

ENGINEERING GEOLOGY

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Summary

Engineering geology is geology which is applied to the practice of engineering. So this chapter describes those results from the study of the planet Earth, geology, which have found a ready use in geotechnical engineering. The results may be summarized under two headings; knowledge of the geological materials which we engineer, and of the natural processes that act on those materials and the structures we make from them.

Descriptions of geological materials begin with descriptions of minerals, the recurring patterns in which the atoms at the Earth's surface organize themselves. The minerals form igneous, metamorphic and sedimentary rocks. Soils are derived from these rocks by weathering and erosion. Rocks are deformed by folding and faulting, processes driven from deep within the Earth. Earthquakes and volcanoes are also signs of movements in the Earth's crust and mantle.

1. Characteristic Properties of Minerals

1.1 Definitions and Classification

Minerals are naturally occurring chemical elements or compounds whose compositions vary between fixed limits. Each mineral has a characteristic arrangement of its atoms or ions in space, a unique crystal structure. Minerals are classified by their chemical composition and structure into eight classes.

1. Native elements
2. Sulfides
3. Oxides and hydroxides
4. Halides
5. Carbonates, nitrates and borates
6. Sulfates, chromates, molybdates and tungstates
7. Phosphates, arsenates and vanadates
8. Silicates

The silicate minerals are by far the most abundant, silicon and oxygen being the most commonly occurring terrestrial elements. Many of the minerals mined for metals are sulfides or oxides. Carbonate minerals are important rock-forming minerals near the earth's surface.

The physical properties of a mineral depend upon its chemical composition (which may vary between limits) and its crystal structure which is constant. Small amounts of impurities affect optical properties more markedly than other properties and we describe these first. Then we consider properties controlled by crystal structure.

1.2 Optical Properties

The color of a mineral depends on its chemical composition. As the chemical composition of the mineral may vary, so the color of a mineral may vary, so the color of a mineral is not fixed. The commonest color-imparting element is iron; for example iron silicates are usually light green to dark green, the intensity of the color increasing with the iron content.

Three terms are used to describe light transmission through minerals:

- Opaque: The mineral will not transmit light.
- Translucent: The mineral transmits light but is not transparent
- Transparent: An object placed on the other side of the mineral is visible through the mineral.

Most minerals will transmit light provided the mineral is sliced thin enough: among the few exceptions are sulfide minerals, native metals and some iron oxides. The distinction between transparent and translucent is blurred by flaws in the crystal structure of the mineral and is not a reliable guide to identification of the mineral.

The luster of a mineral describes the quality of light reflected from its surface and from within the crystals of the mineral. The luster of a mineral may depend upon its grain size and the presence of impurities within the grains.

1.3 Crystallographic Properties

The properties grouped under this heading are largely dependent upon the arrangement of the atoms comprising the mineral. They are insensitive to small changes in composition and are very useful for mineral identification. Common silicate minerals

are built with silica tetrahedra arranged in frameworks (Si:O = 2, quartz for instance), sheets (Si:O = 2.5, e.g. biotite), double chains (Si:O = 2.75, e.g. amphiboles), single chains (Si:O = 3, e.g. pyroxenes) or with island tetrahedra (Si:O = 4, e.g. olivine) isolated by metal ions. These different structures strongly influence the cleavage and habits of silicate minerals.

Many minerals break preferentially along definite planes. This fissile property is cleavage and is controlled by the presence of planes of weakness within the internal crystal structure of the mineral. It is not necessary to break a crystal in order to observe cleavage as cleavage planes are commonly observable as sets of traces on crystal faces. Cleavage planes may be parallel to, or at some angle to, a crystal face. Care is necessary to distinguish crystal faces from cleavage planes. For example, quartz frequently shows well-developed crystal faces but there are no traces parallel to these faces, and hence, no cleavage. Feldspar generally shows well-developed cleavage parallel to pairs of crystal faces; these show up as cleavage traces.

Fracture surfaces may be observed where the mineral has broken along directions other than those of the cleavage; they may be difficult to find in well-cleaved minerals. Three fracture types are noteworthy:

1. Irregular fractures occur in most minerals.
2. Hackly fractures have protuberances like a saw blade and are seen in native metals.
3. Conchoidal fractures have circular or semi-circular ridges and furrows concentric to the point of impact and are typical of quartz.

Habit is a general term for the natural shape of individual crystals. As this is dependent upon their crystal structure and their conditions of growth some variability can be expected. Usually crystals in rocks are not well developed due to mutual interference of their grain boundaries during growth.

Twinning occurs when a mineral grows in different orientations within the same crystal outline. The twinning may be simple, where there are only two parts to the twin, or it may be complex or repeated where several repetitions of two alternate orientations occur. In the latter case, thin layers (lamellae) are arranged alternately in two orientations. The twinning then appears as closely spaced, parallel striations on certain of the crystal faces. The mineral plagioclase often shows lamellar twinning.

1.4 Other Properties

Hardness can be described using a comparative scale, Mohs' Scale, on which a mineral of higher hardness number will scratch one of lower (hardness) number. The scale has ten standard minerals. In practice, it is more convenient to use commonly available materials to test hardness:

- | | |
|-------|--|
| 2 | fingernail |
| 3.5 | copper coin |
| 5-6 | pin, knife, needle, dependent on steel |
| 5.5-6 | glass |

6.5 steel file, streak plate

The presence of iron in the crystal structure of certain minerals renders them magnetic. This property is seen in magnetite (lodestone) which served as a needle in primitive compasses.

Sulfur has an easily identifiable smell. The smell of garlic results from striking an arsenic-bearing mineral with a steel hammer-head. The earthy smell of kaolinite (china clay) is also distinctive.

The relative density of a mineral is the ratio of the weight of the mineral to the weight of an equal volume of water. It is a dimensionless ratio which can be estimated by lifting a specimen, precise measurements require weighing the specimen in air and submerged in water. The relative density of a mineral is a guide to chemical composition; those minerals which concentrate the heavy elements have larger relative densities than their light-element counterparts. For example, common silicates have relative densities ranging from 2.6 to 4.4 sulfides range from 4.1 to 10.6 and native metals range from 8.9 to 19.

1.5 Identification Strategy

There are over 2500 minerals of which about 200 are relatively common. Positive identification of a mineral requires an X-ray examination, but many minerals can be provisionally identified visually. Strategies for doing this can be decision trees or simple expert systems; for instance, arrange minerals first by their color (green, blue, violet to pink, red, brown, orange, yellow, colorless, white, grey, black, banded and metallic), then within each color group by their hardness. Within each hardness group, then arrange minerals by the quality and number of their cleavages. As an example, common black minerals are listed below in order of increasing hardness.

Black Minerals

Hardness	Cleavages	Distinctive Features	Mineral
2.5	1, perfect	platy habit	biotite
6	2, good	60° between cleavages	hornblende
6	2, good	90° between cleavages	augite
6.5	3, poor	relative density, 5.2, magnetic	magnetite

2. Igneous Rocks

2.1 Classification by Texture

Rocks are aggregates of minerals. Rocks can be divided into igneous rocks (Section 2), sedimentary rocks (Section 3), and metamorphic rocks (Section 4), by the ways in which they form. Most of the igneous rocks form by crystallization from a molten silicate liquid.

The texture of a rock describes the size, shape and grain to grain relationships of the

minerals forming the rock. Igneous rocks are formed by the crystallization or solidification of molten material or magma. The magma is usually of silicate composition but other compositions, for example, carbonates occur. The texture of igneous rocks shows how they formed.

Slow cooling of a magma results in the formation of coarse, easily visible crystals greater than 1 mm in size. Slow cooling occurs only at depth within the earth; igneous rocks crystallizing there are called intrusive or plutonic. Rapid cooling at or near the earth's surface is instrumental in producing fine-grained crystals. If cooling is sufficiently rapid, volcanic glass, non-crystalline, solid magma is formed. Magmas which reach the surface prior to solidification form extrusive or volcanic rocks.

A constant cooling rate will produce grains of nearly equal size; such rocks are referred to as equi-granular. If crystallization began at depth and was completed at shallower levels in the earth's crust or at the earth's surface, the resulting rock will contain larger crystals, or phenocrysts within a groundmass of smaller crystals; this texture is called porphyritic. Crystals smaller than 0.1 mm generally indicate that the rock is volcanic or extrusive.

2.2 Composition

The color of igneous rock is a guide to its chemical composition; light coloring usually indicates high SiO₂ or acidic rocks, dark coloration, low SiO₂ or basic rocks. An exception is obsidian, an acid volcanic glass which is dark as a result of small quantities of fine-grained iron oxide in the glass.

Light-colored minerals with large percentages of aluminum and silicon are called felsic minerals. Minerals with large quantities of iron and magnesium are usually dark (one exception is the light green mineral, olivine) and are referred to as mafic; the acronym is formed from "Magnesio-Ferric". The total percentage of mafic minerals in a rock is the color index, a useful criterion for classification.

Color indexes can be expected to decrease with increasing silica contents of rocks associated with increasing silica is an increase in quartz and alkali feldspar and a decrease in plagioclase and mafic minerals. Extremely mafic rocks such as peridotites have color indexes of 100%; felsic rocks such as granites have values of 5-20%.

Magma differentiation describes the physical and chemical processes which change the chemical composition of a magma prior to or during solidification. Gravity differentiation is the process of crystallization and removal of the crystals from the magma, by settling to the bottom or floating to the top of magma chambers. By this process, a magma with the composition of gabbro can form a series of rocks ranging in composition from peridotite to granite as the magma crystallizes.

Volatile phases or gases dissolved in magmas may produce explosive eruptions. Evidence for volatile phases dissolved within silicate melts includes:

1. Vesicles, spherical, ellipsoidal and irregular cavities which are caused by exsolution

and expansion of dissolved gases. The vesicles may become filled with minerals precipitating from aqueous solutions percolating through the rock in the late stages of cooling. Such infilled vesicles are called amygdales.

2. The presence of minerals which contain structurally bound ions such as fluorine, F^- or hydroxyl, OH^- which, if free, would be volatile at the temperature and pressure of a magma. Examples of such minerals are amphiboles and micas, both of which contain structurally-bound water.
3. Volatiles frequently become concentrated in residual silicate liquids, formed by magmatic differentiation. Crystallization of the volatile-rich silicate magmas can form extremely coarse-grained crystalline bodies, called pegmatites. The volatiles may be lost prior to this stage in a crystallizing system, forming hot, aqueous fluids which flow into the rock surrounding an igneous intrusion.

The heat from the cooling of igneous rocks is a major agent in concentrating economically important ore deposits. Deposits may be formed both during igneous intrusion and extrusion. Gravity differentiation of an intrusion can concentrate platinum and chromium minerals in layers within ultramafic rocks. Pegmatites include minerals rich in lithium, beryllium, niobium and tantalum. Hot solutions formed by the convection of water through a crystallized igneous intrusion can leach economically-important elements from the intrusion and the surrounding rock, redepositing them in concentrated form as ores. The copper deposits of the west coast of North America and South America are of this type. Such solutions also percolate through extrusive rock on the ocean floor, forming extensive deposits of metallic sulfides.

3. Sedimentary Rocks

3.1 Classification

Sedimentary rocks form from sediments, which are natural materials derived from pre-existing rocks or organisms, and deposited from suspension, traction, or solution. Sediments may be:

- Clastic sediments, comprising fragments or clasts of rock carried in suspension or by traction from a source area distant from the site of deposition (3.2)
- Chemical sediments, formed by precipitation from solution at the site of deposition (3.3).
- Organic sediments, formed by the activity of organisms or from their remains (3.4).

Minerals comprising of rock fragments present in clastic sedimentary rocks are obviously inherited from their source rocks and may therefore be igneous, sedimentary or metamorphic in origin. Minerals which form synchronously with chemical sedimentary rocks include calcite, dolomite, goethite, quartz, clay minerals, gypsum, halite and, in strongly reducing environments, pyrite, chalcopyrite, sphalerite and galena.

The most common minerals of chemical sediments are the carbonates, calcite and dolomite; these minerals are also very common cementing agents in clastic sedimentary

rocks. Silica, in the form of chert is less common. Gypsum, halite and sylvite also form sediments during the evaporation of shallow bodies of saline water and are collectively called evaporites.

3.2 Clastic Sediments

Clastic sediments are formed from the rock fragments derived from outcrops in a source area. These outcrops are broken down by weathering into clasts which can be transported from the source area. The transport processes are collectively called erosion. Chemical weathering refers to the processes which cause the breakdown of the original minerals of the source rock into the minerals typical of sedimentary rocks. Those processes causing communication of the source rock are physical weathering processes. Chemical weathering includes the solution of some minerals, particularly carbonates, which are later precipitated as chemical sediments. The source area is usually elevated above the sink, where sediments are deposited; gravity is the major agent of transport. Other agents of erosion include wind, water and ice; the latter two are, of course, gravity-controlled. During transport, particles are abraded and fractured, resulting in size reduction and rounding. These processes are referred to as attrition.

With increasing distance from the source, the grains become smaller, rounder and better-sorted. This degree of sorting is a measure of the similarity of sizes of clastic grains in a sediment. Sediments further from the source has small, well-sorted, rounded grains; those sediments closer to the source have larger, angular grains and are more poorly sorted.

Most clastic sediments comprise larger clasts or grains called the framework, visible to the naked eye or with a low-power lens, and smaller grains partly filling the pores or gaps left between the large grains, called the matrix.

A rock is formed if the pore space is filled with a chemically precipitated binding agent to give the material an appreciable tensile strength. This crystalline cement is deposited from aqueous solutions passing through the rock; common cements are calcite and silica. The transformation of a clastic sediment into sedimentary rock by cementation and by consolidation by the weight of the overlying sediments is called lithification.

The lack of any cementing of grains leaves a sediment weak, even if consolidated by large thicknesses of overlying sediments at high pressures. A shock from an earthquake could still disaggregate the sediment quantities of non-structurally bound water.

The physical and chemical processes occurring after sedimentation (including mineralogical changes) are referred to collectively as diagenesis. Diagenesis can involve a reduction, sometimes drastic, in the available pore space in a rock, or alternatively may increase pore space through dissolution. This is an important consideration in the evaluation of a rock's storage potential for natural gas, petroleum or water, as well as its ability to transmit those fluids.

3.3 Chemical Sediments

Many textbooks place all non-clastic sediments, including carbonates, in this category.

However, our current understanding of marine carbonates is that they are largely composed of organic carbonate material (e.g. shells, skeletal components), or the formation of the carbonate is due to the influence of organic activity. Very few carbonates are therefore simple chemical precipitates. Without any outside influences, calcium carbonate represents less than 1% of the solids that will precipitate from evaporation of sea water of normal salinity.

In terms of volume and economic importance, the most significant chemical sedimentary rocks are the evaporites, formed by concentration and evaporation of sea water in restricted basins of warm arid regions. Significant minerals include rock salt (halite), gypsum, and the potash salts (e.g. sylvite). Some marine carbonates are apparently chemical in origin, such as oolitic limestone, so named for its characteristics small, spheroidal carbonate bodies. Carbonates such as travertine and tufa are deposited from springs and groundwaters, while hot springs may produce silica deposits known as sinter.

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Biographical Sketch

David Cruden has taught geology to engineering students at the University of Alberta since 1971. From 1995 to 2000, he chaired the International Union of Geological Sciences' Working Group on World Landslide Inventory.