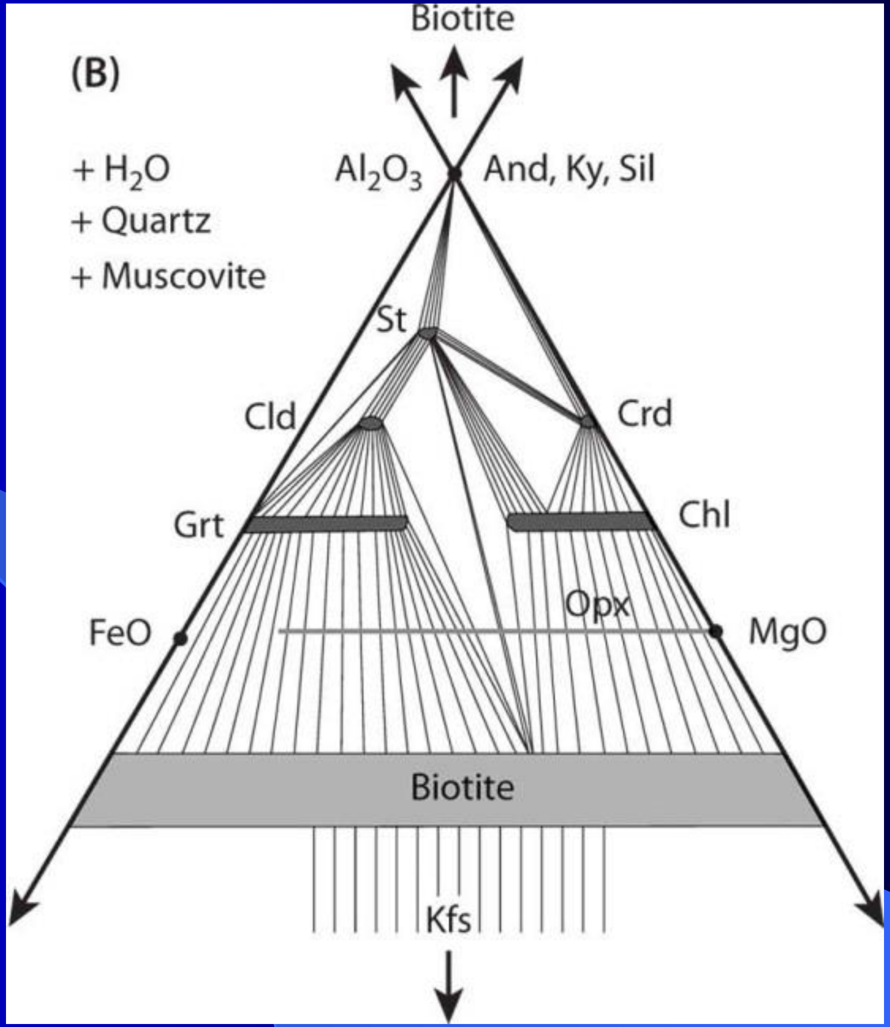


Petrogenetic Grid

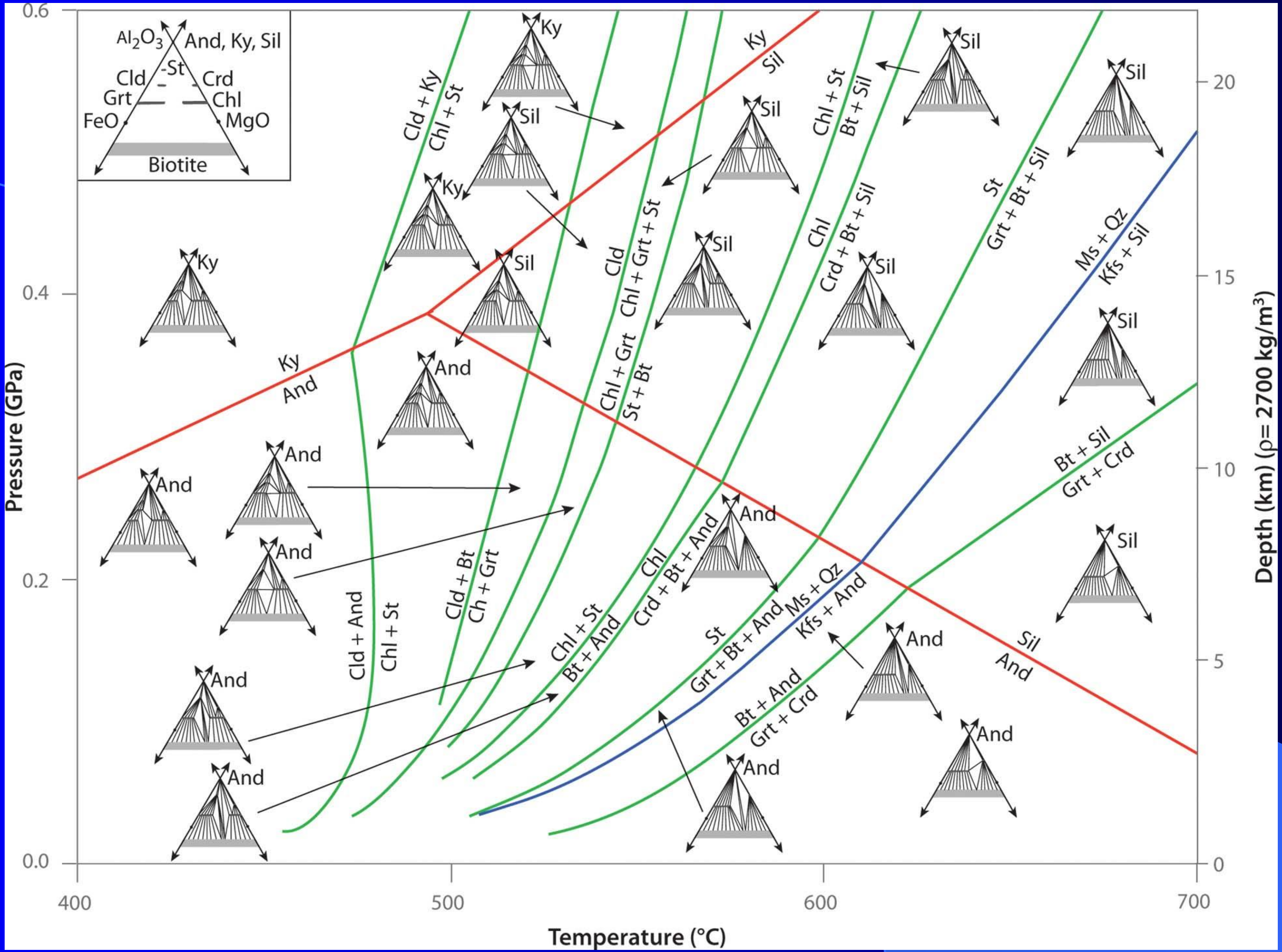


AKFM diagram for pelitic rocks

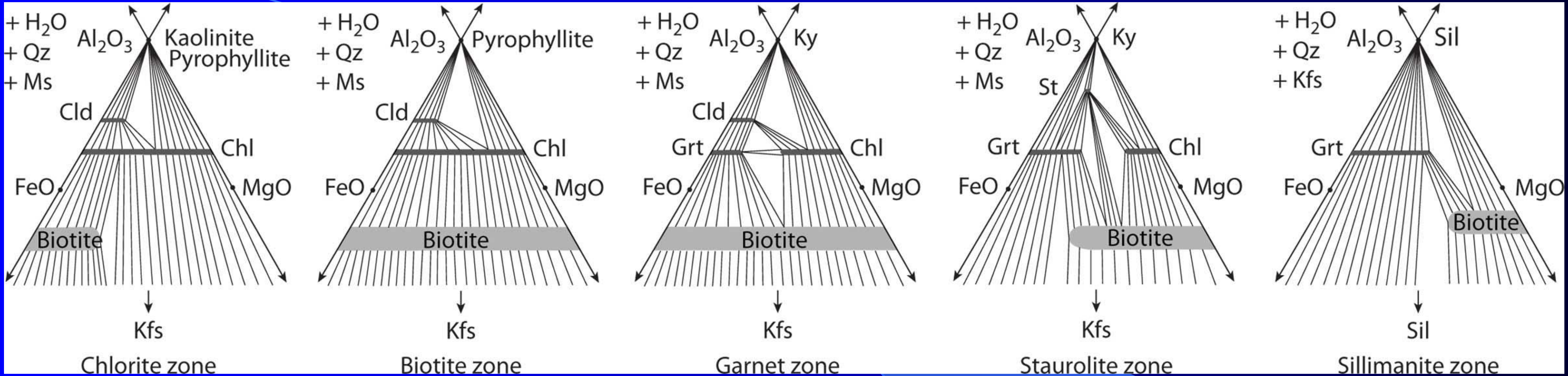


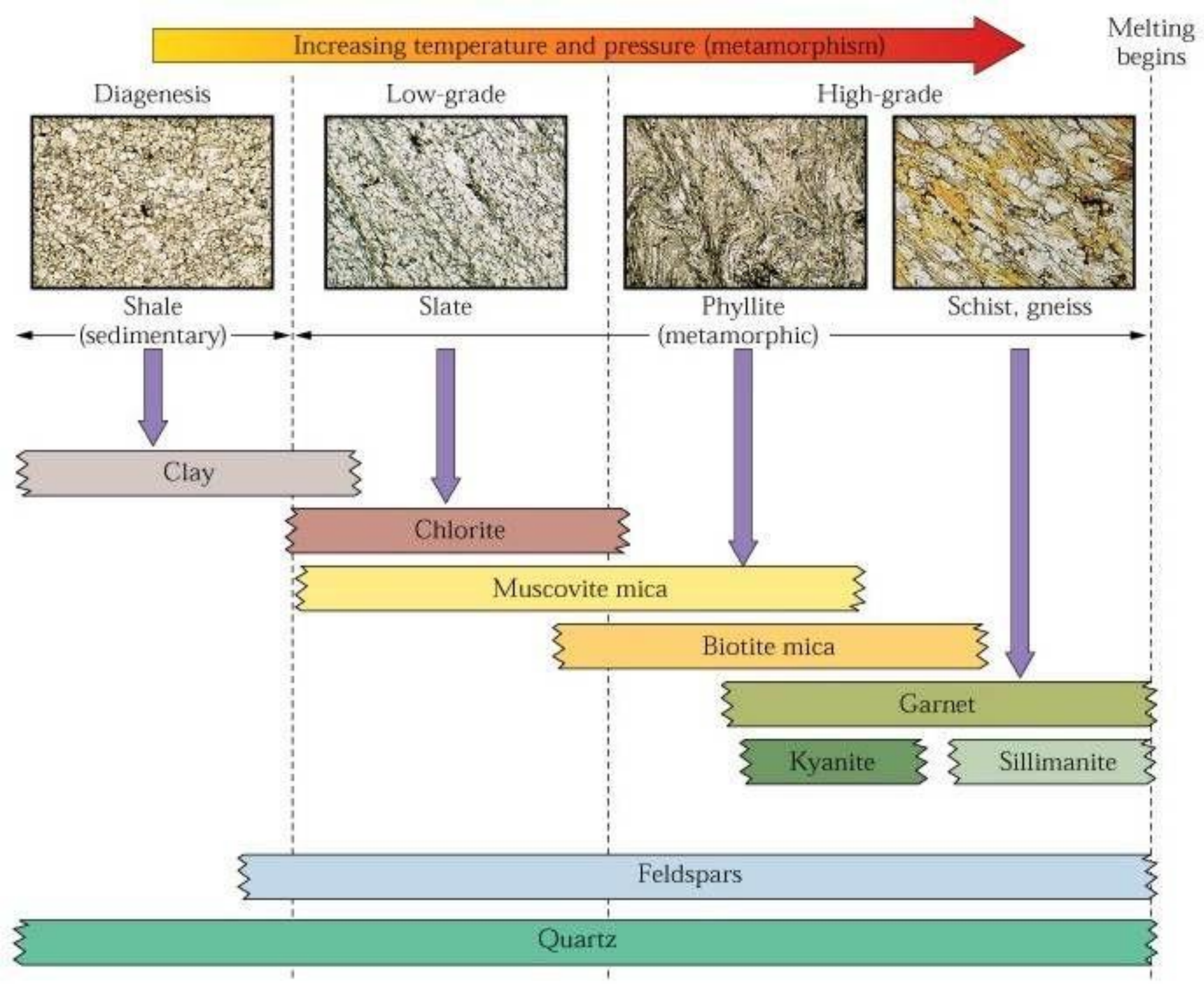


Petrogenetic grid – reactions in metapelites for greenschist and amphibolite facies

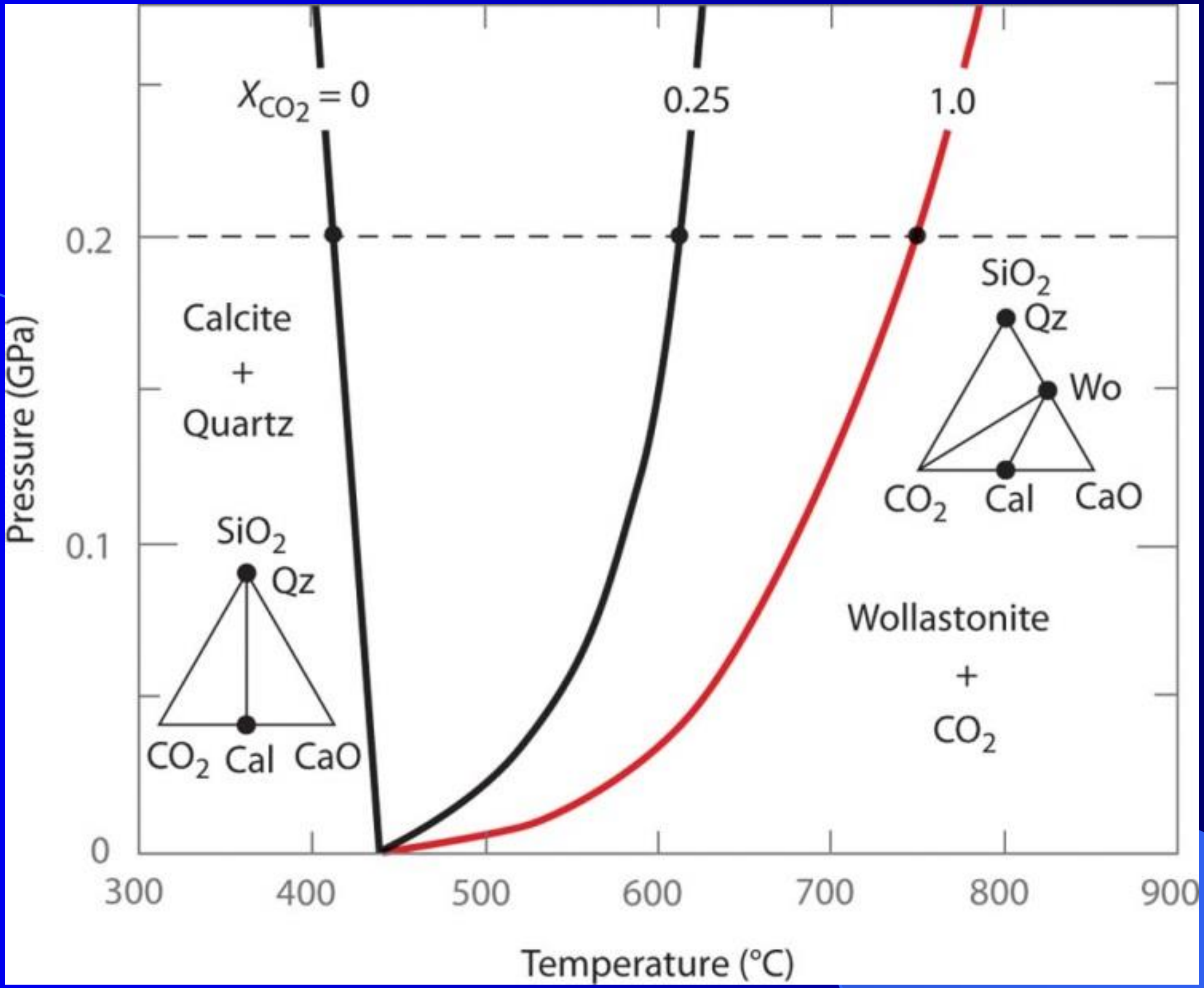


Assemblages in metapelites as a function of metamorphic grade

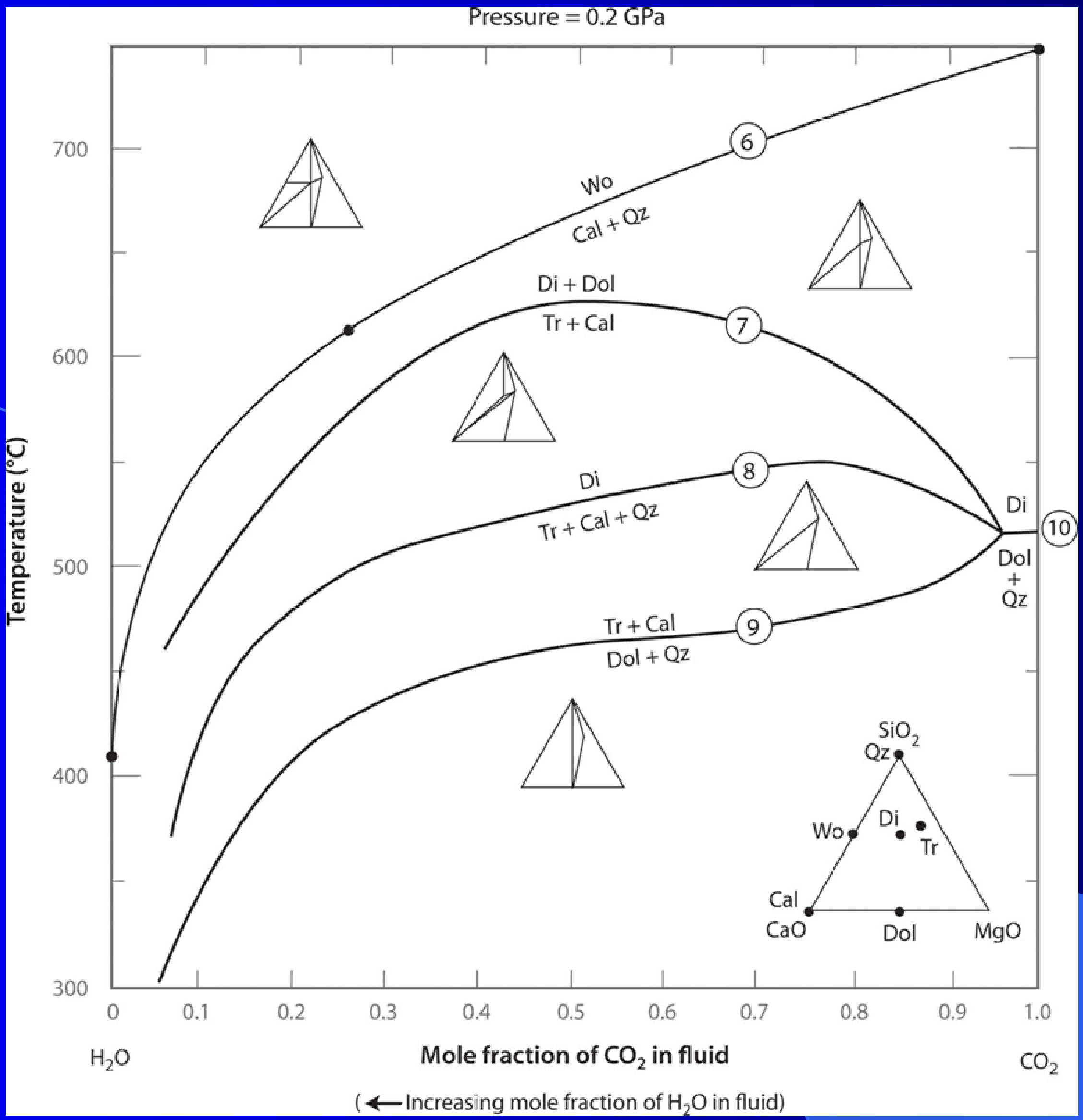



Increasing temperature and pressure (metamorphism)
Melting begins
Diagenesis
Low-grade
High-grade
Shale
Slate
Phyllite
Schist, gneiss
(sedimentary)
(metamorphic)
Clay
Chlorite
Muscovite mica
Biotite mica
Garnet
Kyanite
Sillimanite
Feldspars
Quartz

Role of Fluids in Metamorphism



$CaCO_3 + SiO_2 = CaSiO_3 + CO_2$ (fluid)



$$Ca_2Mg_5Si_8O_{22}(OH)_2 + 3CaCO_3 = 4CaMgSi_2O_6 + CaMg(CO_3)_2 + H_2O + CO_2$$

tremolite calcite diopside dolomite fluid

Metamorphic grade, index minerals, isograds, and metamorphic facies

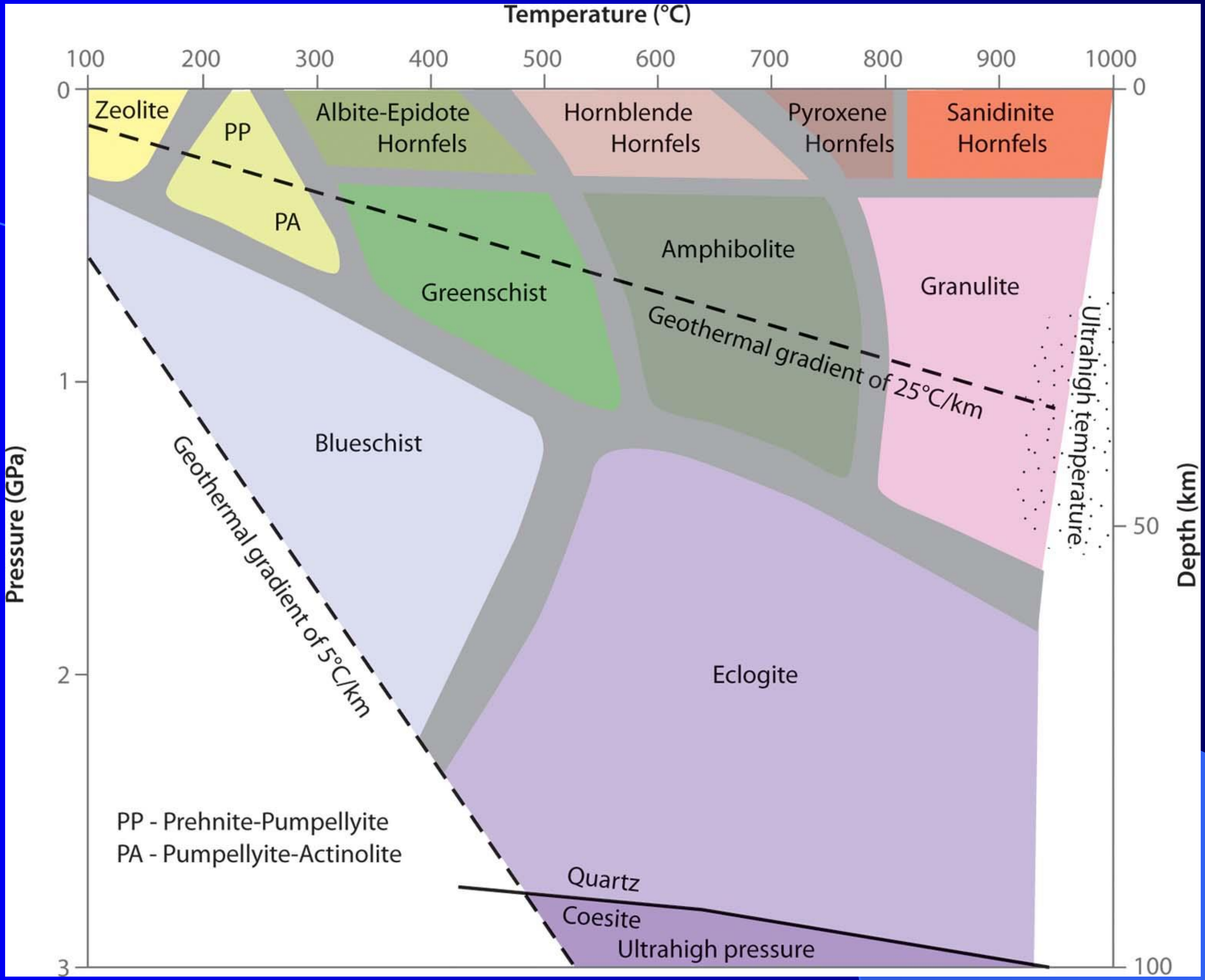


Table 14.1 Common minerals in metamorphic facies.

Facies	Mafic protolith	Pelitic protolith	Carbonate protolith
Zeolite	Chlorite, serpentine, clay minerals, zeolites, analcite, albite, quartz, prehnite, pumpellyite, calcite, dolomite	Chlorite, illite, clay minerals, quartz, albite, calcite, dolomite	Calcite, dolomite, quartz, chlorite, illite, clay minerals, albite
Prehnite-pumpellyite	Chlorite, serpentine, prehnite, pumpellyite, quartz, albite, calcite, dolomite	Chlorite, muscovite, clay minerals, quartz, albite, calcite dolomite	Calcite, dolomite, quartz, clay minerals, albite
Blueschist	Glaucophane, lawsonite (or epidote), quartz, garnet	Glaucophane, Si-rich muscovite, lawsonite (or epidote), quartz, garnet	Aragonite, dolomite, glaucophane, epidote, albite
Greenschist	Chlorite, actinolite, epidote, albite, quartz	**Chlorite zone:** chlorite, muscovite, quartz, albite **Biotite zone:** chlorite, muscovite, biotite, quartz, albite **Garnet zone:** muscovite, biotite, garnet, quartz, albite	Calcite, dolomite, muscovite, quartz, albite
Albite-Epidote hornfels	Albite, pyrophyllite, epidote, actinolite, chlorite, quartz	Muscovite, chlorite, biotite, albite, quartz, pyrophyllite	Calcite, epidote, actinolite, quartz
Amphibolite	Hornblende, plagioclase, quartz, garnet	**Staurolite zone:** muscovite, biotite, quartz, garnet, staurolite, plagioclase **Kyanite zone:** muscovite, biotite, quartz, garnet, kyanite, staurolite, plagioclase **Sillimanite zone:** muscovite, biotite, quartz, garnet, sillimanite, plagioclase	Calcite, dolomite, quartz, biotite, amphibole, diopside, K-feldspar, wollastonite
Hornblende hornfels	Cordierite, plagioclase, anthophyllite, hornblende, diopside, garnet, quartz	Andalusite, muscovite, cordierite, quartz, biotite	Calcite, diopside, grossular, biotite, quartz
Pyroxene hornfels	Diopside, orthopyroxene, plagioclase, biotite, quartz	Andalusite, cordierite, orthoclase, biotite, quartz	Wollastonite, grossularite, diopside, biotite, quartz
Granulite	Clinopyroxene, orthopyroxene, plagioclase, garnet, quartz	Quartz, K-feldspar, plagioclase, sillimanite, garnet, biotite, orthopyroxene, cordierite	Calcite, dolomite, quartz, diopside, wollastonite, K-feldspar, forsterite
Sanidinite	Sanidine, clinopyroxene, orthopyroxene, plagioclase, quartz	Sillimanite or mullite, spinel, sanidine, quartz	Monticellite, melilite, diopside, calcite
Eclogite	Pyrope-rich garnet, jadeite-rich pyroxene, quartz, kyanite, rutile	Si-rich muscovite, quartz, jadeite-rich pyroxene, pyrope-rich garnet, kyanite, rutile	Aragonite, dolomite, jadeite-rich pyroxene, epidote, quartz, Si-rich muscovite, pyrope-rich garnet

Textures of metamorphic rocks

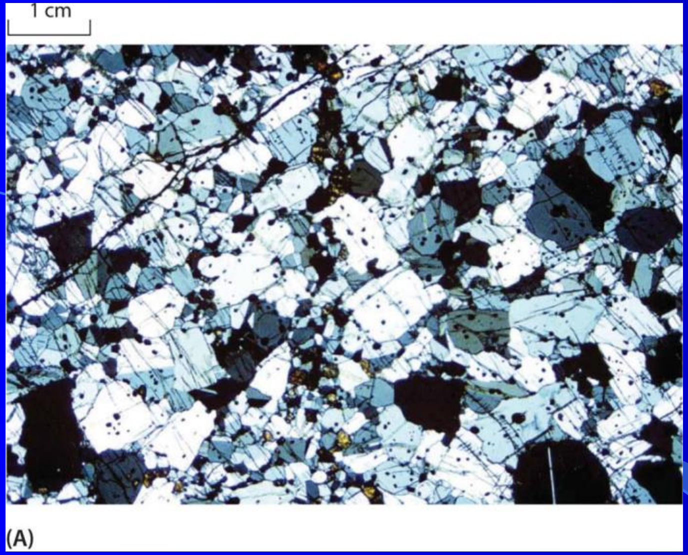
- Excess energy present in deformed crystals (elastic), twins, surface free energy
- Growth of new grains leads to decreasing free energy – release elastic energy, reduce surface to volume ratio (increase grains size, exception occurs in zones of intense shearing where a number of nuclei are formed).
- Activation energy is provided by heating and deformation.
- Minerals with high surface free energy recrystallize before minerals with lower surface free energy. This leads to the Crystalloblastic series. Minerals with higher surface free energy form euhedral crystal faces relative to minerals with lower surface free energy.

Table 14.2 Crystalloblastic series.

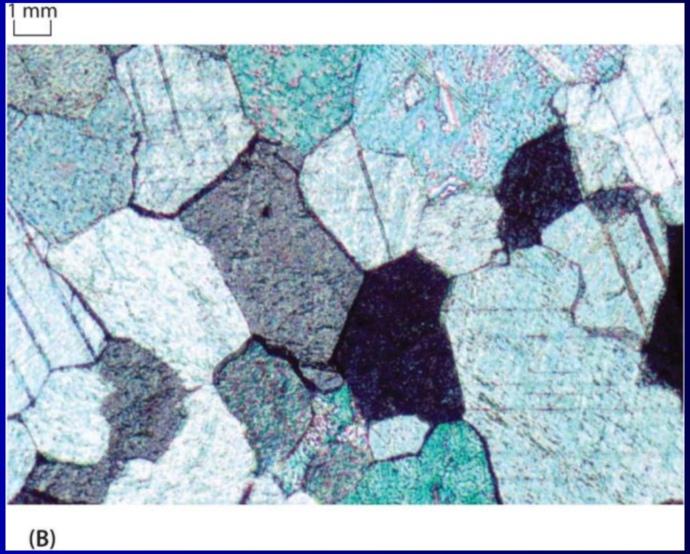
Surface Free Energy ↑

Magnetite, rutile, titanite, pyrite
Sillimanite, kyanite, garnet, staurolite, tourmaline
Andalusite, epidote, zoisite, forsterite, lawsonite
Amphibole, pyroxene, wollastonite
Mica, chlorite, talc, prehnite, stilpnomelane
Calcite, dolomite, vesuvianite
Cordierite, feldspar, scapolite
Quartz

Textures contact metamorphic rocks - Hornfels

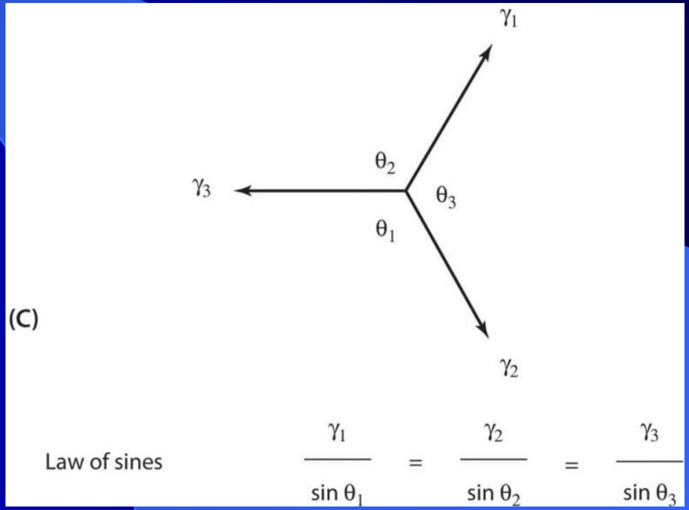


Cordierite and spinel



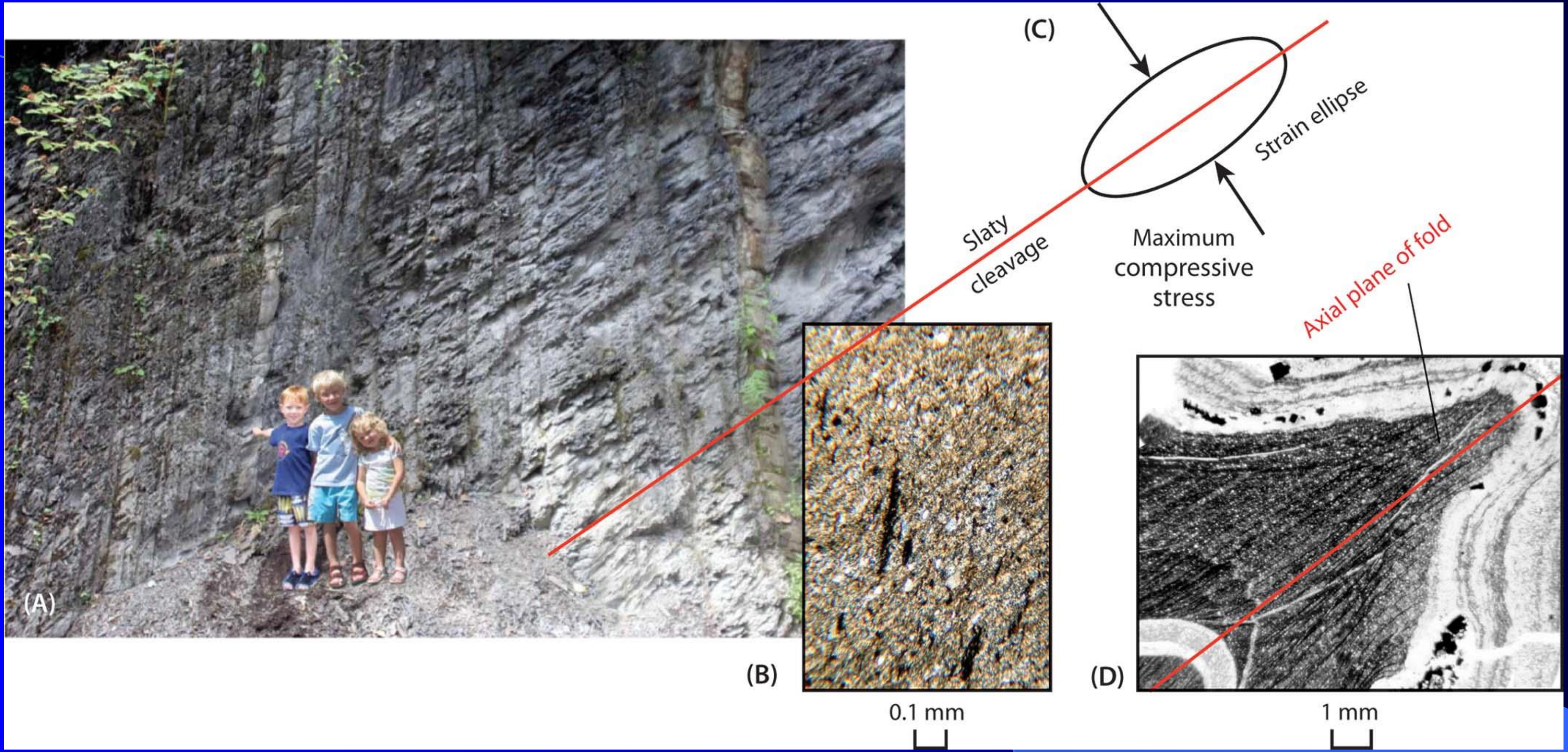
Marble showing 120° grain boundary junctures

Law of sines γ = surface tension

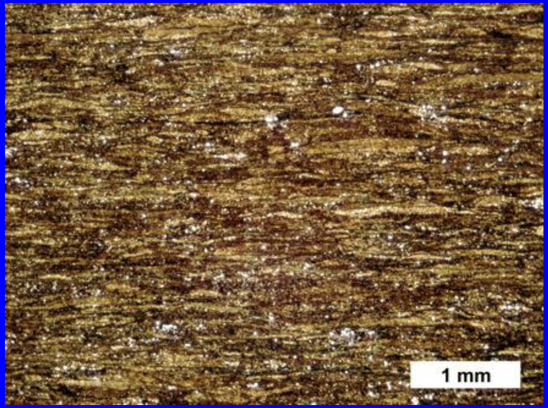


Deformation and textures of regional metamorphic rocks

Slaty cleavage dips to the left. Bedding near vertical.

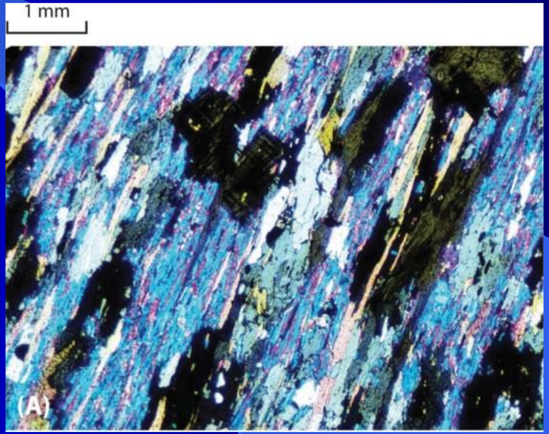


Slate

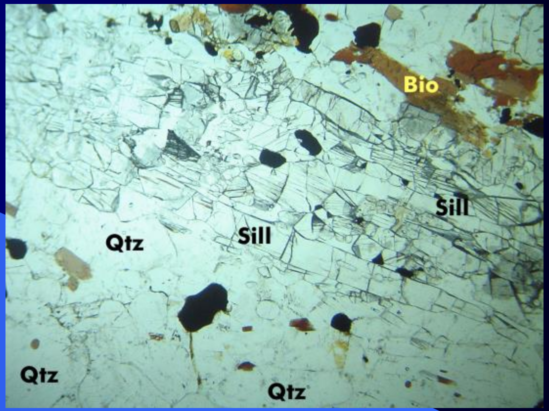


Phyllite

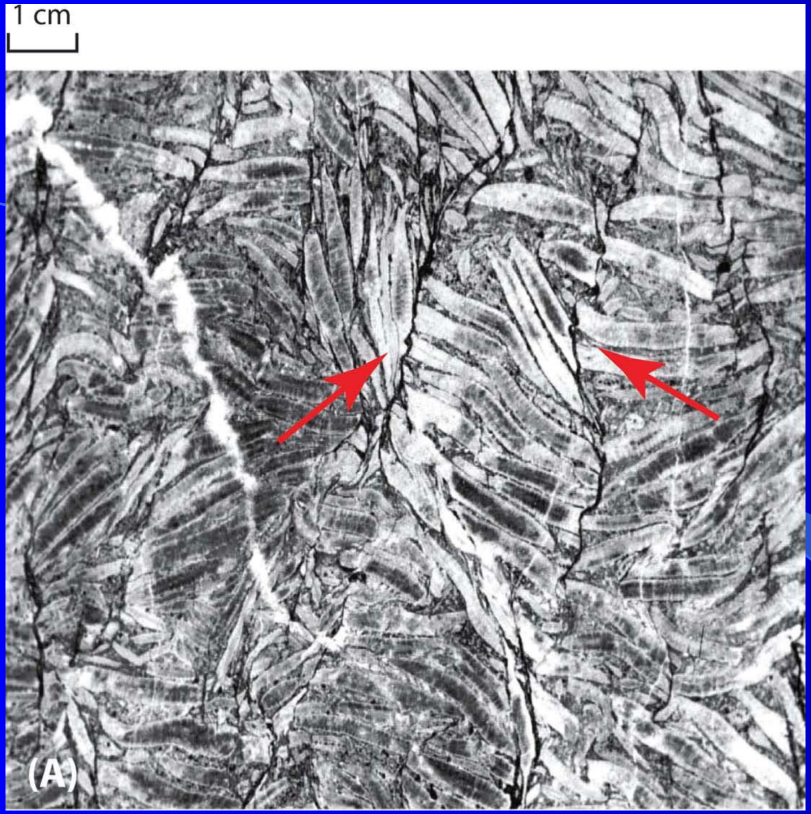
Schist



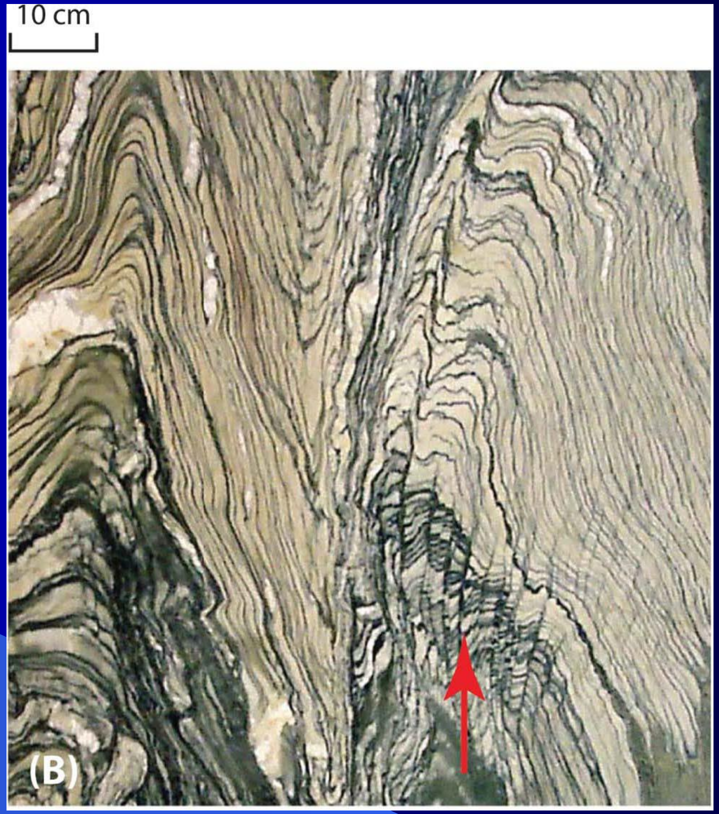
Gneiss



Boudinage

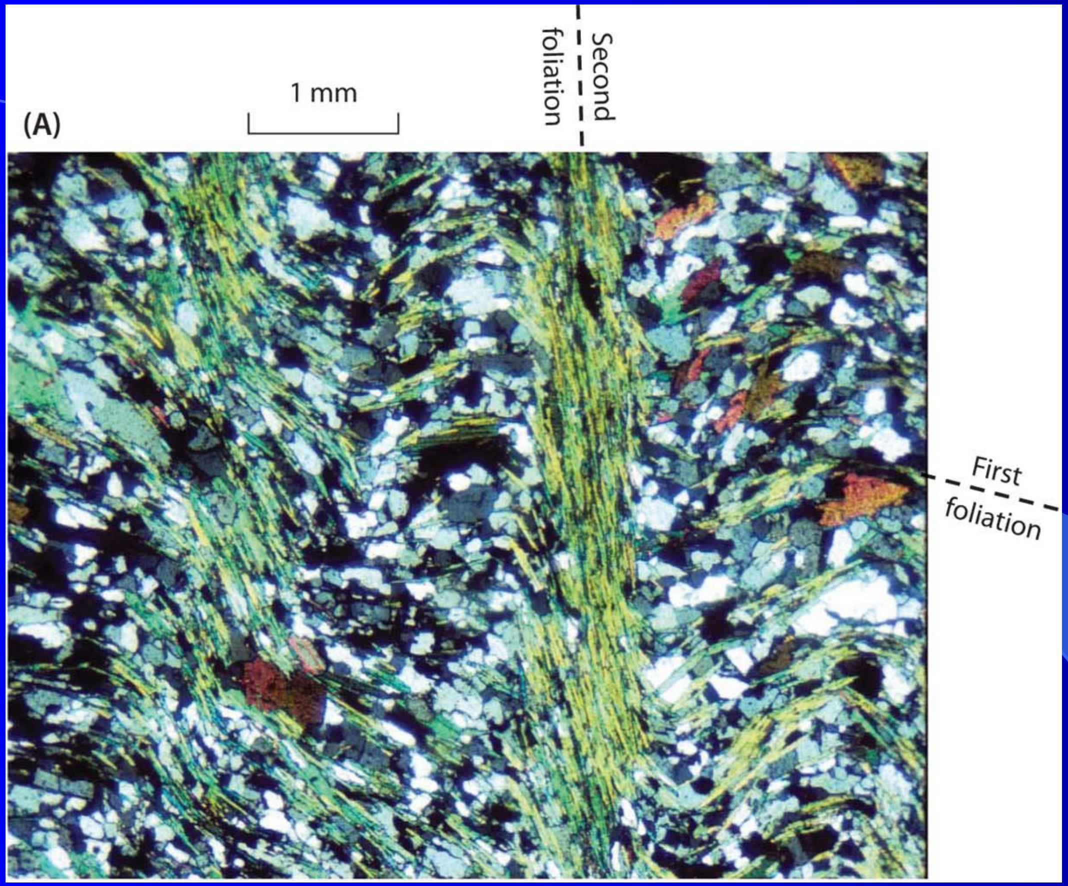


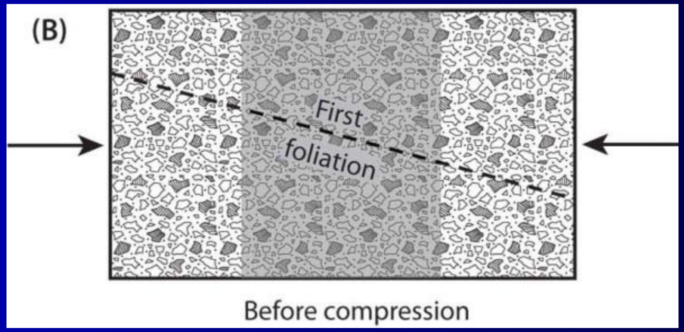
Solution cleavage planes in limestone

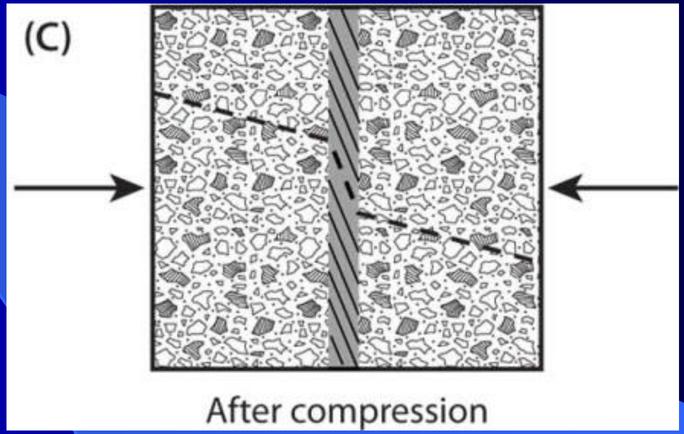


Axial plane solution cleavage in marble

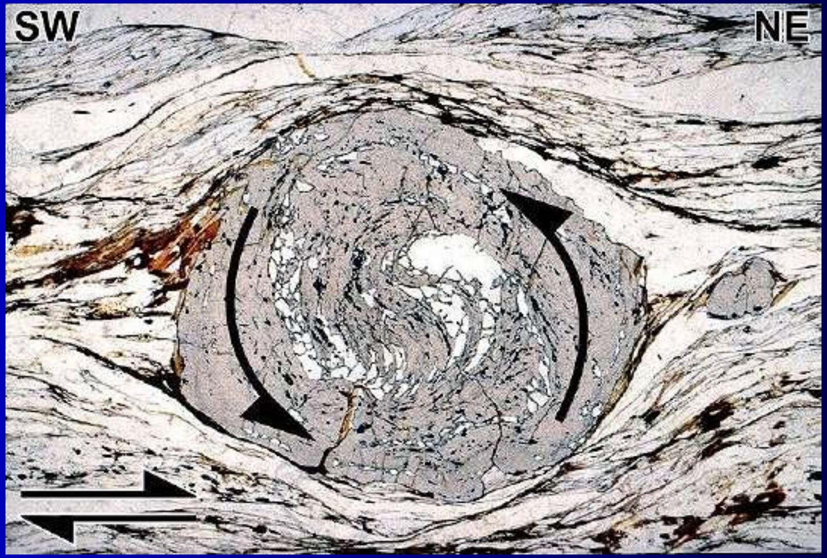
Development of two cleavage directions

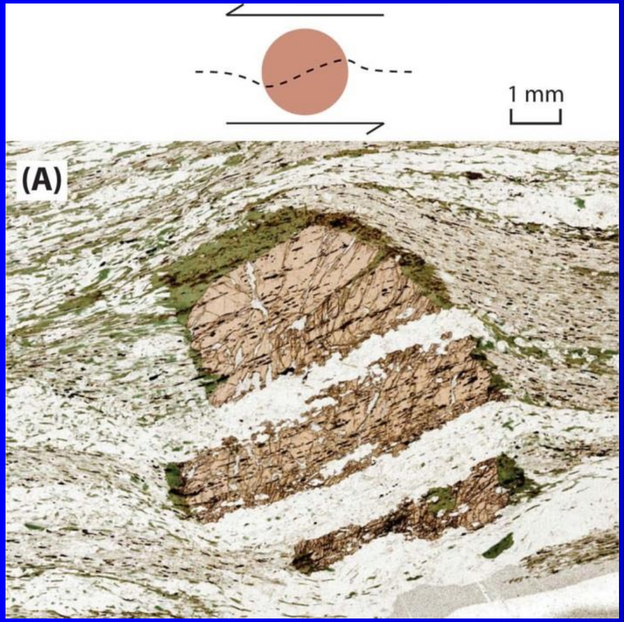


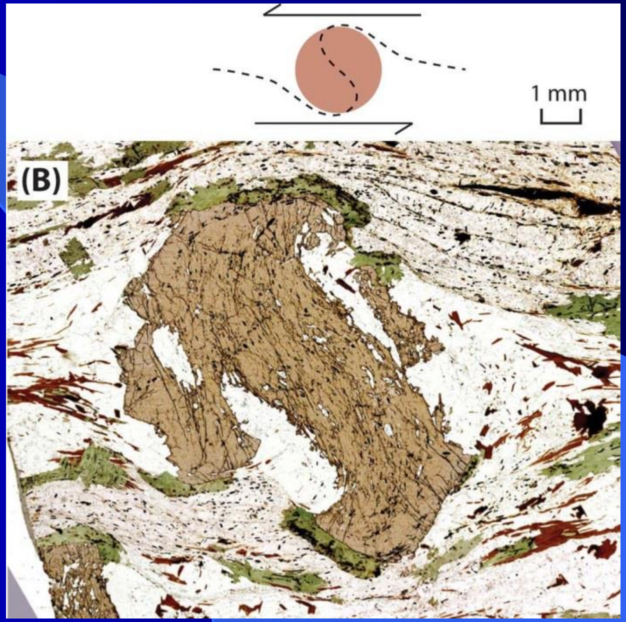




Helicitic texture - bands of inclusions that indicate original bedding or schistosity of the parent rock and cut through later-formed crystals of the metamorphic rock.

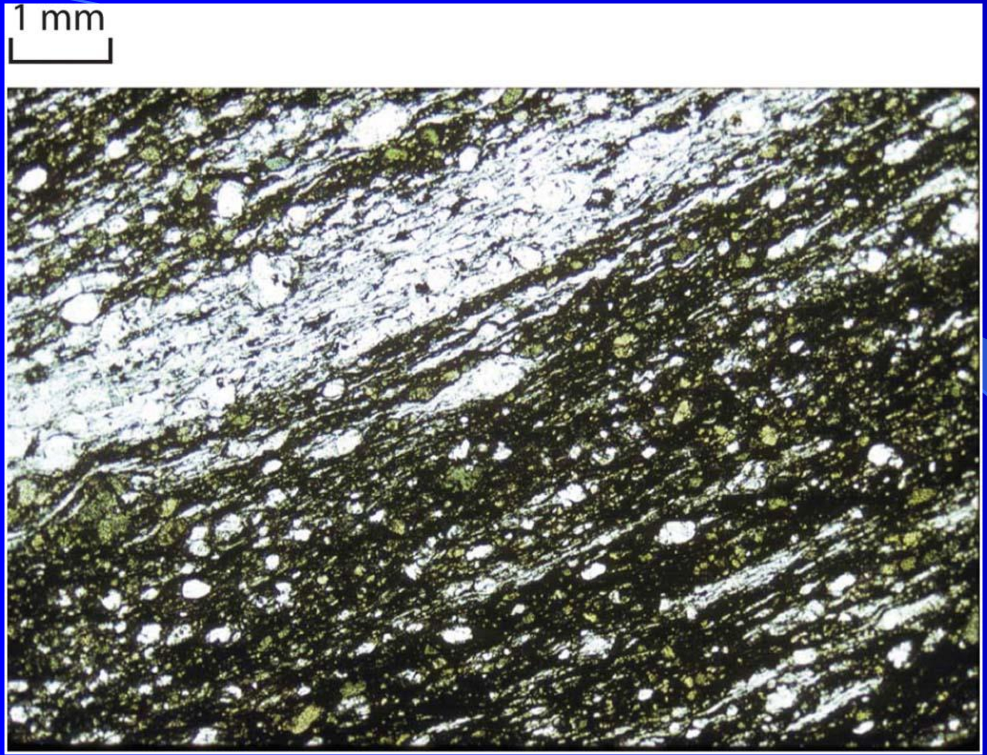


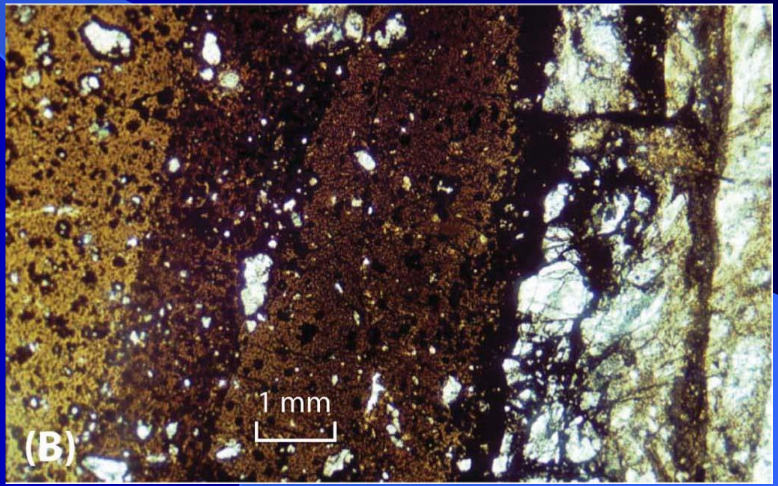


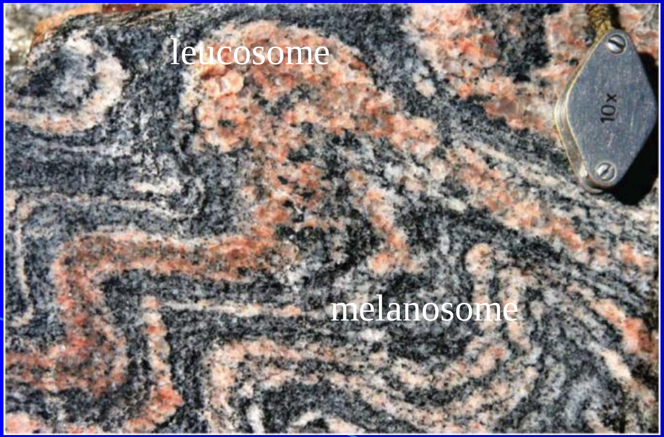


Black veins of pseudotachylite

Plagioclase-hornblende mylonite

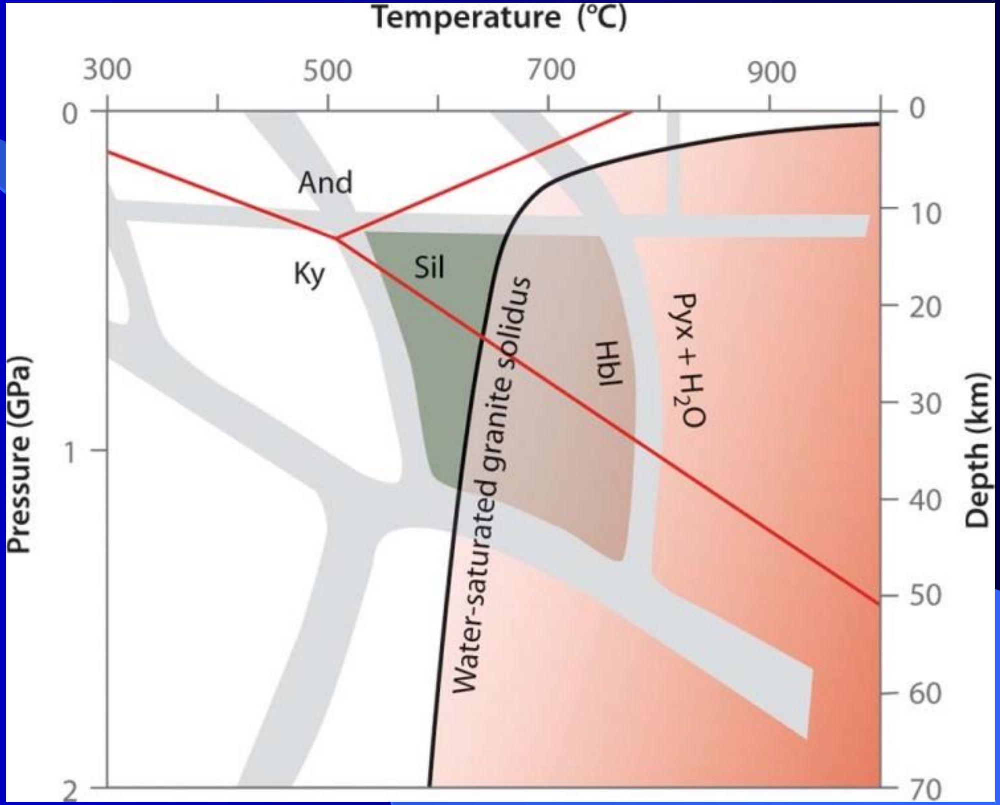






Migmatites

Incipient melting of metamorphic rocks. Diagram below shows melting conditions relative metamorphic facies. A broad zone of Hbl → pyx + H_2O separates amphibolite and granulite facies and provides the water for melting

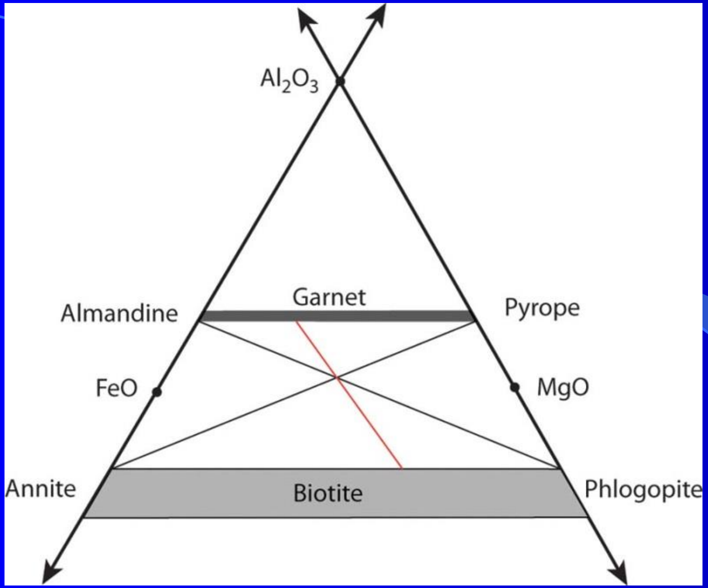


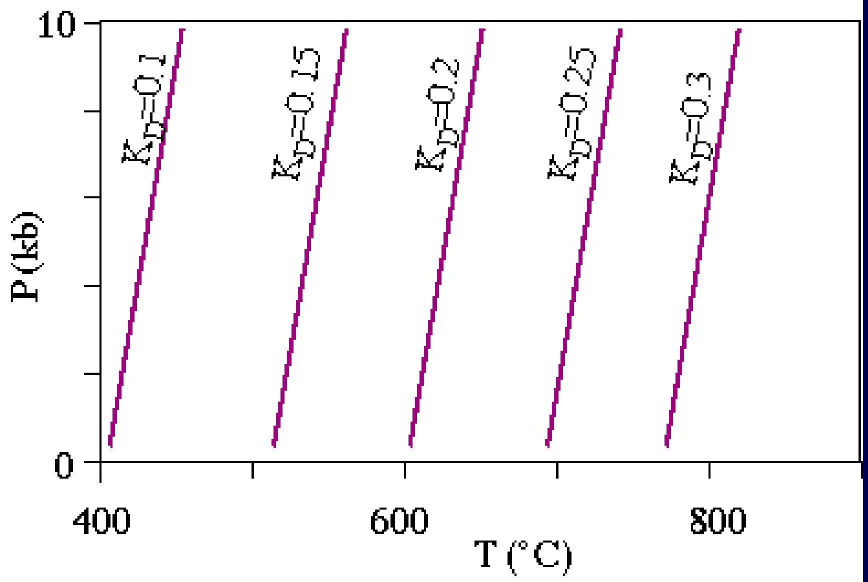
Geothermometers and Geobarometers

GARB – used to calculate temperature (Exchange reaction)

$Fe_3Al_2Si_3O_{12} + KMg_3AlSi_3O_{10}(OH)_2 \leftrightarrow Mg_3Al_3O_{12} + KFe_3AlSi_3O_{10}(OH)_2$

almandine phlogopite pyrobe annite





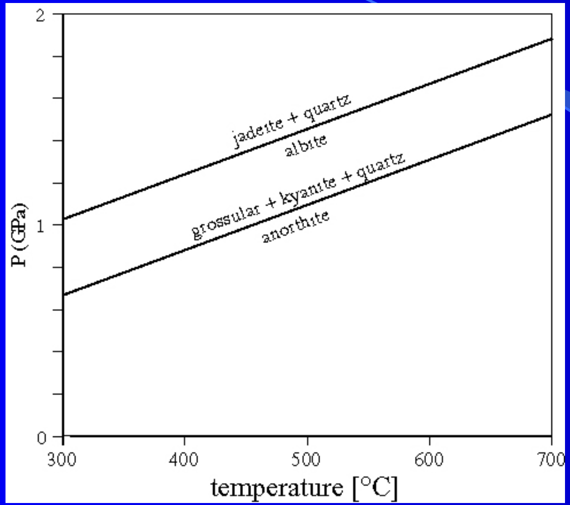
52,110 - 19.51*T(K) + 0.238*P(bar) + RT ln K = 0

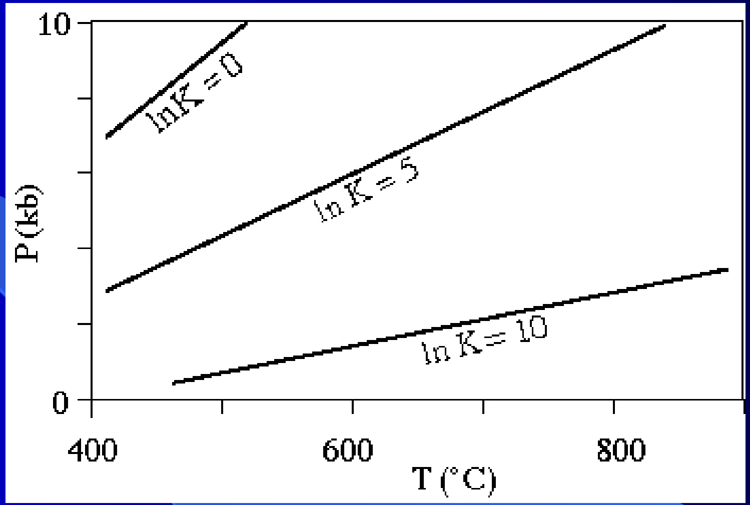
where $K = (X_{Mg}^{gar}\ X_{Fe}^{bio})/(X_{Fe}^{gar}\ X_{Mg}^{bio})$ which is an exchange reaction

GASP – used to calculate pressure (Net-transfer reaction)

Net-transfer reactions cause phases to appear or disappear (in this case anorthotite

$3CaAl_2Si_2O_8$	$= Ca3Al_2Si_3O_{12}$	$+ 2Al_2SiO_5$	$+ SiO_2$
anorthite	= grossular	+ kyanite	+ quartz





-48,357 + 150.66 T(K) -6.608 P (bar) + RT *ln* K = 0

A Complete Example

Let's suppose you analyze a group of minerals that are in equilibrium and find the following compositions:
garnet: $Ca_{0.42}Mg_{0.51}Fe_{2.04}Mn_{0.03}Al_2Si_3O_{12}$
biotite: $KMg_{1.62}Fe_{1.38}AlSi_3O_{10}(OH)_2$
plagioclase: $Na_{0.64}Ca_{0.36}Al_{1.36}Si_{2.64}O_8$
kyanite
quartz

Let's determine the equilibrium P and T.
Determine mole fractions

$X_{grs} = 0.14$
$X_{prp} = 0.17$
$X_{alm} = 0.68$
$X_{ann} = 0.46$
$X_{phl} = 0.54$
$X_{an} = 0.36$

Determine activities, assuming ideal behavior

$a_{grs} = 0.14^3 = 0.0027$
$a_{prp} = 0.17^3 = 0.0049$
$a_{alm} = 0.68^3 = 0.31$
$a_{ann} = 0.46^3 = 0.097$
$a_{phl} = 0.54^3 = 0.16$
$a_{an} = 0.36$

Calculate equilibrium constants:

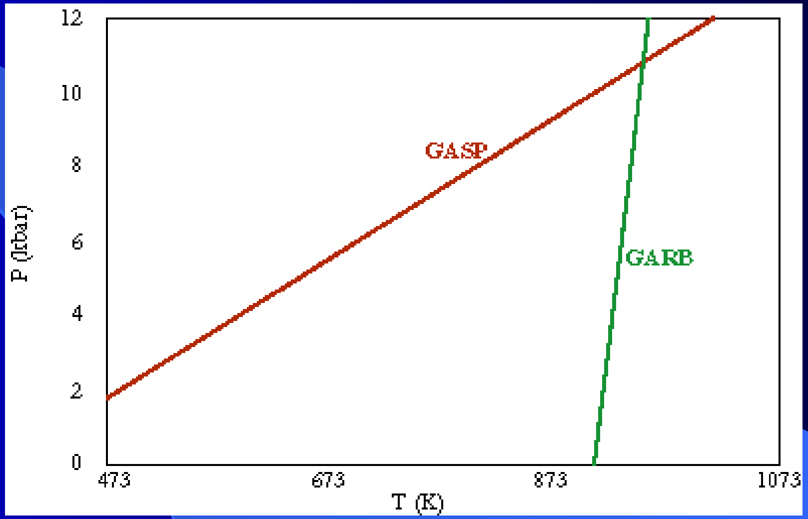
$K_{GASP} = a_{grs} / a_{an}{}^3 = 0.0025 / 0.36^3 = 0.054$
$K_{GARB} = (a_{prp}a_{ann}) / (a_{alm}a_{phl}) = (0.0049 * 0.097) / (0.31 * 0.16) = 0.0096$

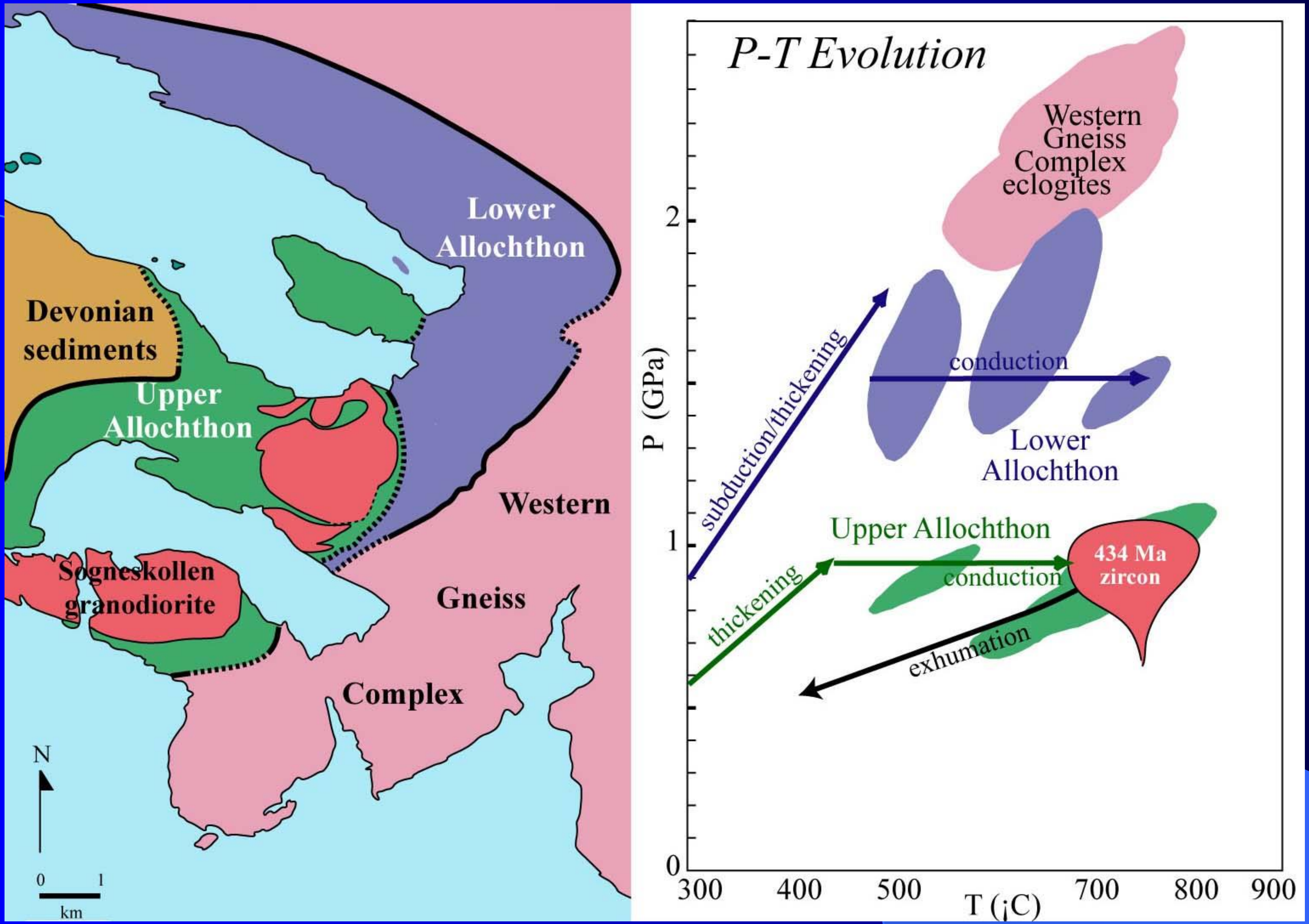
Calculate P and T:

GASP: P (bar) = (-48,357 + 150.66 * T(K) + RT *ln* K) / 6.608
GARB: P (bar) = (52,110 - 19.51 * T(K) + RT *ln* K) / -0.238

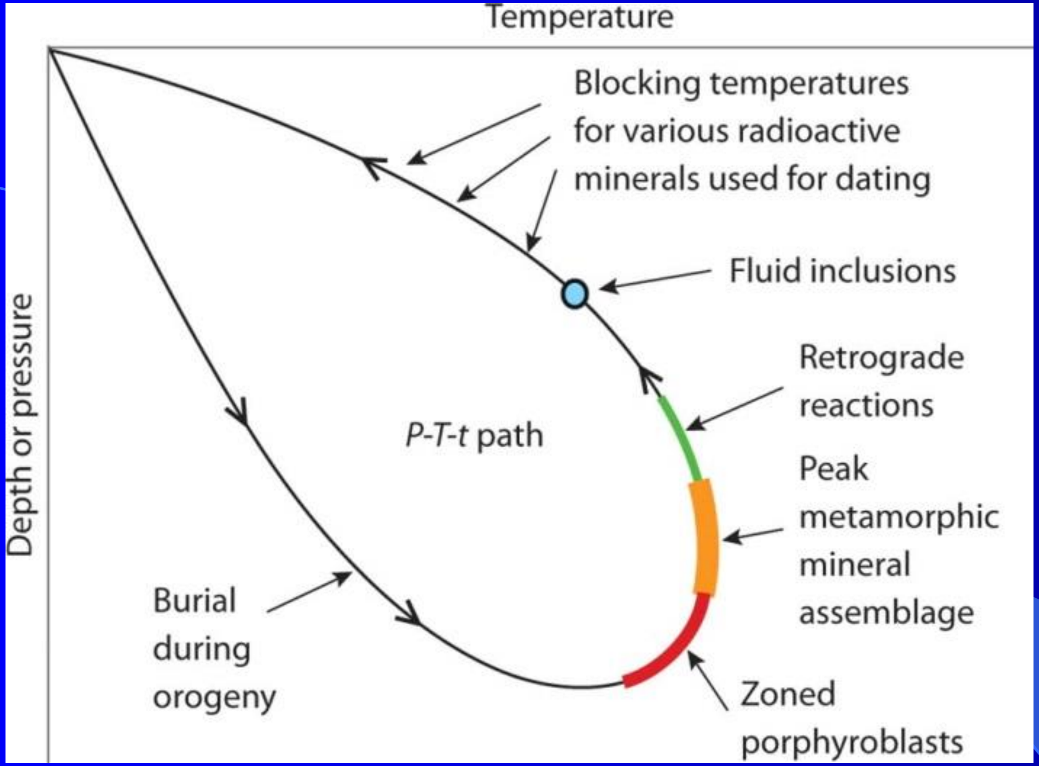
Choose T = 873 K:
GASP P = 1.7 kbar
GARB P = -7.7 kbar

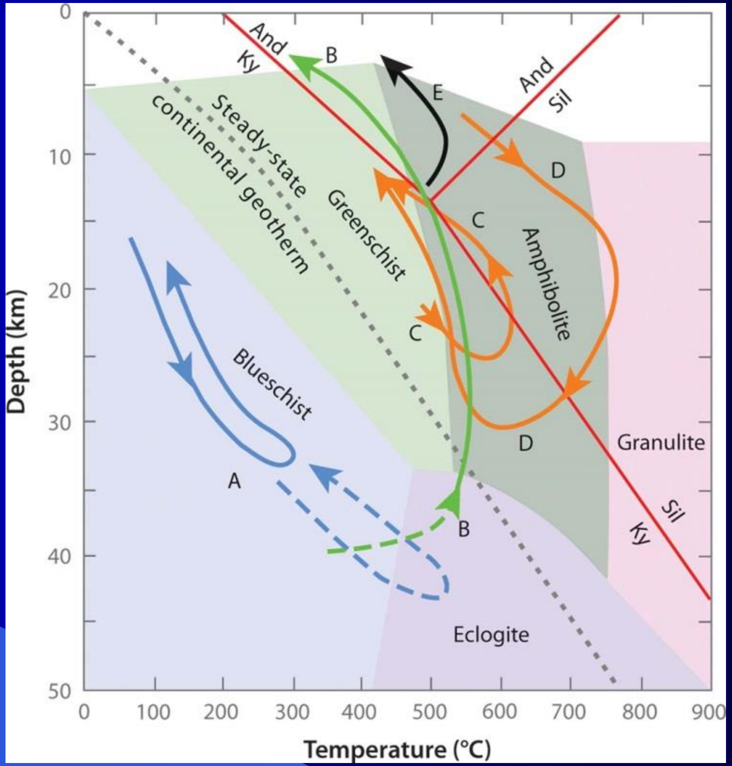
Choose T = 1073 K:
GASP P = 13.2 kbar
GARB P = 40.6 kbar These two lines intersect at ~955K and 10.9 kbar.




Lower Allochthon
Devonian sediments
Upper Allochthon
Western
Sogneskollen granodiorite
Gneiss
Complex
N
0 1
km
P-T Evolution
Western Gneiss Complex eclogites
2
P (GPa)
subduction/thickening
conduction
Lower Allochthon
1
Upper Allochthon
434 Ma zircon
thickening
conduction
exhumation
0
300
400
500
700
800
900
T (¡C)

Pressure-temperature-time (P-T-t) paths





Radiometric dating – application of different systems to metamorphic rocks.

Summary of Geologic Setting and Metamorphic Facies