EENS 2120	Petrology
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Regional Metamorphism	

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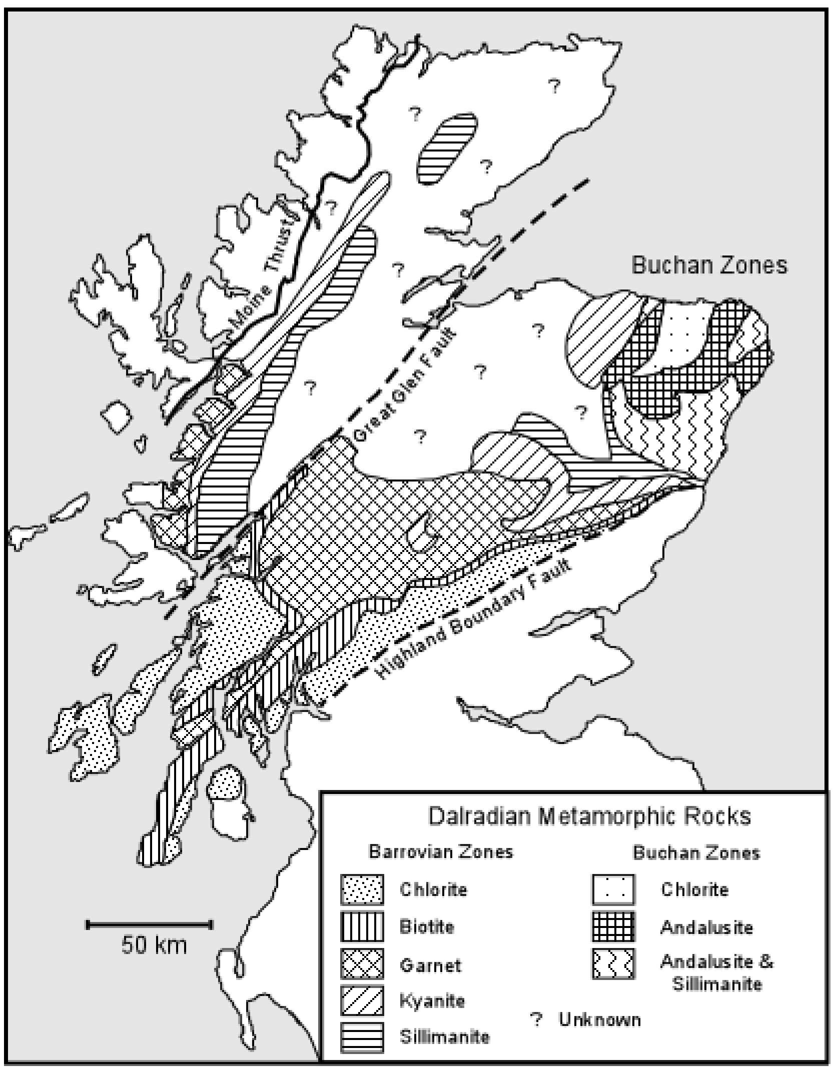
Regional metamorphism is metamorphism that occurs over broad areas of the crust. Most regionally metamorphosed rocks occur in areas that have undergone deformation during an orogenic event resulting in mountain belts that have since been eroded to expose the metamorphic rocks.

Barrovian Facies Series

The Dalradian and Moinian Series of Scotland

The classic example of a regionally metamorphosed area is the Dalradian series of Scotland. The Dalradian Series occurs in a zone 50 to 80 km wide, north of the Highland Boundary Fault. A similar group of metamorphic rocks occurs to the North of the Great Glenn Fault (a strike-slip fault) and is called the Moinian Series.

The rocks were originally shales, limestones, diabase sills, and basalts that had been emplaced in the Precambrian to early Cambrian. In this area, Barrow (1893) mapped metamorphic zones in pelitic rocks based on mineral assemblages he observed in a small part the area. This mapping was later extended across the Scottish Highlands to cover most of the Dalradian and Moinian Series as shown in the map. The series of metamorphic zones mapped by Barrow has since become known as the Barrovian Facies Series (At the time Barrow did his mapping, the facies concept had not yet been developed). In pelitic rocks, Barrow recognized 6 zones of distinctive mineral assemblages, which he recognized as representing increasing grade of metamorphism.



The boundaries for his zones were based on the first appearance of a particular mineral, called an ***index mineral***, which is characteristic of the zone. These boundaries were later called ***isograds*** (equal grade) and likely represent surfaces in a three dimensional sense. He called the zone of lowest grade rocks the "zone of digested clastic mica," but Tilley, mapping the area in 1925, renamed this zone the chlorite zone.

Zone (textural type)	**Mineral Assemblage in Pelitic Rocks**
Chlorite (slates & phyllites)	quartz, chlorite, muscovite, albite
Biotite (phyllites & schists)	biotite begins to replace chlorite, quartz, muscovite, albite
Garnet (phyllites and schists)	quartz, muscovite, biotite, almandine, albite
Staurolite (schists)	quartz, biotite, muscovite, almandine, staurolite, oligoclase
Kyanite (schists)	quartz, biotite, muscovite, oligoclase, almandine, kyanite
Sillimanite (schists & gneisses)	quartz, biotite, muscovite, oligoclase, almandine, sillimanite

Mineral assemblages for pelitic rocks of the Barrovian Zones are listed in the table above. Note the following important points:

- The index mineral that defines a zone, does not necessarily disappear when entering the next higher grade zone. For example the first appearance of biotite is at the biotite isograd where chlorite is seen to be reacting to produce biotite. Biotite does not disappear at the garnet isograd, and, in fact continues to be seen though the garnet, sillimanite, staurolite, kyanite, and sillimanite zones.

- Staurolite, kyanite, and sillimanite only occur in the staurolite, kyanite, and sillimanite zones, respectively.

- The composition of the plagioclase changes with increasing grade of metamorphism. It is nearly pure albite in the chlorite and biotite zones, and becomes somewhat more calcic (oligoclase) in higher grade zones.

- The texture of the rocks changes from slates and phyllites in the chlorite zone to schists in the staurolite and kyanite zones, to schists and gneisses in the sillimanite zone.

As mentioned above, Tilley mapped the area in 1925, and extended the zones across the area between the Highland Boundary Fault and into the Moinian Series, and renamed the chlorite zone. Later, Wiseman (1934), mapped the metabasic rocks and Kennedy (1949) mapped the meta calcareous sediments. Mineral assemblages in these rocks and their correlation with the metamorphic zones in the pelitic rocks are shown in the table below.

<table>
<tr><th>Index Mineral (Pelitic Rocks)</th><th>Basic Rocks</th><th>Calcareous Rocks</th><th>Facies</th></tr>
<tr><td>Chlorite</td><td rowspan="2">Chlorite, albite, epidote, sphene, ± calcite ± actinolite</td><td>qtz, muscovite, biotite, calcite</td><td rowspan="2">Greenschist</td></tr>
<tr><td>Biotite</td><td rowspan="2">garnet, zoisite, sodic plagioclase, biotite or hornblende</td></tr>
<tr><td>Garnet</td><td rowspan="4">Hornblende, plagioclase, ±epidote, ±almandine, ±diopside</td><td rowspan="4">Amphibolite</td></tr>
<tr><td>Staurolite</td><td rowspan="2">garnet, anorthite or bytownite, hornblende</td></tr>
<tr><td>Kyanite</td></tr>
<tr><td>Sillimanite</td><td>garnet, anorthite or bytownite, pyroxene</td></tr>
</table>

Note that the metabasic rocks only define two zones, one corresponding to the chlorite and biotite zones in the pelitic rocks, and the other corresponding to the staurolite, kyanite, and sillimanite zones. The calcareous rocks define four zones. The lowest grade rocks are only metamorphosed in the higher grade parts of the pelitic chlorite zone, another set of minerals occurs in the calcareous rocks throughout the biotite and garnet zones, another mineral assemblage is characteristic of the staurolite and kyanite zone, and a fourth mineral assemblage is found in calcareous rocks of the sillimanite zone.

Note how the Anorthite content of plagioclase increases with increasing grade of metamorphism in the basic rocks and the calcareous rocks.

The facies concept was developed by Eskola in 1939. Recall that the names of Eskola's facies are based on mineral assemblages found in metabasic basic rocks. Applying the facies concept to the Dalradian series of Scotland, one finds only two facies represented. The chlorite and biotite zones represent greenschist facies metamorphism, and the garnet, staurolite, kyanite, and sillimanite zones represent amphibolite facies metamorphism.

The structural history of the Dalradian and Moinian Series is complex. Deformation can be divided into three main stages, based on structures found in the rocks and radiometric dating.

1. Between about 600 and 550 million years ago was a period of large scale recumbent folding.

2. Between 550 and 480 million years ago simple anticlinal flooding with fold axes plunging toward the southwest. During this stage, much of the metamorphism took place.

3. Between 480 and 420 million years ago minor refolding occurred accompanied by minor retrograde metamorphism The retrograde metamorphism consisted of chloritization of biotite and garnet, and seritization of kyanite.

These events occurred during the Caledonian Orogeny, when the European continental block was colliding with the North American continental block, thus, in North America, this event is correlative with the Appalachian Orogenies.

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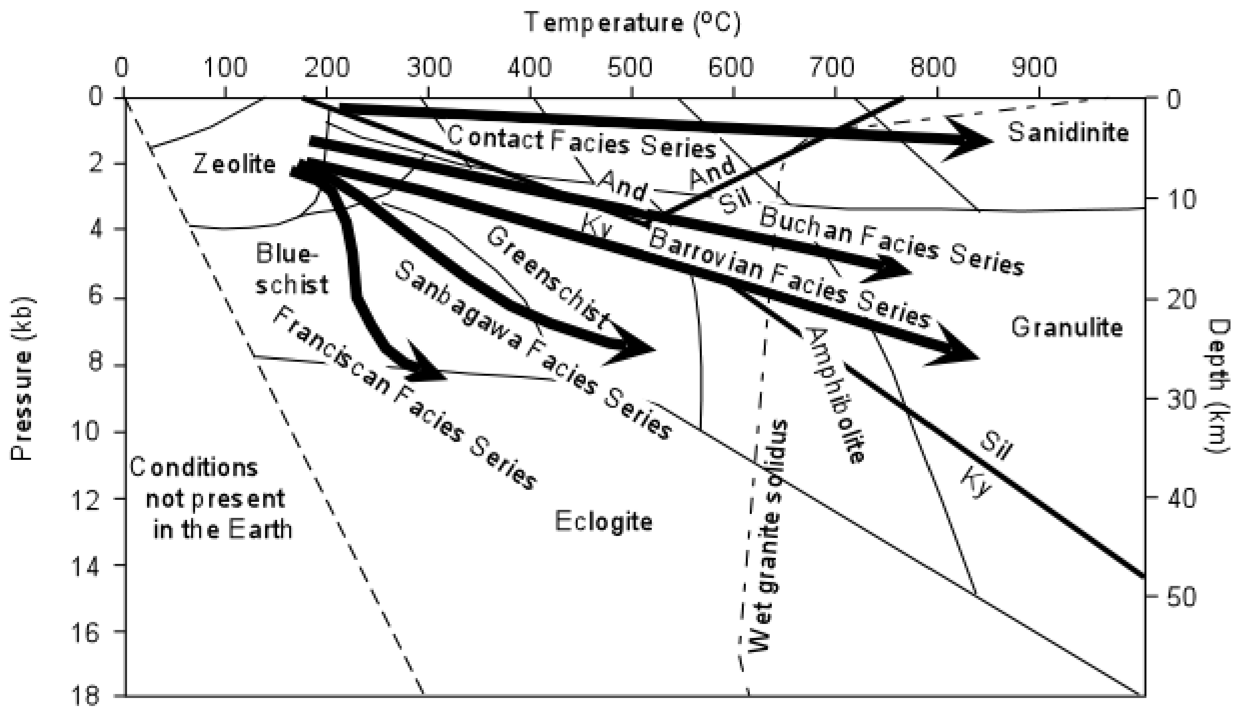
There is apparently no correlation with stratigraphic depth in the Dalradian metamorphic rocks, although there must be a correlation with tectonic depth. Pressure - Temperature estimates for the Sillimanite zone indicate a maximum temperature of about 700^{o}C and maximum pressure of about 7 kb. This corresponds to a depth of about 25 km, and gives a geothermal gradient of about 28^{o}C /km (compared to a normal stable continental geotherm of 25^{o}C /km



Barrovian Facies Series of the Southern Appalachians
The Barrovian Facies Series occurs in the southern Appalachians, extending from Central Virginia to Alabama. Interpretation of the relationship between deformation and metamorphism is complicated by two factors:

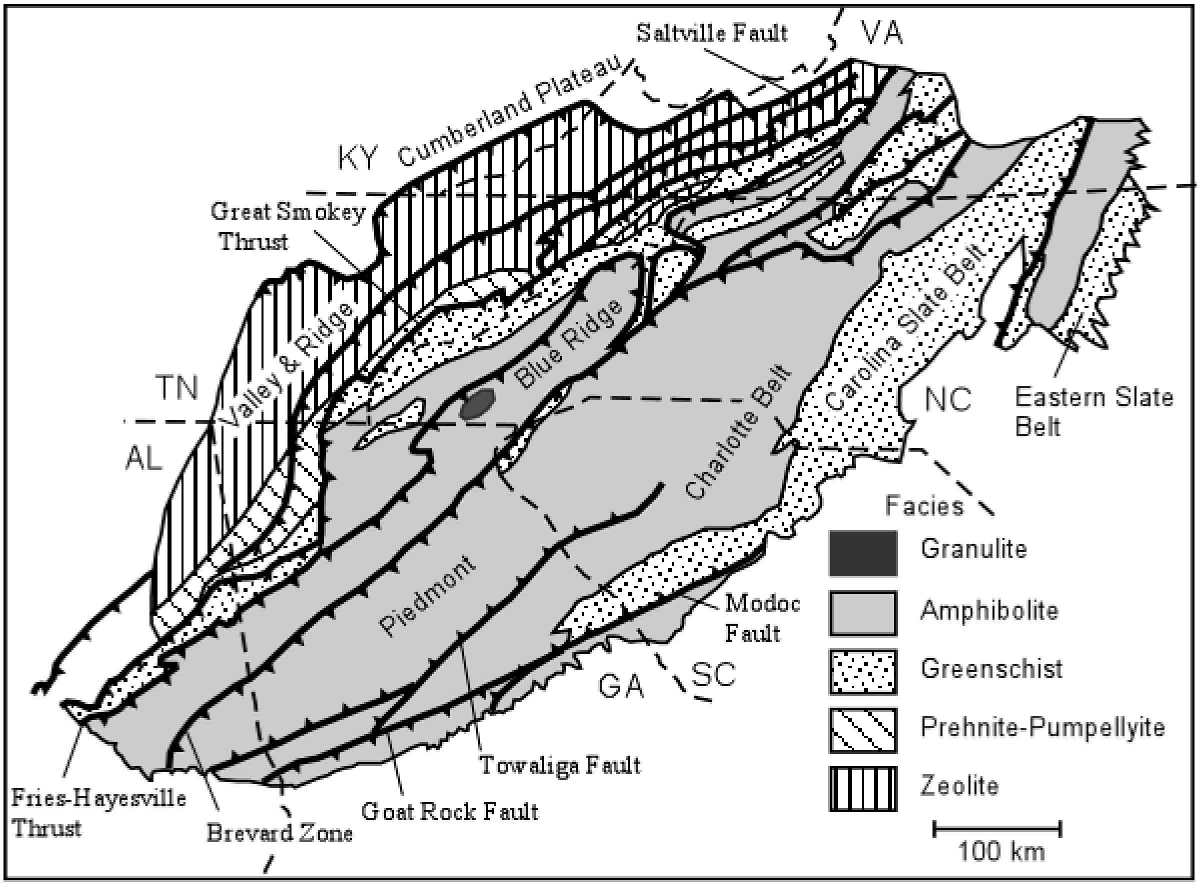
1. Three or more orogenic events affected the region. The most recent are:

    a. The Taconic Orogeny - Ordovician, - 500 to 400 million years ago.

    b. The Acadian Orogeny - Devonian to Mississippian - 400 to 350 million years ago.

    c. The Alleghenian Orogeny - Pennsylvanian to Permian - 325 to 260 million years ago.

2. Thrust faulting during these three orogenic events sliced up the area. Some of these thrust faults, like the Fries-Hayesville Thrust, shown below, occurred after metamorphism.



After Raymond, 1995

- **Zeolite and Prehnite-Pumpellyite Facies Metamorphic Rocks**. These occur mostly in the Valley and Ridge Province, located northwest of the Great Smokey (or Blue Ridge) Thrust. The rocks are Precambrian to Lower Cambrian shales and carbonates that were folded during the Alleghenian Orogeny. Pelitic rocks show only recrystallization of clay minerals, carbonate rocks have an assemblage of calcite or dolomite ± quartz, and rare basic rocks have chlorite, calcite, and rare pumpellyite - $[Ca_4(Mg,Fe)(Al,Fe^{+3})_5Si_4O_{23}(OH)_3 \cdot 2H_2O]$.

- **Greenschist Facies Rocks.** These occur in the Carolina Slate Belt in the east, and near the Great Smokey Fault in the west. Some greenschist facies rocks are also exposed in structural windows within the central Blue Ridge Province. The following mineral assemblages are observed:

    - **Pelitic Rocks**
      Chlorite, sericite, quartz, albite, magnetite, ±garnet (highest grade greenschist facies).

    - **Quartzo-Feldspathic Rocks**
      quartz, sericite, chlorite, K-spar, magnetite ± biotite, ±calcite, ±pyrite.

- **Basic Rocks**
  chlorite, epidote, albite, quartz, hematite or
  actinolite, chlorite, albite, quartz, magnetite.

- **Carbonate Rocks**
  dolomite, calcite, quartz, plagioclase, biotite ± sericite

- **Amphibolite Facies Rocks.** These occur throughout the eastern Blue Ridge Province and in the Piedmont Province. Pressure and temperature calculations suggest that the amphibolite facies rocks were metamorphosed between 500 and 850^{o}C and 5 to 11 kilobars pressure. Migmatites accompany some of the higher grade assemblages, and are expected since the maximum temperatures approach the range of wet granite melting.

  - **Pelitic Rocks**
    quartz, muscovite, k-spar, ±staurolite, ±garnet, ±kyanite

  - **Quartzo-Feldspathic Rocks**
    quartz, muscovite, plagioclase, garnet, ±magnetite ±ilmenite.

  - **Basic Rocks**
    hornblende, plagioclase, garnet, ±quartz, ±epidote, ±biotite, ±magnetite, ±ilmenite, ±pyrite.

  - **Calcareous Rocks**
    rare marbles contain diopside and calcite. More siliceous calcareous rocks are seen as pseudo-diorites (because they look like diorites in hand specimen) with zoisite, garnet, and hornblende.

- **Granulite Facies Rocks.** Granulite Facies rocks occur in a small area near the crest of the Blue Ridge Province in southeastern North Carolina (Winding Stair Gap). The rocks here have suffered some retrograde metamorphism, but original granulite facies assemblages are still discernable. Peak metamorphic conditions were apparently reached in this area during the Taconic Orogeny. Pressure - Temperature calculations indicate that the peak metamorphic conditions reached temperatures of 750 - 775^{o}C and pressures of 6.5 - 7.0 kb. This indicates a geothermal gradient of about 30^{o}C/km.

  - **Pelitic Rocks**
    biotite, garnet, sillimanite, K-spar, andesite, quartz, magnetite, ilmenite.

  - **Quartzo-Feldspathic Rocks**
    Quartz, andesine, K-spar, biotite, garnet, magnetite, ilmenite.

  - **Basic Rocks**
    biotite, orthopyroxene, bytownite, quartz, magnetite, ilmenite, ±hornblende (probably retrograde).

  - **Calcareous Rocks**
    calcite, quartz, scapolite [$Ca_4Al_3(Al,Si)_3Si_6O_{24}(Cl,CO_3,SO_4)$], ±grossularite, ±diopside, ±clinozoisite, ±sphene, ±apatite.

- **Ultramafic Rocks**
  orthopyroxene, andesine, biotite, and retrograde minerals - hornblende, cummingtonite, & quartz.

Buchan Facies Series

The Buchan Facies Series of regional metamorphism is characterized by the presence of andalusite, and sometimes cordierite, in intermediate grade mineral assemblages indicating that the conditions of metamorphism were at lower pressure and along a higher metamorphic field gradient than that recorded in Barrovian Facies Series metamorphic rocks . The type locality of Buchan Facies Series metamorphism is in northeastern Scotland (see map above) in the Dalradian Series. Here the pelitic rocks in the mapped zones contain the following mineral assemblages:

- **Chlorite Zone (Greenschist Facies)**
  chlorite, muscovite, quartz, albite, ilmenite ±chloritoid or
  chlorite, muscovite, biotite, quartz, albite, ilmenite.

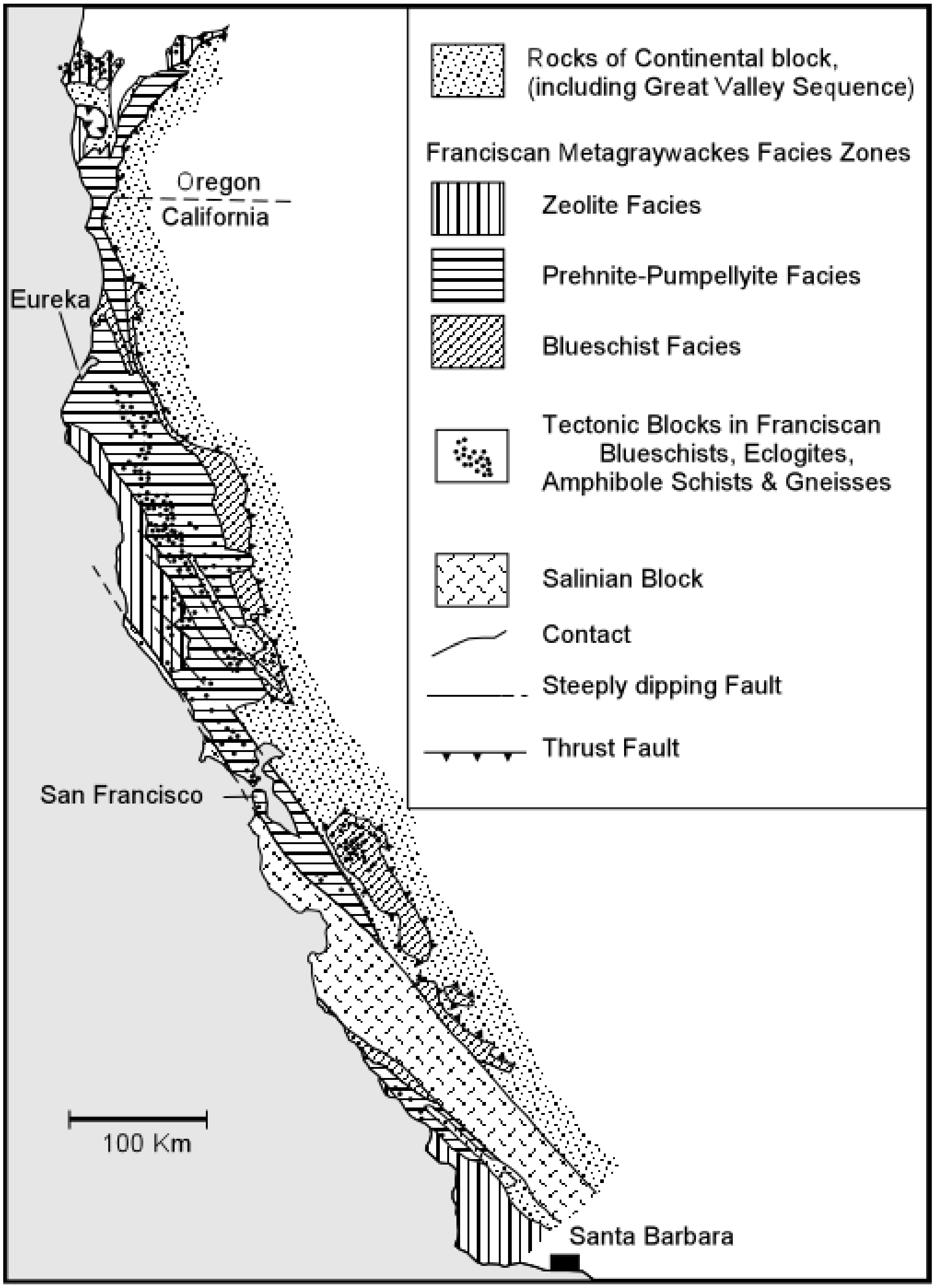
- **Andalusite Zone (Amphibolite Facies)**
  muscovite, biotite, quartz, oligoclase, garnet, andalusite, ilmenite or
  muscovite, biotite, quartz, oligoclase, andalusite, staurolite, cordierite, ilmenite

- **Sillimanite Zone (Amphibolite to Granulite Facies)**
  muscovite, biotite, quartz, oligoclase, andalusite, staurolite, cordierite, garnet, sillimanite, k-spar or
  microcline, biotite, quartz, oligoclase, garnet, sillimanite, cordierite, magnetite.

High Pressure Facies Series

Franciscan Facies Series

Metamorphism along low geothermal gradients results in a series of rocks that pass through the Zeolite, Prehnite-Pumpellyite, Blueschist, and Eclogite Facies of Regional Metamorphism. The best studied example of this type of metamorphism occurs within the Cretaceous Franciscan Complex of California. The Franciscan Complex contains highly folded and faulted blocks and slabs of both unmetamorphosed or weakly metamorphosed rocks, and smaller tectonic blocks bounded by faults. It is structurally complex, and only in a few places can continuous structures be mapped over large areas. For this reason, the complex is called a ***mélange*** (French for mixed). The nonmetamorphosed to weakly metamorphosed rocks are those that are typically found in ophiolite sequences, such as pillow basalts, shales, radiolarian cherts, and limestones, along with clastic sedimentary rocks usually found in oceanic trenches, such as graywackes. These rock types are also found metamorphosed into the Zeolite, Prehnite-Pumpellyite, Blueschist, and Eclogite Facies.



Typical mineral assemblages are as follows:

- **Zeolite Facies** From the mineral assemblage listed below metamorphism of zeolite facies rocks occurred at temperatures of 100 - 200^{o}C and pressures of 1 to 3 kb.
    - **Metagraywackes -** retain their clastic sedimentary textures, contain quartz, feldspars and rock fragments with laumontite ($CaAl_2Si_4O_{12}{\cdot}4H_2O$), prehnite

$[Ca_2Al_2Si_3O_{10}(OH)_2]$ or pumpellyite $[Ca_4(Mg,Fe)(Al,Fe^{+3})_5Si_4O_{23}(OH)_3 \cdot 2H_2O$ in the recrystallized feldspars. Typical rocks have the following mineral assemblages:

quartz, albite, laumontite, chlorite, sericite, hematite
quartz, albite, prehnite, chlorite, sericite, calcite
quartz, albite, K-spar, chlorite, sericite, stilpnomelane, calcite

- **Metabasalts -** again retain their primary igneous textures but contain such minerals as epidote, laumontite, prehnite, and pumpellyite.

- **Prehnite-Pumpellyite Facies.** Temperature - Pressure estimates for the following assemblages indicate that metamorphism occurred at temperatures of 150 to 225^{o}C and pressures between 3 and 4.5 kb.

  - **Metagraywackes** - again retain their clastic sedimentary textures and minerals, along with assemblages such as:

    quartz, albite, k-spar, chlorite, sericite and veins of laumontite and prehnite
    quartz, albite, pumpellyite, chlorite, sericite, hematite
    quartz, albite, prehnite, pumpellyite, chlorite, sericite, hematite

  - **Metabasalts** - relict igneous textures are common.

    chlorite, pumpellyite, albite, quartz, calcite

- **Blueschist Facies -** most of the rocks of the blueschist facies do not retain their original textures, and are now schistose. Typical mineral assemblages in various compositional groups are as follows: Pressure temperature estimates for the mineral assemblages below show a wide range, with temperatures from 125 to 350^{o}C and pressures from 4 to 10 kb.

  - **Pelitic Rocks**
    muscovite, chlorite, quartz, albite, lawsonite $[CaAl_2Si_2O_7(OH)_2 \cdot H_2O]$
    muscovite, chlorite, glaucophane $[Na_2Mg_3Al_2Si_8O_{22}(OH)_2]$, garnet

  - **Quartzo-Feldspathic (Metagraywackes)**
    quartz, muscovite, albite, chlorite, lawsonsite, aragonite, ± jadeitic pyroxene ±glaucophane, ±stilpnomelane ±sphene

  - **Metacherts**
    quartz, crossite $[Na_2(Mg,Fe^{+2})_3(Al,Fe^{+3})_2Si_8O_{22}(OH)_2]$, aegerine, hematite, ±aragonite or
    quartz, stilpnomelane, garnet

  - **Basic Rocks**
    glaucophane, lawsonite, albite, sphene
    glaucophane, lawsonite, stilpnomelane, chlorite, albite, quartz
    glaucophane, albite, quartz, garnet, muscovite

glaucophane, lawsonite, pumpellyite, chlorite, albite, garnet
chlorite, lawsonite, jadeitic pyroxene, glaucophane, quartz, sphene

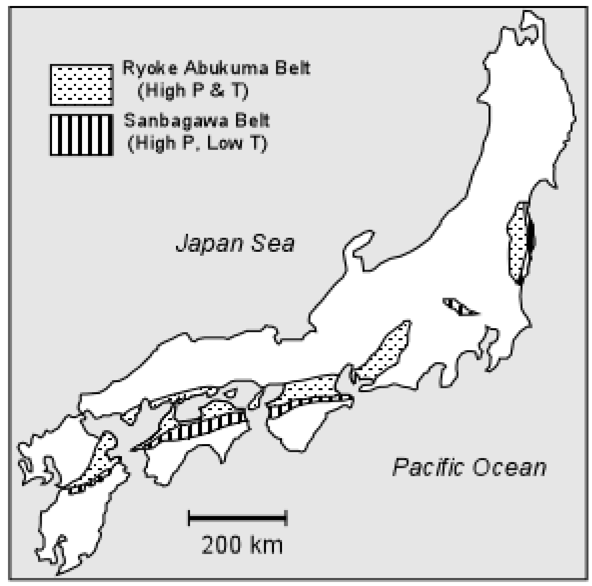
- **Calcareous Rocks**
  aragonite, lawsonite, glaucophane

- **Eclogite Facies** rocks in the Franciscan are only found as exotic tectonic blocks measuring a few meters in diameter. They are all metabasalts, and are characterized by the presence of ***omphacitic pyroxene*** (a complex clinopyroxene rich in the jadeite [$NaAlSi_2O_6$] component. Besides omphacitic pyroxene, the rocks contain garnet (typically up to 50% pyrope component), rutile, sphene, and sometimes quartz. Maximum temperature - pressure conditions for the eclogite mineral assemblages indicate temperatures between 300 and 540^oC and pressures from 6 to 14 kb.

Sanbagawa Facies Series

The Sanbagawa Belt is part of a complex that was accreted to Japan during the Mesozoic. Like the Franciscan Complex, the Sanbagawa Belt contains rocks of the blueschist facies. But, unlike the Franciscan Complex, the Sanbagawa Belt rocks are dominated by pelitic rocks, although basic and calcareous rocks occur, along with some metagraywackes. Also, unlike the Franciscan rocks, the facies sequence is zeolite - prehnite-pumpellyite - blueschist - greenschist - amphibolite, indicating somewhat higher temperatures than in the Franciscan Complex.

Representative mineral assemblages for various rock compositions in the Sanbagawa Facies Series are listed below:



After Miyashiro (1961)

- **Zeolite Facies**

  - **Pelitic Rocks**
    illite/smectite, kaolinite, chlorite, quartz, hematite

  - **Quartzo-Feldspathic Rocks**
    quartz, albite, laumontite, sericite, chlorite, sphene

  - **Basic Rocks**
    laumontite, analcite, pumpellyite, epidote, quartz, chlorite, sericite, sphene

  - **Ultramafic Rocks**
    lizardite (serpentine), magnetite, magnesite, dolomite

  - **Calcareous Rocks**

calcite, dolomite, quartz

- **Prehnite-Pumpellyite Facies**
    - **Pelitic Rocks**
      muscovite, chlorite, quartz, albite, Na-rich amphibole, sphene, ±stilpnomelane
    - **Quartzo-Feldspathic Rocks**
      quartz, albite, muscovite, chlorite, calcite, graphite, sphene
    - **Basic Rocks**
      Prehnite, Pumpellyite, epidote, calcite, albite, quartz, chlorite, sphene
    - **Ultramafic Rocks**
      antigorite (serpentine), brucite, magnetite, dolomite
    - **Calcareous Rocks**
      calcite, prehnite, chlorite, quartz
- **Blueschist Facies**
    - **Pelitic Rocks**
      muscovite, chlorite, chloritoid, quartz, glaucophane, sphene, hematite
    - **Quartzo-Feldspathic Rocks**
      quartz, albite, lawsonite, chlorite, muscovite, calcite, glaucophane
    - **Basic Rocks**
      epidote, glaucophane or crossite, actinolite, chlorite, albite, quartz, sphene
    - **Ultramafic Rocks**
      antigorite, magnetite, magnesite, dolomite
    - **Calcareous Rocks**
      aragonite, chlorite, hematite
- **Greenschist Facies**
    - **Pelitic Rocks**
      muscovite, chlorite, quartz, albite, garnet, graphite
    - **Quartzo-Feldspathic Rocks**
      quartz, albite, epidote, chlorite, muscovite, graphite
    - **Basic Rocks**
      crossite, epidote, chlorite, albite, garnet, quartz, muscovite, rutile
    - **Ultramafic Rocks**
      antigorite, magnesite, brucite

- **Calcareous Rocks**
  calcite, tremolite, quartz

- **Amphibolite Facies**

  - **Pelitic Rocks**
    muscovite, biotite, quartz, oligoclase, garnet, epidote, graphite

  - **Quartzo-Feldspathic Rocks**
    quartz, oligoclase, epidote, garnet, muscovite, rutile

  - **Basic Rocks**
    hornblende, epidote, oligoclase, garnet, quartz, hematite

  - **Ultramafic Rocks**
    olivine, diopside, tremolite, antigorite

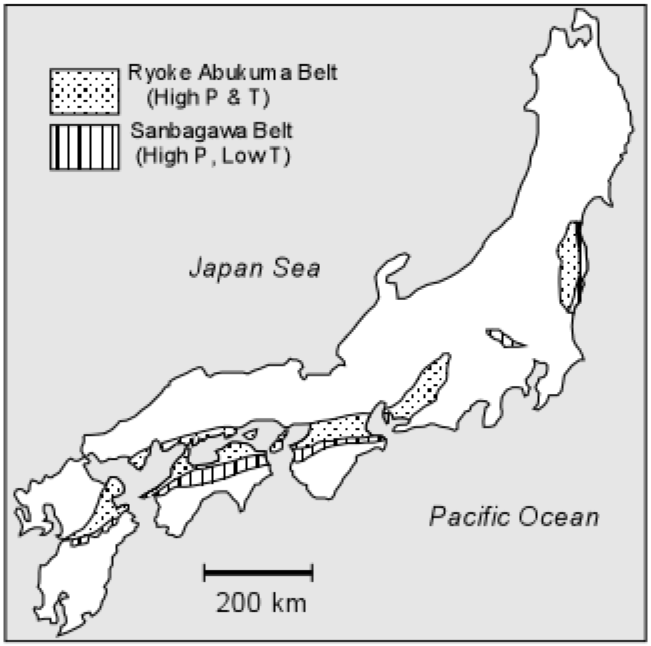
  - **Calcareous Rocks**
    calcite, diopside, quartz, grossularite

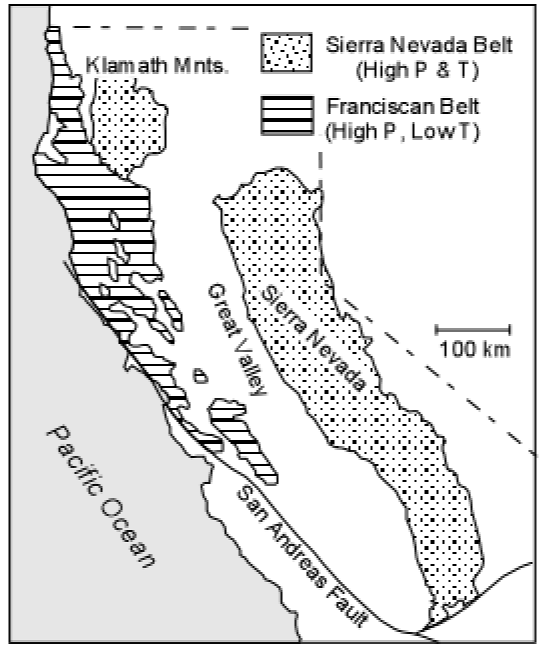
Paired Metamorphic Belts

In 1961, Miyashiro noted that in the cicumpacific region, belts of high pressure, low temperature metamorphism on the oceanic side were associated with belts of high pressure, high temperature metamorphism on the continent side. He termed such an occurrence - ***Paired Metamorphic Belts***. The two examples he cited are:

1. Japan, where the Sanbagawa Belt represents the high pressure, low temperature belt, and an adjacent belt, called the Ryoke-Abukuma Belt, represents the high pressure, high temperature belt. Here the Ryoke-Abukuma belt consists of Barrovian and Buchan Facies series metamorphic rocks.

2. The western U.S., where the Franciscan complex contains rocks metamorphosed at high pressure and low temperature, and rocks exposed in the Klamath Mountains and Sierra Nevada Mountains have remnants of Barrovian and Buchan Facies Series metamorphic rocks. Since most of the Sierra Nevada mountains now consist of batholiths, as discussed previously, one had to look at the roof pendants above the batholiths and in the western foothills of the Sierra Nevada to see the high pressure - high temperature metamorphic rocks.





After Miyashiro (1961)

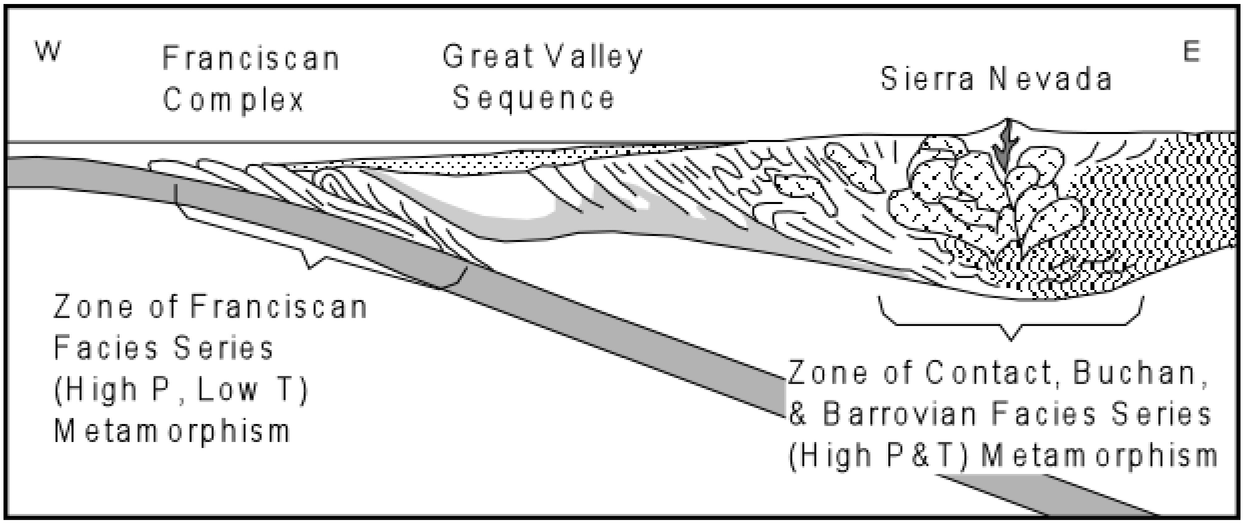
Other occurrences of paired belts have since been recognized throughout the world (see figure 19-12, page 387 in your text) and include areas in New Zealand, Indonesia, Washington State, in the U.S., Chile, and Jamaica. Other such paired belts have been recognized in the Alps of central Europe, the northern coast of South America.

Most of these areas show evidence of having been associated with convergent plate margins, where subduction has occurred. It appears that subduction is necessary to produce the low geothermal gradient necessary to form the belt of high pressure and low temperature. Such belts are probably not more commonly persevered in the geologic record because during blueschist facies metamorphism hydrous minerals are still present. Only if these rocks are uplifted and exposed at the surface relatively rapidly after subduction ceases would they escape being overprinted by facies of normal geothermal gradient, because there would still be fluids available to make the greenschist and amphibolite facies mineral assemblages.

The high pressure- high temperature belts are expected to form in areas beneath the island arc or continental margin volcanic arc. During emplacement of the arc, these areas are subject to higher than normal geothermal gradients that could produce Buchan Facies Series metamorphic Rocks. Furthermore, emplacement of batholiths and isostatic adjustment after magmatism has ceased cause these belts of high T, high P metamorphism to be uplifted and exposed at the surface.

In the case of the Japanese paired belts, the two belts are adjacent to one another likely because subduction has moved farther off the coast. Compressional tectonics between the Pacific and Eurasian Plate has accreted the island arc and trench complex to Japan at the end of the Mesozoic.

In the case of the western U.S., the paired belts are separated from one another. This is because the oceanic ridge that was off the western coast of North America was subducted, and the margin changed from one dominated by compression and subduction to a transform fault margin dominated by strike slip faulting. Isostatic rebound of the highly deformed Franciscan Complex has resulted in its exposure at the surface.



After Raymond (1995)

Examples of questions on this material that could be asked on an exam

1. What mineralogical differences would distinguish between Barrovian and Buchan Facies Series metamorphism of pelitic rocks?
2. Explain why the Barrovian and Buchan Facies series are different.
3. What are most distinguishing features of granulite facies metamorphic rocks?
4. In general, how does the composition of plagioclase change with increasing grade of metamorphism?
5. What are paired metamorphic belts and why are they important?
6. Give two examples of paired metamorphic belts.

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