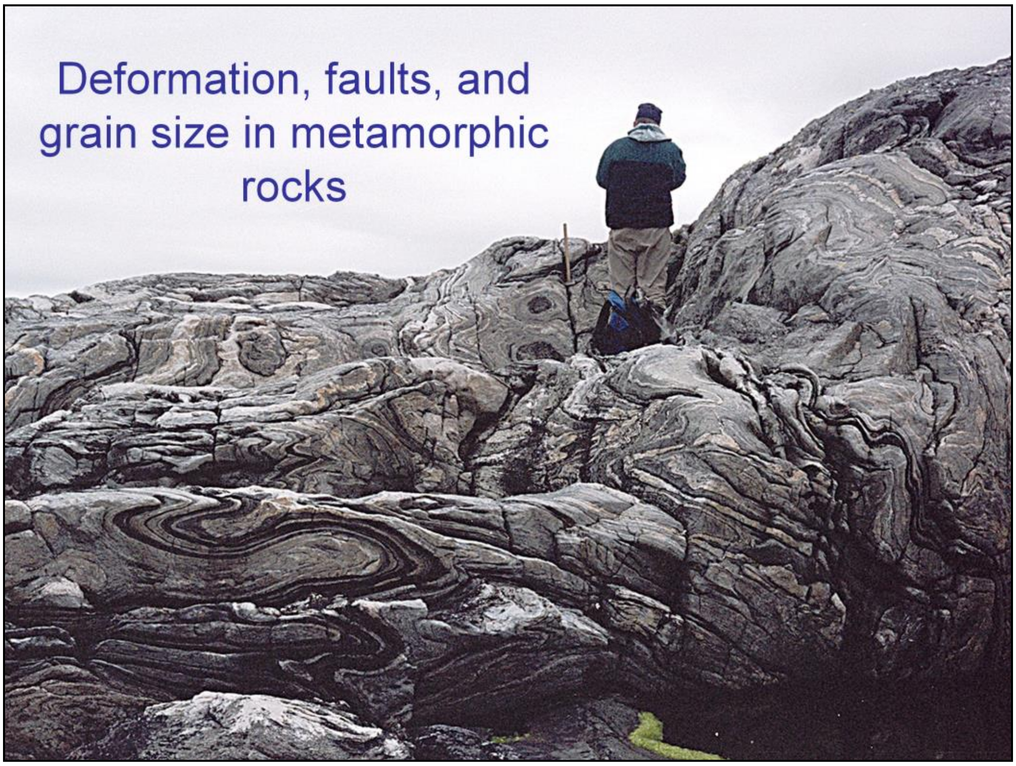
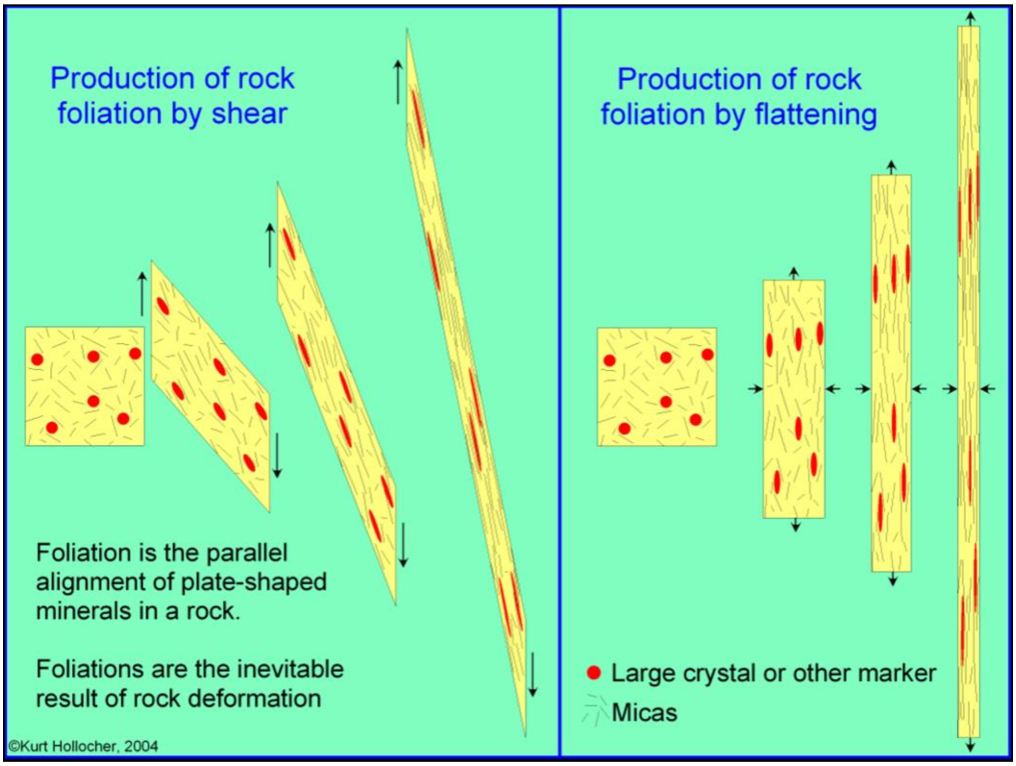


Metamorphic rocks started out as sedimentary or igneous rocks. They were transformed to metamorphic rocks under conditions of high temperature, pressure, and deformation deep within the earth. This photo shows highly deformed (folded) and metamorphosed granite and basalt, now gneiss and amphibolite, respectively, along the west coast of Norway.

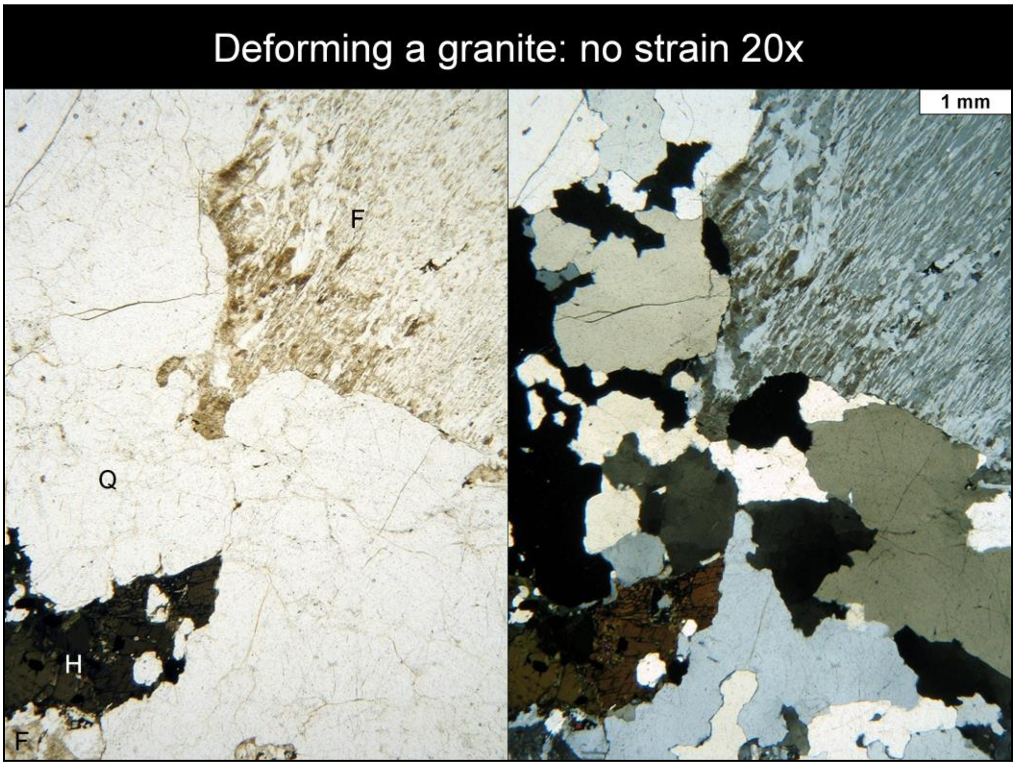
1. Different temperatures and pressures cause different minerals to be stable. As conditions change, unstable minerals break down as new, stable minerals grow.
2. Deformation tends to cause large grains to recrystallize into smaller and more numerous grains.
3. High temperatures tend to cause small grains to recrystallize into larger and fewer grains.
4. The grain size in any particular metamorphic rock is determined by the competition between processes 2 and 3.

NOTE: In most of these slides the photomicrographs are in pairs. The left side is a photomicrograph of a rock thin section in plane polarized light. In these, the minerals have, more or less, their natural color. The right side is a photomicrograph in cross polarized light. In these, light interference causes striking color and shade differences between different orientations of the same minerals. Some minerals like quartz and feldspars have interference colors in shades of gray to white, and others like hornblende and mica have a wide range of bright interference colors. The two types of photos are shown side by side to help show the mineralogy and textures that are not easily seen in only one or the other alone. Mineral color identification is usually with reference to the left-hand plane polarized light image.



Rock foliation develops principally because of the reorientation of mineral grains during deformation, especially the plate-like minerals such as the micas biotite and muscovite. As deformation proceeds, by shear or flattening, grains become increasingly oriented in the direction of rock elongation.

Rock cleavage, like that in slate or schist, is caused by the parallel alignment of plate-like minerals. Because the mineral cleavages are aligned (the planes of easy breaking), the rock breaks most easily parallel to the foliation.

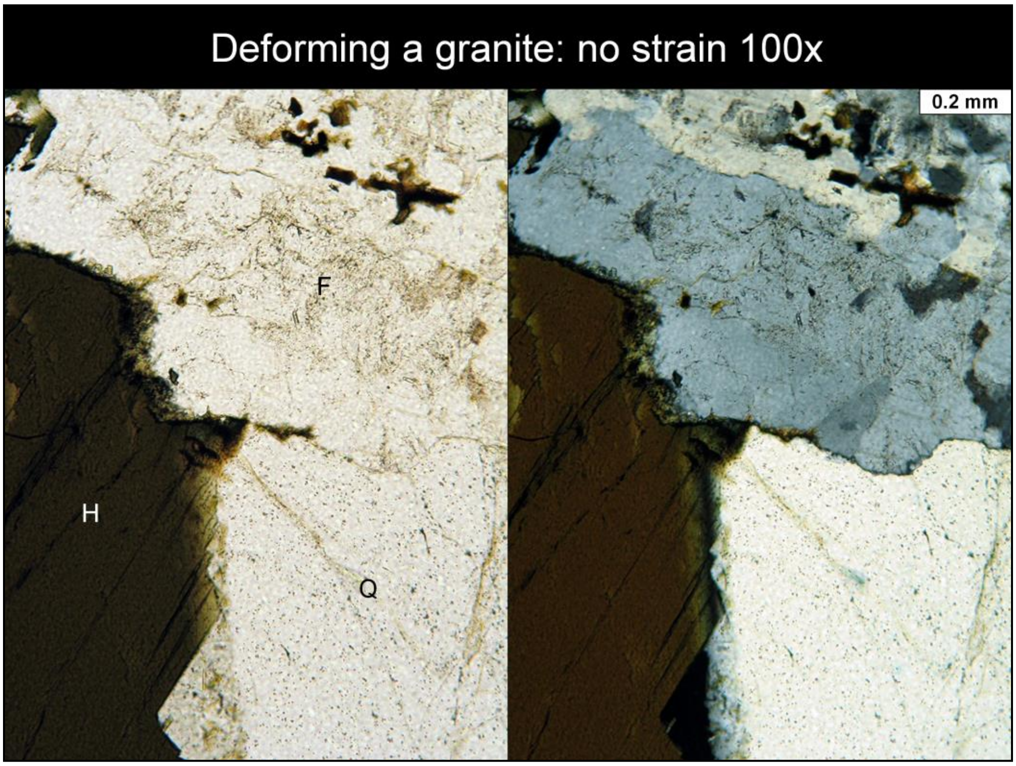


These are photomicrographs of a granite that has not been deformed at all. On the plane light image left, the clear mineral is quartz, the cloudy one in the upper right and lower left is alkali feldspar, and the dark mineral is hornblende. In the cross polarized light right, it becomes clear that there are actually numerous mineral grains that crystallized from the granitic liquid to form this igneous rock.

Q = Quartz

F = Feldspar

H = Hornblende

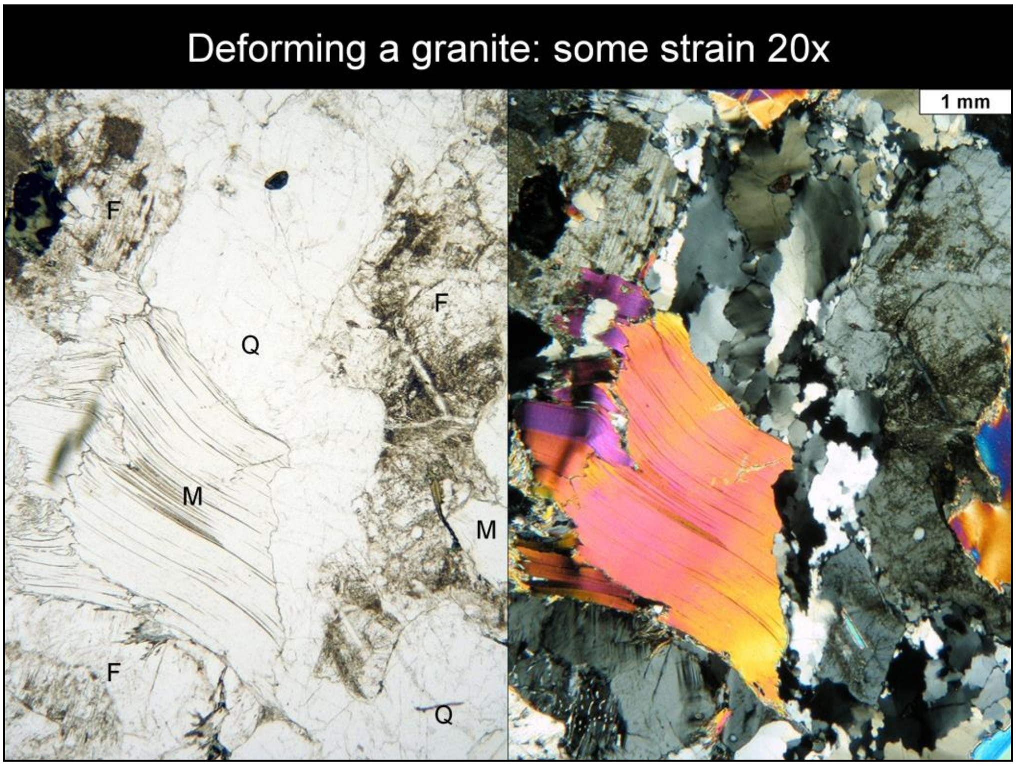


Close up view of the edge of hornblende and quartz. Mineral grain contacts are sharp and have no preferred orientation.

Q = Quartz

F = Feldspar

H = Hornblende

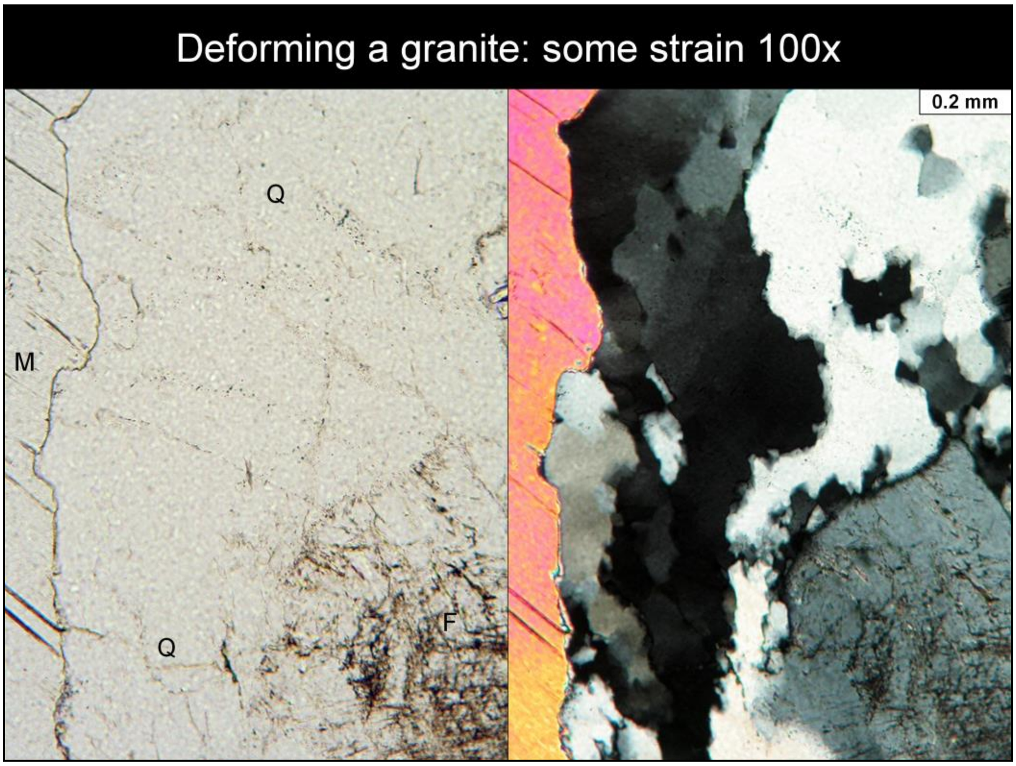


This is a granite that has undergone some deformation. The muscovite mica grains, colorful in cross polarized light right, are bent. The clear quartz grains have been deformed so that they are longer in the vertical direction, and are broken up into smaller crystals.

Q = Quartz

F = Feldspar

M = Muscovite

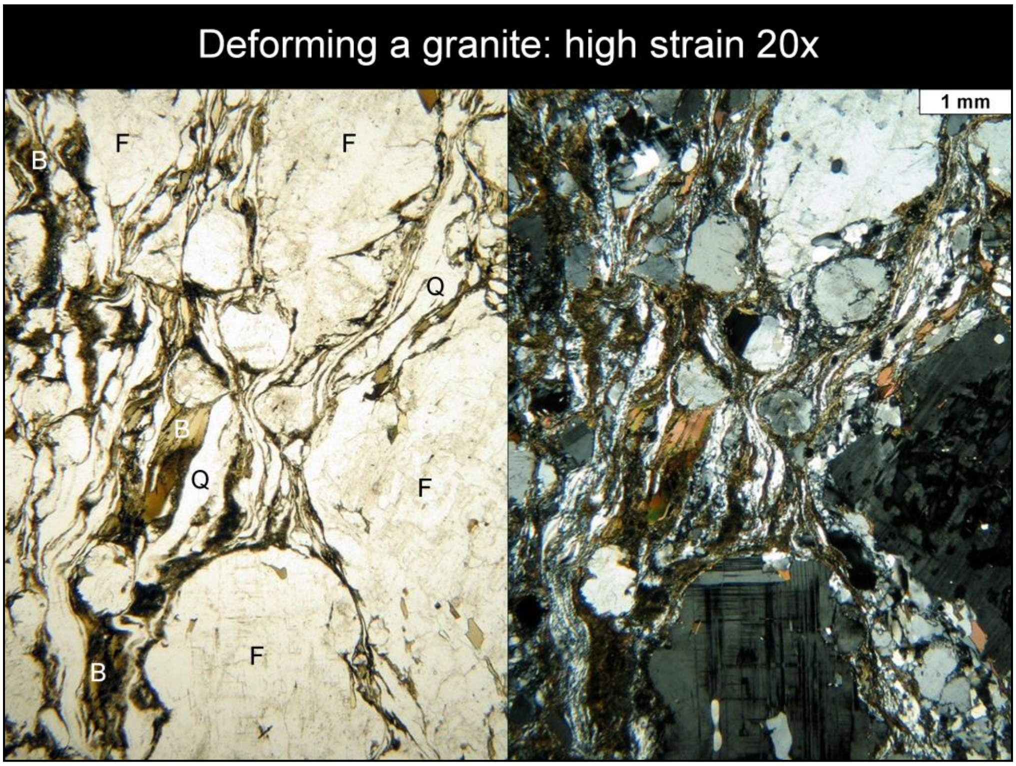


At higher magnification, and in cross polarized light (right) the quartz is more obviously smeared out in the vertical direction, and partly recrystallized into small, more or less polygonal grains.

Q = Quartz

F = Feldspar

M = Muscovite



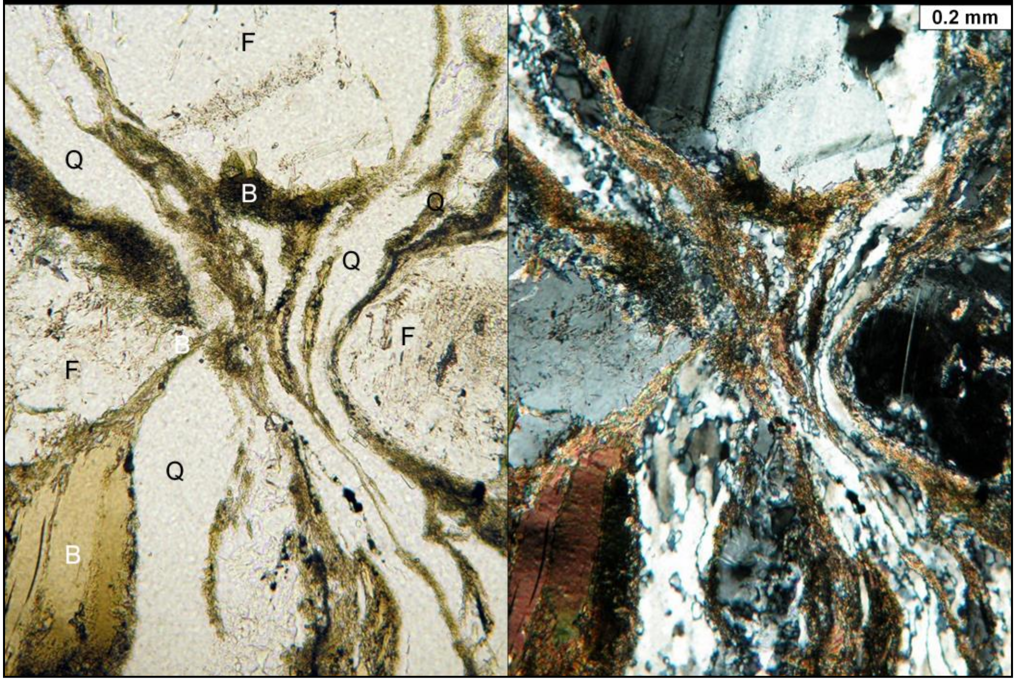
At more extreme deformation, all quartz and micas are strongly smeared out into ribbons. The feldspars remain relatively intact with only minor recrystallization into smaller grains around their margins.

Q = Quartz

F = Feldspar

B = Biotite

Deforming a granite: high strain 100x

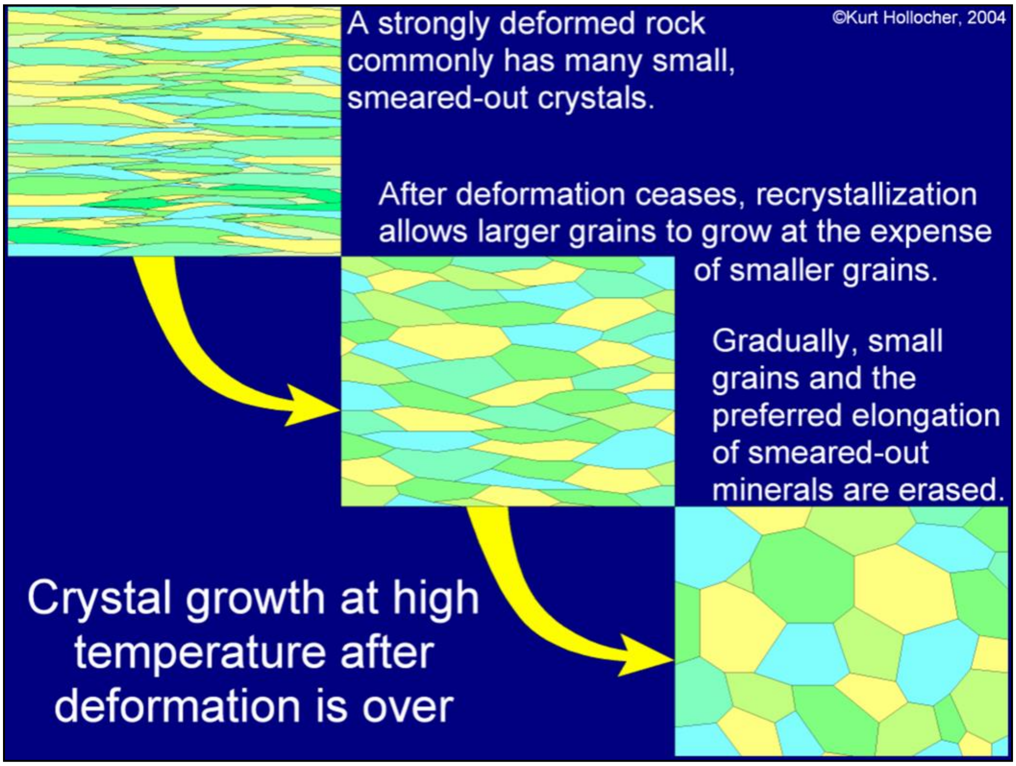


At higher magnification, it is clear that the biotite and quartz have been largely been transformed into ribbons of minute grains, smeared around the stronger feldspars. Despite the hardness of quartz, under metamorphic conditions and with a little water around, quartz is one of the most easily deformed minerals. The feldspars remain among the strongest minerals in the crust.

Q = Quartz

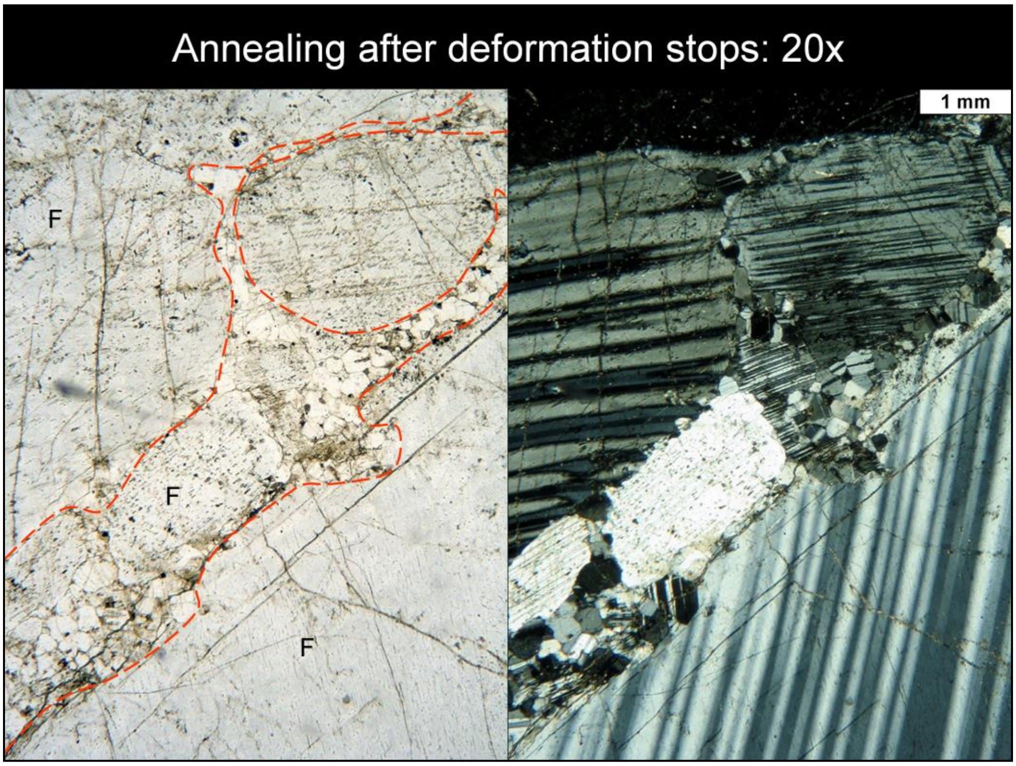
F = Feldspar

B = Biotite



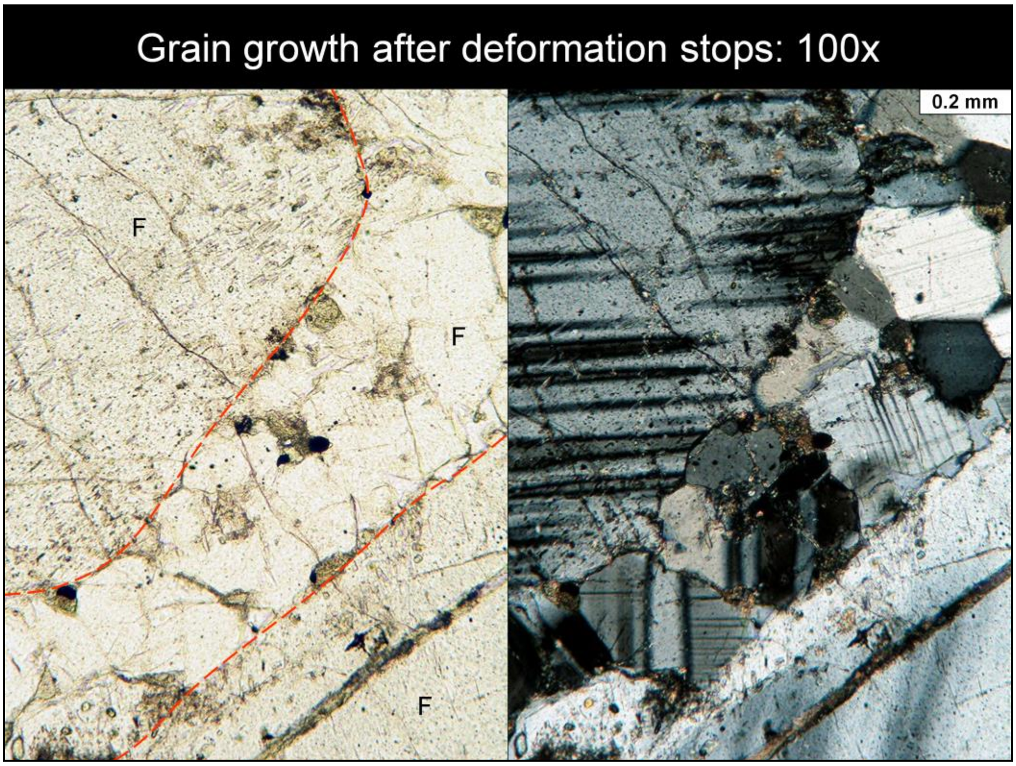
This diagram indicates the processes of grain growth after deformation stops. The smeared out ribbons gradually grow into larger and larger, more and more equidimensional grains as smaller grains vanish. Eventually, the rock becomes mostly equidimensional, large grains and the mineral textures produced during deformation are erased. Renewed deformation starts the process over again.

In fact, grain-size reduction because of deformation and grain growth can occur at the same time. The final rock grain size and texture that results depends on which is dominant late in the history of the rock.



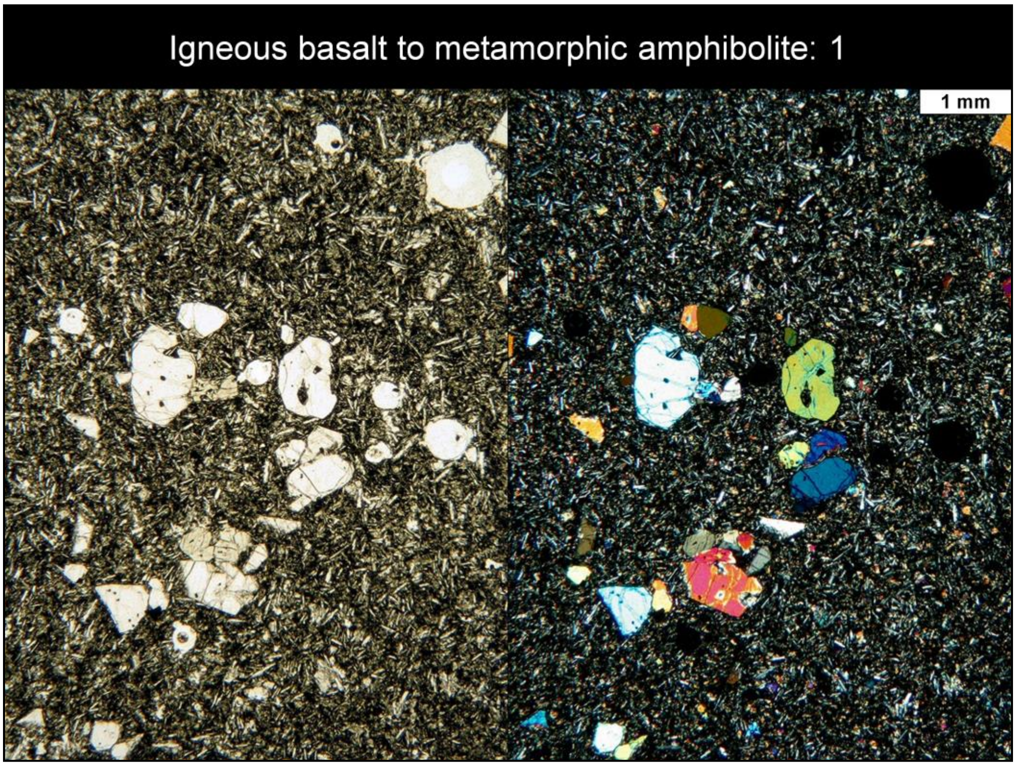
This rock is an anorthosite from the eastern High Peaks region of the Adirondacks. It was originally made up of huge plagioclase feldspar crystals much larger than the field of view here. During metamorphism, the large feldspars were ground past one another, causing large numbers of tiny grains to form on the large crystal margins. This is visible here, outlined in red, except that during a long period of high temperatures after deformation had ceased, the tiny grains grew and became roughly equidimensional, in contrast to the strung-out ribbons typical of freshly deformed rocks.

F = Feldspar



In this closeup you can see the narrow lane of small grains between the two huge feldspars. Originally the lane of small grains would have had grains even smaller, and they would have been long and irregular in the direction of the lane, like those in the **Deformation of a grainite: high strain** slides. Notice the classic 120° grain boundary intersection angles.

F = Feldspar

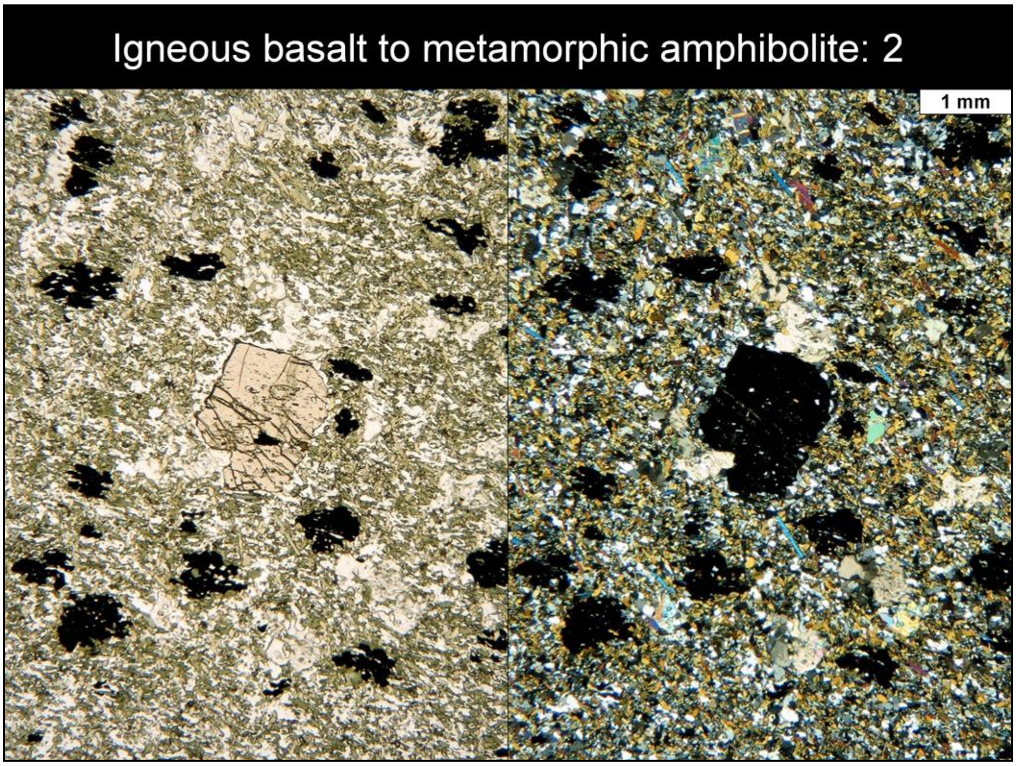


This is a fresh, unmetamorphosed basalt. When it was erupted, it already had larger crystals of pyroxene and olivine (colorful crystals) floating around in the molten rock liquid. The liquid subsequently crystallized to a fine-grained mat of plagioclase, pyroxene, olivine, and magnetite crystals, most of which are too small to see.

Colorful minerals are olivine and pyroxene

small white minerals are plagioclase

Perfectly round things are gas bubbles



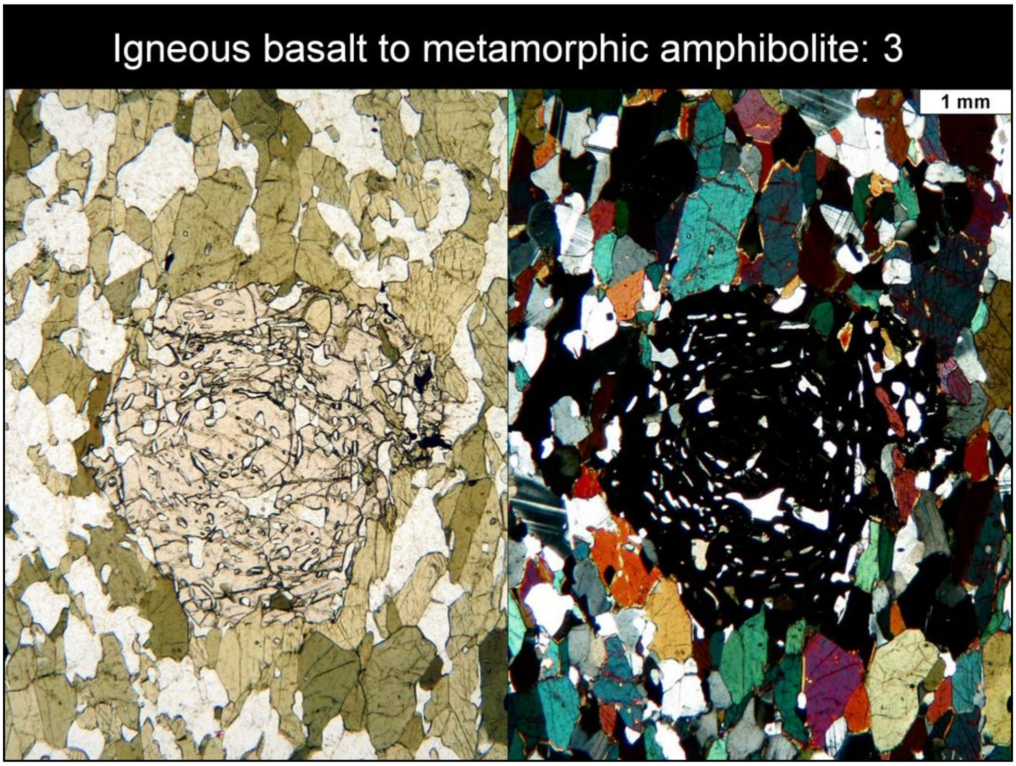
After some metamorphism the basalt would look like this. The basalt is now a fine-grained amphibolite. Its original mineralogy has been completely transformed by metamorphic chemical reactions from the original olivine-pyroxene-plagioclase-magnetite into the new hornblende-epidote-plagioclase-calcite-garnet-quartz-magnetite mineralogy. Even though magnetite occurs in both the original basalt and the metamorphic rock, the magnetite here grew during metamorphism and is chemically different and is a different shape.

Black = Magnetite

Pink = Garnet (largest middle grain)

Green = Hornblende and epidote

White = Quartz, feldspar, and calcite



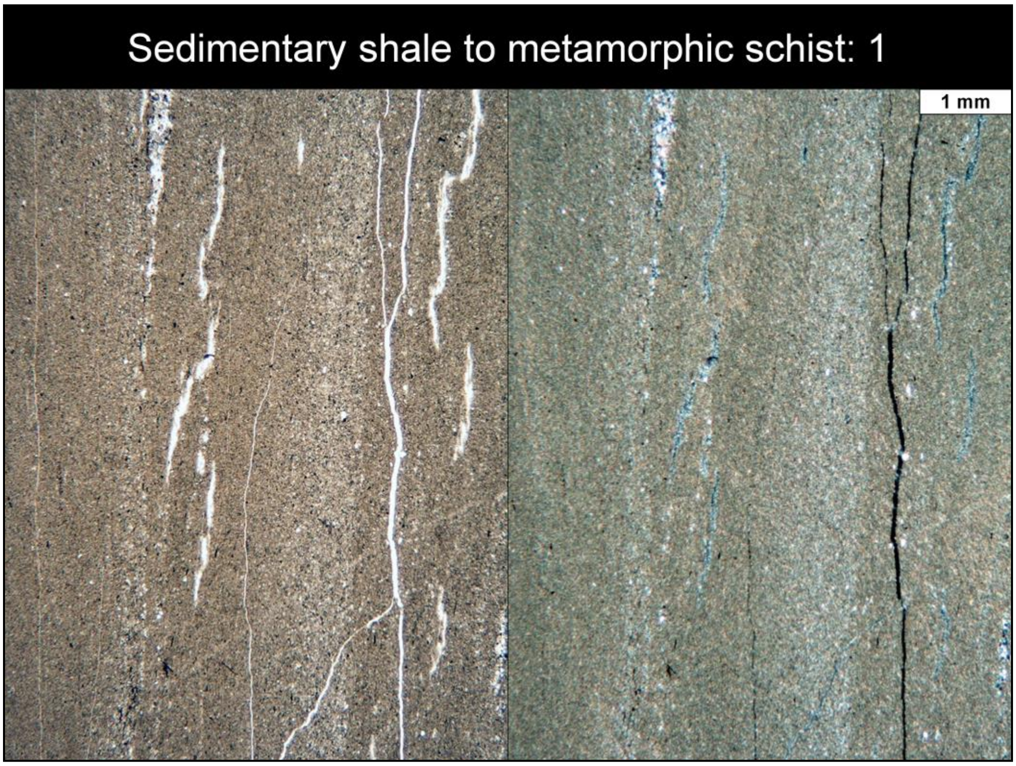
This rock is a high grade amphibolite. Its crystals are larger and the epidote and calcite found at lower grades has vanished while more feldspar and hornblende have grown.

Black = Magnetite

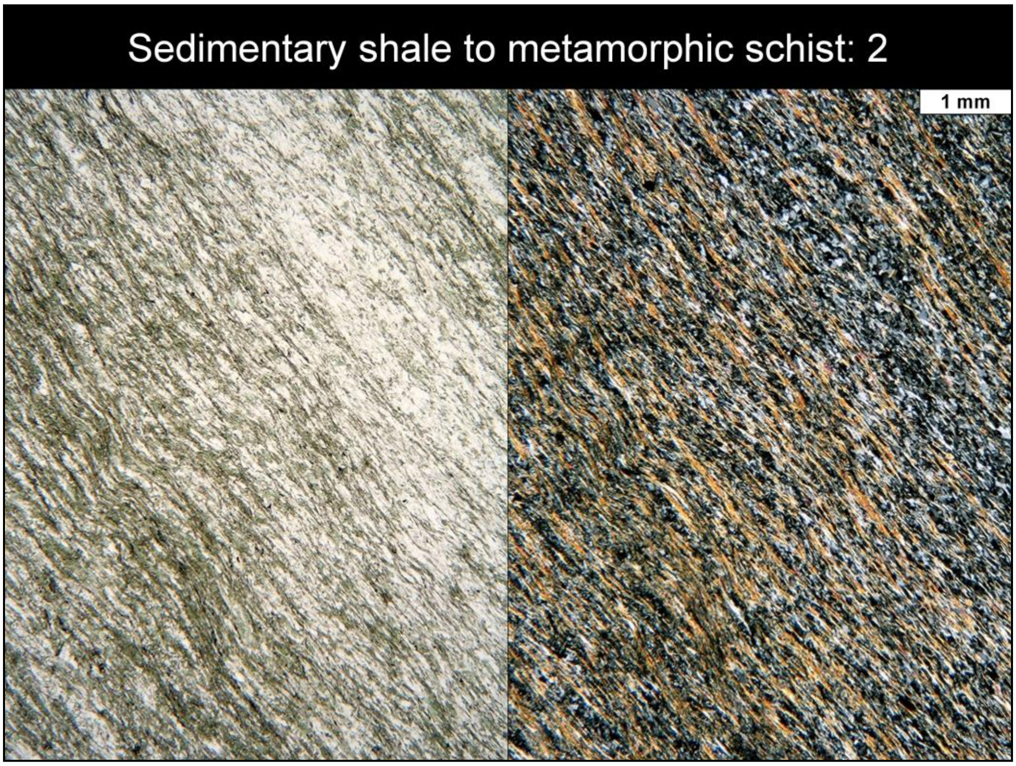
Pink = Garnet (largest middle grain)

Green = Hornblende

White = Quartz, feldspar



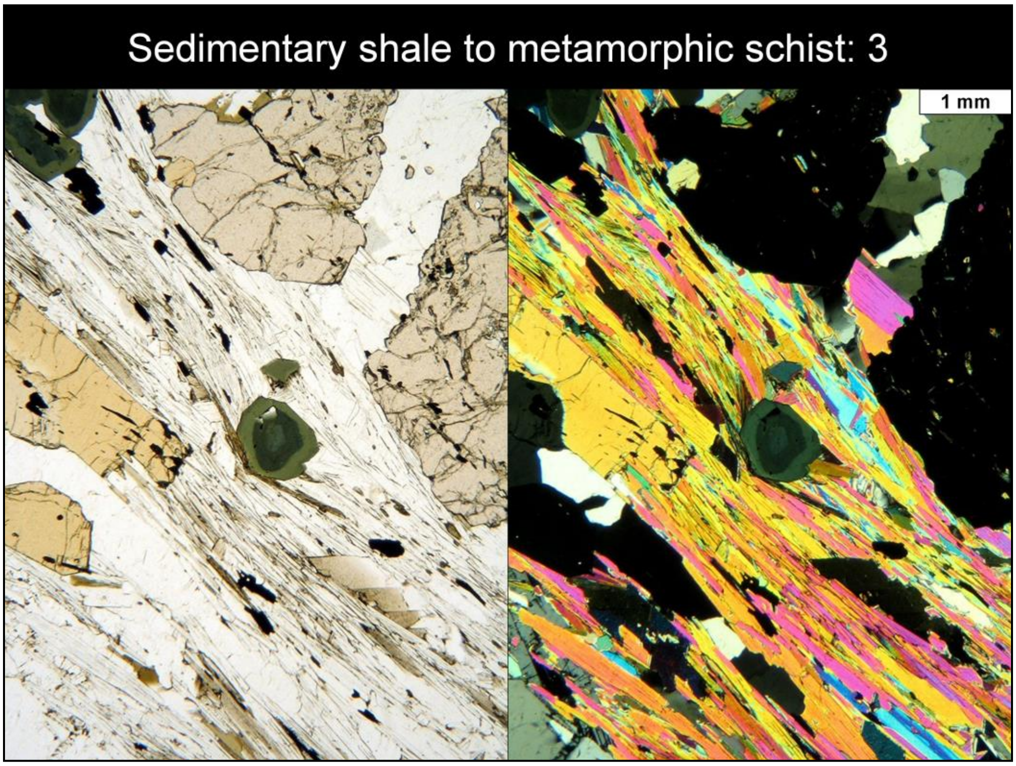
This shale is made up of the fine-grained weathering products of other rocks, deposited in a relatively still flood plain environment. It is made of a some tiny grains of quartz and vast numbers of clay particles that are invisible at this magnification. The long white lines are cracks that formed in the shale when the thin section was made. The cracks are now filled with epoxy glue.



The clay minerals react at moderate temperatures to form minerals like muscovite mica and chlorite. The grains have grown considerably larger, though this would still be considered a fine-grained metamorphic rock.

White = Quartz and muscovite; the muscovite is colorful in cross polarized light (right).

Green = Chlorite



This is a schist, a medium grade metamorphic rock still having the chemical composition of a shale. At higher grade, the rock has been deformed but minerals have grown considerably larger to make a very colorful, texturally beautiful rock.

White = Quartz and muscovite (muscovite is colorful in cross polarized light, right)

Yellow = Staurolite

Pink = Garnet

Greenish = Tourmaline

Medium brown = Biotite mica.

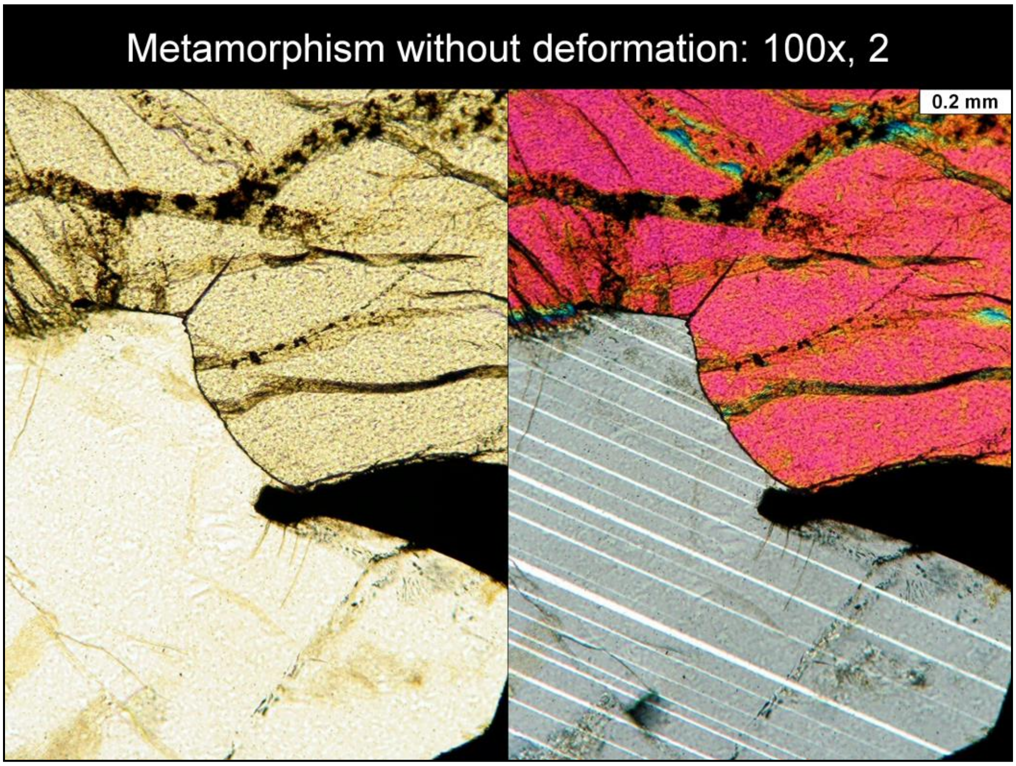
Black = Ilmenite

This is a photomicrograph of a gabbro on the east coast of Greenland (Skaergaard intrusion). It is quite fresh and has not been metamorphosed. The object is to see the large crystals and sharp grain boundaries.

Brownish = Pyroxene and olivine

White = Plagioclase feldspar

Black = Magnetite

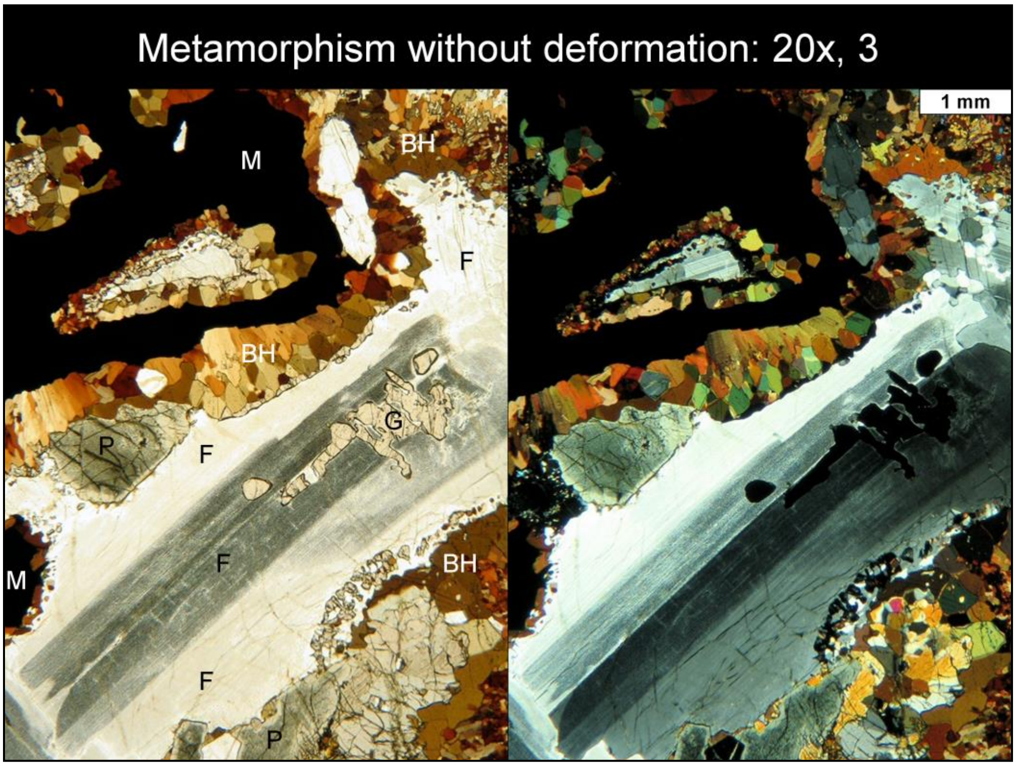


This closeup view shows that the grain boundaries are sharp and the grains are relatively clear. There are several cracks with grungy stuff in them, but otherwise this is a very fresh igneous rock.

Brownish = Olivine

White = Plagioclase feldspar

Black = Magnetite



This is a metamorphosed BUT ALMOST UNDEFORMED gabbro from the eastern Adirondacks. The original minerals included magnetite, plagioclase, olivine, and pyroxene, the same as in the previous gabbro slides. Here, however, chemical reactions during metamorphism have formed polycrystalline metamorphic mineral rims on the original igneous minerals. These form a coating on the original igneous minerals like rust on steel or fungus on wood. The original igneous texture, including large, brick-shaped plagioclase feldspar crystals, can still be seen.

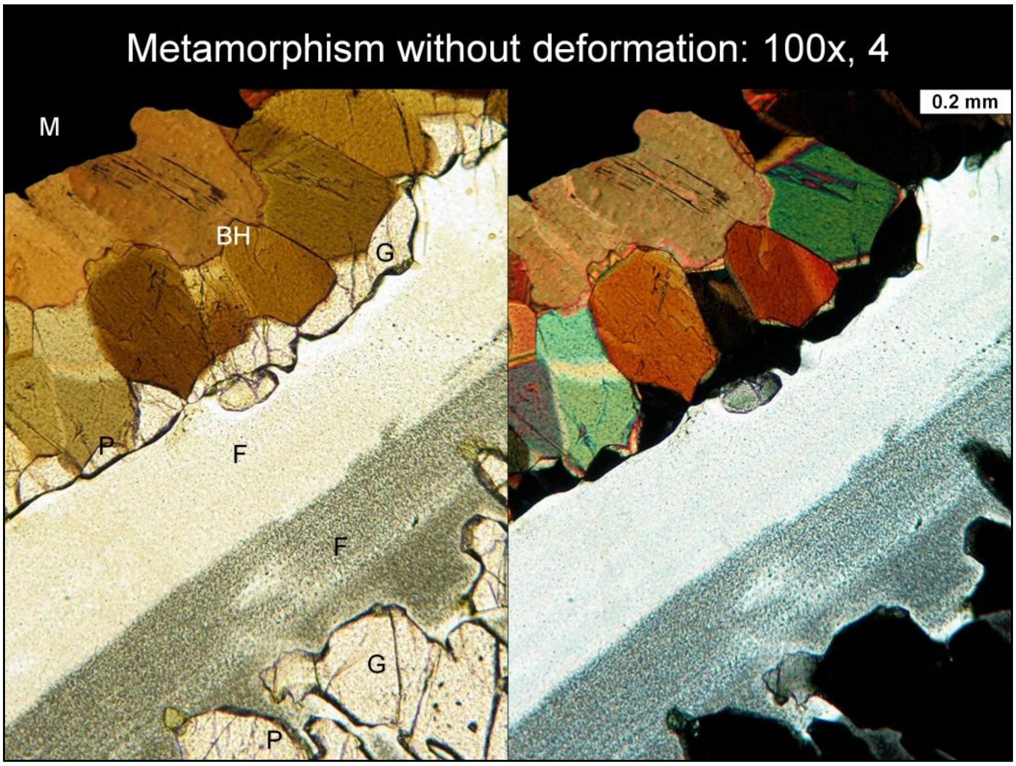
F = Feldspar

M = Magnetite

P – Pyroxene

G = Garnet

BH = Biotite and hornblende



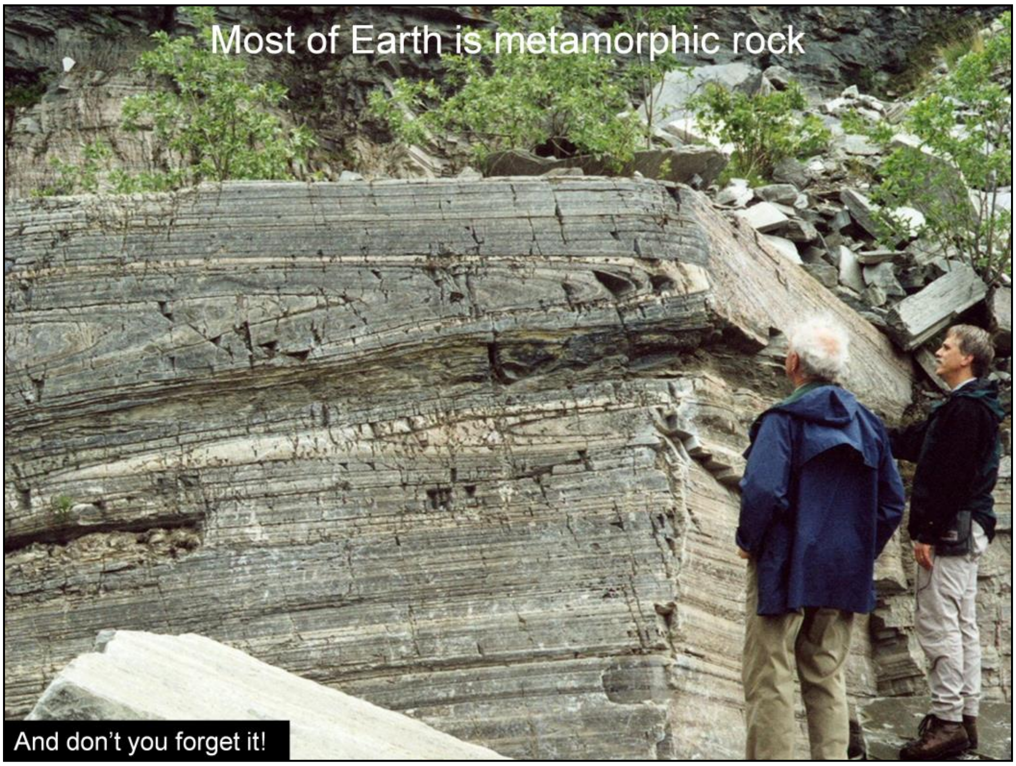
This closeup shows the margin between magnetite and plagioclase feldspar. Some garnet is also growing in the middle of the plagioclase crystal. The gray, dusty material in the feldspar is very fine-grained spinel, which is a product of the metamorphic chemical reactions.

F = Feldspar

M = Magnetite

G = Garnet

BH = Biotite and hornblende



As soon as deformation, recrystallization, and mineralogical changes have progressed a moderate amount, an original sedimentary or igneous protolith rock becomes a metamorphic rock. Probably 80% of the continental crust is metamorphic rock, and so is almost 100% of the earth's mantle and inner core. Thus, considerably more than half of the mass of the earth is metamorphic rock.

The most common metamorphic rock most people are familiar with is snow. The transformation from fine-grained snowflakes into hard, icy corn snow is essentially a metamorphic recrystallization process.

This photo is of metamorphosed sandstone in south-central Norway. The obviously folded layers clearly show that solid rock can flow like clay, given time and sufficient heat and pressure.