Metamorphism of Mafic Rocks

- Mineral changes and associations along T-P gradients characteristic of the three facies series
  - Hydration of original mafic minerals generally required
  - If water unavailable, mafic igneous rocks will remain largely unaffected, even as associated sediments are completely re-equilibrated
  - Coarse-grained intrusives are the least permeable and likely to resist metamorphic changes
  - Tuffs and graywackes are the most susceptible

Metamorphism of Mafic Rocks

Plagioclase:

- More Ca-rich plagioclases become progressively unstable as T lowered
- General correlation between temperature and *maximum* An-content of the stable plagioclase
  - At low metamorphic grades only albite (An_{0-3}) is stable
  - In the upper-greenschist facies oligoclase becomes stable. The An-content of plagioclase thus jumps from An_{1-7} to An_{17-20} (across the peristerite solvus) as grade increases
  - Andesine and more calcic plagioclases are stable in the upper amphibolite and granulite facies
- The excess Ca and Al ® calcite, an epidote mineral, sphene, or amphibole, etc., depending on P-T-X

Metamorphism of Mafic Rocks

- Clinopyroxene breaks down to a number of mafic minerals, depending on grade.
- These minerals include chlorite, actinolite, hornblende, epidote, a metamorphic pyroxene, etc.
- The mafics that form are commonly diagnostic of the grade and facies

Mafic Assemblages at Low Grades

- Zeolite and prehnite-pumpellyite facies
- Do not always occur - typically require unstable protolith
- Boles and Coombs (1975) showed that metamorphism of tuffs in NZ accompanied by substantial chemical changes due to circulating fluids, and that these fluids played an important role in the metamorphic minerals that were stable
- The classic area of burial metamorphism thus has a strong component of hydrothermal metamorphism as well

Mafic Assemblages of the Medium P/T Series: Greenschist, Amphibolite, and Granulite Facies

- The greenschist, amphibolite and granulite facies constitute the most common facies series of regional metamorphism
- The classical Barrovian series of pelitic zones and the lower-pressure Buchan-Abukuma series are variations on this trend

Greenschist, Amphibolite, Granulite Facies

- Zeolite and prehnite-pumpellyite facies not present in the Scottish Highlands
- Metamorphism of mafic rocks first evident in the greenschist facies, which correlates with the chlorite and biotite zones of the associated pelitic rocks
  - Typical minerals include chlorite, albite, actinolite, epidote, quartz, and possibly calcite, biotite, or stilpnomelane
  - Chlorite, actinolite, and epidote impart the green color from which the mafic rocks and facies get their name

Greenschist, Amphibolite, Granulite Facies

- ACF diagram
- The most characteristic mineral assemblage of the greenschist facies is: chlorite + albite + epidote + actinolite ± quartz

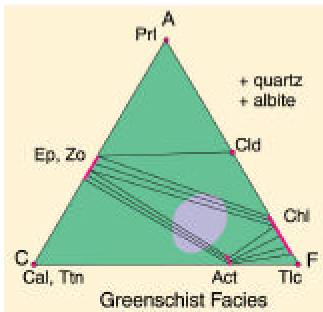


Fig. 25-6. ACF diagram illustrating representative mineral assemblages for metabasites in the greenschist facies. The composition range of common mafic rocks is shaded. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Greenschist, Amphibolite, Granulite Facies

- Greenschist ® amphibolite facies transition involves two major mineralogical changes

1. Albite ® oligoclase (increased Ca-content with temperature across the peristerite gap)
2. Actinolite ® hornblende (amphibole accepts increasing aluminum and alkalis at higher Ts)

- Both transitions occur at approximately the same grade, but have different P/T slopes

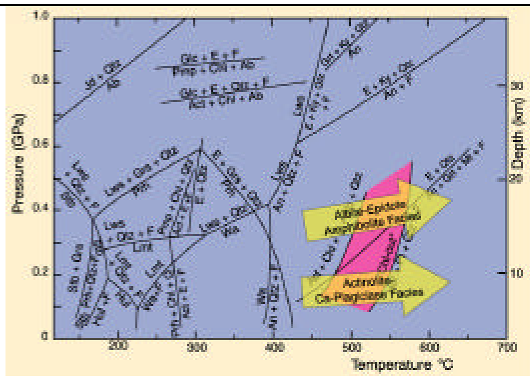


Fig. 26-19. Simplified petrogenetic grid for metamorphosed mafic rocks showing the location of several determined univariant reactions in the CaO-MgO-Al_2O_3-SiO_2-H_2O-(Na_2O) system ("C(N)MASH"). Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Greenschist, Amphibolite, Granulite Facies

- ACF diagram
- Typically two-phase Hbl-Plag
- Amphibolites are typically black rocks with up to about 30% white plagioclase
- Like diorites, but differ texturally
- Garnet in more Al-Fe-rich and Ca-poor mafic rocks
- Clinopyroxene in Al-poor-Ca-rich rocks

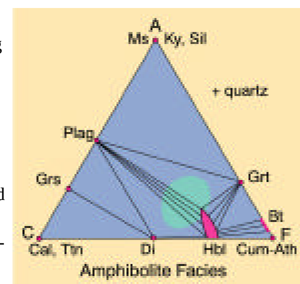


Fig. 25-7. ACF diagram illustrating representative mineral assemblages for metabasites in the amphibolite facies. The composition range of common mafic rocks is shaded. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Greenschist, Amphibolite, Granulite Facies

Greenschist, Amphibolite, Granulite Facies

- Mafic rocks generally melt at higher temperatures
- If water is removed by the earlier melts the remaining mafic rocks may become depleted in water
- Hornblende decomposes and orthopyroxene + clinopyroxene appear
- This reaction occurs over a T interval > 50ºC

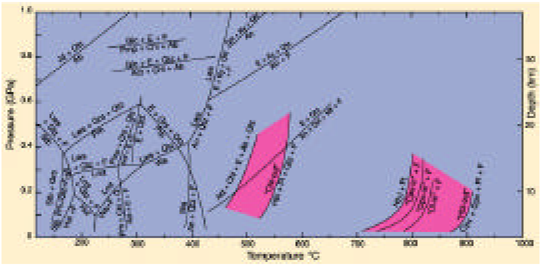


Fig. 26-19. Simplified petrogenetic grid for metamorphosed mafic rocks showing the location of several determined univariant reactions in the CaO-MgO-Al_2O_3-SiO_2-H_2O-(Na_2O) system ("C(N)MASH"). Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Greenschist, Amphibolite, Granulite Facies

- Granulite facies characterized by a largely *anhydrous* mineral assemblage
- Critical meta-basite mineral assemblage is orthopyroxene + clinopyroxene + plagioclase + quartz
  - Garnet, minor hornblende and/or biotite may be present

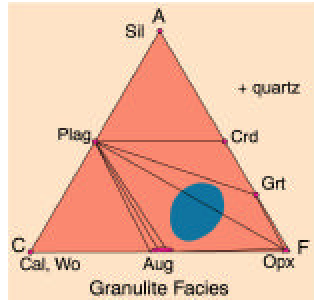


Fig. 25-8. ACF diagram for the granulite facies. The composition range of common mafic rocks is shaded. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Greenschist, Amphibolite, Granulite Facies

Origin of granulite facies rocks is complex and controversial. There is general agreement, however, on two points

1) Granulites represent unusually hot conditions
   - Temperatures > 700°C (geothermometry has yielded some very high temperatures, even in excess of 1000°C)
   - Average geotherm temperatures for granulite facies depths should be in the vicinity of 500°C, suggesting that granulites are the products of crustal thickening and excess heating

Greenschist, Amphibolite, Granulite Facies

2) Granulites are dry
   - Rocks don't melt due to lack of available water
   - Granulite facies terranes represent deeply buried and dehydrated roots of the continental crust
   - Fluid inclusions in granulite facies rocks of S. Norway are CO_2-rich, whereas those in the amphibolite facies rocks are H_2O-rich

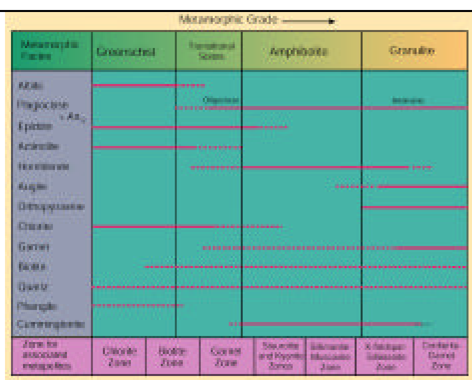
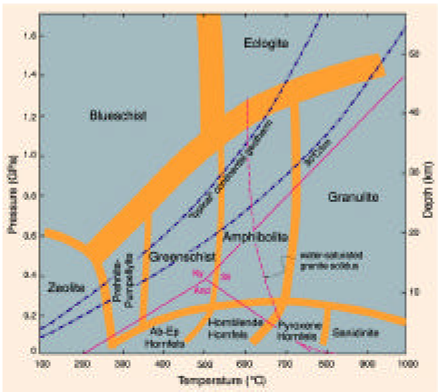


Fig. 25-9. Typical mineral changes that take place in metabasic rocks during progressive metamorphism in the medium P/T facies series. The approximate location of the pelitic zones of Barrovian metamorphism are included for comparison. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Mafic Assemblages of the Low P/T Series: Albite-Epidote Hornfels, Hornblende Hornfels, Pyroxene Hornfels, and Sanidinite Facies

- Mineralogy of low-pressure metabasites not appreciably different from the med.-P facies series
- Albite-epidote hornfels facies correlates with the greenschist facies into which it grades with increasing pressure
- Hornblende hornfels facies correlates with the amphibolite facies, and the pyroxene hornfels and sanidinite facies correlate with the granulite facies

Fig. 25-2. Temperature-pressure diagram showing the generally accepted limits of the various facies used in this text. Winter (2001)



Mafic Assemblages of the Low P/T Series: Albite-Epidote Hornfels, Hornblende Hornfels, Pyroxene Hornfels, and Sanidinite Facies

Facies of contact metamorphism are readily distinguished from those of medium-pressure regional metamorphism on the basis of:

- Metapelites (e.g. andalusite and cordierite)
- Textures and field relationships
- Mineral thermobarometry

Mafic Assemblages of the Low P/T Series: Albite-Epidote Hornfels, Hornblende Hornfels, Pyroxene Hornfels, and Sanidinite Facies

- The innermost zone of most aureoles rarely reaches the pyroxene hornfels facies
  - If the intrusion is hot and dry enough, a narrow zone develops in which amphiboles break down to orthopyroxene + clinopyroxene + plagioclase + quartz (without garnet), characterizing this facies
- Sanidinite facies is not evident in basic rocks

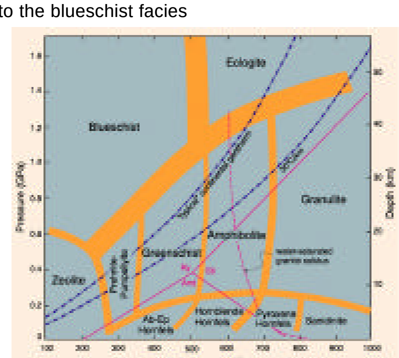
Mafic Assemblages of the High P/T Series: Blueschist and Eclogite Facies

- Mafic rocks (not pelites) develop definitive mineral assemblages under high P/T conditions
- High P/T geothermal gradients characterize subduction zones
- Mafic blueschists are easily recognizable by their color, and are useful indicators of ancient subduction zones
- The great density of eclogites: subducted basaltic oceanic crust becomes more dense than the surrounding mantle

Blueschist and Eclogite Facies

Alternative paths to the blueschist facies

Fig. 25-2. Temperature-pressure diagram showing the generally accepted limits of the various facies used in this text. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



Blueschist and Eclogite Facies

- The blueschist facies is characterized in metabasites by the presence of a sodic blue amphibole stable only at high pressures (notably glaucophane, but some solution of crossite or riebeckite is possible)
- The association of glaucophane + lawsonite is diagnostic. Crossite is stable to lower pressures, and may extend into transitional zones
- Albite breaks down at high pressure by reaction to jadeitic pyroxene + quartz:

$$\underset{Ab}{NaAlSi_3O_8} = \underset{Jd}{NaAlSi_2O_6} + \underset{Qtz}{SiO_2} \quad \text{(reaction 25-3)}$$

Blueschist and Eclogite Facies

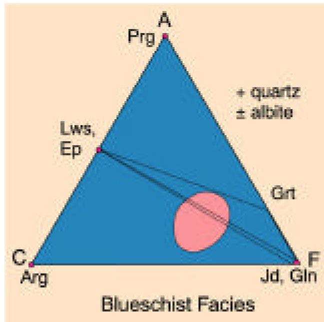


Fig. 25-10. ACF diagram illustrating representative mineral assemblages for metabasites in the blueschist facies. The composition range of common mafic rocks is shaded. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Blueschist and Eclogite Facies

- Eclogite facies: mafic assemblage
- omphacitic pyroxene + pyrope-grossular garnet

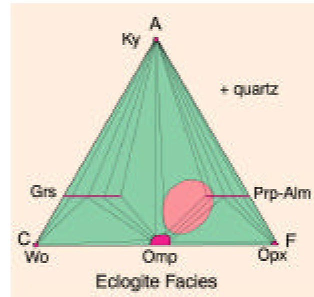
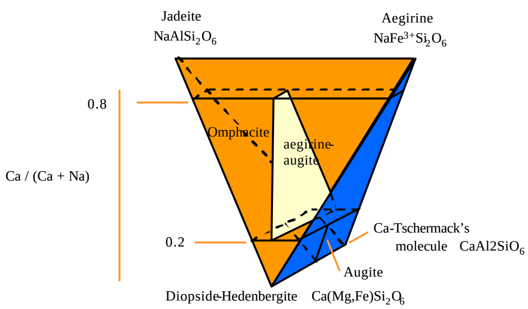


Fig. 25-11. ACF diagram illustrating representative mineral assemblages for metabasites in the eclogite facies. The composition range of common mafic rocks is shaded. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Pyroxene Chemistry

"Non-quad" pyroxenes



Pressure-Temperature-Time (P-T-t) Paths

- The facies series concept suggests that a traverse up grade through a metamorphic terrane should follow a metamorphic field gradient, and may cross through a sequence of facies (spatial sequences)
- Progressive metamorphism: rocks pass through a series of mineral assemblages as they continuously equilibrate to increasing metamorphic grade (temporal sequences)
- But does a rock in the upper amphibolite facies, for example, pass through the same sequence of mineral assemblages that are encountered via a traverse up grade to that rock through greenschist facies, etc.?