Rock Formation and Processes

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1 Introduction

Encompassing our everyday life, rocks are keys to Earth's geologic past. We give special attention to how rocks are formed precisely for that reason. Furthermore, rocks are essential to industry: galena is lead ore, aluminum is mined from bauxite, etc. This handout will highlight the unique formation processes of the three types of rocks as well as providing a concise overview of the most important geologic concepts.

2 Rock Types Overview

There are three main types of rocks: igneous, sedimentary, and metamorphic[1]. Igneous rocks are formed directly from cooling magma. Sedimentary rocks are formed from sediment. Sediment can come from other rocks, come from evaporites, or have a biological origin. (This is addressed more thoroughly in section 4.1.) Metamorphic rocks form from other rocks which have been subjected to heat and pressure, but in the absence of melting. All three rock types are interrelated in the **rock cycle**.

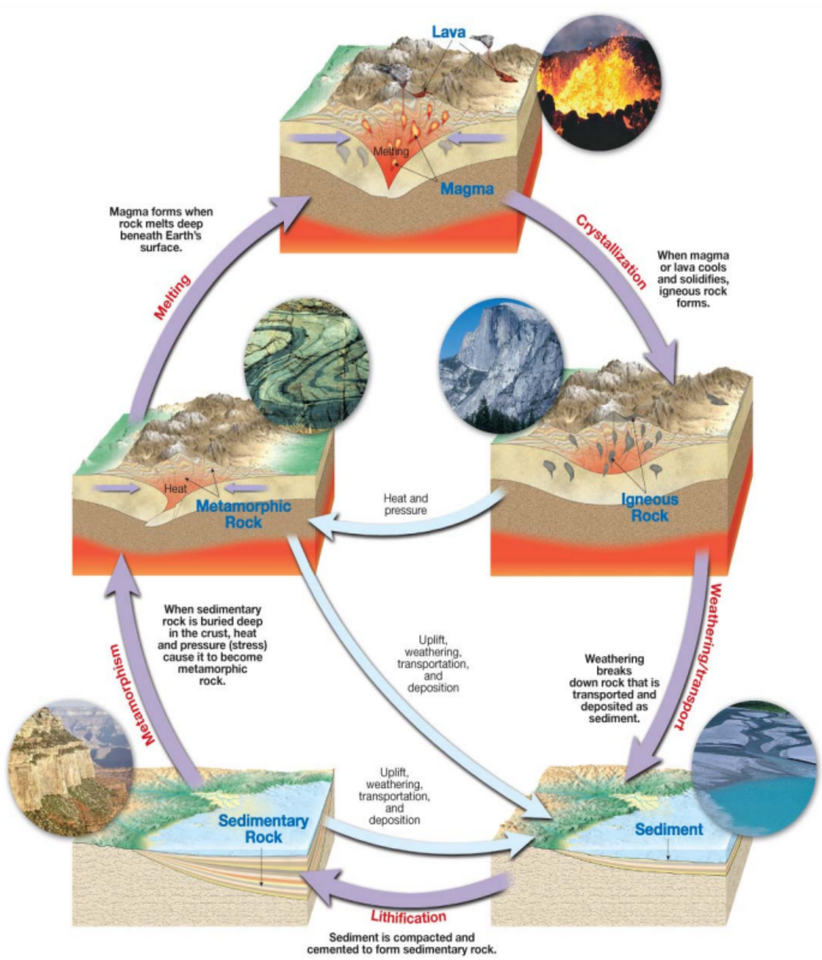


Figure 1: The rock cycle. (Tarbuck, Edward J. Earth Science)

[1]The definitions in this section are meant to be a very brief overview. They are not rigorous, and there are exceptions. For example, migmatite is a metamorphic rock which may form in an environment of partial melting.

3 Igneous Rocks

Igneous rocks, sometimes referred to as plutonic rocks, are rocks that form from the cooling and crystallization of hot magma, which can be extrusive (magma erupts and cools at the Earth's surface) or intrusive (magma cools inside the Earth). First, we will discuss the factors that cause the formation of magma.

3.1 Causes of melting

There are three main causes of melting.

- **Decreasing pressure.** Inside the mantle, the tremendous pressure of the overlying rocks prevents melting. Thus, if the pressure is decreased, the rock may melt, and this process is known as **decompression melting**, which typically happens at divergent plate boundaries (e.g. mid-atlantic ridge).

- **Addition of volatiles.** Volatiles are substances (such as H_2O and CO_2) that evaporate easily and exist in gaseous form on Earth's surface. When oceanic lithosphere subducts, voltatiles are introduced to the asthenosphere (upper mantle), which contains rocks that are near their melting point. The addition of volatiles to rocks helps break chemical bonds and lowers the melting point so that partial melting occurs. This is known as **flux melting** (Figure 2), which typically occurs at subduction zones.

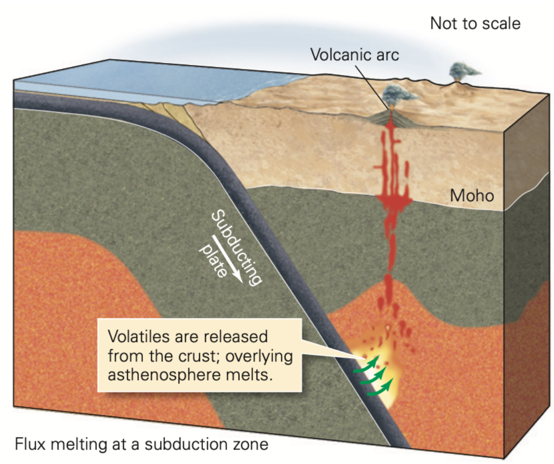


Figure 2: Flux melting. (Source: Marshak)

- **Heat transfer.** When very hot magma from the mantle rise to the crust, the heat is transferred to the surrounding rocks, resulting in melting. This is known as **heat transfer melting**.

3.2 Magma composition

The compositions of igneous rocks vary depending on the parent magma, or the magma a rock was formed from.

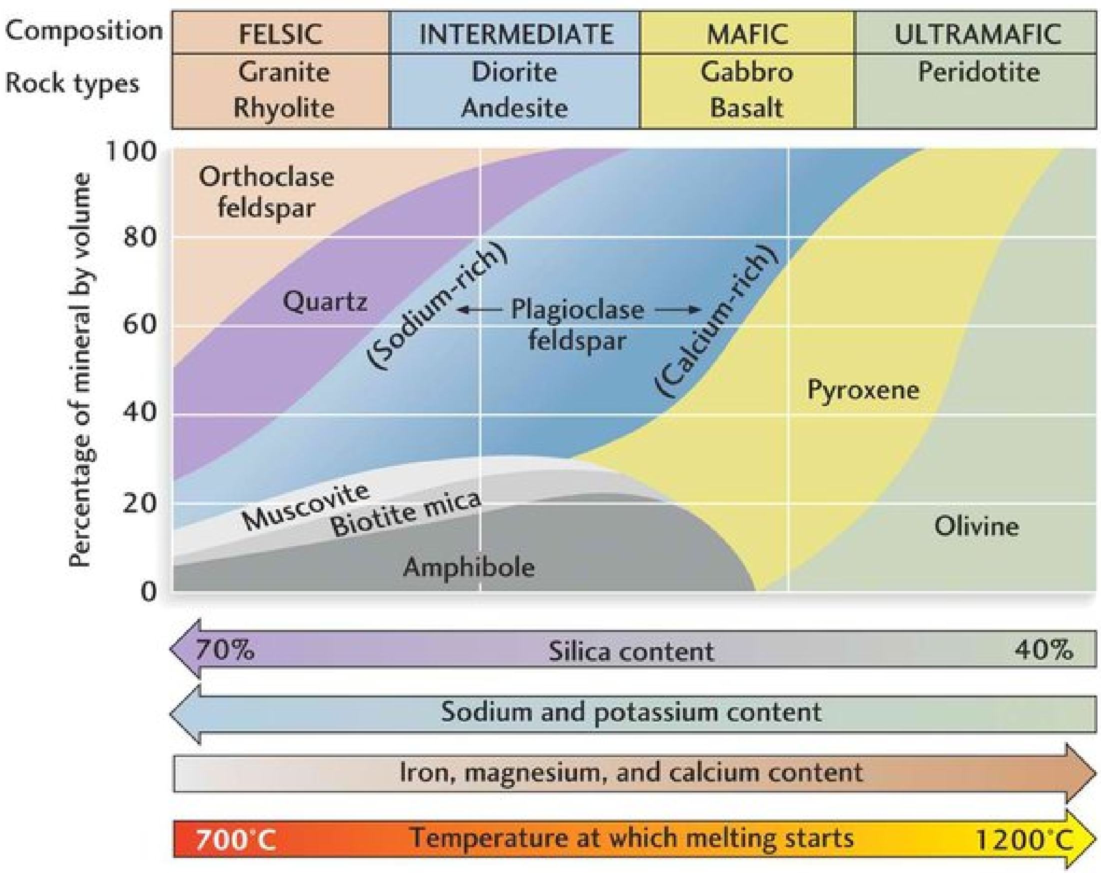


Figure 3: Different igneous rocks have different mineral compositions, depending on the type of magma that the rock solidified from.

- Felsic magma: rich in silica content, low composition of iron- and magnesium-rich (ferromagnesian) minerals. Less dense. Primary constituent of continental crust.
- Mafic magma: low in silica content, high composition of ferromagnesian minerals, denser. Primary constituent of oceanic crust. Ultramafic magma has the same characteristics but more extreme.
- Intermediate magma: standing in-between felsic and mafic magmas.

Magma can change composition in several ways. This is given the umbrella term of **magmatic differentiation**.

- As magma cools inside the Earth, dense mafic minerals such as olivine crystallize first and settle out (crystal settling), leaving the resulting melt more felsic in composition. This is called **fractional crystallization**.
- Also, the magma could melt its surrounding wall rock in the chamber, resulting in a change in composition. This process is called **assimilation**.
- Most importantly, a rock can undergo **partial melting**. Mafic minerals tend to have higher melting points, so partial melting always results in a magma being more felsic in composition.

Example 3.2 (Original question) A batholith is a large body of igneous rock formed beneath the Earth's surface by the intrusion and solidification of magma. Using your knowledge of magmatic differentiation, explain how the silica content of the rock may vary as you go down a cross-section of the batholith.

Solution: As the pluton cools, ferromagnesian minerals will settle out first. This would leave more felsic magma to solidify closer to the surface. Thus, as you go down a cross-section of a batholith, silica content should decrease. Indeed, fractional crystallization leads to a gradation in composition in batholiths.

3.3 Bowen's Reaction Series

The concepts described above were also demonstrated by the petrologist Norman Bowen (1887-1956) in his **Bowen's reaction series**. He showed that mafic silicate minerals (e.g. olivine) have higher melting points than other felsic silicate minerals, because these mafic minerals are less structured silicates, compare to the more structured/polymerized felsic silicate minerals, such as quartz. (These silicate structure stuff will be discussed in-depth in the mineralogy handout. We are just touching the basics here.) Thus, mafic silicate minerals crystallize at higher temperatures and felsic silicate minerals crystallize at lower temperatures.

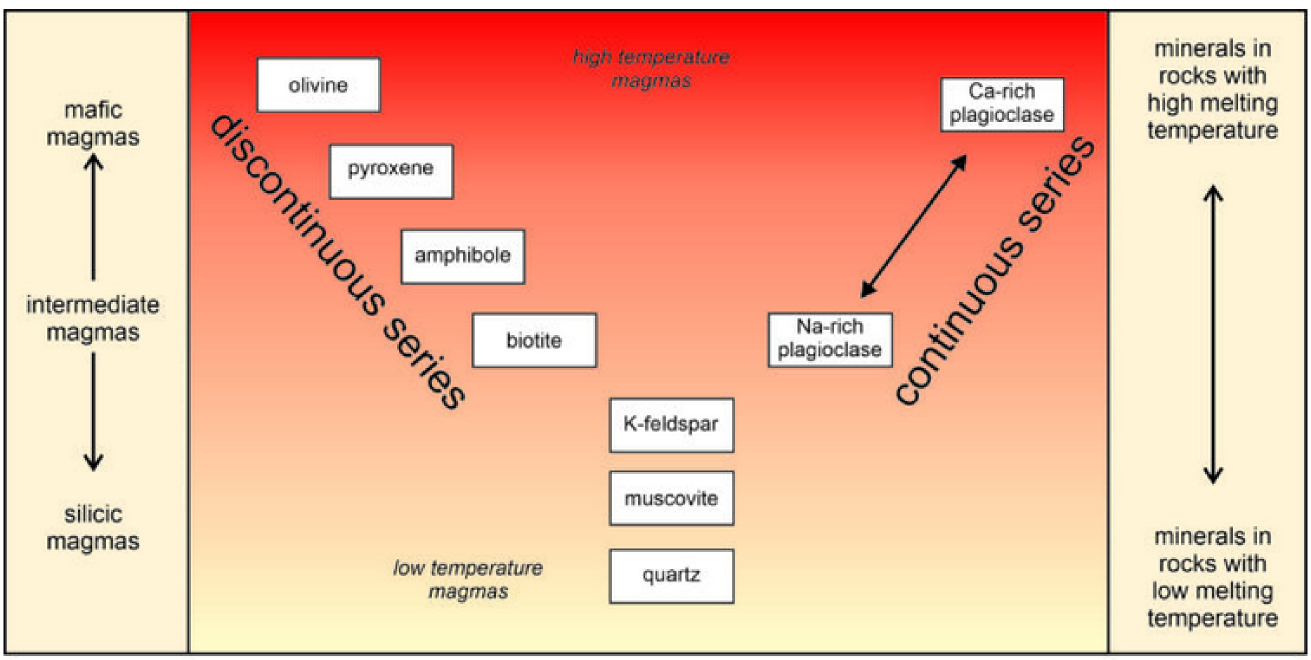


Figure 2: Bowen's reaction series. (Source: Perkins)

3.4 Common igneous rocks

Now we will go over all the common igneous rocks and other very important concepts.

Felsic rocks:

- **Granite**: Felsic intrusive coarse-grained, or having large crystals (phaneritic texture) rock, commonly contains quartz and potassium feldspar (K-feldspar).
- **Rhyolite**: Felsic extrusive equivalent of granite with very tiny crystals (aphanitic texture). Commonly found in continental settings.

Interemediate rocks:

- **Andesite**: Intermediate extrusive rock with aphanitic texture. Rich in plagioclase and amphibole minerals. Forms from the solidification of lava flow from continental stratovolcanoes.
- **Diorite**: Intermediate intrusive equivalent of andesite with phaneritic texture. Composed of sodium-rich plagioclase and minor amounts of other mafic minerals. Often found in intrusions such as sills & dikes, within the continental crust.

Mafic rocks:

- **Basalt**: Mafic extrusive rock with aphanitic texture. Rich in plagioclase and pyroxene minerals. Forms commonly at mid-oceanic ridge from decompression melting.
- **Gabbro**: Mafic intrusive equivalent of basalt with phaneritic texture. On top of basalt's composition, Gabbro contains minor amounts of olivine & amphibole. Forms in plutonic bodies, beneath basalt.

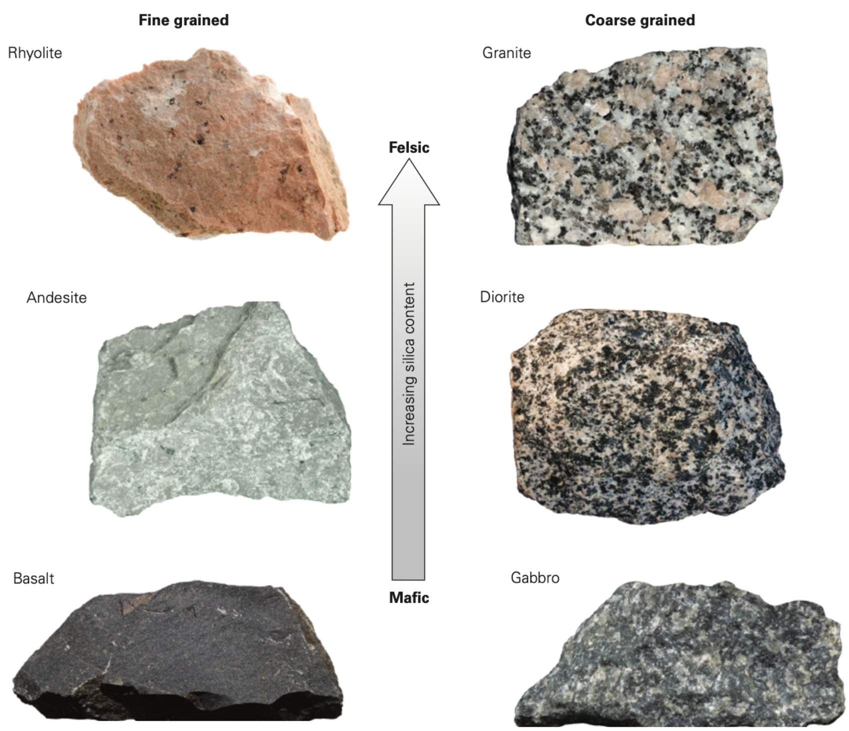
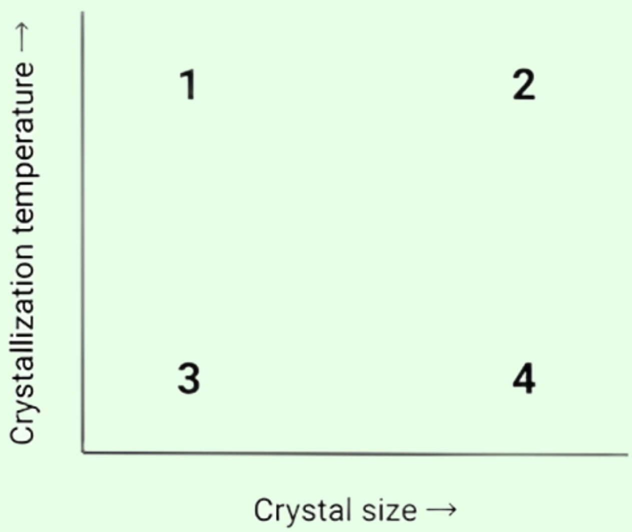


Figure 3: Common igneous rocks. (Source: Marshak)

There are also rocks with unique formation processes. **Obsidian** is an extrusive felsic rock formed from extremely rapid cooling of lava, characterized by its black color and glassy texture. **Pumice** is another felsic extrusive rock with characteristic "holes" called vesicles. These vesicles form from trapped gas bubbles that couldn't escape due to the high viscosity of silica-rich magma. **Scoria** is simply the mafic counterpart of pumice.

If you look at all the rocks we just discussed, a very clear pattern can be detected: the crystal size of the igneous rocks increases the deeper you go, and vice versa, because an intrusive rock has more time to form larger crystals than extrusive rocks which cool much faster. In other words, longer cooling time means larger crystals. This is a very important concept to know.

Example 2.1. (USESO Open Round 2022) A petrologist infers that a rock cooled very quickly from a silica-rich melt. A rock represented by which labeled region(s) of the graph would be consistent with this inference?

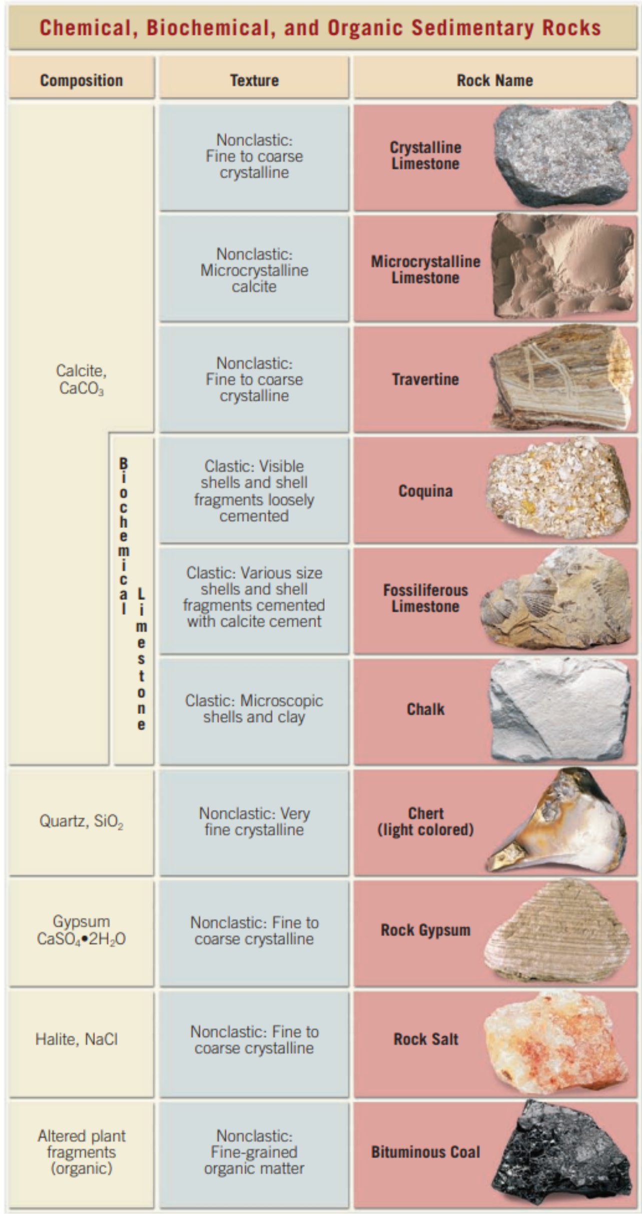


(A) 1 only.
(B) 2 only.
(C) 3 only.
(D) Either 3 or 4.

Solution: Immediately you should recognize that a silica-rich melt is felsic, and felsic minerals are found in the lower half of Bowen's reaction series (Figure 2). As indicated by Bowen's reaction series, felsic melts form at lower temperatures and thus crystallize at lower temperatures. So we eliminate options (A) and (B). The second clue is that the rock cooled very quickly, which means crystals had less time to form, resulting in a smaller overall crystal size. Thus we pick (C).

4 Sedimentary Rocks

Sedimentary rocks are formed from the compaction and cementation of sediments, which are often the result of weathering and erosion.



Chemical, Biochemical, and Organic Sedimentary Rocks

Composition		Texture	Rock Name
Calcite, $CaCO_3$		Nonclastic: Fine to coarse crystalline	Crystalline Limestone
		Nonclastic: Microcrystalline calcite	Microcrystalline Limestone
		Nonclastic: Fine to coarse crystalline	Travertine
	Biochemical Limestone	Clastic: Visible shells and shell fragments loosely cemented	Coquina
		Clastic: Various size shells and shell fragments cemented with calcite cement	Fossiliferous Limestone
		Clastic: Microscopic shells and clay	Chalk
Quartz, SiO_2		Nonclastic: Very fine crystalline	Chert (light colored)
Gypsum $CaSO_4 \bullet 2H_2O$		Nonclastic: Fine to coarse crystalline	Rock Gypsum
Halite, NaCl		Nonclastic: Fine to coarse crystalline	Rock Salt
Altered plant fragments (organic)		Nonclastic: Fine-grained organic matter	Bituminous Coal

Figure 1: Sedimentary Rocks (Tarbuck, Edward J. Earth Science)

4.1 Classification of Sedimentary Rocks

Despite composing a mere 5% of the crust, sedimentary rocks cover the majority of the Earth's surface. Sedimentary rocks are divided into four categories: clastic, chemical, biochemical, and organic.

- **Clastic** sedimentary rocks are made of pieces of other rocks that were broken down by weathering. A common example is sandstone, which forms from the compaction and cementation of sands on beaches. Clastic rocks are sometimes referred to as detrital.

- **Chemical** sedimentary rocks form from the direct deposition of accumulated chemicals over time. Examples of this include salt being left behind after evaporation and the precipitation of dissolved gypsum in water to form selenite.
- **Biochemical** sedimentary rocks form from the accumulation and cementation of organic and inorganic materials, such as shells, coral, algae, and other biological debris, over time. An example would be chalk, which forms from compaction of microscopic marine plankton remains, primarily the single-celled algae known as coccoliths.
- **Organic** sedimentary rocks are sedimentary rocks formed principally by organic means. Such rocks include coals which form from the accumulation of peat, decaying plant matter, in anoxic bogs.

4.2 Formation of Sedimentary Rocks

The following information refers to clast sizes determined by the Wentworth Scale which classifies sediment based on size. Rocks mainly made of grains smaller than sand are referred to as fine-grained while rocks made of grains of sand size or larger are referred to as coarse-grained. Please refer to the following website for any clarification: Wentworth Scale

- Sediment undergoes diagenesis to become sedimentary rocks. This may take place through compaction or cementation, processes termed lithification.
- Fine-grained sediments like silt and clay are easy to compress. Therefore, they are readily compacted when more sediment is deposited on top of them. Over time, this may pack the material together into a rock like shale
- Larger sediments like sand, pebbles, and boulders cannot be compressed as easily. Instead, they are typically cemented together by some chemical such as calcite, or silica.
- Sedimentary rocks form in horizontal beds called strata. Strata can tell us much about the Earth's past since they represent periods of deposition and can also reveal past tectonic action if they are tilted. Strata is separated by bedding planes, lines of weakness where rocks tend to break.
- The size of sediment within sedimentary rocks also tells much about its formation environment. For example, siltstone and shale must have been deposited in low-energy environments since the small particles composing them remain suspended in water at higher velocities. Conversely, conglomerates must be deposited in comparatively higher-energy environments since their clasts are larger.

4.3 Sedimentary Structures

- Various remnants from when sedimentary rocks formed remain after diagenesis occurs. These include the following: fossils, cross-bedding, mud cracks, and ripple marks
- Fossils are some of the most obvious remnants in sedimentary rocks. They are the remains of ancient organisms that can leave permanent impressions on the rock they formed.

- Cross-bedding refers to the way certain strata are deposited during formation. Currents of air or water can push sand in one direction, creating a distinct crest pattern in the resulting rock. When the wind switches direction, the crest also switches direction, hence the name cross-bedding.
- When soil dries, it shrinks. This shrinkage causes cracks to form at its surface, signifying that the area must have been arid. These structures are the same types of cracks seen in photos of drought-stricken land. If diagenesis occurs, these structures can be preserved in the resultant rocks.
- Ripple marks are formed by wave motion. Depending on the shape of the marks, it can be determined which direction waves must have been flowing in the past. This is one of the processes that also forms cross-bedding given time.

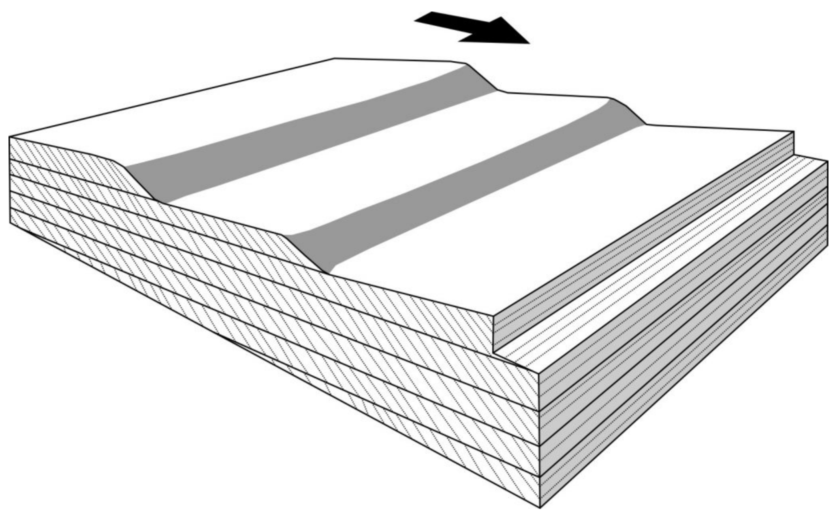
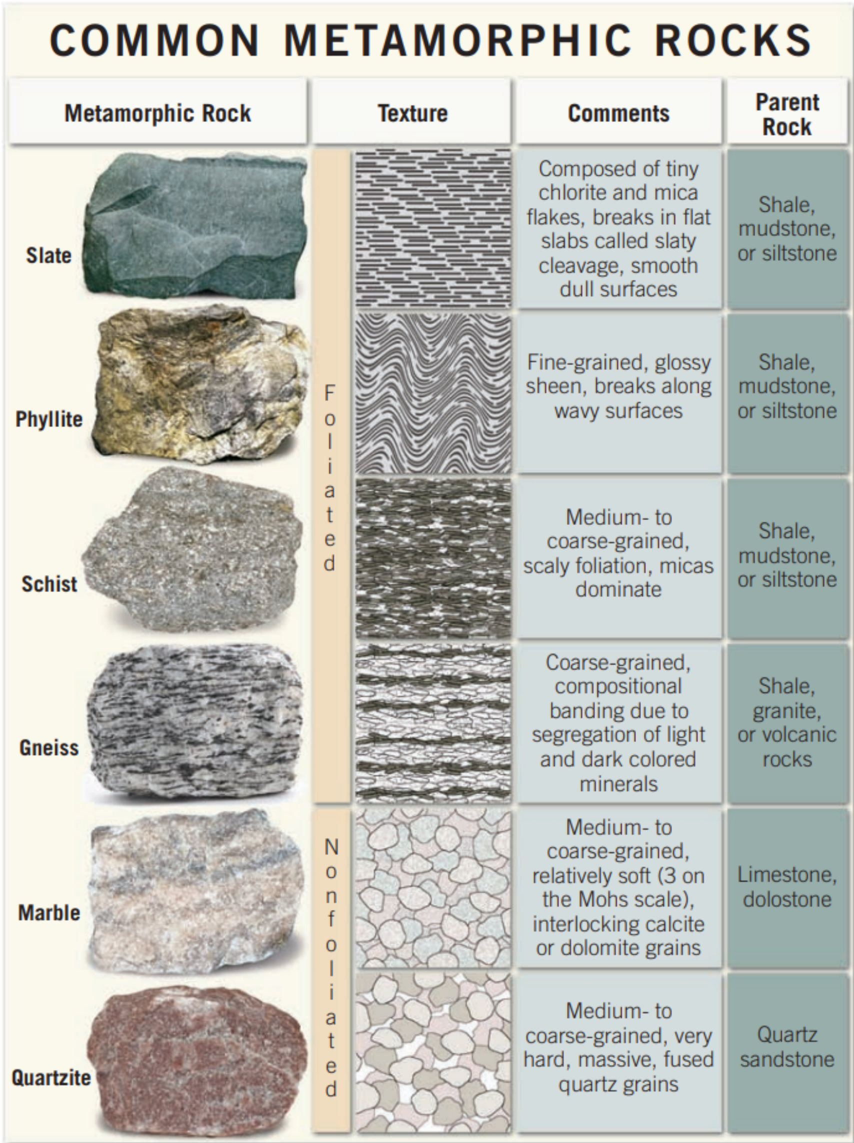


Figure 2: Direction of Current Follows the Arrow (Reineck & Singh, 1975)

- Some miscellaneous structures that may form are concretions and nodules. Nodules are collections of solidified minerals and elements, typically taking the form of a sphere, creating a "hard part" inside of a rock. On the other hand, concretions refer to rocks that are fortified by the addition of minerals, typically silica, also leaving behind a "hard part". These features are typically resistant to weathering and are left behind when their host rocks weather away.

5 Metamorphic Rocks

Metamorphic rocks are rocks that have been structurally altered through intense heat and pressure. Pressure can be applied uniformly across a rock, in this case being called confining pressure. When the pressure is not equal along all sides of a rock, it is called differential stress. When pressure points in different directions, it is called shear stress.


COMMON METAMORPHIC ROCKS

Metamorphic Rock		Comments	Parent Rock
Slate	Foliated	Composed of tiny chlorite and mica flakes, breaks in flat slabs called slaty cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite	Foliated	Fine-grained, glossy sheen, breaks along wavy surfaces	Shale, mudstone, or siltstone
Schist	Foliated	Medium- to coarse-grained, scaly foliation, micas dominate	Shale, mudstone, or siltstone
Gneiss	Foliated	Coarse-grained, compositional banding due to segregation of light and dark colored minerals	Shale, granite, or volcanic rocks
Marble	Nonfoliated	Medium- to coarse-grained, relatively soft (3 on the Mohs scale), interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite	Nonfoliated	Medium- to coarse-grained, very hard, massive, fused quartz grains	Quartz sandstone

Figure 3: Metamorphic Rocks (Tarbuck, Edward J. Earth Science)

5.1 Formation of Metamorphic Rocks

Rocks primarily metamorphize by the following processes: regional, dynamic, and contact metamorphism

- Regional metamorphism refers to the process in which rocks are metamorphized by intense pressures from deep burial, typically along continental-continental convergent orogenic (mountain building) zones.
- Dynamic metamorphism refers to the process in which high differential stress is the cause of metamorphism, typically occurring along fault zones
- Contact metamorphism refers to metamorphism that is caused by high temperatures as a result of being adjacent to a body of magma. Therefore, contact metamorphism will occur most often along subduction zones, hotspots, and next to plutons.

- Metamorphic rocks can form from any other rock type. The rock that a metamorphic rock originates from is called its protolith.
- Normal metamorphism is called prograde metamorphism. When pressure and temperature are relieved, rocks can undergo retrograde or reverse metamorphism. This process is typically slower than prograde metamorphism since volatiles are removed during prograde.

5.2 Features of Metamorphic Rocks

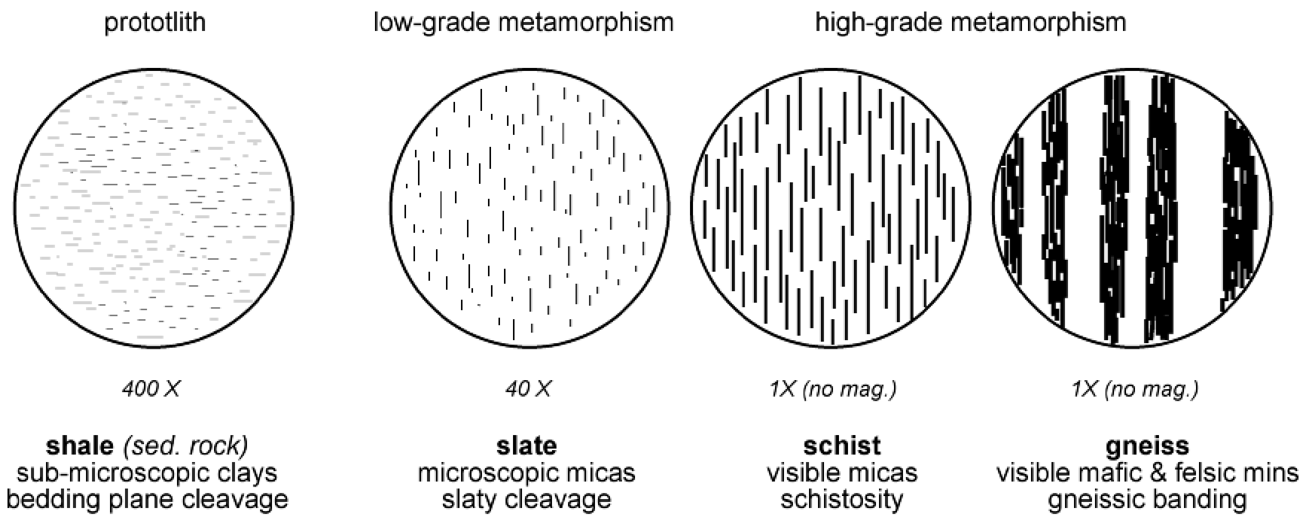


Figure 4: Foliation of Rocks (University of Columbia)

- The high pressures and temperatures associated with metamorphism cause minerals within a rock to change in shape and structure through physical squeezing and the promotion of new chemical reactions in solid solution by a process called recrystallization. This happens in order since the minerals must change to become more stable in their new environment.
- Recrystallization may also occur through the partial melting of the rock. Metamorphic rocks that have undergone significant anatexis (partial melting) are termed migmatites and represent the transition from metamorphic to igneous rocks.
- The high differential stress placed on metamorphic rocks forms alternating layers of minerals aligned perpendicular to the direction of stress. This forms a pattern called foliation. This produces a layered structure of elongated micas called schistosity, making the rock weak along these planes. When a rock approaches a high enough degree of metamorphism, this schistosity will disappear because of the recrystallization of micas.
- Rocks like quartzite and marble lack micaceous minerals and therefore also lack the typical pattern of foliation. Rocks like these are termed non-foliated. The compression of rocks during metamorphism also removes all pores and sedimentary structures like fossils.

5.3 Metamorphic Facies

- As temperature and pressure increase, a typical metamorphic rock of a shale protolith might follow this progression: shale $\longrightarrow$ slate $\longrightarrow$ phyllite $\longrightarrow$ schist $\longrightarrow$ gneiss
- During the progression of metamorphism, temperature and pressure do not increase in the same way every time. Certain conditions will predictably create the same sets of characteristic minerals. A group of these characteristic minerals is called a facies. By identifying these minerals inside a metamorphic rock, one can know what conditions it might have formed under
- Rocks will follow a predictable geothermal gradient with increasing depth based on their formation gradient. For example, subduction zones have high pressure but low temperature while volcanic regions have high temperature but low pressure

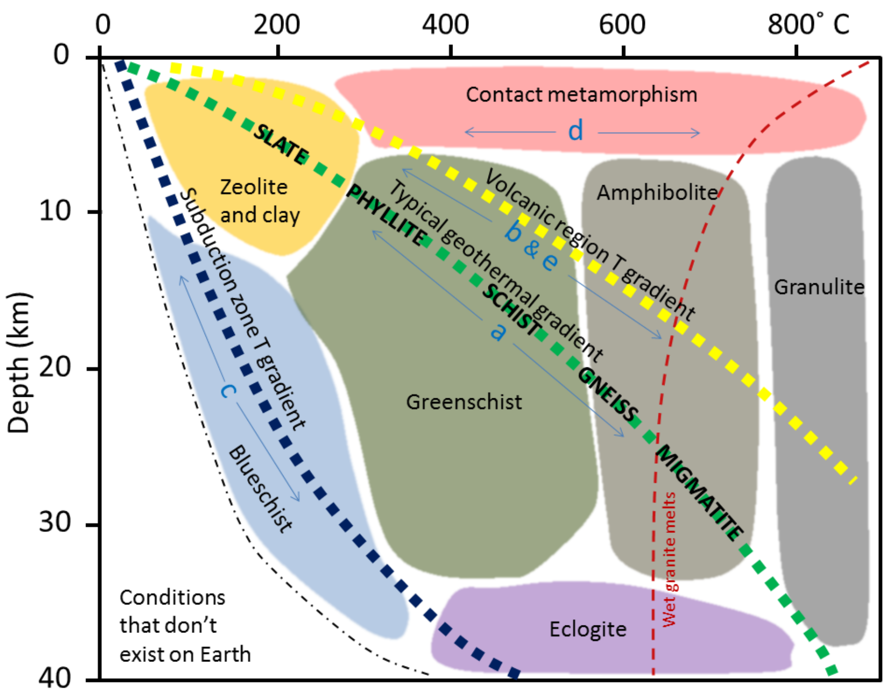
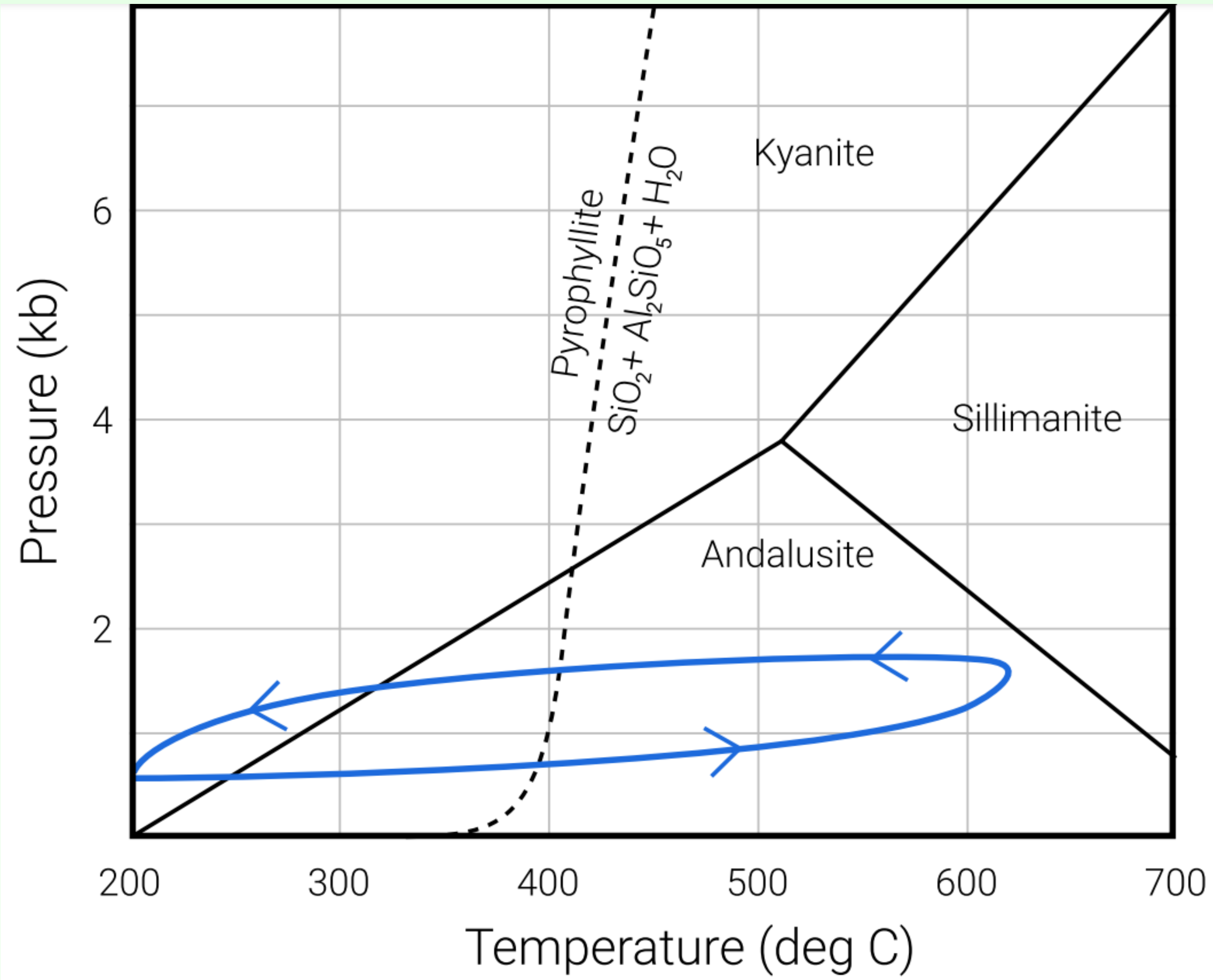


Figure 5: Metamorphic Facies Series (University of Saskatchewan)

Example (2021 USESO Open Exam, Section I, #28)



The phase diagram above shows the stability field of Al_2SiO_5, present as either kyanite, andalusite, or sillimanite. The dashed line divides the stability field of pyrophyllite ($Al_2Si_4O_{10}(OH)_2$) and its dehydrated components. Pyrophyllite dehydrates as such:

$$Al_2Si_4O_{10}(OH)_2 \longrightarrow Al_2SiO_5 + 3\,SiO_2 + H_2O$$

A mass of pure pyrophyllite undergoes metamorphism via the pressure-temperature-time (P-T-t) path shown in blue. Which of the following petrogenic environments is most closely associated with the P-T-t path?

(A) Subduction Zone
(B) Impact Crater
(C) Pluton Aureole
(D) Orogenic Belt

Solution: C. The P-T-t path in the blue region follows a high geothermal gradient with high T and low P, characteristic of contact metamorphism near plutons. Subduction zones have high P and low T, orogenic belts have high P and intermediate T, and impact craters have extreme T and P.

6 Closing

Understanding the basics of rock formation, composition, and evolution is essential to understanding the rest of the geosphere. Rocks are a close second favorite topic of mine after minerals so making this guide was pretty enjoyable. I hope you found this helpful! Happy studying!!

-Sylvie <3