8.2.1 IGNEOUS ROCKS AND MINERALS

8.2.1.1 Igneous Rocks[1,2]

Igneous rocks are formed when magma or lava cools and solidifies. These rocks usually comprise interlocking crystals of the minerals contained in the parent magma or lava, although very rapid cooling of lava can sometimes yield a rock glass. There are relatively few minerals that are important in the formation of common igneous rocks, because the magma from which the minerals crystallise is rich in only certain elements: silicon, oxygen, aluminium, sodium, potassium, calcium, iron, and magnesium. These are the elements that combine to form the silicate minerals, which account for over 90% of all igneous rocks.

The type of igneous rocks that form from magma is a function of three factors:

The chemical composition of the magma—magma can vary chemically in its composition. For example, the amount of silica (SiO_2) found in magma can vary from 75% to less than 45%;

The temperature of solidification—The temperature of cooling determines which types of minerals are found dominating the rock's composition. Rocks that begin their cooling at low temperatures tend to be rich in minerals composed of silicon, potassium, and aluminium. High temperature igneous rocks are dominated by minerals with higher quantities of calcium, sodium, iron, and magnesium; and

The rate of cooling—The rate of cooling is important in crystal development. Igneous rocks that form through a gradual cooling process tend to have large crystals. Relatively fast cooling of magma produces small crystals. Volcanic magma that cools very quickly on the Earth's surface can produce obsidian glass that contains no crystalline structures.

Over 700 types of igneous rocks have been described, most of them formed beneath the surface of the Earth's crust. In fact, igneous rocks make up approximately ninety five percent of the upper part of the Earth's crust, although their great abundance is hidden on the Earth's surface by a relatively thin but widespread layer of sedimentary, metamorphic and of course igneous rocks.

The word *igneous* is derived from the Latin *igneus*, meaning "of fire". Volcanic rocks are named after Vulcan, the Roman god of fire. Intrusive rocks are also called plutonic rocks, named after Pluto, the Roman god of the underworld.

8.2.1.1.1 Classification

While the classification of igneous rocks according to the standard specified by the International Union of Geological Sciences (IUGS) is rather complex, geologists often use a simplified *field classification* scheme to identify samples according to their texture and chemical composition. Texture is generally defined by the size of crystals (coarse, fine, vesicular or glassy) within the rock sample, and its chemical composition by one of the four following groupings, defined by the silica content of the rock:

[1] http://en.wikipedia.org/wiki/igneous_rock
[2] http://www.physicalgeography.net/fundamentals/10e.html

Felsic (acidic)—Igneous rocks derived from felsic magma contain relatively high quantities of sodium, aluminium, and potassium and are composed of more than 65% silica. Rocks formed from felsic magma include granite, granodiorite, dacite, and rhyolite. All of these rock types are light in colour because of the dominance of quartz, potassium and sodium feldspars, and plagioclase feldspar minerals. Dacite and granodiorite contain slightly more biotite and amphibole minerals than granite and rhyolite. Rhyolite and dacite are produced from continental lava flows that solidify quickly. The quick solidification causes the mineral crystals in these rocks to be fine grained. Granite and granodiorite are common intrusive igneous rocks that are restricted to the Earth's continents. Large expanses these rocks were formed during episodes of mountain building on the Earth. Because granite and granodiorite form beneath the Earth's surface their solidification is a relatively slow process. This slow solidification produces a rock with a coarse mineral grain;

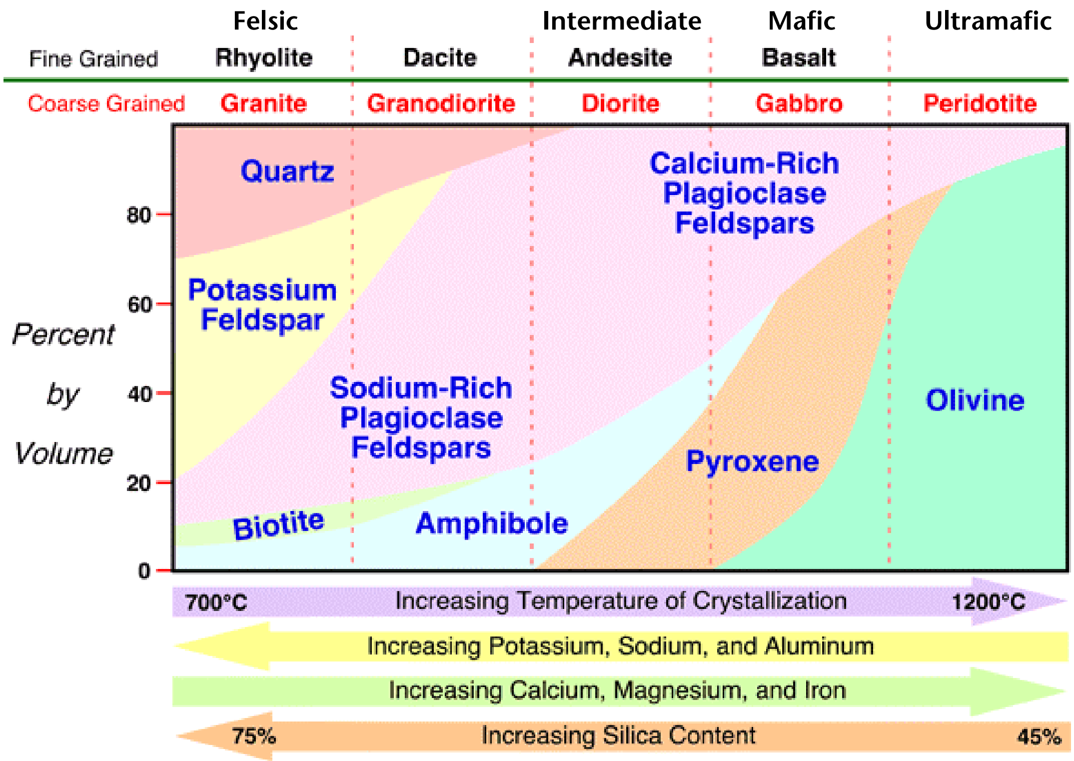
Intermediate—Andesite and diorite are intermediate igneous rocks that have a chemistry between mafic and felsic (silica amounts between 55 to 65%). These rocks are composed predominantly of the minerals plagioclase feldspar, amphibole, and pyroxene. Andesite is a common fine-grained extrusive igneous rock that forms from lavas erupted by volcanoes located along continental margins. Coarse-grained diorite is found in intrusive igneous bodies associated with continental crust;

Mafic (basic)—Mafic magma produces igneous rocks rich in calcium, iron, and magnesium and are relatively poor in silica (silica amounts from 45 to 55%). Some common mafic igneous rocks include fine grained basalt and coarse grained gabbro. Mafic igneous rocks tend to be dark in colour because they contain a large proportion of minerals rich in iron and magnesium (pyroxene, amphiboles, and olivine). Basalt is much more common than gabbro. It is found in the upper portion of the oceanic crust and also in vast continental lava flows like those covering large portions of North America. Gabbro is normally found in the lower parts of oceanic crust and sometimes in relatively small intrusive features in continental crust; and

Ultramafic (ultrabasic)—Ultramafic igneous rocks contain relative low amounts of silica (< 45%) and are dominated by the minerals olivine, calcium-rich plagioclase feldspars, and pyroxene. Peridotite is the most common ultramafic rock found in the Earth's crust, although these rocks are extremely rare at the Earth's surface.

The graphic model opposite describes the difference between nine common igneous rocks based on texture of mineral grains, temperature of crystallisation, relative amounts of typical rock forming elements, and relative proportions of silica and some common minerals.

Igneous rocks with vesicular (*e.g.* pumice and scoria) and glassy (*e.g.* obsidian) textures do not fit neatly into this table. All types of magma will form pumice, so its chemical composition is quite variable. Pumice is nonetheless, a light coloured rock. Scoria is darker in colour with a similarly variable but more intermediate–mafic composition. Obsidian samples have a very high silica content (70–75%), but are also rich in both iron (the black colour derives mainly from the presence of magnetite, Fe_3O_4) and magnesium.



Field Classification of Igneous Rocks

8.2.1.1.2 Intrusive Igneous Rocks

Intrusive igneous rocks, also known as plutonic rocks, are formed from magma that cools and solidifies within the earth. Surrounded by pre-existing rock (called **country rock**), the magma cools slowly, and as a result these rocks are coarse grained. The mineral grains in such rocks can generally be identified with the naked eye. Intrusive rocks can also be classified according to the shape and size of the intrusive body and its relation to the other formations into which it intrudes. Typical intrusive formations are **batholiths**, **stocks**, **laccoliths**, **sills** and **dykes**.

The central cores of major mountain ranges consist of intrusive igneous rocks, usually granite. When exposed by erosion, these cores (batholiths) may occupy huge areas of the Earth's surface.

Coarse-grained intrusive igneous rocks that form at depth within the earth are known as **abyssal** rocks. Intrusive igneous rocks that form near the surface are known as **hypabyssal** rocks.

8.2.1.1.3 Extrusive Igneous Rocks

Extrusive igneous rocks, also known as volcanic rocks, are formed from magma that erupts from volcanoes and cools at the Earth's surface. When it reaches the surface, magma, extruded onto the surface either beneath water or air, is called **lava**.

Magma that erupts from a volcano behaves according to its viscosity, determined by temperature, composition, and crystal content. High-temperature magma, most of which is basaltic in composition, behaves in a manner similar to thick oil and, as it cools, treacle. Long, thin basalt flows with pahoehoe[3] (smooth) surfaces are common.

[3] There are three forms of low-viscosity lava flows—aa (Hawaiian English, pronounced ah-ah), characterised by a rough or rubbly surface, pahoehoe (also from Hawaiian English) characterised by a relatively smooth surface, and pillow lava, a lava flow that occurs under the sea and tends to form large blobs or 'pillows'.

Intermediate composition magma such as andesite tends to form cinder cones of intermingled ash, tuff and lava, and may have viscosity similar to thick, cold molasses or even rubber when erupted. Felsic magma such as rhyolite is usually erupted at low temperature (~1000 °C) and is up to 10,000 times more viscous than basalt magma. Volcanoes with rhyolitic magma commonly erupt explosively, and rhyolitic lava flows typically are of limited extent and have steep margins, because the magma is so viscous.

Felsic and intermediate magmas that erupt often do so violently, with explosions driven by release of dissolved gases—typically water but also carbon dioxide. Explosively erupted material is called **tephra**, and volcanic deposits are called **pyroclastic**—they include tuff, agglomerate and ignimbrite. Fine volcanic ash is also erupted and forms ash tuff deposits that can often cover vast areas.

Because lava cools and crystallises rapidly, it is fine grained. If the cooling has been so rapid as to prevent the formation of even small crystals after extrusion, the resulting rock may be mostly glass (such as the rock obsidian). The more slowly the lava cools, the more coarse-grained will be the rocks that form.

Nonetheless, because the minerals are relatively fine-grained, it is much more difficult to distinguish between the different types of extrusive igneous rocks than between different types of intrusive igneous rocks. Generally, the mineral constituents of fine-grained extrusive igneous rocks can only be determined by examination of thin sections of the rock under a microscope, so only an approximate classification can usually be made in the field.

8.2.1.2 Minerals[4]

Minerals are natural compounds formed through geological processes. The term *mineral* encompasses not only the material's chemical composition, but also the mineral's structure. Minerals range in composition from pure elements and simple salts to very complex silicates with thousands of known forms (organic compounds are excluded). The study of minerals is called mineralogy.

An assortment of minerals

As we noted in the previous section, igneous rocks are made up of minerals.

8.2.1.2.1 Mineral Classification

To be classified as a *true* mineral, a substance must be a solid and have a crystal structure. It must also be an inorganic, naturally-occurring, homogeneous substance with a well-defined chemical composition, although the chemical composition may vary between end members of a mineral system. For example the plagioclase feldspars comprise a continuous series from sodium-rich albite ($NaAlSi_3O_8$) to calcium-rich anorthite ($CaAl_2Si_2O_8$) with four recognized intermediate compositions between. Mineral-like substances that don't strictly meet the definition are sometimes classified as mineraloids.

Chemistry and crystal structure together define a mineral. Two or more minerals may have the same chemical composition, but differ in crystal structure (these are known as

4 http://en.wikipedia.org/wiki/Mineral

polymorphs). For example, pyrite and marcasite are both iron sulfide, but their arrangement of atoms differs. Similarly, some minerals have different chemical compositions, but the same crystal structure: for example, halite (made from sodium and chlorine), galena (made from lead and sulfur) and periclase (made from magnesium and oxygen) all share the same cubic crystal structure.

Crystal structure greatly influences a mineral's physical properties. For example, though diamond and graphite have the same composition (both are pure carbon), graphite is very soft, while diamond is the hardest of all known minerals. This happens because the carbon atoms in graphite are arranged into sheets that can slide easily past each other, while the carbon atoms in diamond form a strong, interlocking three-dimensional network.

There are currently just over 4,000 known minerals, according to the International Mineralogical Association, which is responsible for the approval of and naming of new mineral species found in nature. Of these, perhaps 150 can be called *common*, 50 are *occasional*, and the rest are *rare* to *extremely rare*.

8.2.1.2.2 Minerals and Rocks

A mineral is a naturally occurring, inorganic solid with a definite chemical composition and a crystalline structure. A rock is an aggregate of one or more minerals. (A rock may also include organic remains and mineraloids.) Some rocks are predominantly composed of just one mineral. For example, limestone is a sedimentary rock composed almost entirely of the mineral calcite. Other rocks contain many minerals, and the specific minerals in a rock can vary widely. Some minerals, like quartz, mica or feldspar are common, while others have been found in only one or two locations worldwide. The vast majority of the rocks of the Earth's crust consist of quartz, feldspar, mica, chlorite, kaolin, calcite, epidote, olivine, augite, hornblende, magnetite, hematite, limonite and a few other minerals.

Commercially valuable minerals and rocks are referred to as industrial minerals. Rocks from which minerals are mined for economic purposes are referred to as ores (the rocks and minerals that remain, after the desired mineral has been separated from the ore, are referred to as tailings).

Mineral Composition of Rocks

A main determining factor in the formation of minerals in a rock mass is the chemical composition of the mass, for a certain mineral can be formed only when the necessary elements are present in the rock. Calcite is most common in limestones, as these consist essentially of carbonate of lime; quartz in sandstones and in certain igneous rocks which contain a high percentage of silica.

Other factors are of equal importance in determining the natural association or paragenesis of rock-making minerals, principally the mode of origin of the rock and the stages through which it has passed in attaining its present condition. Two rock masses may have very much the same bulk composition and yet consist of entirely different assemblages of minerals. The tendency is always for those compounds to be formed which are stable under the conditions under which the rock mass originated. A granite arises by the consolidation of a molten magma (a fused rock mass) at high temperatures and great pressures and its component minerals are such as are formed in such circumstances. Exposed to moisture, carbonic acid and other subaerial agents at the ordinary temperatures of the earth's surface, some of these original minerals, such as quartz and white mica are permanent and remain unaffected; others "weather" or decay and are replaced by new combinations. The felspar passes into kaolin, muscovite and quartz, and if any black mica (biotite) has been present it yields chlorite, apidote, rutile and other substances. These changes are accompanied by disintegration, and the rock falls into a loose, incoherent, earthy mass that may be regarded as a sand or soil. The materials thus formed may be washed away and deposited as a sandstone or grit. The structure of the original rock is now replaced by a new one—the mineralogical constitution is profoundly altered—although the bulk chemical composition may not be very different. The sedimentary rock may again undergo a metamorphosis. If penetrated by igneous rocks it may be recrystallised or, if subjected to enormous pressures with heat and movement, such as attend the building of folded mountain chains, it may be converted into a gneiss not very different in mineralogical composition though radically different in structure to the granite which was its original state.

8.2.1.2.3 Physical Properties of Minerals

A mineral can generally be identified by its physical properties, the most commonly used being:

- *Crystal structure and habit*—a mineral may show good crystal habit or form, or it may be massive, granular or compact with only microscopically visible crystals.
- *Hardness*—the physical hardness of a mineral is usually measured according to Moh's scale. This scale is relative, ranging from 1 to 10. Minerals with a given Moh's hardness can scratch the surface of any mineral that has a lower hardness than itself.

Moh's Scale of Hardness

1	Talc	$Mg_3Si_4O_{10}(OH)_2$
2	Gypsum	$CaSO_4 \cdot 2H_2O$
3	Calcite	$CaCO_3$
4	Fluorite	CaF_2
5	Apatite	$Ca_5(PO_4)_3(OH,Cl,F)$
6	Orthoclase	$KAlSi_3O_8$
7	Quartz	SiO_2
8	Topaz	$Al_2SiO_4(OH,F)_2$
9	Corundum	Al_2O_3
10	Diamond	C (pure carbon)

- *Lustre*—the way a mineral's surface interacts with light and can range from dull to glassy (vitreous).
  - Metallic—high reflectivity like metal: galena and pyrite
  - Sub-metallic—slightly less than metallic reflectivity: magnetite
  - Non-metallic lustres:
    - Adamantine—brilliant, the lustre of diamond also cerussite and anglesite
    - Vitreous—the lustre of a broken glass: quartz
    - Pearly—iridescent and pearl-like: talc and apophyllite
    - Resinous—the lustre of resin: sphalerite and sulfur
    - Silky—a soft light shown by fibrous materials: gypsum and chrysotile
    - Dull/earthy—shown by finely crystallised minerals: the kidney ore variety of hematite

- *Colour*—the appearance of the mineral in reflected light or transmitted light for translucent minerals (*i.e.* what it looks like to the naked eye).
  - Iridescence—the play of colours due to surface or internal interference. Labradorite exhibits internal iridescence whereas hematite and sphalerite often show the surface effect.
- *Streak*—the colour of the powder a mineral leaves after rubbing it on an unglazed porcelain streak plate.
- *Cleavage*—the way a mineral may split apart along various planes. In thin section, cleavage is visible as thin parallel lines across a mineral.
- *Fracture*—how a mineral breaks when broken contrary to its natural cleavage planes.
  - Chonchoidal fracture is a smooth curved fracture with concentric ridges of the type shown by glass.
  - Hackley is jagged fracture with sharp edges.
  - Fibrous
  - Irregular
- *Specific gravity*—the relationship between the mineral mass and the mass of an equal volume of water (*i.e.* the density of the material). Most minerals, including all the common rock-forming minerals, have a specific gravity of 2.5 - 3.5.
- Other properties: fluorescence (response to ultraviolet light), magnetism, radioactivity, tenacity (response to mechanical induced changes of shape or form), piezoelectricity and reactivity to dilute acids.

8.2.1.2.4 Chemical properties of minerals

Minerals may also be classified according to chemical composition. The list below, categorised by anion group and following the Dana classification system, is in approximate order of abundance in the Earth's crust..

Silicate class

The largest group of minerals by far are the silicates (most rocks are >95% silicates), which are composed largely of silicon and oxygen, with the addition of ions such as aluminium, magnesium, iron, and calcium. Some important rock-forming silicates include the feldspars, quartz, olivines, pyroxenes, amphiboles, garnets, and micas.

quartz

Carbonate class

The carbonate minerals consist of those minerals containing the anion $(CO_3)^{2-}$ and include calcite and aragonite (both calcium carbonate), dolomite (magnesium/calcium carbonate) and siderite (iron carbonate). Carbonates are commonly deposited in marine settings when the shells of dead planktonic life settle and accumulate on the sea floor. Carbonates are also found in evaporitic settings (*e.g.* the Great Salt Lake, Utah) and also in karst regions, where the dissolution and reprecipitation of carbonates leads to the formation of caves, stalactites and stalagmites. The carbonate class also includes the nitrate and borate minerals.

aragonite

Sulfate class

Sulfates all contain the sulfate anion, SO_4^{2-}. Sulfates commonly form in evaporitic settings where highly saline waters slowly evaporate, allowing the formation of both sulfates and halides at the water-sediment interface. Sulfates also occur in hydrothermal vein systems as gangue minerals along with sulfide ore minerals. Another occurrence is as secondary oxidation products of original sulfide minerals. Common sulfates include anhydrite (calcium sulfate), celestite (strontium sulfate), barite (barium sulfate), and gypsum (hydrated calcium sulfate). The sulfate class also includes the chromate, molybdate, selenate, sulfite, tellurate, and tungstate minerals.

celestite

Halide class

The halides are the group of minerals forming the natural salts and include fluorite (calcium fluoride), halite (sodium chloride), sylvite (potassium chloride), and sal ammoniac (ammonium chloride). Halides, like sulfates, are commonly found in evaporitic settings such as playa lakes and landlocked seas such as the Dead Sea and Great Salt Lake. The halide class includes the fluoride, chloride, and iodide minerals.

halite

Oxide class

Oxides are extremely important in mining as they form many of the ores from which valuable metals can be extracted. They also carry the best record of changes in the Earth's magnetic field. They commonly occur as precipitates close to the Earth's surface, oxidation products of other minerals in the near surface weathering zone, and as accessory minerals in igneous rocks of the crust and mantle. Common oxides include hematite (iron oxide), magnetite (iron oxide), chromite (iron chromium oxide), spinel (magnesium aluminium oxide - a common component of the mantle), ilmenite (iron titanium oxide), rutile (titanium dioxide), and ice (hydrogen oxide). The oxide class includes the oxide and the hydroxide minerals.

hematite

Sulfide class

Many sulfide minerals are economically important as metal ores. Common sulphides include pyrite (iron sulfide—commonly known as fools' gold), chalcopyrite (copper iron sulfide), pentlandite (nickel iron sulfide), and galena (lead sulfide). The sulfide class also includes the selenides, the tellurides, the arsenides, the antimonides, the bismuthinides, and the sulphosalts (sulfur and a second anion such as arsenic).

galena

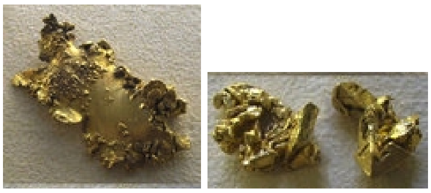
Phosphate class

The phosphate mineral group actually includes any mineral with a tetrahedral unit AO_4 where A can be phosphorus, antimony, arsenic or vanadium. By far the most common phosphate is apatite, which is an important biological mineral found in teeth and bones of many animals. The phosphate class includes the phosphate, arsenate, vanadate, and antimonate minerals.

apatite

Element class

The Elemental group includes metals and intermetallic elements (gold, silver, copper), semi-metals and non-metals (antimony, bismuth, graphite, sulfur). This group also includes natural alloys, such as electrum (a natural alloy of gold and silver), phosphides, silicides, nitrides and carbides (which are usually only found naturally in a few rare meteorites).



gold

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