

Metamorphic Rocks and the Creation of Gemstones

Metamorphosis literally means “a change in form” and metamorphic rocks can be dramatically changed by earth’s heat and pressure. Any preexisting rock may be distorted and changed into a new rock called a **metamorphic rock**. Metamorphic rocks are not melted as they form (that would be igneous), and change takes place in a solid state. Heat and pressure are forms of energy and when any preexisting rock is heated fluids already within the rock may also be involved in changing the rock. **Heat** and **pressure** are the main agents of change, but only one, either heat or pressure, may dominate.

Some rocks are mainly changed by pressure, and we say these rocks have been changed by “**Regional Metamorphism**.” These are usually found in mountainous or ancient mountainous rocks.

Some rocks are mainly changed by heat and we say these rocks have been changed by “**Contact Metamorphism**.” These are usually in igneous regions and intrusion of igneous rocks heats and “**bakes**” the rocks to accomplish the change.

Lastly, Some rocks are mainly changed by hot water and we say these rocks have been changed by “**Hydrothermal Metamorphism**.” These are usually around igneous rocks as well, and some people consider it rather different than the other two types. Often ground water seeps down and is heated by the igneous rocks and then rises because it is hot and carries dissolved minerals upward to form “Hydrothermal Veins.” The veins can be rich in precious metals or can grow crystals such as quartz and even emeralds. Hydrothermal laboratory methods are used to make synthetic gems under conditions similar to how it happens in the earth.

Emeralds are a classic example of a metamorphically formed gemstone and they are usually found in metamorphosed shales (regional metamorphism) or quite separately in veins of hydrothermal origin. Because metamorphism takes place in a **solid state**, inclusions of other solids are usually trapped as the emerald grows around them. Emerald having inclusions of other minerals is so typical, that any flawless emerald is immediately suspected as a synthetic or even a fake! The inclusions in an emerald are referred to as its *jardin* (French for Garden).

Metamorphic Rocks

Metamorphic change, as explained above can happen to any type of **protolith** (proto “first” & lith “rock”, thus the original rock that was metamorphosed). Different minerals will develop from different original rocks. This is important for looking for gems. For example, the mineral jadeite develops when ocean formed igneous rocks are “pinched” under high pressure. For instance, the rocks of Staten Island are part of the ocean crust, pushed up onto the continent by these pressures. The rock was then changed from basalt and gabbro to serpentine. Serpentine is a metamorphic rock. Small patches of serpentine are also found in Manhattan and suggest that ocean crust was pushed onto land in an ancient mountain belt making an “**ophioite**.” The

mineral graphite is formed typically from organic sedimentary rocks rich in carbon such as coal beds that have been metamorphosed.

Sometimes new minerals grow in the metamorphic rock and a good example of a mineral mostly found to be of metamorphic origin is **garnet**. Garnet is really a group of minerals and many garnets form in metamorphic rocks that are formed by pressure as the predominant agent of metamorphosis (Some garnets do grow in igneous rocks.).

An example of Regional Metamorphism

One such rock that contains garnet and several other gem minerals is **mica schist**. Mica schist may have started as an extremely fine grained rock called clay **shale**. As the shale was crushed under enormous pressure during metamorphic processes and also became hot due to friction and deeper burial in a mountain range, the clay minerals (which were **microscopic grains of mineral**) began to **grow and enlarge** and form **mica minerals** such as **biotite** and **muscovite**. These minerals as we have seen form thin sheets. The Manhattan Schist is an example (Figure 1). Gem garnets, tourmaline, and chrysoberyl has been found in the schist.

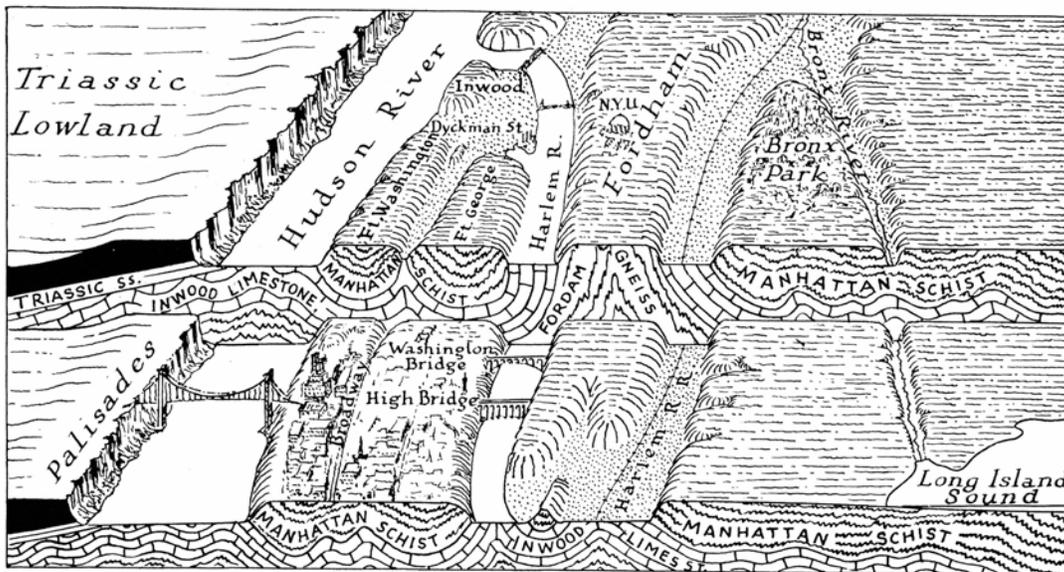


Figure 1. A highly schematic and old-fashioned map showing the metamorphic rocks under New York City. The Manhattan Schist, Fordham Gneiss, and Inwood Limestone (actually a marble) are illustrated. These formed in the roots of an ancient mountain chain that rose some 400+ millions years ago. The oldest rock, Fordham Gneiss may be 1.1 billion years old (Illustration from Lobeck 1932)!

The sheets of mica are **all oriented in the same direction**. Think about how pressure on a house of cards could collapse it under pressure and the card's flatness would align them in a parallel plane. This texture of many parallel minerals makes a **schist** and we call the texture **foliate texture** or a **foliated rock**. So schist has a foliated texture similar to wood grain, or think

also of other things like a deck of playing cards with the edges all lined up, etc.

Foliated texture is extremely important to recognizing regionally metamorphosed rocks and you must be sure to carefully examine the rocks that display it.

With increasing pressure, a segregation of mineral types often occurs and the rock **gneiss**, made of **light and dark mineral bands** may form as the schist is further changed by metamorphism. It may form by gradual change of schist, but also forms by increased metamorphism of other rocks. One example is granite gneiss. Garnet also occurs in gneiss. Your instructor should be able to show you an example of granite gneiss as well as one that is more likely to have formed from shale changed to schist and then further changed to gneiss (Shale—> Slate (as in black boards)—> Schist—> Gneiss). Note, slate is very fine-grained and unlikely to contain gem materials, but is a distinct rock in the overall gradational process discussed above.

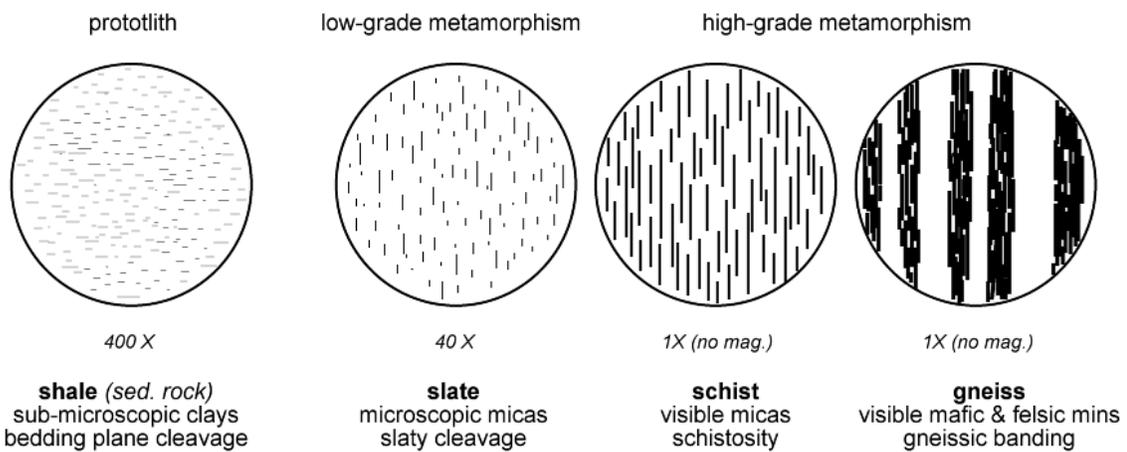
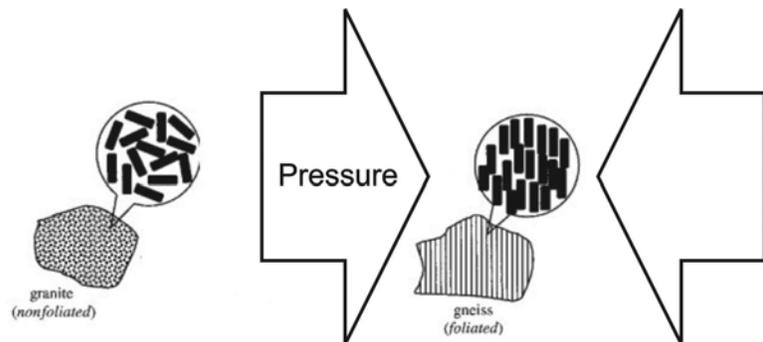


Figure 2. Foliation of metamorphic rocks. Regional metamorphism creates the texture.

Besides the parallelism of mica in schist, the dark and light bands in gneiss also are a type of **foliation (Figures 2 & 3)** and indicate a formation involving pressure and regional metamorphism as the cause of rock formation. As can be seen, new or recrystallized minerals grow in a pressure field at 90° to the pressure (right angles). Subduction is a potential cause of the pressure (Figure 4.)



Lastly, when you look at garnet, notice that it is like a knot (on string or in wood) that breaks up the parallelism. Because garnet

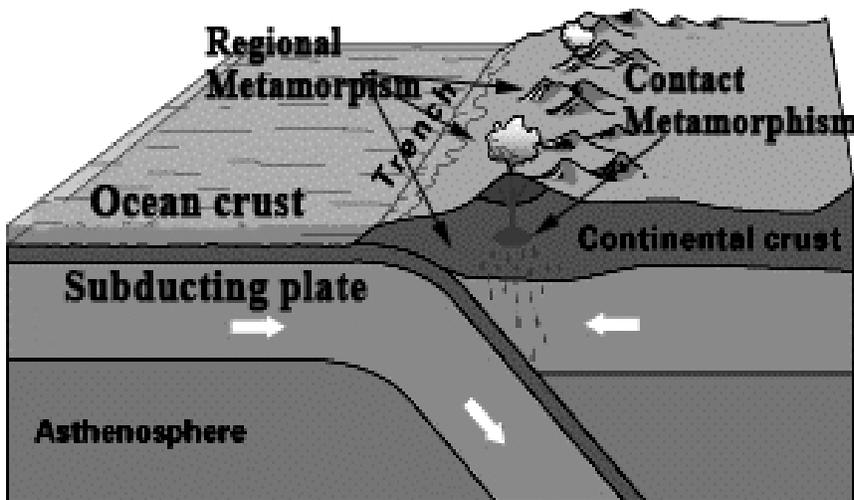
Figure 3. Foliation is due to differential stress. Here granite is changed to gneiss by adding pressure and recrystallization.

grows rather like a ball or 3-D object, it interrupts the parallelism of the mica or other platy or parallel growing minerals. Thus foliation is not necessarily getting better as larger new minerals grow and the rock changes.

How do we get regional metamorphism and the pressure to fold rocks?

Rocks on the surface act as brittle objects, but when confined by more layers and heated by earth's internal sources (geothermal heat), rocks become more ductile and malleable (they can bend). Plate tectonics, particularly at convergent plate boundaries can cause the bending and this leads to **directed pressure that foliates the rock**.

Thus foliation is due to convergence and squeezing (differential stress). It may be at a subduction zone where an ocean plate goes under a continental plate (Figure 3) or where two continents collide, as in the Himalayas where India crashes into the rest of Asia.



Oceanic-continental convergence

Figure 4. Illustration of a convergent plate boundary. Metamorphism occurs regionally along the subduction zone and also near an igneous intrusion (contact metamorphism). The two white arrows are coming at each other represent the differential stress and can lead to foliation of metamorphosed rocks.

Contact Metamorphism

Contact metamorphism is due to heat changing the rocks. An analogy would be a piece of white bread being heated and changed to toast. Bread is soft and malleable, but toast is hard and brittle. Toast required the addition of heat energy to make the change. That is the case with rocks too, heat energy and possibly release reactive fluids cause contact changes around an **igneous intrusion**. Away from the intrusion, the effects gradually reduce until the rock is unheated and in its original condition. Though contact metamorphism is distinct from regional

metamorphism that is mainly due to pressure. The igneous rocks that cause the change may be formed by plate tectonics process that also cause regional metamorphism. Usually the area that is contact metamorphosed is much smaller than the area affected by regional metamorphism. Thus the name “regional—” indicating a large area like a mountain belt (Himalayas, Alps, Appalachians, Andes).

Figure 5 shows a contact metamorphic zone around a magma or plutonic rock in a volcanic terrain. The area affected is called either an aureole or a skarn. Skarns are often formed into limestones creating a marble that can have interesting minerals such as garnets.

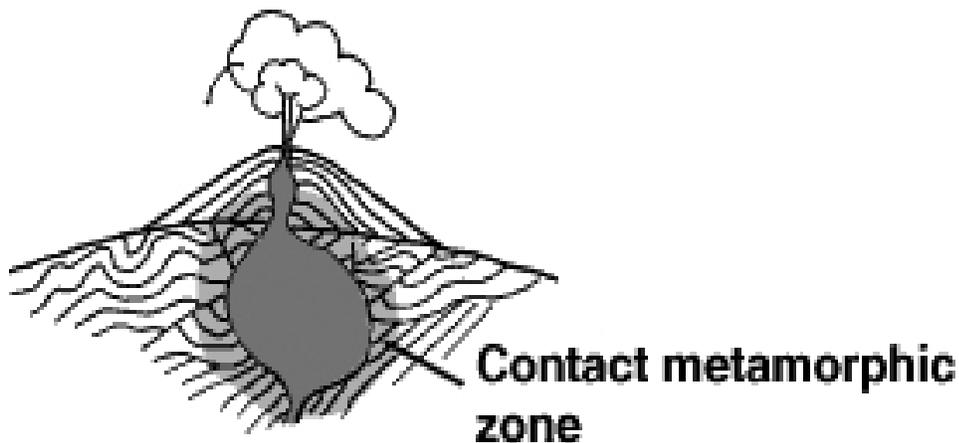


Figure 5. The darkest zone is magma or later plutonic rock on cooling. The zone around it is the aureole or skarn caused by the “burning” of the surrounding rock. The illustration shows fold rocks that were probably metamorphosed by convergence (regional meta) before the intrusion that then contact metamorphosed the surrounding rocks.

Marble is metamorphosed limestone. Limestone is an accumulation of calcite (CaCO_3 ; bubbles with acid), it may be from animal shells or from inorganically precipitated evaporite type deposition of sedimentary origin. Whatever its original source, limestone when heated or put under pressure may recrystallize (the calcite crystals enlarge to visible grains) and form a coarse crystalline rock called marble. Marble may be white, pink, blue, or even dark colors. What distinguishes it from limestone is the coarseness of the calcite crystals and the fact that any fossils are destroyed by the process of recrystallization.

Marbles are usually made of **calcite** which has **two important properties** that effect the rocks appearance. 1) Calcite forms **rhombs**. These are 3-D like garnet and thus it is not easy to “foliate” marble (Figure 6 below). 2) Calcite will **bubble if acid** is applied, but sometimes they are made of a related mineral called dolomite which only bubbles if it is first ground to a powder and then has acid applied.

As the limestone recrystallizes, impurities may provide a source for the formation of garnets, tourmaline, spinel, and most importantly ruby, other gem minerals may occur as well.

Though marble is a good example of a rock that can form from contact metamorphism, not all marble forms this way. In mountainous regions, limestones may under go pressure and regional metamorphism occurs. Thus to interpret a marble's origin, you must see if the other rocks near it are foliated or not.

Metamorphic Rocks We Will Study

Since metamorphic rocks can be formed by changing any preexisting rock by the agents of heat and pressure plus or minus hydrothermal fluids, it means there are a very wide variety of such rocks. We look at only a small sampling. Metamorphic rocks can have a wide variety of gem minerals, but the circumstances of their formation may have more to do with the protolith (original rock that is changed) than the agents of metamorphism. The protolith could be completely destroyed by metamorphism so that we can not see any remnants of the old rock. For instance fossils are lost by metamorphism of limestone to marble (Figure 6.)

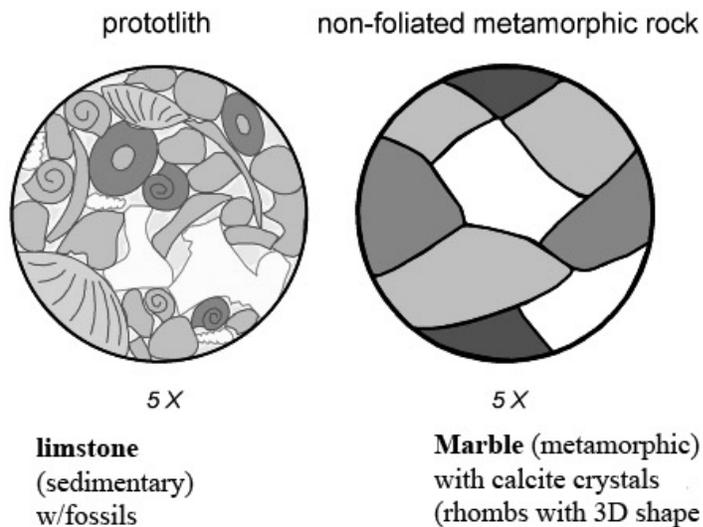


Figure 6. Marble is created by changing limestone (protolith) by recrystallization. The fossils are destroyed. Contact or regional metamorphism can do this.

Identification Table for Metamorphic Rocks

In the table below identify the numbered metamorphic samples. Give the characteristic that helped you name each stone and list criteria that will allow you to recognize future examples. If certain tests such as hardness or reaction to acid are useful, note it.

	Texture	Mineralogy	Rock Name
Foliated (linear texture)	Very finely crystalline; may have slight sheen; more compact than shale	Fine clay minerals are just beginning to enlarge above their size in shale	Slate
	Visible crystals of mica make the rock shiny; garnet knots may interrupt the flow	Mostly muscovite or biotite which may flake off; some garnet, feldspar, and quartz	Schist
	Dark and light (white or pink) banding; bands may be discontinuous or straight through	Mostly quartz, feldspar, and dark minerals; may contain garnet.	Gneiss
	Dark and light (white or pink) banding; bands may be discontinuous or straight through	Extremely similar to regular Gneiss. Less distinct banding	Granite Gneiss
Massive Texture	Usually rather fine-grained. Very hard; will scratch glass	Almost pure quartz. Pink or white colors are common. May be stained other colors	Quartzite
	Large sugary crystals randomly oriented. May be hard or crumbly	Typically calcite or dolomite. Should react with acid. May have other minerals. Pure pieces will not scratch glass	Marble
	Massive texture of fibrous crystals that wrap together. May show splintery fracture	Contains greenish serpentine or jade minerals; may also have feldspar or other non-fibrous minerals mixed in.	Serpentine/Jade

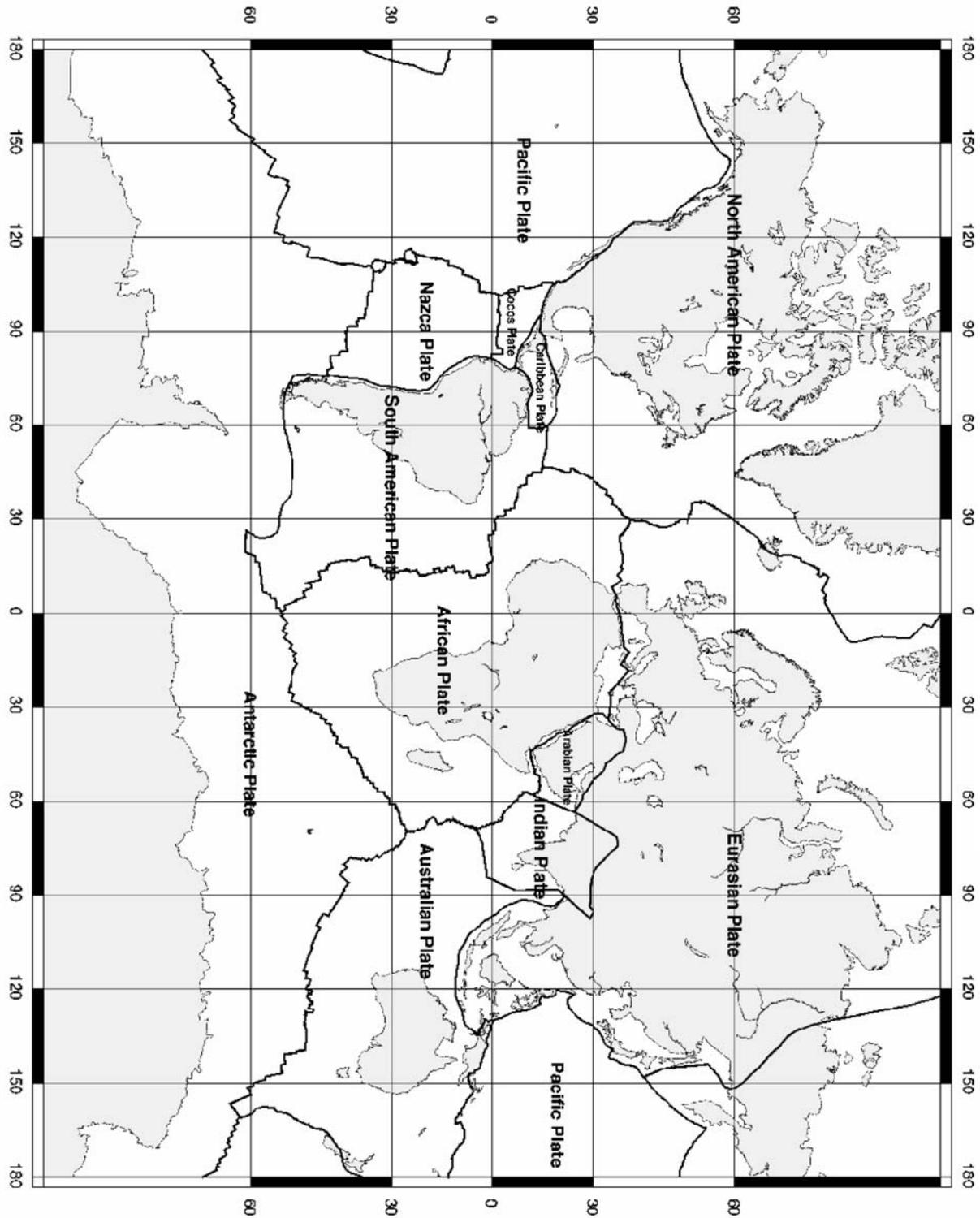
Description of Metamorphic rocks

Number	Characteristics	Name

PLATE BOUNDARY MAP

This map is from Dietmar Mueller, Univ. of Sydney

This map is part of "Discovering Plate Boundaries," a classroom exercise developed by Dale S. Sawyer at Rice University (dale@rice.edu). Additional information about this exercise can be found at <http://terra.rice.edu/plateboundary>.



1) Ruby Crystal in Schist (Be careful, the sample is not that strong!)

Karnataka (including Mysore, India). Another important ruby source is in India. The classic Karnataka Indian locales produce mainly opaque, low-grade star rubies; recently better material has been reported from Orissa, but as of 1994, India mainly supplies lower grade materials as in your example. Probably from a schist or gneiss sample. Your sample appears to be in one of these two matrixes, but the small specimen makes the rock matrix hard to identify.

A) Was this rock be produced by contact or regional metamorphism?

B) Is the sample opaque or translucent? What is its shape and size? Look up ruby crystals for shapes (hint look at number of sides).

C) Is there any structure on the crystal surface? Is there a shape on the surface? A texture?

D) This is not a star ruby. What is a star ruby? Illustrate the shape.

E) Compared to the crystal shape, how should the crystal be cut to create a star? Try to illustrate.

2) Ruby in Zoisite from Tanzania, Africa

A metamorphic rock known as **anyolite** consists of green zoisite with black amphibole and ruby crystals. The rubies as a whole are not of gem quality, but nevertheless their color provides a striking contrast to the green zoisite, and greatly enhances the decorative pieces that are carved from the rock. As well, small sections of some larger crystals are big enough to facet (cut into) melee (a term often used for diamond size).

Both the ruby and the green zoisite are colored by chromium. The chromian zoisite-ruby are the result of very high-grade metamorphism of anorthosite (a mafic rock), an intrusive igneous rock dominated by Ca-rich plagioclase feldspar. The chromium (Cr) in the zoisite and the corundum (ruby = red corundum colored by chromium) is thought to be derived from metamorphic alteration of chromite crystals (FeCr_2O_4 - iron chromium oxide) in the original anorthosite unit.

The anyolite is hosted in gneisses exposed in the Mozambique Collision Belt, an ancient, north-south trending, tectonic collision zone in eastern Africa. That is an area affected by plate convergence (continent to continent collision). It dates to the Pan-African Orogeny (Neoproterozoic), during which the ancient continents of West Gondwana (~modern-day South America & Africa) and East Gondwana (~modern-day India-Australia-Antarctica) collided, forming the long-lived, small supercontinent Gondwana. (James St. John, 2012). Ruby, zoisite, and black amphibole show a little foliation (schistosity; like schist). Besides the foliation, the collision of the plates may have continued after formation of the ruby that appears to rather fractured.

A) Describe the contrasting colors. Is this attractive?

B) Can you see fractures in the rubies?

C) How well formed are the rubies. What shape is their outline?

D) Is ruby likely to show foliation well? Can the crystals be elongate? Could they be parallel to each other in the rock. Look for a slab of ruby zoisite on eBay and see if you can find foliation.

E) Would the difference in hardness between ruby and zoisite be a difficulty in carving this stone?

3) Gore Mountain Garnet

The garnet deposit at Gore mountain is in th Precambrian rocks of the Grenville Series. Located 110 km (70 miles) north of Albany (See Figure 7), it has been mined for abrasive garnet for such uses as sand paper and emery cloth, and for sandblasting, etc. Abrasives must be hard and durable, and the garnet can have a hardness up to around 8 on Mohs' scale. The garnets seem to owe their origin to the mobilization of magnesium, iron, aluminum, and silica, chemical formula $\text{Fe}_3\text{Al}_2(\text{SiO}_4)_3$.



Figure 7. Location map showing Gore Mountain and the Franklin Furnace Zinc mine, New Jersey. This marble deposit makes Franklin the fluorescent mineral capital of the world.

They are mined in an open pit, the original pit on Gore Mountain is now a tourist attraction, but an adjacent property on Ruby Mount produces 1000 tons of garnet a month.

One property of the garnet that is good for abrasive is how it breaks in chisel like shard. The garnet probably formed because of intrusions of gabbro, and other igneous rocks, but it is over a billion years old. A lot has happened in the region and plate tectonics may have regionally metamorphosed the region as well. Consider this later pressure metamorphism as you try to answer the following questions

A) From the pieces of garnet you see, could large gems be faceted (cut)? Look carefully at the texture of the garnet? Explain why or why not?

B) Do you think interesting tiles or cabochons (smoothed over pieces could be made)?

C) What type of garnet is it? Guess based on the information given or look up? Is it very valuable as garnet goes? List its properties. Include some size of actual crystals.

D) Try and decide if this is regional or contact metamorphism. Any reason or reference?

E) What rocks seem to have been changed to make the garnets? Are they igneous?, sedimentary? perhaps this has some bearing on your answer to D?

4) The Franklin and Sterling Hill Mine and Fluorescent Minerals

Franklin Furnace, also known as the Franklin Mine, is a famous mineral location for rare zinc, iron, manganese minerals in old mines in Franklin and Ogdensburg (Sterling Hill), New Jersey, USA. These localities produced more species of minerals and more different fluorescent minerals than any other location. The famous mineral association (assemblage) from Franklin and Sterling Hill Mines includes the zinc minerals (Zn =symbol for zinc), willemite a green mineral (Zn_2SiO_4), zincite a red mineral (ZnO), and franklinite a black mineral $(Zn,Fe)_2O_4$. Willemite fluoresces bright green, zincite sometimes fluoresces yellow, but is not very fluorescent in most cases. Franklinite is non fluorescent and appears black and metallic. Calcite is the gangue mineral but fluoresces a bright red.

During the mid-to-late 19th century the furnace was the center of a large iron making operation and the name furnace refers to the one used to melt iron ore.

The ores (valuable minerals), particularly the element Zinc, are contained within the Franklin Marble. This was deposited as limestone in a Precambrian oceanic rift trough. It was metamorphosed during the Grenville orogeny, approximately 1 billion years ago creating the marble. During the Ice age glaciers strewed trains of ore-bearing boulders for miles to the south, in places creating deposits large enough to be worked profitably.

In the area of the Franklin and Sterling Hill mines at least 357 different minerals occur; this is approximately 10% of the minerals known to science. Thirty-five of these minerals are only found here and ninety-one of the minerals are fluorescent.

Franklin and Sterling Hill are located in the Reading Prong of the New England physiographic province. It is believed ocean sediments and volcanics were formed in a divergent (rift valley type) ocean setting and deeply buried and strongly metamorphosed to the sillimanite grade (high grade up to about 800° C; hot enough to start melting!) later in the Precambrian. Ages for this metamorphism event seem to range from 800 to 1150 Ma.

The rocks were then affected by mountain building and convergence (subduction; see Figure 3), which folded and recrystallized them. Then they were then uplifted from the late Precambrian through early Cambrian (approximately 500 million years ago), their uplifted surface was extensively eroded. Then they were re-buried and exposed again during modern times.

Warning! UV light can burn your eyes! Do not do anything without your instructor!

A) Set up the the fluorescent mineral viewing cabinet with your instructors help.

B) Look at the rocks without UV outside the cabinet. Try to find 1) Franklinite, 2) Willemite, and 3) Zincite. The calcite should be the surrounding white to grey rock. Explain the minerals to the class.

C) Test for calcite with acid. Is there some? Show to class.

D) What is the overall rock type minus the ore minerals?

E) Look at the map and the web to describe how important the Franklin Marble and the mine

deposits at Franklin and Sterling Hill were in the past. Give a little history to the class.

5) Kyanite, a Strange Mineral/Gem. Be careful! The bladed crystals of kyanite are sharp!

Do as Homework

Kyanite crystals (Al_2SiO_5), found in association with staurolite, are found in the schists of St. Gotthard, in the Tyrol Mountains of Switzerland. Other excellent specimens come from many countries around the world, Brazil, India, Nepal, Kenya, in the USA in locations around Massachusetts (including in central Vermont!) and North Carolina, etc. One of our samples in quartz is from Minas Gerais, Brazil. The other with staurolite is in schist from Switzerland.

Though it can form in other environments, most kyanite is metamorphic in origin, and kyanite in metamorphic rocks indicates higher pressures. Higher pressures suggest schist and gneiss created by convergence.

This last specimen is for everyone to look at. Kyanite is an unusual mineral that forms elongated crystals. It is blue approaching in fine specimens a blue almost as good as sapphire.

- A) Is blue intrinsic to this gemstone, that is it must be blue because that is part of its chemistry?
- B) Do you think kyanite is more likely to be in foliated, regionally metamorphosed rocks or in contact metamorphic rocks.
- C) Kyanite hardness is rather strange. Try and find out the strange thing about it and explain.
- D) Would kyanite make a good gemstone (remembering quartz is always around and quite hard)?

6) Plate Tectonics Map

- A) Go to page 9, the map of the plates. Put **arrows** on the major plates showing their direction of motion.
- B) On the main plates mark plate edges that are 1) convergent (subducting) in **Red** and 2) Divergent (ocean ridges) in **Blue**.
- C) Remember that some plate edges are transform and slide past each other. Mark the **San Andreas fault**. Some transform boundaries are harder to mark. Use **Green** for what you can find that is transform in nature.

References

Metamorphic rocks, (http://www.columbia.edu/~vjd1/meta_rx.htm) Accessed, February 22, 2012. Used as Figure 2. Foliated rocks.

James St. John, Anyolite,
(www1.newark.ohio-state.edu/Professional/OSU/Faculty/jstjohn/Anyolite/Anyolite.htm)
accessed Feb 21, 2012.

Lobeck, A. K., 1932, Atlas of American Geology, the Geographical Press, Columbia University, New York, 92 p.

Merguerian, C. and Moss, C. J., Newly Discovered Ophiolite Scrap in the Hartland Formation of Midtown Manhattan
(<http://dspace.sunyconnect.suny.edu/bitstream/handle/1951/47974/Merguerian-ophiolite.pdf;jsessionid=9ABA6F9C035CBEA09356A872ABBF13BC?sequence=1>) accessed, February 21, 2012.

The Rock Cycle

