

Mineral resources of igneous and metamorphic origin

Learning outcomes

1. Describe the processes that act to form igneous rock.
2. Describe the processes that act to form metamorphic rock.
3. Explain how different mineral resources (both igneous and metamorphic) form at plate boundaries.
4. Explain how mineral resources are concentrated by hydrothermal activity and how this links to intrusions, volcanism, and plate tectonics.
5. Give examples and uses of mineral resources that are formed by igneous processes.
6. Identify some of the potential environmental impacts of sulfide mining and associated activities.

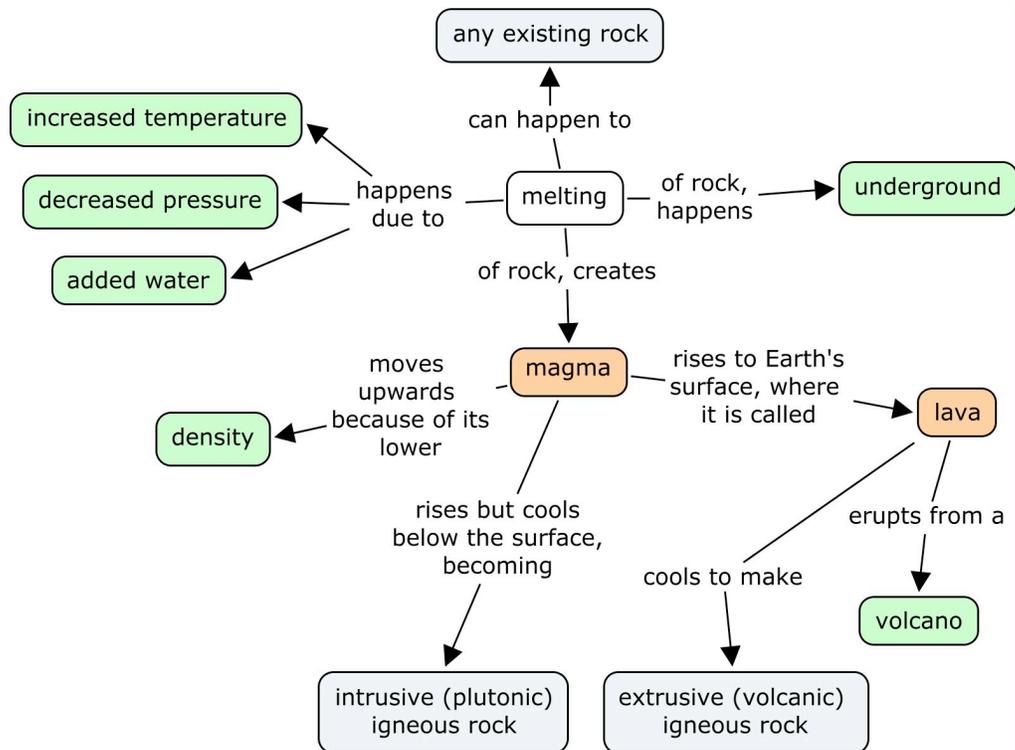
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How Igneous Rocks Form

There is no liquid layer of magma below the surface. Instead, rocks in some parts of the lower crust and/or upper mantle need to *melt* in order to make **magma**. Once magma forms, it will try to rise from higher-pressure regions (deeper in the crust) to lower pressure areas (near Earth's surface) because magma is less dense than solid rock. As magma rises, it cools. Most often, it cools and hardens (the magma crystallizes, meaning that crystals [minerals] form) before it makes it to the surface. But sometimes magma will migrate all the way to Earth's surface and erupt in a **volcano**. Once it erupts, the magma is called **lava**.

By the way, rocks will obviously melt when heated above their melting temperature. But most rocks actually melt because something lowers their melting temperature, not because they are heated. There are two ways that the melting temperature can be lowered. First, pressure squeezes atoms together into a solid. If pressure is reduced, then atoms can move apart, possibly far enough to become liquid. So, lowering pressure will reduce melting temperature. Second, mixtures of substances usually melt at lower temperatures than pure substances. So, adding something to a rock will lower its melting temperature. This is what happens when we put salt on ice. The salt does not warm the ice; rather it causes the ice to melt at a lower temperature. In the earth, the most common thing that is added to rock that lowers its melting temperature is water. Individual water molecules can enter a mineral's structure (only if that mineral is pretty hot already) and lower the mineral's melting temperature.

Igneous rocks are formed when the magma becomes solid. The igneous rocks that form above the surface are called **volcanic** or **extrusive** igneous rocks. Those that crystallize below the surface are called **plutonic** or **intrusive** rocks.



The concept map above shows how igneous rocks form. The blue and tan boxes contain substances, the green boxes show places or material properties, and the white boxes contain igneous processes (some of which are also in the arrow labels).

Igneous Rocks and Plate Boundaries

Intense igneous activity happens along divergent and some convergent plate boundaries.

Divergent plate boundaries are where plates move away from each other. These create rift valleys (on the continents) and mid-ocean ridges (in the oceans). When the plates move apart, the pressure on the rocks in the upper mantle just below the plate boundary drops. The pressure drop lowers the rock's melting temperature, and, because these rocks are already hot, they melt, forming magma.

At **convergent plate boundaries** two plates move toward each other. Convergent plate boundaries can be between two oceanic plates, one continental plate and one oceanic plate, or two continental plates. At ocean–ocean and ocean–continent convergent boundaries, the older/colder/denser oceanic plate sinks into the mantle. This is called **subduction**. The subducting oceanic plate carries water into the mantle. This water lowers the melting temperature of the rocks in the mantle and creates magma. As the magma rises, it can melt part of the overlying plate, which changes its chemistry.

No plate sinks at a continent–continent convergent boundary, so those boundaries have much less igneous activity.

There are some sites of igneous activity away from plate boundaries. These places are called **hot spots**. Here, hot mantle material rises and melts the base of the plates, or as mantle material rises, its pressure drops, causing it to melt. Hawaii and Yellowstone are both hot spots.

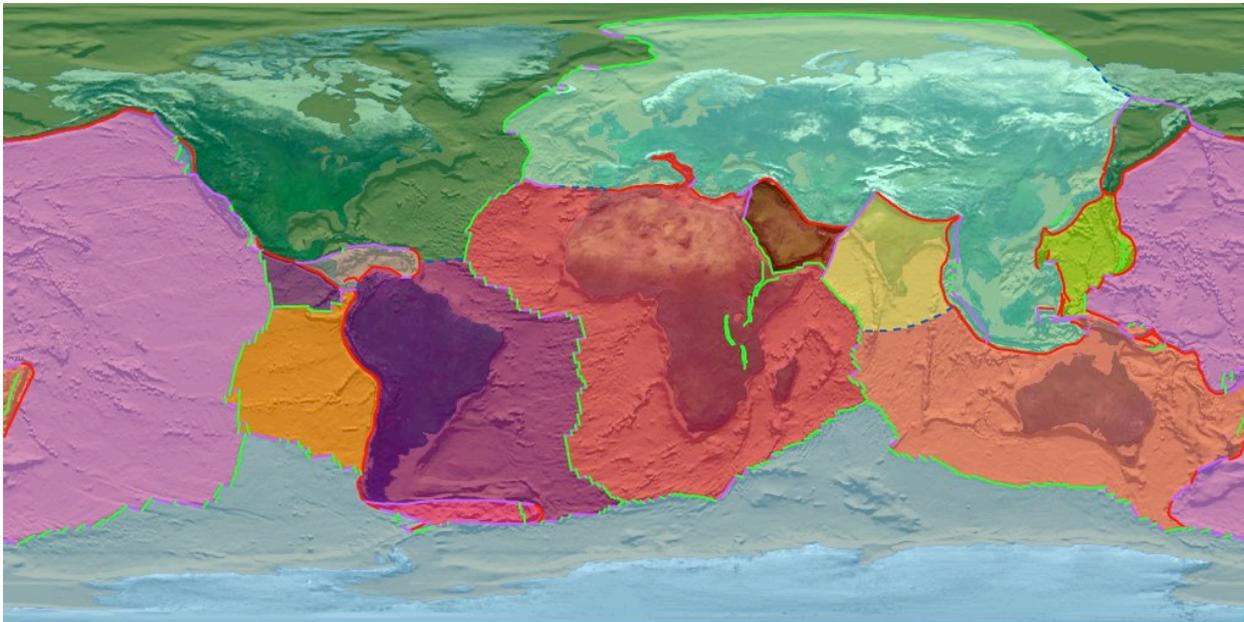


Figure 1. Image of plates (shown in different colors) and plate boundaries. Divergent plate boundaries are shown in light green, convergent plate boundaries are shown in red, and transform plate boundaries are shown in purple. Image created by NASA/Goddard Space Flight Center Scientific Visualization Studio.

All active volcanoes are at plate boundaries or hot spots. However, we can find igneous rock in places with no active plate boundaries. In the past, plate boundaries were in different places than they are now. For example, the igneous rocks in Wisconsin, Georgia, Texas, and Missouri tell us that these places used to be active plate boundaries, although they are now in the middle of the North American Plate.



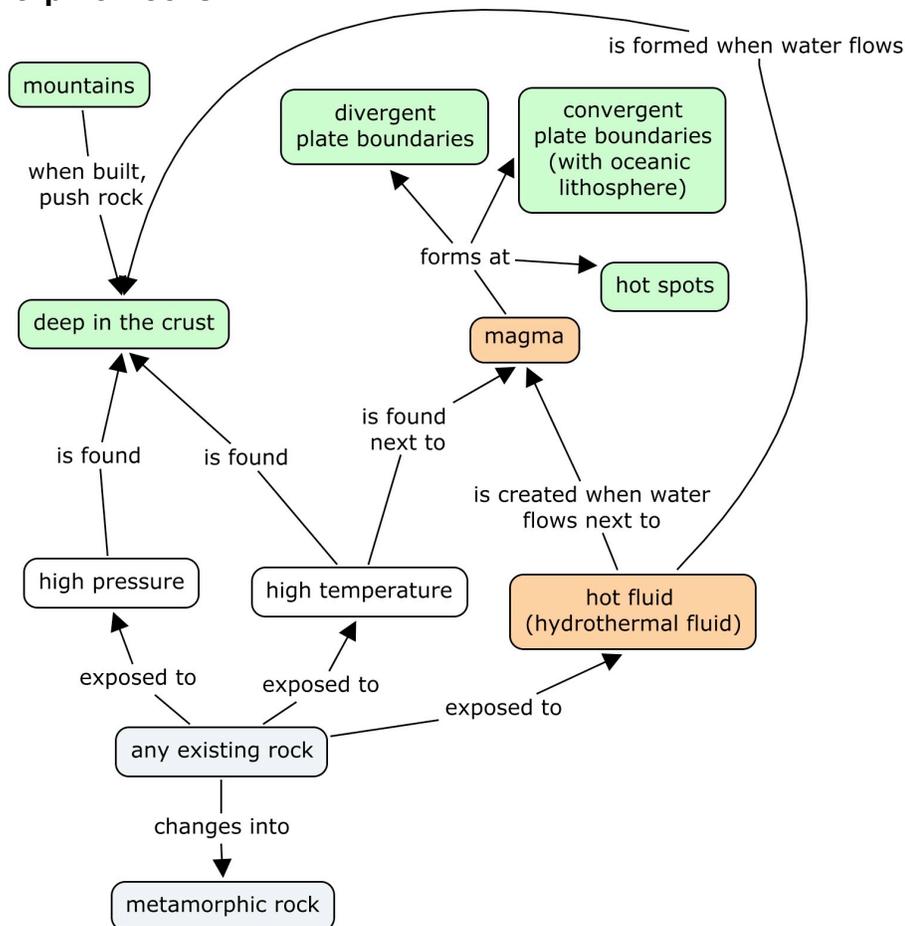
Figure 2. Today, the intrusive igneous rock composing Enchanted Rock in central Texas is far from a plate boundary. Long ago, when this magma formed and cooled, there was a plate boundary near this site. Photo by Maik Pertermann.

Magma and igneous rocks can be categorized according to their composition: felsic (high silica), intermediate, or mafic (low silica). **Felsic** and **intermediate** magmas and rocks tend to form at ocean–continent or ocean–ocean convergent boundaries, or where hot spots are found on land. **Mafic** magmas are formed in divergent plate boundaries and hot spots in the ocean.

Table 1. Igneous rocks and minerals that are mineral resources.

Type of deposit	How these form	Commodities mined
bulk igneous rock	Magma cooling.	granite, gabbro, scoria, etc. (rocks mined for building and landscaping stones or trap rock)
minerals from felsic igneous rock	Large crystals grow in felsic, intrusive igneous rocks.	aluminum (from the mineral nepheline), tin and tantalum (elements), beryllium (element from the mineral beryl), muscovite (mineral), potassium feldspar (mineral)
minerals from mafic igneous rock	Large crystals are carried from mantle in mafic magma.	diamonds (minerals)
layered intrusion	Magma(s) and crystals with different densities settle, forming and crystallizing in distinct layers.	the elements iron, chromium, titanium, nickel, platinum-group elements (PGE)
hydrothermal fluids	Ions dissolved in hydrothermal fluids combine to form mineral deposits.	In/near felsic intrusions, the elements lead, zinc, tin, tungsten, and uranium. In/near mafic intrusions, the elements nickel and cobalt. Also, the elements iron, copper, silver, mercury, gold, and manganese.
porphyry	Intruding magma fractures the rock, and remaining magma and/or fluid flows into the highly fractured and shattered rock.	the elements copper, molybdenum, gold, and tin

Metamorphic Rocks



The above concept map shows how all **metamorphic rocks** form. The blue boxes show substances, and all other boxes show either forces or places in which metamorphic rocks form.

Unlike sedimentary and igneous rocks, metamorphic rocks are made directly from an existing rock. The original rock is heated, squeezed, or exposed to hot, reactive fluids, and these things squeeze minerals into alignment and remove the pores, allowing the minerals in that rock to grow, and the atoms in those minerals to move around and make new minerals. Hence, the rock changes (metamorphoses) into a new rock. By the way, the hot, reactive fluids are also called **hydrothermal fluids** (see below).

Mineral resources formed by metamorphic processes include:

- marble (rock) and other building stones: used in buildings, sculpture, etc.
- talc (mineral): used in personal care items, ceramics, etc.
- asbestos (mineral): mining is banned in the United States, but still used in imported goods like brake pads, and once heavily used in building materials.

Metamorphic Rocks and Plate Boundaries

Like igneous rocks, metamorphic rocks almost exclusively form at plate boundaries.

Metamorphic rocks that form because they are exposed to heat from magma form at the same plate boundaries igneous rocks form: divergent, ocean–ocean convergent and ocean–continent convergent. These types of metamorphic rocks can also form at hot spots.

Metamorphic rocks formed when rocks are buried to depths with high temperature and pressure are found where rocks are squeezed and crumpled into mountains, that is, at convergent plate boundaries.

The hot fluids mostly form when water flows near magma. And this brings us to the next topic.

More about Igneous Activity and Hydrothermal Fluids

Magma heats up water and other fluids with which it comes in contact. The fluid can come from the magma itself (magma releases water as well as chlorine, hydrogen sulfide, sulfur dioxide, carbon dioxide, fluorine, etc.) or from rainwater, groundwater, or seawater. These hot fluids are called hydrothermal fluids. The hydrothermal fluids can also contain metallic ions such as copper, nickel, lead, zinc, silver, gold, and platinum. These elements do not enter rock-forming minerals as the magma crystallizes, so they remain in the fluid.

In addition, hydrothermal fluids also react with minerals in the surrounding rocks, and metal ions from those minerals can enter the fluid.

Several types of metal ions combine with sulfur in the hydrothermal fluids to form metallic sulfide minerals. Thus, the hydrothermal fluids concentrate metals, creating mineral reserves called **metallic ore deposits**.

Metallic ore deposits can form wherever there is igneous activity, due to either vulcanism or plutonism. The metallic ore deposits can be found near sites of recent igneous activity or activity that happened sometime during the geologic past.

The types of metals in the deposit depend on the magma chemistry, which depends on tectonic setting (type of plate boundary).

Metallic Sulfide Minerals and Acid Rock Drainage

Sulfide minerals chemically weather to make sulfuric acid. Unless there is a neutralizing agent (such as limestone) present, the sulfuric acid increases the acidity of nearby soil and water. This is called acid rock drainage, or **acid mine drainage** when the high acidity is specifically linked to mining.

Mining often exacerbates acid rock drainage because it breaks up (mechanically weathers) the rock, creating more surface areas on which chemical weathering can act.

There are several impacts of acid mine drainage. Several organisms can only tolerate certain pH conditions, so increased acidity in surface water can harm ecosystems. Also, water with high acidity ($\text{pH} \leq 2$) can dissolve and transport heavy metals, such as chromium (Cr), copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb), all of which are toxic at elevated concentrations.

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Figure 1. Image created by Eric Sokolowsky at NASA/Goddard Space Flight Center Scientific Visualization Studio (source: <http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=2953>), freely available for reuse under these terms: [http://www.nasa.gov/audience/formedia/features/MP_Photo_Guidelines.html - .U6MgBxbntvU](http://www.nasa.gov/audience/formedia/features/MP_Photo_Guidelines.html#.U6MgBxbntvU)

Figure 2. Photo of Enchanted Rock, Texas, taken by Maik Pertermann

Figure 3. Photos of galena and the Einstein Mine, Missouri, by J. Branlund

Concept maps created by J. Branlund