MINISTRY OF EDUCATION OF THE REPUBLIC OF BELARUS

Belarusian National Technical University

Civil Engineering Faculty

Department "Geotechnics and structural mechanics"

AGREED

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«___»_____________2020г.

AGREED

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Electronic educational-methodical complex for discipline

"Engineering Geology"

for students of specialty 1-70 02 01 - "Industrial and civil construction"

Compiled by:

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Reviewed and Approved

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EXPLANATORY NOTE

The aim of the EEMC in the discipline "Engineering Geology" is the acquisition by students of the practical and theoretical knowledge necessary in the future when studying special engineering building disciplines "Soil Mechanics", "Foundations and Foundations". It is intended for full-time and part-time students, with the aim of acquiring future engineers of modern knowledge in the field of engineering geology, as well as to form the skill of effective independent work. It is recommended for study for students of the CEF and VTF of BNTU.

The electronic educational-methodical complex was developed in accordance with the following regulatory documents: 1. The regulation on the educational-methodical complex at the level of higher education, approved by Decree of the Ministry of Education of the Republic of Belarus No. 167 of June 26, 2011; 2. A standard curriculum in the discipline "Engineering Geology", approved by the Ministry of Education of the Republic of Belarus on December 28, 2011 (registration number I. TD-J.093 / type); 3. The curriculum in the discipline "Engineering geology" (UD-SF64-27 / academic year 30.09.2019).

The content and volume of the EEMC is fully consistent with the educational standard of higher education (first stage), as well as the educational and program documentation of educational programs of higher education (first stage). The electronic educational-methodical complex is developed in printed form and is available in electronic form.

EEMC includes such sections as: theoretical section. It contains information on the lecture theoretical course of the discipline, necessary for independent study and preparation for the final form of control - offset by students of the CEF and VTF of BNTU. Practical section. It provides for the study of collections of rock-forming minerals by describing their physical properties. Attention is paid to the variety of properties of minerals, their classification. This is reflected in a laboratory workshop, which allows applying the name of minerals using the methodology for describing minerals and using hardness standards (Mohs scale), as well as tables describing basic physical characteristics. The laboratory workshop gives a complete description of the most important rock groups and provides a methodology for determining them in accordance with the classification. A link is given to the electronic version of the laboratory works. Knowledge Control Section. Contains topics of abstracts on the discipline, list of references.

Information about the authors: The compilers of the EEMC for the discipline "Engineering Geology" are: Moradi Sani Babak – PhD in Engineering, Associate Professor of the Department of Geotechnics and Structural Mechanics of the Civil Engineering Faculty of BNTU; Ulasik T.M.– PhD in Engineering, Associate Professor of the Department of Geotechnics and Structural Mechanics of the Civil Engineering Faculty of BNTU.

EEMC is recommended to be used to perform the following types of extracurricular activities of students: preparation for lectures, preparation for laboratory classes (admission to laboratory work, defense), preparation of essays, preparation for credit. EEMC in the discipline "Engineering geology" is intended for successful assimilation by students of study material, makes it possible to plan and carry out independent work of students, and provides a rational distribution of study time on topics of the discipline and improvement of the methodology for conducting classes. The electronic educational-methodical complex is aimed at improving the efficiency of the educational process in the discipline "Engineering Geology". The organization of the study of the discipline on the basis of the EEMC assumes effective educational activity, which allows to form the professional competencies of future specialists of the specialty 1-70 02 01 - "Industrial and civil construction".

CONTENT

EDUCATIONAL AND METHODOLOGICAL COMPLEX ON DISCIPLINE

“ENGINEERING GEOLOGY”

Introduction

Geology is the study of the solid matter that makes up the Earth – its interior and its exterior surface, the minerals, rocks and other materials that are around us, the processes that have resulted in the formation of those materials, the water that flows over the surface and through the ground, the changes that have taken place over the vastness of geological time, and the changes that we can anticipate will take place in the near future. Geology is a science, meaning that we use deductive reasoning and scientific methods to understand geological problems. It is, arguably, the most integrated of all of the sciences because it involves the understanding and application of all of the other sciences: physics, chemistry, biology, mathematics, astronomy, and others. But unlike most of the other sciences, geology has an extra dimension, that of time billions of years of it.

Geologists, the scientists who specialize in geology, study many things. They look at how the Earth was formed. They examine how the Earth continues to change over time. Geologists even study rocks to find out what the Earth was like millions of years ago. Geologists study the evidence that they see around them, but in most cases, they are observing the results of processes that happened thousands, millions, and even billions of years in the past. Those were processes that took place at incredibly slow rates (millimeters per year to centimeters per year) but because of the amount of time available, they produced massive results.

Engineering geology is the application of the science of geology to the technology of ground engineering and engineering sciences to design and construction in civil, mining and petroleum engineering, and to the environment Engineering geology has a connection with others sciences (**Fig.1.1.)**:

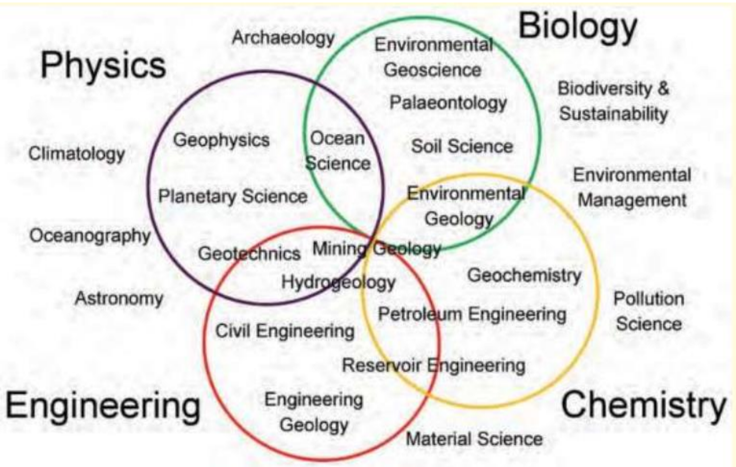


Fig. 1.1. Relating between engineering geology and other fields

The subject requires a comprehensive knowledge of geology, as well as an understanding of engineering properties and behavior of the geological materials. The practice involves site investigation and site characterization specific to the needs of the engineering project. In outline, the investigation should cover the area of terrain that is affected by the project, and any adjacent terrain from which geological processes could affect the project. Engineering geology provides the link between geology and engineering through the formation of geological models which can be used to identify geological hazards and uncertainty, plan effective ground investigations, and define blocks of ground and geological structures in an engineering context to facilitate geotechnical risk assessment and design. The **geotechnical engineer** plays a key role in most civil engineering projects as most structures are built on or in the ground. Geotechnical engineers assess the properties and behavior of soil and rock formations. In order to ensure safety, long term stability and quality control in modern tunneling operations, the acquisition of geotechnical information about encountered rock conditions and detailed installed support information is required.

Branches of Geology – The chief branches of engineering geology with which the engineer is concerned are:

Soil science, which studies rocks as soil;

Engineering geodynamics that studies how natural geological and engineering-geological processes and phenomena;

Regional engineering geology – section engineering geology, studying the patterns of spatial variability of engineering and geological conditions depending on the history of the Earth's crust and modern physical engineering conditions.

Relevance of geology to civil engineering

Most civil engineering projects involve some excavation of soils and rocks, or involve loading the Earth by building on it. In some cases, the excavated rocks may be used as constructional material, and in others, rocks may form a major part of the finished product, such as a motorway cutting or the site of or a reservoir. The feasibility, the planning and design, the construction and costing, and the safety of a project may depend critically on the geological conditions where the construction will take place. This is especially the case in extended ‘greenfield’ sites, where the area affected by the project stretches for kilometers, across comparatively undeveloped ground. In modest projects, or in those involving the redevelopment of a limited site, the demands on the geological knowledge of the engineer or the need for geological advice will be less, but are never negligible. Site investigation by boring and by testing samples may be an adequate preliminary to construction in such cases.

2 – Basic information about the Earth

Earth’s Interior

Figure 2.1 shows the Earth’s three major concentric zones. The **mantle** is the most voluminous of these zones. Although the mantle is solid rock, parts of it flow slowly, generally upward or downward, depending on whether it is hotter or colder than adjacent mantle. The other two zones are the **crust** and the **core.**

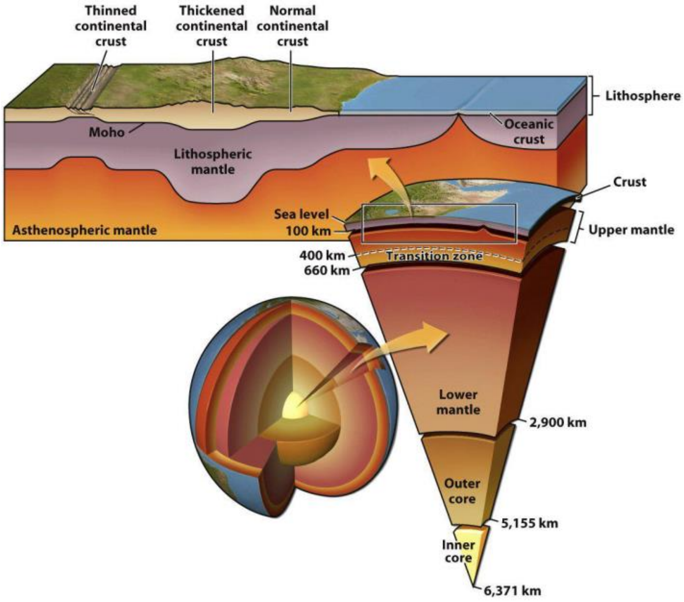


Fig. 2.1. Structure of the Earth

The core is believed to be mostly composed of the metals <u>iron</u> and <u>nickel</u>. It is divided into two zones, the ***solid inner core*** and the ***liquid outer core***.

Earth's Crust

<u>The crust of the Earth is analogous to the skin on an apple. The thickness of the crust is insignificant compared to the whole Earth.</u> It ranges from 5–70 km in depth and is the outermost layer. <u>The two major types of crust are ***oceanic crust*** and ***continental crust***.</u> The thin parts are the oceanic crust, which underlie the ocean basins (5–10 km) and are composed of dense dark igneous rock, like basalt. By contrast, the continental crust averages 35 to 40 kilometers thick but may exceed 70 kilometers in some mountainous regions such as the Rockies and Himalayas. Unlike the oceanic crust, which has a relatively homogeneous chemical composition, the continental crust consists of many rock types, which is less dense and composed of sodium, potassium, aluminum, silicate rocks, like granite. Although the upper crust has an average composition of a *granitic rock* called ***granodiorite***, it varies considerably from place to place. Continental rocks have an average density of about 2.7 gr/cm^3, and some have been discovered that are 4 billion years old. The rocks of the oceanic crust are younger (18 million years or less) and denser (about 3.0 gr/cm^3) than continental rocks.

Earth's mantle

Mantle extends to a depth of 2,890 km, making it the thickest layer of Earth. The pressure, at the bottom of the mantle, is ~140 GPa (1.4 Matm). The mantle is composed of silicate rocks that are rich in iron and magnesium relative to the overlying crust. Although solid, the high temperatures within the mantle cause the silicate material to be sufficiently ductile that it can flow on very long timescales. Convection of the mantle is expressed at the surface through the motions of tectonic plates. The melting point and viscosity of a substance depends on the pressure it is under. As there is intense and increasing pressure as one travels deeper into the mantle, the lower part of the mantle flows less easily than does the upper mantle (chemical changes within the mantle may also be important). The viscosity of the mantle ranges between 1021 and 1024 Pa·s, depending on depth. In comparison, the viscosity of water is approximately 10-3 Pa·s and that of pitch is 107 Pa·s (**Fig. 2.2.**).

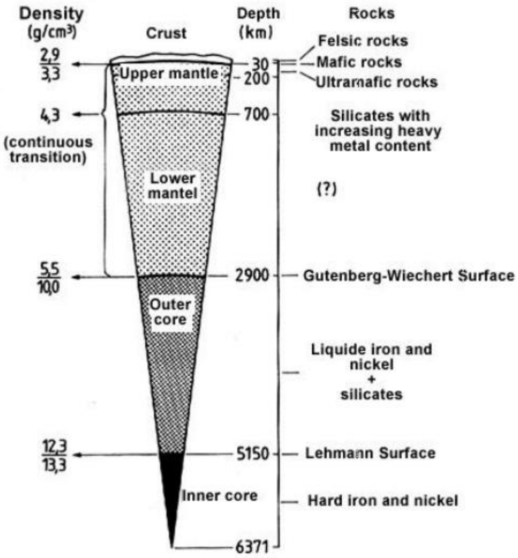


Fig. 2.2. The inner structure of the Earth and the characteristic boundaries

The **crust-mantle boundary** occurs as two physically different events. First, there is a discontinuity in the seismic velocity, which is known as Moho. The cause of the Moho is thought to be a change in rock composition from rocks containing plagioclase feldspar (above) to rocks that contain no feldspars (below). Second, in oceanic crust, there is a chemical discontinuity between ultramafic cumulates, which has been observed from deep parts of the oceanic crust that have been abducted onto the continental crust and preserved as ophiolite sequences. Many rocks now making up Earth's crust formed less than 100 million (1×108) years ago; however, the oldest known mineral grains are 4.4 billion (4.4×109) years old, indicating that Earth has had a solid crust for at least that long **(Fig. 2.3.).**

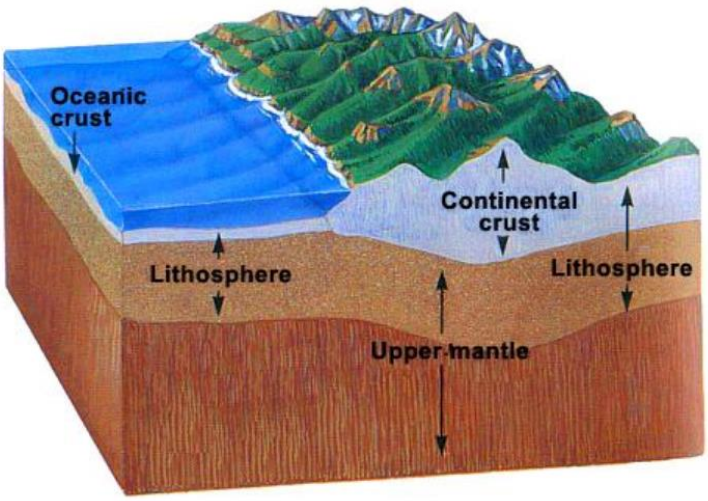


Fig. 2.3. Structure and thickness of the lithosphere

The crust and the uppermost part of the mantle are relatively rigid. Collectively, they make up the **lithosphere.** The uppermost mantle underlying the lithosphere, called the **asthenosphere,** is soft and therefore flows more readily than the underlying mantle.

Where hot mantle material wells upward, it will uplift the lithosphere. Where the lithosphere is coldest and densest, it will sink down through the asthenosphere and into the deeper mantle. The effect of this internal heat engine on the crust is of great significance to geology. The forces generated inside the Earth, called **tectonic forces,** cause deformation of rock as well as vertical and horizontal movement of portions of the Earth's crust. The existence of mountain ranges indicates that tectonic forces are stronger than gravitational forces. Mountain ranges are built over extended periods as portions of the Earth's crust are squeezed, stretched, and raised. Most tectonic forces are mechanical forces. Some of the energy from these forces is put to work deforming rock, bending and breaking it, and raising mountain ranges. The mechanical energy may be stored (an earthquake is a sudden release of stored mechanical energy) or converted to heat energy (rock may melt, resulting in volcanic eruptions). The working of the machinery of the Earth is elegantly demonstrated by plate tectonics.

The layering of Earth has been inferred indirectly using the time of travel of refracted and reflected seismic waves created by earthquakes. The core does not allow shear waves to pass through it, while the speed of travel (seismic velocity) is different in other layers. The changes in seismic velocity between different layers cause refraction owing to **Snell's law**. Reflections are caused by a large increase in seismic velocity and are similar to light reflecting from a mirror (**Fig. 2.4.).**

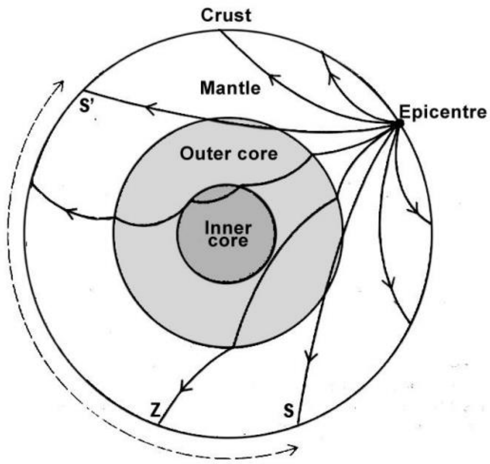


Fig. 2.4. The spreading of earthquake waves in the Earth

3 – Geophysical fields and the main geospheres of the Earth

The two principal divisions of Earth's surface are the continents and the ocean basins. A significant difference between these two areas is their relative levels. The continents are remarkably flat features that have the appearance of plateaus protruding above sea level. With an average elevation of about 0.8 kilometer, continental blocks lie close to sea level, except for limited areas of mountainous terrain. By contrast, the average depth of the ocean floor is about 3.8 kilometers below sea level, or about 4.5 kilometers lower than the average elevation of the continents.

The elevation difference between the continents and ocean basins is primarily the result of differences in their respective densities and thicknesses. Recall that the continents average 35–40 kilometers in thickness and are composed of granitic rocks having a density of about 2.7 g/cm^3. The basaltic rocks that comprise the oceanic crust average only 7 kilometers thick and have an average density of about 3.0 g/cm^3. Thus, the thicker and less dense continental crust is more buoyant than the oceanic crust. As a result, continental crust floats on top of the deformable rocks of the mantle at a higher level than oceanic crust for the same reason that a large, empty (less dense) cargo ship rides higher than a small, loaded (more dense) one.

Major Features of the Continents

The largest features of the continents can be grouped into two distinct categories: extensive, flat stable areas that have been eroded nearly to sea level, and uplifted regions of deformed rocks that make up present-day mountain belts. Notice in Fig. 3.2 that the young mountain belts tend to be long, narrow topographic features at the margins of continents, and the flat, stable areas are typically located in the interior of the continents.

Mountain Belts

The most prominent topographic features of the continents are linear mountain belts. Although the distribution of mountains appears to be random, this is not the case. When the youngest mountains are considered (those less than 100 million years old), we find that they are located principally in two major zones. The circum-Pacific belt (the region surrounding the Pacific Ocean) includes the mountains of the western Americas and continues into the western Pacific in the form of volcanic island arcs (Fig. 3.1).

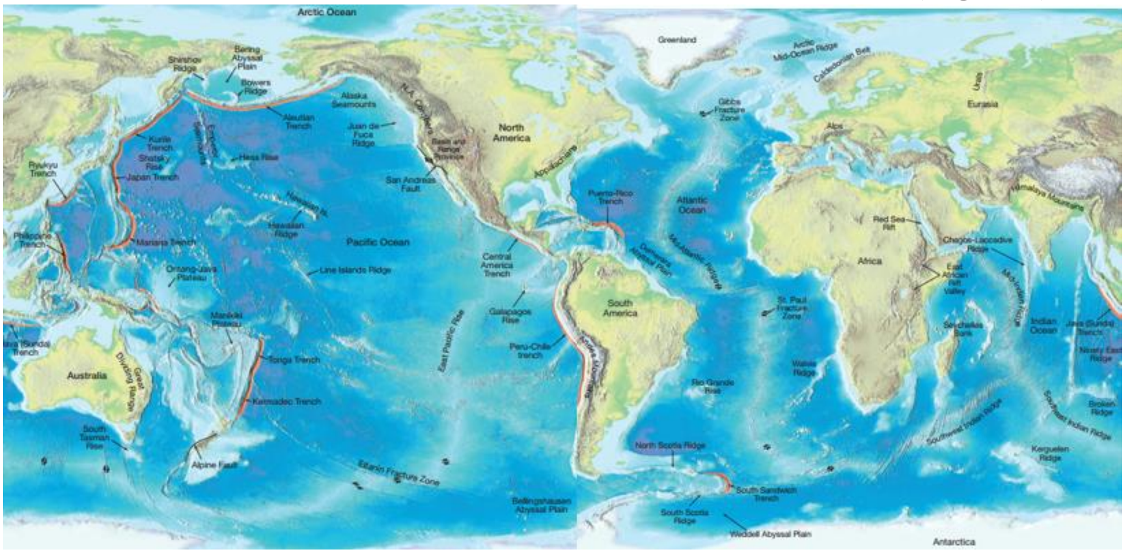


Fig. 3.1. The topography of Earth's solid surface is shown on these two pages

Island arcs are active mountainous regions composed largely of volcanic rocks and deformed sedimentary rocks. Examples include the Aleutian Islands, Japan, the Philippines, and New Guinea. The other major mountainous belt extends eastward from the Alps through Iran and the Himalayas and then dips southward into Indonesia. Careful examination of mountainous terrains reveals that most are places where thick sequences of rocks have been squeezed and highly deformed, as if placed in a gigantic vise. Older mountains are also found on the continents. Examples include the Appalachians in the eastern United States and the Urals in Russia. Their once lofty peaks are now worn low, the result of millions of years of erosion.

The Stable Interior

Unlike the young mountain belts, which have formed within the last 100 million years, the interiors of the continents, called **cratons,** have been relatively stable (undisturbed) for the last 600 million years, or even longer. Typically these crustal blocks were involved in a mountain-building episode much earlier in Earth's history.

Within the stable interiors are areas known as **shields,** which are expansive, flat regions composed of deformed crystalline rock.

All contain Precambrian-age rocks that are more than 1 billion years old, with some samples approaching 4 billion years in age. Even these oldest-known rocks exhibit evidence of enormous forces that have folded, faulted, and metamorphosed them. Thus, we conclude that these rocks were once part of an ancient mountain system that has since been eroded away to produce these expansive, flat regions.

Other flat areas of the craton exist in which highly deformed rocks, like those found in the shields, are covered by a relatively thin veneer of sedimentary rocks. These areas are called **stable platforms.** The sedimentary rocks in stable platforms are nearly horizontal except where they have been warped to form large basins or domes.

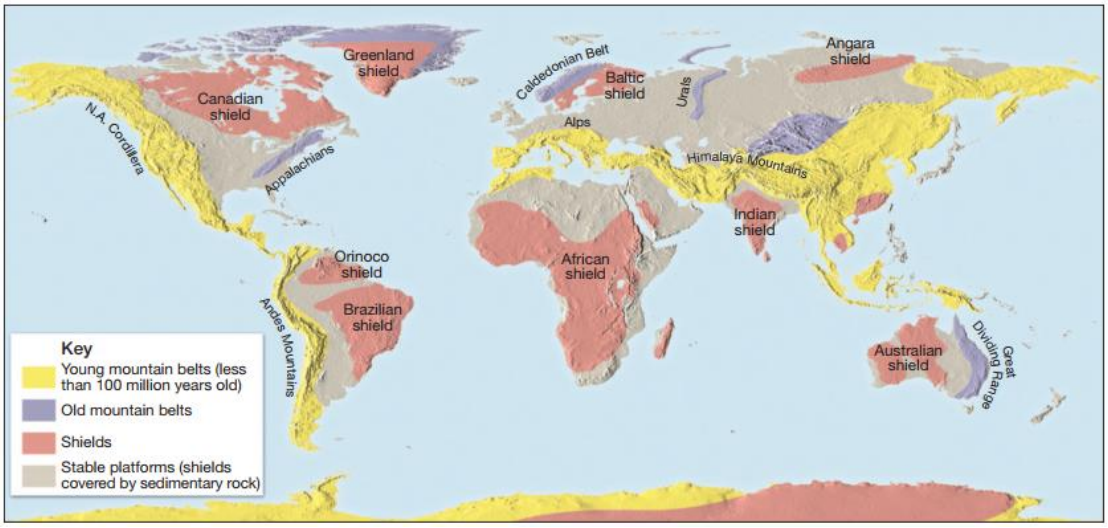


Fig. 3.2This map shows the general distribution of Earth's mountain belts, stable platforms and shields.

Major Features of the Ocean Floor

If all water were drained from the ocean basins, a great variety of features would be seen, including linear chains of volcanoes, deep canyons, plateaus, and large expanses of monotonously flat plains. In fact, the scenery would be nearly as diverse as that on the continents (see Fig. 3.1). During the past 50 years, oceanographers using modern depth-sounding equipment have slowly mapped significant portions of the ocean floor. From these studies they have delineated three major topographically distinct units: **continental margins**, **deep-ocean basins**, and **oceanic (mid-ocean) ridges**.

Continental Margins

The **continental margin** is that portion of the seafloor adjacent to major landmasses. It may include the **continental shelf**, the **continental slope**, and the **continental rise**. Although land and sea meet at the shoreline, this is not the boundary between the continents and the ocean basins. Rather, along most coasts a gently sloping platform of material, called the **continental shelf,** extends seaward from the shore. Because it is underlain by continental crust, it is clearly a flooded extension of the continents. A glance at Fig. 3.1 shows that the width of the continental shelf is variable. For example, it is broad along the East and Gulf coasts of the United States but relatively narrow along the Pacific margin of the continent. The boundary between the continents and the deep ocean basins lies along the **continental slope,** which is a relatively steep drop off that extends from the outer edge of the continental shelf to the floor of the deep ocean (Fig. 3.1). Using this as the dividing line, we find that about 60 percent of Earth's surface is represented by ocean basins and the remaining 40 percent by continents.

In regions where trenches do not exist, the steep continental slope merges into a more gradual incline known as the **continental rise.** The continental rise consists of a thick accumulation of sediments that moved downslope from the continental shelf to the deep-ocean floor. **Deep-Ocean Basins** Between the continental margins and oceanic ridges lie the deep-ocean basins. Parts of these regions consist of incredibly flat features called **abyssal plains.** The ocean floor also contains extremely deep depressions that are occasionally more than 11,000 meters deep. Although these **deep-ocean trenches** are relatively narrow and represent only a small fraction of the ocean floor, they are nevertheless very significant features. Some trenches are located adjacent to young mountains that flank the continents. For example, in Fig. 3.1 the Peru–Chile trench off the west coast of South America parallels the Andes Mountains. Other trenches parallel linear island chains called **volcanic island arcs**. Dotting the ocean floor are submerged volcanic structures called **seamounts,** which sometimes form long narrow chains. Volcanic activity has also produced several large lava plateaus, such as the On tong Java Plateau located northeast of New Guinea. In addition, some submerged plateaus are composed of continental-type crust. Examples include the Campbell Plateau southeast of New Zealand and the Seychelles plateau northeast of Madagascar. **Oceanic Ridges** The most prominent feature on the ocean floor is the **oceanic** or **mid-ocean ridge.**

As shown in Fig**.** 3.1, the Mid-Atlantic Ridge and the East Pacific Rise are parts of this system. This broad elevated feature forms a continuous belt that winds for more than 70,000 kilometers around the globe in a manner similar to the seam of a baseball. Rather than consisting of highly deformed rock, such as most of the mountains on the continents, the oceanic ridge system consists of layer upon layer of igneous rock that has been fractured and uplifted. Understanding the topographic features that comprise the face of Earth is critical to our understanding of the mechanisms that have shaped our planet.

4 –The material composition of the Earth's crust

Rocks and the Rock Cycle

Rock is the most common and abundant material on Earth. To a curious traveler, the variety seems nearly endless. When a rock is examined closely, we find that it consists of smaller crystals or grains called minerals. **Minerals** are chemical compounds (or sometimes single elements), each with its own composition and physical properties. The grains or crystals may be microscopically small or easily seen with the unaided eye.

The nature and appearance of a rock is strongly influenced by the minerals that compose it. In addition, a rock's **texture** – the size, shape, and/or arrangement of its constituent minerals – also has a significant effect on its appearance. A rock's mineral composition and texture, in turn, are a reflection of the geologic processes that created it.

The characteristics of the rocks provided geologists with the clues they needed to determine the processes that formed them. This is true of all rocks. Such analyses are critical to an understanding of our planet. This understanding has many practical applications, as in the search for basic mineral and energy resources and the solution of environmental problems.

Basic Rock Types

Geologists divide rocks into three major groups: **igneous**, **sedimentary**, and **metamorphic**. What follows is a brief look at these three basic rock groups. As you will learn, each group is linked to the others by the processes that act upon and within the planet.

Igneous Rocks

Igneous rocks form when molten rock, called **magma,** cools and solidifies. Magma is melted rock that can form at various levels deep within Earth's crust and upper mantle. As magma cools, crystals of various minerals form and grow. When magma remains deep within the crust, it cools slowly over thousands of years. This gradual loss of heat allows relatively large crystals to develop before the entire mass is completely solidified. Coarse-grained igneous rocks that form far below the surface are called intrusive**.** The cores of many mountains consist of igneous rock that formed in this way. Only subsequent uplift and erosion expose this rock at the surface. A common and important example is **granite** (Figure 4.1).

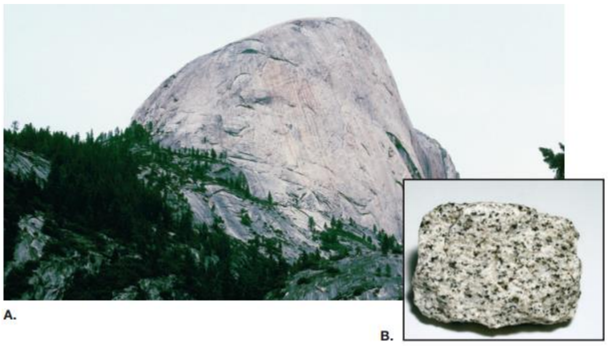


Fig. 4.1 Granite is an intrusive igneous rock that is especially abundant in Earth's continental crust. A. Erosion has uncovered this mass of granite B. This sample of granite shows its coarse-grained texture

Granite and related rocks are major constituents of the continental crust. Sometimes magma breaks through at Earth's surface, as during a volcanic eruption. Because it cools quickly in a surface environment, the molten rock solidifies rapidly, and there is not sufficient time for large crystals to grow. Rather, there is the simultaneous formation of many tiny crystals.

Igneous rocks that form at Earth's surface are described as extrusive and are usually fine-grained. An abundant and important example is **basalt**. This black to dark green rock is rich in silicate minerals that contain significant iron and magnesium. Because of its higher iron content, basalt is denser than granite. Basalt and related rocks make up the oceanic crust as well as many volcanoes both in the ocean and on the continents.

Sedimentary Rocks

Sediments, the raw materials for sedimentary rocks, accumulate in layers at Earth's surface. They are materials derived from preexisting rocks by the processes of **weathering.** Some of these processes physically break rock into smaller pieces with no change in composition.

Other weathering processes decompose rock – that is, chemically change minerals into new minerals and into substances that readily dissolve in water. The products of weathering are usually transported by water, wind, or glacial ice to sites of deposition where they form relatively flat layers called **beds.** Sediments are commonly turned into rock or **lithified** by one of two processes.

Compaction takes place as the weight of overlying materials squeezes sediments into denser masses. Cementation occurs as water containing dissolved substances percolates through the open spaces between sediment grains. Over time the material dissolved in water is chemically precipitated onto the grains and cements them into a solid mass. Sediments that originate and are transported as solid particles are called **detrital sediments**, and the rocks they form are called detrital sedimentary rocks. Particle size is the primary basis for naming the members in this category. Two common examples are **shale** and **sandstone**. Shale is a fine-grained rock consisting of clay-size (less than 1/256 mm) and silt-size (1/256 to 1/16 mm) particles. The deposition of these tiny grains is associated with environments such as swamps, river floodplains, and portions of deep-ocean basins. Sandstone is the name given sedimentary rocks in which sand-size (1/16 to 2 mm) grains predominate. Sandstones are associated with a variety of environments, including beaches and dunes.

Chemical sedimentary rocks form when material dissolved in water precipitates. Unlike detrital sedimentary rocks that are subdivided on the basis of particle size, the primary basis for distinguishing among chemical sedimentary rocks is their mineral composition. Limestone, the most common chemical sedimentary rock, is composed chiefly of the mineral calcite (calcium carbonate, CaCO3). There are many varieties of limestone (Figure 4.2). The most abundant types have a biochemical origin, meaning that water-dwelling organisms extract dissolved mineral matter and create hard parts such as shells. Later these hard parts accumulate as sediment.

Fig. 4.2. Limestone is a chemical sedimentary rock in which the mineral calcite predominates.

Geologists estimate that sedimentary rocks account for only about 5 percent (by volume) of Earth’s outer 16 kilometers. However, the importance of this group of rocks is far greater than this percentage implies. If you sampled the rocks exposed at Earth’s surface, you would find that the great majority are sedimentary. In fact, about 75 percent of all rock outcrops on the continents are sedimentary.

Therefore, we can think of sedimentary rocks as comprising a relatively thin and somewhat discontinuous layer in the uppermost portion of the crust. This makes sense because sediment accumulates at the surface. It is from sedimentary rocks that geologists reconstruct many details of Earth’s history. Because sediments are deposited in a variety of different settings at the surface, the rock layers that they eventually form hold many clues to past surface environments. They may also exhibit characteristics that allow geologists to decipher information about the method and distance of sediment transport. Furthermore, it is sedimentary rocks that contain fossils, which are vital sources of data in the study of the geologic past.

Metamorphic Rocks

Metamorphic rocks are produced from preexisting igneous, sedimentary, or even other metamorphic rocks. Thus, every metamorphic rock has a parent rock – the rock from which it formed. Metamorphic is an appropriate name because it literally means to change form.

Most changes occur at the elevated temperatures and pressures that exist deep in Earth’s crust and upper mantle. The processes that create metamorphic rocks often progress incrementally, from slight changes (low-grade metamorphism) to substantial changes (high-grade metamorphism).

For example, during low-grade metamorphism, the common sedimentary rock shale becomes the more compact metamorphic rock slate. By contrast, high-grade metamorphism causes a transformation that is so complete that the identity of the parent rock cannot be determined. Furthermore, when rocks at depth (where temperatures are high) are subjected to directed pressure, they gradually deform to generate intricate folds. In the most extreme metamorphic environments, the temperatures approach those at which rocks melt. However, during metamorphism the rock must remain essentially solid, for if complete melting occurs, we have entered the realm of igneous activity. Most metamorphism occurs in one of three settings:

1. When rock is intruded by a magma body, contact or thermal metamorphism may take place. Here, change is driven by a rise in temperature within the host rock surrounding an igneous intrusion.

2. Hydrothermal metamorphism involves chemical alterations that occur as hot, ion-rich water circulates through fractures in rock. This type of metamorphism is usually associated with igneous activity that provides the heat required to drive chemical reactions and circulate these fluids through rock.

3. During mountain building, great quantities of deeply buried rock are subjected to the directed pressures and high temperatures associated with large-scale deformation called regional metamorphism.

The degree of metamorphism is reflected in the rock's texture and mineral makeup. During regional metamorphism the crystals of some minerals will recrystallize with an orientation that is perpendicular to the direction of the compressional force. The resulting mineral alignment often gives the rock a layered or banded appearance termed a foliated texture. Schist and gneiss are two examples (Figure 4.3.A).

A. B.

Fig. 4.3. Common metamorphic rocks.
A. The foliated rock gneiss often has a banded appearance and frequently has a mineral composition similar to the igneous rock granite.
B. Marble is a coarse, crystalline, nonfoliated rock whose parent rock is limestone.

Not all metamorphic rocks have a foliated texture. Such rocks are said to exhibit a non-foliated texture. Metamorphic rocks composed of only one mineral that forms equidimensional crystals are, as a rule, not visibly foliated. For example, limestone, if pure, is composed of only a single mineral, calcite. When a fine-grained limestone is metamorphosed, the small calcite crystals combine to form larger, interlocking crystals. The resulting rock resembles a coarse-grained igneous rock. This non-foliated metamorphic equivalent of limestone is called **marble** (Figure 4.3B). Extensive areas of metamorphic rocks are exposed on every continent. Metamorphic rocks are an important component of many mountain belts, where they make up a large portion of a mountain's crystalline core. Even the stable continental interiors, which are generally covered by sedimentary rocks, are underlain by metamorphic basement rocks.

In all of these settings, the metamorphic rocks are usually highly deformed and intruded by igneous masses. Indeed, significant parts of Earth's continental crust are composed of metamorphic and associated igneous rocks.

The Rock Cycle: One of Earth's Subsystems

Earth is a system. This means that our planet consists of many interacting parts that form a complex whole. Nowhere is this idea better illustrated than when we examine the rock cycle. The **rock cycle** allows us to view many of the interrelationships among different parts of the Earth system. It helps us understand the origin of igneous, sedimentary, and metamorphic rocks and to see that each type is linked to the others by processes that act upon and within the planet. Learn the rock cycle well; you will be examining its interrelationships in greater detail throughout this book.

The **Basic Cycle** We begin at the bottom of with magma, molten rock that forms deep beneath Earth's surface. Over time, magma cools and solidifies.

This process, called **crystallization**, may occur either beneath the surface or, following a volcanic eruption, at the surface. In either situation, the resulting rocks are called igneous rocks. If igneous rocks are exposed at the surface, they will undergo weathering, in which the day-in and day-out influences of the atmosphere slowly disintegrate and decompose rocks. The materials that result are often moved downslope by gravity before being picked up and transported by any of a number of erosional agents, such as running water, glaciers, wind, or waves. Eventually these particles and dissolved substances, called **sediment**, are deposited. Although most sediment ultimately comes to rest in the ocean, other sites of deposition include river floodplains, desert basins, swamps, and dunes. Next the sediments undergo **lithification**, a term meaning conversion into rock. Sediment is usually lithified into sedimentary rock when compacted by the weight of overlying layers or when cemented as percolating groundwater fills the pores with mineral matter.

If the resulting sedimentary rock is buried deep within Earth and involved in the dynamics of mountain building or intruded by a mass of magma, it will be subjected to great pressures and/or intense heat. The sedimentary rock will react to the changing environment and turn into the third rock type, metamorphic rock. When metamorphic rock is subjected to additional pressure changes or to still higher temperatures, it will melt, creating magma, which will eventually crystallize into igneous rock. Processes driven by heat from Earth's interior are responsible for creating igneous and metamorphic rocks. Weathering and erosion, external processes powered by energy from the Sun, produce the sediment from which sedimentary rocks form.

Alternative Paths The paths shown in the basic cycle are not the only ones that are possible. To the contrary, other paths are just as likely to be followed as those described in the preceding section. These alternatives are indicated by the blue arrows Igneous rocks, rather than being exposed to weathering and erosion at Earth's surface, may remain deeply buried. Eventually these masses may be subjected to the strong compressional forces and high temperatures associated with mountain building. When this occurs, they are transformed directly into metamorphic rocks.

Metamorphic and sedimentary rocks, as well as sediment, do not always remain buried. Rather, overlying layers may be stripped away, exposing the once buried rock. When this happens, the material is attacked by weathering processes and turned into new raw materials for sedimentary rocks. Although rocks may seem to be unchanging masses, the rock cycle shows that they are not. The changes, however, take time – great amounts of time.

Physical Properties of Minerals

Each mineral has a definite crystalline structure and chemical composition that give it a unique set of physical and chemical properties shared by all samples of that mineral.

For example, all specimens of halite have the same hardness, the same density, and break in a similar manner. Because the internal structure and chemical composition of a mineral are difficult to determine without the aid of sophisticated tests and equipment, the more easily recognized physical properties are frequently used in identification. The diagnostic physical properties of minerals are those that can be determined by observation or by performing a simple test. The primary physical properties that are commonly used to identify hand samples are luster, color, streak, crystal shape (habit), tenacity, hardness, cleavage, fracture, and density or specific gravity. Secondary (or special) properties that are exhibited by a limited number of minerals include magnetism, taste, feel, smell, double refraction, and chemical reaction to hydrochloric acid.

Optical Properties

Of the many optical properties of minerals, four—luster, the ability to transmit light, color, and streak—are most frequently used for mineral identification. **Luster** The appearance or quality of light reflected from the surface of a mineral is known as **luster.** Minerals that have the appearance of metals, regardless of color, are said to have a metallic luster (Fig. 4.4.). Some metallic minerals, such as native copper and galena, develop a dull coating or tarnish when exposed to the atmosphere. Because they are not as shiny as samples with freshly broken surfaces, these samples are often said to exhibit a submetallic luster.

Most minerals have a nonmetallic luster and are described using various adjectives such as vitreous or glassy. Other nonmetallic minerals are described as having a dull or earthy luster (a dull appearance like soil), or a pearly luster (such as a pearl, or the inside of a clamshell). Still others exhibit a silky luster (like satin cloth), or a greasy luster (as though coated in oil).

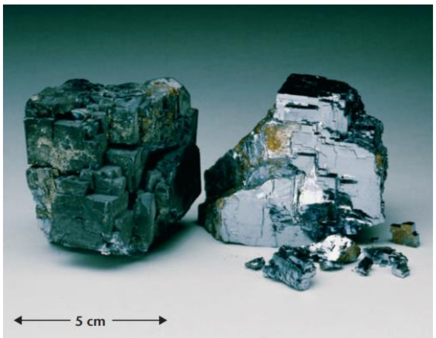


Fig. 4.4. The freshly broken sample of galena (right) displays a metallic luster, while the sample on the left is tarnished and has a submetallic luster.

The Ability to Transmit Light

Another optical property used in the identification of minerals is the ability to transmit light. When no light is transmitted, the mineral is described as opaque; when light but not an image is transmitted through a mineral it is said to be translucent. When light and an image are visible through the sample, the mineral is described as transparent.

Color

Although **color** is generally the most conspicuous characteristic of any mineral, it is considered a diagnostic property of only a few minerals. Slight impurities in the common mineral quartz, for example, give it a variety of tints including pink, purple, yellow, white, gray, and even black. Other minerals, such as tourmaline, also exhibit a variety of hues, with multiple colors sometimes occurring in the same sample. Thus, the use of color as a means of identification is often ambiguous or even misleading.

Streak

Although the color of a sample is not always helpful in identification, **streak**, the color of the powdered mineral, is often diagnostic. The streak is obtained by rubbing the mineral across a piece of unglazed porcelain, termed a streak plate and observing the color of the mark it leaves (Fig. 4.5.). Although the color of a mineral may vary from sample to sample, the streak usually does not. Streak can also help distinguish between minerals with metallic luster and those having nonmetallic luster. Metallic minerals generally have a dense, dark streak, whereas minerals with nonmetallic luster have a streak that is typically light colored.

It should be noted that not all minerals produce a streak when using a streak plate. For example, if the mineral is harder than the streak plate, no streak is observed.

Fig. 4.5. Although the color of a mineral is not always helpful in identification, the streak, which is the color of the powdered mineral, can be very useful.

Crystal Shape or Habit

Mineralogists use the term **habit** to refer to the common or characteristic shape of a crystal or aggregate of crystals. A few minerals exhibit somewhat regular polygons that are helpful in their identification. Recall that magnetite crystals sometimes occur as octahedrons, garnets often form dodecahedrons, and halite and fluorite crystals tend to grow as cubes or near cubes. While most minerals have only one common habit, a few such as pyrite have two or more characteristic crystal shapes (Fig. 4.6.). By contrast, some minerals rarely develop perfect geometric forms. Many of these do, however, develop a characteristic shape that is useful for identification. Some minerals tend to grow equally in all three dimensions, whereas others tend to be elongated in one direction, or flattened if growth in one dimension is suppressed. Commonly used terms to describe these and other crystal habits include equant (equidimensional), bladed, fibrous, tabular, prismatic, platy, blocky, and botryoidal.

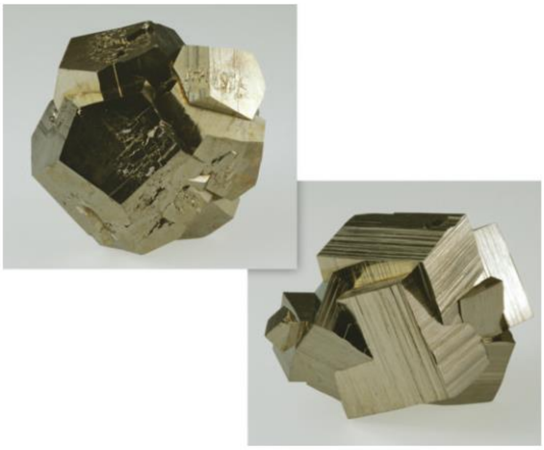


Fig. 4.6. Although most minerals exhibit only one common crystal shape, some, such as pyrite, have two or more characteristic habits. (Photos by Dennis Tasa)

Mineral Strength

How easily minerals break or deform under stress relates to the type and strength of the chemical bonds that hold the crystals together. Mineralogists use terms including tenacity, hardness, cleavage, and fracture to describe mineral strength and how minerals break when stress is applied.

Tenacity

The term **tenacity** describes a mineral's toughness, or its resistance to breaking or deforming. Minerals which are ionically bonded, such as fluorite and halite, tend to be brittle and shatter into small pieces when struck. By contrast, minerals with metallic bonds, such as native copper, are malleable, or easily hammered into different shapes. Minerals, including gypsum and talc, that can be cut into thin shavings are described as sectile. Still others, notably the micas, are elastic and will bend and snap back to their original shape after the stress is released.

Hardness

One of the most useful diagnostic properties is **hardness,** a measure of the resistance of a mineral to abrasion or scratching. This property is determined by rubbing a mineral of unknown hardness against one of known hardness, or vice versa. A numerical value of hardness can be obtained by using the **Mohs scale** of hardness, which consists of 10 minerals arranged in order from 1 (softest) to 10 (hardest). It should be noted that the Mohs scale is a relative ranking, and it does not imply that mineral number 2, gypsum, is twice as hard as mineral 1, talc. In fact, gypsum is only slightly harder than talc. In the laboratory, other common objects can be used to determine the hardness of a mineral. These include a human fingernail, which has a hardness of about 2.5, a copper penny 3.5, and a piece of glass 5.5. The mineral gypsum, which has a hardness of 2, can be easily scratched with a fingernail. On the other hand, the mineral calcite, which has a hardness of 3, will scratch a fingernail but will not scratch glass. Quartz, one of the hardest common minerals, will easily scratch glass. Diamonds, hardest of all, scratch anything.

Cleavage

Some minerals have atomic structures that are not the same in every direction and chemical bonds that vary in strength. As a result, these minerals tend to break, so that the broken fragments are bounded by more or less flat, planar surfaces, a property called **cleavage.** Cleavage can be recognized by rotating a sample and looking for smooth, even surfaces that reflect light like a mirror. Note, however, that cleavage surfaces can occur in small, flat segments arranged in stair-step fashion.

The simplest type of cleavage is exhibited by the micas. Because the micas have much weaker bonds in one direction than in the others, they cleave to form thin, flat sheets. Some minerals have excellent cleavage in several directions, whereas others exhibit fair or poor cleavage, and still others have no cleavage at all. When minerals break evenly in more than one direction, cleavage is described by the number of cleavage planes and the angle(s) at which they meet.

Do not confuse cleavage with crystal shape. When a mineral exhibits cleavage, it will break into pieces that have the same geometry as each other. By contrast, the smooth-sided quartz crystals shown in do not have cleavage. If broken, they fracture into shapes that do not resemble each other or the original crystals.

Fracture

Minerals that have structures that are equally, or nearly equally, strong in all directions **fracture** to form irregular surfaces. Those, such as quartz, that break into smooth curved surfaces resembling broken glass exhibit a conchoidal fracture. Others break into splinters or fibers, but most minerals display an irregular fracture.

Density and Specific Gravity

Density is an important property of matter defined as mass per unit volume usually expressed as grams per cubic centimeter. Mineralogists often use a related measure called specific gravity to describe the density of minerals.

Specific gravity is a unitless number representing the ratio of a mineral's weight to the weight of an equal volume of water.

Most common rock-forming minerals have a specific gravity of between 2 and 3. For example, quartz has a specific gravity of 2.65. By contrast, some metallic minerals such as pyrite, native copper and magnetite are more than twice as dense as quartz. Galena, which is an ore of lead, has a specific gravity of roughly 7.5, whereas the specific gravity of 24-karat gold is approximately 20. With a little practice, you can estimate the specific gravity of a mineral by hefting it in your hand.

Earth's Spheres

Earth can be thought of as consisting of four major spheres: **the hydrosphere**, **atmosphere**, **geosphere**, and **biosphere**. The interactions among Earth's four spheres are incalculable. The shoreline is an obvious meeting place for rock, water, and air. In this scene, ocean waves that were created by the drag of air moving across the water are breaking against the rocky shore. The force of the water can be powerful, and the erosional work that is accomplished can be great.

Hydrosphere

Earth is sometimes called the blue planet. Water more than anything else makes Earth unique. The **hydrosphere** is a dynamic mass of water that is continually on the move, evaporating from the oceans to the atmosphere, precipitating to the land, and running back to the ocean again. The global ocean is certainly the most prominent feature of the hydrosphere, blanketing nearly 71 percent of Earth's surface to an average depth of about 3800 meters. It accounts for about 97 percent of Earth's water. However, the hydrosphere also includes the fresh water found underground and in streams, lakes, and glaciers. Moreover, water is an important component of all living things. Although these latter sources constitute just a tiny fraction of the total, they are much more important than their meager percentage indicates. In addition to providing the fresh water that is so vital to life on land, streams, glaciers, and groundwater are responsible for sculpting and creating many of our planet's varied landforms.

Atmosphere

Earth is surrounded by a life-giving gaseous envelope called the **atmosphere.** Compared with the solid Earth, the atmosphere is thin and tenuous. One half lies below an altitude of 5.6 kilometers, and 90 percent occurs within just 16 kilometers of Earth's surface. By comparison, the radius of the solid Earth (distance from the surface to the center) is about 6400 kilometers! Despite its modest dimensions, this thin blanket of air is an integral part of the planet. It not only provides the air that we breathe but also protects us from the Sun's intense heat and dangerous ultraviolet radiation. The energy exchanges that continually occur between the atmosphere and Earth's surface and between the atmosphere and space produce the effects we call weather and climate. If, like the Moon, Earth had no atmosphere, our planet would not only be lifeless but many of the processes and interactions that make the surface such a dynamic place could not operate. Without weathering and erosion, the face of our planet might more closely resemble the lunar surface, which has not changed appreciably in nearly 3 billion years.

Biosphere

The **biosphere** includes all life on Earth. Ocean life is concentrated in the sunlit surface waters of the sea. Most life on land is also concentrated near the surface, with tree roots and burrowing animals reaching a few meters underground and flying insects and birds reaching a kilometer or so into the atmosphere. A surprising variety of life forms are also adapted to extreme environments. For example, on the ocean floor where pressures are extreme and no light penetrates, there are places where vents spew hot, mineral-rich fluids that support communities of exotic life forms. On land, some bacteria thrive in rocks as deep as 4 kilometers and in boiling hot springs. Moreover, air currents can carry microorganisms many kilometers into the atmosphere. But even when we consider these extremes, life still must be thought of as being confined to a narrow band very near Earth's surface. Plants and animals depend on the physical environment for the basics of life. However, organisms do not just respond to their physical environment. Indeed, the biosphere powerfully influences the other three spheres. Without life, the makeup and nature of the geosphere, hydrosphere, and atmosphere would be very different.

Geosphere

Lying beneath the atmosphere and the oceans is the solid Earth, or **geosphere.** The geosphere extends from the surface to the center of the planet, a depth of nearly 6400 kilometers, making it by far the largest of Earth's four spheres. Much of our study of the solid Earth focuses on the more accessible surface features. Fortunately, many of these features represent the outward expressions of the dynamic behavior of Earth's interior. By examining the most prominent surface features and their global extent, we can obtain clues to the dynamic processes that have shaped our planet. A first look at the structure of Earth's interior and at the major surface features of the geosphere will come later in the chapter. Soil, the thin veneer of material at Earth's surface that supports the growth of plants, may be thought of as part of all four spheres. The solid portion is a mixture of weathered rock debris (geosphere) and organic matter from decayed plant and animal life (biosphere). The decomposed and disintegrated rock debris is the product of weathering processes that require air (atmosphere) and water (hydrosphere). Air and water also occupy the open spaces between the solid particles.

Materials of the lithosphere – petrological bases

As mentioned earlier, the lithosphere is the rigid outermost shell of the Earth. It comprises the crust and the portion of the upper mantle that behaves elastically on time scales of thousands of years or greater. The lithosphere is underlain by the asthenosphere, the weaker, hotter, and deeper part of the upper mantle. Rocks of the lithosphere are generally classified by mineral and chemical composition, by the texture of the constituent particles and by the processes that formed them. These indicators separate rocks into igneous, sedimentary, and metamorphic (Fig. 4.7.).

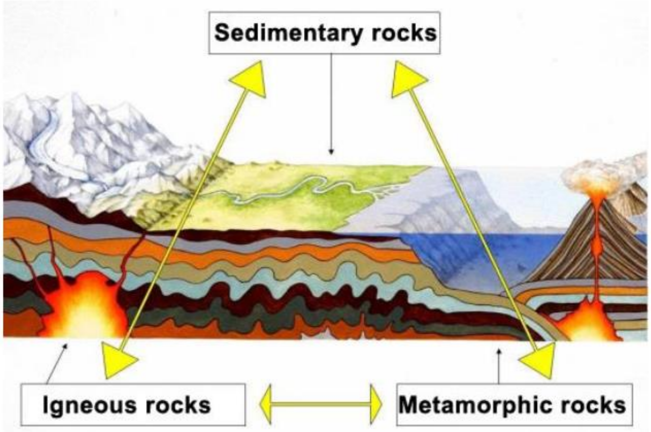


Fig. 4.7. The rock cycle

The material composition of the Earth's crust

This solid crust is made up almost wholly of igneous rock-that is, rock that has solidified from a hot, liquid (molten) condition, either as plutonic rock, found at different depths beneath the surface, as dikes or sills filling crevices, or as lava flows at the surface. Assuming a thickness of 16 km, the composition of the rocks of the crust is esti1nated to be about as follows:

Proportion of rocks of different classes in the earth's crust:

Igneous rocks	95.0
Shales..................................	4.0
Sandstones............................	0.75
Limestone....................·.......	0.25

The metamorphic rocks, such as gneiss and schist, are here included with the igneous rocks. In a study of the chemistry of the crust as a whole such relatively small masses as beds of coal or deposits of salt and ore are negligible, though their presence is significant, and the coating of soil is also negligible.

The most abundant or major constituents, stated as oxides, in the order in which they are stated in the analyses, which is not quite the order of their abundance, are silica ($Si0_2$), Alumina (Al_20), Ferric oxide (Fe_20_3), Ferrous oxide (Fe0), Magnesia (Mg0), Lime (Ca0), Soda (Na_20),·Potash (K_20), and water (H_20). These nine oxides together make up about 98 per cent of the igneous rocks, and all occur in greater or less amount in practically every rock, so-that the quantity of each must be determined in every rock analysis that makes the slightest pretense to good quality (Fig.4.8.).

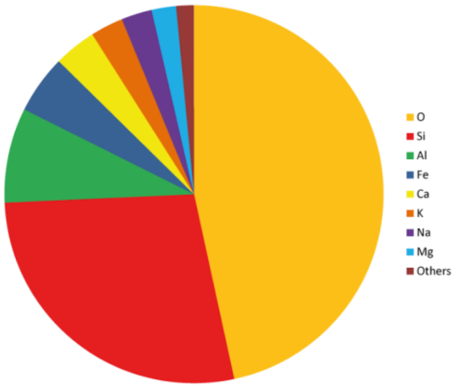


Fig. 4.8. The most common chemical elements in the crust are oxygen (46.6%), silicon (27.7%), aluminum (8.1%), iron (5.0%), calcium (3.6%), potassium (2.8%), sodium (2.6%), and magnesium (2.1%)

The composition of crust depends on whether we want to know which chemical elements, minerals or rock types it is made of. It may be surprising but about a dozen chemical elements, minerals, or rock types is all that it takes to describe approximately 99% of the crust.

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	59. 84	59. 10	62. 39	56. 89	59. 83	64. 04	60. 58	58. 84	56. 93	60. 69	58. 98	54. 22	64. 73
Al_2O_3	15. 12	13. 80	15. 16	15. 54	16. 08	14. 24	16. 43	14. 44	15. 86	14. 67	16. 28	16. 30	15. 92
Fe_2O_3	3. 17	3. 14	2. 40	2. 69	3. 65	3. 65	2. 75	3. 35	3. 72	2. 76	2. 53	4. 28	3. 15
FeO	3. 67	4. 57	3. 04	3. 57	3. 21	3. 41	2. 88	3. 91	3. 78	3. 28	3. 44	5. 54	2. 28
MgO	3. 61	4. 80	3. 79	4. 57	2. 26	1. 82	2. 16	4. 63	4. 15	4. 56	3. 03	5. 02	1. 76
CaO	4. 97	5. 41	3. 92	4. 43	3. 64	3. 25	3. 35	5. 56	6. 45	4. 37	5. 16	7. 60	4. 49
Na_2O	3. 73	3. 55	3. 70	4. 56	5. 10	3. 70	6. 11	3. 45	3. 61	3. 52	3. 72	2. 99	3. 69
K_2O	3. 40	2. 68	3. 23	4. 47	3. 52	3. 82	3. 96	3. 04	2. 96	3. 56	4. 67	1. 92	2. 56
H_2O+	1. 24	1. 44	1. 46	1. 19	. 75	. 84	. 71	1. 40	1. 45	1. 68	. 94	1. 17	1. 03
TiO_2	. 83	. 97	. 75	1. 34	1. 64	. 73	. 56	. 87	. 58	. 65	. 85	. 66	. 31
P_2O_5	. 23	. 22	. 12	. 34	. 12	. 25	. 27	. 29	. 27	. 19	. 22	. 07	. 03
MnO	. 08	. 14	. 01	. 07	. 10	. 15	. 19	. 04	. 14	. 03	. 04	. 14	. 03
Inclusive	. 11	. 18	. 03	. 34	. 10	. 10	. 05	. 18	. 10	. 04	. 14	. 09	. 02
	100. 00	100. 00	100. 00	100. 00	100. 00	100. 00	100. 00	100. 00	100. 00	100. 00	100. 00	100. 00	100. 00

1. Europe; 1,985 analyses.
2. British Islands; 171 analyses.
3. France, including Corsica; 163 analyses.
4. Iberia (Spain and Portugal); 33 analyses.
5. Norway, 107 analyses; including Iceland.
6. Sweden, including Spitzbergen; 206 analyses.
7. Finland, including Kola; 59 analyses.
8. Germany; 474 analyses.
9. Austria-Hungary-Bohemia, excluding Tyrol; 148 analyses.
10. Switzerland, including Tyrol; 217 analyses.
11. Italy, including Sicily, Sardinia, and islands; 276 analyses.
12. Russia, including Ural region and Caucasus, excluding Finland and Siberia; 98 analyses.
13. Balkania, including Greece and Archipelago; 33 analyses.

5 – Magmatism

Igneous rocks

Igneous rock is formed through the cooling and solidification of magma or lava. Igneous rock may form with or without crystallization, either below the surface as intrusive (plutonic) rocks or on the surface as extrusive (volcanic) rocks. This magma can be derived from partial melts of pre-existing rocks in either a planet's mantle or crust. Typically, the melting is caused by one or more of three processes: an increase in temperature, a decrease in pressure, or a change in composition (Fig. 5.1.).

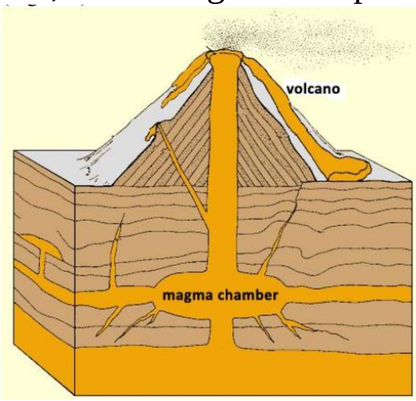


Fig. 5.1. The places of igneous rock formation

Igneous rocks form when **magma cools** and solidifies. **Extrusive**, or **volcanic**, igneous rocks result when **lava** cools at the surface. Magma that solidifies at depth produces **intrusive**, or **plutonic**, igneous rocks.

As magma cools, the ions that compose it arrange themselves into orderly patterns during a process called **crystallization**. Slow cooling results in the formation of rather large crystals. Conversely, when cooling occurs rapidly, the outcome is a solid mass consisting of tiny inter-grown crystals. When molten material is quenched instantly, a mass of unordered atoms, referred to **as glass**, forms (Fig. 5.2.).

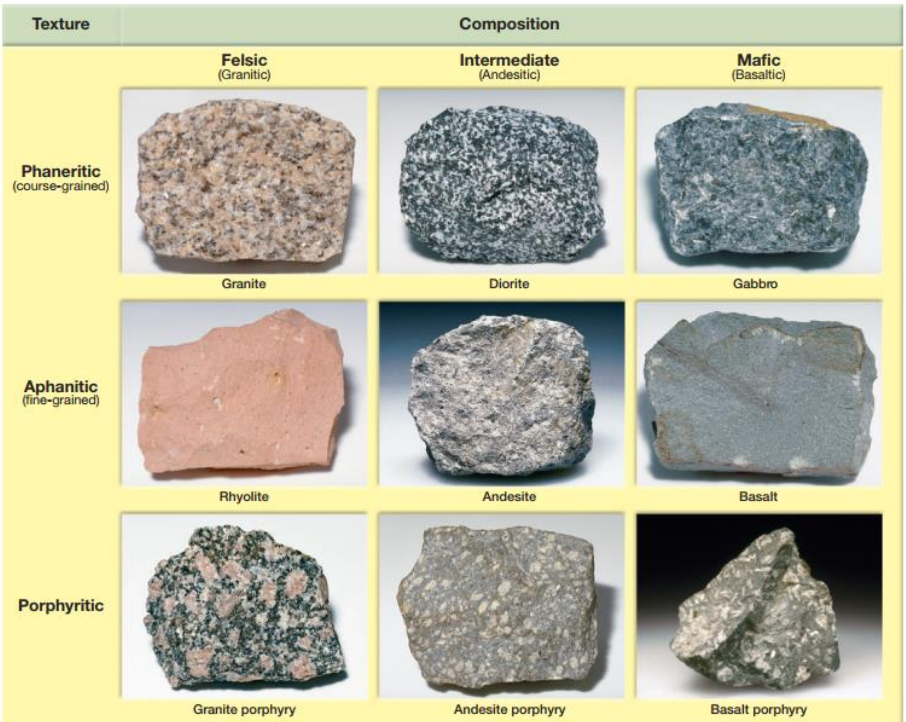


Fig.5.2. Common igneous rocks.

Igneous rocks are most often classified by their **texture** and **mineral composition**.

The texture of an igneous rock refers to the overall appearance of the rock based on the size and arrangement of its interlocking crystals.

Three factors contribute to the textures of igneous rocks:

(1) the rate at which magma cools;

(2) the amount of silica present; and

(3) the amount of dissolved gases in the magma.

Of these, the rate of cooling is the dominant factor, but like all generalizations, this one has exceptions. The most important factor affecting texture is the rate at which magma cools. Common igneous rock textures include **aphanitic**, with grains too small to be distinguished without the aid of a microscope; **phaneritic**, with intergrown crystals that are roughly equal in size and large enough to be identified with the unaided eye; **porphyritic,** which has large crystals (phenocrysts) interbedded in a matrix of smaller crystals (groundmass); and **glassy** (Fig. 5.3.).

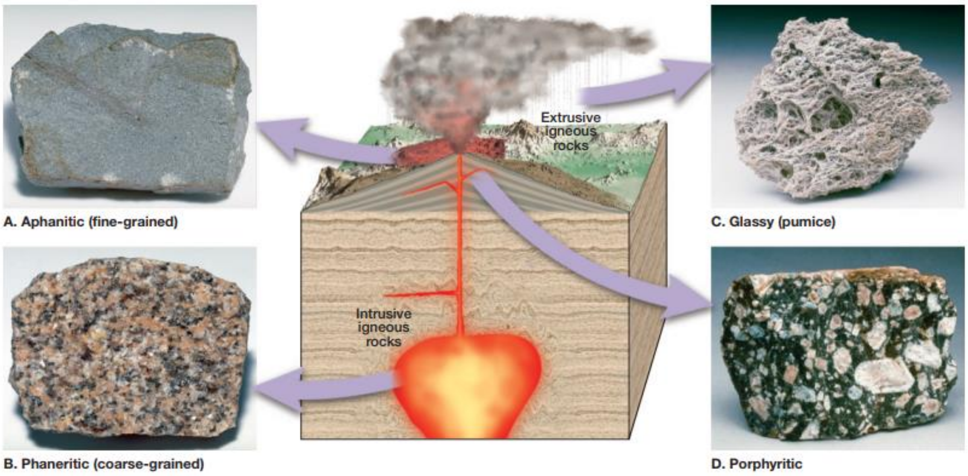


Fig. 5.3. Igneous rock textures.

A. Igneous rocks that form at or near Earth's surface cool quickly and often exhibit a fine-grained (aphanitic) texture.

B. Coarse-grained (phaneritic) igneous rocks form when magma slowly crystallizes at depth.

C. During a volcanic eruption in which silicarich lava is ejected into the atmosphere, a frothy glass called pumice may form.

D. A porphyritic texture results when magma that already contains some large crystals migrates to a new location where the rate of cooling increases. The resulting rock consists of larger crystals (phenocrysts) embedded within a matrix of smaller crystals (groundmass).

The mineral composition of an igneous rock is the consequence of the chemical makeup of the parent magma and the environment of crystallization. Igneous rocks are divided into broad compositional groups based on the percentage of dark and light silicate minerals they contain. **Felsic rocks** (e.g., granite and rhyolite) are composed mostly of the light-colored silicate minerals potassium feldspar and quartz. Rocks of **intermediate** composition, (e.g., andesite and diorite) contain plagioclase feldspar and amphibole. **Mafic rocks** (e.g., basalt and gabbro) contain abundant olivine, pyroxene, and calcium feldspar. They are high in iron, magnesium, and calcium, low in silicon, and are dark gray to black in color.

The mineral makeup of an igneous rock is ultimately determined by the chemical composition of the magma from which it crystallizes. **N. L. Bowen** discovered that as magma cools in the laboratory, those minerals with higher melting points crystallize before minerals with lower melting points. **Bowen's reaction series** illustrates the sequence of mineral formation within magma.

A schematic description of the order in which minerals form during the cooling and solidification of magma and of the way the newly formed minerals react with the remaining magma to form yet another series of minerals. The series is named after geologist Bowen (1887-1956). Bowen determined that specific minerals form at specific temperatures as a magma cools (Fig. 5.4.).

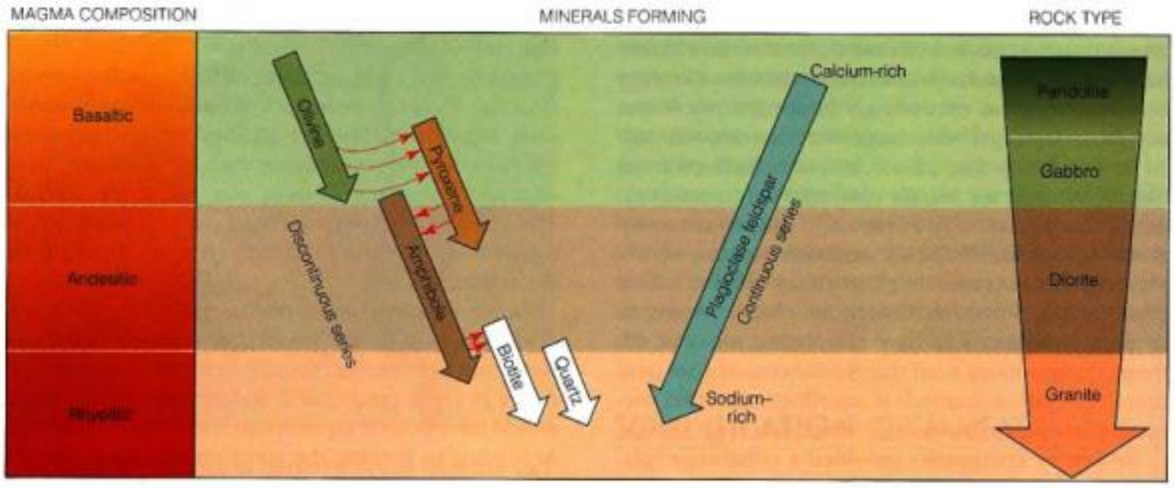


Fig. 5.4. Crystallization model of Bowen

During the crystallization of magma, if the earlier formed minerals are denser than the liquid portion, they will settle to the bottom of the magma chamber during a process called **crystal settling**. Owing to the fact that crystal settling removes the earlier-formed minerals, the remaining melt will form a rock with a chemical composition much different from the parent magma. The process of developing more than one magma type from a common magma is called **magmatic differentiation**.

Once a magma body forms, its composition can change through the incorporation of foreign material, a process termed **assimilation**, or by **magma mixing**.

Magma originates from essentially solid rock of the crust and mantle. In addition to a rock's composition, its temperature, depth (confining pressure), and water content determine whether it exists as a solid or liquid. Thus, magma can be generated by **raising a rock's temperature**, as occurs when a hot mantle plume ponds beneath crustal rocks. A **decrease in pressure** can cause **decompression melting**. Further, the **introduction of volatiles** (water) can lower a rock's melting point sufficiently to generate magma. Because melting is generally not complete, a process called **partial melting** produces a melt made of the lowest-melting-temperature minerals, which are higher in silica than the original rock. Thus, magmas generated by partial melting are nearer to the felsic end of the compositional spectrum than are the rocks from which they formed.

6 – Metamorphism and metamorphic rocks

Metamorphic rocks are derived from pre-existing rock types and have undergone mineralogical, textural and structural changes. The structural changes have been brought about by changes which have taken place in the physical and chemical environments in which the rocks existed. The processes responsible for change give rise to progressive transformation which takes place in the solid state. The changing conditions of temperature and/or pressure are the primary agents causing metamorphic reactions in rocks.

Individual minerals are stable over limited temperature-pressure conditions which means that when these limits are exceeded mineralogical adjustment has to be made to establish equilibrium with the new environment. When metamorphism occurs, there is usually little alteration in the bulk chemical composition of the rocks involved, that is, with the exception of water and volatile constituents such as carbon dioxide.

Metamorphic reactions are influenced by the presence of fluids or gases in the pores of the rocks concerned. For instance, due to the low conductivity of rocks pore fluids may act as a medium of heat transfer. Except at low temperatures the fluid phase in metamorphism is represented by gas with a high density which has many of the properties of a liquid. Not only does water act as an agent of transfer in metamorphism, but it also acts as a catalyst in many chemical reactions. It is a constituent in many minerals in metamorphic rocks of low and medium grade. Grade refers to the range of temperature under which metamorphism occurred.

The quantity of water held in a rock depends upon its permeability and porosity. These two factors depend in turn upon the type of rock and the depth at which it is buried, the deeper the burial the lower the amount of pore fluid. Nonetheless, the H_20 contained within a mineral structure can be liberated by a rise in temperature, for example, this occurs when, because of rising temperatures, muscovite gives place to orthoclase. Thus hydration and dehydration are principally determined by changes in temperature conditions. Minerals such as chlorite, epidote, serpentine, and talc are formed below a certain critical temperature when the pressure is high enough to ensure that water vapor is not a separate phase. According to Winkler (1967) if carbonates and water or OH bearing minerals take part in a metamorphic reaction, then carbon dioxide and water are liberated. The higher the temperature at which the reaction occurs then the smaller the amounts of these two components which are combined in the new minerals.

The phyllosilicates are common minerals in metamorphic rocks of medium and low grade, especially muscovite, biotite and chlorite, and to a lesser extent talc and serpentine.

Of the inosilicates the amphiboles are more typically found in metamorphic rocks of low and medium grade, pyroxenes being developed at higher temperatures. Some of the minerals of this family are almost restricted to the metamorphic rocks, notable examples being actinolite, anthophyllite, cummingtonite and glaucophane amongst the amphiboles, and the pyroxene, jadeite. The phyllosilicates and the inosilicates are amongst the most important minerals in the metamorphic rocks as their structures allow appreciable atomic substitution, so they can adjust to changing conditions. Furthermore, being minerals of fairly high density, their formation is aided by increases in pressure. Nesosilicates like epidote, garnet, staurolite, kyanite, sillimanite and andalusite are typical of metamorphic rocks. However, many of the tectosilicates are unstable under metamorphic conditions, although quartz occurs throughout almost the whole range of metamorphism (Fig. 6.1.)

Fig. 6.1. Metamorphic rock (gneiss) and Igneous Complex
The dark bands are amphibole-rich, the light bands are feldspar-rich.

Two major types of metamorphism may be distinguished on the basis of geological setting. One type is of local extent whereas the other extends over a large area. The first type includes thermal or contact metamorphism and the latter refers to regional metamorphism.

The main factors that control metamorphic processes are:

- the mineral composition of the parent rock,
- the temperature at which metamorphism takes place,
- the amount and type of pressure during metamorphism,
- the types of fluids (mostly water) that are present during metamorphism, and
- the amount of time available for metamorphism.

Classification of Metamorphic Rocks

There are two main types of metamorphic rocks: those that are foliated because they have formed in an environment with either directed pressure or shear stress, and those that are not foliated because they have formed in an environment without directed pressure or relatively near the surface with very little pressure at all. Some types of metamorphic rocks, such as **quartzite** and **marble**, which can form whether there is directed-pressure or not, do not typically exhibit foliation because their minerals (quartz and calcite respectively) do not tend to show alignment (Fig. 6.2).

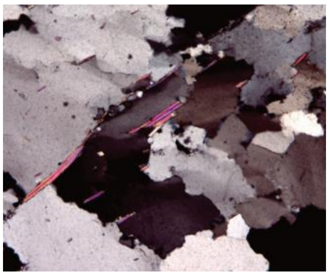


Fig. 6.2. Magnified thin section of quartzite in polarized light. The irregular-shaped white, grey, and black crystals are all quartz. The small, thin, brightly colored crystals are mica. This rock is foliated, even though it might not appear to be if examined without a microscope, and so it must have formed under directed-pressure conditions.

When a rock is squeezed under directed pressure during metamorphism it is likely to be deformed, and this can result in a textural change such that the minerals appear elongated in the direction perpendicular to the main stress (Fig.6.3.). This contributes to the formation of foliation.

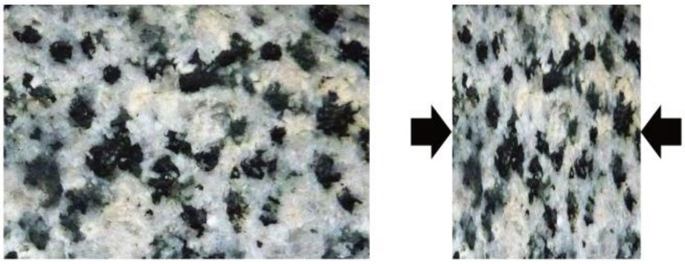


Fig. 6.3. The textural effects of squeezing during metamorphism. In the original rock (left) there is no alignment of minerals. In the squeezed rock (right) the minerals have been elongated in the direction perpendicular to the squeezing.

When a rock is both heated and squeezed during metamorphism, and the temperature change is enough for new minerals to form from existing ones, there is a strong tendency for new minerals to grow with their long axes perpendicular to the direction of squeezing. This is illustrated in Fig. 6.4., where the parent rock is shale, with bedding as shown. After both heating and squeezing, new minerals have formed within the rock, generally parallel to each other, and the original bedding has been largely obliterated.

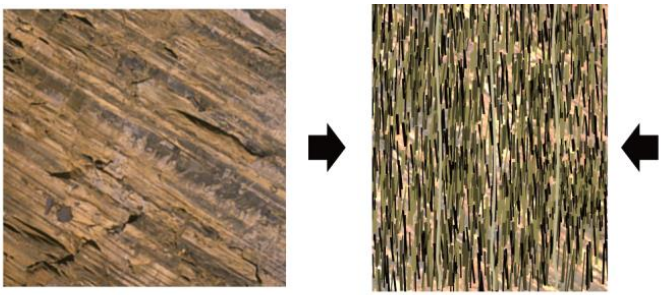


Fig. 6.4. The textural effects of squeezing and mineral growth during regional metamorphism. The left diagram is shale with bedding slanting down to the right. The right diagram represents schist (derived from that shale), with mica crystals orientated perpendicular to the main stress direction and the original bedding no longer easily visible.

The various types of foliated metamorphic rocks, listed in order of the **grade** or intensity of metamorphism and the type of foliation are: **slate**, **phyllite**, **schist**, and **gneiss** (Fig. 6.5). As already noted, slate is formed from the low-grade metamorphism of shale, and has microscopic clay and mica crystals that have grown perpendicular to the stress. Slate tends to break into flat sheets. Phyllite is similar to slate, but has typically been heated to a higher temperature; the micas have grown larger and are visible as a sheen on the surface. Where slate is typically planar, phyllite can form in wavy layers. In the formation of schist, the temperature has been hot enough so that individual mica crystals are big enough to be visible, and other mineral crystals, such as quartz, feldspar, or garnet may also be visible.

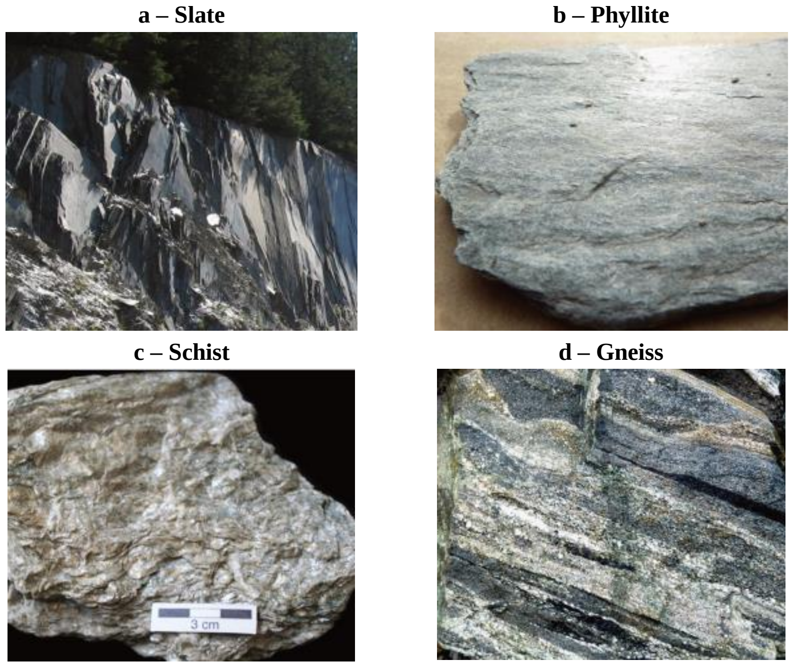


Figure 6.5. Examples of foliated metamorphic rocks: (A) Slate, (B) Phyllite, (C) Schist, (D) Gneiss

If a rock is buried to a great depth and encounters temperatures that are close to its melting point, it may partially melt. The resulting rock, which includes both metamorphosed and igneous material, is known as **migmatite** (Fig. 6.6).

Figure 6.6 Migmatite

The nature of the parent rock controls the types of metamorphic rocks that can form from it under differing metamorphic conditions. The kinds of rocks that can be expected to form at different metamorphic grades from various parent rocks are listed in Table 6.1. Some rocks, such as granite, do not change much at the lower metamorphic grades because their minerals are still stable up to several hundred degrees.

Table 6.1. – A rough guide to the types of metamorphic rocks that form from different parent rocks at different grades of regional metamorphism.

ParentRock	Very Low Grade (150-300°C)	Low Grade (300 –450°C)	Medium Grade (450-550°C)	High Grade (Above 550°C)
Mudrock	slate	phyllite	schist	gneiss
Granite	no change	no change	almost no change	granite gneiss
Basalt	chlorite schist	chlorite schist	amphibolite	amphibolite
Sandstone	no change	little change	quartzite	quartzite
Limestone	little change	marble	marble	marble

Metamorphic rocks that form under either low-pressure conditions or just confining pressure do not become foliated. In most cases, this is because they are not buried deeply, and the heat for the metamorphism comes from a body of magma that has moved into the upper part of the crust. This is **contact metamorphism**. Some examples of non-foliated metamorphic rocks are **marble**, **quartzite**, and **hornfels**. Marble is metamorphosed limestone. When it forms, the calcite crystals tend to grow larger, and any sedimentary textures and fossils that might have been present are destroyed. If the original limestone was pure calcite, then the marble will likely be white as in Figure 6.7., but if it had various impurities, such as clay, silica, or magnesium, the marble could be “marbled” in appearance. Marble that forms during regional metamorphism – and in fact that includes most marble – may or may not develop a foliated texture, but foliation is typically not easy to see in marble.

Fig. 6.7. Marble with visible an outcrop of banded marble

7 – Tectonic processes

In the early 1900s **Alfred Wegener** set forth the continental drift hypothesis. One of its major tenets was that a supercontinent called **Pangaea** began breaking apart into smaller continents about 200 million years ago. The smaller continental fragments then drifted to their present positions. To support the claim that the now separate continents were once joined, Wegener and others used the fit of South America and Africa, **fossil evidence**, **rock types** and **structures**, and **ancient climates**.

One of the main objections to the continental drift hypothesis was its inability to provide an acceptable mechanism for the movement of continents. From the study of **paleomagnetism**, researchers learned that the continents had wandered as Wegener proposed. In 1962, **Harry Hess** formulated the idea of seafloor spreading, which states that new seafloor is continually being generated at **mid-ocean ridges** and old, dense seafloor is being consumed at the **deep-ocean trenches**. Support for seafloor spreading followed, with the discovery of alternating strips of high- and low-intensity magnetism that parallel the ridge crests. By 1968 continental drift and seafloor spreading were united into a far more encompassing theory known as plate tectonics. The plate tectonics theory describes plate motion and the role that this motion plays in generating and/or modifying the major features of Earth’s crust.

According to plate tectonics, Earth's rigid outer layer (lithosphere) overlies a weaker region called the asthenosphere. Further, the lithosphere is broken into **seven** large and numerous smaller segments, called **plates** that are in motion and continually changing in shape and size. As shown in Figure 7.1, seven major lithospheric plates are recognized. They are the **North American, South American, Pacific, African, Eurasian, Australian-Indian**, and **Antarctic plates**. The largest is the Pacific plate, which encompasses a significant portion of the Pacific Ocean basin. Notice from Figure 7.1 that most of the large plates include an entire continent plus a large area of ocean floor (for example, the South American plate). This is a major departure from Wegener's continental drift hypothesis, which proposed that the continents moved through the ocean floor, not with it.

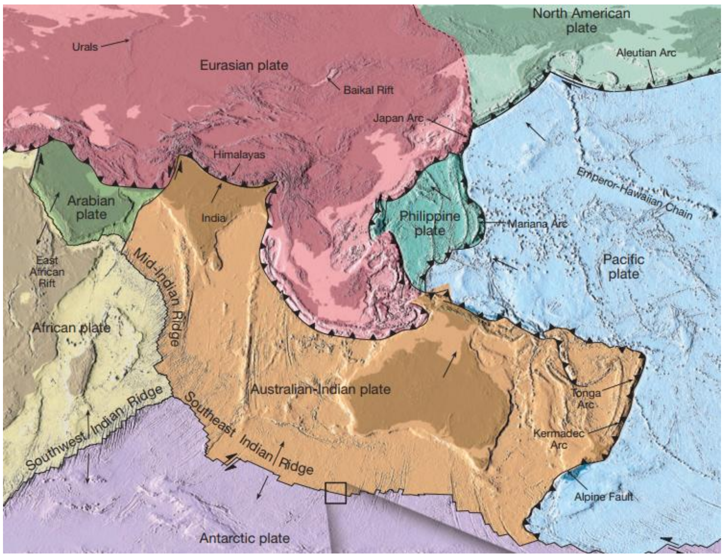


Fig. 7.1. A mosaic of rigid plates constitutes Earth's outer shell

Plates move as relatively coherent units and are deformed mainly along their boundaries.

Divergent plate boundaries occur where plates move apart, resulting in upwelling of material from the mantle to create new seafloor. Most divergent boundaries occur along the axis of the oceanic ridge system and are associated with seafloor spreading, which occurs at rates of 2 to 15 centimeters per year. New divergent boundaries may form within a continent (for example, the East African rift valleys), where they may fragment a landmass and develop a new ocean basin.

Convergent plate boundaries occur where plates move together, resulting in the subduction of oceanic lithosphere into the mantle along a deep oceanic trench. Convergence between an oceanic and continental block results in subduction of the oceanic slab and the formation of a continental volcanic arc. Oceanic–oceanic convergence results in an arc shaped chain of volcanic islands called a volcanic island arc. When two plates carrying continental crust converge, both plates are too buoyant to be subducted. The result is a **collision** resulting in the formation of a mountain belt such as the Himalayas.

Transform fault boundaries occur where plates grind past each other without the production or destruction of lithosphere. Most transform faults join two segments of a mid-ocean ridge. Others connect spreading centers to subduction zones and thus facilitate the transport of oceanic crust created at a ridge crest to its site of destruction, at a deep-ocean trench.

The theory of plate tectonics is supported by the **ages** and **thickness of sediments** from the floors of the deep ocean basins and the existence of island chains that formed over hot spots and provide a frame of reference for tracing the direction of plate motion.

Three basic models for mantle convection the mechanisms that contribute to this convective flow are **slab pull**, **ridge push**, and **mantle plumes**. Slab pull occurs where cold, dense oceanic lithosphere is subducted and pulls the trailing lithosphere along. Ridge push results when gravity sets the elevated slabs astride oceanic ridges in motion. Hot, buoyant mantle plumes are considered the upward flowing arms of mantle convection. One model suggests that mantle convection occurs in two layers separated at a depth of 660 kilometers (Figure 7.2).

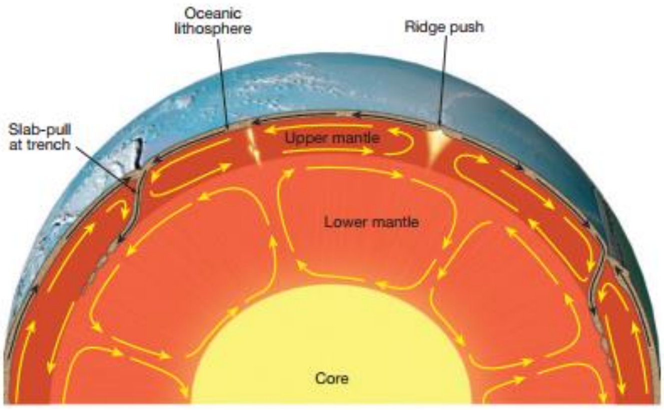


Fig. 7.2. Models for mantle convection. The model shown in this illustration consists of two convection layers—a thin, convective layer above 660 kilometers and a thick one below.

Another model proposes whole-mantle convection that stirs the entire 2900-kilometer-thick rocky mantle. Yet another model suggests that the bottom third of the mantle gradually bulges upward in some areas and sinks in others without appreciable mixing.

Earth is layered with the densest materials at the center and lightest materials forming the outer layer. This layering is a result of gravity, and is similar for all planets.

Earth’s layers consist of the inner core (solid iron), outer core (liquid iron), mantle (dense rock), crust (low-density rock), ocean (water), and atmosphere (gas). Within layers, the density of materials increases with depth due to compression resulting from the increasing pressure.

Within the mantle, increases in density also occur because of mineral phase changes. Because it is impossible to drill deep into Earth, seismic waves are used to probe Earth’s interior. The patterns of seismic waves are complicated because their behavior is influenced by different structures inside the planet before returning to the surface. Seismic waves travel faster through cold rock and slower through hot rock. Seismic waves reflect off of layers composed of different materials. The results of seismic imaging of Earth's interior can be interpreted through comparison with mineral physics experiments. These experiments recreate the temperature and pressure conditions within Earth, and allow scientists to see what rocks and metals are like at various depths.

Oceanic crust and continental crust are very different. Oceanic crust is created at mid-ocean ridges, and is fairly similar in composition and thickness everywhere. Continental crust is highly variable, has many different compositions, and is formed in many different ways. Oceanic crust is nowhere older than 200 million years, whereas continental crust can be older than 4 billion years. Oceanic crust is usually about 7 km thick, but continents can be thicker than 70 km. The boundary between the crust and mantle is called the **Mohorovich**.

The mantle comprises most (82%) of Earth's volume. The upper mantle extends from the Moho to a depth of 660 km, on average. The upper mantle contains part of the stiff lithosphere, the weak asthenosphere, and the transition zone that may contain significant amounts of water. The lower mantle extends from 660 km down to the core–mantle boundary, 2891 km beneath the surface. At the base of the lower mantle is the variable layer.

The core is mostly made of iron and nickel, although it contains about 15 percent lighter elements. Because iron is very dense, the core makes up one-third of Earth's mass, and iron is Earth's most abundant element by mass. The solid inner core grows over time as Earth cools.

Earth's temperature increases from about 0°C at the surface to about 5500°C at the center of the core (though the exact temperature is very hard to determine). Heat flows D – unevenly from Earth's interior, with most of the heat loss occurring along the oceanic ridge system. Earth became very hot early in its history (it may have become entirely molten), largely due to the impacts of planetesimals and heat released by radioactive decay (radiogenic heat). Since then, Earth has slowly cooled. Earth is still geologically active because of the radiogenic heat supplied by long-lived radioactive isotopes, including uranium-238, uranium-235, thorium-232, and potassium-40.

Heat flows from Earth's hot interior to its surface, and does so primarily by convection and conduction. Convection transfers heat through the movement of material. Conduction transfers heat by collisions between atoms or the motions of electrons. Convection is very important within Earth's mantle and outer core, whereas conduction is most important in the inner core, lithosphere, and Within the asthenosphere and the base of the temperature is close enough to the melting point that some partial melting might occur and the rock is weak enough to flow more easily than elsewhere in the mantle. The weak asthenosphere is very important for plate tectonics because it allows the stiff plates (lithosphere) to move easily across the top of it.

Rotation causes Earth's shape to take the form of an oblate ellipsoid, meaning its equator bulges slightly. The combination of Earth's rotation and its ellipsoidal shape cause gravity to vary significantly—from 9.78 m/s^2 at the equator to 9.83 m/s^2 at the poles. Gravity also varies around Earth's surface due to the presence of rocks of different densities. These density differences actually deform Earth's surface, including the ocean surface, by more than 200 meters. This surface is called the **geoid**.

Three-dimensional images of structure variations within the mantle are made from large numbers of seismic waves using **seismic tomography**. These images show that continental lithosphere can extend several hundred kilometers into the mantle. They also show cold subducted oceanic lithosphere sinking to the base of the mantle and large superplumes of hot rock rising from the core mantle boundary. This suggests that convection occurs throughout the mantle.

Convection of the liquid iron in the outer core causes a **magnetic geodynamic** that is responsible for **Earth's magnetic field**. The convection takes the form of spiraling cylinders that are a result of the Coriolis effect. This field is primarily dipolar; that is, it resembles the field from a bar magnet or electromagnet. The patterns of convection in the outer core change rapidly enough that the magnetic field varies noticeably over our lifetimes.

The magnetic field randomly reverses, with the north and south poles swapping positions. A reversal takes only a few thousand years, and involves a significant decrease in the strength of the dipolar field. This is important, because the magnetic field creates a magnetosphere around Earth that protects our planet from much of the Sun's solar wind that would otherwise bombard it. If the magnetosphere weakens, life on land would be adversely affected.

Earthquakes and Faults

The tremendous energy released by atomic explosions or by volcanic eruptions can produce an earthquake, but these events are relatively weak and infrequent. What mechanism produces a destructive earthquake? Ample evidence exists that Earth is not a static planet. We know that Earth's crust has been uplifted at times, because we have found numerous ancient wave-cut benches many meters above the level of the highest tides. Other regions exhibit evidence of extensive subsidence. In addition to these vertical displacements, offsets in fence lines, roads, and other structures indicate that horizontal movement is common. These movements are usually associated with large fractures in Earth's crust called **faults** Fig. 7.3. Typically, earthquakes occur along pre-existing faults that formed in the distant past along zones of weakness in Earth's crust.

FIG. 7.3. Faulting caused the vertical displacement of these beds

The vast majority of faults are inactive and do not generate earthquakes at all. Nevertheless, even faults that have been inactive for thousands of years can rupture again if the stresses acting on the region increase sufficiently. In addition, most faults are not perfectly straight or continuous; instead, they consist of numerous branches and smaller fractures that display kinks and offsets.

Most of the motion along faults can be satisfactorily explained by the plate tectonics theory, which states that large slabs of Earth's lithosphere are in continual slow motion. These mobile plates interact with neighboring plates, straining and deforming the rocks at their margins. In fact, it is along faults associated with plate boundaries that most **earthquakes** occur.

Furthermore, earthquakes are repetitive: As soon as one is over, the continuous motion of the plates adds strain to the rocks until they fail again.

Discovering the Cause of Earthquakes

The actual mechanism of earthquake generation eluded geologists until **H. F. Reid** conducted a study following the great 1906 San Francisco earthquake. The earthquake was accompanied by horizontal surface displacements of several meters along the northern portion of the San Andreas Fault. Field investigations determined that during this single earthquake, the Pacific plate lurched as much as 4.7 meters northward past the adjacent North American plate.

The mechanism for earthquake formation that Reid deduced from this information is illustrated in Figure 7.4. In part A of the figure, you see an existing fault, or break in the rock. In part B, tectonic forces ever so slowly deform the crustal rocks on both sides of the fault, as demonstrated by the bent features. Under these conditions, rocks are bending and storing elastic energy, much like a wooden stick does if bent. Eventually, the frictional resistance holding the rocks in place is overcome. As slippage occurs at the weakest point (the focus), displacement will exert stress farther along the fault, where additional slippage will release the built-up strain (Figure 7.4.C). This slippage allows the deformed rock to **snap back**. The vibrations we know as an earthquake occur as the rock elastically returns to its original shape. The "springing back" of the rock was termed elastic rebound by Reid because the rock behaves elastically, much like a stretched rubber band does when it is released.

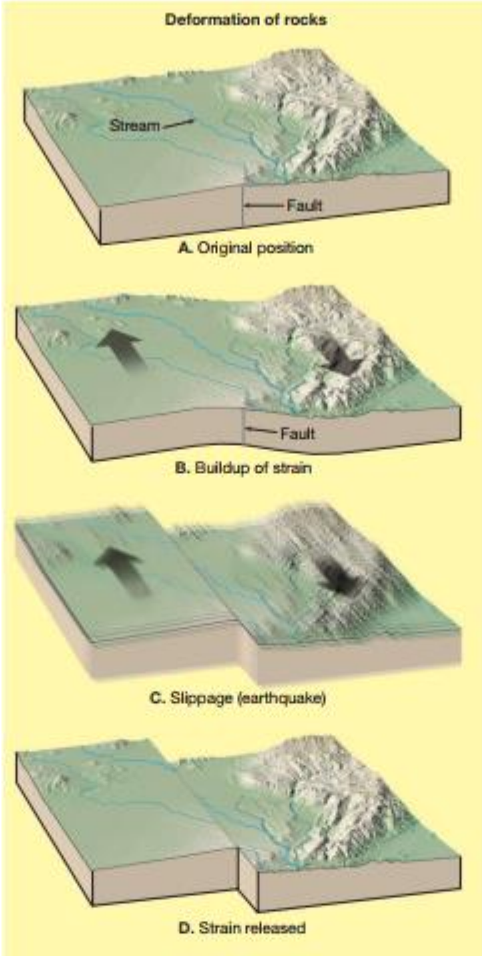


Fig. 7.4. Elastic rebound. As rock is deformed, it bends, storing elastic energy. Once strained beyond its breaking point, the rock cracks, releasing the stored-up energy in the form of earthquake waves.

In summary, most earthquakes are produced by the rapid release of elastic energy stored in rock that has been subjected to great stress. Once the strength of the rock is exceeded, it suddenly ruptures, causing the vibrations of an earthquake. Earthquakes most often occur along existing faults whenever the frictional forces on the fault surfaces are overcome.

Foreshocks and Aftershocks

The intense vibrations of the 1906 San Francisco earthquake lasted about 40 seconds. Although most of the displacement along the fault occurred in this rather short period, additional movements along this and other nearby faults lasted for several days following the main quake. The adjustments that follow a major earthquake often generate smaller earthquakes called aftershocks.

Although these aftershocks are usually much weaker than the main earthquake, they can sometimes destroy already badly weakened structures. This occurred, for example, during a 1988 earthquake in Armenia. A large aftershock of magnitude 5.8 collapsed many structures that had been weakened by the main tremor.

In addition, small earthquakes called foreshocks often precede a major earthquake by days or, in some cases, by as much as several years. Monitoring of these foreshocks has been used as a means of predicting forthcoming major earthquakes, with mixed success. We will consider the topic of earthquake prediction in a later section of this chapter.

Earthquake Rupture and Propagation

We know that the forces (stresses) that cause sudden slippage along faults are ultimately caused by the motions of Earth's plates. It is also clear that most faults are locked, except for brief, abrupt movements that accompany an earthquake rupture. The primary reason most faults are locked is that the confining pressure exerted by the overlying crust is enormous. Because of this, the fractures in the crust are essentially squeezed shut.

Eventually, the stresses that cause the fault to rupture overcome the frictional resistance to slippage. What actually triggers the initial rupture is still not completely understood. Nevertheless, this event marks the beginning of an earthquake.

Earthquakes are vibrations of Earth produced by the rapid release of energy from rocks that rupture because they have been subjected to stresses beyond their limit.

This energy, which takes the form of waves, radiates in all directions from the earthquake's source, called the focus. The movements that produce most earthquakes occur along large fractures, called faults, which are usually associated with plate boundaries. Along a fault, rocks store energy as they are bent. As slippage occurs at the weakest point (the focus), displacement will exert stress farther along a fault, where additional slippage will occur until most of the built-up strain is released. An earthquake occurs as the rock elastically returns to its original shape. The springing back of the rock is termed elastic rebound. Small earthquakes, called foreshocks, often precede a major earthquake. The adjustments that follow a major earthquake often generate smaller earthquakes called aftershocks. Two main types of seismic waves are generated during an earthquake:

1 – surface waves, which travel along the outer layer of Earth, and

2 – body waves, which travel through Earth's interior.

Body waves are further divided into primary, or **P**, **waves**, which push (compress) and pull (expand) rocks in the direction the wave is traveling, and secondary, or **S**, **waves**, which "shake" the particles in rock at right angles to their direction of travel. P waves can travel through solids, liquids, and gases. Fluids (gases and liquids) will not transmit S waves. In any solid material, P waves travel about 1.7 times faster than do S waves. The location on Earth's surface directly above the focus of an earthquake is the epicenter. An epicenter is determined using the difference in velocities of P and S waves. Using the difference in arrival times between P and S waves, the distance separating a recording station from the earthquake can be determined. When the distances are known from three or more seismic stations, the epicenter can be located using a method called triangulation. A close correlation exists between earthquake epicenters and plate boundaries. The principal earthquake epicenter zones are along the outer margin of the Pacific Ocean, known as the circum-Pacific belt, and through the world's oceans along the oceanic ridge system. Seismologists use two fundamentally different measures to describe the size of an earthquake—intensity and magnitude. Intensity is a measure of the degree of ground shaking at a given locale based on the amount of damage.

Although earthquakes begin at a single point, they involve the slippage along an extended fault surface. Stated another way, the initial rupture begins at the focus and propagates (travels) away from the source, sometimes in both horizontal directions along the fault, but often only in one direction. According to one model, the slippage at any one location along a fault is achieved almost instantaneously, in the blink of an eye.

In addition, at any given time, slippage is confined to only a narrow zone along the fault, which continually travels forward. As this zone of rupture proceeds, it can slow down, speed up, or even jump to a nearby fault segment. During small earthquakes, the total slippage occurs along a comparatively small fault surface, or a small segment of a larger fault. Thus, the rupture zone is able to propagate quickly, and the earthquake is short-lived. By contrast, large earthquakes involve slippage along a large segment of a fault, occasionally a few hundred kilometers in length, and thus last much longer. For example, the propagation of the rupture zone along a 300-kilometer-long fault would take about 1.5 minutes. Therefore, the accompanying strong vibrations produced by a large earthquake would not only be stronger but would also last longer than the vibrations produced by a small earthquake.

The Modified **Mercalli Intensity Scale** uses damages to buildings to estimate the intensity of ground shaking for a local earthquake. **Magnitude** is calculated from seismic records and estimates the amount of energy released at the source of an earthquake. Using the **Richter scale**, the magnitude of an earthquake is estimated by measuring the amplitude (maximum displacement) of the largest seismic wave recorded. A **logarithmic scale** is used to express magnitude, in which a tenfold increase in ground shaking corresponds to an increase of 1 on the magnitude scale. Moment magnitude is currently used to estimate the size of moderate and large earthquakes. It is calculated using the average displacement of the fault, the area of the fault surface, and the sheer strength of the faulted rock. The most obvious factors determining the amount of destruction accompanying an earthquake are the magnitude of the earthquake and the proximity of the quake to a populated area. Structural damage attributable to earthquake vibrations depends on several factors, including:

1 – wave amplitudes,

2 – the duration of the vibrations,

3 – the nature of the material upon which the structure rests, and

4 – the design of the structure. Secondary effects of earthquakes include tsunami, landslides, ground subsidence, and fire.

Substantial research to predict earthquakes is under way in Japan, the United States, China, and Russia, countries where earthquake risk is high. No reliable method of short-range prediction has yet been devised. Long-range forecasts are based on the premise that earthquakes are repetitive or cyclical. Seismologists study the history of earthquakes for patterns so their occurrences might be predicted. Long-range forecasts are important because they provide information used to develop the Uniform Building Code and to assist in land-use planning.

The distribution of earthquakes provides strong evidence for the theory of plate tectonics. One aspect involves the close association between deep-focus earthquakes and subduction zones. Additional evidence involves the fact that only shallow-focus earthquakes occur at divergent and transform fault boundaries.

8 – Fundamentals of stratigraphy and geochronology

The history of Earth began about 13.7 billion years ago when the first elements were created during the ***Big Bang***. It was from this material, plus other elements ejected into interstellar space by now defunct stars, that Earth along with the rest of the solar system formed. As material collected, high velocity impacts of chunks of matter called ***planetesimals*** and the decay of radioactive elements caused the temperature of our planet to steadily increase. Iron and nickel melted and sank to form the metallic core, while rocky material rose to form the mantle and Earth's initial crust. Earth's primitive atmosphere, which consisted mostly of water vapor and carbon dioxide, formed by a process called ***outgassing***, which resembles the steam eruptions of modern volcanoes.

About 3.5 billion years ago, photosynthesizing bacteria began to release oxygen, first into the oceans and then into the atmosphere. This began the evolution of our modern atmosphere. The oceans, formed early in Earth's history, as water vapor condensed to form clouds, and torrential rains filled low-lying areas. The salinity in seawater came from volcanic outgassing and from elements weathered and eroded from Earth's primitive crust.

The **Precambrian**, which is divided into the **Archean** and **Proterozoic eons**, spans nearly 90 percent of Earth's history, beginning with the formation of Earth about 4.5 billion years ago and ending approximately 542 million years ago. During this time, much of Earth's stable continental crust was created through a multi-stage process. First, partial melting of the mantle generated magma that rose to form volcanic island arcs and oceanic plateaus. These thin crustal fragments collided and accreted to form larger crustal provinces, which, in turn assembled into larger blocks called ***cratons***.

Cratons, which form the core of modern continents, were created mainly during the Precambrian. Supercontinents are large landmasses that consist of all, or nearly all, existing continents. ***Pangaea*** was the most recent supercontinent, but a massive southern continent called ***Gondwana***, and perhaps an even larger one, ***Rodinia***, preceded it (Fig.8.1.).

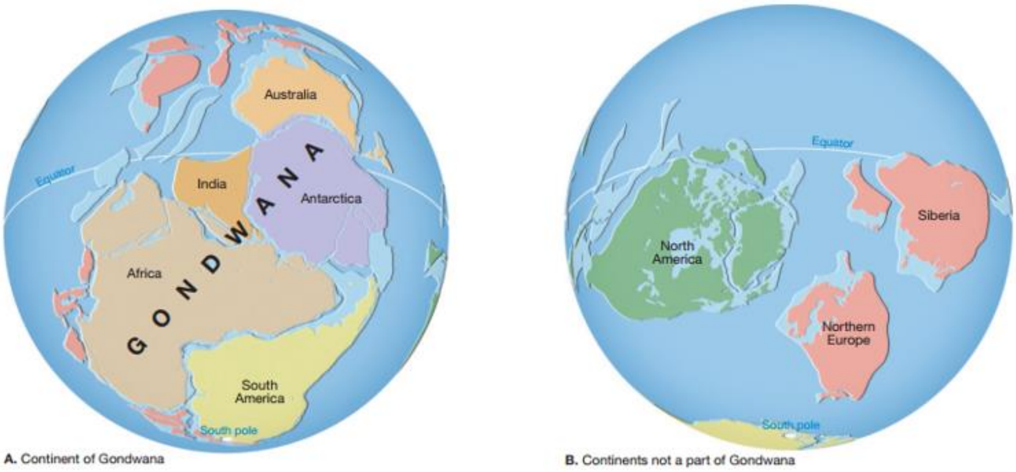


Fig. 8.1. Reconstruction of Earth as it may have appeared in late Precambrian time. The southern continents were joined into a single landmass called Gondwana. Other landmasses that were not part of Gondwana include North America, northwestern Europe and northern Asia

The splitting and reassembling of supercontinents have generated most of Earth's major mountain belts. In addition, the movement of these crustal blocks have profoundly affected Earth's climate, and have caused sea level to rise and fall.

The time span following the close of the Precambrian, called the ***Phanerozoic eon***, encompasses 542 million years and is divided into three eras: ***Paleozoic, Mesozoic,*** and ***Cenozoic*** (Fig.8.2.).

EON	ERA	PERIOD	MILLIONS OF YEARS AGO	KEY EVENTS
Phanerozoic	Caenozoic	Quaternary		Humans evolve
		Tertiary	1.6	
	Mesozoic	Cretaceous	138	Extinction of Dinosaurs
		Jurassic		
		Triassic	240	
	Paleaozoic	Permian		Permian mass extinction
		Carboniferous	330	
		Devonian	410	
		Silurian		Invertebrates become common
		Ordovician	500	
		Cambrian		
Proterozoic		Also known as Precambrian	3500	Earliest life
Archean				
Hadean				

Fig. 8.2. The geologic time scale

The Paleozoic era was dominated by continental collisions as the supercontinent of Pangaea assembled, forming the Caledonian, Appalachian, and Ural Mountains.

Early in the Mesozoic, much of the land was above sea level. However, by the middle Mesozoic, seas invaded western North America. As Pangaea began to break up, the westward-moving North American plate began to override the Pacific plate, causing crustal deformation along the entire western margin of North America.

Most of North America was above sea level throughout the Cenozoic. Owing to their different relations with plate boundaries, the eastern and western margins of the continent experienced contrasting events. The stable eastern margin was the site of abundant sedimentation as isostatic adjustment raised the Appalachians, causing streams to erode with renewed vigor and deposit their sediment along the continental margin.

The first known organisms were single-celled bacteria, ***prokaryotes***, which lack a nucleus. One group of these organisms, called **cyanobacteria**, that used solar energy to synthesize organic compounds (sugars) evolved. For the first time, organisms had the ability to produce their own food. Fossil evidence for the existence of these bacteria includes layered mounds of calcium carbonate called ***stromatolites***.

The beginning of the Paleozoic is marked by the ***appearance of the first life-forms with hard parts*** such as shells. Therefore, abundant Paleozoic fossils occur, and a far more detailed record of Paleozoic events can be constructed.

Life in the early Paleozoic was restricted to the seas and consisted of several invertebrate groups, including **trilobites**, **cephalopods, sponges** and **corals**. During the Paleozoic, organisms diversified dramatically. Insects and plants moved onto land, and lobe-finned fishes that adapted to land became the first amphibians. By the Pennsylvanian period, large tropical swamps, which became the major coal deposits of today, extended across North America, Europe, and Siberia. At the close of the Paleozoic, a mass extinction destroyed 70 percent of all vertebrate species on land and 90 percent of all marine organisms.

The Mesozoic era, literally the era of middle life, is often called the ***Age of Reptiles***. Organisms that survived the extinction at the end of the Paleozoic began to diversify in spectacular ways. ***Gymnosperms*** (cycads, conifers, and ginkgoes) became the dominant trees of the Mesozoic because they could adapt to the drier climates. Reptiles became the dominant land animals. The most awesome of the Mesozoic reptiles were the ***dinosaurs***. At the close of the Mesozoic, many large reptiles, including the dinosaurs, became extinct.

The Cenozoic is often called the ***Age of Mammals*** because these animals replaced the reptiles as the dominant vertebrate life forms on land. Two groups of mammals, the marsupials and the placentals, evolved and expanded during this era. One tendency was for some mammal groups to become very large. However, a wave of late ***Pleistocene*** extinctions rapidly eliminated these animals from the landscape. Some scientists suggest that early humans hastened their decline by selectively hunting the larger animals. The Cenozoic could also be called the ***Age of Flowering Plants.*** As a source of food, flowering plants (angiosperms) strongly influenced the evolution of both birds and herbivorous (plant-eating) mammals throughout the Cenozoic era.

9 – Fundamentals of Engineering Geodynamics

The Geodynamo

As the core fluid rises, its path becomes twisted through a phenomenon called the **Coriolis Effect**, which is a result of Earth’s rotation. The fluid ends up moving in spiraling columns as shown in Figure 9.1. Because the fluid is electrically charged, it generates a magnetic field through a process called a geodynamo that is similar to an electromagnet.

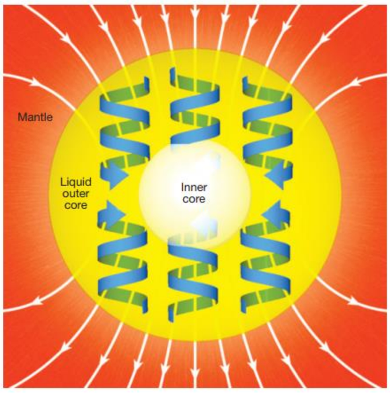
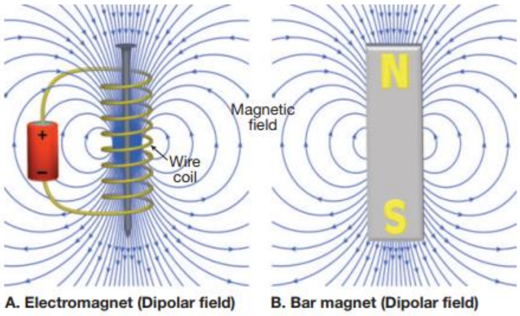


Fig. 9.1. Illustration of the kind of convection patterns within Earth's liquid iron outer core that could give rise to the magnetic field we measure at the surface. It is thought that convection takes the form of cylindrical gyres of rotating molten iron that are aligned in the direction of Earth's axis of rotation.

If a wire is wrapped around an iron nail and an electric current passed through it, the nail will generate a magnetic field that looks a lot like the field from a bar magnet (Figure 12.22A, B). This is called a dipolar field—a type of magnetic field that has two poles (a north and south magnetic pole). As Figure 12.22C shows, the magnetic field that emanates from Earth's outer core has the same dipolar form.



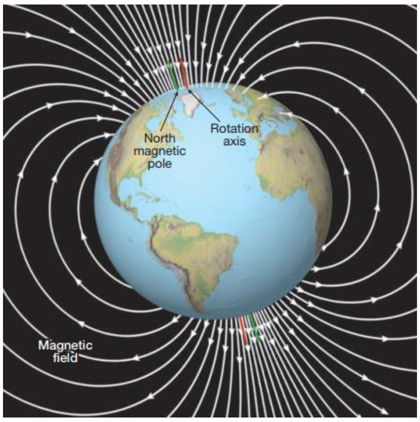


Fig. 9.2. Demonstration of the similarity of Earth's magnetic field to that of an electromagnet (A), which consists of an electrical current passed through a coil of wire, or bar magnet (B). While it was once thought that Earth's core acts like a large bar magnet, scientists now think that Earth's magnetic field (C) is more like an electromagnet, and that the cylinders of spiraling liquid iron shown in Figure 12.21 behave like the coil of current passing through the wires of an electromagnet.

However, the convection in the outer core is not quite so simple. More than 90% of Earth’s magnetic field takes the form of a dipolar field, but the remainder of the field is the result of other more complicated patterns of convection in the core.

In addition, some of the features of Earth’s magnetic field change over time. For centuries sailors have used compasses to determine direction. Consequently, a great deal of attention has been paid to keeping track of the direction that compass needles point. One observed change in the magnetic field is a gradual “westward drift” of the nondipole part of the magnetic field. In order to explain this, we first need to look at how the magnetic field is measured.

At any point on Earth’s surface, the direction that the magnetic field is pointing is measured with two angles, called **declination** and **inclination**. The declination measures the direction to the magnetic north pole with respect to the direction to the geographic North Pole (Earth’s axis of rotation). The inclination measures the downward tilt of the magnetic lines of force at any location. It is what your compass would read if you could tilt it on its side. At the magnetic north pole the field points directly downward. At the equator it is horizontal (Fig. 9.3.).

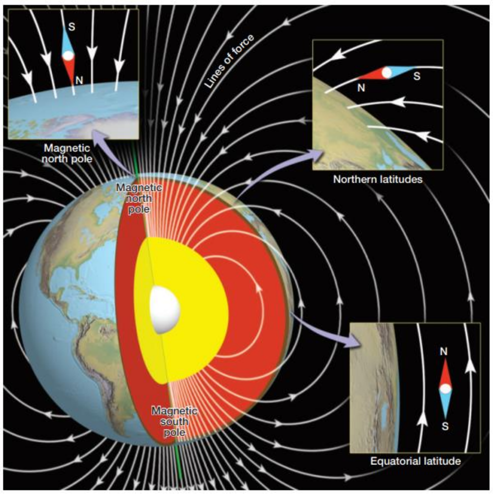


Fig. 9.3. Drawing that shows the direction of the magnetic field at different locations along Earth’s surface.

The location of the magnetic north pole actually moves significant distances during our lifetimes. Earth’s magnetic north pole had been located in Canada, but over the past decade moved northward into the Arctic Ocean and is currently moving rapidly toward Siberia at a rate of about 20 kilometers per year. The process is not symmetric. Though the magnetic north pole has been moving towards the geographic North Pole, the magnetic South Pole has been moving away from the South Pole, passing from Antarctica to the Pacific Ocean. This means that core convection changes significantly on a time scale of decades.

Magnetic Reversals

Although core convection changes over time, causing the magnetic poles to move, the locations of the magnetic poles averaged over thousands of years are layer in space around the planet known as the **magnetosphere**. Along with the atmosphere, the magnetosphere protects Earth's surface from ionized particles emitted by the Sun. These ionized particles form what is called the **solar wind**. If the strength of the magnetic field decreases greatly during a reversal, the increased amounts of solar wind reaching Earth's surface could cause health hazards for humans and other land-based life forms.

Earth is layered with the densest materials at the center and lightest materials forming the outer layer. This layering is a result of gravity, and is similar for all planets. Earth's layers consist of the inner core (solid iron), outer core (liquid iron), mantle (dense rock), crust (low-density rock), ocean (water), and atmosphere (gas). Within layers, the density of materials increases with depth due to compression resulting from the increasing pressure. Within the mantle, increases in density also occur because of mineral phase changes.

Because it is impossible to drill deep into Earth, **seismic waves** are used to probe Earth's interior. The patterns of seismic waves are complicated because their behavior is influenced by different structures inside the planet before returning to the surface. Seismic waves travel faster through cold rock and slower through hot rock. Seismic waves reflect off of layers composed of different materials. The results of seismic imaging of Earth's interior can be interpreted through comparison with mineral physics experiments. These experiments recreate the temperature and pressure conditions within Earth, and allow scientists to see what rocks and metals are like at various depths.

Earth's Magnetic Field

Earth's magnetic field has a north and south magnetic pole. These magnetic poles align closely, but not exactly, with the geographic poles. Earth's magnetic field is similar to that produced by a simple bar magnet. Invisible lines of force pass through the planet and extend from one magnetic pole to the other, as shown in Figure 9.4.

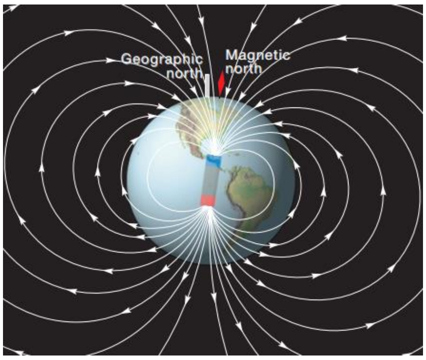


Fig. 9.4. Earth's magnetic field consists of lines of force much like those a giant bar magnet would produce if placed at the center of Earth.

A compass needle, itself a small magnet free to rotate on an axis, becomes aligned with the magnetic lines of force and points to the magnetic poles. Unlike the pull of gravity, we cannot feel Earth's magnetic field, yet its presence is revealed because it deflects a compass needle. In a similar manner, certain rocks contain minerals that serve as fossil compasses. These iron-rich minerals, such as **magnetite**, are abundant in lava flows of basaltic composition. When heated above a temperature known as the **Curie**

point, these magnetic minerals lose their magnetism. However, when these iron-rich grains cool below their Curie point (about 585°C for magnetite), they gradually become magnetized in the direction of the existing magnetic lines of force. Once the minerals solidify, the magnetism they possess will usually remain frozen in this position. In this regard, they behave much like a compass needle; they "point" toward the position of the magnetic poles at the time of their formation. Then, if the rock is moved, the rock magnetism will retain its original alignment. Rocks that formed thousands or millions of years ago and contain a record of the direction of the magnetic poles at the time of their formation are said to possess **fossil magnetism,** or **paleomagnetism.**

Another important aspect of rock magnetism is that the magnetized minerals not only indicate the direction to the poles (like a compass) but also provide a means of determining the latitude of their origin. To envision how latitude can be established from paleomagnetism, imagine a compass needle mounted in a vertical plane rather than horizontally, like an ordinary compass. As shown in Figure 9.5., when this modified compass (dip needle) is situated over the north magnetic pole, it aligns with the magnetic lines of force and points straight down.

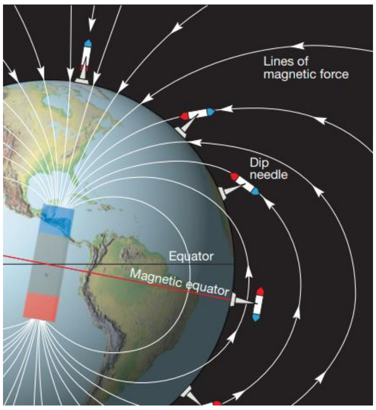


Fig. 9.5. Earth's magnetic field causes a dip needle (compass oriented in a vertical plane) to align with the lines of magnetic force. The dip angle decreases uniformly from 90 degrees at the magnetic poles to 0 degrees at the magnetic equator. Consequently, the distance to the magnetic poles can be determined from the dip angle.

However, as this dip needle is moved closer to the equator, the angle of inclination is reduced until the needle becomes horizontal at the equator. Thus, from the dip needle's angle of inclination, one can determine the latitude. In a similar manner, the inclination of the paleo magnetism in rocks indicates the latitude of the rock at the time it became magnetized. Figure 9.6 shows the relationship between the magnetic inclination determined for a rock sample and the latitude where it formed. By knowing the latitude where a rock sample was magnetized, its distance to the magnetic poles can also be determined.

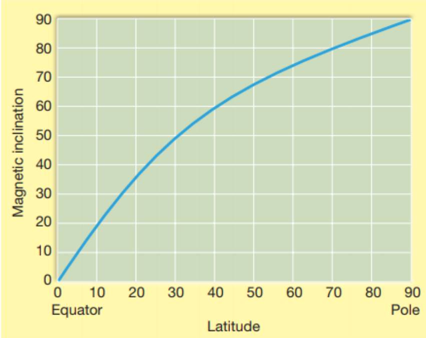


Fig. 9.6. Magnetic inclination and the corresponding latitude.

10 – Gravity processes and phenomena

Mass wasting refers to the downslope movement of rock, regolith, and soil under the direct influence of gravity. In the evolution of most landforms, mass wasting is the step that follows weathering (Fig.10.1). The combined effects of mass wasting and erosion by running water produce stream valleys.

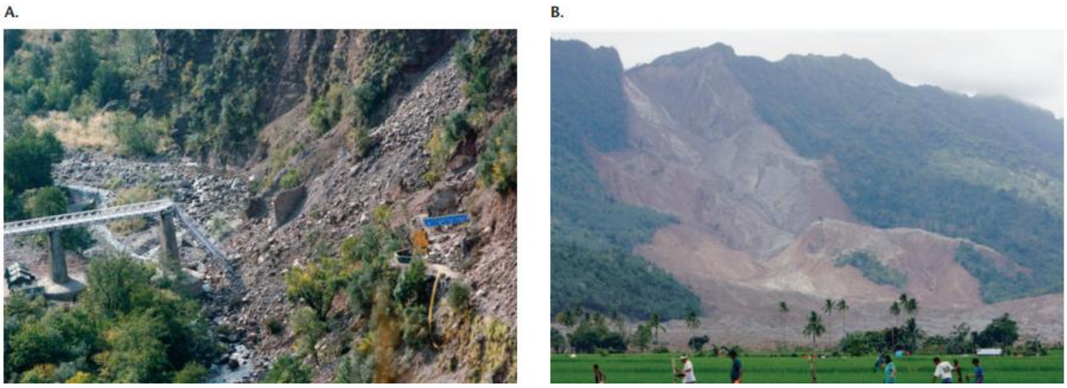


Fig. 10.1. – A. On October 8, 2005, a major earthquake in Kashmir triggered hundreds of landslides including the one shown here – B. In February 2006, heavy rains triggered this mudflow that buried a small town on the Philippine island of Leyte.

The Role of Mass Wasting

In the evolution of most landforms, mass wasting is the step that follows weathering. By itself, weathering does not produce significant landforms. Rather, landforms develop as products of weathering are removed from the places where they originate. Once weathering weakens and breaks rock apart, mass wasting transfers the debris downslope, where a stream, acting as a conveyor belt, usually carries it away. Although there may be many intermediate stops along the way, the sediment is eventually transported to its ultimate destination: the sea. The combined effects of mass wasting and running water produce stream valleys, which are the most common and conspicuous of Earth's landforms. If streams alone were responsible for creating the valleys in which they flow, the valleys would be very narrow features. However, the fact that most river valleys are much wider than they are deep is a strong indication of the significance of mass-wasting processes in supplying material to streams. This is illustrated by the Grand Canyon (Figure 10.2). The walls of the canyon extend far from the Colorado River, owing to the transfer of weathered debris downslope to the river and its tributaries by mass-wasting processes. In this manner, streams and mass wasting combine to modify and sculpt the surface. Of course, glaciers, groundwater, waves, and wind are also important agents in shaping landforms and developing landscapes.

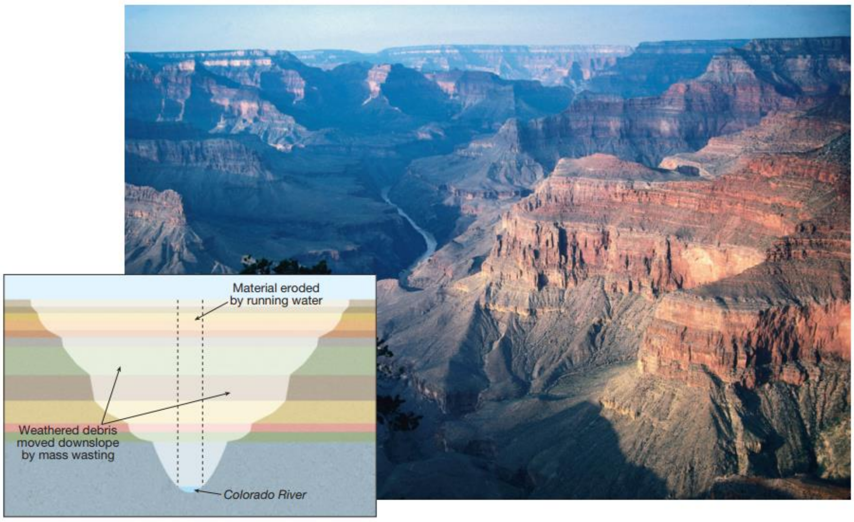


Fig. 10.2 The walls of the Grand Canyon extend far from the channel of the Colorado River. This results primarily from the transfer of weathered debris downslope to the river and its tributaries by mass wasting processes

The Role of Water

Mass wasting is sometimes triggered when heavy rains or periods of snowmelt saturate surface materials. When the pores in sediment become filled with water, the cohesion among particles is destroyed, allowing them to slide past one another with relative ease. For example, when sand is slightly moist, it sticks together quite well. However, if enough water is added to fill the openings between the grains, the sand will ooze out in all directions (Figure 10.3). Thus, saturation reduces the internal resistance of materials, which are then easily set in motion by the force of gravity. When clay is wetted, it becomes very slick – another example of the lubricating effect of water. Water also adds considerable weight to a mass of material. The added weight in itself may be enough to cause the material to slide or flow downslope.

Oversteepened Slopes

Oversteepening of slopes is another trigger of many mass movements. There are many situations in nature where oversteepening takes place. A stream undercutting a valley wall and waves pounding against the base of a cliff are but two familiar examples. Furthermore, through their activities, people often create oversteepened and unstable slopes that become prime sites for mass wasting.

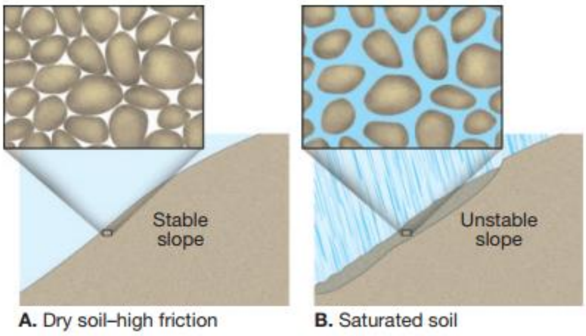


Fig.10.3. The effect of water on mass wasting can be great. A. When little or no water is present, friction among the closely packed soil particles on the slope holds them in place. B. When the soil is saturated, the grains are forced apart and friction is reduced, allowing the soil to move downslope.

Oversteepening is not just important because it triggers movements of unconsolidated granular materials. Oversteepening also produces unstable slopes and mass movements in cohesive soils, regolith, and bedrock. The response will not be immediate, as with loose, granular material, but sooner or later, one or more mass-wasting processes will eliminate the oversteepening and restore stability to the slope.

Gravity is the controlling force of mass wasting. Other factors that influence or trigger downslope movements are saturation of the material with water, over steepening of slopes beyond the ***angle of repose***, **removal of vegetation**, and **ground shaking by earthquakes**. Unconsolidated, granular particles (sand-size or coarser) assume a stable slope called the **angle of repose.** This is the steepest angle at which material remains stable. Depending on the size and shape of the particles, the angle varies from 25 to 40 degrees. The larger, more angular particles maintain the steepest slopes. If the angle is increased, the rock debris will adjust by moving downslope.

The various processes included under the name of mass wasting are divided and described on the basis of (1) the type of material involved (debris, mud, earth, or rock); (2) the type of motion (fall, slide, or flow); and (3) the rate of movement (rapid or slow)

Removal of Vegetation

Plants protect against erosion and contribute to the stability of slopes because their root systems bind soil and regolith together. In addition, plants shield the soil surface from the erosional effects of raindrop impact. Where plants are lacking, mass wasting is enhanced, especially if slopes are steep and water is plentiful. When anchoring vegetation is removed by forest fires or by people (for timber, farming, or development), surface materials frequently move downslope. An unusual example illustrating the anchoring effect of plants occurred several decades ago on steep slopes near Menton, France. Farmers replaced olive trees, which have deep roots, with a more profitable but shallow-rooted crop: carnations. When the less stable slope failed, the landslide took 11 lives.

In addition to eliminating plants that anchor the soil, fire can promote mass wasting in other ways. Following a wildfire, the upper part of the soil may become dry and loose. As a result, even in dry weather, the soil tends to move down steep slopes. Moreover, fire can also bake the ground, creating a water-repellant layer at a shallow depth. This nearly impermeable barrier prevents or slows the infiltration of water, resulting in increased surface runoff during rains. The consequence can be dangerous torrents of viscous mud and rock debris.

Earthquakes as Triggers

Conditions that favor mass wasting may exist in an area for a long time without movement occurring. An additional factor is sometimes necessary to trigger the movement. Among the more important and dramatic triggers are earthquakes. An earthquake and its aftershocks can dislodge enormous volumes of rock and unconsolidated material. The event in the Kashmir region described near the beginning of the chapter is one tragic example.

The more rapid forms of mass wasting include slump, the downward sliding of a mass of rock or unconsolidated material moving as a unit along a curved surface; **rockslide,** blocks of bedrock breaking loose and sliding downslope; **debris flow**, a relatively rapid flow of soil and regolith containing a large amount of water; and **earthflow**, an unconfined flow of saturated clay-rich soil that most often occurs on a hillside in a humid area following heavy precipitation or snowmelt.

The slowest forms of mass wasting include **creep,** the gradual downhill movement of soil and regolith; and **solifluction**, and the gradual flow of a saturated surface layer that is underlain by an impermeable zone. Common sites for solifluction are regions underlain by **permafrost** (permanently frozen ground associated with tundra and ice-cap climates).

Permafrost, permanently frozen ground, covers large portions of North America and Siberia. Thawing produces unstable ground that may slide, slump, subside, and undergo severe frost heaving.

Mass wasting is not confined to land; it also occurs underwater. Many **submarine landslides**, mostly slumps and debris avalanches, are much larger than those that occur on land.

11 – Fundamentals of Geomorphology

Geomorphology is a discourse on Earth forms. It is the study of Earth's physical landsurface features, its landforms – rivers, hills, plains, beaches, sand dunes, and myriad others. Some workers include submarine landforms within the scope of geomorphology. And some would add the landforms of other terrestrial-type planets and satellites in the Solar System – Mars, the Moon, Venus, and so on. Landforms are conspicuous features of the Earth and occur everywhere. They range in size from molehills to mountains to major tectonic plates, and their 'lifespans' range from days to millennia to aeons.

Geomorphology was first used as a term to describe the morphology of the Earth's surface in the 1870s and 1880s. It was originally defined as the genetic study of topographic forms, and was used in popular parlance by 1896. Despite the modern acquisition of its name, geomorphology is a venerable discipline. It investigates landforms and the processes that fashion them. A large corpus of geomorphologists expends much sweat in researching relationships between landforms and the processes acting on them now. These are the **process** or **functional geomorphologists**. Many geomorphic processes affect, and are affected by, human activities. Applied geomorphologists explore this rich area of enquiry, which is largely an extension of process geomorphology. Many landforms have a long history, and their present form does not always relate to the current processes acting upon them. The nature and rate of geomorphic processes change with time, and some landforms were produced under different environmental conditions, surviving today as relict features. In high latitudes, many landforms are relicts from the Quaternary glaciations; but, in parts of the world, some landforms survive from millions and hundreds of millions of years ago. Geomorphology, then, has an important historical dimension, which is the domain of the **historical geomorphologists**. In short, modern geomorphologists study three chief aspects of landforms – **form**, **process**, and **history**. The first two are sometimes termed functional geomorphology, the last historical geomorphology (Chorley 1978). Process studies have enjoyed hegemony for some three or four decades. Historical studies were sidelined by process studies but are making a strong comeback. Although process and historical studies dominate much modern geomorphological enquiry, particularly in English speaking nations, other types of study exist. For example, **structural geomorphologists**, who were once a very influential group, argued that underlying geological structures are the key to understanding many landforms. **Climatic geomorphologists**, who are found mainly in France and Germany, believe that climate exerts a profound influence on landforms, each climatic region creating a distinguishing suite of landforms.

Geomorphology investigates landforms and the processes that fashion them. Form, process, and the interrelationships between them are central to understanding the origin and development of landforms.

In geomorphology, form or morphology has three facets – **constitution** (chemical and physical properties described by material property variables), **configuration** (size and form described by geometry variables), and **mass flow** (rates of flow described by such massflow variables as discharge, precipitation rate, and evaporation rate) (Figure 11.1; Strahler 1980).

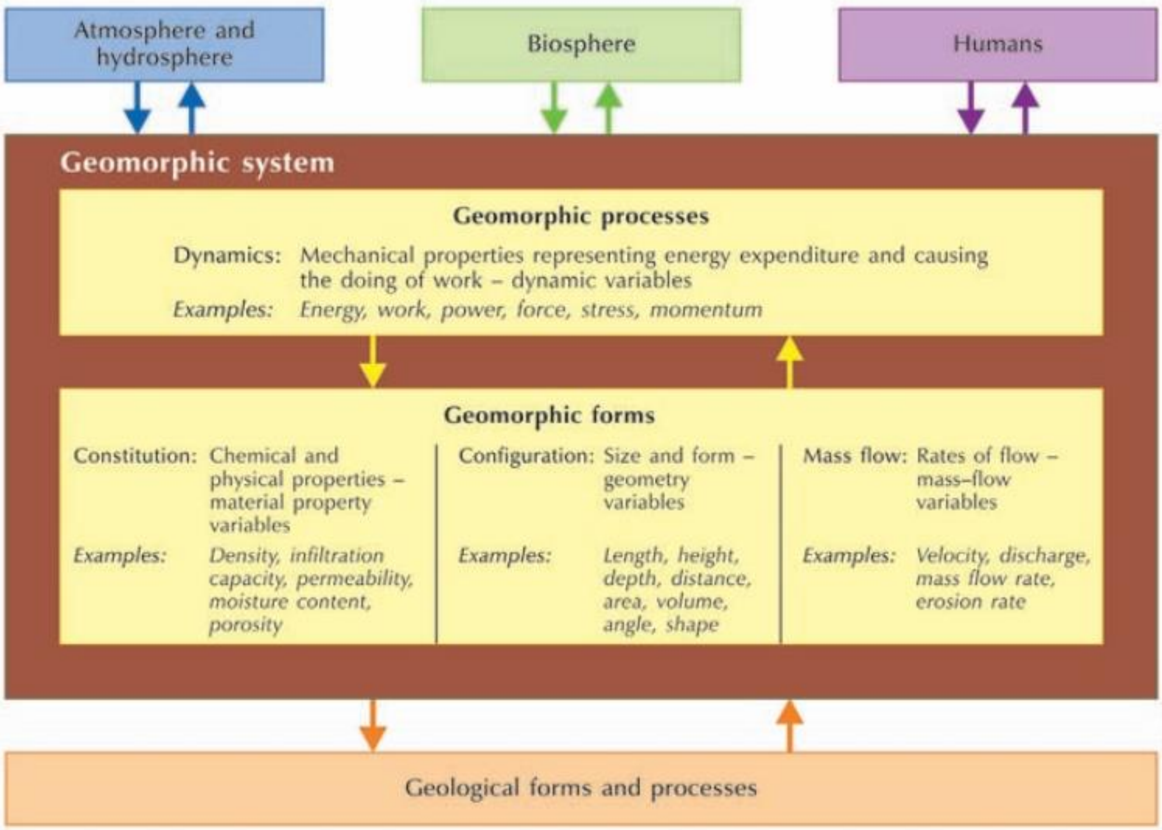


Fig.11.1 Process–form interactions – the core of geomorphology.

These form variables contrast with dynamic variables (chemical and mechanical properties representing the expenditure of energy and the doing of work) associated with geomorphic processes; they include power, energy flux, force, stress, and momentum. Take the case of a beach. Constitutional properties include the degree of sorting of grains, mean diameter of grains, grain shape, and moisture content of the beach; configurational properties include such measures of beach geometry as slope angle, beach profile form, and water depth; mass-flow variables include rates of erosion, transport, and deposition.

Dynamic variables include drag stresses set up by water currents associated with waves (and modulated by tides), possibly by channeled water flowing over the beach, and by wind, and also include forces created by burrowing animals and humans digging beach material.

Geomorphic processes are the multifarious chemical and physical means by which the Earth's surface undergoes modification. They are driven by geological forces emanating from inside the Earth (endogenic or **endogene processes**), by forces originating at or near the Earth's surface and in the atmosphere (exogenic or **exogene processes**), and by forces coming from outside the Earth (**extraterrestrial processes**, such as asteroid impacts). They include processes of transformation and transfer associated with weathering, gravity, water, wind, and ice. Mutual interactions between form and process are the core of geomorphic investigation – form affects process and process affects form. In a wider set - ting, atmospheric processes, ecological processes, and geological processes influence, and in turn are influenced by, geomorphic process – form interactions (Figure 11.1).

The nature of the mutual connection between Earth surface process and Earth surface form has lain at the heart of geomorphological discourse. The language in which geomorphologists have expressed these connections has altered with changing cultural, social, and scientific contexts. In very broad terms, a qualitative approach begun by classical thinkers and traceable through to the mid-twentieth century preceded a quantitative approach.

The first true geomorphologists, such as William Morris Davis and Grove Karl Gilbert, tried to infer how the landforms they saw in the field were fashioned by geomorphic processes. Currently, there are at least four approaches used by geomorphologists in studying landforms:

1. A process–response (process–form) or functional approach that builds upon chemistry and physics and utilizes a systems methodology.

2. A landform evolution approach that has its roots in historical geological science (geo-history) and that explores the important historical dimension of many landforms.

3. An approach that focuses on characterizing landforms and landform systems and that stems from geographical spatial science.

4. An environmentally sensitive approach to land - forms, systems of landforms, and landscapes at regional to global scales.

12 – Groundwater overview

Geologically, groundwater is important as an erosional agent. The dissolving action of groundwater slowly removes soluble rock such as limestone, allowing surface depressions known as **sinkholes** to form as well as creating subterranean caverns (Figure 12.1).

Fig. 12.1 The dissolving action of groundwater created the cavern. Later, groundwater deposited the limestone decorations.

Groundwater is also an equalizer of streamflow. Much of the water that flows in rivers is not direct runoff from rain and snowmelt. Rather, a large percentage of precipitation soaks in and then moves slowly underground to stream channels. Groundwater is thus a form of storage that sustains streams during periods when rain does not fall. Therefore, when we see water flowing in a river during a dry period, it is rain that fell at some earlier time and was stored underground.

When rain falls, some of the water runs off, some returns to the atmosphere by evaporation and transpiration, and the remainder soaks into the ground. This last path is the primary source of practically all subsurface water. The amount of water that takes each of these paths, however, varies greatly both in time and space. Influential factors include steepness of slope, nature of surface material, intensity of rainfall, and type and amount of vegetation. Heavy rains falling on steep slopes underlain by impervious materials will obviously result in a high percentage of the water running off. Conversely, if rain falls steadily and gently upon more gradual slopes composed of materials that are easily penetrated by the water, a much larger percentage of water soaks into the ground.

Some of the water that soaks in does not travel far, because it is held by molecular attraction as a surface film on soil particles. This near-surface zone is called the **zone of soil moisture.** It is crisscrossed by roots, voids left by decayed roots, and animal and worm burrows that enhance the infiltration of rainwater into the soil. Soil water is used by plants in life functions and transpiration. Some water also evaporates directly back into the atmosphere.

Water that is not held as soil moisture percolates downward until it reaches a zone where all of the open spaces in sediment and rock are completely filled with water (Figure 12.2). This is the **zone of saturation**. Water within it is called **groundwater.** The upper limit of this zone is known as the **water table.** Extending upward from the water table is the **capillary fringe** Here groundwater is held by surface tension in tiny passages between grains of soil or sediment.

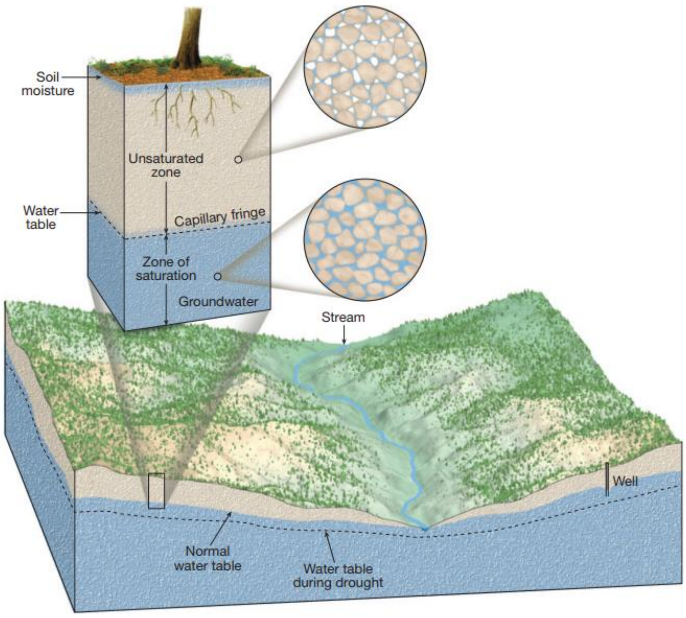


Fig.12.2 Distribution of underground water. The shape of the water table is usually a subdued replica of the surface topography. During periods of drought, the water table falls, reducing streamflow and drying up some wells.

The area above the water table that includes the capillary fringe and the zone of soil moisture is called the **unsaturated zone**. Although a considerable amount of water can be present in the unsaturated zone this water cannot be pumped by wells because it clings too tightly to rock and soil particles. By contrast, below the water table the water pressure is great enough to allow water to enter wells, thus permitting groundwater to be withdrawn for use. We will examine wells more closely later in the chapter.

The Water Table

The water table, the upper limit of the zone of saturation, is a very significant feature of the groundwater system. The water table level is important in predicting the productivity of wells, explaining the changes in the flow of springs and streams, and accounting for fluctuations in the levels of lakes.

Variations in the Water Table

The depth of the water table is highly variable and can range from zero, when it is at the surface, to hundreds of meters in some places. An important characteristic of the water table is that its configuration varies seasonally and from year to year because the addition of water to the groundwater system is closely related to the quantity, distribution, and timing of precipitation. Except where the water table is at the surface, we cannot observe it directly.

One important influence is the fact that groundwater moves very slowly and at varying rates under different conditions. Because of this, water tends to pile up beneath high areas between stream valleys. If rainfall were to cease completely, these water-table "hills" would slowly subside and gradually approach the level of the valleys. However, new supplies of rainwater are usually added frequently enough to prevent this. Nevertheless, in times of extended drought, the water table may drop enough to dry up shallow wells (Figure 12.2). Other causes for the uneven water table are variations in rainfall and permeability from place to place.

Interaction between Groundwater and Streams

The interaction between the groundwater system and streams is a basic link in the hydrologic cycle. It can take place in one of three ways. Streams may gain water from the inflow of groundwater through the streambed. Such streams are called **gaining streams** (Figure 12.3A).

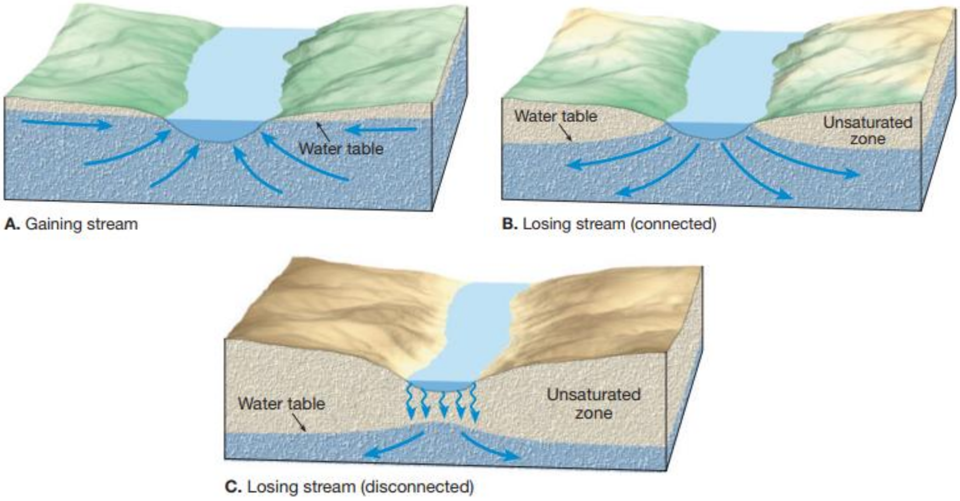


Fig. 12.3 Interaction between the groundwater system and streams. A. Gaining streams receive water from the groundwater system. B. Losing streams lose water to the groundwater system. C. When losing streams are separated from the groundwater system by the unsaturated zone, a bulge may form in the water table

For this to occur, the elevation of the water table must be higher than the level of the surface of the stream. Streams may lose water to the groundwater system by outflow through the streambed. The term **losing stream** is applied to this situation (Figure 12.3B, C). When this happens, the elevation of the water table must be lower than the surface of the stream. The third possibility is a combination of the first two – a stream gains in some sections and loses in others.

Losing streams can be connected to the groundwater system by a continuous saturated zone or they can be disconnected from the groundwater system by an unsaturated zone. Compare parts B and C in Figure 17.3. When the stream is disconnected, the water table may have a discernible bulge beneath the stream if the rate of water movement through the streambed and zone of aeration is greater than the rate of groundwater movement away from the bulge.

In some settings, a stream might always be a gaining stream or always be a losing stream. However, in many situations flow direction can vary a great deal along a stream; some sections receive groundwater and other sections lose water to the groundwater system. Moreover, the direction of flow can change over a short time span as the result of storms adding water near the streambank or when temporary flood peaks move down the channel.

Groundwater contributes to streams in most geologic and climatic settings. Even where streams are primarily losing water to the groundwater system, certain sections may receive groundwater inflow during some seasons.

2. Practical part

Students studying the discipline "Engineering Geology" must have the necessary skills for the successful implementation of all types of professional activities foreseen for the position of civil engineering. Particular attention should be paid to the ability to distinguish, recognizing species of rocks, to find to which of the most important groups of rocks they belong. The basic knowledge for studying rocks is knowledge about the origin and physical properties of rock-forming minerals.

For civil engineers, the most favorable conditions are horizontal bedding of layers, their large thickness, uniformity of composition and increase in strength in depth. Minerals are natural chemical elements or compounds that are homogeneous in composition and structure. Minerals form in the earth's crust. The processes of mineralization are various physicochemical processes in the earth's crust and on its surface. Rocks made up of a variety of minerals.

2.1. Laboratory works

Objective: to study the physical properties of minerals and determine them using a determinant.

Physical properties of minerals

Minerals are natural chemical compounds or elements that are homogeneous in composition and structure, formed in a result of certain physical and chemical processes in the earth's crust and on its surface. It is known that in the earth's crust has more than 7,000 minerals and their varieties. Of the entire variety about 100 minerals can be found quite often, and only a few of them are composing rocks. They are called main or rock-forming, as they are part of certain rocks. The main minerals in the composition of a particular rock from more or less constant combinations and find the basic properties of the rock.

The study of minerals by external signs is to determine and a description of the following physical properties: the colour of the mineral, the colour of the trace, hardness, lustre, cleavage, the shape of crystals, etc. The study of minerals by external signs is to determine and a description of the following physical properties: *the colour of the mineral, the colour of the trace, hardness, lustre, cleavage, the shape of crystals, etc.*

The colour of minerals is one of the main external features. Minerals can be colourless, transparent and have the most diverse colour of all kinds of shades. The colour of the minerals depends on the chemical composition and impurities of elements - iron, nickel, copper, cobalt, chromium, etc.

The colour of the trace. The colour of the line refers to the colour of the mineral in the powder, which is determining by the friction of the mineral on the rough ceramic plate. Many minerals in powder have a different colour than in the piece. Some minerals give a characteristic feature: pyrite in a piece of straw yellow and the powder is almost black; hematite is led black, and powder is blood-red.

Hardness - the ability of a mineral to withstand external mechanical stress (scratching). The relative hardness of minerals is determined by comparison with standards (Mohs scale). Each of the following minerals on this Mohs scale has a higher hardness.

Mohs scale

1. Talc	*2. Gypsum*	*3. Calcite*	*4. Fluorite*	*5. Apatite*
6. Orthoclase	*7. Quartz*	*8. Topaz*	*9. Corundum*	*10. Diamond*

Using the Mohs scale, minerals can be comparing. To determine the ***relative hardness*** of the mineral choose a small flat surface on the test sample and draw on it with a sharp edge of the reference mineral.

In the absence of reference minerals, the Mohs scale is often used to determine the hardness of such objects as a pencil (hardness 1), the nail has hardness 2–2,5; a bronze coin (hardness 3.5–4), glass (hardness 5). **Absolute hardness** is measuring using special instruments - sclenometers. **The luster** of minerals is due to the reflection of light by the surface of the mineral and depends on its refractive index. Minerals can have a metallic luster, metalloid (luster of a tarnished metal surface), glass, greasy, pearlescent, silky, diamond, waxy, matte. **Cleavage** - the ability of a mineral to split upon impact on smooth planes - cleavage planes.

Minerals have the following *types of cleavage*:

very perfect - the mineral is easily split with the formation of one cleavage plane (biotite, muscovite);

perfect - with light impacts, the mineral, cracking, forms three cleavage planes and, as a rule, gives the correct faceted forms (halite, calcite);

middle - the mineral splits into fragments, on which two cleavage planes are found (orthoclase, hornblende);

imperfect - cleavage planes are found with difficulty (apatite);

very imperfect - cleavage is absent, all fragments of the mineral

irregular shape (quartz, corundum).

Special properties of minerals are the ability to exhibit magnetic properties or a salty taste, or soapy to the touch, or reaction with hydrochloric acid.

Method for determining the main rock-forming minerals

according to their physical properties

The determination of an unknown mineral should begin with a thorough analysis of its physical properties by external signs. In this case, a ceramic plate, Mohs scale, diluted hydrochloric acid, a glass plate and other improvised means are used. After establishing the colour, hardness and luster of the test sample, its cleavage, and trait are determined, the reaction with hydrochloric acid is checked, and the presence of magnetic and other special properties is detected.

Mineral Identifier Chart 1

Mineral groups of a certain hardness		
Subgroups	The luster, The color of the trace, cleavage	Sequence number of minerals in the “Description of minerals” section
1	2	3
	Minerals with hardness up to 2 inclusive *With a metallic luster*	
a)	The line is dark gray, to black.	2
	With glass or silky luster	
a)	The line is white, cleavage is very perfect in one direction, aggregates are fibrous, granular, lamellar.	21
	Oily luster	
a)	Pale green, white, dash white, soapy to the touch.	26
b)	White, white line, earthy.	32
в)	Color is yellow, the line is white, fragile.	1

chart continuation

	Minerals with hardness from 2 to 3 inclusive *With a metallic luster*	
a)	Color is lead gray, the line is grayish black.	3
	With glass and pearly luster	
a)	White, gray, line is white, salty to the taste.	7
b)	Brown to black, the line is white, dissected into thin leaves.	27
c)	Light, the line is white, dissected into thin leaves.	28
d)	White, gray, transparent, blue, line is white, boils from hydrochloric acid.	15
e)	Light green to dark green, line is pale green, like mica.	29
	With a greasy or matte luster	
a)	Green of various shades, the line is green, granular.	30
	Minerals with hardness from 3 to 4 inclusive	
	With a metallic luster	
a)	Golden yellow, the line is greenish-gray to black.	4
	With glass, oily, silky or pearly luster	
a)	Color is green, of different shades, the line is white or greenish, often with fibrous veins.	31
b)	Color is white, gray, yellowish, a line of white, boils from hydrochloric acid in powder.	16
c)	Violet, green, blue, transparent, white line.	6
d)	Brown, gray to black, a line in gray or yellow-brown, boils in heated hydrochloric acid	17

chart continuation

c)	White, gray, yellow, line white, boils in pre-heated hydrochloric acid.	19
e)	White, gray, blue, line white, grainy, does not boil from hydrochloric acid.	20
f)	Bright green, line green, boils in hydrochloric acid.	18
	Minerals with hardness from 4 to 5 inclusive	
	With bold, glass or matte luster	
a)	Color is different, line is white.	22
	Minerals with hardness above 5 to 6 inclusive	
	With metal, semi-metal and dull luster	
a)	Black, the line is black, magnetic.	9
b)	Dark brown, yellow-brown, rusty-yellow, yellow to brown.	14
c)	Red, iron-black, the cherry-red line.	8
	With a greasy, silky, dull luster	
a)	Color is different, luster is dull. Amorphous.	13
b)	Color is different, the line is white, bold on a break.	38
c)	Color is green, dark green, greenish-black, a line of gray-green, needle-shaped structure.	25
	Glass luster	
a)	Dark brown to black, the line is light, light green.	24
b)	Color from gray to black, blue tint (irrigation on a cleavage plane).	35
c)	White, gray, colorless, white line, cleavage perfect.	34
d)	Light pink to red, bluish, sometimes yellow-cotton, line white, cleavage at right angles.	36, 37
e)	Light gray, almost white, white line, cleavage perfect in two directions.	33

	Minerals with hardness from 6 to 7 inclusive	
	With a metallic luster	
a)	Golden yellow, the line is greenish black.	5
	With a greasy, matte and glass luster	
a)	Color is bluish-gray, yellow, brown, kink with sharp cutting edges, does not give a line, amorphous.	11
b)	The color is different, the conch is kinky, the luster is bold on the kink and glass luster is on the sides.	10
c)	Olive green, the colorless line, granular.	23
	Minerals with a hardness above 7	
	Glass luster	
a)	Color is different, the line is white.	12

Then you should look at chart 2 "Classification of minerals". Find the name of the mineral from the table 1 number in this table.

We use genetic and chemical classification of Minerals. Genetic - by origin (like rocks). Endogenous genesis (quartz) that arose in the earth's crust at depths, and exogenous (halite) on the surface and the boundary of the lithosphere with the hydrosphere and atmosphere. In the zone of high temperatures - of metamorphic origin (talc, serpentine, asbest).

Often use a simplified classification of minerals:

Primary (when cooling magma); secondary (modified).

The chemical classification by Chetverikov is shown on chart 2.

Mineral classification chart 2

Native Elements Sulfur (1), Graphite(2)
Sulphurous Compounds Pyrite (5), Chalcopyrite (4)
Halide compounds Halite, Sylvin (7), Fluorite(6)
Carbonates Calcite (15), Dolomite (16)
Sulfates Anhydrite (20), Gypsum(21)
Phosphates Apatite (22)
Silicates Labrador (35), Mica: Biotite (27), Muscovite (28), Augite (24), Hornblende (25), Olivine (23),Talc (26), Serpentine (31), Kaolinite (32), Chlorite (29), Microcline (37), Orthoclase (36)
Oxides Hematite (8), Magnetite (9), Quartz (10), Chalcedony (11), Corundum(12), Opal (13), Limonite (14)

The definition of a mineral is based on the property of hardness. According to hardness, all minerals are divided into seven groups. In each group, minerals are divided according to their brilliance into smaller subgroups, where each mineral has a certain serial number, against which the most characteristic features are distinguished that distinguish this mineral from its neighbors in the group. It should be noted that the main characteristics by which the minerals are grouped in the determinant are hardness and gloss.

Characteristics of the most important rock-forming minerals

Minerals classified according to various criteria. The most important from an engineering and construction point of view is the classification by chemical composition. The characteristics of the most important classes of minerals given in chart 3. Minerals form certain groups depending on their chemical composition.

The main properties of minerals chart 3

The mineral classes	**The main properties**	The representatives of mineral classes
1	2	3
Native Elements	Metals and non-metals consist of one chemical element or a mixture of two elements	Sulfur, graphite
Sulphurous Compounds	Compounds of elements with sulfur. Metallic luster, high density, have a colored Pyrite line, chalcopyrite	Pyrite, chalcopyrite
Halide connections	Salts of hydrogen halide. They have a taste, non-metallic luster, medium hardness, dissolve in water	Halite, sylvin, fluorite
Carbonates	Salts of carbonic acid. They are characterized by the ability to react with hydrochloric acid. They have medium hardness, non-metallic luster	Calcite, dolomite, magnesite aragonite
Sulfates	Sulfuric acid salts. Characterized by light color, low hardness, glass luster, good solubility in water	Anhydrite, gypsum
Phosphates	Salts of phosphoric acid. Characterized by non-metallic luster, variegated color, lack of cleavage, fragility	Apatite
Silicates	Salts of silicic and aluminosilicic acids. Subdivided into: 1. Aluminosilicates K-Na - feldspars, Na-Ca - feldspars, plagioclase Feldspatitis Mica 2. Metasilicates Pyroxenes Amphiboles 3. Orthosilicates 4. Secondary silicates 5. Clay minerals	Orthoclase, albite, oligoclase, Labrador, anorthitis Nepheline, leucite Biotite, Muscovite Augite Hornblende Olivine Talc, serpentine Kaolinite, montmorillonite, hydromica

Laboratory work № 2

TOP ROCKS GROUPS

Objective: to study the main groups of rocks.

Rocks

These are aggregates of minerals: consisting of one mineral - monomineral or of several - polymineral.

Over 1,000 different rocks in the earth's crust. About 1,000 species of rocks known. They have different strengths: granite is dense and strong, loose sand has low strength.

The main features of the classification of rocks are the mineral and chemical composition, structure, conditions (forms) of occurrence and the genesis (origin). The properties of the genus are to a decisive extent determined by their origin (genesis).

Genetic classification:

1. Magmatic (erupted): a - deep, b - spilled out.

2. Sedimentary: a - chemical, b - mechanical (clastic), c - organogenic, d - mixed.

3. Metamorphic: a - contact, b - regional metamorphism.

A rock is a natural aggregate consisting of one or several quantitatively constant minerals forming an independent geological body in the earth's crust. Each rock is formed under certain geological conditions under the influence of various processes of internal and external dynamics of the Earth. Rocks have a certain structure, composition and properties.

The main principle of rock classification is genesis, which is the main factor shaping the structure, composition and properties of rocks.

The structural features of rocks largely determine their properties. The concept of structure includes the structure and texture of the rock.

The structure of the rock refers to the size, shape of the components its elements (minerals), the quantitative ratio and nature of the relationship between them. The texture - the relative position or relative distribution of elements, i.e. minerals in the rock. For each type of breed, it is necessary to make a description according to the scheme: a) color, mineralogical and petrographic composition; b) structure, texture, conditions of formation, forms of occurrence; c) distribution; d) basic physical and mechanical properties and use.

Igneous rocks

Igneous or igneous rocks arise as a result of crystallization of magma - a complex silicate melt with a temperature of about 1,000–1,300 ° C - when it cools down in the bowels of the Earth and on its surface. Igneous rocks consist of 600 different species and varieties. Depending on the conditions of formation, the following are distinguished: deep (intrusive), vein, spilled (effusive) and volcanic rocks.

Molten magma breaking through cracks in the earth's crust and freezing in its bowels, leads to the formation of deep rocks.

Deep intrusive rocks form in the environment of previously formed rocks under high pressure, slow and uniform cooling of magma, often with the active participation of gases and vapors dissolved in it.

In this case, a quiet crystallization of magma occurs and clear crystalline rocks form. Such complete crystallization of magma leads to the formation of dense, massive full-crystalline rocks such as granite and gabbro. They occur in large massifs. Consequently, deep rocks have a full crystalline structure, which characterized by that the rock consists entirely of crystals.

If the sizes of the crystals composing the rock are approximately the same, then such rocks are called uniform-grained and are divided into coarse-grained (particle size more than 5 mm), medium-grained (5–2 mm) and fine-grained (small 2 mm). Rocks in which crystals of individual minerals stand out sharply called uneven-grained or porphyritic.

Vein rocks form during crystallization of magma in rock cracks, often with intense hydrothermal exposure. Typically, crystallization occurs without differentiation of the magma substance, which leads to the formation of a characteristic full-crystalline structure of the rock.

Poured (effusive) rocks form on the Earth's surface at low pressures and temperatures, with rapid cooling and degassing of magma melt. Under such conditions, complete differentiation impossible, part of the melt solidifies in the form of an amorphous glassy mass and non-crystalline rocks form. Often crystallization takes place in two phases: slow in the depths of the earth's crust, when individual crystals of minerals form, and then fast on the surface, when intense cooling of the melt occurs. In this case, a non-uniform crystalline (porphyry) structure form.

If the deep rocks are characterized by a massive, dense texture, then it can often be porous in those who pour out.

Volcaniclastic rocks form during volcanic eruptions both on continents and in marine basins. The magma melt cools rapidly with the simultaneous process of intense loss of dissolved gases and vapors. Under these conditions, volcanic glasses, cryptocrystalline highly porous rocks, also specific loose rocks form.

Classification of igneous rocks

The classifications are based on: chemical and mineralogical compositions; conditions and time of education.You need to know the main ones, and derivatives are not necessary.

The SiO_2 content is distinguished:

1. Acidic (SiO_2> 65%)

Deep Outflowing Analogs

Ancient New Analogs

(paleotypic) (kainotype)

granite quartz porphyry liparite

Mineralogical composition: quartz, feldspar (orthoclase) and acidic (plagioclase), mica, hornblende. This is a light breed, relatively light.

2. Medium (SiO_2 - 65-55%)

a) syenite, a non-quartz porphyry trachite (from the word "rough").

Mineralogical composition: corresponds to acidic, but without quartz. They have light colors, but somewhat darker.

b) diorite porphyrite andesite

Mineralogical composition: feldspars, hornblende, mica, augite.

3. Basic (SiO_2 - 45-55%)

gabbro diabase basalt

(labradorite)

Mineralogical composition: feldspars, plagioclases, hornblende, augite, olivine. The rocks are dark, dark gray, dark green, almost black,

4. Ultrabasic (SiO_2 - 45-55%)

pyroxenitis practically does not occur

peridotitis (dunitis)

Mineralogical composition: augite (pyroxenite), olivine (peridotite).

5. Poured rocks with variable mineralogical composition

pumice, volcanic glass (obsidian), lava (volcanic tuffs)

Sedimentary rocks

Sedimentary rocks are formed as a result of precipitation from the water or air of weathering products of all rock groups. The agents of physical or mechanical weathering are temperature fluctuations, wedging of cracks with freezing water, destruction by vegetation cover, etc. Chemical weathering occurs in the form of reactions of minerals and rocks with water and the chemicals contained in it, organic weathering occurs under the influence of plants and living organisms. Depending on the conditions of formation and on the factors that contributed to the accumulation, sedimentary rocks are divided into clastic chemical, organogenic, mixed origin. Sedimentary rocks are characterized by a number of features that reflect the conditions of their formation and significantly distinguishing them from other breeds.

Peculiar features of sedimentary rocks are stratification, porosity, the dependence of the composition and properties of the rock on the climate, and the content of the remains of plant and animal organisms.

The structures of sedimentary rocks are associated with the method of their formation. Distinctive structures are distinguished - different in particle size, chemical structures (crystalline) and organic, in which traces of the structure of animal and plant residues are clearly visible. In texture, the most significant feature is layering. Most of the rocks are clearly layered, which is associated with the method of their formation as a result of the gradual accumulation of material at the bottom of a basin. Separate layers differ in color, particle size, mineralogical composition, etc. The other texture of these rocks is porosity. The size of pores ranges from the thinnest, invisible to the naked eye (clay), to large (gravel).

In the earth's crust is about 5% of the mass, up to 75% of the surface of the Earth.

Builders deal mainly with sedimentary rocks (soils), which are form from igneous or metamorphic rocks during their destruction or weathering. They possess in most high porosity and a number of features. They are classified into chemical, mechanical (debris) organogenic and mixed. Classification of debris (soil) is given in chart 4.

The complex of natural conditions in which sedimentary rocks (soils) are formed. They called facies, of which the main ones are: continental, marine, lagoon.

Classification of sedimentary rocks chart 4

Structure	Diameter, mm	loose		cemented	
		rounded	**non-rounded**	**rounded**	**non-rounded**
Coarse	200	boulders	blocks	conglomer-ates	breccia conglomerates
	200-500	pebble	crushed stone		
	50-20	gravel	dresva		
Sandy	2-1	sand	coarse	sandstone coarse-grained	
	1-0,5	sand	big	sandstone big-drained	
	0,5-0,25	sand	medium	sandstone medium - grained	
	0,25-0,15	sand	small	sandstone small-grained	
Dusty	0,15-0,05	sand	dusty	siltstone	
	0,05-0,005	loess			
Clay	<0,005	Clay		mudstone	

Metamorphic rocks

Formed as a result of the conversion of sedimentary and magmatic rocks when exposed to high temperatures and pressures, as well as under the influence of the introduction of magma into deposited rocks.

The main factors of metamorphism include temperature, pressure, fluids - liquid or gaseous components of magma or circulating deep in the Earth gas-saturated solutions. These factors cause a complex process of changing the initial structure of rocks, their chemical and mineralogical composition. The processes of transformation of rocks are without melting the latter. The nature of the change in rocks is different: from compaction to complete recrystallization of minerals, composing the original breed. Metamorphic rocks are secondary. The degree of metamorphism is different, so there is a fairly large number of transitional rocks. The structure of metamorphic rocks is crystalline, formed with the phenomena of recrystallization, it differs somewhat from the structure of igneous rocks.

The texture of metamorphic rocks serves as the most reliable macroscopic feature for their determination and is divided into the following types:

1) shale - elongated or tabular minerals are located with their long sides mutually in parallel;

2) banded or ribbon - stripes of different mineralogical composition and color alternate;

3) banded - shale planes and strips crumpled into small folds;

4) massive - similar to the texture of igneous rocks.

The following types of metamorphism are distinguished:

1) contact, which develops at the boundary of the intrusion of magma melt with sedimentary rocks. The pressure that arises here, elevated temperature, and magma substances significantly change rocks (for example, limestones turn into marbles, skarns). The structure of rocks of contact metamorphism is crystalline, sugar-like, massive, slightly layered;

2) deep (regional) metamorphism develops under the combined influence of temperatures, high pressure and fluids flowing at great depths. In this case, the mineralogical composition of the rocks sometimes varies significantly. The rocks acquire a characteristic crystalline, shale, banded, dense structure. The presence of shale and streakiness significantly affects the strength of structural bonds in various directions, which leads to anisotropy of rock properties;

3) dynamometamorphism, which is caused by high pressure during mountain building (tectonic) processes. Powerful crumple zones, complex folds occur. Chart 5 provides a classification of metamorphic rocks.

Rocks of contact metamorphism formed during the introduction of magma into the earth's crust at high temperature in contact.

Rocks of regional metamorphism arose in the mobile zones of the earth's crust, called geosynclines, on a large scale at high pressures.

Dynamomorphism is the formation of rocks as a result of great pressure and deformations of the earth's crust (tectonic movements).

Metamorphic rocks in terms of appearance and conditions of occurrence occupy an intermediate position between magmatic and sedimentary rocks, and in mineral composition they are closer to magmatic: mica, quartz, chlorite, talc. When formed from igneous rocks, they retain their bedding form. During metamorphisation of sedimentary rocks, the layering is strongly deformed.

Gneisses and quartzites are the strongest, while schists have different strengths and anisotropy of properties, and the weakest are mica. When the biotite content is much eroded.

Classification of metamorphic rocks chart 5

Source (maternal) roks	The types of metamorphism	Metamorphic rocks	Mineralogical composition
Granite, clay-sandy rocks	Deep (regional) and dynamo metamophism	Gneiss	Quartz, feldspars, hornblende, mica
Various igneous and clay rocks		Shales crystalline	Mica, talc, horny blende, chlorite, graphite, quartz, etc.
Siliceous sandstones (quartz) Limestones, Dolomites Clay roks		Quartzites, jasper Marbles phyllites Clay shales	Quartz and impurities Calcite, dolomite Kaolinite, quartz, mica
Clay rocks, siltstones, mudstones	Contact metamorphism	Hornfels	Hornfels Quartz, feldspars, biotite, hornblende
Limestones, Dolomites		Skarn	calcite, hornblende, ore minerals
same		Marbles	Calcite, Dolomite and impurities

Photos of rock-forming minerals

1- pyrite; 2 – chalcopyrite; 3 - halite; 4 – sylvan;

5– anhydrite;

6 – gypsum plaster; 7– gypsum granular;

8 – gypsum fiber;


9


10

9 – calcite; 10 – dolomite;

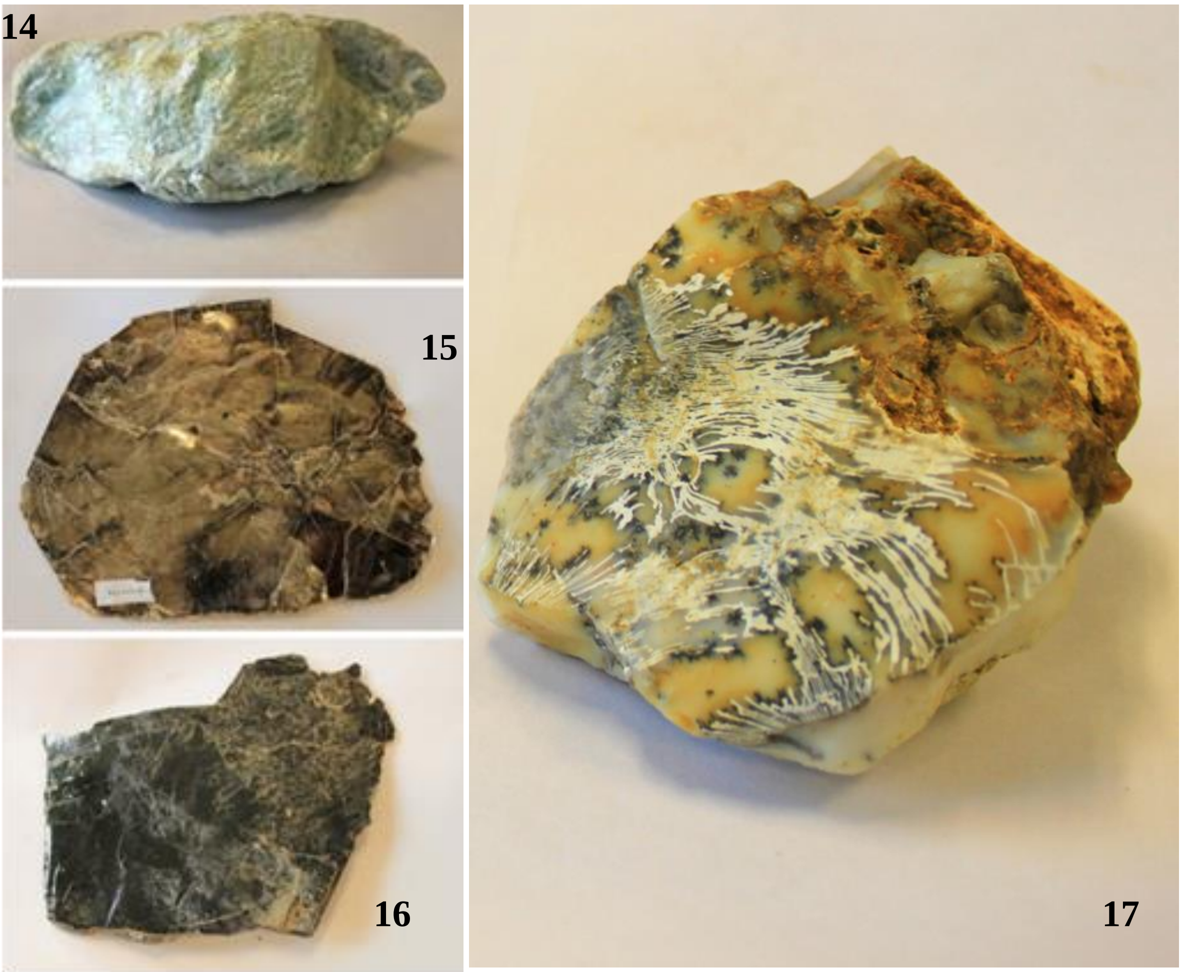

11


12

11,12 – chalcedony;


13

13 – quartz;



14 – talc; 15 – biotite; 16 –muscovite; 17 – opal;

18 –chlorite; 19 – orthoclase.

3. Knowledge Control Section

Sample topics of essays for independent work

1. Modern field methods for dynamic soil testing.
2. Features of the study of soil properties in situ in urban agglomerations.
3. Modern methods for studying the dynamic properties of water-saturated soils
4. Dynamic properties of soils and their assessment in the analysis of vibrations of foundations of various types.
5. Modern geophysical methods in engineering-geological surveys in the field of permafrost distribution.
6. World experience in the application of static sensing in engineering-geological research.
7. Features and applicability of the method of dynamic sounding of soils in the territories of megacities.
8. Quicksand as the basis of structures and methods for their research.
9. The method of georadar in solving engineering and geological problems.
10. Modern field methods for dynamic soil testing.
11. A shallow frequency sounding method for solving engineering and geological problems in urban areas of various engineering and geological conditions.

Guidelines for organization and implementation students' independent work

It is recommended to use the following forms of independent work when studying the discipline :

- students work themselves in the form of solving individual problems in the audience during laboratory classes under the supervision of a teacher in accordance with the schedule;
- preparation of essays on individual topics, including the use of patent materials.

Sample checklist

1. What are theories about the origin of the Earth?
2. What methods are used to study the internal structure of the Earth?
3. What geospheres of the Earth stand out and what is their composition?
4. What is the structure of the earth's crust? Her power?
5. How to determine the absolute age of the rocks?
6. What eras and periods are highlighted in the geochronological column?
7. Define the concept of "mineral."
8. Give the classification of minerals by chemical composition
9. What can be the origin of the mineral?
10. What are the physical properties and external characteristics of minerals?
14. What is called a rock?
15. How are metamorphic rocks formed?

16. How are sedimentary rocks formed?
17. How are igneous rocks formed?
18. What are the rock-forming minerals of igneous, metamorphic, sedimentary rocks?
19. Define the concept of “soil”.
20. How is dispersed soil classified according to particle size distribution?
21. What are the field methods for determining the properties of soils?
22. What types of water are in the ground?
23. Give the classification of groundwater by the conditions of occurrence
24. What is called an aquifer?
25. Classification of groundwater by chemical composition.
26. Darcy's Law.
27. Geodynamic zoning of groundwater.
28. Types of engineering-geological maps.
29. Types of engineering-geological classifications of geological processes and phenomena. The value of classifications.
30. What methods of waterlogging control do you know? What determines the choice of methods?

List of references

Main literature

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