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Practical Guide in Geology

Tutorials

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Preface

Geology is one of the fundamental sciences with broad purposes and applications. It operates at multiple scales, from the crystal level to the comprehension of tectonic plate movements. Geology is a pillar of science that helps resolve mysteries concerning the origin of life, the diversification of ecosystems in ancient oceans, and the invasion of land by early tetrapods. A solid background in geology enables biologists to understand how species dispersed and evolved in different regions by studying the movements of tectonic plates, which connect or disconnect exchanges between various communities. Geology also describes and categorizes different soils and their properties, which are known to influence microbial activity, agricultural productivity, and the composition of ecosystems. Moreover, geology is the only science that allows us to reconstruct past climate change by analyzing ice cores, sediments, and fossils. These records reveal major shifts in temperature and the occurrence of wildfires, helping biologists to better understand biodiversity through time. Land and marine pollution are among the greatest challenges of this century. Geologists provide indispensable information in cases of natural pollution. For example, water flowing from certain rivers may contain elevated concentrations of heavy metals. While these contaminants are often released into marine ecosystems by industry, they can also originate from the weathering and alteration of igneous and metamorphic rocks. In this contribution, eight main themes are presented, all related to the curriculum of biology students. These tutorials may also be useful for first- and second-year geology students. The first chapter concerns mineralogy, in which I describe the diversity and properties of minerals and introduce simplified methods to identify them. Mineralogy provides the basis for the second chapter, which focuses on rocks. The third chapter introduces igneous rocks, the most abundant group in the deep crust. The fourth chapter addresses sedimentary rocks, the most common at the Earth's surface. The fifth chapter is dedicated to metamorphic rocks, the final major rock group. Chapter six provides an overview of topography. This chapter is particularly important for biology students, as it will help them read topographic maps, calculate distances, and construct topographic profiles. The book concludes with chapter seven, an introduction to geological mapping, which will help students understand how rocks are distributed in the Earth's crust. This knowledge is essential for further studies in soils and related fields.

Contents

Chapter 1

Minerals

1.1 introduction

Mineralogy, regarded as one of the oldest disciplines within the Earth Sciences, focuses on the study of minerals, defined as natural elements or compounds that constitute the Earth's crust. By extension, it also encompasses the examination of minerals contained in meteorites and originating from other celestial bodies. Since rocks are most often aggregates of small-sized minerals, and as the Earth itself is essentially composed of rocks, mineralogical study is fundamental for understanding the composition and evolution of our planet. Mineralogical properties are commonly investigated through several subdivisions: chemical mineralogy, physical mineralogy, and crystallography. The description of properties, classification, modes of formation, occurrences, and uses of minerals fall under descriptive mineralogy, while their identification on the basis of chemical, physical, and crystallographic criteria is the domain of determinative mineralogy. The use of minerals dates back to prehistory, when early human groups fashioned lithic tools for hunting, butchering, and constructing shelters. They also discovered the pigments derived from certain minerals, which were employed in cave paintings. Over time, humans learned to exploit stone for architecture, to model clay, and to process metals to produce weapons, ritual objects, tools, and utensils. Beyond their historical role, minerals are essential for nutrition and biological functions. Plants absorb through their roots macronutrients such as calcium, phosphorus, and potassium, complemented by trace elements including iron, cobalt, zinc, manganese, nickel, and copper. Animals, for their part, obtain primarily from their diet the iron, calcium, sodium, and potassium required for growth and metabolism. For humans, daily mineral intake is indispensable to maintaining health, and only a balanced and varied diet can adequately provide these needs. In modern society, the industrial applications of minerals are both vast and diverse: silica in glass production, clay in ceramics, titanium dioxide in paints, mica in electronics, talc in cosmetics, aluminum in food packaging, and various minerals in pharmaceuticals. In construction, building foundations are made of concrete, a mixture of gravel, sand, and cement; walls are built from clay bricks bonded with limestone-based mortar; water circulates through copper pipes to ceramic or stainless-steel fixtures; while electrical energy and telecommunications rely on copper conductors. Minerals also play a major role in jewelry, art, and decoration. Gold, silver, diamonds, and gemstones have always been employed for the manufacture of ornaments and valuable objects. Likewise, rocks such as marble, limestone, slate, and granite, composed of multiple minerals, are widely used as ornamental stones. From antiquity to the present day, artists and craftsmen have taken advantage of the aesthetic qualities of minerals, sculpting statues in marble or creating refined objects from agate, onyx, jade, or jasper.

1.2 Definition and Nature of Minerals

A mineral is a natural substance, typically solid and inorganic, with a defined chemical composition and a characteristic crystalline structure. It is distinct from a rock, which is an aggregate of minerals or mineraloids and does not possess a specific chemical composition. A mineral represents a natural chemical species, most often organized in the form of a crystalline network (crystal) of variable dimensions. In contrast, macerals refer to organic constituents. Minerals are formed through biogeochemical processes and are defined by a specific chemical composition, an ordered atomic arrangement, and distinct physical properties.

Minerals may consist of simple pure elements or highly complex salts, particularly silicates, of which several thousand forms are known.

1.3 Diversity and Properties of Minerals

Today, more than 5,300 mineral species have been identified, with over 5,090 officially approved by the International Mineralogical Association (IMA). Each year, between 50 and 80 new species are discovered and described. The diversity and abundance of minerals are largely determined by the chemistry of the Earth. Silicon and oxygen account for about 75% of the Earth's crust, which explains the predominance of silicate minerals, representing more than 90% of the crust. Differences in chemical composition and crystalline structure define mineral species, and these characteristics are strongly influenced by the geological environment in which minerals form. Variations in temperature, pressure, or chemical composition within a rock mass can therefore lead to mineral transformations. Minerals are identified through a variety of physical properties related to their structure and chemical composition. The most commonly used criteria include: crystalline structure and habit, hardness, luster, transparency, color, surface features, tenacity, cleavage, fracture, parting, and relative density. Finally, certain specific tests are used to refine the characterization of some minerals, such as magnetism, taste or odor, radioactivity, and reaction to strong acids.

1.4 Identification of minerals

More than 4,000 minerals are known, each identified by their distinct physical and chemical properties. These physical properties are largely determined by the atomic structure and crystal chemistry of the mineral. Among the most common characteristics used for identification are crystal form, color, hardness, cleavage, and specific gravity.

1.4.1 Physical Determination

It is important to note that several diagnostic tests are destructive to the specimen. If the available sample is limited, such methods should be used only as a last resort and applied to portions of the sample that hold the least mineralogical interest. Minerals can be identified through a set of physical properties, some relatively simple to recognize, while others require careful testing. The principal properties are described below.

Hardness: Hardness is one of the most fundamental diagnostic properties of minerals. It measures the resistance of a mineral to scratching, abrasion, or penetration. This property is relative and expressed on a scale ranging from 1 to 10. The most widely used reference is the Mohs scale of hardness (1822), which orders ten representative minerals by increasing hardness. Practical tools include simple standards such as a fingernail (2–2.5), a copper coin (3.5), a knife blade (5.5), and a glass plate (6.5). A mineral that scratches glass, for example, has a hardness greater than 6.5 (e.g., quartz, corundum, diamond), while a mineral that can be scratched by a fingernail has a hardness below 2.5 (e.g., talc, gypsum). Testing requires care: the scratch should occur without applying excessive pressure. After scratching, one must confirm that the mark is a true scratch rather than a superficial trace by wiping it with a moist finger or testing with the nail. Each reference mineral scratches those lower on the scale and is scratched by those higher (Figure 1.1).

Streak: Streak refers to the color of the powdered mineral, obtained by rubbing it against the unglazed side of a porcelain plate. For example, hematite, typically gray to black in hand specimen, produces a blood-red streak, while goethite, also black in appearance, yields a yellow-brown streak. Minerals harder than porcelain must be ground into powder and then rubbed

Figure 1.1: The Mohs scale: Stockholm precision tool sptab.com

on the plate. Very soft minerals (e.g., graphite, molybdenite) may be tested directly on paper. Notably, streak color is often more diagnostic than surface color.

Cleavage and Fracture: Cleavage is the tendency of a mineral to break along specific planes dictated by its crystal structure. Depending on the mineral, one to three directions of cleavage may be observed. Cleavage quality is usually ranked on a six-level scale:

- Excellent (e.g., muscovite)
- Very good (e.g., galena, calcite)
- Good (e.g., orthoclase)
- Fair (e.g., apatite)
- Poor
- Absent (e.g., pyrite), in which case fracture is observed.

Fracture refers to breakage that does not follow crystallographic planes. Quartz, for example, exhibits a characteristic conchoidal fracture. Other

Figure 1.2: Example for fracture type : conchoidal and splintery

Figure 1.3: Cleavages in both Muscovite and Pyrite

types include irregular and splintery fractures (Figure 1.2). Some minerals, such as gypsum, may exhibit both cleavage and fracture depending on how stress is applied (Figure 1.3).

Color: Although color is the most immediately visible property, it is not always reliable for identification. Many minerals exhibit a range of colors (e.g., quartz varieties), while others display consistent hues (e.g., albite is typically white, azurite is blue, chlorite is usually green). Minerals can be classified by the origin of their color:

• Achromatic: colorless, light passes without modification (e.g., rock crystal).

• Idiochromatic: intrinsic coloration due to essential elements in the structure (e.g., azurite—Cu, rhodonite—Mn).

• Allochromatic: coloration from trace impurities or inclusions (e.g., amethyst, smoky quartz).

• Pseudochromatic: apparent coloration caused by optical effects such as iridescence, opalescence, or play of light.

Transparency : Transparency refers to the ability of a mineral to transmit light:

• Transparent: objects visible through the specimen (e.g., quartz).

• Semitransparent: blurred vision through the mineral (e.g., fluorite, calcite).

• Translucent: light passes but objects are not visible (e.g., chalcedony, agate).

• Subtranslucent: light passes only in thin sections (e.g., actinolite).

• Opaque: no light transmission (e.g., pyrite, galena).

1.4.2 Chemical Determination

Reactivity with Acids, Bases, and Water: One of the simplest tests for chemical determination involves the reaction of minerals with acids or bases. The most essential reagent is dilute hydrochloric acid (HCl), though white vinegar can also be used with less obvious but still visible results.

Many carbonates (see section Carbonates) react with acids. For example, calcite, the most common representative of this group, produces a visible effervescence when exposed to a few drops of acid.

Qualitative Analysis: Qualitative analysis can be performed in two main ways: wet methods and dry methods. In both cases, the sample tested must be a clean fragment of the mineral, free from impurities, coatings, or inclusions that might distort the results (e.g., oxide crusts on the surface).

Wet Analysis: Wet Wet Analysis chemical analysis provides reliable results but requires access to laboratory reagents and equipment, some of which are hazardous. The method generally consists of dissolving the mineral in a strong acid (commonly concentrated nitric acid, HNO) and then adding specific reagents to observe diagnostic reactions such as the formation of colored precipitates. Characteristic reactions exist for many elements (e.g., Fe, Bi, Cu) and for specific anionic groups (e.g., carbonates, phosphates). Basic equipment: glassware (beakers, funnels, glass rods), filter paper, tongs, gloves, protective goggles, and preferably a cotton lab coat. Basic reagents: concentrated nitric acid (68%), hydrochloric acid (30%), sulfuric acid (30–37%), ammonia solution (20–30%), and sodium hydroxide (30%). Most can be obtained commercially, except nitric acid, which is restricted due to its potential use in explosives.

Dry Analysis: Dry methods require less equipment than wet analysis, but they are less precise. These tests involve heating the mineral directly and observing changes in fusibility, flame color, and residue formation. Common procedures include:

- Flame color tests: observing the characteristic flame color of elements when a mineral fragment, briefly dipped in HCl, is placed in the non-luminous zone of a Bunsen flame.
- Heating in open or closed tubes: observing volatility, fusibility, color changes, luminescence, gas emissions, and residues.
- Charcoal tests: heating in oxidizing and reducing flames to detect sublimates, residues, or characteristic odors.
- Borax bead and phosphate bead tests: heating the mineral with borax or sodium ammonium phosphate in oxidizing and reducing flames to observe bead coloration.

Flame coloration is a useful method for identifying certain elements in minerals. The test is carried out by placing a fresh, sharp-edged fragment of the mineral—previously dipped in hydrochloric acid—into the non-luminous part of a flame. To ensure accuracy, it is important to avoid contamination from skin oils, tools, or other substances. Different elements produce distinct flame colors: arsenic gives a faint azure color, barium shows yellow-green, calcium produces an orange to brick-red flame, copper yields an emerald green, and copper(II) chloride turns azure. Potassium burns with a pale violet flame, lithium with a crimson red, manganese with green, and molybdenum with yellow-green. Sodium strongly colors the flame bright yellow, while lead produces a gray-green to bluish tone. Rubidium gives a blue color, antimony a faint blue-green, selenium a blue flame, strontium a crimson red, and tellurium a greenish hue when present as oxides. Thallium briefly produces a green flame that fades rapidly, and zinc gives a green to blue coloration.

Chapter 2

Rocks

2.1 Introduction

A rock is an assemblage of minerals, of crystals (except in rare cases where a glassy phase is present). Rock is a fundamental resource and a cornerstone of the economy. Its study is essential, for example, to identify areas suitable for gold extraction. Indeed, economically valuable ores are rare, their distribution is limited, and they are often associated with specific geological zones. Furthermore, analyzing the properties of rocks, such as porosity and the degree of fracturing, makes it possible to estimate the capacity of petroleum reservoirs. Rocks are also widely used in the construction of buildings and infrastructure. Finally, they are a key element in understanding Earth's history, as many geological events have left traces within them. The study of rocks therefore makes it possible to reconstruct when and how these events occurred.

Figure 2.1: Photographs of polished rock plates showing different mineral grains which are randomly distributed (left) and the rock marked by X-shaped fractures (right).

2.2 Fundamental Characteristics of Rocks

In general, the term rock may refer either to a small specimen, such as a sample used for laboratory tests, or to a large-scale geological body in rock engineering. The latter is usually termed rock mass, which incorporates structural features such as joints, faults, in situ stresses, groundwater, and other natural factors. The fundamental characteristics of rocks can be summarized as follows:

2.2.1 Composite of Multiple Mineral Grains

Rocks are composites made up of multiple mineral grains. Most rocks consist of more than one type of mineral, and the grains usually vary in size, as illustrated by the polished granite plate in Fig. 3.2a. Because mineral grains differ in their physical and mechanical properties, rocks are inherently nonuniform (Figure 2.1).

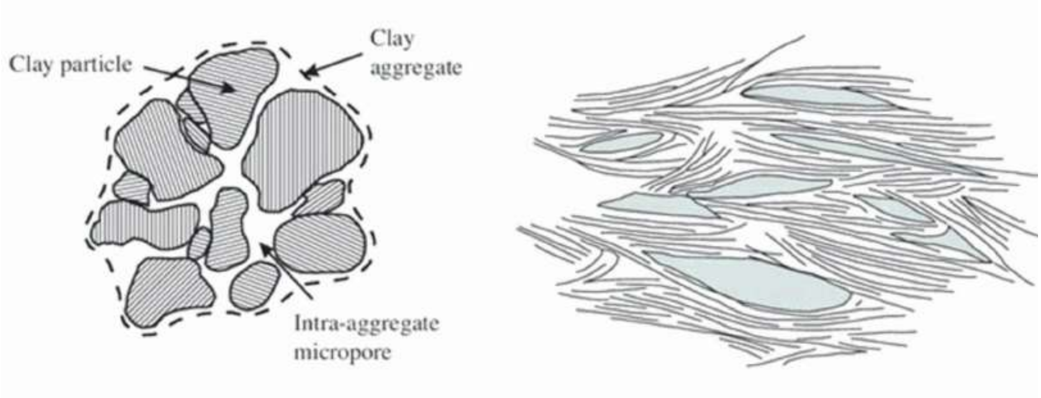


Figure 2.2: grain boundary. A cluster of clay particles and tiny pores form inside the cluster (left). (b) A Both tiny pores inside the clusters (intra-aggregate) and larger pores between the clusters (right). Christidis et al. (2011)

2.2.2 Grain Boundaries

Grain boundaries strongly influence the mechanical behavior of rocks. They may consist of cementing materials, such as clay, or may be voids in the form of cavities. Unlike engineered materials such as steel, rocks form under natural, uncontrolled conditions, meaning that grain boundaries can behave differently even within the same specimen. Depending on factors such as the rock's origin and formation temperature, grain boundaries may be either stronger or weaker than the mineral grains themselves (Figure 2.2).

2.2.3 Discontinuities

Rocks commonly contain discontinuities of various scales, including cracks, fissures, joints, cavities, bedding planes, and faults. These features range from microscopic cracks to faults extending for kilometers. For example, multiple long fissures are typically referred to as joints, while large-scale

Figure 2.3: Bedding structures in the Ben Zireg section (Bechar Basin, Algeria, left) . Succession of limestones with the tops of beds toward the left. Soft-sediment (convolute) structures overlie laminar bedding (right).

fractures exceeding one kilometer are termed faults. Cavities may also occur, varying from small voids to openings up to half a meter, which can significantly affect tunnel stability and blasting operations. Bedding structures are characteristic of sedimentary rocks but may also appear in igneous rocks at smaller scales. Such structures impart anisotropy, meaning that the rock's response to stress depends on the direction of loading. Discontinuities strongly affect rock strength and deformation behavior, although their influence also depends on factors such as stress state and loading conditions. In cases where joints are randomly distributed and no large-scale discontinuities exist, rocks can still be treated as a continuous and homogeneous medium (Figure 2.3).

2.2.4 Porosity

Due to the presence of cavities and voids, rocks are porous and therefore permeable to water and other fluids. Water or moisture may exist under

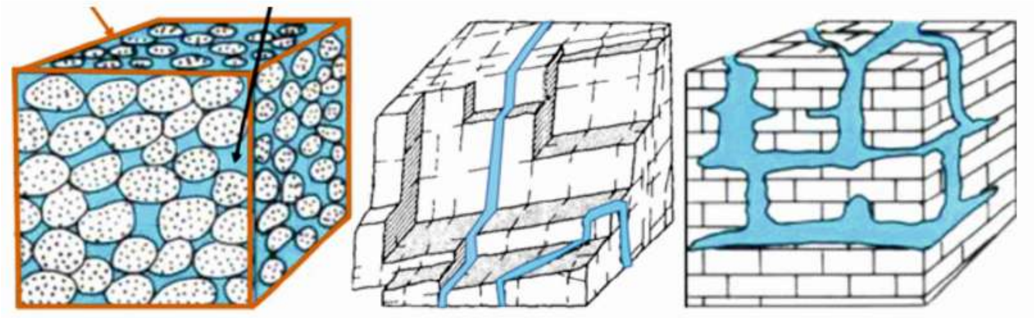


Figure 2.4: Water occupies subsurface spaces in: (a) pores between sediment particles (Heath, 1983), (b) rock fractures (Gale, 1982), and (c) caverns or cavities in carbonate rocks, known as karst (Heath, 1983).

pressure within pore spaces, fissures, and other discontinuities. The porosity of sedimentary rocks ranges from nearly 0% to as high as 90%, with sandstones typically averaging around 15%. In contrast, igneous rocks generally have porosities below 1–2%, and metamorphic rocks show similarly low values, often less than 2%. Under normal conditions, rocks are typically brittle materials: their tensile strength is much lower than their compressive strength. As a result, rocks fracture more easily under tensile loading than under compression. However, under high-stress states, particularly at high confining pressures, their brittleness decreases (Figure 2.4).

2.3 The Rock Cycle

Due to the presence of cavities and voids, rocks are porous and therefore permeable to water and other fluids. Water or moisture may exist under pressure within pore spaces, fissures, and other discontinuities. The porosity of sedimentary rocks ranges from nearly 0% to as high as 90%, with sandstones typically averaging around 15%. In contrast, igneous rocks generally have porosities below 1–2%, and metamorphic rocks show similarly low values, often less than 2Under normal conditions, rocks are typically brittle materials: their tensile strength is much lower than their compressive strength. As a result, rocks fracture more easily under tensile loading than under compression. However, under high-stress states, particularly at high confining pressures, their brittleness decreases.

2.3.1 Genesis of Igneous Rocks

The cycle begins within the Earth's mantle, where rocks occur in a viscous state. Despite their high viscosity, they are capable of extremely slow movements, which underpin large-scale geodynamic processes such as plate tectonics. Pockets of magma are generated in several distinct tectonic environments: (Figure 2.5)

• Mid-ocean ridges, where ascending mantle material undergoes adiabatic decompression, leading to partial melting.

• Hot spots, where anomalously high geothermal gradients, caused by the ascent of deep mantle plumes, induce melting.

• Subduction zones, where the descending slab releases water during metamorphic reactions. This fluid lowers the solidus of the overlying mantle wedge, thereby promoting magma generation.

Upon cooling and solidification, magma crystallizes to form igneous rocks (from the Latin igneus, meaning "fire"):

• Rapid cooling at or near the surface produces fine-grained or microlithic textures (e.g., basalt).

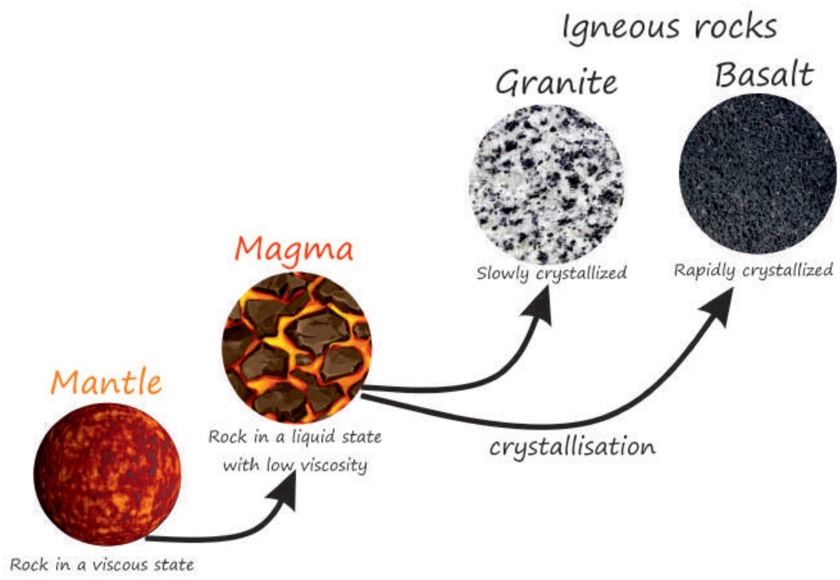


Figure 2.5: Genesis of Igneous Rocks

• Slow cooling at depth allows the development of well-formed crystals, yielding coarse-grained or phaneritic rocks (e.g., granite).

Igneous rocks may subsequently undergo remelting, thereby re-entering the magmatic stage of the cycle.

2.3.2 Weathering, Sedimentation, and Sedimentary Rocks

Once exposed at the surface, igneous and metamorphic rocks are subject to exogenic processes including physical weathering (e.g., frost wedging, abrasion) and chemical alteration (e.g., dissolution by acidic waters). These processes generate sediments, which are transported by agents such as rivers,

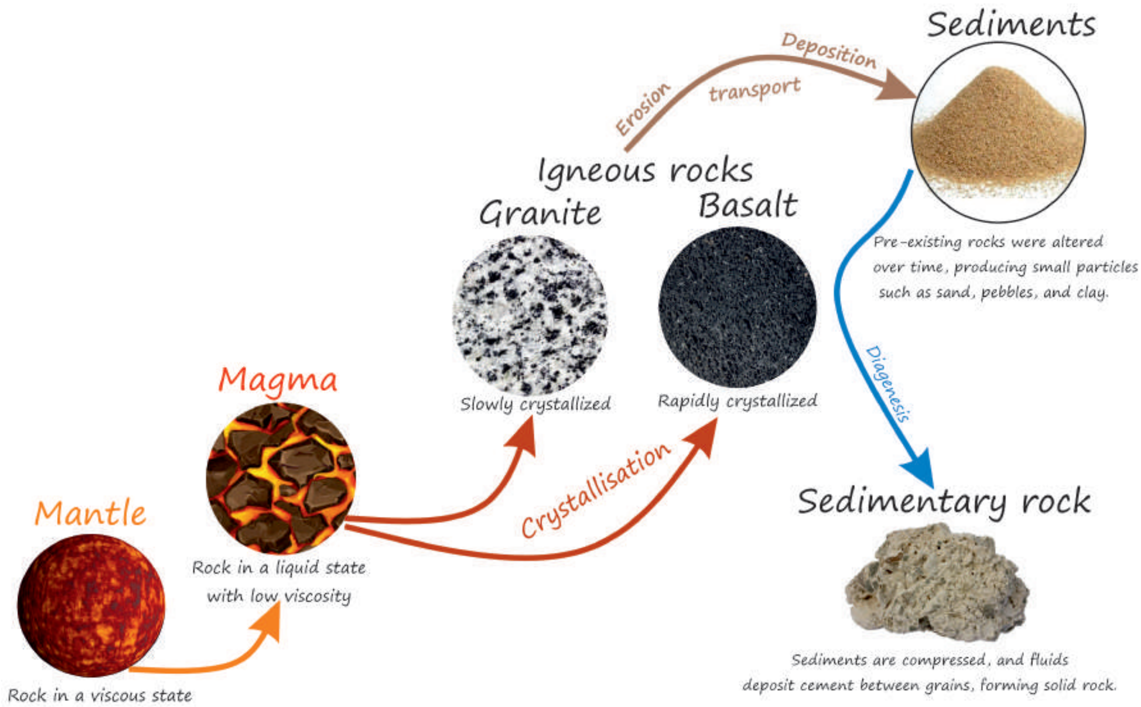


Figure 2.6: Weathering, Sedimentation, and Sedimentary Rocks

wind, and glaciers, and eventually deposited in sedimentary basins (lakes, seas, and oceans). Progressive burial increases both pressure and temperature, while interstitial fluids facilitate diagenesis, involving compaction and cementation (Figure 2.6). This transformation results in the formation of sedimentary rocks. When subsequently uplifted and exposed, sedimentary rocks may once again undergo weathering and erosion, thus perpetuating the cycle of sediment production.

2.3.3 Metamorphism and Metamorphic Rocks

Igneous and sedimentary rocks buried to sufficient depths may be subjected to elevated pressures and/or temperatures, resulting in metamorphism. During this process, mineral assemblages and textures are reconfigured:

- Igneous rocks may recrystallize into banded mineral structures, such as gneisses.

- Sedimentary rocks may develop foliation or slaty cleavage, as exemplified by slates.

Metamorphic rocks exposed at the surface may once again be weathered into sediments, or, under extreme conditions, may melt and revert to a magmatic state, thereby linking back to the initial stage of the cycle.

2.3.4 Recycling and Continuity of the Cycle

At the Earth's surface, the rock cycle proceeds through the production of sediments, their lithification into sedimentary rocks, and their subsequent deformation and metamorphism during burial. The erosion of orogenic belts exposes these rocks anew, reinitiating the cycle. In subduction zones, sedimentary sequences, oceanic crust, and associated lithologies are recycled into the mantle, where partial melting generates new magma. This process underscores the cyclical and interconnected nature of lithospheric evolution, linking Earth's internal and external geological systems into a single dynamic framework.

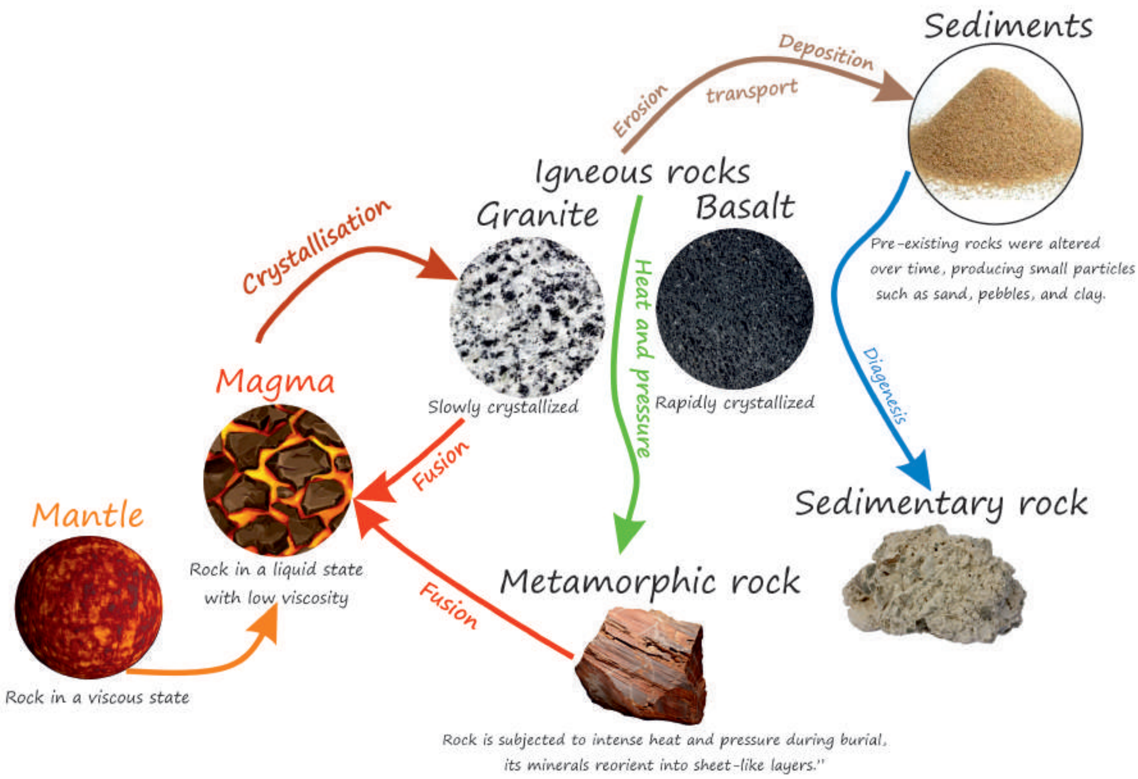


Figure 2.7: Continuity of the Cycle

Chapter 3

Igneous rocks

3.1 Definition

Igneous rocks form the uppermost portion of the Earth's crust. They are produced through the cooling and solidification of magma. When magma cools rapidly, the resulting igneous rocks often contain fine-grained minerals, and their chemical composition closely resembles that of the original magma. In contrast, when magma cools slowly, crystallization occurs, leading to significant differences between the chemical composition of the magma and the rock. Common examples of igneous rocks include granite, gabbro, basalt, andesite, rhyolite, and diorite. Their textures vary depending on the conditions of formation. Some igneous rocks display tightly packed but unevenly distributed mineral grains. Granite, for instance, is a well-known crystalline igneous rock.

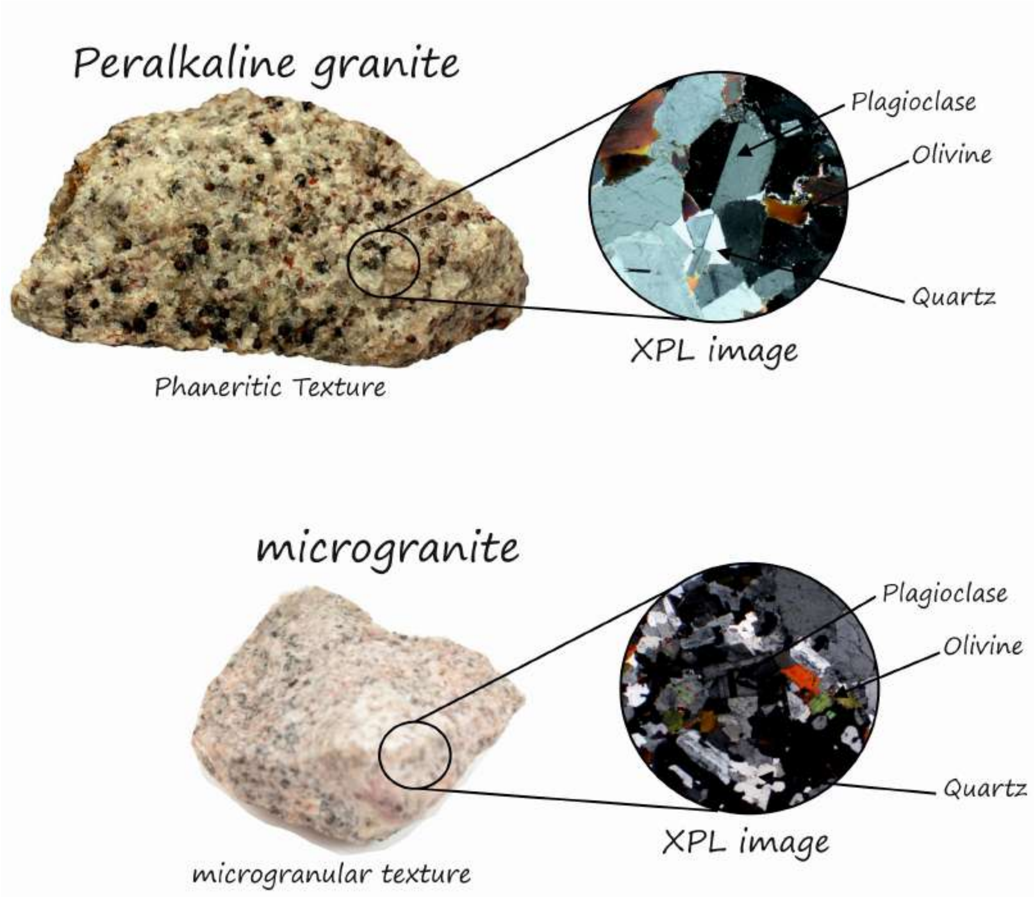


Figure 3.1: phaneritic and microgranular textures, case of peralkaline granite and microgranite

3.2 Classification

3.2.1 Classification based on rock texture

Intrusive Igneous Rocks: Intrusive, or plutonic, igneous rocks originate from magma that cools and solidifies slowly within the Earth's crust. The prolonged cooling period allows sufficient time for crystals to develop, producing a coarse-grained (phaneritic) texture in which minerals are clearly visible to the naked eye (Figure 3.1).

Typical examples include granite, which constitutes a significant portion of the continental crust, and gabbro, a major component of the oceanic crust. In shallower intrusions, such as dikes and sills, cooling occurs more rapidly, giving rise to medium-grained (microgranular) textures. These rocks remain holocrystalline but contain a finer matrix, occasionally with visible phenocrysts; microgranite represents a common case.

Intrusive rocks may also exhibit porphyritic textures, characterized by large, well-formed crystals (phenocrysts) embedded within a finer groundmass. This dual texture indicates a two-stage cooling history: initial slow crystallization at depth followed by more rapid cooling as the magma ascended toward the surface. Such textures provide valuable insights into the dynamic conditions of magma emplacement and cooling within the crust.

Etrusive Igneous Rocks :Extrusive, or volcanic, igneous rocks are produced when lava erupts at or near the Earth's surface, where cooling is rapid due to the stark thermal contrast with the surrounding environment. This accelerated cooling results in fine-grained (microlitic) textures, in which most crystals are too small to be resolved without magnification (Figure 3.2).

Representative examples include basalt, which dominates the oceanic crust, as well as andesite and trachyte, which are commonly associated with continental volcanic settings. In extreme cases, where cooling occurs almost instantaneously, atoms cannot arrange into an ordered lattice, forming volcanic glass such as obsidian. Explosive volcanic activity may further fragment magma into discrete particles collectively known as pyroclasts. Their sizes range from volcanic ash (¡2 mm) to volcanic bombs (¿6.4 cm), with pumice

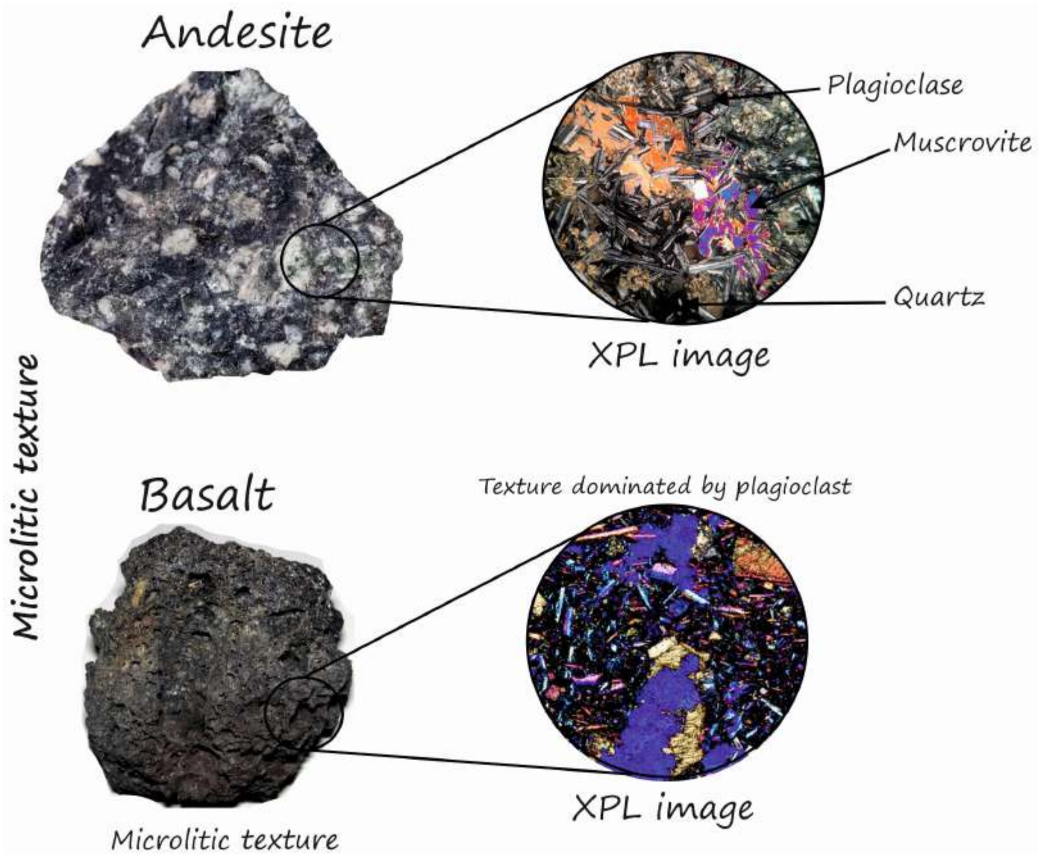


Figure 3.2: microlitic texture, case of Basalt and the Andesite

representing an intermediate, vesicular type. Particularly hazardous are pyroclastic flows, which consist of dense, fast-moving currents of superheated gas and ash descending volcanic slopes at high velocity. Overall, extrusive igneous rocks display a spectrum of textures—fine-grained, glassy, or pyroclastic, that reflect the rapid cooling processes and often violent conditions of volcanic environments.

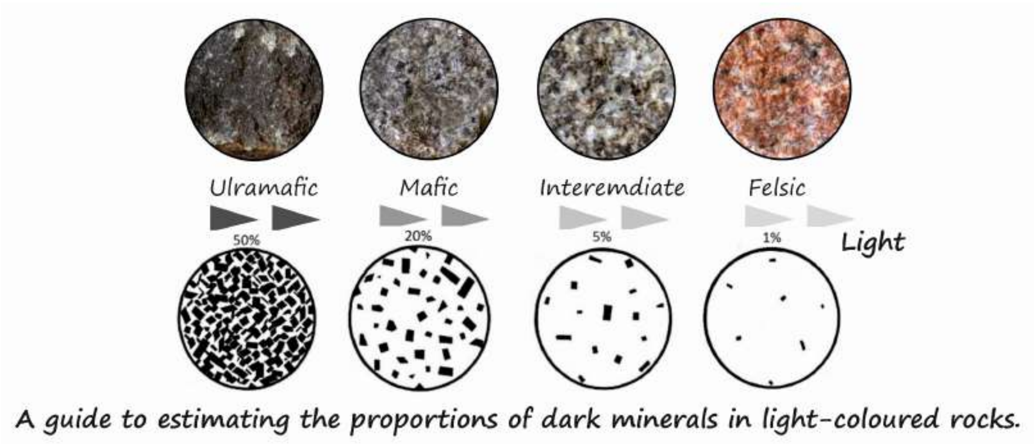


Figure 3.3: mineralogical compositions of Igneous rocks

3.2.2 Classification based mineralogical compositions

Igneous rocks can also be classified according to their mineralogical composition, which strongly influences both their colour and, to some degree, their texture. On this basis, four principal groups are recognised: felsic, intermediate, mafic, and ultramafic.

Felsic rocks : Granite and rhyolite are dominated by light-coloured minerals such as quartz, feldspar, feldspathoids, and muscovite. They are rich in silica (approximately 65–75% SiO), but relatively poor in iron and magnesium. These minerals, characterised by low melting points and low specific gravity, crystallise relatively late. Minor amounts of dark-coloured minerals, such as amphibole or biotite, may also be present. While coarse-grained felsic rocks like granite appear light in colour, their rapidly cooled equivalents can form dark volcanic glasses such as obsidian or pitchstone (Figures 3.3-4).

Intermediate rocks: They represent a compositional transition between felsic and mafic types. They contain nearly equal proportions of light minerals (such as plagioclase feldspar) and dark ferromagnesian minerals (such as amphibole). Their silica content is intermediate, generally ranging from 55–60%. **Mafic rocks**: Both basalt and gabbro are dominated by dark ferromagnesian minerals such as pyroxene, olivine, amphibole, and biotite, along with plagioclase feldspar. They are comparatively rich in iron and magnesium but poor in silica (about 45–50% SiO). These minerals have higher melting points, greater specific gravity, and tend to crystallise earlier than felsic minerals. **Ultramafic rocks**: They are composed almost entirely of olivine with some pyroxene, reflecting an extreme enrichment in magnesium and iron and a very low silica content (less than 40%). These rocks are rare at the Earth's surface but predominate in the upper mantle, where they occur as peridotite (Figure 3.3.4).

- Felsic minerals: Quartz, feldspar, feldspathoids, muscovite.
- Mafic minerals: Pyroxene, amphibole, olivine, biotite, iron oxides

3.3 Petrographic features of the main igneous rocks

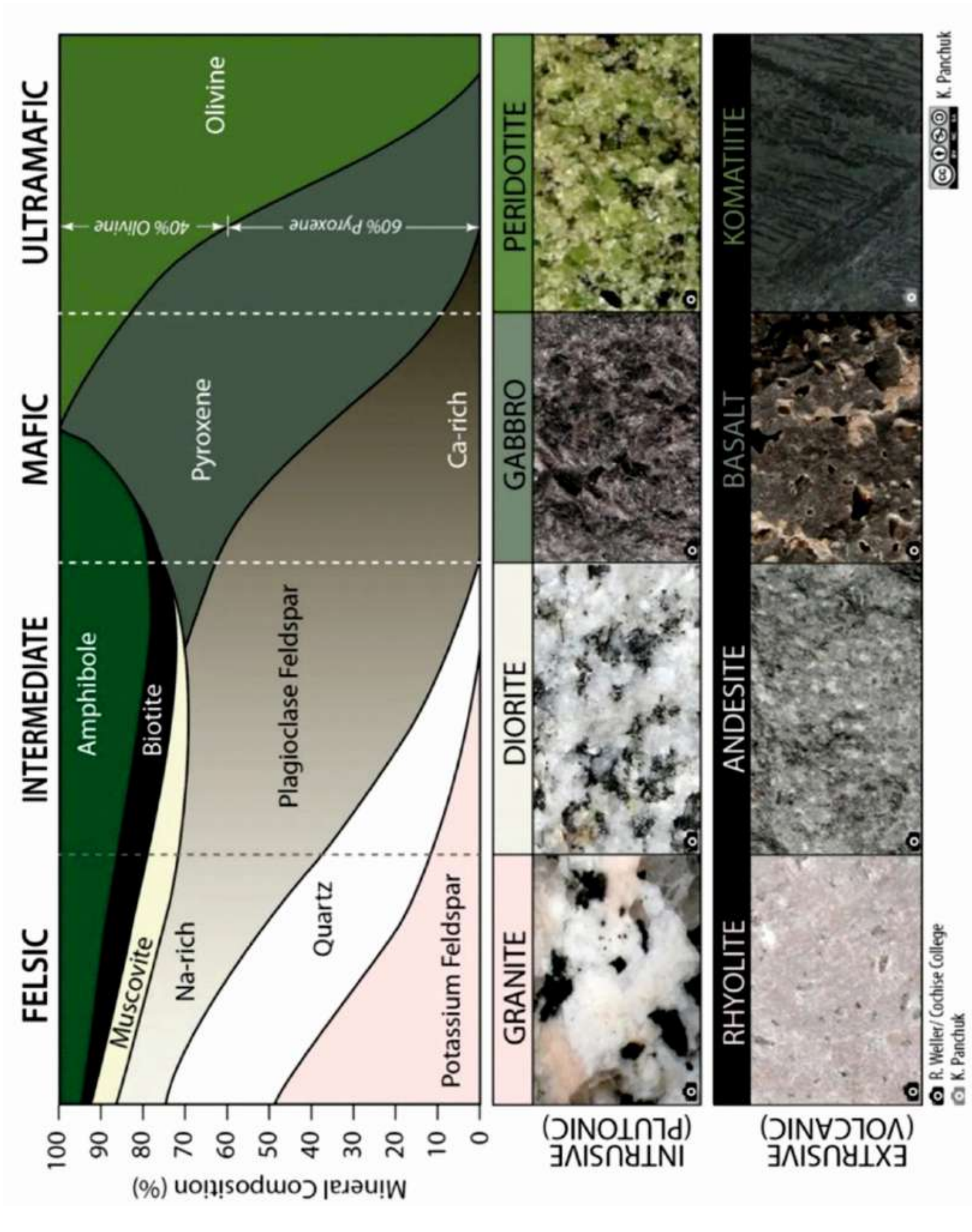


Figure 3.4: classification of igneous rocks based primarily on mafic and felsic minerals proportions

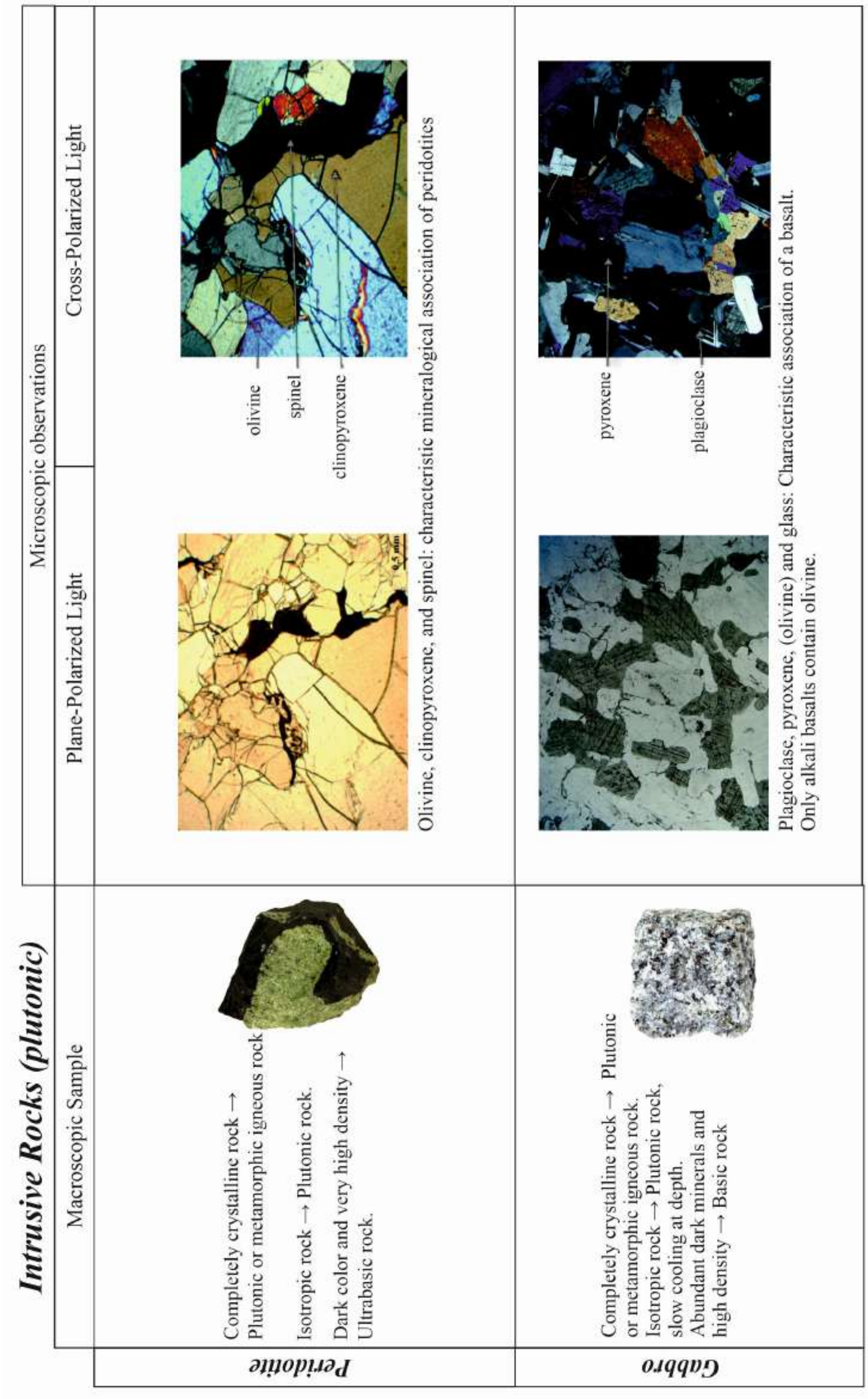


Figure 3.5: Main petrographical features of intrusive rocks (Peridotite and Gabbro

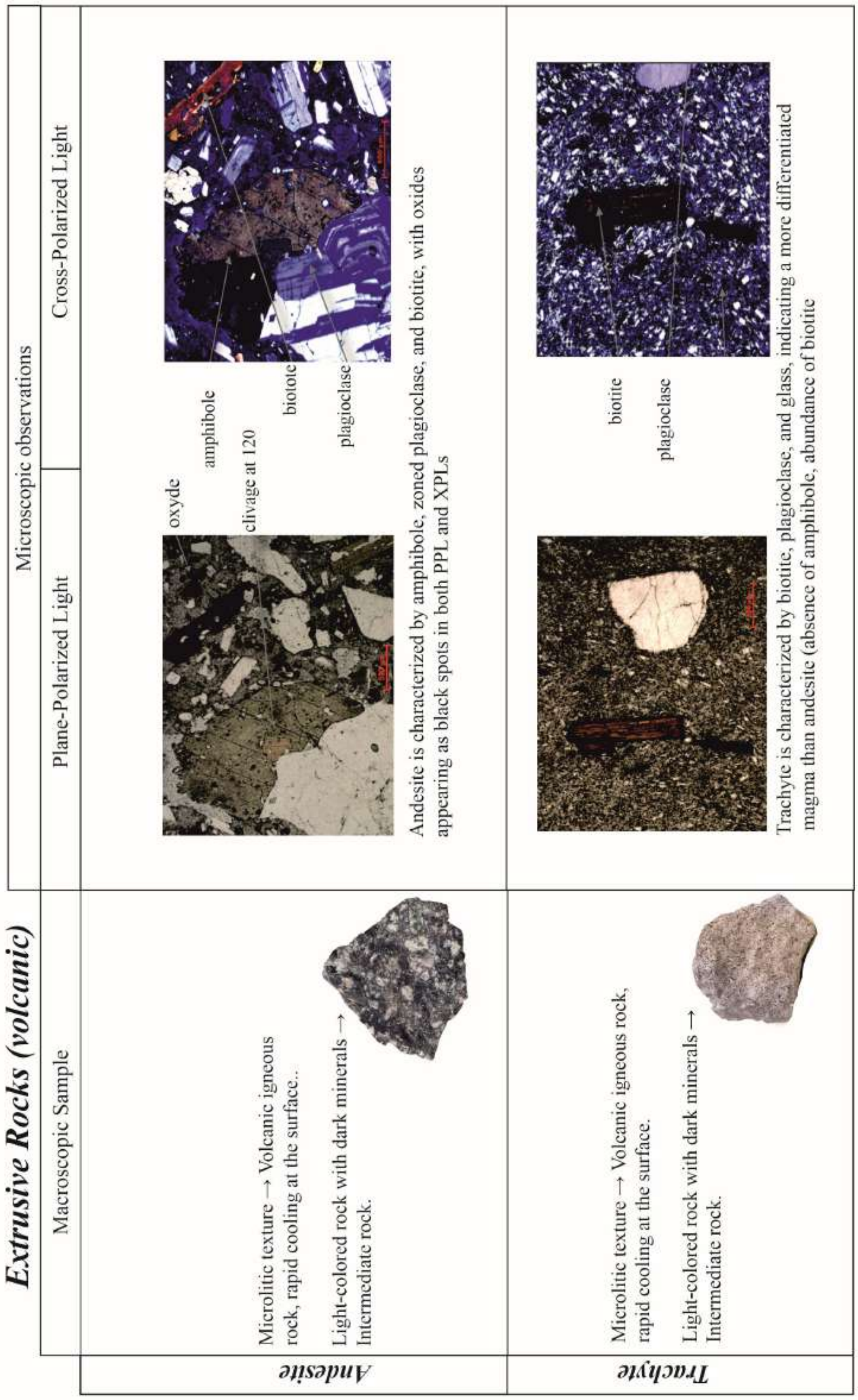


Figure 3.6: Main petrographical features of extrusive rocks (Andesite and Trachyte

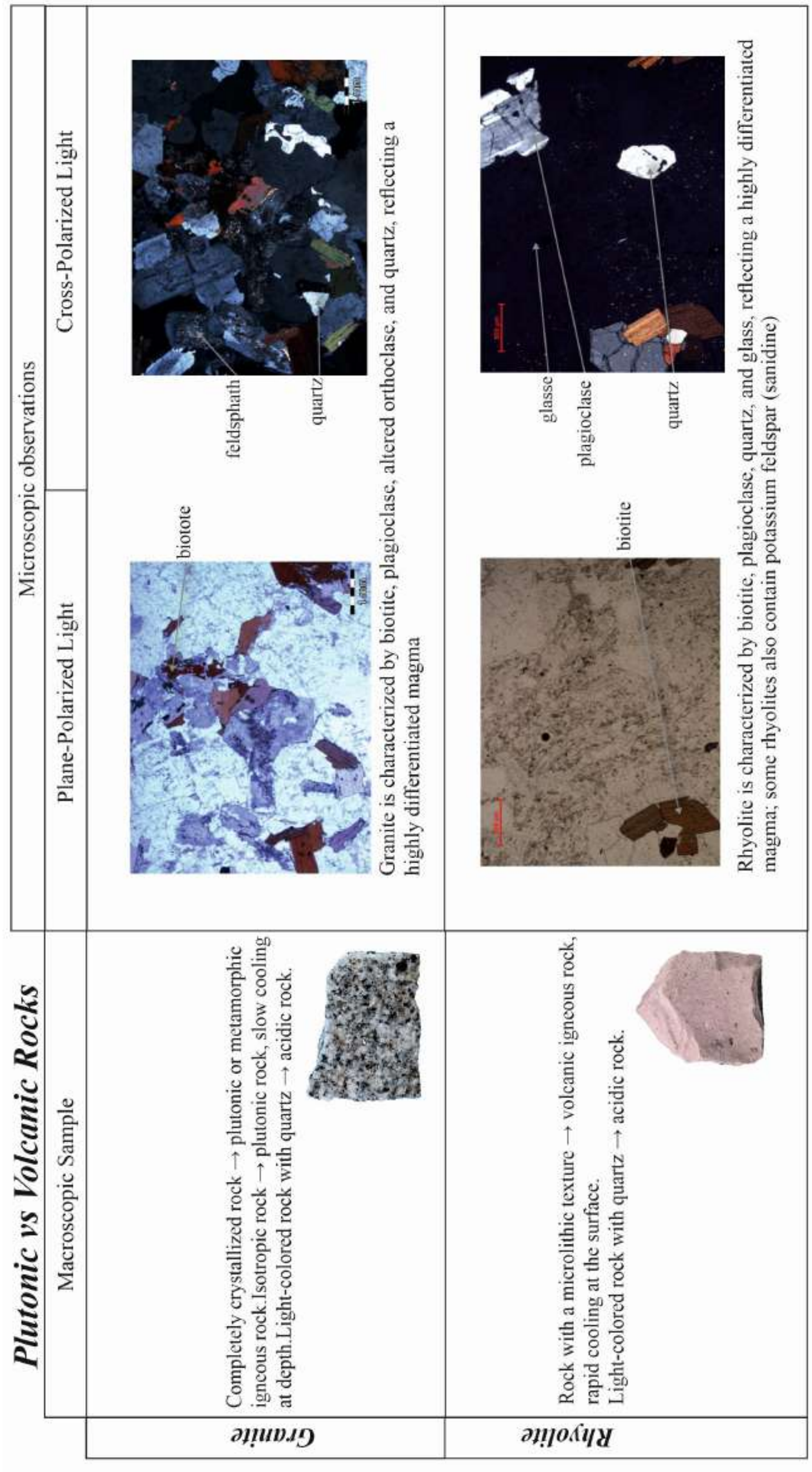
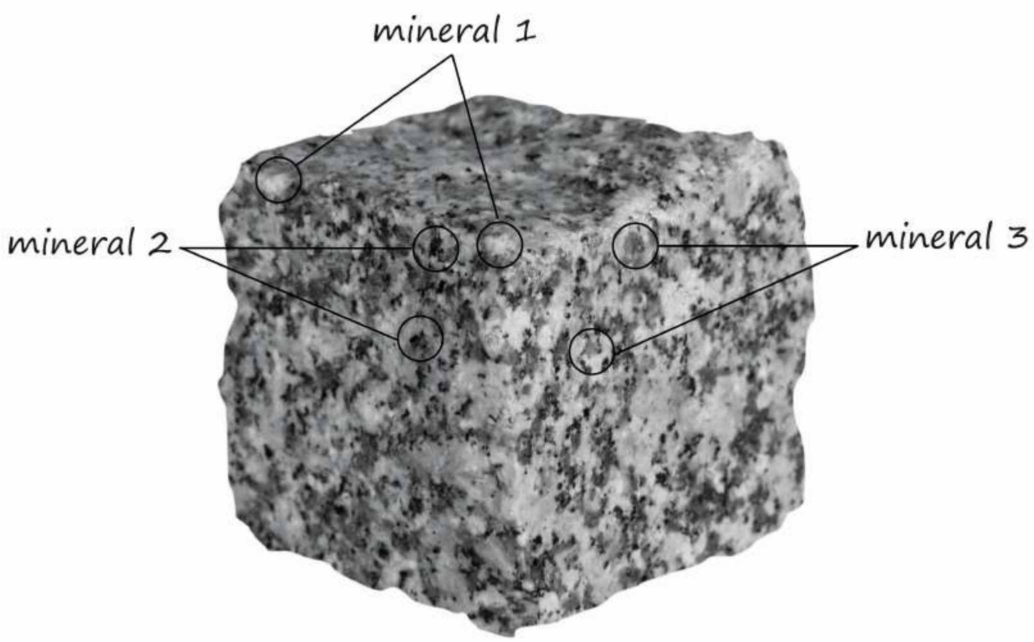


Figure 3.7: Main petrographical features of Granite (intrusive) and Rhyolite (extrusive)

3.4 Exercises

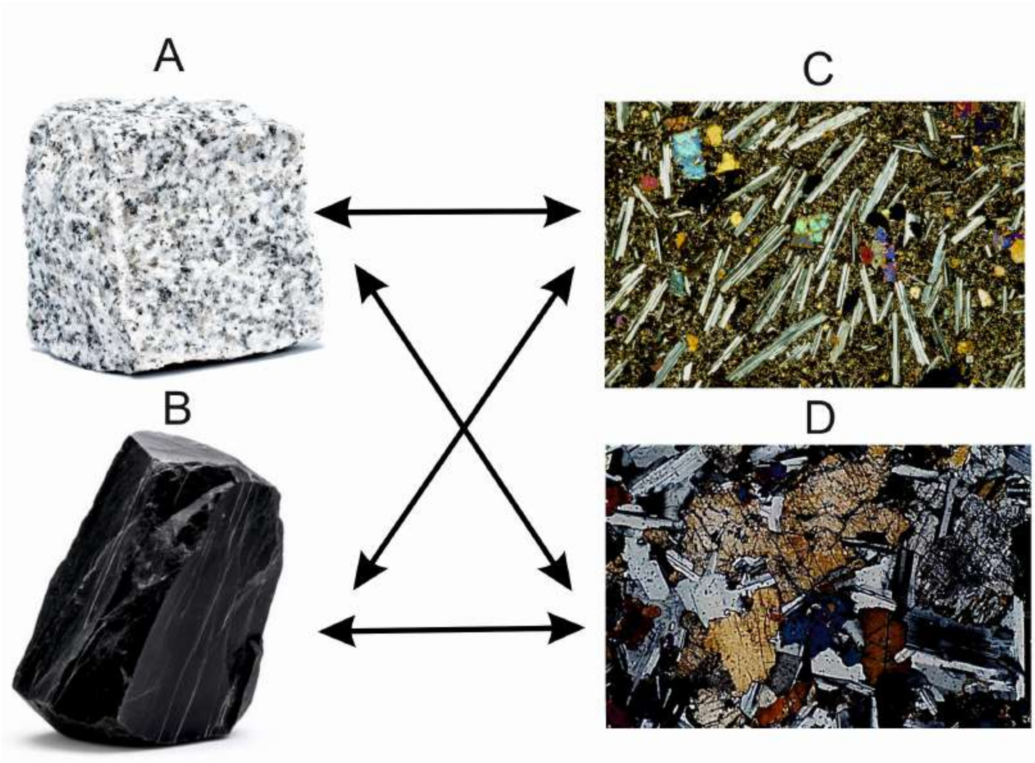
3.4.1 Exercise 1

Identify three minerals in this rock and give a name to the rock



3.4.2 Exercise 2

Using arrows, match rocks A and B with their corresponding textures C and D. By examining the pictures, try to estimate which of the two major minerals are present in the thin sections. Finally, describe the texture type of C and D.

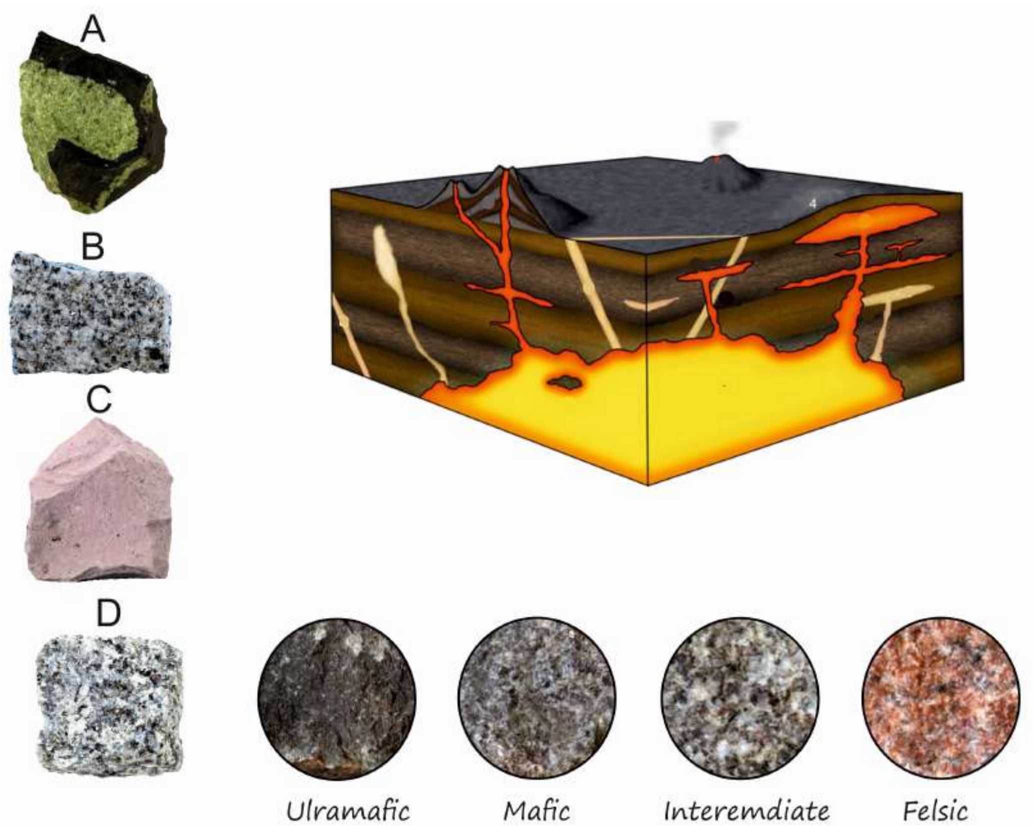


3.4.3 Exercise 3

• Describe the rocks A, B, C, and D.

• Match each rock with the correct mineralogical classification (felsic, intermediate, mafic, ultramafic).

• Based on the provided 3D figure, suggest the approximate environment where each rock formed and explain the formation process



Chapter 4

Sedimentary rocks

4.1 Introduction

Sedimentary rocks form at or near the Earth's surface through the weathering, erosion, transport, and deposition of pre-existing rocks. The transported particles, known as sediments, accumulate in layers, with each layer often differing in composition, structure, color, and thickness. Common examples of sedimentary rocks include limestone, sandstone, siltstone, shale, conglomerate, and breccia, which are typically rich in quartz or calcite. Compared with igneous and metamorphic rocks, sedimentary rocks generally have lower strength, higher porosity, greater water absorption, and weaker structural density, making them more susceptible to erosion but easier to mine, as they are usually found near the surface. Based on their formation processes, sedimentary rocks are classified into mechanical, chemical, and biological types. Another classification, according to the nature of their binding material, distinguishes siliceous rocks (e.g., quartzite, sandstone, conglomerate, diatomite), argillaceous rocks (e.g., mudstone, shale, oil shale), and calcareous rocks (e.g., limestone, dolomite, marl, lime-breccia).

4.2 Sediments versus sedimentary rocks

Sediments and sedimentary rocks differ primarily in their state and degree of consolidation. Sediments consist of particles or ions derived from the weathering of pre-existing rocks or from the remains of organisms. They are typically loose, unconsolidated, and particulate in nature. Examples include sand, while dissolved ions in solution may also be considered sediments despite being invisible to the naked eye during transport and erosion. By contrast, sedimentary rocks are consolidated materials composed of sedimentary particles, crystallized ions, and, in some cases, biological fragments. These components have undergone compaction and cementation to form a coherent mass, which may range from friable to relatively hard. Sandstone, for instance, represents the lithified form of sand grains. In rocks formed through ion precipitation, the processes of deposition and diagenesis often occur simultaneously, with crystallization corresponding directly to the diagenetic stage (Figure 4.1).

4.3 Stages of the sedimentary process

The formation of sedimentary rocks involves several sequential stages that together constitute the sedimentary process. Initially, particles or mobile ions are generated primarily through the weathering of pre-existing rocks. This

Figure 4.1: sedimentary particles vs sedimentary rock

source material is occasionally referred to as the "parent rock," although in sedimentology this term is typically reserved for rocks rich in organic matter, particularly hydrocarbons. Once produced, these particles are removed from their source through erosion and transported over variable distances by natural agents such as water, wind, or ice. Following transport, the particles accumulate within a sedimentary basin, forming sediment deposits. Over time, these deposits undergo compaction and cementation, transforming into sedimentary rocks through the process known as diagenesis Figure 4.2.

4.4 Internal elements of sedimentary rocks

Sedimentary rocks may be homogeneous or contain dispersed sedimentary elements embedded within a finer binding phase. The primary components of sedimentary rocks include clasts, which are the fundamental sedimentary particles generally visible to the naked eye, and the binding phase, which

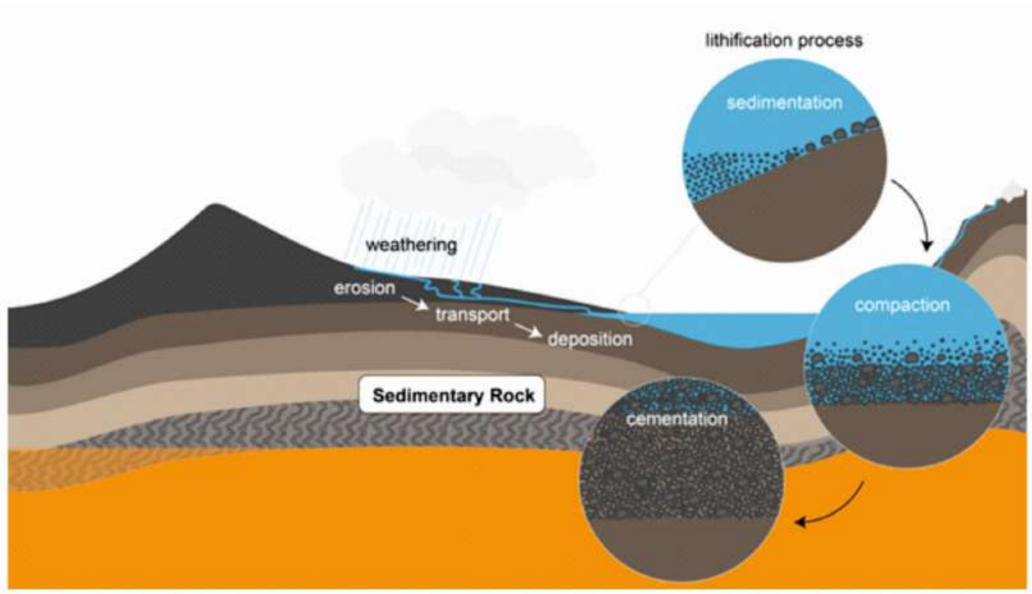


Figure 4.2: Main processes in the formation of sedimentary rocks

is composed of finer materials that link the grains together. The binding phase may take the form of a matrix, consisting of fine sediment that fills the spaces between grains, or a cement, which is a crystallized material such as calcite, silica, or fine quartz that typically forms after the deposition of the grains. Most sedimentary rocks also contain pores, which can trap or allow the circulation of fluids. The porosity of a rock is defined as the ratio of the pore volume to the total volume of the rock.

4.5 Classification of sedimentary rocks

4.5.1 Detrital sedimentary rocks

Detrital, or clastic, sedimentary rocks are composed of fragments of pre-existing rocks that have undergone weathering and erosion. These fragments

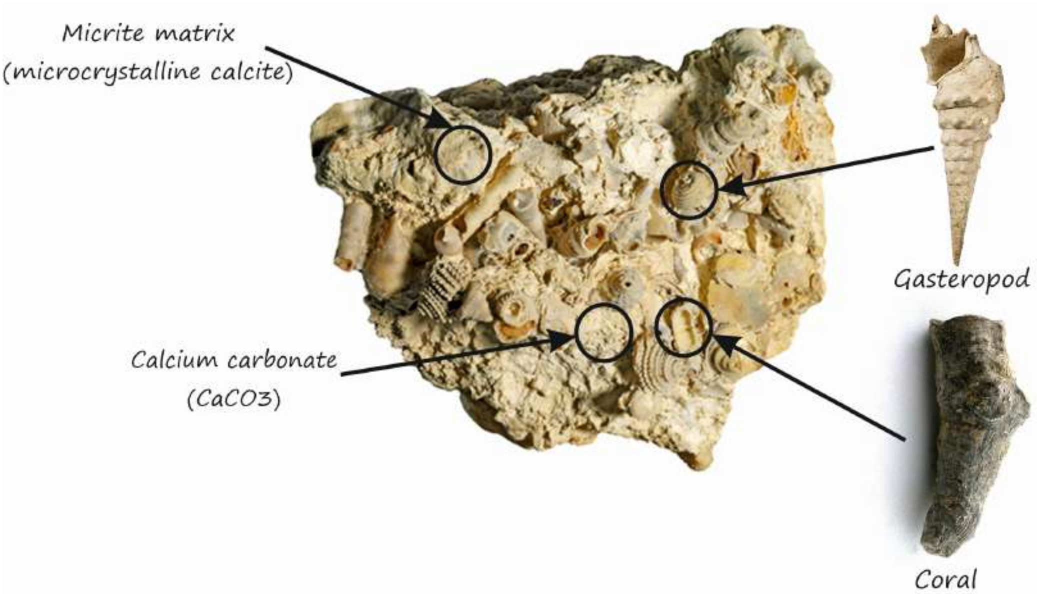


Figure 4.3: Main components of sedimentary rocks

are primarily the product of mechanical weathering of bedrock, although some clasts may also originate from chemically precipitated rocks. This dual origin occasionally creates overlap between clastic and chemical sedimentary categories. The classification and nomenclature of detrital sedimentary rocks are primarily based on grain size.

Grain Size: The main way geologists classify detrital sedimentary rocks is by looking at grain size. Grain size simply refers to the average diameter of the particles that make up the rock. To describe this, geologists often use the Wentworth scale, which arranges particles from the largest to the smallest. On this scale, any fragment larger than 2 mm is considered a coarse clast. These include boulders, cobbles, pebbles, and gravel. Sand falls between 2 mm and 0.0625 mm in size (Figure D.4). This is important because sand is about the smallest grain size that the human eye can still see without

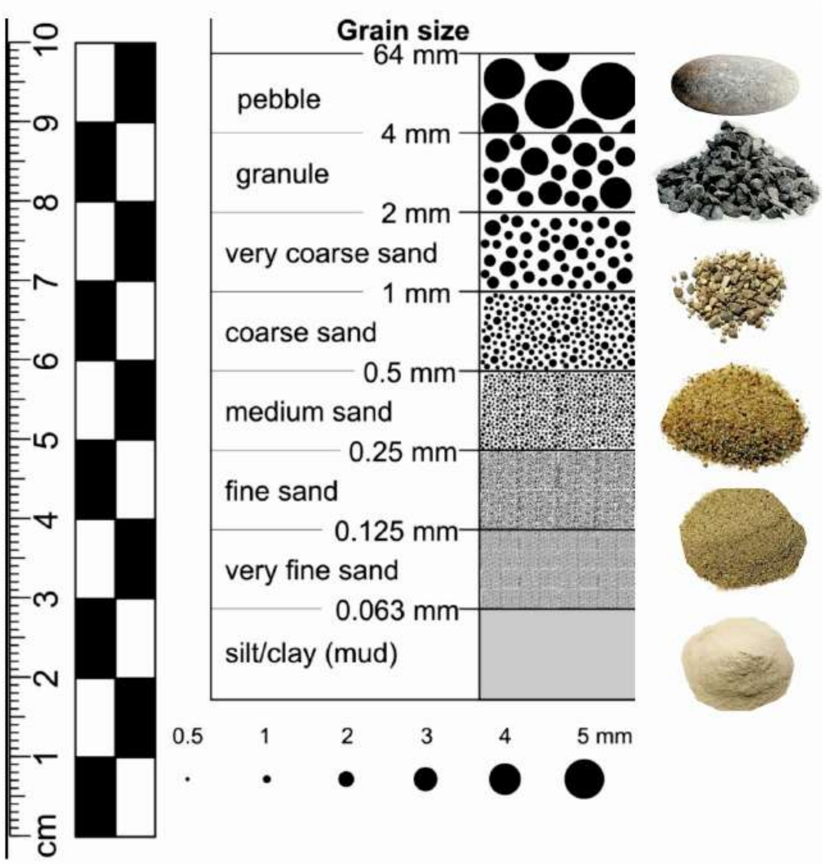


Figure 4.4: Chart for a visual estimation of grain size

a microscope. Anything smaller than sand is called silt. Silt is interesting because it cannot be seen with the naked eye, but you can still feel it: it has a gritty texture, like fine powder or dust between your fingers or teeth.

Sorting and Rounding: Sorting describes how similar or different the grain sizes are within a sedimentary deposit. If the grains are almost all the same size, the deposit is said to be well-sorted. If it contains a wide variety of grain sizes, it is considered poorly sorted. It is important to note that engineers use these terms differently: in soil engineering, "well-graded" means a mixture of many grain sizes, while "poorly graded" means grains of

Figure 4.5: A visual reference for descriptions of sorting of grains in clastic sedimentary rocks

similar size. In geology, however, the focus is on how uniform the particles are. Sorting is very useful because it tells geologists about the energy and transport process of sediments. For example, wind-blown sand dunes are usually very well sorted, because wind tends to carry and deposit grains of the same size. In contrast, glacial deposits are usually poorly sorted, as glaciers carry everything from huge boulders to fine silt. Generally, coarse and poorly sorted sediments are found close to the source, such as in a fast-flowing mountain stream where boulders and pebbles are common. Finer, well-sorted sediments, like sand and silt, are carried farther away and deposited in quieter environments such as lakes. If large clasts (big rock fragments) are found in a lake deposit, this often means another transport process was involved, such as a rockfall caused by ice or plant roots breaking the rock (Figure 4.5).

Rounding refers to how smooth or sharp the edges of sediment grains are. When grains are well-rounded, they appear smooth with no sharp corners. By contrast, angular grains still keep their sharp edges and corners. Most sediment grains begin as fragments of bedrock, which usually break with sharp edges. As these grains are carried by wind, water, or ice, they collide with other particles and surfaces, a process called abrasion. This gradually

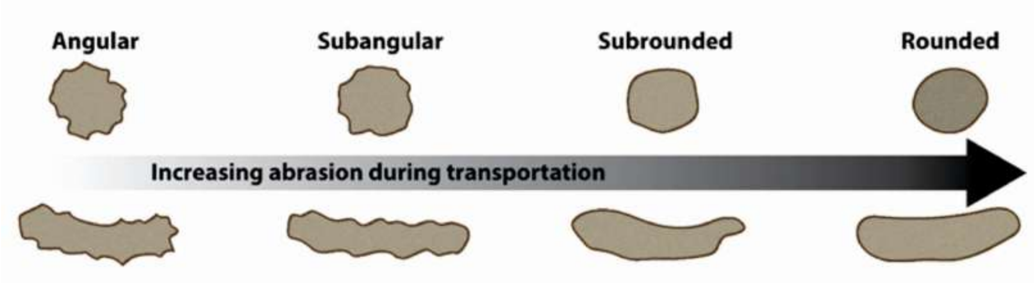


Figure 4.6: A visual reference for descriptions of roundness of grains in detrital sedimentary rocks

smooths their edges. The degree of rounding gives geologists clues about a grain's history of transport. Grains that are more rounded usually indicate longer travel distances, longer exposure to erosion, or transport by more energetic processes (such as fast-moving rivers or strong waves). The hardness of the mineral also plays a role: softer minerals round more quickly, while harder ones keep their edges for longer (Figure 4.6).

Classification of detrital rocks : Clastic sedimentary rocks are classified and named according to both their composition and texture. Composition refers to the mineral or rock fragments that make up the grains, which is especially important in the classification of sandstones. Texture describes features such as grain size (measured with the Udden–Wentworth scale), roundness (the degree to which grains have been smoothed during transport), and sorting (the range of grain sizes within the rock). These combined properties help geologists distinguish between different types of clastic rocks (Figure 4.7).

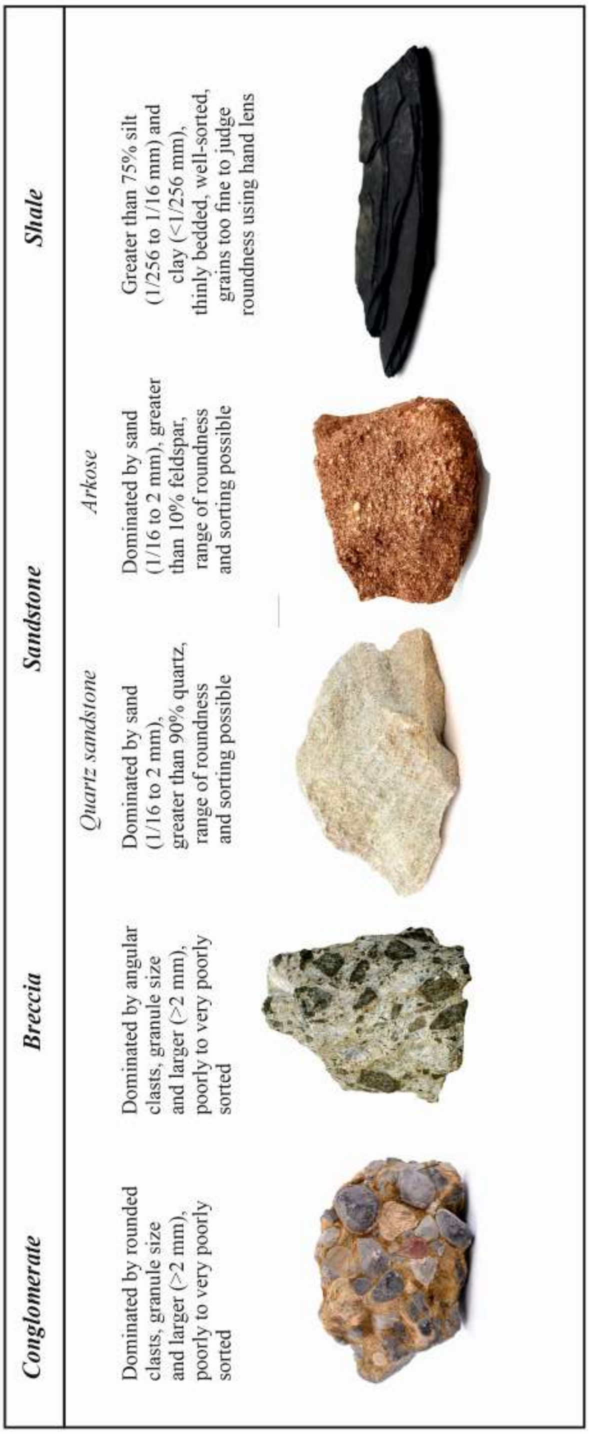


Figure 4.7: Classification of detrital rocks

4.5.2 Chemical sdimentary rocks

Chemical sedimentary rocks form mainly through the precipitation of minerals from water or by the alteration of pre-existing material in place. The most common chemical sedimentary rock is limestone, followed by chert, chalk, evaporites (such as rock gypsum and rock salt), and coal. Biological processes play a significant role in the formation of some chemical rocks. For instance, limestone is largely composed of fragments of marine organisms that produce calcite for their shells and skeletal structures. Similarly, chert often contains the silica tests (shells) of microscopic marine organisms, such as diatoms and radiolarians. Coal, on the other hand, forms in fluvial or deltaic environments from decaying plant material that accumulates in long-lasting, low-oxygen swamps. Because the dissolved ions that contribute to chemical rocks can remain in solution for long periods and travel vast distances, it is often difficult to trace these rocks directly back to their original sources.

Identification of chemical sedimentary rocks : Chemical sedimentary rocks are classified primarily according to their composition. Because these rocks are often monomineralic (composed mostly of a single mineral). For example, rock gypsum consists mainly of the mineral gypsum and can be easily recognized by its softness (hardness H = 2), allowing it to be scratched with a fingernail (Figure 4.8). The name of a chemical sedimentary rock can also include a textural descriptor to provide more information about its appearance or formation. Common textures include crystalline, oolitic, bioclastic, fossiliferous, and amorphous. A simplified classification chart for

Figure 4.8: monomineralic sedimentary rock (Gypsium)

chemical sedimentary rocks is provided in table below to help with identification and comparison (Figure D.9).

Limestone :Limestone is one of the most common chemical sedimentary rocks, and it is mainly composed of the mineral calcite (CaCO). It usually forms by the chemical precipitation of calcium carbonate from seawater, although biological processes also play an important role. For example, many marine organisms, such as corals, mollusks, and algae, extract calcium carbonate from seawater to build their shells or skeletons. When these organisms die, their remains accumulate on the seafloor, gradually forming limestone through compaction and cementation. One of the most important properties of limestone is its reaction with dilute hydrochloric acid, which produces vigorous effervescence (bubbling). This reaction, caused by the release of carbon dioxide gas, is a quick and reliable test to identify the rock. The classification of these rocks is based on :

• Grain size: Calcirudite is composed of coarse carbonate fragments larger than 2 mm (lime-rubble) and is considered the carbonate equivalent of a con-

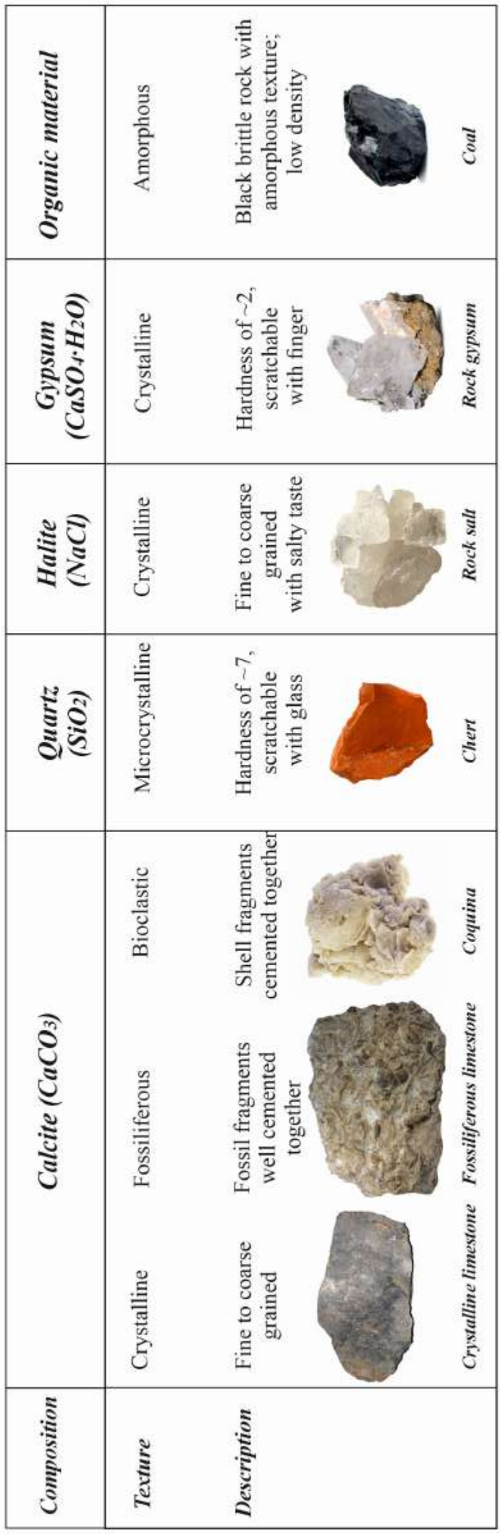


Figure 4.9: Classification chart for chemical sedimentary rocks

Figure 4.10: : Classification of three limestone according to the grain size

glomerate; while many authors use the term regardless of clast shape, others prefer the designation lime-breccia when the fragments are angular (Figure D.10). Classification of three limestone according to the grain size. Calcarenite consists of sand-sized carbonate grains ranging from 0.0625 to 2 mm (lime-sand). Calcilutite, on the other hand, is a fine-grained limestone with particles smaller than 0.0625 mm (lime-mud). Some researchers further refine this category by distinguishing calcisiltite (0.004–0.0625 mm) and micrite (¡ 0.004 mm).

- Texture : Dunham (1962) classified carbonate rocks by texture and the amount of micrite (mud) they contain (Figure 4.11). This approach recognizes whether the rock is matrix-supported, grain-supported, or massive. Mudstone has very few grains (¡10%) in a mud matrix and forms in calm, low-energy environments. Wackestone has more grains but is still supported by mud. Packstone is grain-supported, with the spaces between grains filled by mud. Grainstone is also grain-supported but has no mud, and the spaces are empty or filled with sparry calcite; these form in high-energy places like beaches. Boundstone is made by living organisms such as corals, stromatolites, and bryozoans, which build and bind the rock while alive, like the

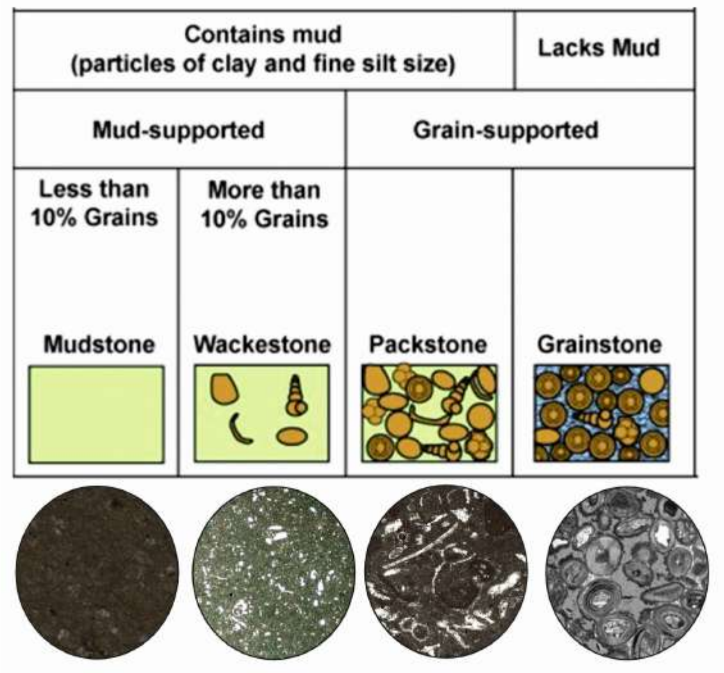


Figure 4.11: Classification of limestone samples according to their texture

Great Barrier Reef.

Evaporite: Evaporites form in arid regions where lakes or inland seas have no outlets, so water leaves only through evaporation (Figure 4.12). As water evaporates, dissolved salts become more concentrated until they reach saturation and begin to crystallize. Although each evaporite deposit is unique due to differences in water chemistry, a general sequence of mineral precipitation is observed. When the water volume is reduced to about 50% of its original amount, small amounts of carbonates start to form. Gypsum (CaSO·HO) precipitates when the water is reduced to about 20%, and halite (NaCl) forms at around 10%. Other important evaporite minerals include sylvite (KCl) and borax (NaBO·10HO).

Chert : Chert is a hard sedimentary rock made of very fine quartz crys-

Figure 4.12: formation of evaporite (Salty) Rocks

tals. It is usually of biological origin, forming from the petrified remains of siliceous ooze that accumulates on the deep ocean floor (Figure 4.13). This ooze contains the microscopic skeletons of organisms such as diatoms, silicoflagellates, and radiolarians. Depending on its formation, chert may include microfossils, small macrofossils, or both. The color of chert varies widely, from white to black, but gray, brown, grayish-brown, light green, and rusty red are most common. These colors reflect the trace elements in the rock, with red and green shades often caused by iron in oxidized and reduced forms, respectively.

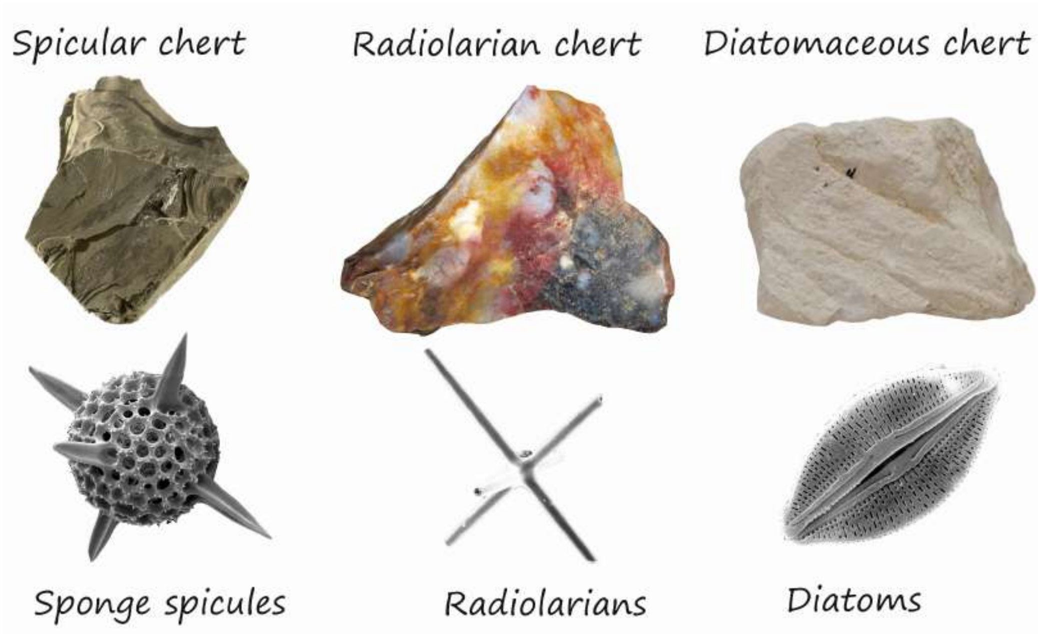


Figure 4.13: Varieties of chert classified according to their fossil constituents

Chapter 5

Metamorphic rocks

5.1 Introduction

Metamorphism is the process that changes an existing rock into a new type of rock when it is exposed to different conditions inside the Earth. These conditions are usually high temperature, high pressure, or contact with hot fluids. Unlike melting, metamorphism happens while the rock stays solid. The original rock before it changes is called the protolith. This starting rock can be igneous, sedimentary, or even another metamorphic rock. During metamorphism, new minerals and new textures often appear, but the overall chemical composition of the rock usually stays similar to the protolith. The main factors that control how a rock changes during metamorphism are:

- the minerals in the original rock,
- the temperature,
- the pressure,
- the presence of fluids (mainly water),

- the length of time the rock is exposed to these conditions.

Metamorphic rocks cover about 12% of the Earth's surface. They are very important for geologists because they provide clues about what happens deep inside the Earth, where we cannot directly observe. For example, they help us understand how mountains form, how rocks are deformed, and even the conditions that can lead to earthquakes.

5.2 Main factors of metamorphism

5.2.1 Protolith (Parent Rock)

The protolith, also called the parent rock, is the original rock before it goes through metamorphism. Both sedimentary and igneous rocks can act as parent rocks. While metamorphic rocks can undergo further metamorphism, they are usually not considered the true parent rock (Figure 4.1). For example: if mudstone changes into slate, and then is buried deeper and transforms again into gneiss, the parent rock of gneiss is still mudstone, not slate. The most important feature of the parent rock is its mineral composition. This is because when temperature and pressure increase, some minerals may no longer remain stable. Instead, they recrystallize and form new minerals—but this happens while the rock stays solid (it doesn't melt).

5.2.2 Temperature

Temperature is one of the most important factors controlling metamorphism because it affects the stability of minerals in rocks. Every mineral is stable

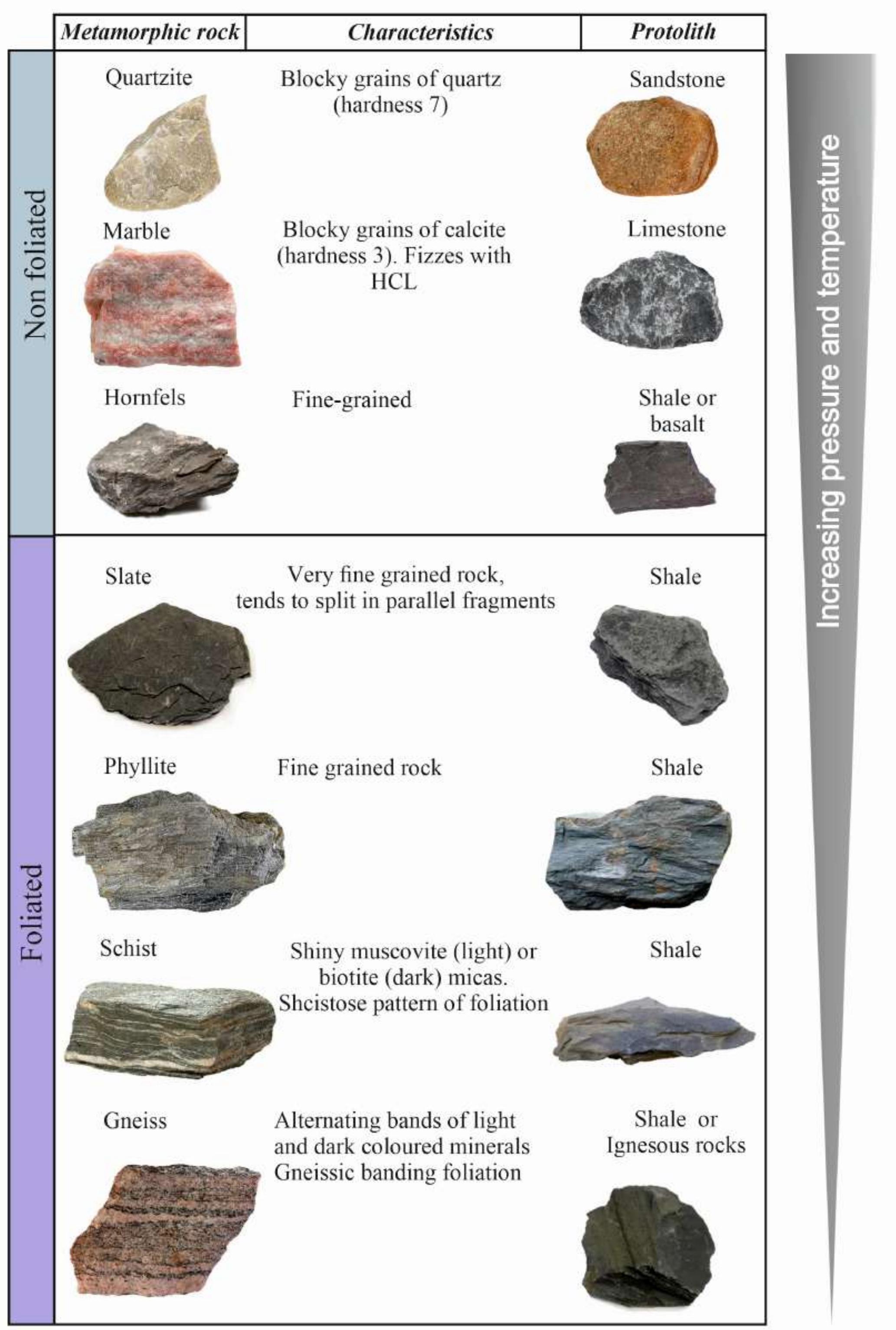


Figure 5.1: Key characteristics of major metamorphic rocks and their corresponding protoliths.

only within a certain range of temperature (and pressure).

• Quartz is stable over a very wide range, from surface conditions up to about 1800 °C.

• Clay minerals are stable only at relatively low temperatures (up to about 150–200 °C). When heated beyond this, they transform into mica minerals.

• Feldspars are generally stable up to between 1000–1200 °C.

• Most other common minerals fall somewhere between 150 °C and 1000 °C.

Water and pressure can also shift these stability ranges. For example, higher pressure tends to increase the maximum stability temperature, while the presence of water lowers it.

5.2.3 Pressure

Pressure plays an important role in metamorphic processes for two main reasons. First, it affects the stability of minerals (Figure 5.1). Second, it influences the texture of metamorphic rocks. When rocks are exposed to very high confining pressure (pressure that is equal in all directions), they usually become denser. This happens because the mineral grains are pressed tightly together (Figure 5.1) and also because new minerals with more closely packed atoms—and therefore higher density—can form. Types of Pressure on Rock (Figure 5.2).

• Confining pressure: pressure is the same in all directions.

• Directed pressure: pressure is stronger in one direction than in others, for example, at plate boundaries where two tectonic plates collide.

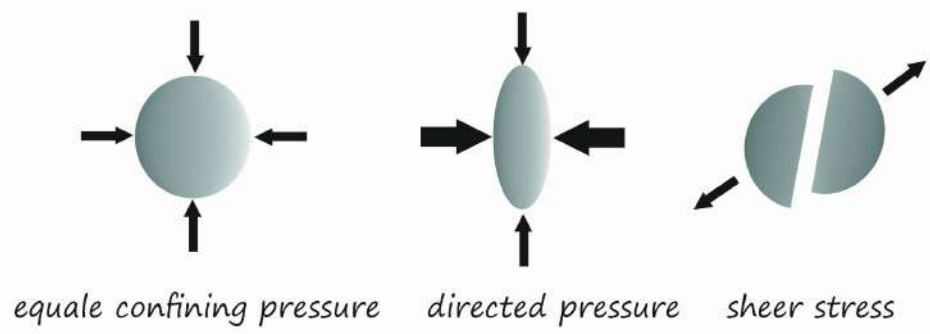


Figure 5.2: Main pressures affecting rocks

• Shear stress: pressure comes from different directions at the same time, often when blocks of the crust slide past each other.

Because of plate tectonics, rocks within the crust are rarely under equal pressure in all directions. In convergent zones, the strongest pressure is usually perpendicular to the collision. In other areas, rocks may experience shear stress as plates move in opposite directions. Foliation One major result of directed pressure and shear stress is foliation. This means the minerals in the rock are rearranged to form layers or bands, giving the rock a directional texture. Foliation is one of the most important features of metamorphic rocks and will be explained in more detail later in the chapter.

5.2.4 Water

Water is the main fluid present in crustal rocks and plays a key role in metamorphic processes. It facilitates the movement of ions between and within minerals, which increases the speed of metamorphic reactions. Although water does not change the final result of metamorphism, it allows reactions to occur more quickly or enables processes that might otherwise be too slow to fully complete. In addition, water, especially when hot, can carry high concentrations of dissolved elements, making it an effective medium for transporting minerals through the crust. This movement of elements is important for hydrothermal processes and the formation of mineral deposits.

5.3 Classification of metamorphic rocks

5.3.1 Classification based on texture

Foliated metamorphic rocks textures: Foliated textures occur when mineral grains align parallel to each other, giving the rock a layered or banded appearance. These textures are typical in metamorphic rocks exposed to high pressure or directed stress.

Schistose texture: Schistose texture is a type of foliated metamorphic texture marked by the parallel arrangement of platy or elongated minerals. These rocks are usually fine- to medium-grained and can be easily split along the mineral-aligned planes. Schistose rocks commonly form in regions of high-temperature and high-pressure metamorphism. Examples include mica schist, amphibole schist, and quartz schist (Figure 5.3).

Gneissic texture: Gneiss displays gneissic banding, alternating dark and light mineral layers. Horizontal bands in Figure indicate that the greatest pressure acted vertically. Subsequent pressure can fold or distort these bands, as shown in Figure 5.3.

Non foliated metamorphic rocks textures: Non-foliated metamorphic rocks do not show lineations, foliation, or any alignment of mineral

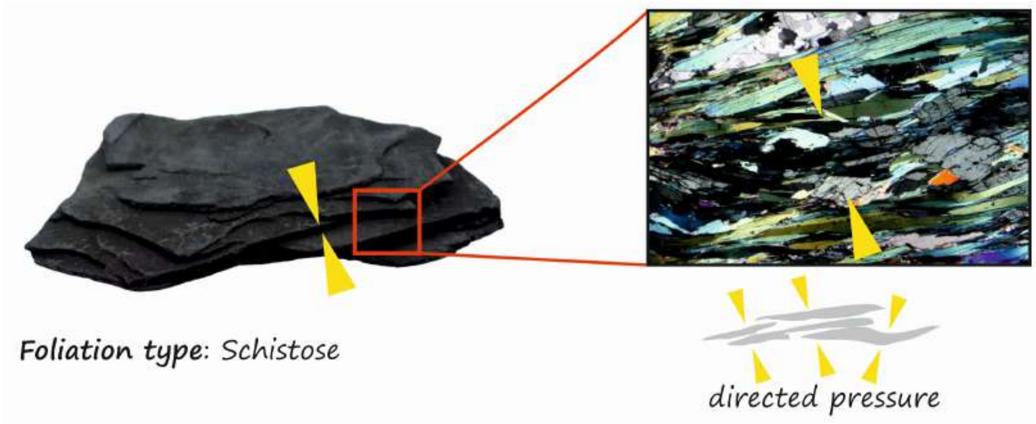


Figure 5.3: Expression of foliation in shale at macro and micro scales

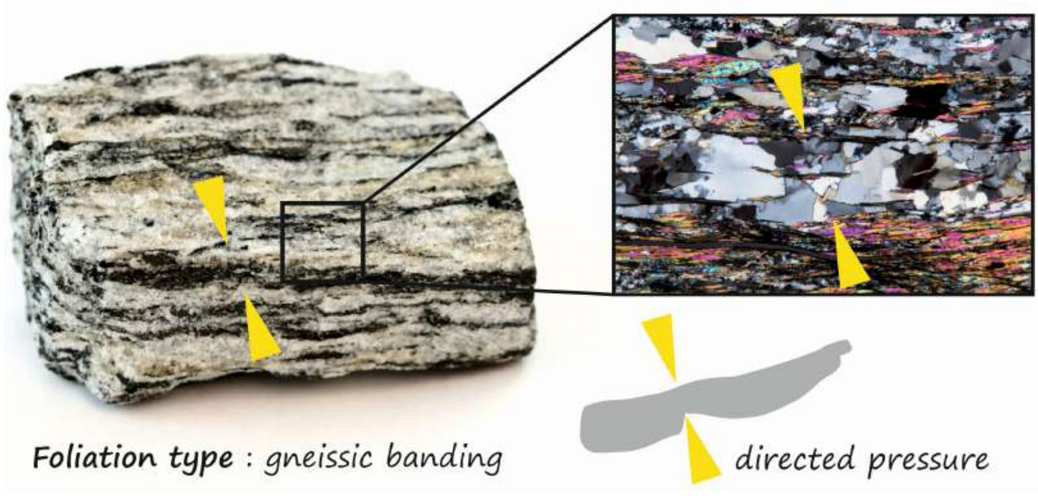


Figure 5.4: Expression of foliation in gneiss at macro and micro scales

grains. They are usually made of a single dominant mineral, and the effects of metamorphism are seen mainly through recrystallization, where crystals grow together without forming a preferred direction. Quartzite and marble are the most common non-foliated rocks. Quartzite forms from sandstone. During metamorphism, the quartz grains in sandstone enlarge and interlock. A key way to tell quartzite apart from sandstone is that when broken, quartzite fractures across the quartz grains, while in sandstone the grains separate because they are held together only by a thin cement. Quartzite is very hard and resistant to weathering due to its high quartz content (Figure 5.4). Marble forms from limestone or dolostone. Metamorphism causes the calcite or dolomite crystals to grow larger and interlock. Marble and quartzite can look similar, but marble is much softer. Marble can also be identified by a reaction with dilute hydrochloric acid, which causes fizzing if calcite is present. Another non-foliated rock is hornfels, which is dense, fine-grained, hard, and often has a blocky or splintery texture. Hornfels contains several silicate minerals, but the crystals are usually so small that specialized study is needed to identify them. Hornfels commonly forms near intrusive igneous bodies, and its original rock (protolith) can be difficult to determine, ranging from mudstone to basalt (Figure 5.5).

5.3.2 Classification based on the type of metamorphism

Burial metamorphism: Burial metamorphism occurs at depths greater than 2000 meters, mainly in sedimentary basins. It represents a transition from diagenesis, where increasing temperature and confining pressure trans-

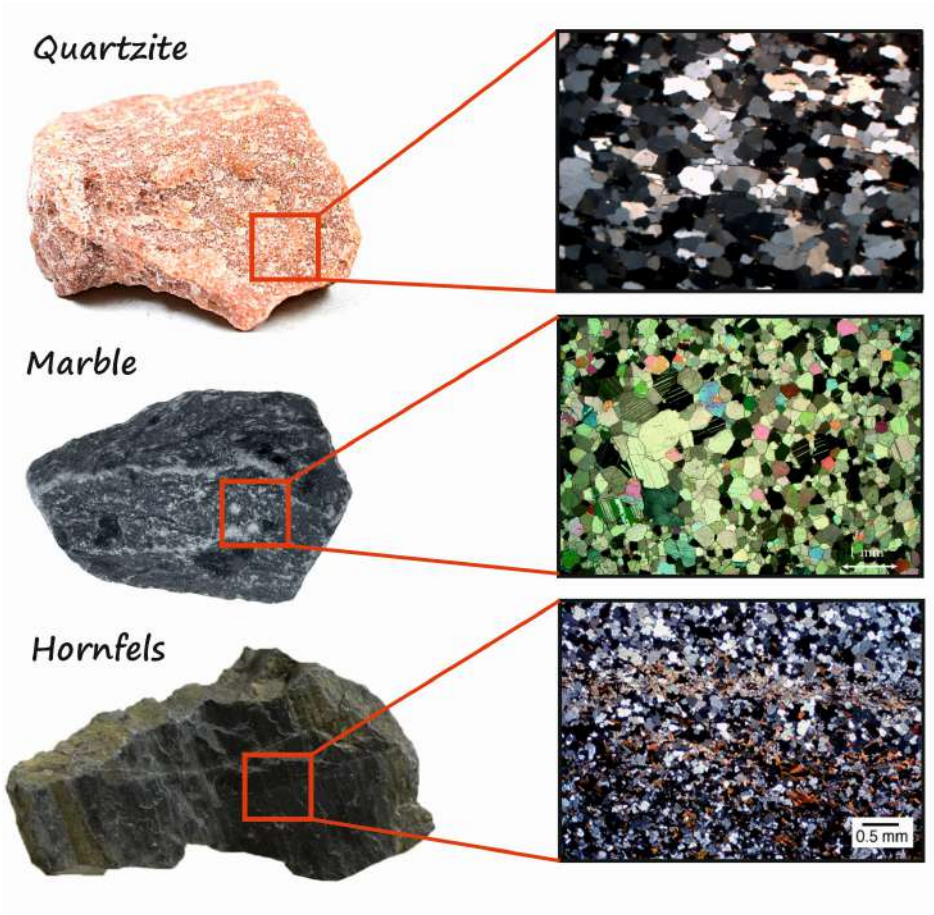


Figure 5.5: Non-foliated metamorphic rocks (Quartzite, Marble and Hornfels) at macro and micro scales

form minerals (e.g., smectite to illite, sandstone to quartzite).

Contact metamorphism: Magmas typically have temperatures ranging from about 700° to 1200°C, depending on their composition. As heat diffuses outward from an intrusion, the temperature of the surrounding country rocks increases, producing strong thermal gradients that drive metamorphism. This process, known as contact metamorphism, occurs when rocks are subjected to high temperatures but relatively low pressures, generally near magma intrusions or lava flows. The resulting facies depend largely on the protolith: shale or basalt commonly transform into hornfels, sandstone recrystallizes into quartzite, and limestone becomes marble. At shallow levels, hornfels facies dominate, whereas at greater depths, higher-pressure facies such as greenschist, amphibolite, or even granulite may develop. In deeper settings, contact metamorphism often produces concentric aureoles rings of distinct mineral assemblages, surrounding the intrusion (Figures 5.6 and 7).

Regional metamorphic : Regional metamorphism typically occurs in conjunction with deformation and folding at convergent plate boundaries, producing orogenic belts that may extend over thousands of square kilometers. High pressures and elevated temperatures drive this process. Platy minerals, such as micas, and elongated minerals, such as hornblende, tend to reorient or recrystallize perpendicular to the applied stress, while other minerals recrystallize to form new stable crystals suited to the increased pressure and temperature conditions (Figures 5.5 and 6).

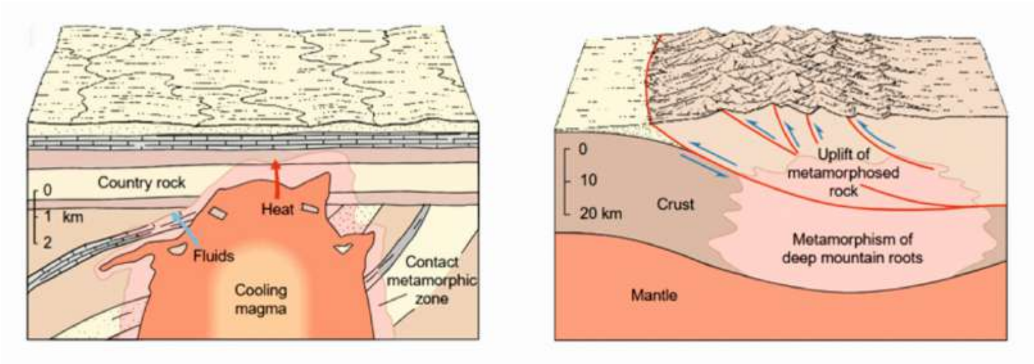


Figure 5.6: Contact metamorphism (left) and regional metamorphism (right). (faculty.ksu.edu.sa)

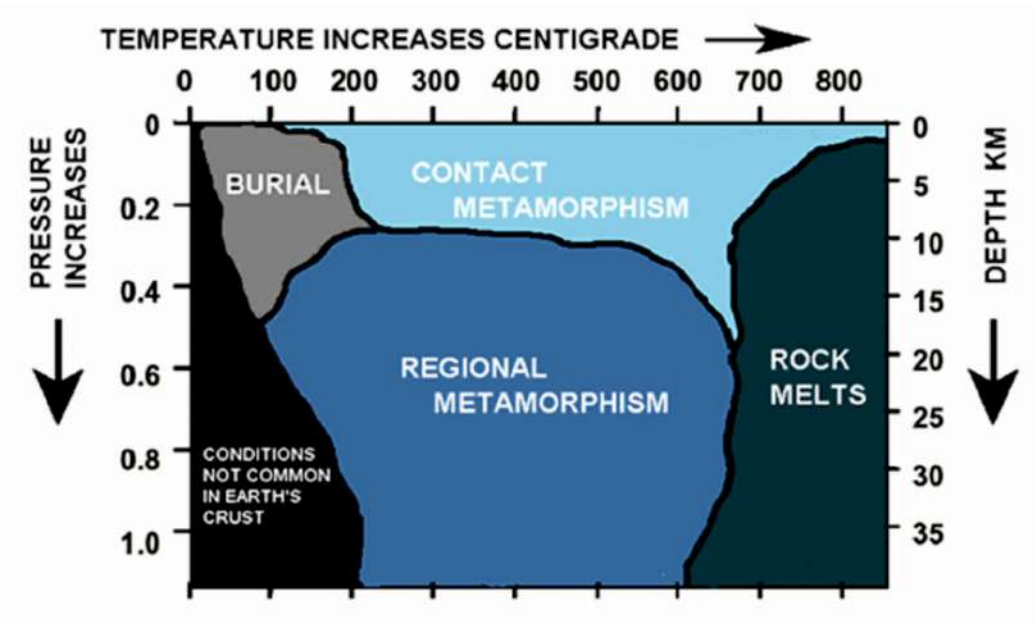


Figure 5.7: Main types of metamorphic rocks and their corresponding formation conditions (msnucleus.org).

5.3.3 Classification according metamorphic grades

Low-grade metamorphic rocks: Low-grade metamorphic rocks form at relatively shallow depths in the Earth's crust, where temperatures and pressures are low, typically below 400°C. They commonly develop in regions affected by regional metamorphism, such as areas of mountain building or near mid-ocean ridges. These rocks are generally fine-grained because the low temperatures limit crystal growth and often retain many characteristics of their original parent rocks. A distinctive feature of low-grade metamorphism is slaty cleavage, allowing the rock to split into thin layers, and minerals such as quartz and feldspar are commonly present, though not exclusively (Figure 5.8).

Intermediate-grade metamorphic rocks : Intermediate-grade metamorphic rocks develop at greater depths than low-grade rocks, typically in regions of regional metamorphism such as convergent mountain belts. They are also common in the cores of mountain ranges and areas experiencing moderate to deep burial. These rocks form under moderate temperatures (approximately 400–600°C) and pressures, resulting in medium- to coarse-grained textures. They exhibit pronounced foliation, or schistosity, allowing the rock to split into thin, irregular sheets, along with increased recrystallization and the formation of new mineral assemblages, making foliation and banding more distinct than in low-grade metamorphic rocks (Figure 5.7).

High-grade metamorphic rocks : High-grade metamorphic rocks form at considerable depths within the Earth's crust, typically in the roots of mountain belts where both temperatures and pressures are very high, often

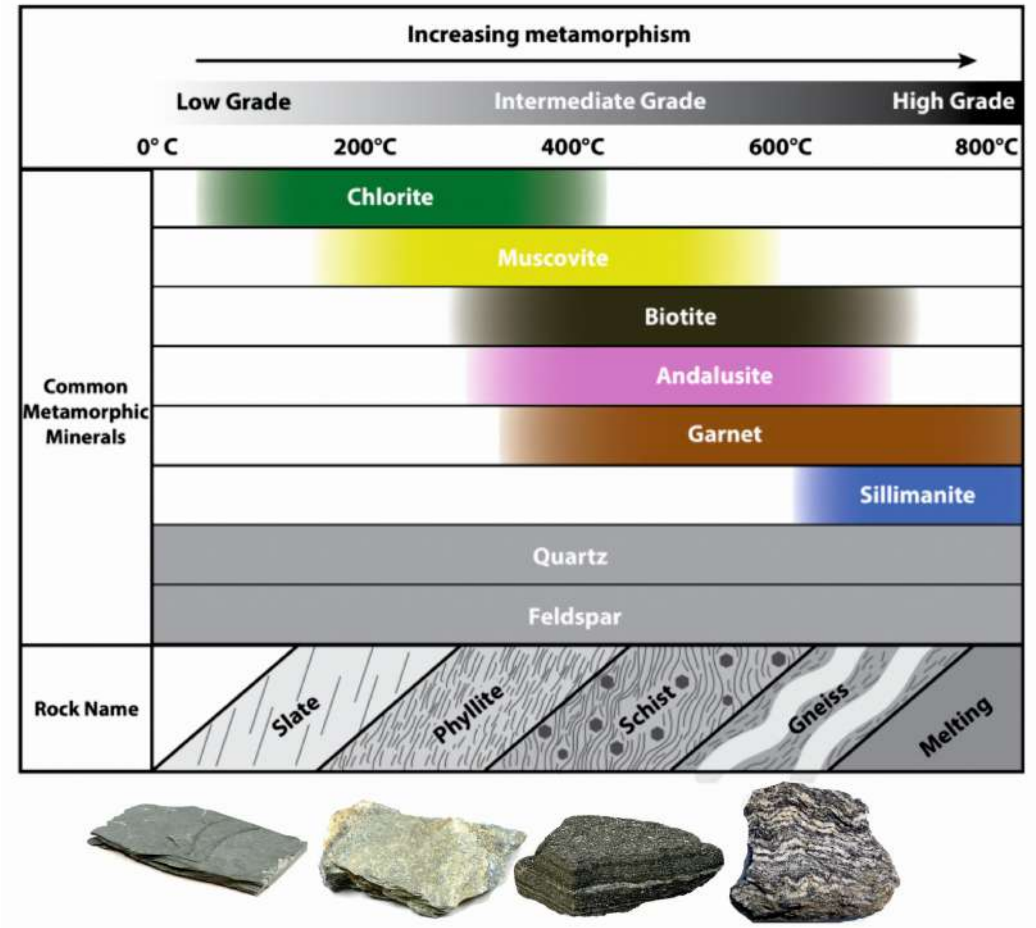


Figure 5.8: Classification of metamorphic rocks according to their grade (OpenEducationalAlberta.ca).

exceeding 600°C. They are common in regions of continental collision and subduction zones. These rocks are coarse-grained, with well-developed foliation and distinct banding, resulting from extensive recrystallization that produces high-grade minerals and large, visible mineral grains. In some cases, high-grade metamorphism can cause partial melting, leading to the formation of migmatites (Figure 5.7).

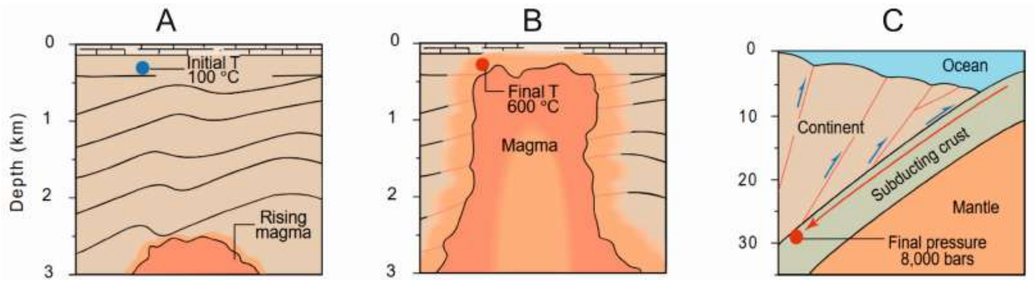
5.3.4 Exercises

Exercise 1:

- Describe the types of pressure illustrated in the figure below.
- Explain what foliation is and how it forms in each rock.
- Describe the metamorphic grade of the first two rocks.

Exercise 2:

- Describe the type of metamorphism for Figures A, B, and C
- Place rocks cited in the synthesis figure into each figure
- Place metamorphic grade for every tectonic context



Chapter 6

Topography

6.1 Topographic Map

6.1.1 Objectives

The purpose of a topography course is to provide students with the necessary knowledge to measure land surfaces and accurately mark specific points on the ground. These skills are primarily acquired through numerous field exercises under varying conditions. Practical work on-site can be supplemented with paper-based exercises. Technical concepts serve only as a support and are introduced based on practical needs.

6.1.2 What is a Topographic Map?

Topographic maps provide a detailed view of the Earth's surface, showing its features, shapes, and terrain, including elevation. Elevation, the height of the land above or below sea level, can be measured using methods such as surveying or remote sensing with pulsed laser light, which reflects off the landscape and is recorded by sensors. On a topographic map, elevation is represented using contour lines that connect points of equal height, often depicted in 3D relief to illustrate differences in terrain. These maps are valuable for understanding and managing natural environments. They help identify steep slopes that could cause landslides affecting water quality, low-lying areas prone to flooding, and suitable locations for forest restoration, taking into account elevation, slope, and the direction a slope faces (aspect). Since the Earth is a slightly flattened sphere (a geoid), creating a flat map requires a projection system, which can introduce distortions. To reduce these, projections such as Bonne and Lambert are commonly used, and for smaller areas, the Earth's surface is often approximated as a horizontal plane.

6.1.3 How to read a topographic map

Legend : The legend is the most important part of a topographic map because it explains key details. It shows the map's title, the year it was first made, and the date of its latest update. It may also include a dot or rectangle to indicate the location of the area within a larger region, such as a province or state, and it lists the names of nearby maps that cover surrounding areas, like the northeast section (Figure 6.1). The legend also explains the meaning of colors on the map: red represents roads, black shows man-made objects, blue indicates water, green marks vegetation, white is for areas with little or no vegetation such as deserts, sand, rocks, or snow, and purple highlights features added from aerial photographs that have not been verified in the

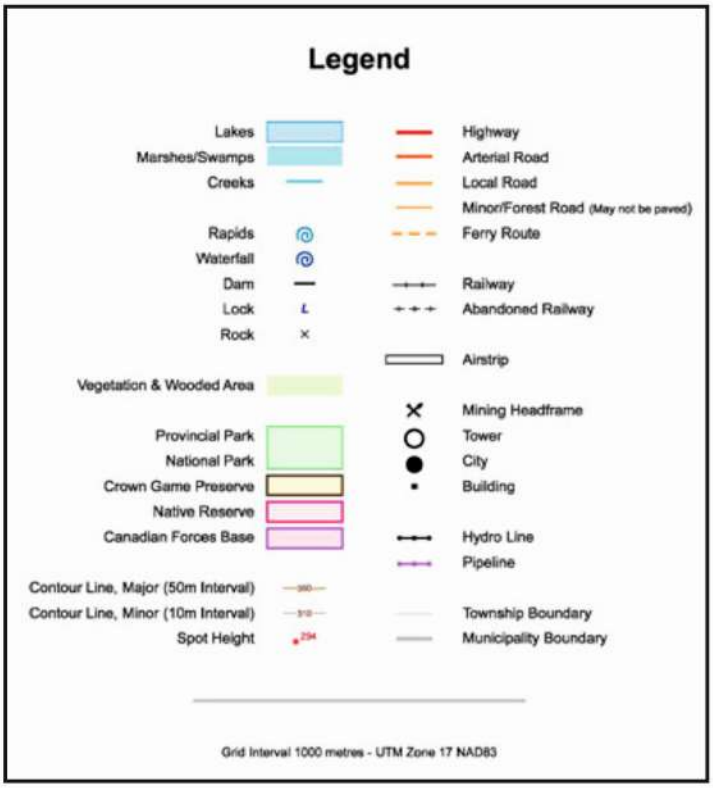


Figure 6.1: example of legend (Southern Ontario, Canada)

field.

Scale : In topography, scale is a fundamental concept that enables the representation of a portion of the Earth's surface on a map or plan. It is defined as the ratio between a measured distance on the map and the corresponding horizontal distance on the ground. This ratio is unitless and is most commonly expressed as a numerical scale, such as 1:50,000, meaning that 1 cm on the map represents 50,000 cm, or 500 meters on the ground. There are several forms of scale representation:

- The numerical scale, typically written as a fraction (1/L), where the numerator is always 1, and the denominator indicates the reduction factor.

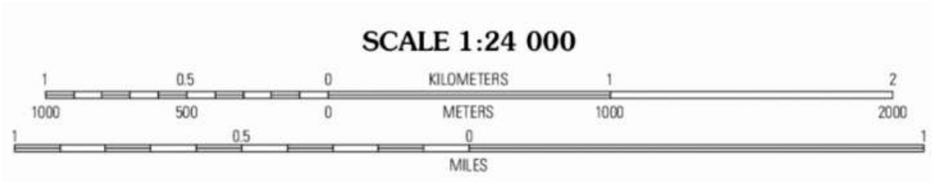


Figure 6.2: representation of both numerical and graphical scales

For example, a scale of 1:24,000 means that distances on the map are 24,000 times smaller than in reality (Figure 6.2).

• The graphic scale, represented by a graduated line or bar with real-world units (meters or kilometers), allows for a direct reading of distances. It is especially useful when a map is enlarged or reduced, as it preserves proportions even if the numerical scale becomes inaccurate (Figure 6.2).

The choice of scale depends on various factors, including the size of the paper format, the extent of the area to be represented, the level of detail required, and the purpose of the document. The smaller the denominator, the larger the scale, and the greater the level of detail shown. Three main scale categories are typically recognized:

• Large scale (1:1 to 1:25,000): used for cadastral plans, detailed topographic surveys, and agricultural maps. For example, at 1:10,000 scale, 1 cm on the map equals 100 m in the field.

• Medium scale (1:25,000 to 1:100,000): suitable for geological maps, military maps, and regional overviews. Small scale (greater than 1:100,000): used for national maps, road maps, and continental or global maps, where the covered area is broad but detail is reduced. For fieldwork, it is recommended to use both the numerical and the graphic scale, as the latter ensures reliable distance interpretation even after the map is resized or reproduced.

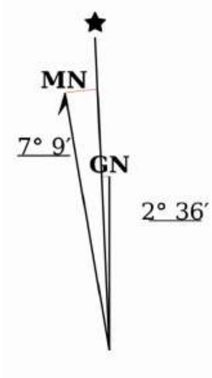


Figure 6.3: representation of Magnetic north (MN) and Grid North (GN)

Directions : Maps usually include a north point diagram in the margin, showing the directions of true north, grid north, and magnetic north at the map's center (Figure E.3). True north (TN) points to the Earth's geographic North Pole, while grid north (GN) follows the vertical grid lines on a topographic map, with the angle between TN and GN called grid convergence. This difference is generally small, less than 2°, and varies depending on the location. Magnetic north (MN) points toward the Earth's north magnetic pole, and the angle between TN and MN is known as magnetic declination. Since GN is more commonly used in map reading, the angle between GN and MN—called the grid/magnetic angle—is especially important In Algeria, the magnetic declination varies depending on the location. For instance, in Algiers, the magnetic declination is approximately +2.02° east of true north. In other areas like Taihit, the declination is around +0.68° east.

In topographic map, the edge represents a meridian, indicating true north (geographic north). Consequently, whenever a map is consulted, the top of the map corresponds to true north. To align the map's features with those on the ground, the map must be oriented using a compass, meaning it should

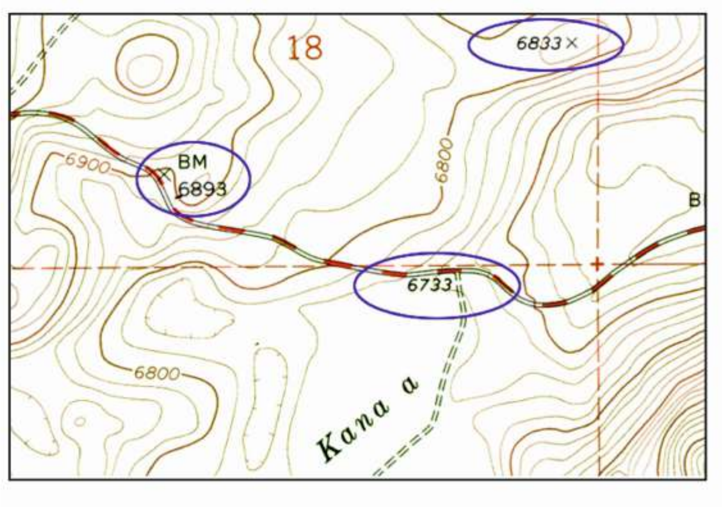


Figure 6.4: Spot elevations and benchmarks (Kensas map, USA)

be adjusted so that its north matches the magnetic north indicated by the compass needle. (Note: This accounts for the difference between true north and magnetic north, which may require declination adjustment depending on location.)

Benchmarks: Benchmarks indicate precise locations where surveyors have measured elevations above sea level. They are often used to mark the elevations of mountains, hilltops, road intersections, or airport runways. If a physical marker was placed at the site, the benchmark is shown with a triangle; otherwise, it appears as a black "X" or the letters "BM." In addition to the symbol, the exact elevation at that point is usually written in black, which distinguishes it from the brown numbers on contour lines. Benchmarks are rarely located directly on a contour line; instead, they are usually found between contour intervals (Figure 6.4).

Contour lines: The most important feature of a topographic map is the contour line, usually shown in brown. Contour lines connect points of

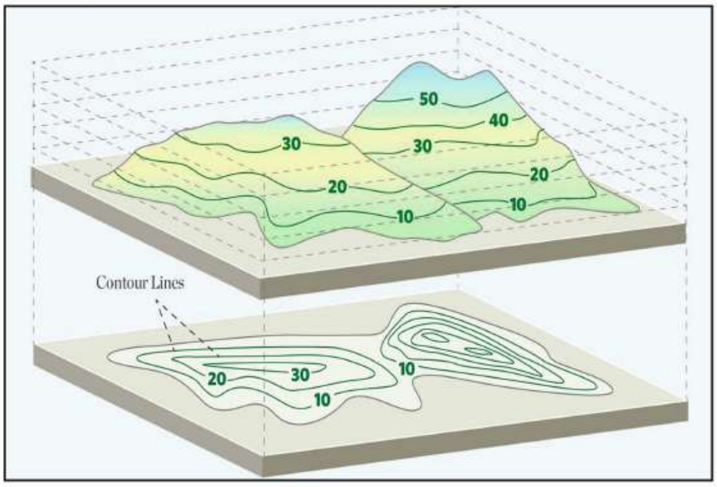


Figure 6.5: 2D and 3D presentations of contour lines

equal elevation, forming shapes that mirror the terrain, and the spacing between them represents changes in elevation (Figure 6.5). Closely spaced lines indicate steep slopes, while widely spaced lines show gentle slopes. By following these lines and their elevation labels, you can determine how much the land rises or falls. However, contour lines do not capture every small bump in the landscape, and sudden changes in height between two lines may not always appear. There are three main types of contour lines:

• Index contours: drawn with thicker lines, usually every fifth or tenth line, and labeled with the elevation value.

• Intermediate contours: thinner lines placed between index contours to show finer changes in elevation.

• Supplementary contours (or auxiliary contours): shown as dashed lines in areas of very gentle slopes. These represent elevation changes that are half the regular contour interval to provide greater detail.

Interpreting Contour Shape and Spacing: Contour lines can show the

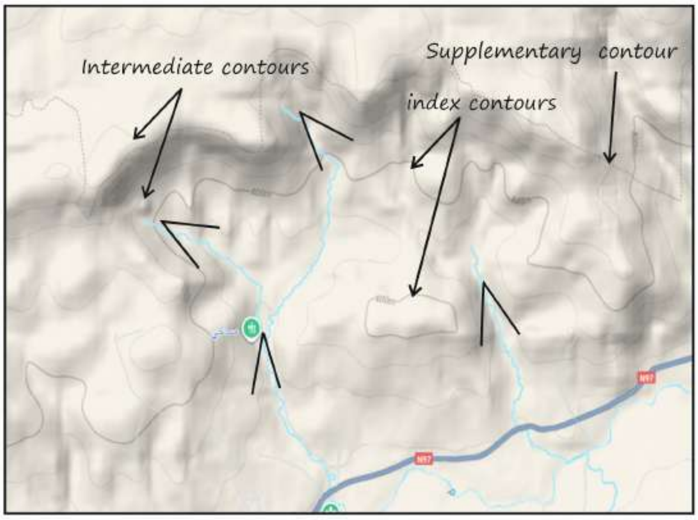


Figure 6.6: The "Rule of the V's". This is an easy way to determine the direction of stream drainage.

shape of the land and the direction of streams. When they cross a stream, the lines form a V shape, and the point of the V always points upstream or uphill, showing the flow direction. Contour lines never cross or split (Figure 6.6). You can also tell how steep the land is by looking at the spacing of the lines: lines far apart mean a gentle slope, while lines close together indicate a steep slope (Figures 6.7-8)

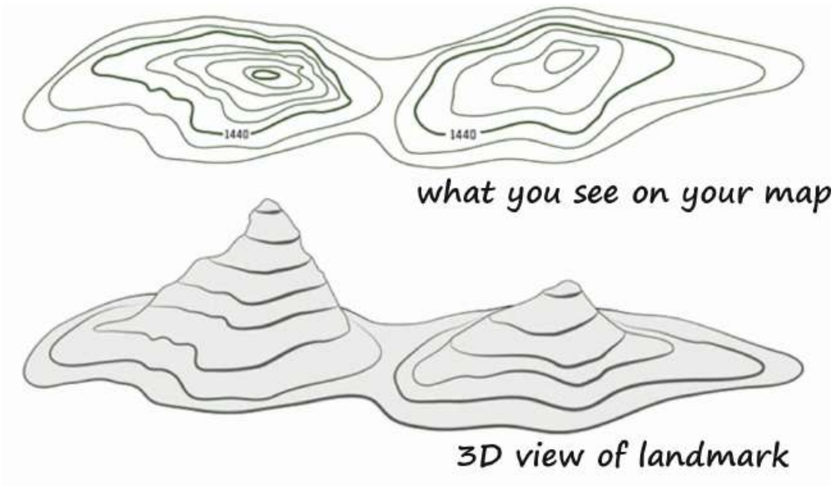


Figure 6.7: graphic representation of Contour line spacing on map and 3 D view landmark.

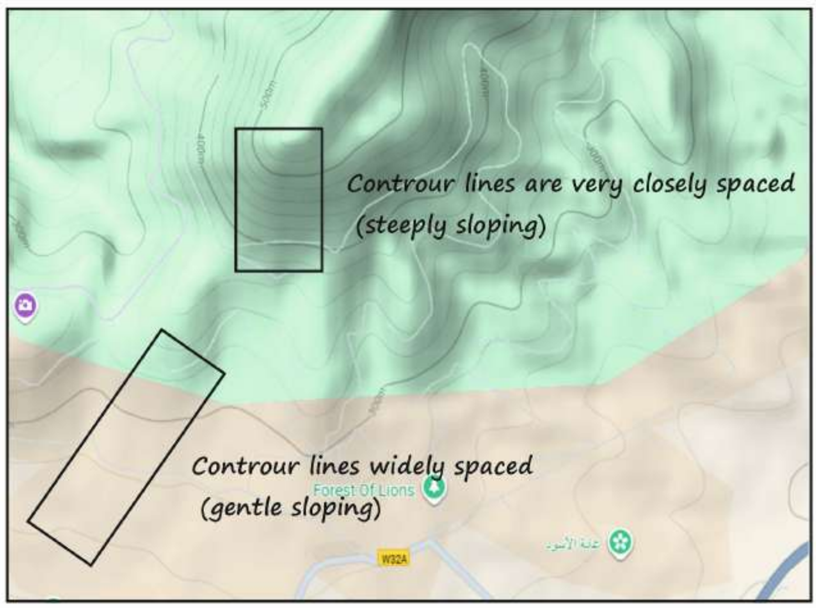


Figure 6.8: graphic representation of Contour line spacing on map and 3 D view landmark.

6.2 Topographic profile

6.2.1 Definition

A topographic profile shows a side view along a chosen line on the map, allowing you to see how the land's elevation changes. For example, in Figure 6.11, the top image is a map of a hill with two peaks, while the bottom image shows the corresponding topographic profile along the line A-B. The profile includes horizontal elevation lines that match the contour intervals on the map. These lines are evenly spaced along the vertical axis. If you trace the points where the contour lines meet the surface of the hill and project them onto the profile along line A-B, they align with the map's contour intervals. This relationship is essential for creating accurate topographic profiles.

6.2.2 How to draw a topographic profile

To make a topographic profile, you will need a topographic map, blank paper, a ruler, and a pencil. Use Figure E.9 as a reference while following these steps:

• Draw or choose a line across the map through your area of interest (e.g., a hill). In Figure 6.9, this line is labeled A-B.

• On your blank paper, draw a horizontal line of the same length. This will be the x-axis of your profile.

• Draw perpendicular y-axis lines at either end of the x-axis.

• Add horizontal elevation lines across the y-axis at intervals equal to the map's contour intervals. Include one line below the lowest contour and one above the highest. Use the same scale as the map (e.g., 1 cm = 10 m for a

1:100,000 map).

• Align your paper so the x-axis is parallel to the line on the map. Transfer elevation points from where contour lines intersect the chosen line onto the corresponding elevation lines on your paper. Only plot points at these intersections.

• Connect the points with a smooth curve. You may need to estimate the terrain between points, so your profile might slightly differ from others

• Ensure hilltops are slightly rounded to represent the crest without exceeding the next elevation line. For instance, a hill with a top contour of 50 m has an actual height between 50 and 60 m. Similarly, the valley floor between two hills might be below 40 m but above 30 m, as shown on the map.

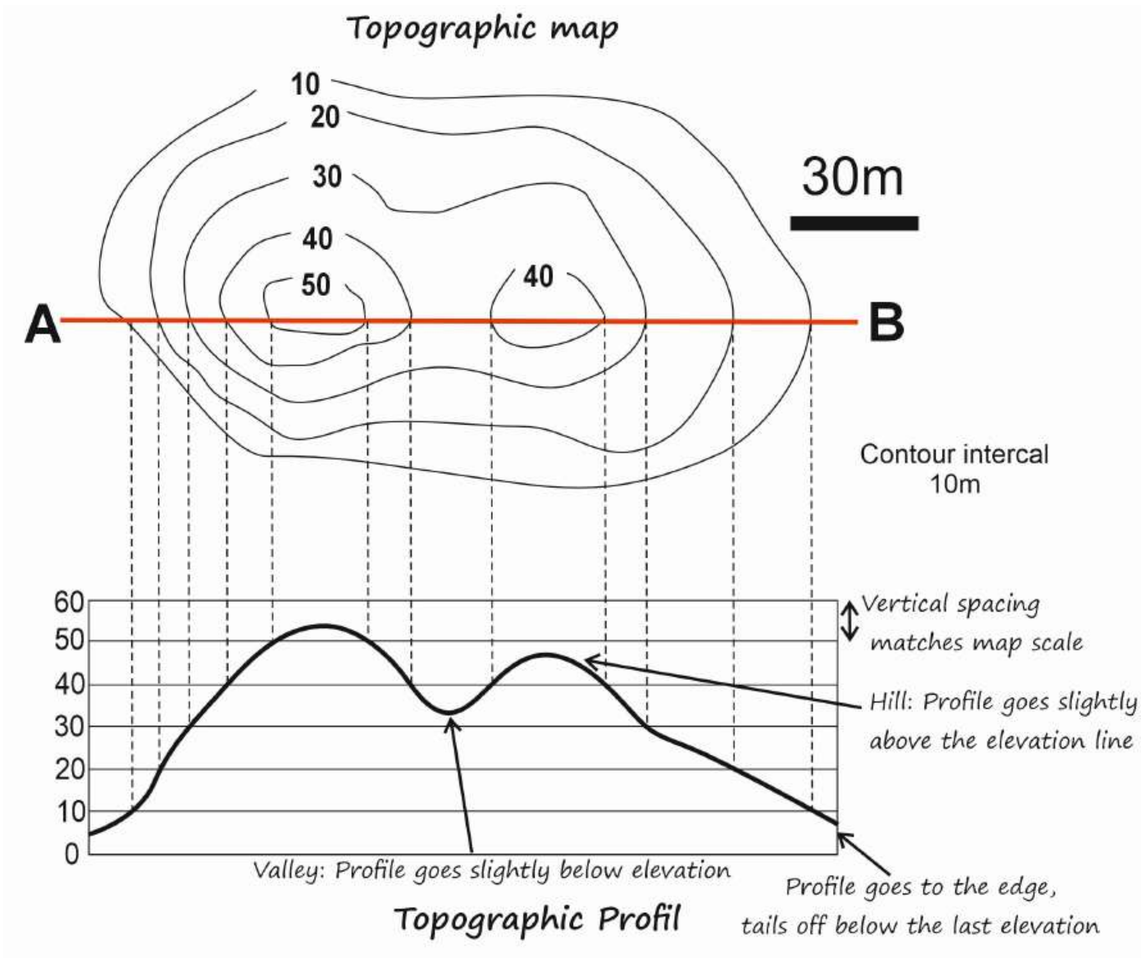


Figure 6.9: Topographic map and topographic profile of two hills with a valley between them. Source: Karla Panchuk (2020)

6.2.3 Exercises

Exercise 1: The topography of El Bayadh:

The topographic map provided represents the northern northwestern region of El Bayadh (Figure 6.10). Based on your lecture and the interpretation of the contour line sequences, draw two topographic profiles on graphic paper, along axes A and B.

Exercise 2: The topography Douar Oued Cheliff The topographic map provided herein is a detailed representation of the Oued Cheliff region's terrain (Algeria, Figure 6.11). It's aiding scientific analysis and land planning by providing insight into elevation, landforms, and geographical features. This map is invaluable for understanding the area's physical landscape. Based on this map, provide answers to the following questions.

1. How many sets of relief features are visible on the Oued Cheliff topographic map?

2. How many peaks are visible on the same map (calculate their altitudes)?

3. What are the most prominent sedimentary environments in this region?

4. Draw two topographic profiles along axes A and B.

5. Show, with arrows on the drawn profiles, two types of hydraulic erosion affecting the Oued Cheliff region.

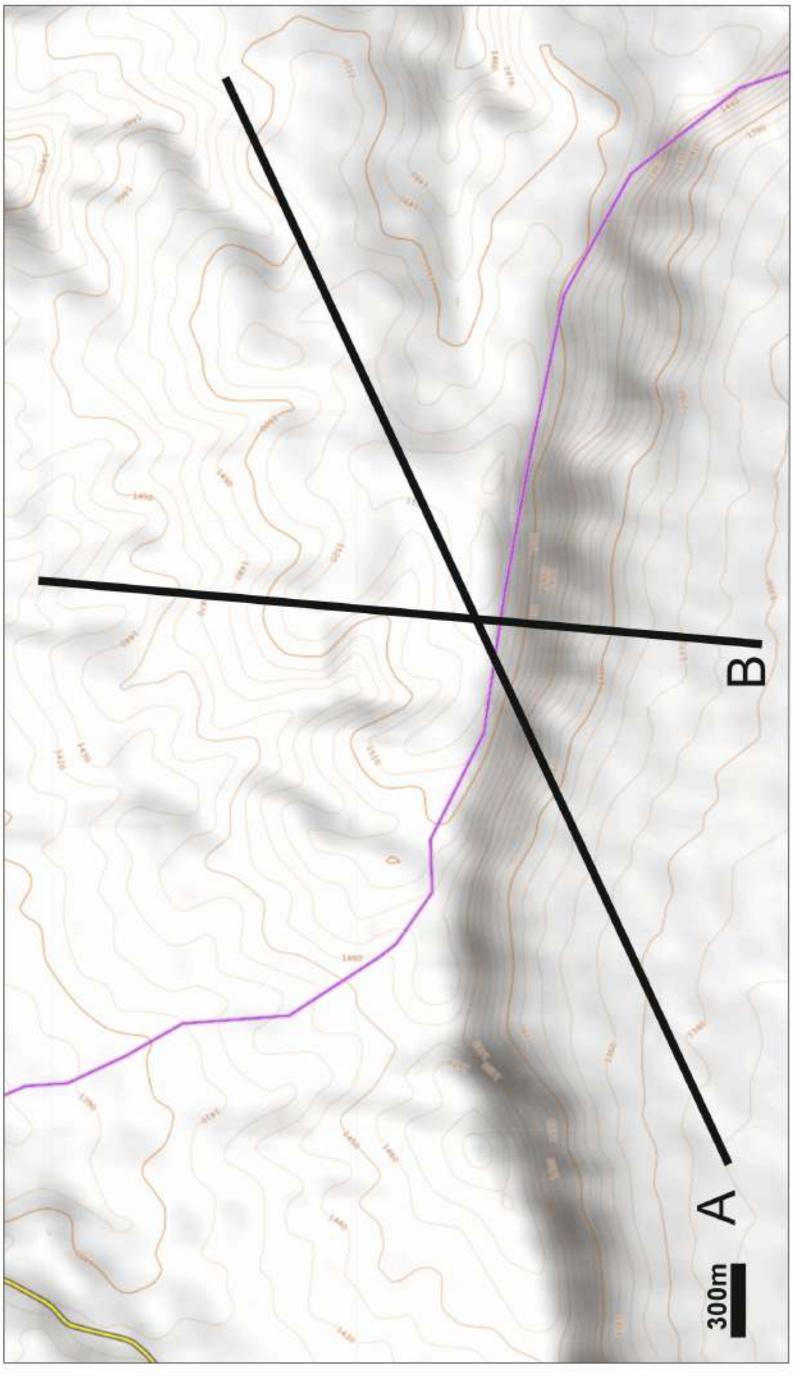


Figure 6.10: The topography map of El Bayadh

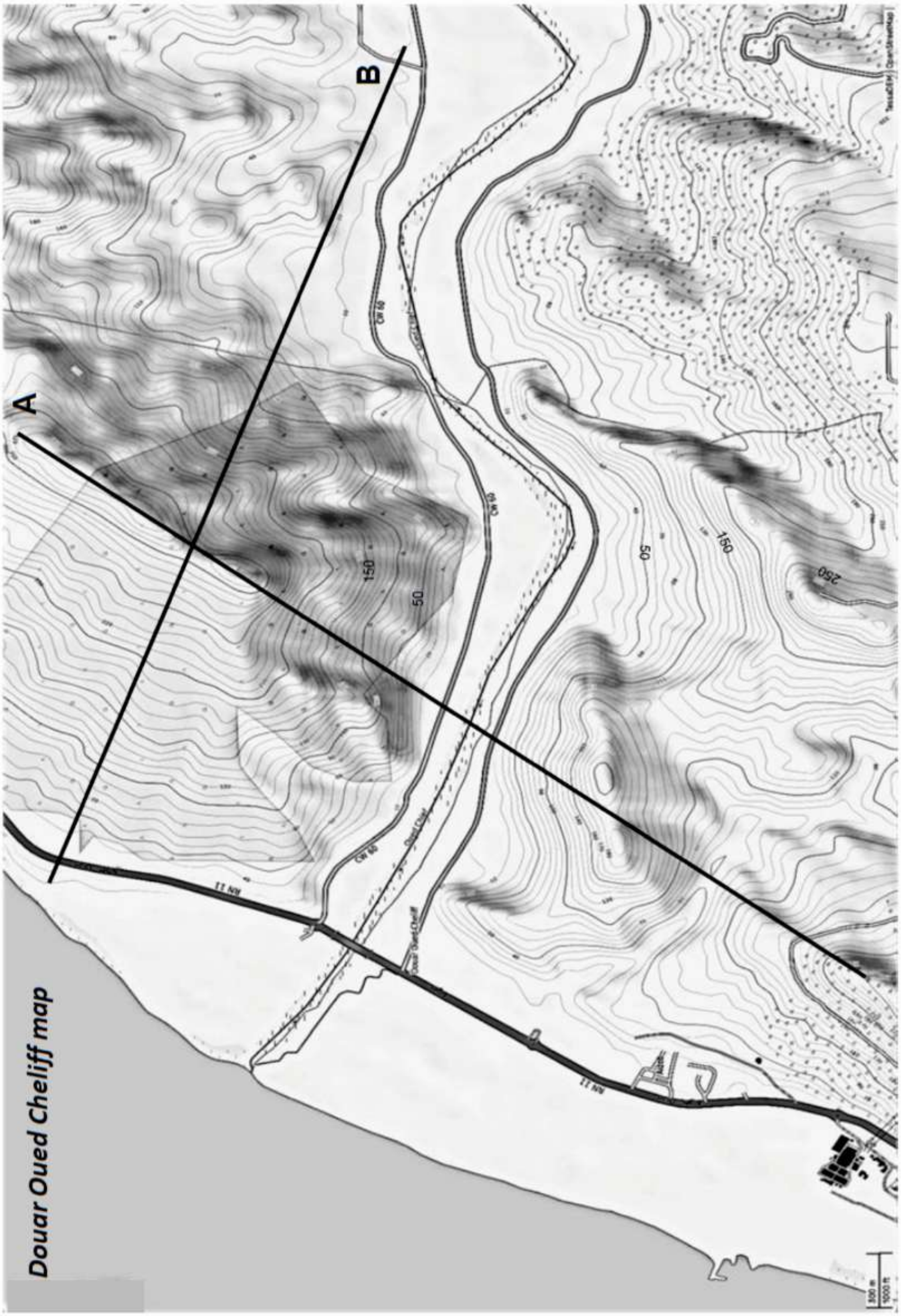


Figure 6.11: The topography map of Oued Cheliff

Chapter 7

Geological maps

7.1 Introduction

Geological maps are not merely inventories of spatially arranged rock outcrops; they also serve as records of the Earth's evolutionary history. They represent interpretations that reveal geological processes extending beyond what is directly observable in surface landscapes. These maps are produced at various scales, sometimes through direct field observations and sometimes by integrating prior work. Increasingly, mapping products are disseminated openly, particularly by national geological surveys. Nonetheless, geological maps remain interpretive rather than strictly factual records. Among the key challenges are the incorporation of alternative interpretations to account for uncertainty and the maintenance of consistency when multiple geologists contribute. Digital platforms now provide innovative means to address these challenges, with space agencies setting an example by openly sharing planetary imagery and associated datasets. Geologists have historically embraced technological advances, although their adoption often depends on cost and accessibility. Contemporary developments include tools for constructing "virtual outcrops" and the growing use of scanning electron microscopy for high-resolution rock characterization. Consequently, geological maps are now generated using a diverse range of instruments and for an expanding array of purposes.

7.2 What is geological map ?

A geological map is a specialized map that illustrates the distribution and relationships of rock units and geological features at the Earth's surface (Figure 7.1). Different formations are represented by colors or symbols, while structural elements such as faults, folds, foliations, and alignments are depicted using strike-and-dip or trend-and-plunge symbols to indicate their three-dimensional orientation. Stratigraphic contour lines may be added to show the surface of a chosen geological horizon, revealing subsurface trends, while isopach maps highlight variations in the thickness of rock units. In essence, a geological map is a two-dimensional representation of subsurface information, superimposed on a simplified topographic base. The topography not only helps users orient themselves in the field but also conveys the relief of the studied area. One can think of the colors and lines as representing the rocks immediately beneath the surface, as if the soil were stripped away. However, for professionals such as engineers, who need to plan tunnels or drilling projects, a deeper interpretation is required. Reading a geological map means extracting as much information as possible about the arrangement and sequence of geological structures.

7.3 Components and reading of Geological maps

7.3.1 The legend

On the geological map, the legend is displayed along the right-hand or down side, providing a summary of the geological information. Each major rock unit in the area is shown using a specific colour and symbol. A rock unit refers to a geologically distinct area made up of similar rock types, and the same unit may appear in different parts of the map. Symbols usually consist of two or three letters (e.g., Qa for Quaternary) to help differentiate units with similar colours. In the legend, each symbol and its matching colour are placed inside a small box (Figure 7.2). Next to the box, a description of the rock is provided. Where several rock types occur together, more than one description is listed. For clarification of technical terms, a glossary is included at the end of the booklet. The legend also indicates the relative ages of the different rock units.

Rock nature: A brief description of each rock unit is provided beside its corresponding box in the legend. In areas where several rock types occur together, multiple descriptions are listed. To assist with technical terms, a glossary is included at the end of the booklet.

Geologists classify rocks into three main groups:

- Igneous rocks – formed by the cooling and solidification of molten ma-

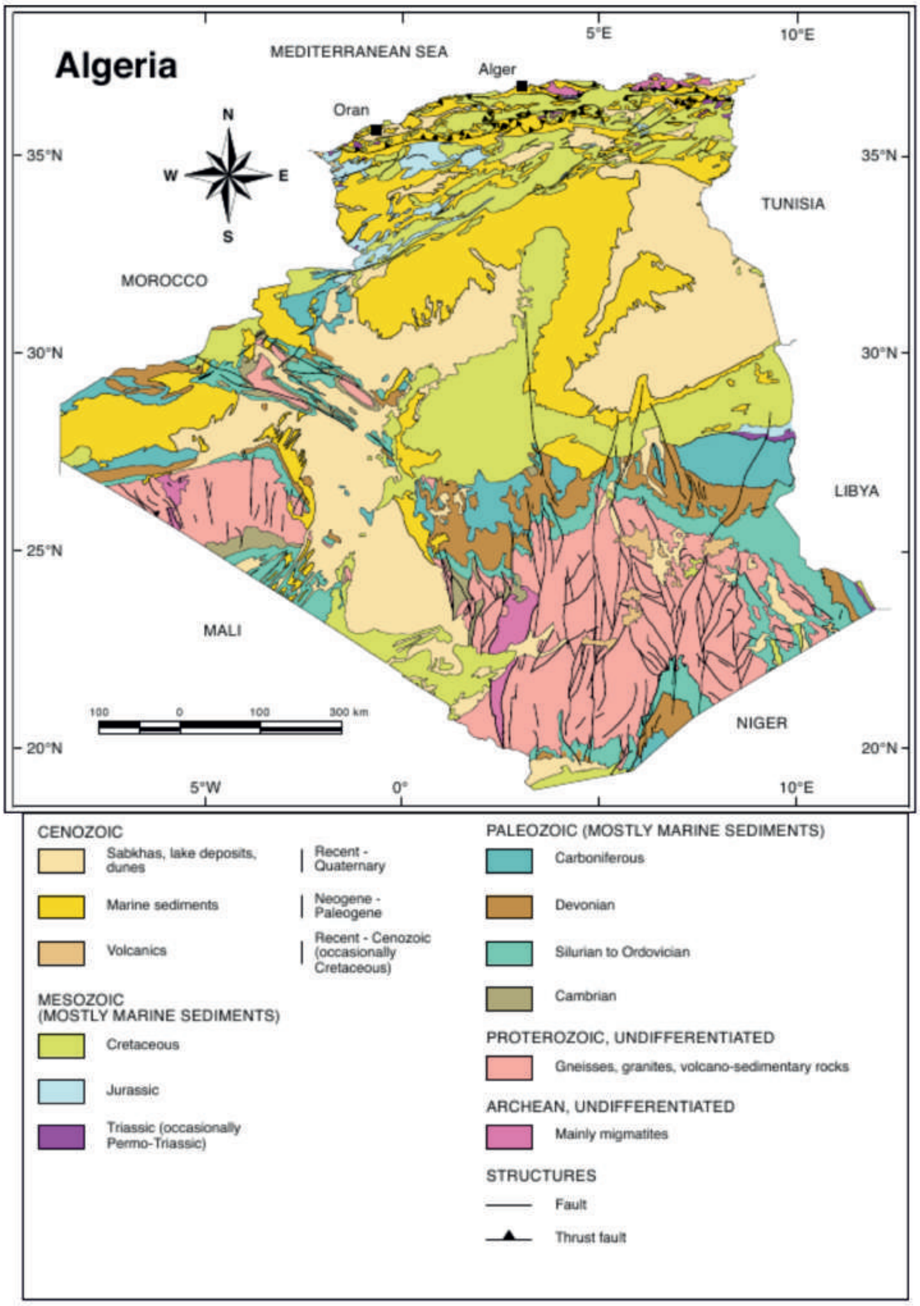


Figure 7.1: Geological map of Algeria

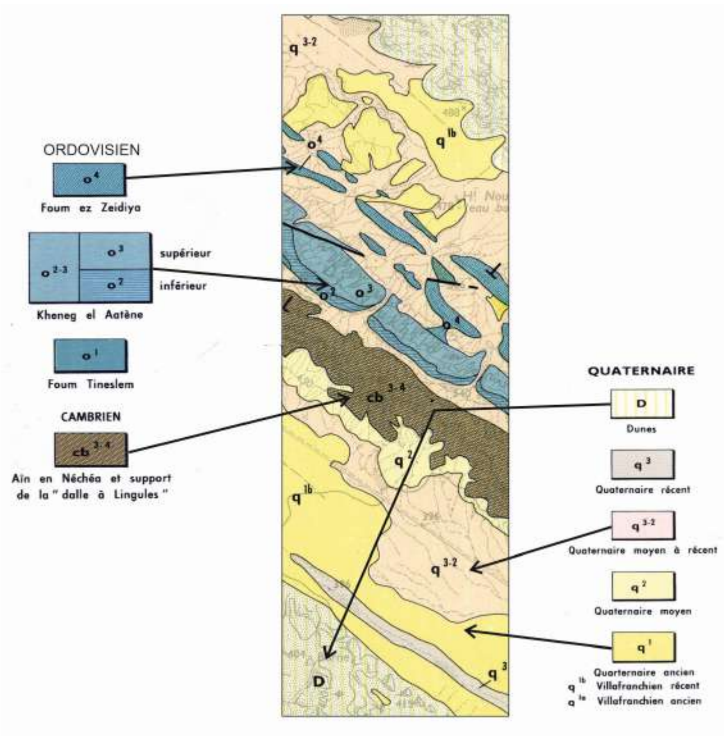


Figure 7.2: Extract of the Map Legend from the Ougarta Basin, Algerian Sahata

terial.

• Sedimentary rocks – produced from the compaction and cementation of sediments such as sand, pebbles, clay, or mud. These rocks may also contain fragments of older rocks, as well as remains of plants and animals.

• Metamorphic rocks – developed when pre-existing rocks are altered (recrystallised) through heat and/or intense pressure, without melting.

The Age of Rocks: Geologists measure time on the scale of millions of years. To represent Earth's history—stretching back about 4,600 million years—they use a geological timescale or timeline. The ages of rocks are determined through fossil evidence and/or radiometric dating. For convenience, this timescale is divided into major units called eras (from the Hardean to the Cenozoic) and smaller units called periods (from the Siderian to the Quaternary). A simplified version of this timescale is shown on the following page (Figure 7.4). On the studied map legend, the oldest rocks (formed during the Proterozoic) are placed at the bottom, with progressively younger units listed above them. Consequently, the youngest rocks appear at the top of the legend.

Formations : Geologists classify sequences of rock layers within a given region into larger units known as formations, such as the Oued Ali and Zeimlet Formations illustated in Ougarta basin (Figure 7.3). Each formation can be further subdivided into units, and in some cases into smaller subdivisions referred to as members, terms, or sequences. These formations, together with their distribution on the map, are presented in the legend and have been extensively described in earlier studies of the Ougarta Basin.

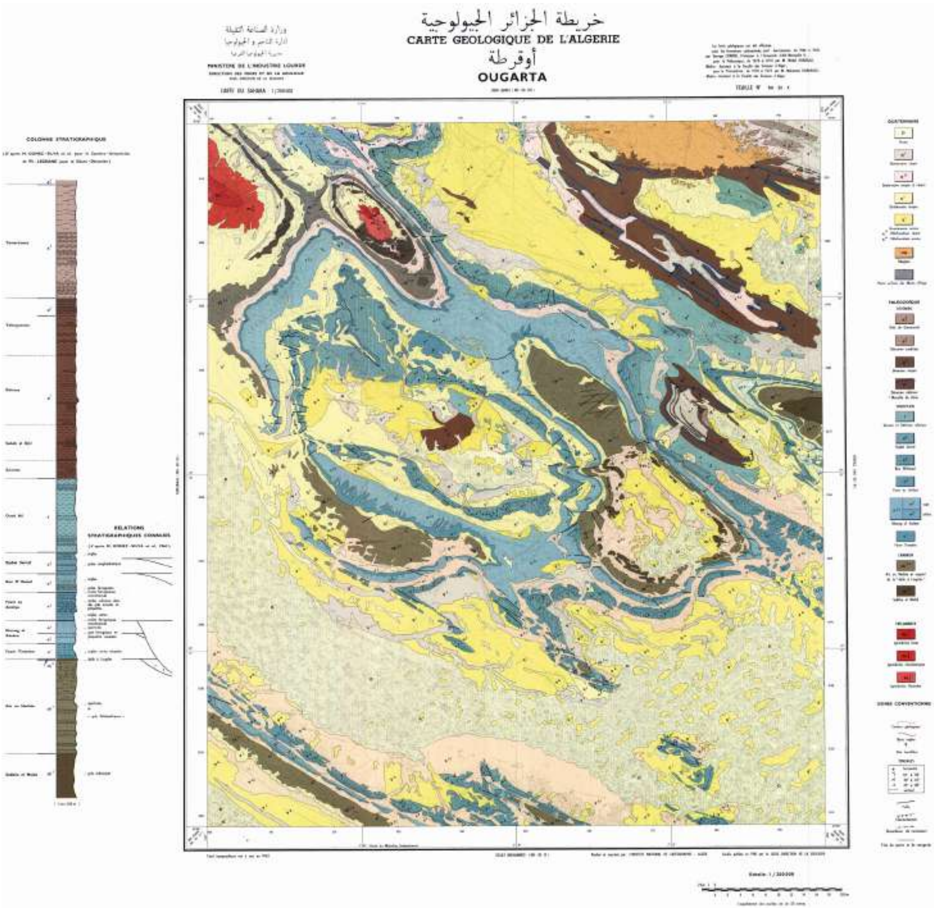


Figure 7.3: Geological map of Ougarta basin, Algerian Sahara

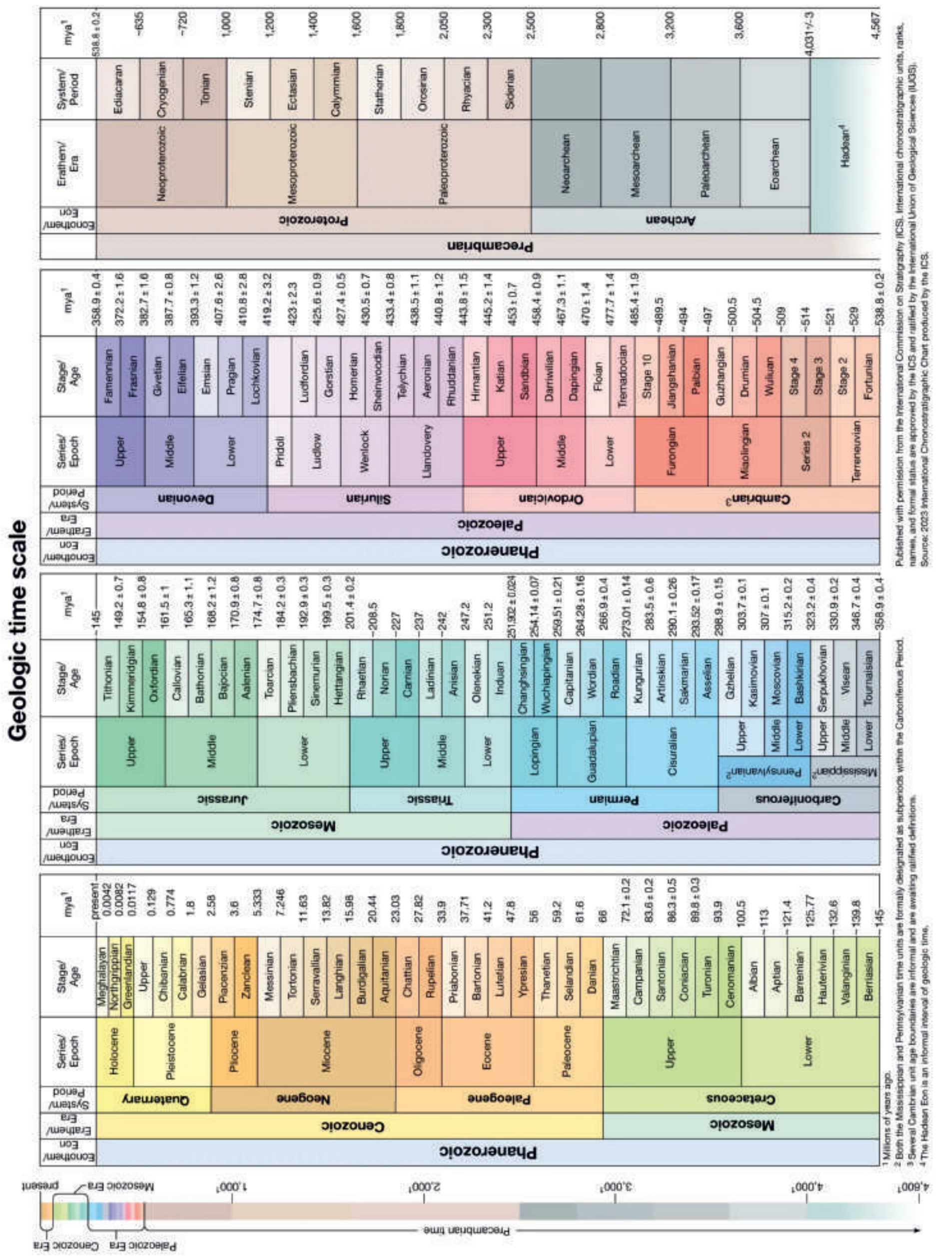


Figure 7.4: Geological time scale

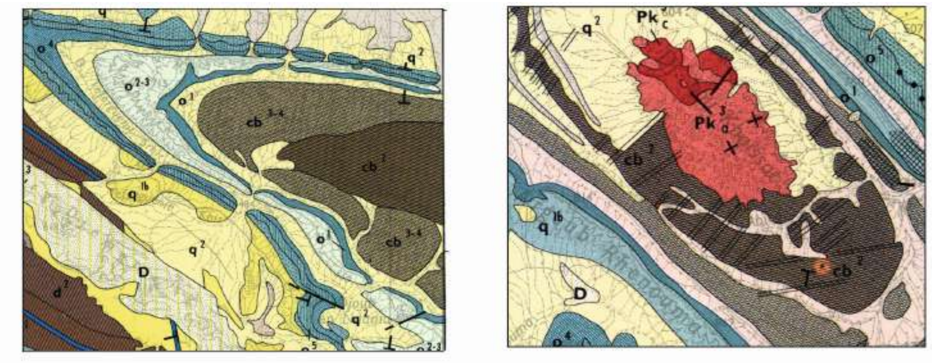


Figure 7.5: Extract of the Sebkha El Melah Formation (Cb2) from the Geological Map of the Ougarta Basin

Formation of Sebkha el Melah (cb2) : The map area contains several formations, among which the Sebkha el Melah Formation is composed mainly of arkosic sandstone. This unit represents the second oldest stratigraphic formation in the region, dated to around 541 million years ago, and was subsequently influenced by tectonothermal processes that caused folding and heating of the succession (Figure 7.5). When producing the map, geologists used trend lines to represent the general orientation and geometry of folds and faults.

Formation of Temertasset (d3,) : This formation represents the youngest unit depicted on the studied map of Ougarta and is assigned to the Devonian (D3) (Figure 7.6). It can be subdivided into two units: a lower unit consisting of thin calcareous beds interlayered within a thick clay succession, commonly referred to as the Marhouma Clay; and an overlying unit composed of massive detrital deposits known as the Ouarourout Sandstone, dated to the Upper Devonian–Carboniferous boundary. According to the map, this formation is only weakly affected by tectonics, with no significant faulting represented. It

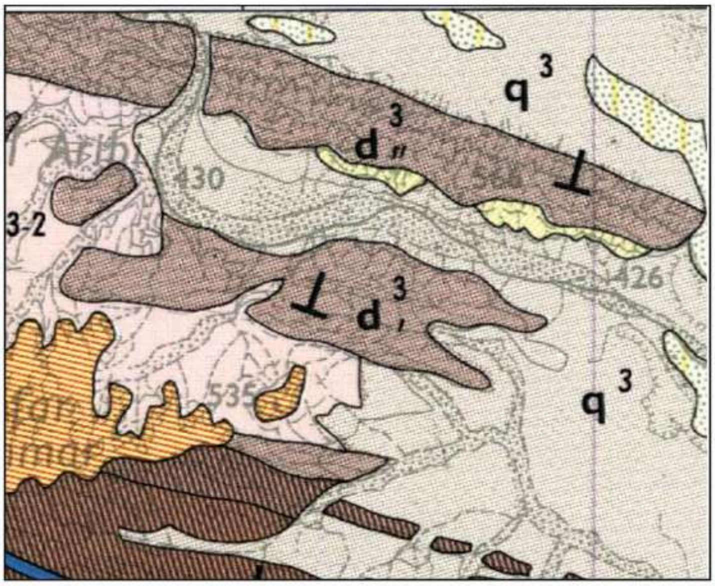


Figure 7.6: Extract of Formation of Temertasset Formation from the Geological Map of the Ougarta Basin

is also noteworthy that the Upper Devonian strata are overlain by Quaternary alluvial sediments (Q3).

Note: Between the Sebkha el Melah Formation (cb2) and the Temertasset Formation (D3), several other formations with distinct lithologies are exposed in the map area. The student is invited to provide a brief description of each of these formations.

Symbols: A table located at the bottom right-hand corner of the map presents the additional symbols employed. While most of these are self-explanatory, the principal geological symbols are described below. It should be noted that when lines representing faults, folds, or similar features are shown as dashed, they indicate that the structures are inferred—meaning they are not directly observable but are interpreted by geologists based on indirect evidence (Figure 7.7). Layer boundaries—also known as "geological

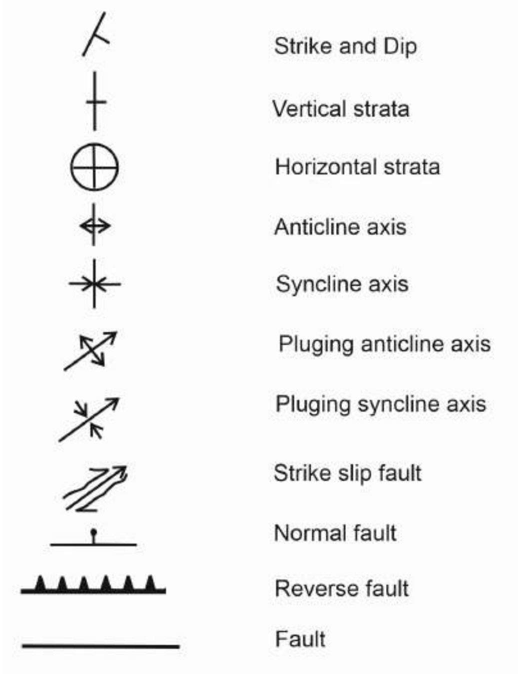


Figure 7.7: Main symbols in Geological map

contours"—are represented by fine lines, sometimes dashed when uncertain. Faults, unconformities, and other major structural features are drawn as thick, continuous black lines. The line may be dashed if the structure is obscured by scree or superficial deposits (Figure 7.7).

Unconformity : a geological boundary representing a significant gap in time between the erosion of older rock layers and the deposition of younger ones. The older strata may have been folded and tilted before being eroded, after which, millions of years later, new layers of rock were deposited above them.

Anticline and Syncline : geological structures formed by the folding of rock layers (Figures 7.8-9)

Fault: it is a fracture in the rock along which displacement occurs as a

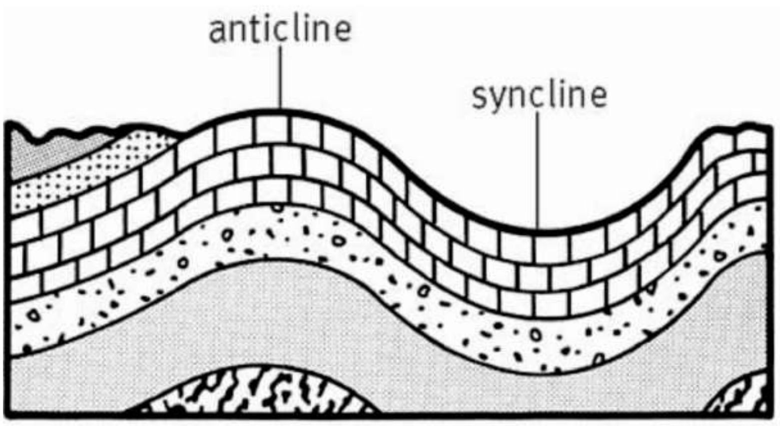


Figure 7.8: Anticline and syncline

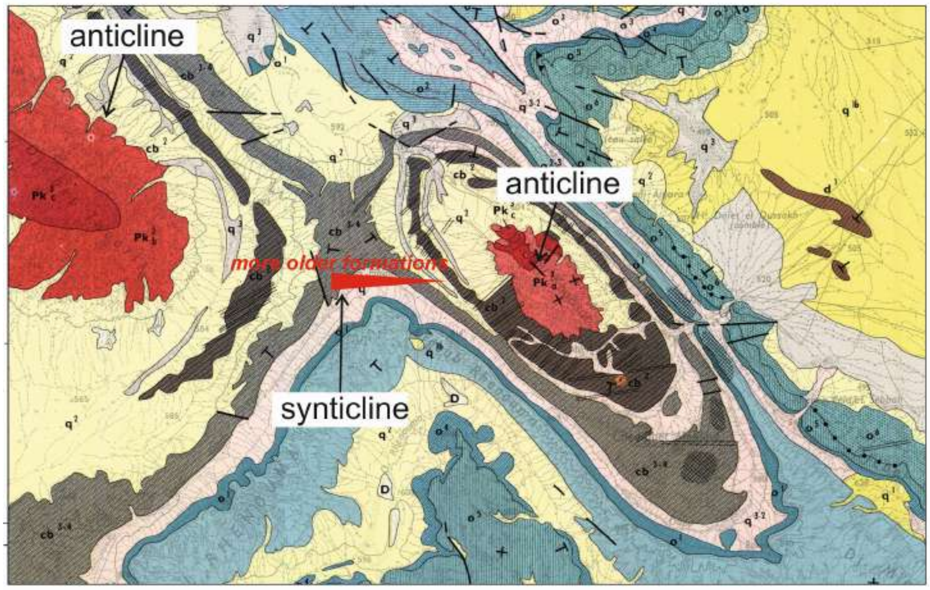


Figure 7.9: Illustration of anticline and syncline from geological map

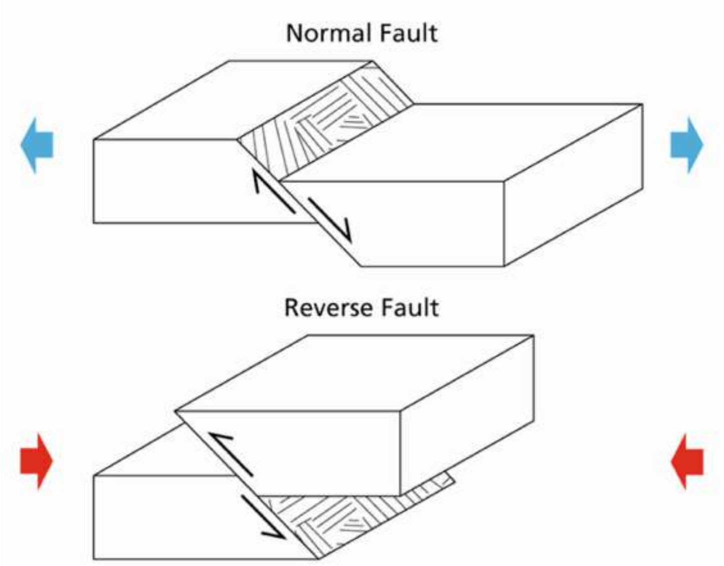


Figure 7.10: 3D illustration of normal and reverse faults

result of stress. Earthquakes are generated when rocks slide past one another along such faults, although the majority of faults are presently inactive. The two principal types are normal faults and reverse faults.

Normal fault: it is a structural discontinuity that develops under extensional tectonic stress, where the hanging wall block is displaced downward relative to the footwall block along the fault plane (Figure 7.10).

Reverse Fault: it is a structural discontinuity that forms under compressional tectonic stress, where the hanging wall block is displaced upward relative to the footwall block, often resulting in one rock mass being thrust over another (Figure 7.10).

Strike and Dip: Dip refers to the maximum inclination of a rock layer relative to the horizontal plane, measured in degrees. Geologists often also record the dip direction, which is the compass bearing toward which the layer is inclined. Strike represents the compass bearing of a horizontal line on the

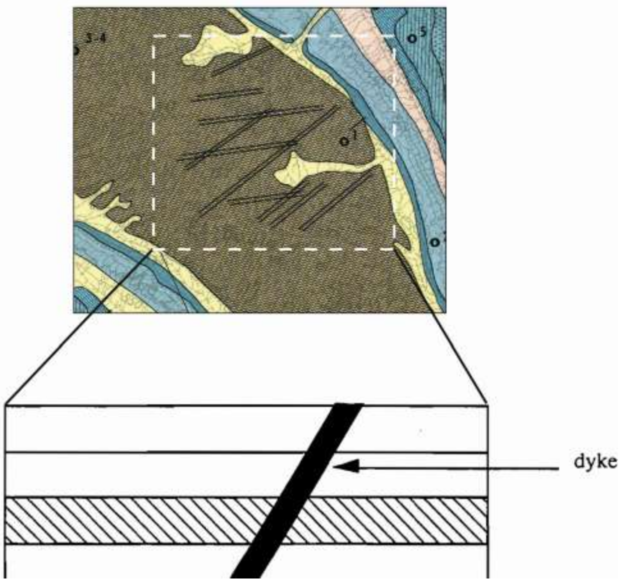


Figure 7.11: Joints in Ougarta map

plane of the rock bed, oriented at 90° to the dip direction. On geological maps, strike is depicted as a short line, with an adjacent tick mark indicating the dip direction and the corresponding dip angle.

Trend Lines: linear features identified through air-photo interpretation, used to indicate the presence of folded rock strata.

Joints: fractures within rock layers that occur at an angle to the bedding planes along which the rocks were originally deposited. Unlike faults, joints show no displacement of the rock masses on either side (Figure 7.11).

Shear Zone: a structural domain characterized by the concentration of numerous closely spaced faults, accommodating significant deformation.

Dyke: a tabular igneous intrusion that cuts discordantly across pre-existing rock layers, emplaced along a fracture and typically forming a sheet-like body of variable thickness.

Intrusion: an igneous body formed from magma (molten rock) that cooled

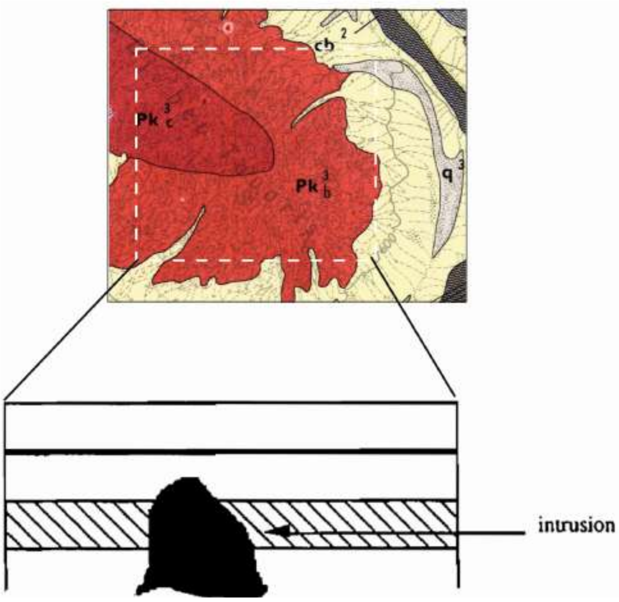


Figure 7.12: Intrusion in Ougarta map

beneath the Earth's surface. Such rocks are said to "intrude" into pre-existing formations (Figure 7.12). The intense heat of the magma may cause contact metamorphism in the surrounding country rocks. On the Ougarta map, a large granitic intrusion is illustrated along the western margin. Magmas typically intrude at temperatures ranging between 700 °C and 1000 °C.

7.4 Geological Mapping Accuracy

In the Ougarta region (Algerian Sahara), geological maps were produced mainly through systematic field prospecting conducted by teams of geologists. Unlike areas where air-photo interpretation predominates, mapping here relied primarily on direct field observations and traverses, which ensured greater reliability. The duration of mapping depends on the complexity of the geology, accessibility, and the intended scale. In remote areas such as Ougarta, geologists operated from base camps equipped with vehicles, camping facilities, communication tools, and essential geological instruments. Field teams divided the area into sectors, conducting traverses by foot and vehicle to collect data. Because much of the geology is concealed beneath alluvium, sand cover, and weathered surfaces, the reconstruction of the geological framework required combining surface evidence with complementary tools such as GPS and geophysical surveys.

7.5 Geological Cross-sections

A geological cross-section illustrates the spatial relationships between rock units in a given area. It depicts features such as stratigraphic layers, faults, folds, and erosional surfaces, while also reflecting the chronological sequence of geological processes. Typically, the lowest rock unit in a cross-section represents the oldest formation, whereas the uppermost unit is the youngest—unless structural deformation has overturned the sequence.

Cross-sections are constructed using field data from outcrops, measurements of dip and strike, road cuttings, and other exposures. Ultimately, they represent a geologist's interpretation of the subsurface structure based on available evidence.

The figure below shows a simplified example of a geological cross-section (Figure 7.13), where siltstone is the oldest rock layer and limestone is the youngest. In this section, no folding or faulting has occurred.

In the second figure the cross-section illustrates a complex geological his-

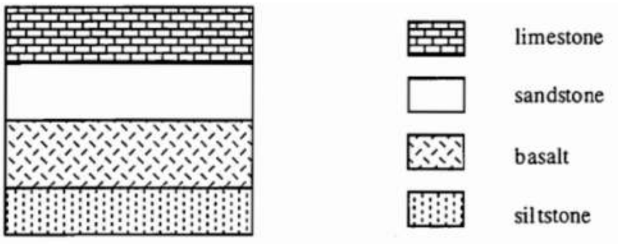


Figure 7.13: Simplified Geological cross-section

tory characterized by multiple phases of deposition, deformation, and erosion (Figure 7.14). The stratigraphic sequence begins with the deposition of siltstone, followed successively by mudstone, sandstone, and a tuff layer. This was subsequently overlain by a basalt flow, derived from volcanic activity and cooling of extruded lava. The entire succession was later subjected to folding, after which normal faulting occurred. The relative timing of these events is established by the continuity of the fault trace across folded strata, indicating that the faulting postdates the folding; if folding had occurred later, the fault plane itself would have been bent or disrupted. Following these tectonic events, the sequence experienced a phase of erosion that produced an unconformity, marking a significant temporal gap in the record. Younger deposits of siltstone, shale, and sandstone were then laid unconformably above the older folded and faulted units. Finally, subsequent erosion shaped the present-day landscape.

7.5.1 The Ougarta Cross section

Most geological maps include cross-sections, often referred to as tectonic sections, typically illustrated at the bottom of the map. The primary purpose of these sections is to provide an overview of the structural configuration of the

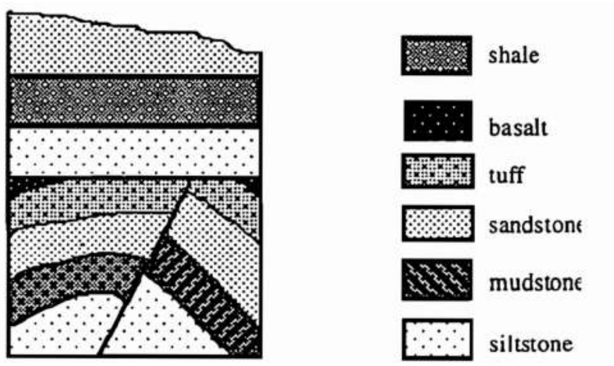


Figure 7.14: Folded layers overlain by tabular layers

basin, highlighting the geometry of folds, the position of major faults, and the occurrence of shear zones. Such representations are frequently employed by petroleum geologists to identify stratigraphic intervals with potential hydrocarbon reservoirs. The cross-section presented below (Figure 7.15) was constructed along two principal directions: from southwest to northeast, and from north-northeast to south-southwest. It should be noted that the geometry of the cross-section varies depending on the orientation chosen; for instance, a north–south profile would yield a different structural interpretation. The illustrated section extends over approximately 80 km and reveals a succession of anticlines and synclines. The Gharet Yhoud anticline, located at the western margin, is characterized by a weak dip and is followed by two relatively smaller anticlines whose cores are composed of Lower Devonian strata. To the east, two synclines, including the Bou M'Haoud syncline, are separated by subhorizontal strata attributed to the Ordovician. A major structural feature in this section is the Koudiat el Mdaga thrust fault, which truncates Ordovician units O2-3, O4, and O5-6, indicating that its emplacement postdates the deposition of these strata.

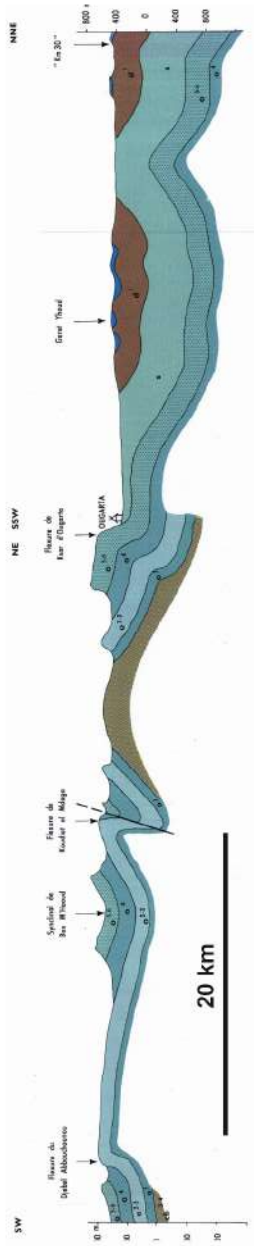
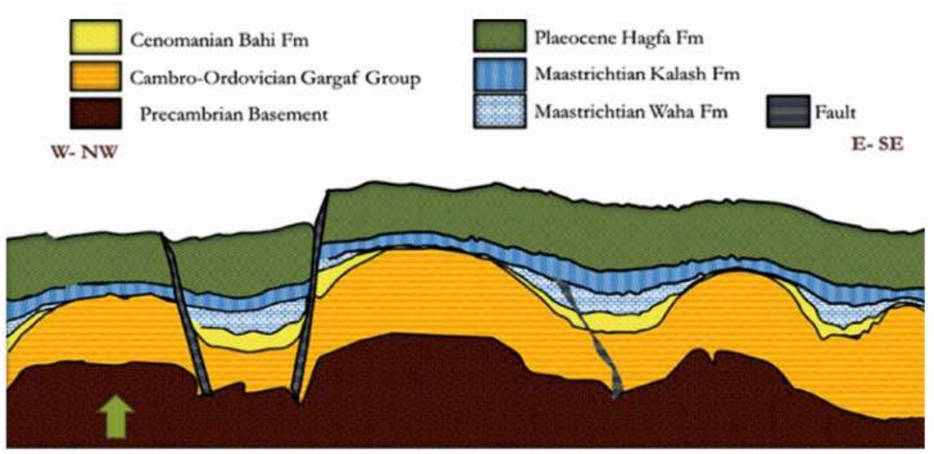


Figure 7.15: Geological section of Ougarta basin

7.6 Exercises

Exercise 1:

- In a few lines, define the main differences between a topographic map



and a geological map.

• Can a topographic map be useful for studying the main structures of basins? Explain briefly.

Exercise 2 :

• Identify all the deformations observed in this section.

• Describe the features of each deformation in a separate line.

Exercise 3: The map shown below corresponds to the Gold Coast and Hinterland region (USA). Based on this map:

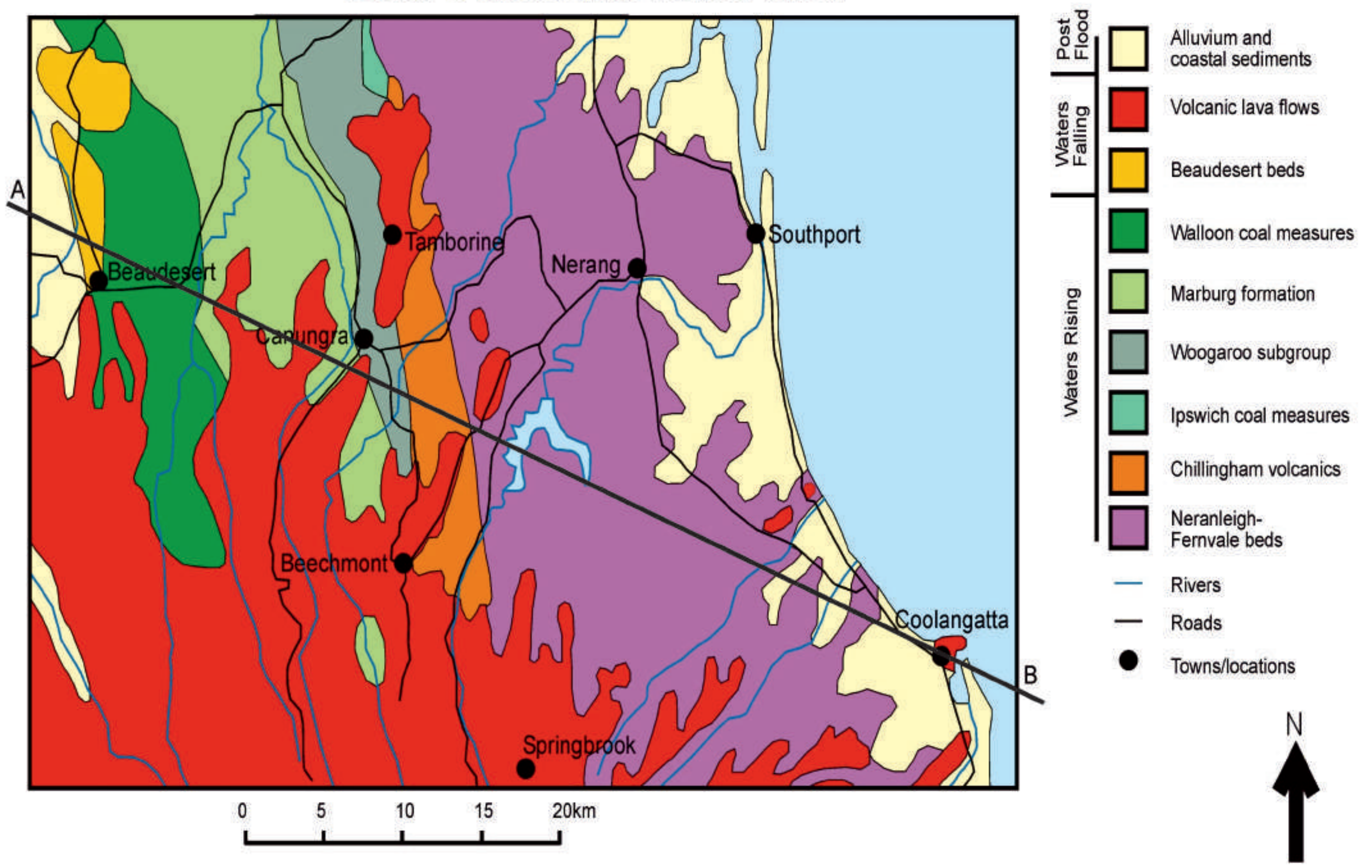
• Which formation is the most recent and which is the oldest? Explain why.

• Identify the formation(s) indicated by arrows that are defined by magmatic rocks.

• Does this map display major or minor faults?

• Draw a simple sketch (without calculation) of the geological cross-section along the AB axis.

Gold Coast and Hinterland



Chapter 8

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