In general, metamorphic rocks do not drastically change chemical composition during metamorphism, except in the special case where metasomatism is involved (such as in the production of skarns). The changes in mineral assemblages are due to changes in the temperature and pressure conditions of metamorphism. Thus, the mineral assemblages that are observed must be an indication of the temperature and pressure environment that the rock was subjected to. This pressure and temperature environment is referred to as *Metamorphic Facies*. (This is similar to the concept of sedimentary facies, in that a sedimentary facies is also a set of environmental conditions present during deposition). The sequence of metamorphic facies observed in any metamorphic terrain, depends on the geothermal gradient that was present during metamorphism.

A high geothermal gradient such as the one labeled "A", might be present around an igneous intrusion, and would result in metamorphic rocks belonging to the hornfels facies. Under a normal to high geothermal gradient, such as "B", rocks would progress from zeolite facies to greenschist, amphibolite, and eclogite facies as the grade of metamorphism (or depth of burial) increased. If a low geothermal gradient was present, such the one labeled "C" in the diagram, then rocks would progress from zeolite facies to blueschist facies to eclogite facies.

Thus, if we know the facies of metamorphic rocks in the region, we can determine what the geothermal gradient must have been like at the time the metamorphism occurred. This relationship between geothermal gradient and metamorphism will be the central theme of our discussion of metamorphism and plate tectonics.

The facies concept was developed by Eskola in 1939. The names of Eskola's facies are based on mineral assemblages found in metabasic basic rocks.

- Thus, since basic rocks metamorphosed to the greenschist facies contain the green
minerals, chlorite and actinolite, along with other minerals like plagioclase, biotite, and garnet, the rocks were called greenschists.

- Basic rocks metamorphosed to the blueschist facies contain the blue sodic amphibole, glauacophane (along with garnet and lawsonite) are thus blueschists.

- Basic rocks metamorphosed to the amphibolite facies are amphibolites, containing mostly hornblende and plagioclase.

- Basic rocks metamorphosed to the eclogite facies are eclogites, containing the green sodic pyroxene called omphacite and garnet.

- The granulite and hornfels facies were named after the textures of the rocks, with hornfels being the rocks commonly found in contact metamorphic aureoles (high temperature, low pressure environments) and granulites being coarse grained rocks with a granulitic texture and being generally free of hydrous minerals.

- The Zeolite facies was introduced well after Eskola first developed the facies concept, but, was its name is consistent with Eskola's original concept in that zeolite facies metamorphic rocks include basic rocks containing zeolite minerals.

**Metamorphism and Plate Tectonics**

At present, the geothermal gradients observed are strongly affected by plate tectonics.

- Along zones where subduction is occurring, magmas are generated near the subduction zone and intrude into shallow levels of the crust. Because high temperature is brought near the surface, the geothermal gradient in these regions becomes high (geothermal gradient "A" in the figure above) and may be in the range of 50 to 70°C/km, and contact metamorphism (hornfels facies) results.

- Because compression occurs along a subduction margin (the oceanic crust moves toward the volcanic arc) rocks may be pushed down to depths along either a normal or slightly higher than normal geothermal gradient 25°C/km ("B" in the figure above). Actually the geothermal gradient is likely to be slightly higher than B (30°C/km), because the passage of magma through the crust will tend to heat the crust somewhat. In these regions we expect to see greenschist, amphibolite, and granulite facies metamorphic rocks.

- Along a subduction zone, relatively cool oceanic lithosphere is pushed down to great depths. This results in producing a low geothermal gradient (temperature increases slowly with depth) of 10 - 15°C/km. This low geothermal gradient ("C") in the diagram above, results in metamorphism into the blueschist and eclogite facies.
Paired Metamorphic Belts

In 1961, Miyashiro noted that in the Circumpacific 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 (Blueschist and Greenschist facies), and an adjacent belt, called the Ryoke-Abukuma Belt, represents the high pressure, high temperature belt (Greenschist and Amphibolite facies).

2. The western U.S., where the Franciscan complex contains rocks metamorphosed at high pressure and low temperature (Blueschist and Elogite facies), and rocks exposed in the Klamath Mountains and Sierra Nevada Mountains have remnants of high temperature, low to high pressure metamorphic rocks (Greenschist and Amphibolite facies). Since most of the Sierra Nevada mountains now consist of batholiths, 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.
Other occurrences of paired belts have since been recognized throughout the world 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 preserved 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 Amphibolite to Granulite facies 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

After Miyashiro (1961)

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.

**Continent - Continent Collision Zones**

In convergent margin settings where ocean basins close, continental lithosphere can approach and eventually collide with continental lithosphere on the opposing plate. As the two plates with continental lithosphere begin to collide, subduction will eventually cease as it becomes difficult to subduct low density continental lithosphere. Compressional stresses generated in the collision zone will result in folding and thrust faulting of the rocks to ultimately create a fold-thrust mountain belt. Some rocks will be thrust upward to create the high peaks of the mountain range and some will be pushed downward to higher temperatures and pressures and become metamorphosed.

Any previously existing high pressure low temperature metamorphic belts generated during the prior subduction event will eventually become overprinted with the higher temperature and pressure metamorphism that occurs during the compressional deformation accompanying the collision. Only when erosion and uplift occurs will these metamorphic rocks become exposed at the surface.

Such collisional events are currently taking place along the Alpine Himalayan belt which extends from western Europe to southern Asia and has resulted in the mountain ranges known as the Alps and the Himalayas.
Areas where collision has ceased and the mountain belts have eroded include the Urals, in central Asia, the Appalachians of the eastern U.S., and the central Rockies of the western U.S. Geothermal gradients generated during these collisional events can range from normal (as illustrated by geothermal gradient "B" in the first diagram in this set of notes) to somewhat higher than normal (25 - 35°C/km). Thus metamorphic facies will range from zeolite through greenschist, amphibolite, to granulite facies. This can be seen in the northern Appalachians of New England, as shown in the map to the right, or in the southern Appalachians as seen on the map below, which illustrates the complexity of these belts due to the complex structural and deformational history of the collisional event. More detail of this type of regional metamorphism will be given in the lecture to follow.