Igneous and Metamorphic Rocks

Geology 200

Geology for Environmental Scientists
Part 1, Igneous Rocks
Magma Compositions

- Ultramafic - composition of mantle
- Mafic - composition of basalt, e.g. oceanic crust. 900-1200°C, 50% SiO₂
- Intermediate - mix of oceanic and continental crust
- Felsic or Silicic or Sialic - composition of continental crust. <850°C, 75% SiO₂
Two Major Divisions

- Intrusive igneous rocks - magma that solidifies below the surface of the earth
- Extrusive igneous rocks - magma that cools on the surface of the earth
- The rock textures are different for each division.
Texture of Igneous Rocks

- Glassy: caused by rapid cooling; no crystals
- Pyroclastic: fragments of glass and crystals; volcanic ash and bombs
- Aphanitic: microscopic crystals
- Phaneritic: macroscopic crystals
- Porphyritic: grains of two distinct sizes; can occur in phaneritic or aphanitic matrix
Can you fill in the question marks?
Can you fill in the question marks?
Classification of Igneous Rocks - Fig. 4.4

based on both composition and texture
Figure 4.3B. Aphanitic texture in rhyolite (the black glass are not crystals)
Figure 4.3C. Phaneritic texture in granite –
Has macroscopic crystals
Figure 4.3D. Pyroclastic texture
Felsic and intermediate igneous rocks

(A) Granite: K-feldspar, quartz, plagioclase, and biotite.
(B) Rhyolite: K-feldspar, plagioclase, quartz, and biotite.
(C) Diorite: plagioclase, amphibole, quartz, and biotite.
(D) Porphyritic andesite: plagioclase, pyroxene, and amphibole.
Mafic and ultramafic igneous rocks

(E) Gabbro: pyroxene, plagioclase, and olivine.

(F) Porphyritic basalt: plagioclase, pyroxene, and olivine.

(G) Peridotite: olivine and pyroxene.

(H) Komatiite: olivine, pyroxene, and plagioclase. (D. A. Williams)
Granite -- K-feldspar, quartz, plagioclase, amphibole, biotite
Rhyolite -- an extrusive felsic igneous rock
Basalt -- an extrusive mafic igneous rock
Andesite -- an extrusive intermediate igneous rock
A welded tuff formed from hot ash and glass.
Fig. 4.14: A composite volcano composed of ash layers and lava flows.
Fig. 4.18: Genesis of different types of intrusive igneous bodies
Devil’s Tower, WY, a volcanic neck
WVU Students on a Gabbro Dike in Maine during Geology Field Camp
A Xenolith in a Magma Chamber or Pluton, Maine
Origin and Differentiation of Magma

• Source rock composition - what rocks were melted?
• Partial melting - produces magmas of different composition than source rocks; more felsic or silicic.
• Fractional crystallization - increases silica content of remaining melt.
• Magma mixing
• Assimilation - xenoliths fall into magma chamber
Figure 4.21. Processes of magma differentiation

Assimilation

Magma mixing

Fractional crystallization

Different sources
Figure 4.22 - The Temperature of Crystallization: Bowen’s Reaction Series

Granite-rhyolite | Diorite-andesite | Gabbro-basalt
---|---|---
(Sodic) | Plagioclase | (Calcic)
Amphibole | Mg - Olivine | Mg - Pyroxene
Quartz | Biotite |
K-feldspar | Muscovite |
Bowen’s Reaction Series

The order of crystallization for the discontinuous series from olivine to pyroxene to amphibole to biotite to quartz and K-feldspar follows a sequence of increasingly complex arrangements of silicon-oxygen tetrahedra. These arrangements progress from single tetrahedra, to single chains, to double chains, to sheets, and finally to framework arrangement of tetrahedra.
Figure 3.18 -- The silicon-oxygen tetrahedron
Figure 3.19 -- Silicon-oxygen tetrahedral groups

- Isolated
- Single chain
- Double chain
- Two-dimensional sheet
- Three-dimensional framework
Igneous Rocks and Plate Tectonics

- Divergent plate boundaries - convection cells move mantle peridotite closer to the surface. These rocks are at high temperatures so the pressure reduction causes partial melting and production of basaltic magmas.
Igneous Rocks and Plate Tectonics

- Convergent plate boundaries - the subduction of oceanic crust produces partial melting of the hydrated basalt. This produces intermediate (andesitic) magmas which rise to form mountains (e.g. Andes). These magmas can in turn melt continental crust producing granitic magmas.
Types of Convergent Boundaries

Oceanic-Continental

Oceanic-Oceanic

Continental-Continental
Igneous Rocks and Plate Tectonics

• Over geologic time these processes first created oceanic crust from ultramafic mantle rocks. In turn, the mafic oceanic crust created felsic continental crust from partial melting of hydrated basalt. Continental crust is less than 1% of earth’s mass, so there isn’t a lot of felsic material in the earth. Most has risen to the crust.
Continental crust is less than 1% of Earth’s mass
Part 2, Metamorphic Rocks
Regionally metamorphosed rocks shot through with migmatite dikes. Black Canyon of the Gunnison, Colorado
Regionally metamorphosed rocks shot through with magnetite dikes. Black Canyon of the Gunnison, Colorado.
Metamorphic rocks from Greenland, 3.8 Ga
(3.8 billion years old)
Major Concepts

• Metamorphic rocks can be formed from any rock type: igneous, sedimentary, or existing metamorphic rocks.
• Involves recrystallization in the solid state, often with little change in overall chemical composition.
• Driving forces are changes in temperature, pressure, and pore fluids.
• New minerals and new textures are formed.
The Rock Cycle
Major Concepts

- During metamorphism platy minerals grow in the direction of least stress producing foliation.
- Rocks with only one, non-platy, mineral produce nonfoliated rocks such as quartzite or marble.
- Two types of metamorphism: contact and regional.
Metamorphism of a Granite to a Gneiss

Before metamorphism

After metamorphism

Stress

Stress

Stress
Asbestos, a metamorphic amphibole mineral. The fibrous crystals grow parallel to least stress.
Foliated rock
Two sets of foliations = two episodes of metamorphism
Fig. 6.6. Two major types of metamorphism -- contact and regional

Contact Metamorphism

Regional Metamorphism
Major Concepts

- **Foliated rocks** - slate, phyllite, schist, gneiss, mylonite
- **Non-foliated rocks** - quartzite, marble, hornfels, greenstone, granulite
- **Mineral zones** are used to recognize metamorphic facies produced by systematic pressure and temperature changes.
Origin of Metamorphic Rocks

- Below 200°C rocks remain unchanged.
- As temperature rises, crystal lattices are broken down and reformed with different combinations of atoms. New minerals are formed.
- The mineral composition of a rock provides a key to the temperature and pressure of formation (Fig. 6.5).
Fig. 6.5. Different minerals of the same composition, \( \text{Al}_2\text{SiO}_5 \), are stable at different temperatures and pressures.
Where does the heat come from?

• Hot magma ranges from 700-1200°C. Causes contact metamorphism.
• Deep burial - temperature increases 15-30°C for every kilometer of depth in the crust. Subduction and continental collision bury rocks to depths of 10’s of kms. This is regional metamorphism. Most metamorphic rocks form this way.
Pressure

- **Hydrostatic pressure** - produced by the weight of overlying rocks.
- **Directed pressure** - lateral forces produced by plate tectonics. Directed pressure produces the foliation in regionally metamorphosed rocks.
Chemically Active Fluids

- **Metasomatism** - fluid transport during metamorphism can result in the gain or loss of atoms. Clays release H₂O (de-watering) as they change to minerals such as kyanite or garnet.

- **Hydrothermal alteration** - injection of hot water into rocks from metasomatism can produce metallic ores such as lead and zinc.
Slate with fractures. The fractures are filled with quartz crystallized from fluids (de-watering) expelled from the slate during metamorphism.
Chemically Active Fluids

- **Seafloor metamorphism** - ocean water heated by contact metamorphism is a form of metasomatism. This converts the olivine and pyroxene in basalt into hydrated silicates such as serpentine, chlorite, and talc. This changes basalt to greenstone.

Press & Siever
Textures of Metamorphic Rocks

- **Foliated** (Latin for leaf) - grades from slate to phyllite to schist to gneiss. Produced by platy minerals growing in direction of least stress.
- **Nonfoliated** - typical when parent rock is sandstone or limestone. Also occurs in contact metamorphism and extreme metamorphism (granulite facies).
- **Mylonitic** - formed along faults; rare.
Kinds of Metamorphic Rocks

- **Slate** - low grade metamorphosed shale; very fine grained; slaty cleavage should not be confused with bedding planes.
- **Phyllite** - next step up from slate, larger mica grains give the rock a luster.
- **Schist** - a strongly foliated rock with large grains of platy minerals. Named for its minerals; e.g., chlorite schist.
The formation of cleavage in metasedimentary rocks.

**Figure 10.7**

SLATY CLEAVAGE

Slaty cleavage is a type of foliation that develops in low-grade metamorphic rocks. The cleavage develops perpendicular to the direction of maximum stress. In A, maximum stress is due to the weight of overlying rock and so is perpendicular to the bedding. (Slaty cleavage in this case is parallel to bedding.) In B, strata are squeezed and deformed. Maximum stress is indicated by the arrows; slaty cleavage forms at an angle to bedding. In C, slaty cleavage is developed at an angle to bedding in the Martinsburg Formation, near Palmerton, Pennsylvania. Maximum stress is indicated by the arrows. The sample is about the length of your arm across.
Phyllite on the left, Slate on the right
Schist -- a foliated, micaceous metamorphic rock
Kinds of Metamorphic Rocks

- **Gneiss** - a coarse grained granular rock in which foliation results from alternating layers of light and dark minerals. Compositionally similar to granite with quartz, feldspar, biotite, and amphibole. Forms during regional high grade metamorphism. May grade into migmatite and even granite.
Gneiss -- a banded metamorphic rock
Migmatite -- a high grade metamorphic rock in which some minerals reached the melting point.
Migmatite in the Grand Canyon
Kinds of Metamorphic Rocks

• Parent rock and type of gneiss:
  
  granite \rightarrow biotite gneiss
  sediments \rightarrow garnet gneiss
  basalt \rightarrow amphibolite gneiss
Granite on the left, Gneiss on the right
Kinds of Metamorphic Rocks

• Nonfoliated Rocks
  – quartzite - metamorphosed sandstone
  – metaconglomerate - metamorphosed conglomerate
  – marble - metamorphosed limestone
  – hornfels - contact metamorphism of shale; very hard, like a brick
  – greenstones - seafloor metamorphism of basalt
  – granulite - highest grade metamorphic rocks; all water driven off so no platy minerals left
Stretched pebbles in a Metaconglomerate
Non-foliated metamorphic rocks: Marble above, Quartzite below
Quartzite -- metamorphosed sandstone
Marble -- metamorphosed limestone
Fig. 6.13: Parent Rocks and Metamorphic Rocks

- shale $\rightarrow$ slate
- rhyolite $\rightarrow$ schist
- granite $\rightarrow$ gneiss
- basalt $\rightarrow$ amphibolite
- limestone $\rightarrow$ marble
- sandstone $\rightarrow$ quartzite
Shale to Schist

Increasing temperature and pressure (metamorphism)

- Diagenesis
- Shale (sedimentary)
- Clay
- Chlorite
- Muscovite mica
- Biotite mica
- Garnet
- Kyanite
- Sillimanite
- Feldspars
- Quartz

Melting begins at 800°C
Metamorphic Facies

- Defined on the basis of associated minerals
- **Greenschist facies** - low grade metamorphism; chlorite, talc, serpentine, muscovite, sodic plagioclase, quartz
- **Amphibolite facies** - medium grade metamorphic rocks; new minerals include amphibole, biotite, garnet, andalusite, kyanite
Metamorphic Facies

- **Granulite facies** - high grade metamorphic rocks; characteristic minerals are pyroxene, sillimanite, and garnet. Close to melting point, migmatite often present.

- **Blueschist facies** - a high pressure, low temperature facies; color from blue amphibole

- **Eclogite facies** - very high pressure (upper mantle) and temperature; pyroxene and garnet
Fig. 6.16. Metamorphic facies
Fig. 6.15. Regional Metamorphic Gradients in New England.
Greenschist on the left, Amphibolite on the right
Blueschist on the left, Eclogite on the right
Eclogite: garnet and pyroxene
Metamorphic Rocks and Plate Tectonics

- **Greenschist facies** - upper continental crust in mountain ranges, and seafloor metamorphism of basalt
- **Amphibolite and granulite facies** - form progressively deeper in the roots of mountains
- **Contact metamorphic rocks** - form near igneous intrusions in mountain ranges
Metamorphic Rocks and Plate Tectonics

- **Blueschist facies** - shallow part of subduction zone
- **Eclogite facies** - deeper part of subduction zone and upper mantle
Figure 6.19 - Metamorphic rocks and Plate Tectonics
Fig. 6.19. The origin of metamorphic rocks